A STUDY OF THE DISTRIBUTION OF CARBON IN THE NEARBY UNIVERSE

Inaugural-Dissertation

zur
Erlangung des Doktorgrades
der Mathematisch-Naturwissenschaftlichen Fakultät
der Universität zu Köln

vorgelegt von

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aus Bochum

Köln
2017
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für Theresa
Abstract

The composition and the evolution of the interstellar medium (ISM) is a major topic in the current research debate. The present thesis aims to gain a wider perspective of the distribution and composition of C$^+$, C$^0$, CO and H$_2$ in the Milky Way and in the nearby spiral galaxy M33. $[^{12}\text{C}]$, $[^{13}\text{C}](1–0)$, $^{12/13}\text{CO}(1–0)$, $^{12}\text{CO}(2–1)$ and $^{12}\text{CO}(4–3)$ emission spectra are primarily used to trace and characterise the physical and chemical conditions within the ISM and to study its evolution. Three major samples were analysed, each providing an insight into different aspects of the ISM.

First, the nature and composition of clouds along the line of sight towards the quasars B0355+508 and B0212+735 is investigated. These clouds were identified as warm non–LTE diffuse clouds with a temperature of $T\sim30$ K and subthermal excited CO lines for roughly two decades. If the clouds were indeed diffuse, $[^{3}\text{C}]$ emission lines with an integrated line intensity of few K km/s were expected. SOFIA/GREAT $[^{3}\text{C}]$ observations, carried out within this thesis, do not show such $[^{3}\text{C}]$ lines. It is shown that the observations are not compatible with the scenario of warm diffuse clouds. The clouds towards B0355+508 and B0212+735 can not be diffuse. Furthermore, it is shown that all the observational data is fully consistent with an ensemble of cold dense clumps, that have volume densities of $n(\text{H})\sim10^{3.5}$ cm$^{-3}$ to $10^{4}$ cm$^{-3}$ and core temperatures of $T\sim15$ K.

Secondly, the latitudinal and radial distribution of carbon in the fourth quadrant of the Milky Way, is studied. The study is based on the analysis of spectrally resolved latitudinal observations of $^{12/13}\text{CO}(1–0)$, $^{12}\text{CO}(2–1)$, $^{12}\text{CO}(4–3)$ and $[^{1}\text{C}](1–0)$. These lines were observed between $b=\pm2^\circ$ at eight galactic longitudes between $l=306^\circ$ to $354^\circ$. I have determined and analysed the latitudinal and radial distribution of the different transitions. The study shows that the most of the $[^{1}\text{C}](1–0)$ emission can not be observed in the absence of low–J CO lines. This indicates that C$^0$ primarily arises from the surface of the CO photodissociation layer. The observed latitudinal profiles of CO and $[^{1}\text{C}](1–0)$ have a asymmetrical shape and can not be described by a single Gaussian. The scale height of the different transitions is determined at different distances to the Galactic Centre. It is found that the radial distribution of the scaleheight can be fitted with a power law, $\propto\sqrt{R_{\text{GCC}}}$. The profiles have a similar shape as synthetic $[^{3}\text{C}]$ profiles carried out within the SILCC–project. That might indicate that the local structure of the Milky Way is triggered to a large degree by supernovae.

The distribution and composition of carbon and hydrogen are investigated in the case study of five giant molecular clouds (GMCs) in the nearby galaxy M33. M33 is of interest as it has a half solar metallicity. I present $[^{1}\text{C}](1–0)$ observations of these GMCs. With the use of comple-
mentary [C\textsc{ii}], $^{12}/^{13}$CO(1–0), CO(2–1), H\textsc{i} and [N\textsc{ii}]122\mu m data, I am able to determine the column densities of all major carbon species, CO, C$^0$ and C$^+$ and the column densities of neutral atomic hydrogen. The amount of H\textsubscript{2} is directly determined via the carbon column densities in the molecular phase. In addition, the fraction of CO dark H\textsubscript{2} is derived. Furthermore, I discuss the radial and spectral distribution of the different gas species. H\textsubscript{2} conversion factors for the observed line transitions are calculated. Finally, the individual positions are discussed in detail. The results indicate that the CO dark H\textsubscript{2} fraction is presumably higher towards lower metallicities. Probably up to $\sim$2/3 of the H\textsubscript{2} is CO dark in M33. The majority of this CO dark H\textsubscript{2} is traced by [C\textsc{ii}], not by [C\textsc{i}](1–0). I also discuss the effect of different assumed [C\textsc{ii}] excitation temperatures. It is shown that the assumed [C\textsc{ii}] excitation temperature deeply affects the estimated amount of carbon and hydrogen, in particular the amount of CO dark H\textsubscript{2}. 

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Zusammenfassung

Die Zusammensetzung und die Entwicklung des interstellaren Mediums (ISM) ist eine bedeutendes Thema der aktuellen Forschung. Die vorliegende Arbeit soll ein tieferes Verständnis für die Verteilung sowie die Zusammensetzung von $C^+$, $C^0$, CO, sowie von $H_2$ in der Milchstraße und deren Nachbargalaxie M33 vermitteln. Hierzu wurden hauptsächlich Spektren von $[\text{CII}]$, $[\text{CI}](1–0)$, $^{12/13}\text{CO}(1–0)$, $^{12}\text{CO}(2–1)$ und $^{12}\text{CO}(4–3)$ analysiert. Die Daten erlauben einen Einblick in die physikalischen und chemischen Bedingungen des ISM und ermöglichen es seine Evolution zu erforschen. Die vorliegende Arbeit basiert hauptsächlich auf der Analyse dreier unterschiedlicher Beispiele, die diverse Aspekte des ISM beleuchten.

Ich untersuche hierzu zuerst die Zusammensetzung von Wolken entlang der Sichtlinie zu den Quasaren B0355+508 und B0212+735. Diese Wolken werden seit gut zwei Jahrzehnten für warme diffuse Wolke gehalten ($T \sim 30$ K), in welchen sich das CO in einem subthermal angeregten Zustand befindet. Sollten die Wolken tatsächlich diffus sein, müssten in ihnen $[\text{CII}]$ Linien mit einer integrierten Linienintensität von einigen K km/s beobachtbar sein. Die $[\text{CII}]$ Beobachtungen, welche mit SOFIA/GREAT durchgeführt wurden, zeigen diese Linien jedoch nicht. Im Rahmen dieser Arbeit wird gezeigt, dass diese Beobachtungen unvereinbar mit warmen diffusen Wolken sind. Des Weiteren wird dargestellt, dass alle Beobachtungen durch ein Ensemble kalter, dichter Klumpen, mit Volumendichten von $n(\text{H}) \sim 10^{3.5}$ cm$^{-3}$ bis $10^4$ cm$^{-3}$ und Kerntemperaturen von etwa $T \sim 15$ K, erklärt werden können.

Anhand von $^{12/13}\text{CO}(1–0)$, CO(2–1), CO(4–3) und $[\text{CI}](1–0)$ Beobachtungen betrachte ich die radiale und vertikale Verteilung von Kohlenstoff im vierten Quadranten der Milchstraße. Die spektral aufgelösten Daten wurden bei acht unterschiedlichen galaktischen Längengraden zwischen $l=306^\circ$ und $l=354^\circ$ Länge, in einem Bereich zwischen den galaktischen Breitengraden $b=\pm 2^\circ$ beobachtet. Die Analyse zeigt, dass der größte Teil von $[\text{CI}](1–0)$ nicht in der Abwesenheit von niedrigen CO Rotationslinien beobachtet werden kann. Dies impliziert, dass $[\text{CI}](1–0)$ wahrscheinlich von der CO–Photodissoziationsschicht emittiert wird. Die vertikalen Profile, senkrecht zu der galaktischen Ebene, von $[\text{CI}](1–0)$ und den CO Übergängen haben eine asymmetrische Form und können nicht durch eine einzige Gaußkurve beschrieben werden. Ebenso wurde die Skalenhöhe der einzelnen vertikalen Verteilungen bei unterschiedlichen Entfernungen zum galaktischen Zentrum bestimmt. Deren radiale Verteilung kann mittels eines Potenzgesetzes ($\propto \sqrt{R_G}$) beschrieben werden. Des Weiteren weisen die beobachteten Profile starke Ähnlichkeiten zu synthetischen $[\text{CII}]$ Profilen auf, welche im Rahmen des SILCC-Projekts simuliert wurden. Dies könnte darauf hinweisen, dass die lokalen Strukturen der Milchstraße zum größten Teil durch Supernova–Explosionen bestimmt wird.
Am Beispiel von fünf Riesenmolekülwolken (GMCs) analysiere ich die Verteilung und die Zusammensetzung von Kohlenstoff und Wasserstoff in M33. Diese fünf GMCs befinden sich auf der Hauptachse dieser Galaxie. M33 ist von großer Bedeutung für diese Arbeit, da ihre Metallizität nur halb so groß ist wie die der Milchstraße. Ich präsentiere [C\text{\textsc{i}}](1–0) Beobachtungen von diesen GMCs und kombiniere diese mit komplementären [C\text{\textsc{ii}}], \(^{12}/^{13}\)CO(1–0), CO(2–1), H\text{\textsc{i}} und [N\text{\textsc{ii}}]122\text{\textmu}m Daten. Diese Daten erlauben die Bestimmung der Säulendichten von CO, C\text{\textsc{0}} und C\text{\textsc{+}} sowie der des neutralen atomaren Wasserstoffs. Die Menge von H\text{\textsc{2}} wird aus den Kohlenstoffsäulendichten der molekularen Phase bestimmt. Der Anteil des H\text{\textsc{2}}, der nicht durch CO–Linienübergänge bestimmt werden kann (CO dunkles H\text{\textsc{2}}), wird ebenfalls bestimmt. Ich diskutiere außerdem die radiale und die spektrale Verteilung der einzelnen Gasarten. Zuletzt werden die einzelnen GMCs nochmals im Detail besprochen. Die Ergebnisse deuten darauf hin, dass der Anteil des CO dunklen H\text{\textsc{2}} bei einer niedrigeren Metallizität erhöht ist. Ungefähr \(~2/3\) des H\text{\textsc{2}} in M33 ist nicht mit CO assoziiert. Die Mehrzahl des molekularen Wasserstoffs kann wahrscheinlich durch [C\text{\textsc{ii}}] ausfindig gemacht werden, nicht jedoch durch die [C\text{\textsc{i}}](1–0) Linie. Der Einfluss von unterschiedlicher Anregungstemperaturen von [C\text{\textsc{ii}}] wird ebenfalls diskutiert. Ich zeige, dass die angenommene [C\text{\textsc{ii}}] Anregungstemperatur einen großen Einfluss auf die Berechnungen der Gesamtmenge von Kohlenstoff und Wasserstoff besitzt, insbesondere auf den Anteil von CO dunklem H\text{\textsc{2}}.
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Part I

INTRODUCTION & MOTIVATION
Chapter 1

Introduction

The overall goal of this thesis is to create a wider perspective of the distribution and composition of the interstellar medium (ISM) in the nearby universe. This study is focused on the analysis of ionised (C$^+$) and neutral atomic (C$^0$) carbon as well as on carbon monoxide (especially its low rotational transitions between $J=1–0$, 2–1 & 4–3) emission spectra in the Milky Way and in the nearby galaxy M33. This thesis uses these lines to trace and characterize the physical and chemical conditions within the ISM and to study its evolution. Of particular interest is the distribution and the fraction of molecular hydrogen.

The following section will give a brief introduction of the ISM and explain the motivation as well as the goals of this thesis.

Since Jansky (1933) detected 'Electrical Phenomena that apparently are of Interstellar Origin' in 1933, the interstellar medium has been studied. Since then astronomers have studied the composition of the ISM, its role and impact on the formation of stars and galaxies as well as their evolution. The composition of the ISM is not uniform. It consists of different gas phases. Each phase represents gas at specific, different temperatures and densities, such as hot diffuse ions and cold dense molecular clouds with a complex chemistry and molecules (cf. chapter 2). The mass of the ISM is dominated by hydrogen ($\sim$74%). The majority of the remaining mass is helium ($\sim$23%; cf. Alfaro & Delgado 2011). The remaining mass is comprised by the heavier elements.

Hydrogen occurs in its ionised ($H^+$), neutral ($H^0$) and/or molecular form ($H_2$) in the ISM. $H^+$ dominates the hot phase of the ISM and $H^0$ the warm and cold neutral phase. Molecular hydrogen dominates the mass in the dense cold regions of the ISM. The emission of $H^+$ and $H^0$ can be easily observed from ground based observatories, while molecular hydrogen is almost invisible for the observer, even though it is the most abundant molecule in the universe (e.g. Field, Somerville & Dressler 1966, cf. chapter 4). Therefore, $H_2$ is commonly studied indirectly via tracers. Common tracers for $H_2$ are low rotational transitions of carbon monoxide (cf. e.g Young & Scoville 1982; Liszt 1982; Bloemen et al. 1986; Scoville & Sanders 1987; Wilson & Scoville 1989; Bolatto et al. 2013) and the

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i Single ionised hydrogen can be observed at a wavelength of 656.3 nm. Neutral atomic carbon is commonly observed via its ground state hyper-fine transition at 21 cm. The physic of line transition is explained in detail in section 4.1.

ii $H_2$ is a symmetrical molecule. It has no permanent dipole moment. Therefore rotational transitions are forbidden and no radio transitions can be observed. For details see Section 4.1
emission of dust (e.g. Hollenbach & Salpeter 1971; Jura 1975; Hollenbach & Tielens 1999; Röllig et al. 2013). Not all H$_2$ is traced by CO transitions. It is assumed that about one third of the molecular mass in molecular clouds in the Milky Way is located in H$_2$ regions where the carbon is exclusively ionised (C$^+$) or/and neutral atomic (C$^0$) in the absence of CO (Hollenbach & Tielens 1999; Wolfire et al. 2010). This molecular hydrogen is often denoted as ’dark gas’ (Grenier et al. 2005) and ’CO dark H$_2$ gas’ (Leroy et al. 2011). Therefore, it is of great interest to study the transitions of C$^+$ and C$^0$. Furthermore, the transition of single ionised carbon is almost ubiquitous in the ISM, and it is a dominant coolant for major phases. It is further assumed that neural atomic carbon is associated with diffuse interstellar clouds (in formation) (e.g. Bergin et al. 2004; Beuther et al. 2014) as well.

The key to study the ISM and to gain an almost complete overview of its composition is the combination of spatially and spectrally resolved observations of different lines which trace the different processes and phases. The study of different lines provides information about the physical and chemical conditions of the ISM. The comparison of different line transitions allow for instance to estimate the densities and temperatures within the source of interest. Spatially resolved data show the line intensities at the projected two dimensional sky. Spectral data provides an additional velocity dimension. Spectrally resolved data is thus in particular suitable to the study of the ISM. The spectral information provide a direct insite into the kinematics within molecular clouds. They allow to distinguish between different possible velocity components along the line of sight, as they have different central velocities. The line-shape supplies information about the physical conditions within the observed sources as well. The comparison of different line profiles delivers further information about the physical and chemical conditions in molecular clouds in three dimensions. A central point of thesis will be the comparison of CO and the transitions of neutral atomic and ionised carbon. This allows inter alia to allocate the distribution of CO-dark H$_2$ in molecular clouds.

The examination of spectral lines of ionised, neutral and molecular carbon (especially carbon monoxide) is predestined for this task. The observation and combination of different carbon transitions allow to gain thus an almost full picture of the ISM as each transition is tracing a designated phase of the ISM (cf. section 2.1).

These carbon transitions have frequencies within the the sub–millimetre and millimetre regime, which corresponds to frequencies of a few 10$^2$ Gigahertz (GHz) to a few Terahertz (THz). The observation of these frequencies (especially THz frequencies) is a technically demanding challenge. State of the art receivers$^{iii}$ and telescopes allow to study GHz and THz frequencies with the required spatial and spectral resolution ($\lesssim 1'$ and $\lesssim 10^{-1}$ km/s) within the last years. The observations require a dry atmosphere$^{iv}$, as these frequencies are easily absorbed by water vapour. Therefore, (sub–)millimetre telescopes are commonly located at high al-

$^{iii}$ Often heterodyne receivers are used to observe spectra with a high spectral resolution. For details see the Appendix B.

$^{iv}$ As thumb rule: Higher frequencies require a dryer atmosphere. By experience it can be said that [C$\text{ii}$] (1–0) (492 GHZ) requires a precipitable water vapor (pwv) of $\lesssim 0.7$ mm. [C$\text{ii}$] observations (1900 GHZ) require a pwv<0.1mm. I recommend Guan (2013) concerning the effect of the atmosphere for sub-millimeter observations.
introduction

Figure 1.1: The Stratospheric Terahertz Observatory (STO) shortly before the launch at the 12th January 2012 near the McMurdo station in Antarctica.

Credit: Left: Antony A. Stark;
Right: Screen-shot from the Operation Video of the Columbia Scientific Balloon Facility (CSBF)/NASA few second before the launch of STO.

titudes, such as the Mauna Kea (Hawaii, $\sim 4000$ m), the Pampa la Bola (Atacama desert, $\sim 5000$ m), the Antarctic plateau$^v$, in air planes or in space.

Facilities that are particularly worth mentioning in this context are the Herschel space observatory (Pilbratt et al. 2010) with the HIFI (de Graauw et al. 2010), PACS (Poglitsch et al. 2010) and SPIRE receivers (Griffin et al. 2006; 2010) as well as the air borne submillimeter telescope SOFIA (e.g. Becklin et al. 2007; Becklin 2015) with the GREAT, and upGREAT–receiver (Heyminck et al. 2012; Risacher et al. 2015) allowing observations of ionised carbon.

The transitions of neutral atomic carbon can be observed by the Caltech Submillimeter Observatory (CSO, Phillips 1996; Kooi 2009; Kooi et al. 2010), APEX with the APEX-3-receiver (Güsten et al. 2006; Vassilev et al. 2008), AST/RO (Balm 1996; Stark et al. 2001) and Nanten2/SMART (Kawamura et al. 2005; Graf et al. 2002; 2008). Prominent observatories for low $J$–transitions of carbon monoxide are Mopra (Moorey et al. 1997; Burton et al. 2013a), IRAM-30m (Brunswig 1993; Mauersberger 2003) and the Plateau de Bure interferometer (PdB; Blondel et al. 1996; Karastergiou & Neri 2006).

Recently, a small number of studies have investigated the ISM by use of all the different carbon transitions. These studies are preliminary focused on individual objects. Examples can be found in the studies by Beuther et al. (2015) of infrared dark clouds, García et al. (2014) of the warm ISM in the region around Sgr A*, the N159 star-forming region in the Large Magellanic Cloud by Okada et al. (2015), the S109 region by Schneider et al. (2003) and the study of M17 SW by Pérez-Beauquets et al. (2015).

$^v$ The South Pole for example is located 'only' at an altitude of $\sim 2800$ m. Nevertheless the atmosphere is very dry, pwv $\sim 0.25$ mm, due to the low atmospheric pressure ($\sim 700$ millibar) and the low temperatures. The driest atmosphere for ground based observations can be found at the Dome A ($\sim 4000$ m), located at the summit of the Antarctic plateau (Kulesa et al. 2008; Burton et al. 2014)

$^vi$ HIFI is a heterodyne spectrometer with a spectral resolution of $\lesssim 1$ MHz. PACS and SPIRE are bolometers. Bolometers provide no, or only low resolved (by using filters), spectral information. I would like to refer to Appendix B, for further details.
The Herschel space observatory key program GOT C$^+$ studied the distribution of [Cii] in the Milky Way at the galactic latitude $b=0^\circ$ (Pineda et al. 2013; Langer et al. 2014b; Pineda et al. 2014).

A full sample of all the carbon lines at galactic scales has not been performed so far. An attempt to gain such a full sample of major parts of the Milky Way was the Mopra–STO–Nanten2 Atomic and Molecular Gas Survey (Burton et al. 2012). This survey had planned to map the C$^+$, C$^0$ and CO distribution within the the fourth quadrant of the Milky Way with an overall spatial resolution of $\Delta\delta \lesssim 1^\prime$ and $\Delta v \lesssim 0.1$ km/s. $^{12/13}\text{C}^{16/17/18}\text{O}(1-0)$ observations of this region are performed within the Mopra Southern Galactic Plane CO Survey. The balloon-born Stratospheric Terahertz Observatory (STO; Walker et al. 2008; 2010; Walker 2012; cf. Fig. 1.1) tried to map the [Cii] emission within $b=\pm 0.5^\circ$ the galactic latitude. After the launch on January 12th 2012 near the McMurdo station, STO circumnavigated the Antarctic continent for 14 days at an altitude of almost $\sim 40$ km. Technical problems with the cryostat which appeared shortly after the launch, and problems with the star-camera, prevented a [Cii]–mapping of the Milky Way. Therefore, no [Cii] data is provided within this project. STO was the major motivation to map the distribution of C$^0$ and CO transitions in the fourth quadrant of the Milky Way. The $^{12/13}\text{C}^{16/17/18}\text{O}(1-0)$ transitions are mapped between $350^\circ \leq l \leq 310^\circ$ and $-0.5^\circ \leq b \leq 0.5^\circ$ (Burton et al. 2013a; Braiding et al. 2015). The vertical distribution of [C] (1–0), CO(2–1), CO(4–3) and $^{12/13}\text{C}^{16/17/18}\text{O}(1–0)$ was mapped between $-2^\circ \leq b \leq 2^\circ$ at selected galactic longitudes by observations with AST/RO and Morpa (cf. Fig. 1.2).

It is planned to provide complementary [Cii] observations for the $b$–strips with SOFIA/upGREAT. Complementary Hi data of this quadrant is available from the Southern Galactic Plane Survey (SGPS; McClure-Griffiths et al. 2005) obtained by the Australia Telescope Compact Array (ATCA) and the Parkes radio observatory with a dish–diameter of 64 m.

An other attempt to gain a full sample of all the carbon lines in a galaxy is the Herschel open time key project HERM33ES (Kramer et al. 2010). A goal of the HERM33ES is to gain an almost complete overview of the ISM of M33, with respect to the galactic radius. M33 was intensively studied by all three instruments on-board Herschel: HIFI, PACS, SPIRE. SPIRE observed the $250\mu\text{m}$, $360\mu\text{m}$ and $520\mu\text{m}$ emission of the almost entire galaxy. PACS and HIFI observed i.a. [Cii] in selected regions along the major axis. Complementary CO and HI data was observed within the HERM33ES-project as well.

This thesis studies the distribution of carbon within the ISM. To a large extent this study is based on data that is provided within the Mopra–STO–Nanten2 Atomic and Molecular Gas Survey and the HERM33ES project. In order to achieve this goal, this thesis combines data of the CO, C$^0$ and C$^+$ transitions in the Milky Way and M33. Some missing line transitions are complemented by own observations, that are published in this thesis. This thesis was also intended to analyse the STO [Cii]–observations and vii The project observed the [Cii] transition, using Herschel/HIFI, at $b=0^\circ$ via a systematic sparse sampling of the Galactic disk, with a longitudinal spacing of 0.87$^\circ$ to 4.5$^\circ$.

viii The fourth quadrant of the Milky Way is given by the galactic longitudes $360^\circ \leq l \leq 270^\circ$.

ix These strips are denoted as $b$–strips in the following.
to compare the observations with complementary CO and C\(^0\) data. The technical problems of STO prevented this study.

The study is led by the overall question:

*What is distribution of carbon in the ISM and what conclusions can be drawn for the ISM in general?*

This major question is divided and accompanied by the following question:

1. *What are the composition and nature of clouds that are identified as diffuse CO clouds?*

The nature and composition of diffuse clouds are not well known. Diffuse clouds are commonly identified by the absorption of mm–waves in front of a bright foreground source. Liszt & Lucas (1998) succeeded in detecting CO \((J=1\rightarrow 0)\) and CO \((J=2\rightarrow 1)\) emission, identified to be associated with the diffuse clouds in a representative sample of mm–wave absorption towards the lines-of-sight to quasars. Pety et al. (2008b) identified these clouds as warm non-LTE\(^x\) diffuse clouds with a temperature of \(T\gtrsim30\) K and subthermal excited CO lines. Liszt &

\(^x\) Local Thermal Equilibrium (LTE)
Pety (2012) was able to map the CO (1–0) emission with a few arcmin extent around these positions. Small scale CO variations were interpreted as variations within the chemistry, not as density or column–density variations in the clouds.

The hypothesis is tested at the example of two nearby clouds from Liszt & Pety (2012) by SOFIA /GREAT [CII] observations. This question is tackled in chapter 5.

II What is the radial and vertical distribution of C0 and CO in the Milky Way?

The distribution of the C0 transitions in the ISM is not well studied. The distribution of C+ and CO(1–0) in the galactic plane was investigated in recent studies. The GOT C+ project has studied the distribution of ionised carbon along the galactic plane at b=0° (Pineda et al. 2013; Langer et al. 2014b; Pineda et al. 2014). The Mopra Southern Galactic Plane CO Survey (Burton et al. 2011; 2013a; Braiding et al. 2015) investigates the distribution of 12/13C16/17/18O(1–0) in the southern galactic plane between b=±0.5° galactic latitude. This thesis tries to fill the carbon gap between these surveys by analysing [CII](1–0) observations.

In chapter 6 I analyse spectral resolved 12/13CO(1–0), CO(2–1) and CO(4–3) and [CII](1–0) strip–data between the galactic latitudes b=±2 (so called b-strips) at different galactic longitudes, provided by observations with AST/RO and Mopra. The radial and the vertical distribution of these transitions is determined as well as the average width of the gas perpendicular to the galactic disc ("scale height"). Further the data is analysed regards the question whether there are differences in the distribution of the CO transitions and [CII](1–0).

III Which processes drive the large scale structure of the ISM within the Milky Way?

The comparison of the vertical distribution of CO and [CII](1–0) with simulated [CII] maps (Walch et al. 2015; Franeck et al. submitted) allows conclusions about the dominant processes that drive the evolution of the ISM (chapter 6).

IV How does the metallicity affect the distribution of carbon and the fraction of 'CO-dark H2 gas'?

The affect of a half solar metallicity onto the distribution of carbon is studied at the example of the nearby galaxy M33 in chapter 7. The fraction of CO dark H2 in M33 is studied as well. It is assumed that the fraction of CO dark H2 is increased towards lower metallicities.

In this thesis, I present spectral resolved [CII](1–0) observations of five giant molecular clouds (GMCs) along the major axis of M33. The observations were performed with the APEX, CSO and Nanten2 telescopes. The data is combined with complementary HI, [CII] and low J–CO observations provided within the framework of the HERSCHEL open key time project HERM33ES (Kramer et al. 2010). The combination of these data allows to determine the distribution of C+, C0 and CO in the M33. Based on these calculations I determine the fraction and the (radial and spectral) distribution of H2 that is
traced by the different carbon species. The fraction of CO dark H$_2$ is calculated and is compared with theoretical predictions by Wolfire, Hollenbach & McKee (2010).

Based on the derived H$_2$ column densities and the integrated line intensities I will calculate H$_2$ conversion factors for the integrated [Cii], [Cl](1–0) and CO(2–1) line intensities. These conversion factors are intended to be a simple and workable method to estimate the amount of H$_2$ in molecular clouds. The calculated conversion factors will be compared to established conversion factors in the Milky Way and with theoretical predictions for environments with a lower metallicity.
Part II

SCIENTIFIC BACKGROUND
Chapter 2

The interstellar medium

The following chapter provides a general introduction into the structure and composition of the ISM.

2.1 OVERVIEW OF THE INTERSTELLAR MEDIUM

In general, the term interstellar medium refers to all the baryonical matter located between the stars\(^1\). The majority of the baryonic mass within the Milky Way is bound in stars or stellar remnants (Draine 2011). The fraction of the ISM to the total baryonic mass within the Milky Way is \(\sim 10\% - 15\%\) (Draine 2011). Nevertheless, the ISM is of tremendous importance for galaxies, despite its relatively small mass fraction. The ISM itself consists mainly of hydrogen (~70\% by mass and ~91\% by atoms) and helium (~28\% of the mass and ~9\% by the number of atoms). Heavier elements contribute in total to ~1.5\% to its mass (~0.1\% of the atoms) (Ferrière 2001).

The ISM consists of a wide range of different phases. Each phase represents gas and dust within a range of specific temperatures and densities. The description of the following section is mainly based on the categorisation of Tielens (2010) and Ferrière (2001).

**Hot ionized medium:** The hot ionized medium (HIM) consisting of hot gas with typical high temperature of \(T \sim 10^{5.5-6}\) K, heated by supernova shock (Aschenbach 1988; McCammon & Sanders 1990), and low volume densities of \(n \sim 10^{-3}\) cm\(^{-3}\). The HIM represents ~30-70\% of the gas volume within the galaxy (Ferrière 2001).

**HII regions:** The HII regions are named after their dominant gas form, ionized hydrogen. HII-regions are commonly located nearby hot young O and B–type stars\(^2\). Their UV radiation penetrates the gas and photo-ionizes the hydrogen. The temperatures of HII regions are ~10\(^4\) K (Spitzer 1947; Mallik 1975; Draine 2011). The densities

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\(^1\) Besides the baryonical matter the universe consists of dark matter and the dark energy. Baryons have a mass fraction of \(\approx 4.8\%\) to the total energy of the modern universe. The fraction of dark matter is \(\approx 25.8\%\). The majority of energy in the universe consists of dark energy (Planck Collaboration et al. 2014a;b).

\(^2\) Johnson & Morgan (1953) classify stars by their spectral type into seven main types: O, B, A, F, G, K, M, the so-called Morgan-Keenan spectral classifications. Within this classification system, the blue O-type stars have the highest mass and temperature. The red M-type stars have the lowest mass and temperatures.
within these regions vary between \( n \sim 10^{-1} \text{cm}^{-3} \) to \( 10^4 \text{ cm}^{-3} \). This phase is predominantly cooled by the forbidden line transitions\(^{iii}\) such as ionized nitrogen ([N\(\text{II}\)]205\(\mu\text{m}\) and [N\(\text{II}\)]122\(\mu\text{m}\)) and oxygen ([O\(\text{I}\)] and [O\(\text{III}\)]), but also by the transition of single ionized carbon, [C\(\text{II}\)].

**WARM IONIZED MEDIUM**: Low dense H\(\text{II}\) gas (\( n \sim 10^{-1} \text{ cm}^{-3} \)) (Struve & Elvey 1938) is also denoted as the *warm ionized medium (WIM)*. A significant fraction of the hydrogen mass, \( \sim 23\% \), and of the volume, \( \sim 10-20\% \), of the ISM can be assigned to the WIM.

**NEUTRAL ATOMIC GAS**: The neutral atomic gas can be divided into the following two phases (Ferrière 2001): the *warm neutral medium (WIM)* and the *cold neutral medium (CNM)*. Both phases have in common that they mainly consist of neutral atomic hydrogen. The dominant coolant in both phases is the [C\(\text{II}\)] fine structure transition. The warm neutral medium is characterised by broad emission lines. Typically, it has kinetic gas temperatures of \( T \sim 5000 \text{ K} \) and volume densities of \( n \sim 0.6 \text{ cm}^{-3} \). This gas phase is widely distributed in the galaxy with a volume fraction of \( \sim 40\% \).

The cold neutral medium is characterised by narrow lines with widths of a few km/s, that are observed in emission or absorption. The CNM mainly consists of cold clouds with temperatures of \( T \simeq 50-200 \text{ K} \) and densities from \( n \sim 10^1 \text{ cm}^{-3} \) to \( 10^2 \text{ cm}^{-3} \). The CMN contributes \( \sim 1 \) to \( 5\% \) to the total volume fraction of the ISM in the Milky Way. Nevertheless, it contains a non-negligible amount of its baryonical mass which amounts to \( \sim 1/3 \).

**MOLECULAR GAS**: The densest and coldest phase of the ISM is formed by *molecular gas*, \( T \sim 10^1 \text{ K} \) to \( 10^2 \), which is commonly assembled

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\(^{iii}\) The physics of these transitions is explained in detail in section 4.1
in gravitationally bound molecular clouds. Compared to the other phases, they are relatively compact and dense. The typical volume densities can be measured on a scale of \( n \sim 10^{-6} \text{ cm}^{-3} \) and fill \( \sim 5\% \) of the ISM volume. In comparison to its modest volume fraction, this molecular gas contains about \( \sim 20\% \) a rather big percentage of the total mass of the ISM. In this context, the star formation occurs in the densest and coldest regions of this phase. Molecular clouds are commonly traced by low \( J\text{–CO} \) transitions or dust emission, but neutral and ionized carbon are also associated with these clouds.

**DUST:** Despite its rather small percentage of \( \sim 1\% \) to the total mass of the ISM, dust plays an important role in galaxies (e.g. Parkin et al. 2012; Zavala et al. 2015). The dust in the ISM is mainly composed of graphite (Mathis et al. 1977; Draine & Lee 1984; Jones 2009), (amorphous) olivine\( ^{iv} \) and water ice (e.g. van Dishoeck et al. 1998). The distribution of the dust grain-sizes can be described by a power law (Mathis et al. 1977). The diameter of the dust particles ranges from \( \sim 1 \) to \( 10^{-3} \) \( \mu \)m with an open passage to the Polycyclic Aromatic Hydrocarbons (PAHs) (Gillett, Forrest & Merrill 1973; Leger & Puget 1984; Allamandola, Tielens & Barker 1985) at the lower end\( ^{v} \).

The dust grains in the ISM absorb a substantial fraction of the incoming radiation of stars (on average 1/3; Shull & Beckwith 1982; Kennicutt 2008; Draine 2011). Therefore, they contribute significantly to the shielding and the cooling of molecular clouds. The temperatures of the dust grains range from \( \sim 10^1 \) to \( 10^2 \) K. These low temperatures enable the gravitational bounding of molecular gas. Furthermore, dust grains are crucial for the formation of many molecules. The dust shields molecules from the penetrating UV radiation. Furthermore, the surface of icy dust grains serves as a catalyst to the formation of \( \text{H}_2 \) and therefore they are crucial for the bulk of the molecular mass in the ISM \( ^{vi} \). The continuum emission of dust correlates well with the line emissions that are associated with molecular clouds and the CNM (e.g. Bohlin 1975; Hollenbach & Tielens 1999; Planck Collaboration et al. 2014a).

There are no sharp boundaries amongst the different phases of the ISM. In fact, the different phases interact in a highly dynamic way as they are commonly assembled at relatively small scales of a few \( 10^1\)pc to a few \( 10^2\)pc. These regions are commonly denoted as Giant Molecular Clouds (GMCs).

For a general overview of the allocation of the different phases see Figure 2.1.

The amount of dust and PAHs along the path of the photons is commonly expressed by the extinction of photons with a wavelength of \( \lambda = 550 \)\nm.\n
\( ^{iv} \) Olivine is assigned to the group of silicate minerals. Olivine particles of interstellar origin are collected by the ‘Stardust’ spacecraft (Westphal et al. 2014). The olivine particles of interstellar origin are thus the first to be examined in a laboratory. Presumably 36 interstellar dust grains, analysed by the Cosmic Dust Analyzer (Srama et al. 1996) of the Cassini space-craft, consist of olivine as well (Altobelli et al. 2016).

\( ^{v} \) For a detailed review of the interstellar dust I recommend Henning (2010).

\( ^{vi} \) The formation processes of molecular hydrogen are described in section 2.3.
nm (green light). The extinction is described via $I(V) = I(0) \times 10^{A_v/2.5}$, with $A_v$ being the so-called optical extinction at 550 nm in the magnitudes unit (mag) and $I(V)$ being the visual intensity at a given $A_v$. If the ratio of dust to gas is constant, the optical extinction can be linearly correlated to the number of hydrogen nuclei along the path of the photons. In that case, the column density of hydrogen nuclei can be described via $N(H) \approx 2 \times 10^{21} A_v \text{ cm}^{-2} \text{ mag}^{-1}$. Interstellar clouds are often classified by their optical extinction, into diffuse, translucent and dense clouds (cf. e.g. Snow & McCall 2006). Diffuse clouds have a typical column density of $N(H) < 2 \times 10^{21} \text{ cm}^{-2}$ ($A_v < 1$ mag), dense (and dark) clouds have a typical column density of $N(H) \sim 10^{22} \text{ cm}^{-2}$ ($A_v > 4$ mag), while the column densities of translucent clouds are somewhere in between.

The different gas phases represent the different stages in the 'life cycle of matter in galaxies' (Knapp 1995). The interaction between the stars, the ISM and the recycling of matter determines the physical and chemical composition of the ISM as well as the stars and thus the evolution of galaxies. Stars are formed by and consist of the matter of the ISM. In turn, the ISM consists (at least partially) of the repository of stellar ejecta (Tielens 2010).

The diffuse phases of the ISM, such as the HIM, WIM and CNM, can be compressed to dense cold molecular regions (cf. Elmegreen 1996; Burton et al. 2013b), either triggered by a self-gravitational collapse of the clouds (Ostriker & Kim 2004), a collision of clouds (Kwan & Valdes 1987), converging flows in a turbulent medium (Hennebelle & Pérault 2000), by stellar winds and outflows and/or shocks induced by supernovae (McCray & Kafatos 1987). Currently it is a topic of research which of these processes are dominant. These dense molecular clouds can be considered as the birthplace of stars. The stars interact with the ISM via their ra-

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*I highly recommend Storey (1984) with regard to the physics of Protostellar outflows.*
2.2 PHOTON-DOMINATED REGIONS

The following section focuses on the physical and chemical properties of photon-dominated regions, PDRs \(^x\). PDRs are almost ubiquitous in the ISM. They represent \(\sim 90\%\) of its total molecular mass (Hollenbach & Tielens 1999). Therefore, it comes as no surprise that the majority of the sources studied in this thesis are photon-dominated regions as well.

This section is intended to provide a basic overview of PDRs. This is based on contributions made in Hollenbach, Takahashi & Tielens (1991), Sternberg & Dalgarno (1995), Hollenbach & Tielens (1999), Tielens (2010), Wolfire, McKee, Hollenbach & Tielens (2003), Wolfire, Hollenbach & Mc-

\(^{\text{ix}}\) This 'life cycle of matter in galaxies' is illustrated in Figure 2.2

\(^{\text{x}}\) The term 'photon-dominated regions' is coined by Sternberg & Dalgarno (1995).

Photon-dominated regions are often denoted as photo-dissociation regions (likewise abbreviated as PDRs) Hollenbach & Tielens (1999),
The physics, chemistry and structure of major parts of the ISM is driven and defined by the penetrating UV radiation. The main source to the UV photons are O- and B-type stars. Ultraviolet photons with energies $h\nu > 13.6$ eV ionize the hydrogen around these stars. These photons create Hii-regions known as Strömgren spheres. Ultraviolet photons with energies between $6eV < h\nu < 13.6eV$ are denoted as Far Ultraviolet photons (FUV). These photons do not ionize hydrogen, but they do have enough energy to ionize other atoms and ions, as carbon for example, to photo-dissociate molecules (e.g. $H_2$ and CO) and to heat the dust. The connection between PDRs and O and B stars is not exclusive. PDRs can be produced by the average interstellar radiation field (ISFR) as well. Its strength is briefly discussed in the following section.

The strength of the penetrating FUV field is commonly expressed in multiples of the average ISFR near the sun and measured in Habing units$^{xii}$.  

2.2.1 STRUCTURE OF A PDR

FUV photons interact with the ions, atoms, molecules and dust/PAHs particles in the molecular clouds in multiple ways. The FUV photons ionize atoms, photo-dissociate molecules and are absorbed by dust grains and PAHs. The strength of the FUV field is thus declining deeper into the cloud and the ISM is heated by the energy input of the penetrating FUV radiation.

The strength of the incident FUV fields influences many import aspects of the PDRs, such as its chemical compositions, the abundance of molecules, atoms and ions, the amount of free electrons and the temperature and densities. Therefore, a large number of chemical reactions in PDRs are triggered by the FUV radiation. For example, CO is photo-dissociated by FUV photons and $C^0$ is ionized to $C^+$. $C^+$ can capture an electron and recombine to $C^0$. $C^0$ can react with OH to CO (cf. Fig. 2.5).

PDRs possess different distinguished chemical zones for different $A_v$, each have specific prioritised chemical reactions. The abundance of the different molecules, atoms and ions can be roughly assigned to specific optical excitations. At specific FUV fields intensities, the destruction rate of a gas species is equal to its formation rate, forming a transition layer between the specific gas species.

The chemical transition zones of hydrogen, $H^+\rightarrow H^0$ and $H^0 \rightarrow H_2$, as well as the transition zones of carbon, $C^+$, $C^0$ and CO, are commonly used to describe the structure within a PDR (cf. Fig. 2.4). The next paragraph will describe these layers and their transition zones. The de-

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$xii$ Habing (1968) estimated the strengths of the IFRS to be $1.2 \times 10^{-4}$ erg cm$^{-2}$ sr$^{-1}$. This strength is commonly denoted as a ’Habing field’ in his honour. Draine (1978) showed that the strength of the average local ISFR is $\sim 1.7$ times higher than originally calculated, $G_0 = 1.7$ Habing $\sim 2 \times 10^{-4}$ erg cm$^{-2}$ sr$^{-1}$. The average local average interstellar radiation field of 1.7 Habing is often denoted as a ’Draine-field’, $\chi$, in honour of Bruce T. Draine
Figure 2.4: Schematic illustration of the hydrogen (upper panel) and carbon layers (lower panel) of a cloud, which is penetrated by UV-radiation from the left side. The region that is dominated by FUV radiation (Photo-dominated region) is marked by solid arrows at the top of the illustration. The visual extinction and total hydrogen column density is illustrated at the lower x-axis with increasing values towards higher distances from the surface of the PDR. The gas temperature rises towards the PDR-surface which is illustrated by the upper x-axis. C$^+$ is associated with the phases where the hydrogen is in its ionized, neutral atomic and molecular form. C$^0$ and CO is associated with H$_2$. The dotted line at the right shows a position where the cloud is stopped to be dominated by photons. At a higher $A_V$, CO starts to freeze out onto dust grains.

The surface of a PDR is defined by the transition layer between H$^+$ and H$^0$. It is determined by an average FUV energy of 13.6 eV. That corresponds to an $A_V \sim 0.1$ mag. Due to the high extinction rate, which is caused by the FUV radiation, only a few dust particles are present within the transition zone. Atomic ionized carbon is present at both sides of this layer. The next transition layer is the transition layer between H$^0$ and H$_2$. It is located at an $A_V \approx 1$-2 mag. This transition zone is mainly controlled by 'self shielding' of H$_2$. Due to the large amount of molecular hydrogen in PDRs, H$_2$ can become optically thick ($N$(H$_2$)$\sim 10^{14}$ cm$^{-2}$) and block all the photons which can photo-dissociate H$_2$ at larger cloud depths. Therefore, these photons are not present towards larger cloud depths. The self-shielding entails the effect that the H$^0$/H$_2$ transition layer is located at lower $A_V$ than expected from the pure dissociation energy of the H$_2$ molecule of 4.48 eV. CO, for example, has a higher dissociation energy of 11.09 eV, while its transition layer is associated with higher cloud depths of $A_V \approx 2$-4 mag (see below).

The transition layers between C$^+$, C$^0$ and CO are located between an $A_V$ of $\sim 2$ to 4 mag, accordingly they are associated with a higher optical extinction than the H$^0$/H$_2$ transition layer. Carbon has an ionisation energy of 11.60 eV while CO is photo-dissociated at 11.09 eV. C$^0$ is expected to be within these boundaries. The transition layers of the photo-dissociation
of CO and C$^+$ can be moved to lower $A_V$ by self-absorption\textsuperscript{xi}. The precise position of these transition layers are difficult to estimate and are still discussed in the current research debate. Various studies propose a C$^+$/C$^0$/CO transition layer in which C$^0$ cannot be observed in the absence of C$^+$ and CO (e.g. Tielens & Hollenbach 1985a;b; Sternberg & Dalgarno 1989). Hollenbach, Takahashi & Tielens (1991), Wolfire et al. (2003) and Wolfire et al. (2010) propose an additional gas phase dominated by neutral atomic carbon\textsuperscript{xiv}. These transition layers are of great relevance for this thesis.

Note that C$^+$ is associated with ionized, neutral atomic and molecular hydrogen, whereas C$^0$ and CO are associated exclusively with $\text{H}_2$. Molecular hydrogen, that is not directly associated with CO, is denoted as 'CO dark $\text{H}_2$'\textsuperscript{xv} (Leroy et al. 2011). The position of CO dark $\text{H}_2$ in a PDR is schematically illustrated in Figure 2.4.

The gas within the ISM has a no homogeneous distribution. It has a fractal structure (e.g. Elmegreen 1996). This fractal structure can be described by an ensemble of clumps. The distribution of the clump-masses as well as the relation of the clump size and mass, is described by a power law relation (Stutzki et al. 1998; Andree-Labsch et al. 2014).

2.2.2 Heating and Cooling Processes

The following section describes the energy balance in PDRs. Various heating and cooling processes determine the energy balance of a PDR which finally determine the chemical and physical structure of PDRs as well. Different gas heating and gas cooling scenarios are shown exemplified in Fig 2.6, in this case referring to a plane-parallel PDR.

\textsuperscript{xi} [CII] self-absorption, for example, is observed towards NGC 2024 (Stutzki et al. 2013).
\textsuperscript{xiv} Observations in M17 SW (Pérez-Beaupuits et al. 2015) as well as observations in M33 presented in this thesis, have found C$^0$ in the absence of CO
\textsuperscript{xv} for further details see section 2.2.4
2.2 Photon-dominated Regions

2.2.2.1 Heating

The heating of a PDR is mainly dominated by the deposit of energy via FUV photons that interact with gas and dust particles within the clumps. FUV photons interact via multiple processes with these particles. Major heating processes are described in the following:

**Photoelectric effect and photo ionization** The heating of PDRs is dominated by the photoelectric effect. When a FUV photon is absorbed by a dust grain or PAH, its energy is transformed into the kinetic energy of an electron. The electron is injected into the gas phase if the kinetic energy of the electron exceeds the coulomb potential and the work function of the grain. The excess of the kinetic energy is transferred to the kinetic energy of the other particles in the ISM via collisions which consequently heat the ISM.

The efficiency of the photo electric heating is at its maximum with a density of $\lesssim 3 \times 10^3$ cm$^{-3}$ and a kinetic gas temperature of $T \lesssim 100$ K. The heating amounts to about $\Gamma \simeq 5 \times 10^{-26} G_0$ erg (H-Atom)$^{-1}$ s$^{-1}$.

The ionization of carbon via FUV photons is an additional heating source of PDRs. These ejected electrons also are the major source of free electrons in PDRs.

**Collisional de-excitation of vibrational excited H$_2$** is an important heating process in these PDR-layers in which the hydrogen is mainly neutral atomic ($A_v \lesssim 2$ mag). Line absorbed FUV photons vibrational excite the H$_2$-molecules. At low densities ($n \lesssim 10^{-4}$ cm$^{-2}$) the excited states are de-excited to the ground vibrational state via a cascade of emitted infrared photons.
photo-dissociation of H$_2$ The photo-dissociation of H$_2$ is another heating source. The surplus energy of the resulting two single hydrogen atoms is re-partitioned to the other particles of the ISM.

formation of H$_2$ on dust grains This heating mechanism is of relevance for the inner regions of PDRs. H$_2$ is formed on dust grains$^{xvi}$. The formation of a H$_2$ molecule releases a binding energy of 4.48 eV. This energy is used to release the molecule from the dust grain into the gas phase to rotationally excite the molecule and to increase its kinetic energy. If it is assumed that the energy is equally partitioned, 1.5 eV can be used to heat the gas (Röllig et al. 2013).

cosmic ray heating The cosmic ray heating is a major heating source at large clouds depths ($A_V \gtrsim 6$ mag). At these $A_V$ the FUV radiation is almost extinct, while the cosmic ray particles can also penetrate higher cloud depths ($A_V \sim 100$ mag). The energy of the injected electrons is collisionally re-partitioned to the other gas components which heat the gas.

The penetrating cosmic ray heating amounts to $\sim 3 \times 10^{-27}$ erg (H-Atom)$^{-1}$ s$^{-1}$.

gas-dust grain collisions and turbulence The collisions of gas particles and dust grains as well as the turbulent dissipation are other heating mechanisms.

2.2.2.2 Cooling

PDRs are cooled via the emission of continuum IR radiation of dust grains ($\sim 90\%$) and the emission of far infrared photons produced by fine-structure and rotational transitions ($\sim 10\%$). The necessary condition for the cooling via dust IR continuum radiation are collisions of dust grains, which are the case in the dense regions of the clouds$^{xvii}$. In that case the temperatures of the dust and gas are coupled.

Due to the low number of dust grain collisions at low densities and high temperatures (diffuse gas), the cooling of the diffuse phases is dominated by the fine-structure transitions of ions. In this context the [CII] transition is worth mentioning, as it is inter alia the major coolant for diffuse H$_2$.

The cooling via line transitions has a maximal efficiency in optically thin gas as the photons can leave the PDRs. If the gas is optically thick, the emitted photons can be reabsorbed. Thus, the dwell time of the energy within the clumps is increased.

The observation of line transitions is of great interest in all the different regions of the ISM, as these lines provide information about the kinematics within the sources. That is not the case for IR continuum emission from dust. The physic of fine structure and rotational transitions is described in section 4.1.
2.2.3 Metallicity Effects and Defects of Different Clump Sizes

The metallicity is of great importance for the structure and the composition of PDRs. Environments with a low metallicity have a lower dust to gas ratio compared to those with a high metallicity. In a low metallicity environment the average UV field generally has higher energies. In addition, the FUV radiation is less excited and can hence penetrate gas at larger clump depths. For example, in dwarf galaxies with a low metallicity \((Z \sim 0.1 \ Z_\odot)\) almost \(\sim 10\%\) of the incoming FUV radiation is absorbed by dust grains and re-emitted in the infrared. This value rises to more than \(99\%\) in the circumnuclear regions of many infrared-luminous galaxies (Kennicutt 2008). The FUV photons can hence ionize atoms and photodissociate molecules in larger clouds depths at low metallicities. The transition layers between the different chemical regions are consequently moved to higher distances from the cloud surface.

The width of the chemical layers, \(D\), are affected by the metallicity as well. At low metallicities \(C^+\) and \(C^0\) fill a larger fraction of the volume within the PDRs, while the fraction of CO decreases. The width of the \(C^+\) and \(C^0\) layer are thus expected to increase, while the width of the CO zone decreases. The width of the \(C^+\) layer is approximately inversely proportional to the metallicity, \(D_{C^+} \propto Z^{-1.1}\) (Röllig et al. 2006). Under certain conditions, such as a strong UV-field, small clump sizes, low densities and low metallicities, all CO can be photo-dissociated. At low metallicities and at low clump masses the fraction of CO dark \(H_2\) increases compared

\[xvi \text{ see section 2.3}\]

\[xvii \ n \gtrsim \text{ few } 10^4 \text{ cm}^{-3}, \ I \text{ like to refer to section 4.2 for further details}\]
to clumps with a high metallicity and mass. At metallicities $Z \lesssim 0.1 \ Z_\odot$, CO is only marginally observed in PDRs.

The effect of different metallicities on the distribution of C$^+$, C$^0$ and CO to clumps with a constant size in an uniform radiation field is illustrated in Figure 2.7. C$^+$ and C$^0$ transitions are assumed to be reliable tracers for H$_2$ at low metallicities.

The fraction of CO dark H$_2$ is affected by the size of the clumps, as well. Its fraction increases towards smaller clump sizes (therefore smaller mass surface densities as well) compared to larger clumps. In a constant radiation field, the widths of the CO core decreases towards smaller clump sizes and towards smaller clumps sizes, while the widths of the C$^+$ and C$^0$ layers remain constant. Therefore, the fraction of H$_2$ traced by C$^+$ and C$^0$ increases towards smaller clump sizes as well. The effect is illustrated in Figure 2.7.

2.2.4 FRACTION OF CO DARK H$_2$ IN PDRS

The following section discusses a method to estimate the fraction of CO dark H$_2$ as function of the metallicity and clump diameter. Wolfire et al. (2010) estimated the fraction of CO dark H$_2$ in a spherical GMC as function of the the metallicity, cloud density (measured in $A_V$), FUV field. Equation (A9) in Wolfire et al. (2010) derived the relative CO dark H$_2$ fraction via

$$f(DG)_{W10} = 1 - \left[ 1 + \left( \frac{k_\alpha - 1}{3 - k_\alpha} \right) \frac{0.76 \Delta A_{V,DG}}{Z'N_{22}(H)} \right]^{\frac{3-k_\alpha}{k_\alpha-1}} \quad (2.1)$$

with $k_\alpha$ being the power-law gradient of the mean density in the GMC, $Z$ the metallicity in fractions of $Z_\odot$, $N_{22}(H)=N(H)_{tot} \times 10^{-22}$, and $\Delta A_{V,DG}$ the extinction of the CO dark gas layer in the GMC.

Figure 2.8 shows the fraction of CO dark H$_2$ for different column densities and metallicities for constant $\Delta A_{V,DG}$ and $k_\alpha$. In the Milky Way roughly 1/3 of the H$_2$ is CO dark (Wolfire et al. 2010). This fraction increases to $\sim 0.5$ for a half solar metallicity.

2.3 H$_2$ FORMATION

H$_2$ is the most abundant molecule in the universe. H$_2$ is involved in a number of chemical processes. The formation of H$_2$ is thus of great interest. This section is mainly based on Tielens (2010) and Röllig et al. (2013).

H$_2$ is formed predominantly on the surface of dust grains, but can also be formed in the gas phase.

The formation of H$_2$ in the gas phase is generally of subordinate importance in the present universe, as these formation processes are slow. Excited molecular hydrogen, H$_2^*$\footnote{The "*" indicates that the molecule is excited.} can be formed in the gas phase via the reaction of two H atoms (H + H $\rightarrow$ H$_2^*$). Radiative transitions are strongly forbidden in H$_2$ (cf. section 4.1). The surplus energy has thus a long dwell time in the molecule, and the reaction occurs at a slow rate of $\lesssim 10^{-23} \ cm^{-3} \ s^{-1}$.\footnotetext{\textsuperscript{xviii}}
2.3 H$_2$ formation

Another H$_2$ formation process in the gas phase is the reaction of a H$^-$ ion with H (H$^-$ + H → H$_2^*$ + e$^-$). Due to the short life time of H$^-$ in molecular clouds, this process is very slow as well\textsuperscript{xix}.

The formation of H$_2$ in the modern universe occurs predominantly on the surface of dust grains. Hydrogen atoms can stick to the grain surface via chemisorption and physisorption\textsuperscript{xx}. The hydrogen atoms can move on the surface via tunnelling and thermal diffusion. At low temperatures ($T \lesssim 100$ K) the moving of physisorbed atoms via tunnelling-processes dominates, and vice versa the thermal diffusion of chemisorbed atoms at high temperatures ($T \gtrsim 100$ K). Excited H$_2$ is formed when a hydrogen atom meets a recombination partner. The surplus energy of the excited H$_2$ is largely absorbed by the dust-grain. A fraction of this surplus energy can be transformed into the kinetic energy of the H$_2$ molecules, which is needed to release the molecule into the gas phase.

A detailed description of the H$_2$–formation on dust grains can be found in Röllig et al. (2013).

\textsuperscript{xix} This formation processes may have been of importance in the early universe (red-shift $z \gtrsim 6.5$), before dust has been formed (Lepp & Shull 1984; Sobral et al. 2015).

\textsuperscript{xx} Chemisorption designates the strong covalent bond between the atom and the grain surface. Physisorption denotes a weak bind interaction between the grain surface an the atom via the Van der Waals force.
Chapter 3

The Milky Way and M33

This thesis is based on observations in the Milky Way and the nearby galaxy M33. This section provides the reader with a short description of these two galaxies. I will describe their morphology and basic physical parameters. First I will allocate these galaxies within the nearby universe.

3.1 THE LOCAL GROUP

Galaxies are assembled in groups and clusters. The Milky Way and M33 are members of the so called Local Group, which is a subgroup of the Virgo supercluster. The local group is a small group of galaxies of more than 50 galaxies (van den Bergh 2000a). Its most massive members are the spiral galaxies M31 (alias the Andromeda Galaxy), the Milky Way and M33 (alias Triangulum Galaxy). The other galaxies are small irregular dwarf galaxies. Most of them are satellites of M31 and the Milky Way. The Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) are prominent satellites of the Milky Way. M33 might be a companion of M31.

3.2 THE MILKY WAY

The Milky Way (MW) is a barred spiral galaxy (Chen et al. 1996), classified as SBbc (Benjamin et al. 2005) in the de Vaucouleurs system (de Vaucouleurs 1959). The diameter of the Milky Way is still discussed in current research debate. Its diameter is declared to be between ∼30 kpc (Draine 2011) to ∼50 kpc (Xu et al. 2015). The Milky Way has a total baryonical mass of ∼5×10^{11} M_☉ (Draine 2011).

The majority of the gas and dust in the Milky Way is assembled in its spiral arms. The structure of the Milky Way is not trivial to determine, as the solar system is located within the galactic disc. Although the first suggestion of a spiral arm structure of the Milky Way is dated back to the year 1852 (Alexander 1852) its exact composition is still disputed.

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i M31 is the most massive galaxy in the Local group, with a mass of ∼1.5 × 10^{12} M_☉, followed by the Milky Way with a mass of ∼5×10^{11} M_☉ and M33 with a total mass of 5×10^{10} M_☉.

ii M33 is observed in the constellation Triangulum

iii see section 3.3
Four logarithmic main spiral arms (Scutum–Crux/Centaurus, Sagittarius–Carina, Perseus and the Norma or Cygnus/Outer arm, respectively)\textsuperscript{iv} have their origin at or near the outer edges of the bar(s) (Vallée 2008; Churchwell et al. 2009; Steiman-Cameron et al. 2010) at distances of ∼3 kpc from the galactic centre (Rodriguez-Fernandez & Combes 2008; Rodríguez-Fernández 2011). Note that resent estimations give a total bar half-length of up to ∼ 5 kpc (Wegg, Gerhard & Portail 2015). The existence of an elongated second bar is discussed (Nishiyama et al. 2005; Wegg, Gerhard & Portail 2015). The outer edges of the bars are connected by the two so called 3-kpc (expending) arms (Rougoor & Oort 1960; Rodríguez-Fernández 2011). The Scutum-Centaurus and the Perseus arms are in general brighter and more massive than the Norma and Sagittarius arms.

A kneed shape of the main spirals at distances ≥ 9 kpc is suggested (Efremov 2010). Furthermore, the Milky Way consists of several spurs and bridges located between the main spirals. The solar system is located in the so called Orion-Cygnus spur. The precise distance between the galactic centre and the sun is still controversially discussed in current research debates, as the established standard methods have different problems and lead to different distances \textsuperscript{v}. Recent studies set the distance to $R_{GC}$~7 to 9 kpc (e.g. Bica et al. 2006; Vanhollebeke, Groenewegen & Girardi 2009). The present study uses the current IAU recommendation of $R_{GC}$=8.5 kpc (e.g. McClure-Griffiths & Dickey 2007). A schematically illustration of MW is shown in figure 1.2.

The main spiral arms of the Milky Way can be described by logarithmic spirals (von der Pahlen 1911; Danver 1942; Roberts, Roberts & Shu 1975; Vallée 2008; Steiman-Cameron et al. 2010)\textsuperscript{vi} The spiral arms form a relativity thin warped disc (Kalberla & Kerp 2009). The thickness of the disc depends on the discussed gas phase\textsuperscript{vii}. The molecular gas, for example, is assembled in a relative thin disc with a total width of ~ 100 pc, while the WIM has an average thickness of ~500 pc.

The metallicity within the Milky Way has a gradient along the galactic radius (e.g. Shaver et al. 1983; Ferrini et al. 1994; Peeters et al. 2002; Rudolph et al. 2006; Maciel & Costa 2010; Magrini et al. 2015)\textsuperscript{viii}. Within the inner regions of the galaxies $R_{GC} ≤ 10$ kpc the metallicity decreases from $12+\log(O/H)≈9$ to 8.5 with a power slope of $\sim -0.06$ dex/kpc (Rudolph et al. 2006; Maciel & Costa 2010). The metallicity at the location of the

\textsuperscript{iv} The designation of the spirals is ambiguous. Due to historical reasons the names of the spiral arms depend on their location at the sky, cf Fig 1.2.

\textsuperscript{v} The distance to the galactic centre is commonly estimated via RR Lyr variables in the galactic bulge, the optical extinction at dust, and observations of globular clusters in the galactic halo, and the measurement of the trigonometric parallaxes of stars near the galactic centre using VLBI (e.g. Reid 1993; Bica et al. 2006; Groenewegen, Udalski & Bono 2008; Vanhollebeke, Groenewegen & Girardi 2009; Majaess 2010, Reid et al. 2014).

\textsuperscript{vi} von der Pahlen (1911) showed for the first time that the spiral arms of M33, M51 and M74 can be described by logarithmic spirals. Danver (1942) concludes that the spiral of galaxies can be fitted by logarithmic spirals. The theoretical work by Roberts, Roberts & Shu (1975) showed that density waves within axisymmetric galaxies are described by logarithmic spirals as well. For further details see section 6.3.3.

\textsuperscript{vii} The widths of the different gas layers, as well as the underlying physics, is discussed in detail in chapter 6.

\textsuperscript{viii} The gradient was observed for the first time by Shaver et al. (1983). Rudolph et al. (2006); Maciel & Costa (2010); Magrini et al. (2015), who give current estimates of this gradient.
sun is $12 + \log(O/H) \approx 8.7$. Note that the slope of the gradient is less steep for $R_{GC} \gtrsim 10$ kpc. The metallicity decreases $\sim 0.01$ dex/kpc (Maciel & Costa 2010; Magrini et al. 2015). A metallicity gradient perpendicular to the galactic disc is observed as well (Ivezić et al. 2008; Schlesinger et al. 2012).

3.3 M33

The following section is dedicated to the spiral galaxy M33. I recommend the work by Hodge (2012) and Buchbender (2013) for further details.

The late type spiral galaxy M33 is classified as a SA(s)cd galaxy in the Vaucouleurs scheme. M33 is the third most massive galaxy in our Local Group, with a total mass of $\sim 5 \times 10^{10} M_\odot$ (Corbelli 2003). M33 is located at a distance of $\sim 840$ kpc from the sun (Freedman, Wilson & Madore 1991). An angle of 1" at the sky corresponds thus to $\sim 4.1$ pc in M33. M33 is seen at a low inclination of $\sim 56^\circ$ (Regan & Vogel 1994). The combination of the distance and the low inclination angle allows to study individual sources in an extragalactic source even with single dish telescopes, with a low depth along the line-of-sight.

M33 is a chemical young galaxy (Druard et al. 2014). The metallicity of M33 is about half solar and is roughly independent of galactic radius, $R_{M33}$. The oxygen-hydrogen abundance can be fitted by $12 + \log(O/H) \approx 8.42 - 0.03 R_{M33}$ (Magrini et al. 2009). Its metallicity is thus similar to those of the Large Magellanic Cloud (LMC; Pagel et al. 1978; Hunter et al. 2007). The fraction of the dust to the gas is relatively high, compared to the Milky Way. The dust to gas ratio is $\sim 170$ to $290$ (Buchbender 2013), while the Milky Way has a gas-to-dust ratio of $\sim 100$ to $150$ (Draine 2011). Roughly $\sim 6\%$ of its total mass is gas, $\sim 3 \times 10^9$ ($H^0$, $H_2$, He) (Corbelli 2003).

The major axis of M33 has a length of $\sim 20$ kpc ($\sim 84'$) in the optical (Holmberg 1958) and a length of $\sim 30$ kpc ($\sim 135'$) in $H_1$ (van den Bergh 2000b). M33 has no perfect global spiral structure. The spiral structure is often described as 'flocculent' (Elmegreen et al. 2003; Hodge 2012; Buchbender 2013). The precise arm structure is still controversially debated, although this galaxy was one of the first cases where the spiral structure was examined (Dauver 1942). Two distinctive spiral arms are observed in M33, a northern and a southern arm. These arms are pronounced in $H_1$, as well in the submillimetre regime (e.g. Hermelo et al. 2016). The southern spiral can be described by a smooth logarithmic spiral, while the northern arm has a kneed structure. The northern arm hosts a number of prominent GMCs and $H_1$-region, i.a. NGC604, the second most massive $H_1$-region in the local group, with $\sim 200$ O and B stars (Hunter et al. 1996). Besides these two spirals the ISM is relatively fractionated. Further fainter spiral arms are for example identified by Humphreys & Sandage (1980) and Regan & Vogel (1994). The current study examines individual GMCs on the northern and southern spiral and sources in the centre and a source north of the northern spiral arm.

ix The distance is determined via the photometry of Cepheid in M33
x The kneed structure of the northern spiral is discussed in section 7.6.2
xi The most massive $H_1$-region in the local group is 30 Doradus, located in the Large Magellanic Cloud
The centre of M33 hosts no super massive black hole. The upper limit for a possible central black hole is $< 2 \times 10^4 \, M_\odot$ (Lauer et al. 1998). The lack of a central massive black hole is suggested to explain the high star formation efficiency in M33, as a momentum to stabilize the structure is missing (Kormendy & McClure 1993; Lauer et al. 1998). Nevertheless, a source in its centre is worth to mention. The centre of M33 contains the most luminous steady X-ray source in the local group, M33-X8\textsuperscript{xii}.

M33 is thought to be closely associated with M31. These galaxies have a distance of $\sim 200$ kpc (e.g. Galleti et al. 2004). A HI stream between both galaxies is observed (Braun & Thilker 2004). The stream is possibly formed by a close encounter of both galaxies 1 to 3 GYr ago (Braun & Thilker 2004; Putman et al. 2009). Tidal interactions between both galaxies are used to explain the warped outer disc of M33 (Corbelli, Schneider & Salpeter 1989; Putman et al. 2009). A halo of dwarf galaxies around M33 is not observed, which is uncommon for a spiral galaxy (e.g. Martin et al. 2009)\textsuperscript{xiii}. Therefore M33 cannot be seen as an isolated galaxy.

M33 is denoted as a stepping stone between irregular objects, as the LMC and SMC, and late-type galaxy as the Milky Way or M31 (e.g. Druard et al. 2014), based on its spiral structure, relatively low metallicity and mass, the high dust to gas ratio, the high star formation efficiency and the missing halo of dwarf galaxies.

M33 is extensively studied within the frame work of the Herschel open time key project HERM33ES (Kramer et al. 2010; Boquien et al. 2011; Gratier et al. 2010; Mookerjea et al. 2012; Xilouris et al. 2012; Buchbender et al. 2013; Buchbender 2013; Druard et al. 2014; Mookerjea et al. 2016).

\textsuperscript{xii} M33-X8 is formed by binary system of a star with $\sim 10 \, M_\odot$ and a black hole with $\sim 70 \, M_\odot$. It has a luminosity of $\simeq 2.2 \times 10^{39}$ erg/s (Peres et al. 1989; Takano et al. 1994; Lauer et al. 1998; Weng et al. 2009).

\textsuperscript{xiii} The Milky Way and M31 have a halo of $\sim 20$ to 30 dwarf galaxies (e.g. Martin et al. 2009; Belokurov et al. 2014).
Figure 3.1: Optical image of M33 observed with the VLT Survey Telescope (VST).
Credit: ESO
Chapter 4

Studying the ISM with spectral line measurements

The interstellar medium includes a large number of molecules, atoms and ions. The Cologne Database for Molecular Spectroscopy (CDMS) lists almost 800 entries for molecules and ions of astrophysical interest (Müller et al. 2001; 2005; 2008). All the different molecules, atoms and ions have different physical and chemical properties and origins. The understanding of their creation and destruction can shed light on the physical and chemical conditions of their environment. Of particular interest for this study are the (hyper-)fine structure and rotational transitions of H\(_0\), C\(^+\), C\(^0\) and CO. These transitions have low excitation energies. They are observed at (sub-)millimetre wavelengths. These transitions are excited even at low temperatures and are observed in the cold regions of the ISM. Thus, they provide an insight into the regions where stars are formed.

The following chapter describes methods that allow to derive physical parameters from observed lines. The special focus lies on methods to determine the column and volume density as well as temperature and pressure in the ISM. The described methods will be used within this thesis. In a first step, it is necessary to recapitulate the physics of electro-magnetic line transitions in molecules, atoms and ions.

Section 4.1 will briefly summarise the physics of line transitions, the excitation of molecules and atoms and the population of energy levels. Section 4.2 describes in which way the number of atoms in the line of sight (column density), can be derived from the observed line intensity. Methods to deduce the optical depths of a line, the pressure in the ISM and the strengths of the ambient UV field will be described in the following sections.

4.1 FINE STRUCTURE, HYPER-FINE STRUCTURE AND ROTATIONAL TRANSITIONS

This thesis is largely based on the observation and the analysis of the hyperfine transition H\(_0\), the fine structure transitions of ionised and neutral atomic carbon, and the rotational transition of carbon monoxide. The following thesis assumes that the reader is familiar with the physics of (hyper-)fine structure and rotational transitions. A good description of their physics can be found in Häsel & Neumann (1995) and Draine (2011). For the physics of ISM-related hyper-fine structure transitions, I also highly

\(\text{i} \) https://www.astro.uni-koeln.de/cdms/
The transitions of H\(^0\), C\(^+\), C\(^0\) and CO are of a great importance for this thesis. I will briefly discuss these transitions in the following. The transitions of molecular hydrogen and other symmetrical molecules will be discussed as well.
4.1 fine structure transition of $C^+$

Single ionised carbon has the ground state configurations $^2P_{1/2}$ and $^2P_{3/2}$. The only possible fine structure transitions of the ground state, $^2P_{1/2} \rightarrow ^2P_{3/2}$, has an energy difference of $\Delta E/k_B=91.3$ K, resulting in line transition at $\Delta E/h=\nu=1.901$ THz ($\lambda=157.7$ $\mu$m) (cf. Figure 4.1). In spectroscopic notation, this transition is denoted as [Cii].

[Cii] is the major cooling line in significant parts of the ISM. Carbon is singly ionised at 11.26 eV. This is below the ionisation energy of hydrogen of 13.60 eV. The ionisation energy of other elements is above the one of hydrogen. For example, nitrogen and oxygen possess ionisation energies of 13.62 eV and 14.53 eV. The [Cii] line is thus, the dominant and almost ubiquitous present coolant for major phases of the neutral ISM (Dalgarno & McCray 1972; de Jong, Dalgarno & Boland 1980; Tielens & Hollenbach 1985a;b).

4.1.2 fine structure transitions of $C^0$

The ground configuration of neutral atomic carbon, $^3P$, is split into three fine structure levels: $^3P_0$, $^3P_1$, and $^3P_2$. Therefore, two fine structure transitions are possible: $^3P_1 \rightarrow ^3P_0$ and $^3P_2 \rightarrow ^3P_1$. These transitions have energies of $\Delta E/k_B=23.6$ K and $\Delta E/k_B=62.5$ K and are observable at $\nu=492.16$ GHz and 809.34 GHz (cf. Figure 4.1). These transitions are denoted as [C](1–0) and [C](2–1).

4.1.3 hyper-fine transition of neutral atomic hydrogen, $H^1$

The spins of the electron and proton in neutral atomic hydrogen are parallel or antiparallel. The energy difference between the antiparallel spin configuration and the parallel configuration (with a slightly higher energy) in the ground state is $5.87 \times 10^{-6}$ eV $\equiv 6.82 \times 10^{-3}$ K. This corresponds to the famous wavelengths of $\lambda=21.1$ cm respectively $\nu=1420.4$ MHz. Due to the low energy needed, the excitation of the energy levels can be induced by the Cosmic Microwave Background ground radiation (CMB). In spectroscopic notation, this transition is denoted as $H^1$. For historical reasons, $H^1$ is denoted without squared brackets, whereas the transition is 'forbidden'.

4.1.4 rational transitions of CO

Carbon monoxide is the second abundant molecule in space and the 'working horse' to study the dense cold regions in molecular clouds. Ground-state CO has a dissociation energy of 11.09 eV (e.g. Visser, van Dishoeck & Black 2009).

The energy difference between $J=1$ to $J=0$ is 5.53 K for $^{12}$CO. Due to this low energy difference, CO excites even in the cold region of molecular clouds. This energy corresponds to a frequency of $\Delta E/h=115.271$ GHz.

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*van de Hulst 1945; Ewen & Purcell 1951; Muller & Oort 1951

$A_{10}(H^1)=2.87 \times 10^{-15}$ s$^{-1}$, c.f. Table 4.1
The transition is commonly denoted as CO(1–0). Further CO transitions that are of relevance for this thesis are $^{13}$CO(1–0), $^{12}$CO(2–1) and $^{12}$CO(4–3). The frequencies of CO transitions used in this thesis are listed in Table 4.1.

### 4.2 Calculating the Column Densities in Local Thermal Equilibrium

The following section is about a method that allows to determine the column density of a gas species from the observed line intensity in an assumed local thermal equilibrium (LTE). The argumentation is mainly based on Mangum & Shirley (2015).

In LTE, the energy levels of a system are in a statistical equilibrium. The level population of a multiple level system with the levels $i$ and $j$ can be determined by a matrix equation, in which the probabilities of the spontaneous and stimulated emission, absorption and collision between the energy levels are in balance. The probabilities of the spontaneous and stimulated emission, as well as of the absorption, are described by the Einstein rate coefficients $A_{ij}$, $B_{ij}$ and $B_{ji}$.

In thermal equilibrium, the upwards and downwards transitions within the system are in balance. The resulting relative population of the energy levels are described by the Boltzmann distribution,

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-\frac{h \nu_{ul}}{k_B T_{ex}}}$$  \hspace{1cm} (4.1)$$

with $T_{ex}$ being the excitation temperature. The excitation temperature of a system is given by the mean of the kinetic gas temperature, $T_{kin}$, and radiation temperatures, $T_{rad}$, weighted with the relative radiative and collisional rate coefficients. At high densities, the population of the energy levels is dominated by collisions with other gas particles. The density in which the spontaneous emission is in equilibrium with the de-excitation by collisions is the so-called critical density. The critical density is given by (e.g. Goldsmith et al. 2012)

$$n_{\text{crit}} = \frac{1 - e^{-\tau}}{\tau} \frac{A_{ul}}{C_{ul}}$$  \hspace{1cm} (4.2)$$

### Table 4.1: Frequency, Einstein A coefficient and energy of transitions used in this thesis. The values are obtained from the CDMS.
with \( \tau \) being the optical depth of a cloud. The optical depth corresponds
to the maximal path lengths in which a photon can travel before it is
scattered or absorbed. The term \((1-e^{-\tau})/\tau\) in Equation (4.2) describes
the escape probability of a photon out of the cloud, the so-called opacity.
At low optical depths \((\tau \ll 1)\), the medium is transparent and the whole
volume of the medium is observable. At high optical depths \((\tau \gg 1)\), only
photons from the surface of the medium are observed. At high densities,
\( n \gg n_{\text{crit}} \), the \( T_{\text{ex}} \) is equal to the kinetic temperature of the gas. In this
case the population of the energy levels is described by the Boltzmann
distribution, and the gas is called thermalised. If \( n \ll n_{\text{crit}} \), \( T_{\text{ex}} \) is equal
to the radiation temperature and the energy levels of the gas are sub–
thermally excited.

The path of a photon through a medium is described by the radiative
transfer equation. It equates the absorption and emission of the pho-
tons along the path. For further details I recommend Mangum & Shirley

The lines discussed in this thesis, have wavelengths of \( \lesssim 10^{-3} \) m, and thus
\( h \nu \ll k_B T \). Therefore, the Rayleigh–Jeans approximation can be used in
the following. The radiative transfer equation in terms of the main beam
radiation temperature of a source, \( T_{\text{mb}} \), in LTE for an assumed constant
excitation temperature, is expressed by

\[
T_{\text{mb}} = (\mathcal{J}_\nu(T_{\text{ex}}) - \mathcal{J}_\nu(T_{\text{BG}})) (1 - e^{-\tau_\nu}) \phi_B
\]

(4.3)

with \( \phi_B \) being the so–called beam filling factor and

\[
\mathcal{J}_\nu(T) = \frac{h \nu}{k_B} \left[ e^{\frac{h \nu}{k_B T}} - 1 \right]^{-1}.
\]

(4.4)

The beam filling factor is defined as the spatial fraction of a source within
the beam. The term \( \mathcal{J}_\nu(T_{\text{BG}}) \) subtracts possible background radiation
from the observational data. For example, dust emission is an important
background source. The Cosmic Microwave Background radiation
(CMB) at \( T_{\text{CMB}} \approx 2.73 \) K (Penzias & Wilson 1965; Planck Collaboration
et al. 2014a)\(^{vi}\) has to be considered for CO(1–0).

In the optically thin case \((1 - e^{-\tau}) \rightarrow \tau \). Using this approximation, Equation
(4.3) can be transformed to

\[
\tau = \frac{T_{\text{mb}}}{\mathcal{J}_\nu(T_{\text{ex}}) - \mathcal{J}_\nu(T_{\text{BG}})\phi_B}.
\]

(4.5)

The Equations (4.4) and (4.3) allow to express the excitation temperature via
\( T_{\text{mb}} \) and \( \tau_\nu \).

\[
T_{\text{ex}} = \frac{h \nu}{k_B} \left[ \ln \left( \frac{(1 - e^{-\tau})\phi_B}{k_B T_{\text{mb}} + \mathcal{J}(T_{\text{CMB}})} + 1 \right) \right]^{-1}.
\]

(4.6)

Vice versa Equation (4.6) can be solved for \( \tau \)

\[
\tau = -\ln \left( 1 - \frac{k_B}{\phi_B h \nu} \left( T_{\text{mb}} + \mathcal{J}(T_{\text{CMB}}) \right) e^{\frac{h \nu}{k_B T_{\text{ex}}}} \right).
\]

(4.7)

\(^{vi}\) First detection of the CMB by Penzias & Wilson (1965). The actual precise value is
determined by Planck Collaboration et al. (2014a).
Both equations are used in chapter 7.

The column density of a molecule in the upper energy level \( u \) is defined as the integral of the number of molecules \( n \) along the pathlength \( s \)

\[ N_u \equiv \int n_u ds. \tag{4.8} \]

The number of molecules along the path is directly related to the optical depths \( \tau_\nu \) via

\[ N_u = \frac{8\pi\nu^2}{c^2} \frac{1}{\nu e^{\frac{h\nu}{k_B T_{\text{ex}}}} - 1} \frac{1}{A_{ul}} \int \tau_\nu d\nu. \tag{4.9} \]

To estimate the total number of molecules, \( N_{\text{tot}} \), \( N_u \) has to be related to the population of all energy levels. The relation is given by

\[ \frac{N}{N_u} = \frac{Q g_u e^{\frac{h\nu}{k_B T_{\text{ex}}}}}{g_u}, \tag{4.10} \]

with \( Q \) being the so-called partition function. The partition function gives the weighted sum over all energy levels. The partition function is given by

\[ Q = \sum_u g_u e^{\frac{h\nu}{k_B T_{\text{ex}}}}. \tag{4.11} \]

The combination of the Equations (4.10) and (4.9) gives the total column density

\[ N_{\text{tot}} = \frac{8\pi\nu^2}{c^3} \frac{Q}{g_u A_{ul}} \frac{1}{e^{\frac{h\nu}{k_B T_{\text{ex}}}} - 1} \int \tau_\nu d\nu \tag{4.12} \]

where the relation \( d\nu = \frac{\nu}{c} dv \) is used. This relation converts the integration over the frequencies to an integration over velocities.

The optical depth \( \tau_\nu \) is not directly measured. It is, therefore, of interest to express Equation (4.12) via the brightness temperature. The combination of the Equations (4.5) and (4.12) gives the total column density in the optically thin limit

\[ N_{\text{thin}} = \frac{8\pi\nu^2}{c^3} \frac{Q}{g_u A_{ul}} \frac{1}{e^{\frac{h\nu}{k_B T_{\text{ex}}}} - 1} J_\nu(T_{ex}) - J_\nu(T_{BG}) \Phi_B \int T_{mb} dv. \tag{4.13} \]

The total column density is given by

\[ N_{\text{tot}} = \frac{\tau}{1 - e^{-\tau}} \times N_{\text{thin}} \tag{4.14} \]

with \( \tau/(1 - e^{-\tau}) \) being the correction term for the opacity.

The Einstein \( A \) coefficients used in this thesis are listed in Table 4.1.

For the sake of simplicity, concrete total column density equations for the CO transitions, as well as for [Cl](1–0), [Cii] and HI, are listed in Appendix A.
4.3 OPTICAL DEPTHS VIA ISOTOPE LINE RATIOS

The optical depth $\tau$ of a transition can be calculated numerically via the observed peak temperature of two isotopes $T_{mb}$ and the relative isotope ratio. In the following, I discuss the examples of $^{13}$CO and $^{12}$CO. The relation of the $^{13}$CO and $^{12}$CO peak temperature and their optical depths $\tau_{12}$ and $\tau_{13}$ is given by

$$\frac{T_{mb}^{(12\text{CO}(J_u - J_l))}}{T_{mb}^{(13\text{CO}(J_u - J_l))}} = \frac{1 - e^{-\tau_{12}}}{1 - e^{-\tau_{13}}}$$

$$\Leftrightarrow \frac{T_{mb}^{(12\text{CO}(J_u - J_l))}}{T_{mb}^{(13\text{CO}(J_u - J_l))}} = \frac{1 - e^{-x_{12}^{13} \times \tau_{13}}}{1 - e^{-\tau_{13}}} \quad (4.15)$$

with $x_{12}^{13}$ being the isotope ratio $^{12}$C/$^{13}$C.

The isotope ratios are commonly determined via the intensity ratio of optically thin line transitions. Within the uncertainties of $\sim 20\%$, the local interstellar medium has a $x_{12}^{13} \approx 70$ (e.g. Milam et al. 2005; Casassus et al. 2005). This ratio is no global constant. The $^{12}$C/$^{13}$C ratio depends on the age of the gas. In particular, type II supernovae enrich the ISM with $^{12}$C. This leads to a decrease of $x_{12}^{13}$ in regions with a higher supernovae rate.

In consequence, $^{12}$C/$^{13}$C ratio shows a radial gradient within the Milky Way with a lower $x_{12}^{13}$ towards the Galactic Centre. The isotope ratio can be approximated by $x_{12}^{13} \approx 6.2 \times R_{GC} + 18.7$ with $R_{GC}$ being the distance from the Galactic Centre in kpc (Milam et al. 2005).

4.4 CONVERSION BETWEEN VELOCITY INTEGRATED INTENSITIES AND LINE FLUXES

This section discusses the conversion between velocity (and frequency) integrated intensities $I$ and fluxes $I$. The velocity integrated intensities give the main beam brightness temperatures that are integrated over the width of a line. The flux of a line shows directly the energy that is received at the telescope. Two different lines with identical integrated intensity have different fluxes as the emitted energy is a function of the frequency. The flux $I$ in the units erg cm$^{-2}$ s$^{-1}$ of a transition with a frequency $\nu$ can be calculated from the observed velocity integrated line intensity $\int T_{mb} dv = I(\text{line})$ in K km s$^{-1}$ via

$$I(\text{line}) = \frac{2kB\nu^3}{c^3} \times 10^5 \int T_{mb} dv = K_{\text{line}} \times I(\text{line}) \quad (4.16)$$

with $K$ being a constant conversion factor for different line transitions. Conversion factors for important line transitions are listed in Table 4.2.

4.5 THERMAL INFRARED LUMINOSITY AND FAR UV FLUX

The following discusses a relation between the emitted thermal infrared luminosity, $L_{TIR}$, and the penetrating far ultraviolet flux, FUV.

Far ultraviolet radiation is a major heating source of the ISM. In a first approximation, it can be be assumed that all incoming FUV radiation is
Table 4.2: Conversion factor, $\kappa$, for different line transitions, used to convert velocity integrated intensities, $I$, and fluxes, $\mathcal{I}$; $\mathcal{I} = \kappa \times \int T_{\text{mb}} \, dv$.

<table>
<thead>
<tr>
<th>Transition</th>
<th>$\nu$ [GHz]</th>
<th>$\kappa$ [erg K$^{-1}$ cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI</td>
<td>0.14</td>
<td>$2.937 \times 10^{-33}$</td>
</tr>
<tr>
<td>$^{12}$CO(1–0)</td>
<td>115.3</td>
<td>$1.570 \times 10^{-9}$</td>
</tr>
<tr>
<td>$^{12}$CO(2–1)</td>
<td>230.5</td>
<td>$1.256 \times 10^{-8}$</td>
</tr>
<tr>
<td><a href="1%E2%80%930">CII</a></td>
<td>492.2</td>
<td>$1.222 \times 10^{-7}$</td>
</tr>
<tr>
<td>[CI]</td>
<td>1900</td>
<td>$7.035 \times 10^{-6}$</td>
</tr>
<tr>
<td>[NII]122$\mu$m</td>
<td>2459</td>
<td>$3.196 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

absorbed by the dust surface of a PDR. The dust cools via the emission of far infrared photons. The penetrating FUV flux is linear related to the $L_{\text{TIR}}$ via (e.g. Mookerjea et al. 2012; Buchbender 2013)

$$G_0 = 4\pi 0.5 L_{\text{TIR}}$$

with $G_0$ being the strength of the penetrating FUV field in units of Habing field ($1.6 \times 10^{-3}$ erg s$^{-1}$ cm$^{-2}$). $L_{\text{TIR}}$ is in the units erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$.

### 4.6 Volume Density from Thermal Pressure

The following section is about a method that estimates the hydrogen volume density based on the thermal pressure at the surface of a PDR.

The thermal pressure $P_{\text{therm}}$ is directly proportional to the thermal energy of the gas particles $k_B T$ and their density, $n$ (e.g. Wolfire et al. 2003).

$$P_{\text{therm}} = 1.1 n \times k_B T$$

If the heating is dominated by FUV radiation, as it is the case on the surface of a PDR (Section 2.2), it is possible to equate the penetrating FUV radiation and the thermal pressure within a cloud. Wolfire et al. (2003) gives the thermal pressure as function of the penetrating FUV Field $G'_0 = G_0/1.7$ (in Habing units, $1.3 \times 10^{-4}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$), the dust / PAH abundance $Z'_d/Z_d/10^{-4}$, the gas-metal abundance $Z'_g/Z_g/10^{-4}$ and the total gas ionisation rate $\zeta'_t=\zeta_t/10^{-16}$ via

$$P_{\text{therm}} = \frac{8500 k_B G'_0 Z'_d}{(1 + 3.1 \left( G'_0 \frac{Z'_g}{Z'_d} \right)^{0.365})}$$

The volume density as function of the ambient FUV field is given by the combination of the Equations (4.18) and (4.19).

$$n \equiv \frac{P_{\text{therm}}}{1.1 k_B T}$$

$$\approx \frac{8500 G'_0 Z'_d}{(1 + 3.1 \left( G'_0 \frac{Z'_g}{Z'_d} \right)^{0.365}) \times 1.1 T} \left[ \text{cm}^{-3} \right]$$

This formula is valid for clouds in which the gas is in thermal balance, $T \lesssim 1000$ K and the cooling of the gas is dominated by [CII] and [OII].
4.7 OPTICAL EXTINCTION

Bohlin et al. (1978) found a linear correlation between the colour excess \( E(B-V) \) and the mean total hydrogen column density \( N(H) = N(H_1 + H_2) = N(H_1) + 2 \times N(H_2) \)

\[
\frac{N(H)}{E(B-V)} = 5.8 \times 10^{21} \text{cm}^{-2} \text{mag}^{-1}. \tag{4.22}
\]

The optical extinction is related to the colour excess via (Savage et al. 1977)

\[
A_v = 3.1 \times E(B-V). \tag{4.23}
\]

4.8 H\(_2\) CONVERSION FACTORS

An established method to calculate the molecular hydrogen column density in GMCs is the use of carbon monoxide as a proxy for \( H_2 \). The molecular hydrogen column densities are commonly estimated by multiplying an \( H_2 \) conversion factor with the observed integrated line intensity of a low–\( J \) \( CO \) transition or \([\text{CI}](1–0)\).

A number of studies of molecular clouds in the Milky Way, and in other disk galaxies with a similar metallicity, have found a power–law correlation between the viral mass of clouds and their emitted \( ^{12}\text{C}^{16}\text{O}(1–0) \) luminosity (e.g. cf. Solomon et al. 1987; Dame, Hartmann & Thaddeus 2001; Bolatto, Wolfire & Leroy 2013). This relation can be translated into a linear correlation between the molecular hydrogen column density \( N(H_2) \) and the emitted velocity integrated \( ^{12}\text{CO}(1–0) \) emission

\[
\int T_{\text{mb}}(\text{CO}(1–0)) \, dv = I(\text{CO}(1–0)) \quad \text{as elaborated in Solomon et al. (1987).}
\]

Dickman (1975) proposed to calculate the amount of molecular hydrogen in a cloud by scaling \( I(\text{CO}(1–0)) \) with a \( H_2 \)-\( CO \) conversion factor \( X_{\text{CO}} \)

\[
N(H_2) = X_{\text{CO}} \times I(\text{CO}(1–0)). \tag{4.24}
\]

\( N(H_2) \) is in the units \([ \text{cm}^{-2} ]\) and the integrated line emission in \([ \text{K km s}^{-1} ]\). Within uncertainties of \( \sim 30\% \), a \( X_{\text{CO}}=2\times10^{20} \text{ cm}^{-2} \text{K km s}^{-1}\) is established for the \( ^{12}\text{C}^{16}\text{O}(1–0) \) line in the Milky Way (Bolatto, Wolfire & Leroy 2013).

The \( CO-H_2 \) conversion factor does not show huge variations within the clouds of galaxies with a similar metallicity as in the Milky Way. This is explained by the relative constants of the cloud properties, such as temperature, surface density and velocity dispersion that determine \( X_{\text{CO}} \) (Narayanan & Hopkins 2013; Glover & Clark 2015).

A constant conversion factor described in the previous paragraph, may not be suitable for clouds with a high column density (Glover & Mac Low 2011; Carlhoff et al. 2013), strong UV-radiation (Weiß et al. 2001; Offner et al. 2014; Glover & Clark 2015) and/or low metallicity \((Z)\) (Israel 1997; Gratier et al. 2010; Glover & Clark 2015). In the following, I will discuss the concrete impact of the metallicity on the \( H_2-CO \) conversion factor. I will also discuss alternatives to the ‘standard’ \( H_2-CO \) above mentioned as well.

In dense regions, \( (A_v \gtrsim 3-4 \text{ mag}) \), \(^{12}\text{CO}\) becomes optically thick and, hence, saturates. Conversion factors \( X_{\text{CO}} \) based on optically thin \( CO \)
transitions (e.g. $^{13}$CO, C$^{18}$O) are used in regions with a high $A_v$, as an alternative for a $H_2^{12}$CO(1–0) conversion factor (e.g. Carlhoff et al. 2013).

Studies of Weiß et al. (2001), Offner et al. (2014) and Glover & Clark (2015) have shown that the $H_2$–CO conversion factor is deeply affected by the penetrating radiation field. In a strong UV field, as found for example in a starburst environment, the rotational levels of CO are populated at higher $J$ than in a low UV field. Low–$J$ are less populated. Hence, the CO emission of high–$J$ CO transitions is higher and the emission of low–$J$ CO lines is lower compared to a faint UV-field. In consequence, a constant $H_2$–CO conversion could underestimate the amount of $H_2$ (Weiß et al. 2001; Buchbender 2013). The precise influence on $X_{CO}$ is hard to estimate. Simulations with the ORION adaptive mesh refinement code (Offner et al. 2013) and the PDR-code 3D-PDR (Bisbas et al. 2012) by Offner et al. (2014) and Glover & Clark (2015) show that $X_{CO}$ is sensitive to the penetrating FUV-field. The conversion factor shows high fluctuations for different UV-fields. Offner et al. (2014) and Glover & Clark (2015) propose to use a $H_2$–[Cl](1–0) conversion factor as [Cl](1–0) is less affected by the ambient FUV-field (see below).

A large number of studies imply a significantly increased $X_{CO}$ at low metallicities (Wilson 1995; Israel 1997; Madden et al. 1997; Leroy et al. 2009; Gratier et al. 2010; Glover & Mac Low 2011; Druard et al. 2014; Glover & Clark 2015). A lower metallicity results in a lower dust to gas ratio as elaborated in Section 2.2.3. In regions with a low dust to gas ratio dust absorbs less of the incoming UV-radiation. Besides the population of higher $J$ energy levels, CO is easily photodissociated in strong UV fields\textsuperscript{vii}. Thus, the fraction of $C^0$ and $C^+$ increases towards lower metallicities. The fraction of CO compared to $C^0$ and $C^+$ is, hence, lower at low metallicities. To compensate the missing CO, the $H_2$–CO conversion factor has to be higher at low $Z$. In first order, $X_{CO}$ can be approximated by an inverse relation of the metallicity $Z$ and the $H_2$–CO conversion factor (Wilson 1995)

$$X_{CO} Z = \frac{X_{CO} H_2^{\odot}}{Z}.$$  

(4.25)

Based on observations of low metallicity CO clouds in the LMC, SMC and other irregular galaxies, Israel (1997) establishes a link between the $H_2$–CO conversion factor and the far infrared luminosity. The correlation of the $H_2$–CO conversion factor with $L_{TIR}$ can be explained by the relation between the far infrared luminosity and the FUV field (c.f. Section 4.5). For a half solar metallicity the $H_2$–CO conversion factor is given by (Buchbender 2013)

$$X_{CO} = 1.17 \times 10^{20} \frac{L_{TIR}}{10^6 \times L_{\odot}}.$$  

(4.26)

whereby $L_{TIR}$ is the far infrared luminosity of the cloud and $L_{\odot}$ the luminosity of the sun.

Recent studies propose to use a $H_2$–[Cl](1–0) conversion factor to calculate the total amount of $H_2$ in molecular clouds as an alternative to \textsuperscript{vii} The photodissociation energy of CO is 11.1 eV (e.g. Visser, van Dishoeck & Black 2009).
the $H_2$–CO conversion factor (Offner et al. 2014; Lo et al. 2014; Glover et al. 2015; Glover & Clark 2015). Carbon monoxide is not directly associated with all molecular hydrogen in molecular clouds as described above. This is emphasised in an environment with a low metallicity. $[\text{Cl}] (1–0)$ is expected to be a more reliable tracer for $H_2$ at low metallicities. Furthermore this transition is expected to have an optical depth of $\tau \lesssim 1$ even in massive clouds as opposed to the $^{12}\text{CO}$ transitions. Furthermore, these simulations imply that a $H_2$–$[\text{Cl}] (1–0)$ conversion factor is relatively invariant towards the penetrating FUV radiation (Offner et al. 2014) in opposite to the $X_{\text{CO}}$. According to these simulations, the $H_2$–$[\text{Cl}] (1–0)$ conversion factor increases roughly $\sim 10$ to $30\%$ if the incoming FUV flux increases by a factor ten. These values were calculated for a solar metallicity. The increase changes to $\sim 100\%$ for $Z = 0.5 Z_\odot$ (Glover & Clark 2015).

Simulations with the ORION adaptive mesh refinement code (Offner et al. 2013) and the PDR-code 3D-PDR (Bisbas et al. 2012) give a $H_2$–$[\text{Cl}] (1–0)$ conversion factor of $X_{\text{Cl MW}} = 1.1 \times 10^{21}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ for the Milky Way (Offner et al. 2014). Adopting this conversion factor with Equation (4.25) gives a conversion factor of $X_{\text{Cl0.5Z}} = X_{\text{Cl MW}} / 0.5 = 0.22 \times 10^{22}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ for a half solar environment. Glover & Clark (2015) calculated a $H_2$–$[\text{Cl}] (1–0)$ conversion factor of $\sim 0.16 \times 10^{22}$ s cm$^{-2}$ K$^{-1}$ km$^{-1}$ for a metallicity of $Z = 0.5 Z_\odot$ and radiation field strengths of $G_0 = 1$, a $X_{\text{Cl0.5Z}} \sim 0.3 \times 10^{22}$ s cm$^{-2}$ K$^{-1}$ km$^{-1}$ for $G_0 = 10$ and a $X_{\text{Cl0.5Z}} \sim 0.5 \times 10^{22}$ s cm$^{-2}$ K$^{-1}$ km$^{-1}$ for $G_0 = 100$.

After the explanation of the theoretical background, I will now pass to the scientific part of this thesis.
Part III

INVESTIGATING THE DISTRIBUTION OF CARBON IN THE MILKY WAY AND M33
Chapter 5

SOFIA/GREAT [C\textsc{ii}] observations in nearby clouds

near the lines of sight towards B0355+508 and B0212+735

The following section is dedicated to the composition and the energy balance of clouds which are identified as diffuse clouds, with relatively warm gas. This assumption is tested with [C\textsc{ii}] observations at the example of clouds towards the line of sight to the quasars B0355+508 and B0212+735. The results are compared to the expected [C\textsc{ii}] line intensities of warm diffuse clouds and in an ensemble of cold dense clumps.

A version of this chapter has been published in Glück et al. (2017).

5.1 INTRODUCTION

Interstellar clouds are classified as diffuse, dense or translucent (cf. e.g. Snow & McCall 2006 and Section 2.1). The composition of diffuse clouds has not been studied well, as these clouds are difficult to observe. Diffuse and translucent clouds have been identified mainly by means of their absorption spectra against bright mm-wave or optical background sources (Sonnentrucker et al. 2007; Burgh, France & McCandliss 2007; Sheffer et al. 2007; Sheffer, Rogers, Federman, Abel, Gredel, Lambert & Shaw 2008) and by optical extinction mapping (Savage et al. 1977). The conditions and composition within these clouds is currently a topic of research.

Liszt & Lucas (1998) succeeded in detecting CO(1–0) and CO(2–1) emission, identified to be associated with diffuse clouds because of their matching velocity characteristics with mm-wave absorption spectra, in a representative sample of mm-wave absorption lines-of-sight against background quasar sources. Liszt & Pety (2012) were able to map the CO (1–0) emission with a few arcminutes extent around these positions. The typical total hydrogen column density $N(\text{H})=N(\text{H}\text{I})+2N(\text{H}_2)$ in these clouds was derived to be a few times $10^{21}$ cm$^{-2}$ with a typical H$_2$ fraction of $\lesssim 1/3$ (Liszt et al. 2010; Liszt & Pety 2012).

The observations show that the clouds in the sample of Liszt & Pety (2012) presumably located near the edge of the local bubble at distances of about 150 pc from the sun (Liszt & Pety 2012), are surprisingly highly
structured with small scale, bright spots in CO, localised both spatially ($\lesssim 1 \times 10^{-2}$pc) and spectrally ($\Delta v \sim 1$–$2$ km/s).

Small scale CO variations were interpreted as variations in the chemistry, rather than density, or column-density variations in the clouds (Pety et al. 2011). The observed high line intensities of CO (1–0), typically $I$(CO)$\sim 5$–$20$ K km/s, together with the observed, almost uniform, CO (J=2–1)/(J=1–0) integrated intensity ratio of around 0.725 (Liszt & Lucas 1998; Pety, Lucas & Liszt 2008a), were explained as sub–thermal excitation in a diffuse cloud (Goldreich & Kwan 1974; Pety, Lucas & Liszt 2008a) with kinetic temperatures above 30 K, typically $T \approx 40$–$80$ K (Pety, Lucas & Liszt 2008a). Note here that the CO (J=2–1) vs. (J=1–0) line ratios observed in the clouds towards B0355+508 by Pety, Lucas & Liszt (2008a), however, are also consistent with the one expected in cold ($T \approx 14$ K), dense gas (Pety, Lucas & Liszt 2008a). The CO spectra shown in Liszt & Lucas (1998) imply similar CO (J=2–1)/(J=1–0) ratio for the clouds towards B0212+735 and B0355+508. The clouds further show a mean $^{12}$CO/$^{13}$CO brightness temperatures ratio of $T(^{12}$CO)/$T(^{13}$CO)$\sim 10$ to $15$ (e.g. Pety et al. 2011). The ratio was explained by chemical fractionation of $^{12}$/$^{13}$CO and C$^+$ in diffuse clouds (Pety, Lucas & Liszt 2008b; Liszt, Pety & Lucas 2010; Pety, Liszt & Lucas 2011). In the diffuse cloud scenario the typical CO column densities are a few times $10^{16}$cm$^2$. The derived hydrogen column densities $N$(H) in diffuse clouds of a few times $10^{21}$cm$^2$ (cf. Section 5.4) implies that only about $\sim 4$–$7$% of the carbon in diffuse clouds is in the form of CO (Sofia et al. 2004; Pety et al. 2011). Therefore, the majority of carbon ($\sim 90$%) must exist in another form, presumably ionized carbon [CII] (Sofia et al. 2004; Liszt & Lucas 2000). Thus, the [CII] $^2P_{3/2} \rightarrow ^2P_{1/2}$ fine structure transition at 1.9005369 THz is the major cooling line in the diffuse ISM (Dalgarno & McCray 1972; Tielens & Hollenbach 1985b). For the translucent regime the neutral carbon hyperfine transitions ($^3P_1 \rightarrow ^3P_0$ and $^3P_2 \rightarrow ^3P_1$) are expected to contribute up to $\sim 30$% of the [CII] cooling amount of the cloud cooling (Juvela et al. 2003).

These predictions provided the motivation to search for the [CII] emission from these clouds using SOFIA/GREAT.

5.2 OBSERVATIONS AND DATA PROCESSING

In November 2013 and February 2014 [CII] was observed in the interstellar clouds near the lines of sight towards B0355+508 and B0212+735 (cf. Table 5.1 and Fig. 5.1) using the dual-channel, single pixel, German Receiver for Astronomy at Terahertz frequencies (GREAT; Graf et al. 2006; Heyminck et al. 2012) onboard the airborne Stratospheric Observatory for Infrared Astronomy (SOFIA; Stutzki 2006; Becklin et al. 2007; Gehrz et al. 2009; Young et al. 2012). A Fourier transform spectrometer (FFTS), with 8192 channels and a bandwidth of 1.5 GHz was used, providing a native resolution of $\sim 0.03$ km/s. The observations were performed in single-point total power mode.

Out of a sample of 5 sources, selected for their expected high [CII] brightness from the CO maps by Liszt & Pety (2012), B0355+508 and B0212+735 were selected as they matched the flight plan of SOFIA.
Table 5.1: Coordinates (J2000) of B0355+508 and B0212+735 (1). The rows (2) and (3) show the relative offsets to the CO-peak and CO-void. The relative offsets of the Off-positions are listed in row (4). Images of the integrated CO emission of the sources are shown in Fig. 5.1.

<table>
<thead>
<tr>
<th>Source</th>
<th>Center Position (J2000)</th>
<th>CO-peak rel. offsets (&quot;&quot;')</th>
<th>CO-void rel. offsets (&quot;&quot;')</th>
<th>Off-position rel. offsets (&quot;&quot;')</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0355+508</td>
<td>03:59:29.73 50:57:50.1</td>
<td>-7</td>
<td>-6</td>
<td>-57</td>
</tr>
<tr>
<td>B0212+735</td>
<td>02:17:30.81 73:49:32.6</td>
<td>+47</td>
<td>-64</td>
<td>-187</td>
</tr>
</tbody>
</table>
Figure 5.1: Integrated CO (1–0) emission around B0355+508 (Liszt & Pety 2012) and B0212+735 (Pety & Liszt in prep.). Small crosses mark the positions observed in [CII]. The large cross in the middle marks the line of sight towards B0355+508 and B0212+735. The length of the white bar corresponds to 0.05 pc in B0355+508 and 0.1 pc in B0212+735 for an assumed source distance of 150 pc (Liszt & Pety 2012).
In each individual source two positions were observed. One position was centred on the brightest CO emission (CO-peak). The second position was pointed towards a region with faint, but clearly detectable, CO emission (CO-void). These positions are marked in Figure 5.1, and their coordinates are given in Table 5.1. This observation strategy was designed to collect information about the C$^+$ abundance and [CII] cooling in these clouds.

The off-source positions for B0355+508 and B0212+735 (coordinates see Table 5.1) were selected at regions with minimal 100 µm emission (IRAS, Neugebauer et al. 1984) and a minimal $A_V$ (from $E_{B-V}$ FIRAS/-COBE measurements, Schlegel et al. 1998). Due to their expected low column and volume densities these positions are hence likely to be free of detectable [CII]-emission. Additional CO(1–0) data of the B0212+735 off-position (Pety, priv. comm.) show these positions to be free of CO emission.

The actual allocation of telescopes does not allow any search for neutral carbon neither in B0355+508 and B0212+735, as both sources have a relative high declination in the northern sky. Actually all Telescopes for [C$i$](1–0) (and [C$i$](2–1)) observations are located on the southern hemisphere exclusively. Therefore I searched for possible C0 in clouds along the line of sight towards the quasar B0528+134 (Ra:05:30:46.41, Dec:12:31:55.1, J2000) as well. This cloud was within the sample of five sources that were proposed for the SOFIA/GREAT observations. This source has similar CO(1–0) and HCO$^+$ intensities as for the one found for B0355+508 and B0212+735. This source shows similar CO(1–0) and HCO$^+$ intensities as found in B0355+508 and B0212+735. The [C$i$](1–0) transition was observed towards this source in October 2014 in a ‘footprint’ of 110''×220'', with the Nanten2 telescope at the Pampa la Bola, Chile. The total on-source integration time was 52 minutes.

The [C$i$](1–0) observations were performed with the 460–490 GHz channel of the 2×8 pixel SMART receiver (Graf et al. 2002; 2008). The back-ends of SMART consist of sixteen eXtended bandwidth Fast Fourier Transfer Spectrometer (XFFTS; Klein et al. 2012) with a used bandwidth of 1 GHz and a spectral resolution of 76 kHz.

5.2.1 GREAT AND SMART DATA PROCESSING

The calibration of the SOFIA–data was performed with the standard pipeline for GREAT data (Guan et al. 2012). All spectra were converted to a main beam brightness temperature scale using $T_{mb} = T_A^{*}/\eta_{mb}$, with a main beam efficiency $\eta_{mb} = 0.67$ (Heyminck et al. 2012).

---

i Prominent submillimetre telescopes at the northern hemisphere that allowed [C$i$](1–0) observations in these sources were the Caltech Submillimetre Observatory (CSO) and the James Clark Maxwell telescope (JCMT, both located on the Mauna Kea on Hawaii). The CSO has closed for external observes in summer 2013 and the JCMT does not have any detector for the C0 transitions.

ii [C$i$](1–0) and [C$i$](2–1) can be observed with the Nanten2 and APEX telescope, both located in the Atacama desert, Chile. Both [C$i$] transitions are observed from the Antarctica as well, for example with HEAT (Burton et al. 2014).
<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$v_{\text{LSR \ CO}}$</td>
<td>$\Delta v_{\text{CO}}$</td>
<td>$I(\text{CO})_{P/V}$</td>
<td>$I([\text{CII}])$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[km/s]</td>
<td>[km/s]</td>
<td>[K km/s]</td>
<td>[K km/s]</td>
<td></td>
</tr>
<tr>
<td>B0212+735 CO-peak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$A_P$</td>
<td>$-16.9 \pm 0.1$</td>
<td>$2.4 \pm 0.1$</td>
<td>$6.4 \pm 0.7$</td>
<td>$&lt;0.3$</td>
</tr>
<tr>
<td></td>
<td>$B_P$</td>
<td>$-13.8 \pm 0.1$</td>
<td>$1.2 \pm 0.4$</td>
<td>$1.1 \pm 0.8$</td>
<td>$&lt;0.3$</td>
</tr>
<tr>
<td></td>
<td>$C_P$</td>
<td>$-9.8 \pm 0.1$</td>
<td>$1.2 \pm 0.1$</td>
<td>$20.0 \pm 2.0$</td>
<td>$&lt;0.4$</td>
</tr>
<tr>
<td>B0212+735 CO-void</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$A_V$</td>
<td>$-17.6 \pm 0.1$</td>
<td>$1.1 \pm 0.1$</td>
<td>$5.2 \pm 0.6$</td>
<td>$&lt;0.5$</td>
</tr>
<tr>
<td></td>
<td>$B_V$</td>
<td>$-13.8 \pm 0.1$</td>
<td>$1.1 \pm 0.1$</td>
<td>$1.8 \pm 0.3$</td>
<td>$&lt;0.5$</td>
</tr>
<tr>
<td></td>
<td>$C_V$</td>
<td>$-8.9 \pm 0.1$</td>
<td>$1.9 \pm 0.1$</td>
<td>$4.9 \pm 0.5$</td>
<td>$&lt;0.6$</td>
</tr>
<tr>
<td>B0212+735 CO-peak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$G_P$</td>
<td>$3.5 \pm 0.1$</td>
<td>$1.4 \pm 0.1$</td>
<td>$8.4 \pm 0.9$</td>
<td>$&lt;0.5$</td>
</tr>
<tr>
<td>B0212+735 CO-void</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$G_V$</td>
<td>$2.3 \pm 0.1$</td>
<td>$1.8 \pm 0.1$</td>
<td>$5.5 \pm 0.6$</td>
<td>$&lt;0.4$</td>
</tr>
</tbody>
</table>

Table 5.2: Observed upper limits of the integrated [CII] intensities compared to CO lines intensities of separated CO velocity components at the observed positions CO-peak and CO-void in B0355+508 & B0212+735.  
(1) Designation of the individual velocity components. The CO-peak and -void positions are marked by the subscripts P and V, respectively.  
(2) $v_{\text{LSR}}$ of the CO component(s) in the sources.  
(3) Width of the CO line.  
(4) Integrated CO line intensity in the positions CO-peak and CO-void, labeled by the footnotes P and V.  
(5) Upper limits for the observed integrated [CII] intensity $I([\text{CII}])$. To be able to estimate the upper limit of $I([\text{CII}])$ it is assumed that the [CII] line is located at the same $v_{\text{LSR}}$ as CO and that the [CII] line-width is equal to $\Delta v_{\text{CO}}$. 
The \([\text{C}\text{ii}]\) and \([\text{O}\text{i}]\) data were processed with the software package CLASS, version: jan14a.

A fifth order baseline was subtracted from all spectra. In spectra that showed sinusoidal standing wave patterns, sinusoidal baselines with standing wave periods between 8 and 27 km/s were fitted to the spectra. If the fit improved the RMS by more than 1/5 compared to a linear baseline fit, the fitted sinusoidal pattern was subtracted from the spectrum.

The data for B0212+735 and B0355+508 were smoothed to 0.4 km/s and 0.8 km/s respectively, a factor \(~3\) below the CO line widths, for better comparison.

The Nanten2/SMART \([\text{C}\text{i}]\)\((1–0)\) data were average to a single spectra and smoothed to 0.4 km/s (cf. Fig. 5.4).

### 5.2.2 Observational results

- **B0355+508:**
  Sixteen minutes integration time were spent on the CO-peak achieving a RMS of 0.09 K in a velocity bin of 0.8 km/s, corresponding to 1/3 of the line width of the brightest CO line. Two minutes of integration time were spent at the CO-void, achieving a RMS of 0.17 K. In both positions no \([\text{C}\text{ii}]\) emission was detected. The 3\(\sigma\) upper \([\text{C}\text{ii}]\) lines with widths corresponding to those of the CO lines thus are \(\lesssim 0.37\) K km/s for the CO-peak and \(\lesssim 0.71\) K km/s for the CO-void.

- **B0212+735:**
  About ten minutes integration time were spent on each position in B0212+735. A RMS of \(\approx 0.21\) K is reached in the CO-peak and \(\approx 0.22\) K in the CO-void in a velocity bin of 0.4 km/s, corresponding to 1/3 of the line width of the CO line of \(\sim 1.5\) km/s. Within the RMS no line could be detected. The 3\(\sigma\) upper limit for the \([\text{C}\text{ii}]\) line thus is \(\lesssim 0.45\) K km/s at both positions.

The listed 3\(\sigma\) limits are upper limits to the integrated \([\text{C}\text{ii}]\) line intensities, derived from the RMS of the velocity bins given. Additional smoothing of the data shows no signs for \([\text{C}\text{ii}]\) lines broader than the CO lines.

The averaged \([\text{C}\text{i}]\)\((1–0)\) data of B0528+134 reached a RMS of 0.22 K in velocity bins of 0.4 km/s. No line could be detected within the RMS (cf. Fig. 5.4).

### 5.2.3 Complementary observations

In the following sections three positions per cloud are discussed, the CO-peak (marked as P), CO-void (V), and the line of sight (Q) towards the quasar. CO\((1–0)\) emission spectra are available for all positions. HCO\(^+\) and H\(\text{I}\) absorption spectra are only available for the LOS towards the quasars.

iii available at http://www.iram.fr/IRAMFR/GILDAS
Table 5.3: HCO$^+$ absorption and CO emission along the line of sight towards B0355+508 and B0212+735.

(1) Designation of the velocity components
(3) FWHM of the HCO$^+$ absorption. From Lucas & Liszt (1996)

The CO(2–1) and CO(1–0) emission spectra along the LOS towards the quasars have been observed by Liszt & Lucas (1998) and Liszt & Pety (2012). The CO(1–0) emission spectra towards the CO-peak and -void positions were extracted from maps with a few arcmin extent around the quasars observed by Liszt & Pety (2012) and (Pety & Liszt in prep.). As errors for the CO data standard calibration uncertainties of 15% are assumed.

HCO$^+$ absorption along the line of sight towards the quasars B0355+508 and B0212+735 have been observed with the Plateau de Bure Interferometer by Lucas & Liszt (1996) and Liszt & Lucas (2000). Complementary Hi 21 cm absorption spectra towards the quasars are available from Dickey et al. (1983).

5.3 CO, HCO$^+$ AND HI IN B0355+508 & B0212+735

The following section describes the individual velocity components as seen in emission and absorption along the line of sight towards the quasars (Section 5.3.1 and 5.3.2). The association of these absorption components with corresponding CO emission components at the CO-peak and CO-void is discussed in Section 5.3.3 and 5.3.4.
Figure 5.2: [C\textsubscript{II}] (black) and CO (red; Liszt & Pety 2012) spectra at the positions CO-peak and CO-void in B0355+508 (left) and B0212+735 (right). The spectra of B0355+508 are smoothed to a velocity resolution of $\Delta v = 0.8$ km/s; B0212+735 spectra are smoothed to $\Delta v = 0.4$ km/s. The blue dashed line shows the HCO\textsuperscript{+} absorption spectra along the lines of sight towards the quasars B0355+508 and 0212+735 (Liszt & Lucas 1996, 2000). The red letters mark CO velocity components in the CO-peak and the CO-void, blue letters mark HCO\textsuperscript{+} absorption components along the line of sight towards the quasar. Identical capital letters mark related velocity components in the three positions. For better clarity the HCO\textsuperscript{+} absorption component $F_Q$ at $v_{L SR} = 2.5$ km/s in B0212+735 (cf. Table 5.3), which was identified by Lucas & Liszt (1996) is not shown.
5.3.1 The Line of Sight Towards B0355+508

B0355+508 is located at a Galactic latitude of $b = -1.6^\circ$. This low Galactic latitude implies that several diffuse clouds are observed simultaneously along the line of sight.

The HI absorption features in the spectra are very broad. The line-width is $\sim 55$ km/s and the absorption is located between $v_{\text{LSR}} \approx -40$ km/s and $+10$ km/s except for the molecular absorption features observed at $v_{\text{LSR}} = -10$ km/s and $v_{\text{LSR}} = -8$ km/s (velocity components $C$ & $D$ in Table 5.3) the HI the molecular lines (cf. Liszt & Pety 2012). This implies that a large amount of HI is in the foreground and background of the source.

The molecular absorption line profiles of CO(1–0) and HCO$^+$ show a complex structure along the line of sight towards B0355+508 (cf. Liszt & Pety 2012). Five individual HCO$^+$ components can be distinguished between $v_{\text{LSR}} \simeq -17$ km/s and $v_{\text{LSR}} \simeq -5$ km/s. Two CO emission components at $v_{\text{LSR}} \approx -17.2$ km/s and -10.3 km/s can be observed. They are associated with the two HCO$^+$ absorption velocity components $A_Q$ and $C_Q$ (Table 5.3).

5.3.2 The Line of Sight Towards B0212+735

B0212+735 is located at a galactic latitude $b \sim 12^\circ$. Two prominent HI absorption features can be observed in B0212+735 (cf. Liszt & Pety 2012). The largest amount ($\sim 80\%$) of HI $v_{\text{LSR}} \sim -12$ km/s (cf. Liszt & Pety 2012). Roughly 20 % of the total HI absorption arises from a fainter HI absorption component, located at $\sim +4$ km/s. Interestingly, all molecular absorption lines and the CO emission line are located in the velocity range of the fainter HI absorption component. No molecular absorption line lies within the strong HI absorption feature. Lucas & Liszt (1996) identified two close-by narrow HCO$^+$ absorption lines at $v_{\text{LSR}} = 2.5$ and 3.5 km/s by using a Gaussian decomposition of the line profile (components $F_Q$ and $G_Q$’ in Table 5.3), whereby the majority of the absorption arises from the component $G_Q$. Due to similar velocities, the CO emission component at this position (Liszt & Lucas 1998) can be associated with the HCO$^+$ absorption component $G_Q$ at 3.5 km/s.

5.3.3 Co-peak & Co-void of B0355+508

At the CO-peak of B0355+508 two bright spectral components can be observed in CO (components $A_P$, and $C_P$; cf. Fig. 5.2 and Table 5.2). These components are associated with the components $A_Q$ and $C_Q$ along the line of sight towards B0355+508 (Table 5.3). A possible third faint CO component ($B_P$) may be associated with the HCO$^+$ absorption component $B_Q$ (cf. Fig. 5.2 and Table 5.2).

Similar to the CO-peak three spectral CO-components can be resolved at the CO-void, $A_V$, $B_V$ & $C_V$, which are associated with the CO and HCO$^+$ components along the line of sight towards the quasar analogous to their counterparts at the CO-peak. (cf. Table 5.2 & 5.3 and Fig 5.2).
5.3.4 CO-peak & CO-void of b0212+735

The CO-peak position shows one prominent CO component \((G_P)\) at \(v_{\text{LSR}} = 3.5\) km/s with a width of \(\Delta v \approx 1.4\) km/s. It is located within the HCO\(^+\) absorption features. The same component appears in the CO-void \((G_V)\), although at a slightly lower velocity of \(v_{\text{LSR}} = 2.3\) km/s.

In conclusion, all CO emission spectra at the observed positions are associated with HCO\(^+\) absorptions along the lines of sight towards the quasars, while not all HCO\(^+\) absorptions are associated with CO emission velocity components. Liszt & Pety (2012) took this discrepancy as an indication that the \(^{12}\)CO(1–0) spatial distribution maps chemical fluctuations and not the cloud density.

5.4 HYDROGEN DENSITIES

In the following section I discuss the amount of molecular, neutral and total hydrogen in the observed clouds. The calculations of the molecular hydrogen column densities \(N(H_2)\) from the HCO\(^+\) absorption and CO emission are based on two different approaches.

- In the interpretation of Liszt & Lucas (2000) the molecular hydrogen densities derived from the HCO\(^+\) absorptions are representative for the densities of the whole cloud. The CO intensity fluctuations in the specific CO-maps were interpreted as local variations in the cloud chemistry, induced by local changes of the ambient physical circumstances, as for instance temporary dissipation of turbulent energy, not as variations of the cloud density (Liszt & Lucas 2000; Liszt & Pety 2012). As a consequence, regions with a low CO abundance should have a higher C\(^+\) abundance than regions with a high CO abundance (Liszt & Lucas 2000, cf. Section 5.5).

- Alternatively, deriving the molecular hydrogen column \(N(H_2)\) from the CO line integrated emission is based on the assumption that the CO-maps trace the intrinsic density structure of the source. In that case the position with a high CO emission would have a high column density as well. In consequence also the [C\(\text{ii}\)] emission would be higher in these positions, as \(I([\text{C\(\text{ii}\)}])\) is proportional to the \(N(H)\) (cf. Section 5.5 and 5.6).

The following sections estimates the integrated [C\(\text{ii}\)] intensities that are expected in these two scenarios. Alternatives to explain the non-detection of [C\(\text{ii}\)] reported here are also discussed. First I review the different ways that were previously used to estimate the amount of molecular hydrogen in these clouds from HCO\(^+\) absorption and CO emission (Section 5.4.1). Section 5.4.2 discusses the estimated molecular and total hydrogen column densities in the positions. Section 5.5 tests and discusses these two approaches by estimating the expected integrated [C\(\text{ii}\)] intensities. Finally Section 5.6 offers an alternative scenario to explain the observations.
Observations towards B0355+508 and B0212+735: 

Column density of the cold interstellar gas along the lines of sight towards the quasars. From Dickey et al. (1983).

\[
\frac{N(\text{H})}{N(\text{H})} = \frac{2}{10^2}, \quad \text{(12)} \]  

\[
N(\text{H}) = 0.3 \text{ pc}; \quad d = 0.15 \text{ for an assumed cloud distance of 150 pc}. \]

\[
\text{CO} \quad \text{HCO}^+ \quad \text{volume hydrogen densities, derived by dividing the total amount of hydrogen by the assumed cloud diameter.} \]

\[
\frac{V}{P} = \frac{10^2}{10^2}, \quad \text{co}-\text{footnotes Q, P, V represent the positions LOS towards the quasar.} \]

\[
\text{The (unknown) contribution of H}_n \quad \text{N(11) lower limits of the total hydrogen column density derived from the CO emission; Liszt et al. (2010) gives a}\]

\[
\text{CO-peak and CO-void. \quad The footnotes CO and HCO} \quad \text{Estimated molecular and total hydrogen column densities and volume densities along the line of sight towards the quasar and in the positions CO-peak and CO-void.} \]

<table>
<thead>
<tr>
<th>Component</th>
<th>CO-peak</th>
<th>CO-void</th>
<th>LOS towards quasar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B0355+508</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B0212+735</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4: Molecular, neutral and total hydrogen column densities and volume densities in the positions CO-peak, CO-void and the LOS towards the quasar.
5.4.1 Calculating Molecular Hydrogen Density

The total hydrogen column density can be estimated via the optical extinction $E_{B-V}$ using equation (4.22)\(^\text{iv}\) (Bohlin et al. 1978; Rachford et al. 2009; cf. Section 4.7).

By using this, the molecular hydrogen column density in diffuse clouds can be derived from HCO$^+$ column densities and using some additional arguments (Liszt & Lucas 1996; Liszt et al. 2010), as follows:

The optical extinction of diffuse clouds shows a correlation to the optical depth of HCO$^+$ with

$$\int \tau(\text{HCO}^+)[\text{Kkm/s}] \simeq 2 \times (E_{B-V})^{0.7}[\text{mag}] \quad (5.1)$$

This equation is derived from Liszt et al. (2010). The HCO$^+$ column density $N(\text{HCO}^+)$, in turn, can be calculated from the optical depth using the relation.

$$N(\text{HCO}^+) = 1.12 \times 10^{12} \text{cm}^{-2} \int \tau(\text{HCO}^+)d\nu \quad (5.2)$$

Liszt, Pety & Lucas (2010) derived an H$_2$ fraction of typically $f(\text{H}_2) = 2 N(\text{H}_2)/(2 N(\text{H}_2) + N(\text{H}^0)) = 0.35$ for the clouds, discussed here. The molecular hydrogen column density $N(\text{H}_2)$ in diffuse clouds can then be approximated by the combination of Equation (4.22), (5.1) and (5.2) via (Liszt, Pety & Lucas 2010; Liszt & Pety 2012).

$$N(\text{H}_2)_{\text{HCO}^+} \approx \frac{N(\text{HCO}^+)}{8 \times 10^{-10}} 2 + \frac{1-f(\text{H}_2)}{f(\text{H}_2)} = \frac{N(\text{HCO}^+)}{3.1 \times 10^{-9}} \quad (5.3)$$

The last equation refers to an assumed H$_2$ fraction of $f(\text{H}_2) = 0.35$. The molecular hydrogen column densities derived from the HCO$^+$ observations are listed in Table 5.3.

Alternatively, the molecular hydrogen column density in diffuse clouds can be estimated from the integrated CO(1–0) line intensity by use of a H$_2$–CO conversion factor $X_{\text{CO}}$ (c.f. Section 4.8)

$$N(\text{H}_2)_{\text{CO}} = X_{\text{CO}} \times I(\text{CO}) \quad (5.4)$$

Liszt et al. (2010) derived a $X_{\text{CO}} = 2.04 \times 10^{20} \text{ cm}^{-2}$ for diffuse clouds. Note that this value is coincidentally equal to the mean H$_2$–CO conversion factor measured in the Milky Way (Bolatto, Wolfire & Leroy 2013)\(^v\), which is discussed in Pety, Liszt & Lucas (2011).

5.4.2 Neutral, Molecular and Total Hydrogen Densities in b0355+508 and b0212+735

Table 5.4 summarizes the molecular hydrogen column densities for the individual velocity components derived with equations 5.3 and 5.4. For almost all CO velocity components in all discussed positions the derived $N(\text{H}_2)_{\text{CO}}$ exceeds the $N(\text{H}_2)_{\text{HCO}^+}$ of their counterparts along the line of

\(^{iv}\) N(H) = $5.8 \times 10^{21} \text{ H cm}^{-2} E_{B-V}$

\(^{v}\) See also Section 4.8
sight to the quasar derived from the HCO\(^+\) absorptions. If the densities in the observed clouds are roughly constant, the CO velocity components would overestimate the expected amount of molecular hydrogen by up to a factor of \(\sim 10\) (e.g. velocity component \(C\) in B0355+508). On the other hand CO would significantly underestimate the amount of molecular hydrogen for HCO\(^+\) velocity components which have no or only faint corresponding counterparts in CO. In that case it can by expected, especially for the velocity components \(B_p\), \(B_V\), \(E_p\), \(E_V\) and \(G_V\) a relatively bright [C\(\text{ii}\)] emission.

If the CO emission traces the intrinsic density structure of the source, the [C\(\text{ii}\)] emission should have a distribution similar to the CO emission. The total amount of H\(^\text{i}\) in the cold interstellar gas along the lines of sight towards the quasars is listed in Table 5.4 (Dickey et al. 1983). The total amount of hydrogen for the individual velocity components identified is hard to determine as there are no H\(^\text{i}\) absorption measurements available at the CO-peak and CO-void. In addition the H\(^\text{i}\) absorptions lines towards the line of sight to the quasars are relatively broad (\(\Delta v(\text{H}^\text{i}) \gg \Delta v(\text{HCO}^+)\)), so that the fractional amount of neutral hydrogen associated with the individual HCO\(^+\) absorption features cannot be easily determined. As the \(N(H_2)_{\text{HCO}^+}\) calculations are based on an \(H_2\) fraction of 35\%, resulting in \(N(\text{H}^\text{i}) \approx 3.7 \times N(H_2)\). Therefore, total hydrogen column densities of \(N(\text{H})_{\text{HCO}^+} = 2 \times N(H_2)_{\text{HCO}^+} + N(\text{H}^\text{i}) = 5.7 \times N(H_2)_{\text{HCO}^+}\) based on the HCO\(^+\) absorptions are assumed. As a lower limit for the total hydrogen based on the CO emission it is assumed that all hydrogen is in molecular form; \(N(\text{H})_{\text{CO}} = 2 \times N(H_2)_{\text{CO}}\). The thus derived total hydrogen column densities for the individual velocity components are listed in Table 5.4. Note that the derived total hydrogen column densities for the majority of the velocity components are \(\gtrsim 2 \times 10^{21}\) cm\(^{-2}\); corresponding to an \(A_V \gtrsim 1\) mag. These \(A_V\) classify the majority of the clouds at the upper limit of the diffuse regime or even in the translucent regime.

With the assumption that the cloud diameter \(d_C\) is equal to the depth of the cloud it is possible to estimate the volume hydrogen density \(n(\text{H})\) in the individual clouds with \(n(\text{H}) = N(\text{H}) / d_C\). Based on the typical sizes of the structural features in the CO(1–0)-maps (Fig. 5.1), cloud diameter of 0.15 pc (200′′) for B0355+508 and 0.3 pc (400′′) for B0212+735 based on assumed clouds-distances of 150 pc (Liszt & Pety 2012) are estimated. The cloud diameter (in parsec) is given by \(d_C[\text{pc}] \approx 4.85 \times 10^{-6} \rho[\text{′′}] d[\text{pc}]\), whereby \(\rho[\text{′′}]\) is the diameter of the cloud in arcsec and \(d[\text{pc}]\) the cloud-distance in parsec. The thus derived \(n(\text{H})\) for the individual velocity components are listed in Table 5.4. The densities derived from \(N(\text{H})_{\text{HCO}^+}\) span between \(\sim 4000\) to \(7000\) cm\(^{-3}\) and between \(\sim 2400\) to \(17000\) cm\(^{-3}\) derived from \(N(\text{H})_{\text{CO}}\). These densities are unusually high for diffuse clouds. Diffuse clouds are normally associated with a \(n(\text{H})\sim 100\) cm\(^{-3}\) (cf. Tielens 2010), roughly 20-100 times less than the derived values. These densities are commonly found in translucent and dense molecular clouds.

5.5 EXPECTED DIFFUSE CLOUD [C\(\text{ii}\)] INTENSITIES

I will now discuss the heating (Section 5.5.1) and cooling (Section 5.5.2) in diffuse clouds. With the assumption that the cooling of diffuse clouds is dominated by [C\(\text{ii}\)] the expected lower limit of the integrated [C\(\text{ii}\)] in-

expected diffuse cloud $[\text{C} \text{ii}]$ intensities, emitting from the observed positions (Section 5.5.2) are calculated.

5.5.1 Heating in Diffuse Clouds

In diffuse clouds with a visual extinction around unity and an ambient interstellar radiation field of $G_0 = 1$ (Habing 1968) photo-electric heating is expected to be the major heating source. For low density clouds with a density $\lesssim 3 \times 10^3 \text{ cm}^{-3}$ and a temperature $T \lesssim 100 \text{ K}$, the efficiency of photo-electric heating is at its maximum (Tielens 2010), and the heating amounts to about $\Gamma \simeq 5 \times 10^{-26} G_0 \text{ erg (H-Atom)}^{-1} \text{ s}^{-1}$ (Bakes & Tielens 1994; Tielens 2010), about 17 times stronger than the penetrating cosmic ray heating of $\sim 3 \times 10^{-27} \text{ erg (H-Atom)}^{-1} \text{ s}^{-1}$ (Tielens 2010). Additional heating may be due to turbulent dissipation, resulting in local hot spots, a mechanism favored to explain the unexpectedly high abundance of some species in diffuse clouds, in particular CH$^+$ (Falgarone et al. 2010a; Godard et al. 2010; Falgarone et al. 2010b). In addition, the formation of H$_2$ may contribute some heating to the clouds (Liszt & Lucas 1996). Hence photoelectric heating alone provides a lower limit to the heating. Further heating of the diffuse clouds may be induced by magnetohydrodynamic shocks and C-shocks (Pineau des Forets, Roueff & Flower 1986; Draine & Katz 1986; Gusdorf et al. 2008). Chemical reactions induced by these shocks would increase the C$^+$ column densities in diffuse gas significantly and could explain the detected HCO$^+$ (Draine & Katz 1986).

5.5.2 Cooling of Diffuse Clouds; Expected $I([\text{C} \text{ii}])$ in Diffuse Clouds

The $[\text{C} \text{ii}] 158 \mu\text{m}$ fine structure line is expected to be the dominant coolant in diffuse clouds (Hollenbach & Tielens 1999). Due to its relatively low critical density ($\sim 3 \times 10^3 \text{ cm}^{-3}$) (Goldsmith et al. 2012) C$^+$ gets easily excited in diffuse clouds. Oxygen is neutral in diffuse gas, but the $[\text{O} \text{i}] 63 \mu\text{m}$ ground state fine structure line has a much too high critical density to be significantly excited (Tielens & Hollenbach 1985a; Wolfire, Tielens & Hollenbach 1990); nitrogen will be neutral and hence cannot radiate. Where the carbon is in molecular form (CO), carbon monoxide rotational line cooling should dominate. The above line of reasoning allows to estimate an expected $[\text{C} \text{ii}]$ brightness of the CO-clouds near the lines of sights towards B0355+508 and B0212+735, in case they are indeed diffuse clouds.

The contribution of $[\text{C} \text{ii}]$ cooling does not exceed $\sim 30 \%$ of the $[\text{C} \text{ii}]$ cooling (Juvela et al. 2003). Therefore it is not considered in the following.

In thermal equilibrium the cloud heating is in balance with the cooling. The expected integrated $[\text{C} \text{ii}]$ line intensity can be estimated by equating the photoelectric heating at a given $G_0$ with the $[\text{C} \text{ii}]$ cooling function,

$$I([\text{C} \text{ii}]) \left[ \frac{\text{K}}{\text{km} \text{ s}^{-1}} \right] = \frac{1}{4\pi} \frac{\epsilon^3}{2k_B b^3} 10^{-5} \Gamma G_0 N(\text{H}) = 1.1 \times 10^4 \Gamma G_0 N(\text{H}) \quad (5.5)$$
Figure 5.3: Expected $I([\text{C}\text{ii}])$ for $n(\text{H})=4500 \text{ cm}^{-3}$ (left) and $n(\text{H})=2300 \text{ cm}^{-3}$ (right) at different total hydrogen column densities $N(\text{H})$ and temperatures calculated from equation 5.7. The filled grey areas show the expected $I([\text{C}\text{ii}])$ for a $T=30 \text{ K}$. The blue areas show the expected $I([\text{C}\text{ii}])$ for a cold cloud with a kinetic gas temperature of $14 \text{ K}$, as indicated by the CO(2–1)/CO(1–0) ratio. The dashed lines (---) represent the $I([\text{C}\text{ii}])$ for a beam filling factor of $\Phi_b=0.5$. The upper and lower edge of the grey and blue filled areas shows the $I([\text{C}\text{ii}])$ for a beam filling factor of $\Phi_b=1$ and $\Phi_b=0.1$. The red areas mark the upper limits of the here presented $[\text{C}\text{ii}]$ observations.
5.5 Expected Diffuse Cloud [CII] Intensities

Table 5.5: Lower limits for the expected $I([\text{CII}])$ in diffuse clouds derived from the photoelectric heating rate following Equation (5.6).

<table>
<thead>
<tr>
<th></th>
<th>$I([\text{CII}])_{\text{HCO}^+}$</th>
<th>$I([\text{CII}])_{\text{CO}_P}$</th>
<th>$I([\text{CII}])_{\text{CO}_V}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS toward quasar</td>
<td>CO-peak</td>
<td>CO-void</td>
<td></td>
</tr>
<tr>
<td>B0355+508</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>1.4±0.2</td>
<td>1.5±0.2</td>
<td>1.2±0.1</td>
</tr>
<tr>
<td>B</td>
<td>1.5±0.2</td>
<td>0.3±0.2</td>
<td>0.4±0.1</td>
</tr>
<tr>
<td>C</td>
<td>1.5±0.2</td>
<td>4.7±0.5</td>
<td>1.1±0.1</td>
</tr>
<tr>
<td>D</td>
<td>1.3±0.2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>E</td>
<td>1.4±0.2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>B0212+735</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.8±0.1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>G</td>
<td>3.5±0.5</td>
<td>1.9±0.2</td>
<td>1.3±0.1</td>
</tr>
</tbody>
</table>

(1) Designation of the assigned velocity components.
(2) Expected integrated [CII] intensity based on the total hydrogen column $N(\text{H})_{\text{HCO}^+}$ derived from the HCO$^+$ absorptions and an H$_2$ fraction of 35%.
(3) Expected integrated [CII] intensities in the positions CO-peak ($I([\text{CII}])_{\text{CO}_P}$) and CO-void ($I([\text{CII}])_{\text{CO}_V}$) based on molecular hydrogen column densities derived from the CO CO column density. The contribution of H$_i$ to the total amount of hydrogen is not considered.

For an assumed photoelectric heating rate of $\Gamma \simeq 5 \times 10^{-26}$ erg (H-Atom)$^{-1}$ s$^{-1}$ and an ambient interstellar field of $G_0=1$, Equation (5.5) gives an expected integrated [CII] line intensity $I([\text{CII}])$ of

$$I([\text{CII}]) \left[ \frac{\text{K km s}^{-1}}{\text{molec}} \right] = 5.7 \times 10^{-22} N(\text{H}) \left[ \frac{\text{K km s}^{-1}}{\text{molec}} \right] \quad (5.6)$$

The expected $I([\text{CII}])$ for the total hydrogen column densities (cf. Table 5.4) of the individual velocity components derived with Equation (5.6) are listed in Table 5.5.

- In the scenario that the spatial variations in the CO-maps are indeed induced by chemical and not by density variations, the expected $I([\text{CII}])$ is based on the total hydrogen column density derived from the HCO$^+$ absorption, $N(\text{H})_{\text{HCO}^+}$. The derived intensities range from $I([\text{CII}])=1.3$ K km/s to 3.5 K km/s, a factor $\sim$3 to 7 above the upper limits for a 3$\sigma$ [CII] detection in the observed positions.
  Note that these intensities are based on an assumed H$_2$ fraction of 35%. Neglecting the additional hydrogen column present in H$_i$ would still lead to an expected $I([\text{CII}])=0.5$ K km/s in B0355+508 and 1.2 K km/s in B0212+735. Even in that case [CII] lines $>3\sigma$ should have been observed for almost all velocity components.

- In the scenario that the CO emission traces the density and not chemical variations, the derived lower limits of the [CII] emission are a factor $\sim$3 to 15 above the upper limits for a 3$\sigma$ [CII] detection for the majority of the velocity components. The expected $I([\text{CII}])$ spans from $\sim$0.3 ($B_P$) to 4.7 K km/s ($C_P$), where the majority of the components have an expected $I([\text{CII}])$ of 1-2 K km/s. Note that
6.4 [CII] OBSERVATIONS TOWARDS B0355+508 AND B0212+735

Figure 5.4: [CII](1–0) (black) and CO(1–0)(red) spectra towards B0528+134. The HCO\(^+\) absorption spectra is shown by the blue line. The CO(1–0) and HCO\(^+\) spectra are extracted from Liszt & Pety (2012).

these densities are lower limits; adding the additional (but unknown) HI-column density in these positions would increase the total.

The fraction of neutral carbon is undetermined in these clouds. It cannot be excluded that a fraction of the cloud cooling occurs due to the C\(^0\) hyperfine transitions, thus leading to fainter [CII] emission lines. Using the upper limit for C\(^0\)-cooling of \(\sim30\%\) estimated by (Juvela et al. 2003), the emission should still have been detected. The [CII](1–0) observations in B0528+134 show no [CII](1–0) with the RMS of 0.22K (cf. Fig. 5.4). If the conditions in B0528+134 are similar to those in B0355+508 and B0212+735, these observations indicate that C\(^0\) has a minor significance for the cooling of the clouds, discussed here.

In summary, the balance between heating and cooling calculated for the diffuse cloud case predicts that integrated [CII] intensity are roughly a factor \(\sim3\) up to a factor 15 above the 3\(\sigma\) detection limit for the cloud components identified in CO. This indicates that the underlying assumption of the clouds being diffuse and warm is not adequate: there is no way to hide the [CII] column that complements the detected CO, unless the [CII] is less excited. This can be the case either with lower densities, resulting in a conflict with the sizes and column densities of the clouds or with a lower temperature as discussed below.

5.6 [CII] AND CO EMISSION FROM COLD DENSE CLOUDS

In the following section I show that observed low–J CO line intensities and the upper limits on the integrated [CII] intensities are consistent with the scenario of PDR layers on cold and dense cloud fragments.

Note that the scenario of dense clouds is encouraged by the derived high molecular hydrogen volume and column densities of the individual velocity components (cf. Table 5.4). As described in Section 5.4.2 the derived \(N(\text{H})\) correspond to optical extinction of \(A_v\approx1-4\) mag. These \(A_v\) classify them as translucent and as dense molecular clouds, which is
also consistent with the derived $n(\text{H})$ density of a few times $10^5 \text{ cm}^{-3}$. In translucent clouds the photoelectric heating is less efficient, thus the clouds would be colder and $[\text{C}\text{ii}]$ would be less excited. In such clouds ($n \sim$ few $10^3 \text{ cm}^{-3}$; $T<20 \text{ K}$) bright CO lines in the absence of $[\text{C}\text{ii}]$ are expected and observed (e.g. Pineda, Langer & Goldsmith 2014), as only molecules with a low excitation energy, such as the low–$J$ CO lines are excited.

First it is shown, that a cold cloud, with a temperature consistent with the low–$J$ CO intensity ratio in the thermalised limit, which hypothetically has all its carbon in the form of $\text{C}^+$ by itself has a sufficiently low $[\text{C}\text{ii}]$ intensity consistent with the upper limits of the observations. By applying PDR-modelling, it is shown, that the predicted $[\text{C}\text{ii}]$ intensity stays below the upper limit for the observed intensity even if one includes a PDR-layer on such a dense and cold cloud fragment.

5.6.1 Temperature Dependency of $I([\text{C}\text{ii}])$

Observations by Liszt & Lucas (1998) and Pety, Lucas & Liszt (2008a) found an almost uniform CO(2–1)/CO(1–0) ratio of $\approx 0.725$ in the observed clouds. This would indicate a gas temperature of 14 K for a cloud in local thermal equilibrium (LTE). Pety, Lucas & Liszt (2008a) rejected such a LTE solution in favour of a non-LTE explanation with sub-thermally excited CO lines (Goldreich & Kwan 1974; Pety, Lucas & Liszt 2008a) with cloud-temperatures above 30 K, typically $T \approx 40$ to 80 K (Pety, Lucas & Liszt 2008a).

As it is shown in the previous section, the $[\text{C}\text{ii}]$ intensity expected from such a warm, low density cloud would be well above the observed upper limit. The following paragraphs show that for the observed column densities, a cold, dense cloud would have $[\text{C}\text{ii}]$ intensities well below the observed upper limit, even if the full column density has all carbon in the form of $\text{C}^+$.

By adapting formula A3 in Crawford et al. (1985) the $[\text{C}\text{ii}]$ emission for a low density cloud is given by

$$I([\text{C}\text{ii}]) = 1.3 \times 10^{-3} e^{-91/T} X_{\text{C}^+} n(\text{H}) N(\text{H})_{21} \Phi_b \left[ \frac{\text{ergs}}{\text{s cm}^2 \text{ sr}} \right]$$

$$\approx 185 e^{-91/T} X_{\text{C}^+} n(\text{H}) N(\text{H})_{21} \Phi_b \left[ \frac{\text{K km/s}}{\text{s}} \right].$$

(5.7)

where $N(\text{H})_{21}$ is the total hydrogen column density in units of $10^{21} \text{ cm}^{-2}$ and $n(\text{H})$ the volume hydrogen density in cm$^{-3}$. The following calculations use a $\text{C}^+$ abundance of $X_{\text{C}^+}=1.4 \times 10^{-4}$ (cf. Langer et al. 2014a). As the spatial extent of the clouds exceeds the beam of SOFIA and to take the clumpy structure of clouds into account a beam filling factor of $\Phi_b=0.5$ is assumed, in order to have a conservative estimate.

Fig. 5.3 illustrates the expected $I([\text{C}\text{ii}])$ for gas temperatures of $T=14$ K and 30 K and typical column and volume densities as found in the observed clouds. As an example, for a $T=14$ K and typical densities of $n(\text{H})=4500 \text{ cm}^{-3}$ and $N(\text{H})=2 \times 10^{21} \text{ cm}^{-2}$ Equation (5.7) gives an $I([\text{C}\text{ii}]) \approx 0.17 \text{ K km/s}$. That is well below the 3$\sigma$ detection limit for the $[\text{C}\text{ii}]$ observations.

In the scenario of warm clouds with temperatures of $T \geq 30$ K this simple analysis confirms that the $[\text{C}\text{ii}]$ line should have been detectable for all
velocity components, except for the lowest total hydrogen column densities. Even for a low beam filling factor of $\Phi_b=0.1$, [CII] line detections would have been expected for both volume densities (cf. Fig. 5.3).

Low temperatures imply shielding of the clouds from the ambient radiation field. This can be realized by cloud cores embedded within large H$_i$-clouds, which absorb the majority of the incoming radiation. The observed wide H$_i$ absorption lines embedding the narrow HCO$^+$ and CO velocity components (Section 5.3) can be interpreted this way. Effectively, such a shielding layer is a photon-dominated surface layer with carbon being atomic and ionized. I will now discuss if the observed intensities are consistent with such a PDR scenario.

### 5.6.2 PDR Modeling of the Observations

PDR-modeling can reproduce the observed CO intensities as well as the observed upper limits for [CII], as shown in the following paragraph.

The observations are modelled with the stationary KOSMA–$\tau$ PDR-model (Röllig et al. 2006; 2013; Röllig & Ossenkopf 2013; Andree-Labsch, Ossenkopf & Röllig 2014). The numerical KOSMA–$\tau$ code simultaneously solves the energy balance, chemical equilibrium and radiative transfer of spherical clumps. The chemical fraction of carbon in PDRs is handled as well (Röllig & Ossenkopf 2013). The clumps are characterized by their total hydrogen mass, the surface hydrogen volume density, the strengths of the incident FUV field and the metallicity. Only solar metallicities are considered. Pre-shielding of the penetrating FUV radiation by a H$_i$ envelope is not considered. The code is applicable for a single clump as well as for an ensemble of clumps. Both is tackled in the following. The radial volume density of the clump(s) is determined by a power law function of the clump radius and the individual surface hydrogen volume density (e.g. Stoerzer, Stutzki & Sternberg 1996; Cubick et al. 2008). Note that the KOSMA–$\tau$ code is a stationary PDR-model. The initial conditions of the cloud formation are not considered.

Single clumps and ensembles of clumps with total masses in the range of $M=1$–10 $M_\odot$ are modelled. They are embedded in the standard Draine field of $\chi=1$. The calculations for the single clump refer to a beam filling factor of $\Phi_b=0.5$.

Figure 5.5 shows that the upper intensity limits for [CII], the observed absolute CO intensities, as well as the observed CO(2–1)/CO(1–0) ratio of $\approx$0.73±0.16 can be reproduced by PDR modelling. The model gives integrated line intensities in the order of $I$(CO(1–0))$\approx$10 K km/s and $I$([CII])$\lesssim$0.3 K km/s for cloud volume hydrogen densities of $n$(H)$\approx$10$^{3.5}$ to 10$^4$ cm$^{-3}$ for all the studied cases. Furthermore, the simulations give a $^{12}$CO/$^{13}$CO ratio of $\approx$11 for a $n$(H)$\approx$10$^3$ cm$^{-3}$ and $\approx$5 for a $n$(H)$\approx$10$^4$ cm$^{-3}$. The ratio is roughly in agreement with the observations. The $^{12}$CO/$^{13}$CO ratio is affected by the density of the clumps. $^{12}$CO is less self-absorbed in clumps with a lower density, so that the $^{12}$CO/$^{13}$CO ratio is increased compared to denser clumps. A higher $^{12}$CO/$^{13}$CO ratio can therefore be explained by a halo of smaller clouds around an ensemble of clumps with higher densities. Hence the clouds do not have to be diffuse to produce the observed $^{12}$CO/$^{13}$CO ratio.
5.6 [CI] and CO in Cold Dense Clouds

Figure 5.5: PDR-modeling (KOMSA–\(\tau\) model; Röllig et al. 2006) of clumps with masses of \(M=1\) and \(10\ M_\odot\) for surface volume hydrogen densities of \(n(H)=10^3\) to \(10^5\) \(\text{cm}^{-3}\). The images on the left (A and C) illustrate the modelling for an ensemble of clumps. The images on the right (B and D) show the modelling for a single clump. For the single clump a beam filling factor of \(\Phi_b=0.5\) is anticipated.

The images at the top (A and B) show the modelled [CI] and \(^{12}\text{CO}(1-0)\) integrated line intensities. The black and grey lines show the modelled integrated line intensities of \(^{12}\text{CO}(1-0)\) and [CI]. The style of the line marks the anticipated clump mass. The grey areas show the rough lower and/or upper limits of the here discussed \(^{12}\text{CO}(1-0)\) and [CI] observations.

The images at the bottom (C and D) illustrate the modelled \(^{13}\text{CO}(2-1)/^{12}\text{CO}(1-0)\) ratio for clumps with \(M=1\) and \(10\ M_\odot\). The range of the observed \(^{13}\text{CO}(2-1)/^{12}\text{CO}(1-0)\) ratio (\(\pm 0.73\pm 0.16\)) is marked by the grey area.
Figure 5.6: Chemical profile of a clump with a surface volume hydrogen densities of $n(H)=10^3$ cm$^{-3}$ and a mass of 10 $M_\odot$ penetrated by a standard Draine field of $\chi=1$. The relative densities of $H^0$, $H_2$, $C^+$, $C^0$, $^{12}/^{13}$CO and HCO$^+$ as function of $A_V$ are shown by the black/grey lines (left axis). The temperature profile within the clump is shown by the red line (right axis).

Note that the assumed cloud-masses in the PDR-model are consistent with the anticipated cloud diameters of the discussed clouds. A cloud mass of 10 $M_\odot$ and a density of $n(H)=5000$ cm$^{-3}$ corresponds to a diameter of $d_C\approx0.4$ pc; 1 $M_\odot$ is equal to $d_C\approx0.2$ pc.

The modelled chemical profiles meet the expectations of a ‘standard’ PDR. The carbon towards the PDR-surface is dominated by $C^+$, while the inner region of the PDR is dominated by CO. The transition zone between $C^+/C^0/CO$ is located at an $A_V\sim0.5$ mag. $C^+$ is associated with kinetic gas temperatures of $T\sim30$ K to 20 K, while CO is associated with $T\sim15$ K gas. The hydrogen is predominantly in molecular form throughout the simulated clumps. HCO$^+$ has a similar distribution as CO in all simulated cases. The fraction of HCO$^+$ increases beyond the $C^+/C^0/CO$ transition zone. HCO$^+$ is formed at slightly higher $A_V$ than CO ($\sim0.7$ mag compared to $\sim0.5$ mag). The $^{12}/^{13}$CO/HCO$^+$ ratio is thus maximal near the $C^+/C^0/CO$ transition zone ($^{12}$CO/HCO$^+\approx1\times10^7$) and decreases towards the centre of the clumps ($^{12}$CO/HCO$^+\approx0.5\times10^7$). The simulations show no significant variations of the ratio in clumps with $n(H)=10^3$ cm$^{-3}$ and $n(H)=10^4$ cm$^{-3}$. A detailed chemical profile and a temperature profile are shown in Figure 5.6.

However a $^{12}$CO/$^{13}$CO ratio of higher than $\sim5$ requires clumps with masses significantly lower than 1 $M_\odot$, just because both CO lines tend to become optically thick, pushing the line ratio towards unity. Clumpy PDR ensembles do not suffer from this and are able to reproduce ratios $^{12}$CO/$^{13}$CO$>10$ for higher masses as well.

Therefore, the observations can be explained as emission from PDRs. An ensemble of cold dense clumps with $n(H)\sim3000$ to 10000 cm$^{-3}$ penetrated by a Draine field of $\chi=1$, reproduces the observed CO intensities, the upper limits for [CII], the $^{12}$CO/$^{13}$CO line ratio and clump sizes. Note that the hydrogen volume densities are fully consistent with those calculated in Section 5.4.2 as well.
5.7 SUMMARY AND CONCLUSION

This chapter presents [C\textsc{ii}] observations in two nearby molecular clouds near the lines of sight towards the quasars B0355+508 and B0212+735. Within the RMS of $\sim 0.1$-0.3 K, in neither of the positions was a [C\textsc{ii}] line detected.

The observed upper [C\textsc{ii}] intensity limits of $I([\text{C\textsc{ii}}]) \lesssim 0.5$ K km/s are in contradiction with the scenario proposed by Pety, Lucas & Liszt 2008a and Liszt & Pety 2012 of warm non-LTE diffuse clouds ($T \gtrsim 30$ K) with sub-thermally excited CO bright lines. In diffuse clouds the photo-electric heating rate is at its maximum and the cooling is dominated by [C\textsc{ii}]. The upper [C\textsc{ii}] intensity limits in the observed clouds were estimated by balancing the heating with the cooling. If the observed clouds were indeed diffuse, the expected integrated [C\textsc{ii}] intensities should be a factor $\sim 3$ up to 15 above the $3\sigma$ detection limit for the cloud components identified in CO emissions.

The [C\textsc{ii}] non-detection implies that C$^+$ is less excited than expected for diffuse clouds. As lower densities are in conflict with the cloud sizes and column densities, the gas must therefore be colder. Cloud temperatures of $\sim 15$ K are supported by the observed CO(2–1)/CO(1–0) ratios. In addition the total hydrogen column density in the clouds corresponds to an $A_V \sim 1$ to 4 mag and their volume density is typically $n(\text{H}) \sim 5000$ cm$^{-3}$, which is hard to reconcile with clouds being diffuse. These densities classify the clouds as being in the translucent regime, or even as moderately dense molecular clouds.

The observed low–J CO absolute line intensities and their ratio, the non-detection of [C\textsc{ii}] 158\textmu m within the observed upper limits and the observed $^{12}$CO/$^{13}$CO ratio are consistent with a PDR–scenario (using the KOSMA–$\tau$ PDR model), in which PDR clump densities are in agreement with our derived column and volume densities. The observations, the derived column and volume densities and the size of the cloud are thus consistent with an ensemble of cold dense clumps.

In summary the observations, calculations and simulations indicate that the clouds along the line of sight towards B0355+508 and B0212+735 consist of an ensemble of cold dense clumps, with volume densities of $n(\text{H}) \sim 10^{3.5}$ cm$^{-3}$ to $10^4$ cm$^{-3}$ and core temperatures of $T \sim 15$ K. The observations are not compatible with the scenario of warm diffuse clouds.

The study is based on a small sample of positions and relatively short integration times. Further mapping would significantly increase the statistical representativeness of this study. It would be worth investigating if the emission from other clouds which have been identified as being diffuse are also consistent with a cold and dense clump scenario, once the [C\textsc{ii}] intensity is observed and taken into account.
Chapter 6

Large scale distribution of [C\textsc{i}](1–0) and low–\textit{J} CO transitions in the fourth quadrant of the Milky Way

The following chapter is dedicated to the study of the radial and latitudinal distribution of carbon monoxide and neutral atomic carbon in the fourth quadrant of the Milky Way. I will compare the distribution of [C\textsc{i}](1–0) relative to different low–\textit{J} CO transitions and determine the radial distribution of gas perpendicular to the galactic disc. The width of the galactic disc (’scale height’) is discussed as well. The results will be compared with [C\textsc{ii}] observations and simulated [C\textsc{ii}]–maps as well as with the scale height of H\textsc{i}. This will shed light onto the composition of the ISM and will give an insight into the dominant processes which trigger the evolution of the ISM.

6.1 INTRODUCTION

Stars are born within dense regions of molecular clouds (cf. section 2.1). Different processes, such as supernovae, stellar winds, self-gravitational collapse of clouds or turbulences are proposed to trigger the agglomeration of (more or less) diffuse gas and to finally form dense clouds. It is currently a topic of research, which of these processes dominate. A number of theoretical studies proposed a phase where the molecular hydrogen is predominantly traced by C\textsuperscript{+} and C\textsuperscript{0}, in the absence of CO (CO–dark H\textsubscript{2}, Hollenbach, Takahashi & Tielens 1991, Wolfire et al. 2003 and Wolfire et al. 2010; cf. section 2.2). The fraction of CO–dark H\textsubscript{2} depends \textit{inter alia} on the metallicity of the ambient medium (c.f section 2.2.4). The metallicity within the Milky Way decreases towards larger radial distances to the Galactic centre, \(R_{\text{GC}}\), as well as towards larger vertical distance, \(z\), from the Galactic plane (e.g. Koeppen & Cuisinier 1994; Molla et al. 1997; Schlesinger et al. 2014). Therefore a higher fraction of CO–dark H\textsubscript{2} towards larger \(R_{\text{GC}}\) and \(z\) is expected. Hence, the fraction of C\textsuperscript{+} and C\textsuperscript{0} compared to CO should increase towards higher galactic latitudes and \(R_{\text{GC}}\).

This section will discuss these issues based on the vertical distribution of CO, C\textsuperscript{0} and [C\textsc{ii}] in the Milky Way. The distribution of gas perpendicular to the disc is affected by the hydrostatic pressure within the ISM, which reflects the mass distribution, the energy balance and its kinematics. The hydrostatic pressure of a cloud is given by the equilibrium of dispersing
forces like the thermal pressure, the dynamical motion of the gas, the pressure by the radiation and the cohesive force of gravity (Langer, Pineda & Velusamy 2014a). It has a significant impact on the formation of GMCs and the formation of stars (Wong & Blitz 2002; Blitz & Rosolowsky 2004). The ambient hydrostatic pressure in the disc is directly and almost linearly connected to the star formation rate and the ratio of neutral and molecular gas (Blitz & Rosolowsky 2006). Thus, the hydrostatic pressure of the ISM is directly reflected in the width of the galactic disc, also denoted as the 'scale height', \( z_{1/2} \). It is of great interest to study the scale height of the ISM components in the galaxy. The precise relation between the hydrostatic pressure and the scale height is discussed in section 6.4.1.

A number of studies have focused on the latitudinal distribution of CO(1–0), based on spectrally resolved observations (e.g. Sanders, Solomon & Scoville 1984; Dame et al. 1987; Clemens et al. 1988; Malhotra 1994a;b; Jackson et al. 2006; Braiding et al. 2015). These studies found out that the predominant amount of molecular gas, traced by CO, is located in a thin layer of self-gravitating molecular clumps (Narayan & Jog 2002) centred around the galactic midplane at \( b=0^\circ \), and also high latitude clouds are observed (e.g. Knapp et al. 1985, Malhotra 1994a;b; Fukui et al. 2014). This layer has a typical half width of \( z_{1/2}(R_0)\sim 70 \) pc for CO(1–0) at the location of the sun. The width of the layer (and thus those of H\(_2\) traced by CO) increases towards higher distances from the Galactic Centre (Sanders, Solomon & Scoville 1984 ,Clemens et al. 1988; Malhotra 1994a;b) with \( z_{1/2}\propto R_{\text{Gal}}^{0.5} \) (e.g. Sanders, Solomon & Scoville 1984). A recent study investigated the scale height of [C\(_i\)] in the Milky Way (Langer, Pineda & Velusamy 2014a). The result of this study was that the scale height of [C\(_i\)] is higher than that of CO with a mean scale height of 86 pc for galactic distances between \( R_{\text{GC}}\sim 4 \) to 8 kpc. This [C\(_i\)] scale height refers to the total [C\(_i\)] emission perpendicular to the galactic disc, not only the [C\(_i\)] emission which is associated with molecular gas. It was not possible to distinguish between the [C\(_i\)] emission that is associated with molecular clouds and those from diffuse regions, due to the missing spectral information. Therefore, its radial distribution could be directly determined. It was therefore assumed that its radial distribution is similar to those of CO(1–0).

The scale height of other important carbon bearing transitions has not been studied so far, neither those of [C\(_i\)](1–0), CO(2–1) nor CO(4-3). So it is of great interest to determine the radial distribution of their scale heights and compare it to CO(1–0) and [C\(_i\)]. In this chapter I will first give an overview of the analysed data in section 6.2. Here, the emission of [C\(_i\)](1–0) and CO will be compared as well. The radial distribution of the gas will be determined in section 6.3. The distribution of the observed transitions perpendicular to the galactic disc will be discussed in section 6.4.
Figure 6.1: Top: Artist illustration of the Milky Way. The red stripes mark the line of sight of the $b$-stripes observed with AST/RO (image A).

*Credit:* R. Hurt, NASA/JPL-Caltech

Bottom: Image B shows the galactic plane at 857 GHz (Planck Collaboration et al. 2014a). The red stripes show the regions observed with AST/RO.
6.2 DATA PROCESSING AND OBSERVATIONAL RESULTS

This section provides an overview of the observational data used in the following analysis. The data processing is also described in the following.

6.2.1 DATA PROCESSING

The present analysis is based on observational data of the transitions $^{12}$CO(4–3), $^{12}$CO(2–1) and [C\textsc{i}](1–0) towards the galactic longitudes $l = 306.0^\circ$, $315.6^\circ$, $323.1^\circ$, $300.0^\circ$, $336.4^\circ$, $348.0^\circ$ and $354.0^\circ$ between the galactic latitudes $-2^\circ < b < 2^\circ$, in so called ‘$b$-strips’ (cf. Figure 6.1). This data is provided by observations with the Antarctic Submillimeter Telescope and Remote Observatory, (AST/RO)\textsuperscript{i} and is obtainable at the AST/RO homepage\textsuperscript{ii}. The page provides likewise data of $l = 295^\circ$, which are not considered in the following analysis, as the CO(4–3) and [C\textsc{i}](1–0) data have a relatively low quality compared to the other $b$–strips\textsuperscript{iii}.

The [C\textsc{i}](1–0) and CO(4–3) transitions were observed with the double sideband SIS waveguide receiver ’Wanda’, having a noise temperature of $\sim 172$ K at 492 GHz (Walker et al. 1992; Honingh et al. 1997). The CO(2–1) data was observed with a SIS receiver with a double-sideband noise temperature of $80–170$ K (Kooi et al. 1991). The spectrometer consisted of two higher resolution acousto-optical spectrometers (HRAOSs), each having 2048 channels and a bandwidth of 1.1 GHz (Schieder, Tolls & Winnewisser 1989), which corresponds to a resolution of 63 MHz ($\sim 0.08$ km/s for 230 GHz, $\sim 0.04$ km/s for 492 GHz) per channel.

The data was observed in the on the flight mode. The data reduction was performed with the COMB data reduction package as described in (Stark et al. 2001). The spectra were converted to the main beam brightness scale with a main beam efficiency of 0.81 for CO(2–1) and 0.72 for CO(4–3). A first order baseline was removed from all the spectra (Stark priv. communication).

The data is provided in the form of 3 dimensional pv-diagrams, with the dimensions velocity, galactic latitude and main beam brightness temperature, $T_{\text{mb}}$. The data covers the velocity ranges from $v = -150$ km/s to $+100$ km/s, with a velocity resolution of $\Delta v = 0.44$ km/s, between the galactic latitudes $b = \pm 2^\circ$. The data is spatially oversampled, providing a latitudinal binning of $0.015^\circ (\approx 54''$). The CO(2–1) and [C\textsc{i}](1–0) datasets

\textsuperscript{i} The Antarctic Submillimeter Telescope and Remote Observatory, AST/RO (Stark 1992; Stark et al. 2001), was an offset Gregorian submillimeter telescope located nearby the Amundsen–Scott South Pole Station at an altitude of 2847 m, operated between January 1995 and December 2005 (Stark 2013). The diameter of the primary mirror was 1.7m, corresponding to a beam size of $\sim 110''$ at 492 GHz and $\sim 180''$ for 230 GHz. The widths of the $b$-strips is equal to the beam-size. The telescope-optic was designed with an offset to its major axis to avoid undesired reflections and resonances. The primary mirror had an accuracy of $\sim 9$ $\mu$m, allowing observation even in the Terahertz regime. AST/RO was the first ground based observatory which observed [N\textsc{ii}] at 1.46 THz (Oberst et al. 2006; 2011). For further information to the AST/RO–design see Stark et al. (1997).

\textsuperscript{ii} www.cfa.harvard.edu/~aas/adair/www-docs/AST_RO.html

\textsuperscript{iii} The data at $l = 295^\circ$ has a large number of standing waves and artefacts, so that a reliable identification of sources is not possible.
have a mean RMS of \( \sim 0.05 \) K referring to this resolution, while those of CO(4–3) are slightly higher with \( \sim 0.08 \) K. The precise RMSs for the individual \( b \)-strips are listed in table 6.1.

Complementary data of \( ^{12}\text{C}^{16}\text{O}(1–0), \, ^{13}\text{C}^{16}\text{O}(1–0), \, ^{12}\text{C}^{18}\text{O}(1–0) \) and \( ^{12}\text{C}^{17}\text{O}(1–0) \) (denoted as \( ^{12}\text{CO}(1–0), \, ^{13}\text{CO}(1–0), \, ^{18}\text{CO}(1–0) \) and \( ^{17}\text{CO}(1–0) \) in the following) were observed with the 22-m diameter Mopra telescope\(^{iv} \) at \( l = 315.6^\circ, 323.1^\circ, 300.0^\circ, 336.4^\circ, 342.5^\circ \) and \(-2^\circ \leq b \leq 2^\circ \) within the Mopra Southern Galactic Plane CO Survey (Burton et al. 2011) in April and May 2010. Each strip had a width of 6′ with an angular resolution of 35″ after the median filter convolution (Ladd et al. 2005; Burton et al. 2013a).

The Monolithic Microwave Integrated Circuit receiver (MMIC) of Mopra and the UNSW Mopra Spectrometer (MOPS) filter bank were used for the observations. MMIC covers the spectral range from 77 GHz to 117 GHz. The bandpass of MOPS has a width of 8 GHz. It was centred at 112.5 GHz to observe the four CO transitions simultaneously. The observations used the zoom mode of MOPS, with \( 4 \times 137.5 \) MHz wide, dual–polarisation bands, each having 4096 channels (Burton et al. 2013a), resulting in a spectral resolution of \( \sim 0.09 \) km/s. This observing strategy gave \( ^{12}\text{CO}(1–0) \) data in the velocity range between \( v_{\text{LSR}} = -204 \text{ km/s} \) to \(+156 \text{ km/s} \), \( ^{13}\text{CO}(1–0) \) between \( v_{\text{LSR}} = -114 \text{ km/s} \) to \(+260 \text{ km/s} \), \( ^{17}\text{CO}(1–0) \) between \( v_{\text{LSR}} = -114 \text{ km/s} \) to \(+260 \text{ km/s} \) and finally \( ^{18}\text{CO}(1–0) \) between \( v_{\text{LSR}} = -131 \text{ km/s} \) to \(+247 \text{ km/s} \).

The data was calibrated with LIVEDATA\(^{vi} \). The calibration process is described in detail in Burton et al. (2013a). The data was converted to the main beam brightness temperature using the main beam efficiency of \( \eta_{\text{mb}} = 0.42 \).

The position–velocity diagrams were created with the GRIDZILLA software package\(^{vii} \). To compare the Mopra data with the AST/RO–observation, I have regridded the data to the same spatial and spectral resolution, whereby a first order base line was subtracted from the spectra. The thus processed data have a RMS in the order of \( \sim 0.05 \) K in the majority of

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<th>( l )</th>
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<th>( ^{12}\text{CO}(2–1) )</th>
<th>( ^{12}\text{CO}(4–3) )</th>
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<td>0.06</td>
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</tr>
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<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>354.0°</td>
<td>–</td>
<td>–</td>
<td>0.05</td>
<td>0.08</td>
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Table 6.1: Mean RMS of the \( b \)-strips \((-2^\circ \leq b \leq 2^\circ \)) for a velocity resolution of 0.44 km/s.

\(^{iv} \) Mopra is a CSIRO telescope with a diameter of 22 m. It is located near Coonabarabran in NSW, Australia

\(^{v} \) \( v_{\text{LSR}} \) is the velocity relative to the local standard of rest.

\(^{vi} \) http://www.atnf.csiro.au/computing/software/livedata

\(^{vii} \) http://www.atnf.csiro.au/computing/software/livedata
The precise values for all the \( b \)-strips are listed in Table 6.3. \([\text{Cl}](1–0)\) in the absence of \( \text{CO}(2–1)\) is shown by the white areas in the Figures 6.4 and 6.5 as well. The weighted average ratios over all the galactic longitudes are listed in the bottom row.

The AST/RO data is illustrated in the Figures 6.2 and 6.3.

The AST/RO data is illustrated in the Figures 6.2 and 6.3.

<table>
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<tr>
<th>( \theta )</th>
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<th>( \frac{T_{\text{mb}}^{12}\text{CO}(1–0)}{T_{\text{mb}}^{\text{CI}(1–0)}} )</th>
<th>( \frac{T_{\text{mb}}^{\text{CO}(2–1)}}{T_{\text{mb}}^{\text{CI}(1–0)}} )</th>
<th>( \frac{T_{\text{mb}}^{\text{CO}(4–3)}}{T_{\text{mb}}^{\text{CI}(1–0)}} )</th>
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<td>348.0°</td>
<td>-</td>
<td>-</td>
<td>6.0±3.6</td>
<td>1.8±0.8</td>
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<tr>
<td>354.0°</td>
<td>-</td>
<td>-</td>
<td>5.4±3.5</td>
<td>1.7±1.1</td>
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<td>Mean</td>
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<td>1.3±0.6</td>
<td>5.0±1.7</td>
<td>1.4±0.5</td>
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Table 6.2: Ratio of the brightness temperatures of \([\text{Cl}](1–0)\) to \( ^{12}/^{13}\text{CO}(1–0)\), \( \text{CO}(2–1)\) and \( \text{CO}(4–3)\). Only pixels are considered which show emission of both lines and have a S/N\( \geq 3\). The weighted average ratios over all the galactic longitudes are listed in the bottom row.

The different \( b \)-strips show several prominent spectral features with typical peak brightness temperatures of \( \sim 2.5 \) to 4 K for \([\text{Cl}](1–0)\), \( \sim 5 \) to 15 K for \( ^{12}\text{CO}(1–0)\), \( \sim 1 \) to 3 K for \( ^{13}\text{CO}(1–0)\), \( \sim 5 \) to 10 K for \( \text{CO}(2–1)\) and \( \sim 2 \) to 18 K for \( \text{CO}(4–3)\). The major fraction of the line emission is observed at velocities between \( -100 \) km/s \( \lesssim v_{\text{LSR}} \lesssim 0 \) km/s. The data show strong correlation between \([\text{Cl}](1–0)\) and the \( \text{CO} \) line transitions. No significant \([\text{Cl}](1–0)\) emission could be detected outside the \( \text{CO} \) emitting clouds. The \([\text{Cl}](1–0)\) emission is surrounded by pixels that show \( \text{CO} \) emission, both spatially and spectrally. Only 1 to 2 \% of the pixels with a \([\text{Cl}](1–0)\) signal with \( T_{\text{mb}} \gtrsim 3 \times \text{S/N} \) do not exhibit a \( \text{CO} \) emission signal. A comparison of the pixels with \( T_{\text{mb}} \gtrsim 3 \times \text{S/N} \) shows that \( \sim 1 \) to 2 \% of the pixels show \([\text{Cl}](1–0)\) emission in the absence of \( \text{CO}\)\(^\text{viii}\). This fraction is reduced to almost zero for pixels where the \( T_{\text{mb}} \gtrsim 5 \times \text{S/N} \).

The ratio of the brightness temperatures of the \( ^{12}\text{CO} \) transitions relative to \([\text{Cl}](1–0)\) is on average \( \sim 6 \) for \( ^{12}\text{CO}(1–0)\), \( \sim 5 \) for \( ^{13}\text{CO}(1–0)\) and almost unity for \( ^{12}\text{CO}(4–3) \) (cf. Fig 6.10), similar as for \( ^{13}\text{CO}(1–0)\). Histograms of the ratios are illustrated in the Figures 6.6 to 6.9. The ratio is commonly maximal towards the edges of the regions with \([\text{Cl}](1–0)\) emission and minimal towards their centre as illustrated by the example of \( T_{\text{mb}} ^{^{12}\text{CO}(2–1)}/T_{\text{mb}} ^{([\text{Cl}](1–0))} \) in the Figures 6.4 and 6.5. This can be explained by optical depth effects, which I will discuss in the following section.

The \( ^{12}\text{CO}(1–0) \) and \( ^{13}\text{CO}(1–0) \) data allow the estimation of the optical depths of \( ^{12}\text{CO}(1–0) \), \( \tau_{2} \), as elaborated in Section 4.3. The optical

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\(^{viii}\) The precise values for all the \( b \)-strips are listed in Table 6.3. \([\text{Cl}](1–0)\) in the absence of \( \text{CO}(2–1)\) is shown by the white areas in the Figures 6.4 and 6.5 as well.
Figure 6.2: Illustration of the CO(2–1), CO(4–3) and [C\textsc{i}](1–0) emission within the b-strips at $l=306.0^\circ$, 315.6°, 323.1° and 330.0°. CO(2–1) is shown by the colours. The emission of [C\textsc{i}](1–0) (black contours) and CO(4–3) (red contours) are superimposed. The contour lines of [C\textsc{i}](1–0) have steps of 0.25 K. The contour lines of CO(4–3) have steps of 0.5 K.
Figure 6.3: Illustration of the CO(2–1), CO(4–3) and [C\textsc{i}](1–0) emission within the $b$-strips at $l=336.4^\circ$, 342.6°, 348.0° and 354.0°. CO(2–1) is shown by the colours. The emission of [C\textsc{i}](1–0) (black contours) and CO(4–3) (red contours) are superimposed. The contour lines of [C\textsc{i}](1–0) have steps of 0.25 K. The contour lines of CO(4–3) have steps of 0.5 K.
Figure 6.4: Ratios of $T_{mb}(\text{CO}(2–1))/T_{mb}(\text{CI}(1–0))$ in the $b$-strips towards $l=306^\circ$, $315^\circ$, $323^\circ$ and $330^\circ$. The ratio is illustrated by the colour coding. Positions with no $\text{[CI]}(1–0)$ but $\text{CO}(2–1)$ are shown by the dark blue areas. Positions with $\text{[CI]}(1–0)$ in the absence of $\text{CO}(2–1)$ are shown in white. Only pixels with a S/N $> 3 \times \langle \text{RMS} \rangle$ were considered.
Figure 6.5: Ratios of $T_{mb}(\text{CO}(2-1))/T_{mb}(\text{C}(1-0))$ in the $b$-strips towards $l$=336°, 342°, 348° and 354°. The ratio is illustrated by the colour coding as in Figure 6.4.
Figure 6.6: Histogram illustrating the amount of pixels at a certain ratio of $\frac{T_{\text{mb}}(\text{CO}(2-1))}{T_{\text{mb}}(\text{CI}(1-0))}$.

Figure 6.7: Histogram illustrating the amount of pixels at a certain ratio of $\frac{T_{\text{mb}}(\text{CO}(4-3))}{T_{\text{mb}}(\text{CI}(1-0))}$. 
Figure 6.8: Histogram illustrating the amount of pixels at a certain ratio of $T_{\text{mb}}(^{12}\text{CO}(1-0))/T_{\text{mb}}(\text{CI}(1-0))$.

Figure 6.9: Histogram illustrating the amount of pixels at a certain ratio of $T_{\text{mb}}(^{13}\text{CO}(1-0))/T_{\text{mb}}(\text{CI}(1-0))$. 
Table 6.3: Fraction of pixels where [C\textsc{i}](1–0) was observed, respectively not observed, to pixels where CO was observed, respectively not observed. 100\% correspond to the total number of pixels where either [C\textsc{i}](1–0) or/and the specific CO transitions was detected.

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depths are calculated by the numerical solution of equation (4.15)\textsuperscript{x} for each pixel. It was further assumed that the $^{12}\text{CO}/^{13}\text{CO}$ isotope ratio is equal to the value in solar neighbourhood, $x_{12}=70$. The radial gradient of $x_{12}$ in the Milky Way was neglected as the sources as observed in CO(1–0) lie within a distance of $\lesssim$4 kpc to the sun\textsuperscript{x}. The calculation is further based on the assumption that $^{13}\text{CO}(1–0)$ is optically thin. If that is not the case $\tau_{12}$ would become larger. Note that $\tau_{12}$ can only be calculated for the positions where $^{13}\text{CO}(1–0)$ is detected as well. $^{12}\text{CO}(1–0)$ is optically thick in all positions where $^{13}\text{CO}(1–0)$ is observed. The optical depths vary between $\tau_{12}$~10 and 15 for major parts of the molecular clouds and rise to $\tau_{12}$~40–70 in their centres (cf. Fig 6.11). The calculated optical depths are illustrated in Figure 6.11. $[^{\text{Cl}}](1–0)$ is presumably optically thin, while the optical depths of the $^{12}\text{CO}$ transitions is higher towards the centre of the molecular clouds. Hence the ratio of the $^{12}\text{CO}$ brightness temperatures to those of $[^{\text{Cl}}](1–0)$ lowers towards the centre of the molecular clouds and increases towards the edges.

The present data suggests that the $[^{\text{Cl}}](1–0)$ emission in the Milky Way arises primarily from the surface of molecular clouds where CO is photodissociated. Clouds that show $[^{\text{Cl}}](1–0)$ emission in the absence of CO are not observed. Based on the present data the fraction of these clouds must be low compared to molecular clouds that show CO emission.

6.3 RADIAL DISTRIBUTION OF THE SOURCES

The galactic longitudes of the b–strips combined with the velocity information within the data, allow to determine the kinematic distances of the observed sources to the sun as well as to the Galactic Centre\textsuperscript{xi}. With the distance of the source to the solar system, the angular latitudinal information can be transferred to a vertical distance in units of lengths. Then this is used to estimate the vertical distribution of the emission around the galactic midplane (scale height). With the distance of the source from the Galactic Centre it is possible to study the radial distribution of the

\[ T_{\text{mb}}(^{12}\text{CO}(J_u - J_l)) = \frac{T_{\text{mb}}(^{13}\text{CO}(J_u - J_l))}{1 - \frac{e^{-x_{12}}}{1 - e^{-x_{13}}} \times \tau_{13}} \]

\textsuperscript{x} The radial distribution of the sources is discussed in section 6.3.

\textsuperscript{xi} The method is described in van de Hulst, Muller & Oort (1954) and Kwee, Muller & Westerhout (1954) for the first time. These studies examined the distribution of HI in the Milky Way.
scale height as well (section 6.4), and to associate the observed sources with the spirals arms of the Milky Way (section 6.3.3).

6.3.1 **Galactic Rotation Curve**

This section discusses the relation between the observed $v_{\text{LSR}}$, the galactic longitudes and the distance of the sources to the Galactic centre and to the solar system. The following argumentation is mainly based on Burton et al. (2013a).

To determine the distance for a given galactic latitude and a $v_{\text{LSR}}$ it is necessary to know the orbital motion of the gas around the Galactic Centre. This study uses the orbital speed given by the galactic rotation curve derived by McClure-Griffiths & Dickey (2007) for the inner galaxy,
$R_{GC} \leq 8.5 \text{kpc}$\(^{xii}\). For the outer galaxy, $< 8.5 \text{kpc}$, the galactic rotation curve by Brand & Blitz (1993) was used.

\[
v(R_{GC}) = \begin{cases} 
  v_0 \times \left( 0.186 \frac{R_{GC}}{R_0} + 0.887 \right) & \text{for } R_{GC} \leq R_0 \\
  v_0 \times \left( 1.008 \left( \frac{R_{GC}}{R_0} \right)^{0.039} + 0.007 \right) \times s_{\kappa} & \text{for } R_{GC} > R_0 
\end{cases}
\]  

(6.1)

To avoid a discontinuity at $R_{GC} = R_0$ the galactic rotation curve by Brand & Blitz (1993) was scaled with the factor $s_{\kappa} = 1.056$. The IAU standard values of $R_0 = 8.5 \text{kpc}$ and $v_0 = 220 \text{ km/s}$ were further assumed as distance of the sun from the Galactic Centre and the orbital speed of the sun around the Galactic Centre (McClure-Griffiths & Dickey 2007). Note that this equations gives an orbital velocity of the sun around the Galactic Centre of $v(R_0) = 236 \text{ km/s}$.

The projected velocity of a source relative to the local standard of rest is given by

\[
v_{\text{LSR}}(R_{GC}) = v(R_{GC}) \cos(\alpha) - v_0 \sin(l)
\]  

(6.2)

with $\alpha$ being the angle measured, as seen from the Galactic Centre, between the source and the tangential position along the line of sight for the galactic longitude (cf. Figure 6.12 and Burton et al. 2013a). The full trigonometry of these calculations is illustrated in Figure 6.12.

Both angles are related to each other by the distance from the Galactic Centre to the tangential position along the line of sight $R_{\text{perp}}$ via $\cos(\alpha) = R_{\text{perp}} / R_{GC}$ and $\sin(l) = R_{\text{perp}} / R_0$. Equation (6.2) can now be arranged to

\[
v_{\text{LSR}}(R_{GC}) = \left( v(R_{GC}) \frac{R_0}{R_{GC}} - v_0 \right) \sin(l).
\]  

(6.3)

The distances of the source to the sun ($D_\odot$), the distance of the source to the Galactic Centre, and $R_0$ are related via

\[
R_{GC}^2 = R_0^2 + D_\odot^2 - R_0 D_\odot \cos(l).
\]  

(6.4)

\(^{xii}\) The rotation curve by McClure-Griffiths & Dickey (2007) is based on fits to HI data from the Southern Galactic Plane Survey, (SGPS McClure-Griffiths et al. 2005), of the first and fourth quadrant of the Milky Way.
Figure 6.13: Kinematic distances from the sun, $D_S$, and from the galactic centre, $R_{GC}$, as function of the $v_{LSR}$ for the galactic latitudes, discussed in this section.
<table>
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Table 6.4: Used parameters to describe the four spiral arms of the Milky Way. The values are taken from Steiman-Cameron, Wolfire & Hollenbach (2010).

The combination of the Equations (6.1), (6.3) and (6.4) allows to determine the distance of a source to the Sun as well as their distance to the Galactic Centre based on the observed source $v_{\text{LSR}}$ at a the discussed galactic longitude.

These equations give two solutions for the source distances to the sun unless $l \neq n \times \pi/2$, $n \in \mathbb{N}_0$, and no adequate solution for $l = n \times \pi$ as $v_{\text{LSR}}=0$ km/s for all distances in this case. The solution for the source distance to the Galactic Centre is unambiguous unless $l \neq n \times \pi$.

The distances to the sun and the distances to the Galactic Centre as function of the $v_{\text{LSR}}$ at the galactic longitudes, discussed here, are shown in Figure 6.13.

Note that the calculated kinematic distances have high uncertainties. The motion of the gas within the molecular clouds and the motion of clouds within the spiral arm can result in uncertainties of up to 100% (Reid et al. 2009).

However, these calculations allow to determine the position of the observed sources within the Milky Way, as described in the following section. To compare the emissions with the spiral arms I first briefly discuss the spiral structure of the Milky Way.

### 6.3.2 Spiral structure of the Milky Way

The spiral arms of the Milky Way can be described by logarithmic spirals (e.g. von der Pahlen 1911; Danver 1942; Roberts, Roberts & Shu 1975; Vallée 2008; Steiman-Cameron, Wolfire & Hollenbach 2010). A logarithmic spiral is given by

$$R_{\text{GC}}(\phi) = ae^{\alpha \phi}$$  \hspace{1cm} (6.5)

with $a$ and $\alpha$ being constants. The orientation of the spiral is given be $a$, while $\alpha$ defines its pitch angle $p$. Hence, the shape function $\phi$ is described by

$$\phi(R_{\text{GC}}) = \ln \left( \frac{R_{\text{GC}}}{a \alpha} \right).$$  \hspace{1cm} (6.6)

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xiii von der Pahlen (1911) showed at the example of M33, M51 and M74 for the first time, that the spiral arms of galaxies can be described by logarithmic spirals. Danver (1942) concluded that the spiral of galaxies can be in general fitted by logarithmic spirals, based on a representative study of 98 galaxies. The theoretical work by Roberts, Roberts & Shu (1975) showed that density waves within an axisymmetric galaxy are described by logarithmic spirals as well. Vallée (2008) and Steiman-Cameron, Wolfire & Hollenbach (2010) provide current descriptions of the spiral arm structure. Both studies show no major differences.
The pitch angle is given by

\[ p = \arctan(\alpha). \]  

The parameters \( a, \alpha \) and \( p \), for the different spirals arms are taken from Steiman-Cameron, Wolfire & Hollenbach (2010)\textsuperscript{xiv}, listed in Table 6.4. The thus estimated spiral arms are shown in Figure 6.15.

### 6.3.3 Location of the observed emission in the Milky Way

The emission within the \( b \)-strips is mainly associated with the spirals arms, as shown in the Figures 6.14 and 6.15. Almost all the features can

\textsuperscript{xiv} Steiman-Cameron, Wolfire & Hollenbach (2010) derived the spiral arm parameters \( a, \alpha \) and \( p \) from [C\( \text{ii} \)] and [N\( \text{ii} \)]205\( \mu \text{m} \) COBE/FIRAS and BICE maps of the Milky Way by fitting various spiral arm models to the longitudinal resolved data.
Figure 6.15: Spiral structure of the Milky Way, based on the model by Steiman-Cameron, Wolfire & Hollenbach (2010). The positions of the clouds are superimposed. The size of the circles correspond to the velocity integrated CO(2–1) intensity of the sources, average over the full range of the galactic latitudes (Δb=4°). The average velocity integrated CO(2–1) intensity were calculated via a Gaussian decomposition of the average emission over the b-strips, shown in Figure 6.14. The ambiguity of the source distances is indicated by the colour coding: The near solution is shown by the light grey circle, while the far solution is shown in dark grey. For the sake of a better comparability the colour-code of the spirals is identical with those used in Vallée (2008). Their labels are shown in the same colour. Steiman-Cameron, Wolfire & Hollenbach (2010) gives no position angle for the galactic bar. The galactic bar is, therefore, shown for a position angle of 32°, as proposed by Vallée (2008). The position of the solar system is marked by the symbol '⊙', at a distance of 8.5 kpc from the Galactic Centre (red •). Isodistances, in steps of 2 kpc, around the Sun and the Galactic Centre are shown by the dotted circles.
be associated with the near side of the spiral arms. Dominant features arise from the Carina–Sagittarius arm at distances of $D_{\odot} \sim$1 to 3 kpc, the Crux–Scutum arm (alias Centaurus arm) at distances of $D_{\odot} \sim$4 to 5 kpc, as well as from the Norma and/or the 3 kpc arm at distances of $D_{\odot} \sim$6 to 7 kpc. The features of the Carina–Sagittarius arm are observed in all the $b$-strips. Those of the Crux arm are observed in all $b$-strips but at $l=306.0^\circ$ and $315^\circ$ and those of the Norma arm in the $b$-strips at $l \geq 336.4^\circ$.

The feature at $v_{\text{LSR}} = +27$ km/s, $b = -0.5^\circ$ at $l=306.0^\circ$ might have its origin in the outer Carina arm at a distance of $D_{\odot} \sim$13 kpc and $z \sim$110 pc above the galactic plane$^{xv}$.

6.4 VERTICAL AND RADIAL DISTRIBUTION OF THE EMISSION AROUND THE GALACTIC MIDPLANE

The following section is dedicated to determine the scale height, $z_{1/2}$, of [Cl](1–0), CO(2–1) and CO(4–3). Their radial distribution is studied as well. These results are compared with the complementary Mopra CO(1–0) data and with the values of $z_{1/2}$(CO(1–0)) derived by Sanders, Solomon & Scoville (1984) and Clemens et al. (1988). Finally, the results are compared with the scale height of [Cii] (Langer, Pineda & Velusamy 2014a) and HI (Dickey & Lockman 1990). First, I will give a brief introduction into the theoretical background of the scale height.

6.4.1 THEORETICAL BACKGROUND OF THE SCALE HEIGHT

As already mentioned the vertical distribution of the gas in a disc, estimated with the scale height, reflects the hydrostatic pressure within the disc. The scale height of a disc in hydrostatic equilibrium is determined by the equilibrium of the pressure in the ISM and the gravitational force of the mass in the disc. This includes the mass of the gas and the stars (Sanders et al. 1984) as well as the dark matter (Narayan & Jog 2002). In an isothermal disc the pressure depends on the velocity dispersion perpendicular to the disc of the considered medium $\langle v_z \rangle$. The scale height is related to $\langle v_z \rangle$ via (Talbot & Arnett 1975; Sanders, Solomon & Scoville 1984)

$$z_{1/2} = \frac{1}{2} \sqrt{\frac{\langle v_z^2 \rangle}{2\pi G \rho(0)}} \quad (6.8)$$

where $G$ is the gravitational constant and $\rho(z)$ the total density distribution of the considered medium along the $z$-axis. The vertical distribution of the density in a isothermal disc is described by a hyperbolic secant–function (accordingly also a cosine–function) via (Spitzer 1942; van der Kruit & Searle 1981a;b; Wegg et al. 2015)

$$\rho(z) = \frac{\rho(0)}{\cosh^2 \left( \frac{z-z_c}{z_{1/2}} \right)} = \rho(0) \operatorname{sech}^2 \left( \frac{z-z_c}{z_{1/2}} \right) \quad (6.9)$$

where $z_c$ is the offset in vertical direction of the centre of the disc.

Gaussians are often used as an approximation of Equation (6.9) (e.g. Talbot & Arnett 1975; Sanders, Solomon & Scoville 1984; Langer, Pineda

$xv$ The distance of a source from the galactic plane is calculated with Equation (6.12), cf. Section 6.4.
& Velusamy 2014a and Figure 6.20). Equation (6.9) can be than approximated by

\[ f(z) = f(z_0) e^{-0.5 \left( \frac{z-z_c}{z_{1/2}} \right)^2} \]  

(6.10)

The scale height \( z_{1/2} \) is then related to the full width half maximum, FWHM, via

\[ z_{1/2} = \frac{\text{FWHM}}{2\sqrt{2\ln(2)}}. \]  

(6.11)

In virial approximation the velocity dispersion of the gas is described by the Maxwell–Boltzmann distribution. In this case the square of the velocity dispersion \( \langle v_z^2 \rangle \) is proportional to the temperature of the medium, \( \langle v_z^2 \rangle = \frac{3k_B}{m} T \), with \( m \) being the mass of a gas particle. Colder gas phases therefore obtain a generally higher pressure and therefore lower scale heights compared to warmer gas phases (cf. Fig 6.20 and Langer, Pineda & Velusamy 2014a). This explains the different scale height of H\(_1\) in the CNM and WIM where the gas temperature have values of \( \sim 10^2 \) K, and a few \( \sim 10^5 \) K. It also explains the different scale height of CO(1–0) and [C\(_i\)] as mentioned in Section 2.1 CO(1–0) is in general associated with lower gas temperatures (few \( \sim 10^0 \) to \( 10^1 \) K) than [C\(_i\)] \( \sim 10^2 \) to \( 10^4 \) K), and thus, \( z_{1/2}(\text{CO}(1-0))<z_{1/2}(\text{[C\(_i\)])}. \)

If C\(_0\) is associated with a gas phase in between CO and C\(_+\) it would be expected that its gas temperatures are between those of CO and ionized carbon. In that case the observable scale height of the C\(_0\) transitions should be higher than those of CO but lower than \( z_{1/2}(\text{[C\(_i\)])}. \)

### 6.4.2 Observed distribution perpendicular to the disc and an alternative definition of the scale height

The distance of an emission from the galactic plane \( z \) can be calculated via the simple trigonometrical relation

\[ z = \tan(b) \times D_\odot, \]  

(6.12)

with \( D_\odot \) being the (presumably) known distance of the source from the sun, and \( b \) being the the galactic latitude (cf. Figure 6.16).

The \( b \)-strips reflect the individual conditions at the specific longitudes. To minimize the impact of the local conditions and to gain a more general overview of the scale height at different galactic radii, it is necessary to integrate over a large sample of clouds within a certain range of \( R_{GC} \). To determine their scale height they have to be within similar distances from the sun. To study the radial distribution of the scale height it is also necessary that the clouds have similar distances to the Galactic Centre.
Figure 6.17 illustrates $R_{GC}$ and $D_{\odot}$ of the individual clouds for the different $b$-strips. More than 95% of the observed emission is associated with regions that have a width of $\Delta(D_{\odot})=1$ kpc and $\Delta(R_{GC}) \approx 1$ to 2 kpc. These regions are marked by the 'red boxes' in Figure 6.17. Its precise borders are listed in Table 6.6. Within these borders all the line emission at the same galactic latitude was integrated. The distance from the galactic plane was determined via Equation (6.12). It is assumed that the emission arises from the middle of the discussed $D_{\odot}$, with uncertainties of $\pm 0.5$ kpc. The thus derived latitudinal distributions of the line emission are shown in Figure 6.18. For the sake of a better comparability, the distributions are normalised to the specific maximal line emission within the chosen $D_{\odot}$ and $R_{GC}$.

Figure 6.18 shows the vertical profiles of [C\textsc{i}](1–0), \textsuperscript{12}CO(1–0), CO(2–1) and CO(4–3) for distances up to $D_{\odot}=7.5\pm0.5$ kpc. The profile of the \textsuperscript{13}CO(1–0) transitions are only shown for distances up to $D_{\odot}=5.5\pm0.5$ kpc, since no $b$-strips at $l=306.0^\circ$, 348.0$^\circ$ and 354.0$^\circ$ are provided by the Mopra observations, and the $v_{LSR}$ ranges to $v_{LSR} \gtrsim -110$ km/s. The vertical distribution of the gas exceeds the observed latitudinal range of $b=\pm 2^\circ$ for the inner $D_{\odot} \lesssim 3$ to 4 kpc. Therefore the observations do not fully sample the vertical gas distribution for $D_{\odot} \lesssim 3$ to 4 kpc.

All profiles have a non sech\textsuperscript{2} profile and for this reason also a non Gaussian shape. The profiles are asymmetrical, have offsets from the galactic plane and show several individual features. They are therefore not fitable with a single Gaussian profile. Therefore, it is necessary to define the scale height and the vertical offset from the galactic plane by other criteria. I define the centroid offsets from $b=0^\circ$, $z_c$, as the $z$–position of the mean emission

$$z_c = \frac{\int T_{mb} z \, dz}{\int T_{mb} \, dz}. \quad (6.13)$$

The scale height $z_{1/2}$ is defined as the square root of the variance of the $z_c$

$$z_{1/2} = \sqrt{\text{Var}(z_c)} \quad (6.14)$$

$$= \sqrt{\frac{\int T_{mb} (z_c - z)^2 \, dz}{\int T_{mb} \, dz}}. \quad (6.15)$$

The uncertainties of the scale height were calculated via the statistical method 'bootstrap'.

6.4.3 DISTRIBUTION OF [C\textsc{i}](1–0), CO(2–1) AND CO(4–3) IN THE FOURTH QUADRANT OF THE MILKY WAY

The perpendicular distribution of the normalised line emission for the different distances to the sun and the Galactic Centre are shown in Figure

\textit{Bootstrapping} is a statistical method which is based on the random sampling of the data points with replacement (Efron 1979; Efron & Tibshirani 1994). The uncertainty for a specific scale height, $z_{1/2}(R_{GC})$, was determined via the square root of the variance of $2 \times n \times \ln(n)$ randomly composed datasets. Each dataset consists out of the randomly composed $n=267$ data points of the specific latitudinal emission distribution.
Figures 6.17: Illustration of $R_{GC}$ and $D_⊙$ derived from the kinematic distances for all sources. The size of the circles correspond to the velocity integrated CO(2–1) intensity of the sources, averaged over the full range of the galactic latitudes discussed here ($\Delta b=4^\circ$). The colour coding indicates the ambiguity of the source distances. The emission within the marked areas, shown by the ’red boxes’, were integrated.

6.18. These profiles are complex and have an asymmetric shape. They show several individual features, with typical widths of $\sim 5$ to 30 pc. The profiles are not single Gaussian. A Gaussian profile would require a large sample of positions (cf. e.g. Sanders, Solomon & Scoville 1984 or Langer, Pineda & Velusamy 2014a) The majority of the emission is located within the inner 100 pc around the centre of the disc. Nevertheless, several individual features can be observed at distances up to $z\sim 200$ pc above the galactic disc. For $R_{GC}\geq 5.6\pm 1.1$ kpc the latitudinal distribution of the gas exceeds the shown range. This is caused by the observational limitation to the inner $b=\pm 2^\circ$.

The calculated $z_c$ and $z_{1/2}$ for the different $R_{GC}$ are summarized in table 6.6. The $z_c$ and $z_{1/2}$ as function of $R_{GC}$ are shown in Figure 6.19. The $z_{1/2}$ and $z_c$ for $R_{GC}\geq 5.6\pm 1.1$ kpc have to be interpreted with caution because the data does not represent the complete latitudinal distribution of the gas.

All the lines, $^{12/13}$CO(1–0), $^{12}$CO(2–1), $^{12}$CO(4–3) and [CI](1–0), have nearly the same scale heights at the same $R_{GC}$, within the uncertainties. The distribution of [CI](1–0) shows no significant differences to CO. The calculated scale heights vary between $\sim 25$ pc at $R_{GC} = 1.9\pm 0.9$ kpc to $\sim 55$ pc at $R_{GC}=4.7\pm 1.1$ kpc. The scale height increases towards the direction of the sun for the inner $R_{GC}(\leq 3.7\pm 1.1$ kpc). CO(4–3) has a
Figure 6.18: Derived vertical galactic distribution in parsec of the normalised $^{12}$CO(1–0) (blue), $^{13}$CO(1–0) (yellow), $^{12}$CO(2–1) (green), $^{12}$CO(4–3) (red) and $[\text{C}\text{ii}](1–0)$ (black) intensities for different distances to the sun, $D_\odot$, and to the Galactic Centre, $R_{GC}$. The used distances correspond to the distances marked by the red boxes in Figure 6.16. Only intensities which are 4 times above the respective noise were considered. The shown vertical distribution of gas is based on the middle values of the considered $D_\odot$ bins, i.e. $D_\odot=0.5$, 1.5, 2.5 kpc. The dashed coloured lines mark the positions of the mean line emission. The dotted lines show the square root of the variance of the specific lines.
slightly lower scale height at low $R_{\text{GC}}(\leq 3.7\pm 1.1 \text{ kpc})$, compared to CO(2–1) and [Cl](1–0). At higher $R_{\text{GC}}$ all scale heights are similar. The scale height of [Cl](1–0) and CO(2–1) are equal within the uncertainties as well. Note that the scale heights seem to decrease towards sources near the sun ($R_{\text{GC}}\geq 5.6\pm 1.1 \text{ kpc}$, $D_{\odot}\lesssim 3.5\pm 0.5 \text{ kpc}$). This is presumably induced by the observational limitation to the inner $b=\pm 2^{\circ}$. The low scale height of CO(4–3) near the Galactic Centre has its origin presumably in the higher confusion limit, compared to CO(2–1) and [Cl](1–0). Note again that almost all the profiles show a strong asymmetry in the emission and have no single Gaussian shape.

The $z_{1/2}$ of the inner $R_{\text{GC}}$ can be fitted by a power law function

$$z_{1/2}(R_{\text{GC}}) = A \times R_{\text{GC}}^B$$ (6.16)

with power law exponents of $B\sim 0.5\pm 0.2$ for $^{12}\text{CO}(1–0)$, $0.5\pm 0.4$ for CO(2–1), $1\pm 0.3$ for CO(4–3) and $0.5\pm 0.2$ for [Cl](1–0). Note that the probability of the fits is not high. The fit [Cl](1–0) and CO(1–0) has a $\chi^2$~8 and 9 respectively, CO(4–3) has a $\chi^2$~14, while the $\chi^2$ for CO(2–1) is ~2. The precise parameters are listed in table 6.5, and illustrated in Figure 6.18. The power law exponent of CO(4–3) might be caused by the relative high confusion limit of these observations. The fitted distributions are hence similar to the radial distribution for CO(1–0) $z_{1/2}(R_{\text{GC}}) = 26 \times R_{\text{GC}}^{0.47}$ found by Sanders, Solomon & Scoville (1984). The increase of the CO(1–0) scale height towards higher $R_{\text{GC}}$ can be explained by the lower gravitational potential in the disc induced by the lower gas mass and density towards higher galactic distances (cf. Dame et al. 2001; Freeman & Bland-Hawthorn 2002).

The extrapolation of Equation (6.16) with the fitted parameters allows the estimation of the scale heights at the position of the sun, $z_{1/2}(R_0)$. The fit gives scale heights at the sun of $z_{1/2}(R_0)=62\pm 7 \text{ pc}$ for [Cl](1–0), $61\pm 9 \text{ pc}$ for $^{12}\text{CO}(1–0)$, $71\pm 12 \text{ pc}$ for CO(2–1) and $82\pm 26 \text{ pc}$ for CO(4–3) (cf. Table 6.5). These scale heights are consistent with the values found for $^{12}\text{CO}(1–0)$ by other studies, thus as $z_{1/2}(R_0)=70\pm 18 \text{ pc}$ by Sanders, Solomon & Scoville (1984), $72\pm 8 \text{ pc}$ by Clemens et al. (1988) and $57 \text{ pc}$ by Malhotra (1994a; b)xvii.

The almost equal scale heights of CO and [Cl](1–0) indicates that neutral carbon is associated with the CO–photodissociation layer in the Milky Way. An increase of the [Cl](1–0) scale height relative to those of the CO transitions towards higher $R_{\text{GC}}$ is not observed. An increase would have indicated a higher C$^0$ fraction compared to CO, and in the end a higher fraction of H$_2$ traced by C$^0$, compared to H$_2$ traced by CO, but that is not the case.

Now I will discuss the displacement of the line centroids from $b=0^{\circ}$, $z_c$. In the following text positive $z_c$ are associated with positive latitudes and vice versa for negative values. The data gives positive $z_c$~20 to 40 pc for the inner $R_{\text{GC}}\leq 4.3\pm 0.7 \text{ kpc}$ and negative offset of ~10 to -20 pc for $R_{\text{GC}}=6.5\pm 1.0$ and $7.2\pm 0.7 \text{ kpc}$. The mean offset of all available lines at $R_{\text{GC}}=8.0\pm 0.5 \text{ kpc}$ gives no significant displacement of the solar system

xvii These calculations are based on linear fits to CO(1–0) observations by Knapp et al. (1985). Malhotra (1994b) gives no error for $z_{1/2}(R_0)$
6.4 VERTICAL AND RADIAL DISTRIBUTION OF THE EMISSION AROUND THE GALACTIC MIDPLANE

<table>
<thead>
<tr>
<th>$\frac{z_{1/2}}{R_{GC}}$</th>
<th>$A$</th>
<th>$B$</th>
<th>$z_{1/2}(R_0)$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$CO(1–0)</td>
<td>19.2±2.6</td>
<td>0.54±0.22</td>
<td>61±9</td>
<td>8.7</td>
</tr>
<tr>
<td>CO(2–1)</td>
<td>23.7±4.0</td>
<td>0.51±0.06</td>
<td>71±12</td>
<td>2.1</td>
</tr>
<tr>
<td>CO(4–3)</td>
<td>9.4±2.9</td>
<td>1.01±0.32</td>
<td>82±26</td>
<td>14.2</td>
</tr>
<tr>
<td><a href="1%E2%80%930">C$\text{ii}$</a></td>
<td>27.2±3.0</td>
<td>0.39±0.15</td>
<td>61±7</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Table 6.5: Fit parameters of $z_{1/2}$ for $^{12}$CO(1–0), CO(2–1), CO(4–3) and [C$\text{ii}$](1–0) as a function of $R_{GC}$ for the inner 6.1±0.6 kpc. The reliability of the specific fits are shown by the $\chi^2$ values in the right column. The scale height of the line at the position of the sun, $z_{1/2}(R_0)$ is listed in column four.

from the galactic plane, $z_c$(8.0±0.5 kpc)=-1.5±8.5 pc. The offsets found here are consistent with the value found by Sanders, Solomon & Scoville (1984) of -5.4±10.0 pc based on CO(1–0) data.

The variation of the $z_c$ along $R_{GC}$ show the warping of the galactic plane. The data implies a warping with amplitudes of ~60 pc and a wavelength of ~3 to 4 kpc in direction towards the galactic centre, in accordance with the values found by Sanders, Solomon & Scoville (1984) and Clemens et al. (1988) for the first quadrant of the Milky Way.

6.4.4 COMPARISON OF THE PROFILES WITH [C$\text{ii}$] AND HI OBSERVATIONS

The following section compares the vertical distribution of CO and [C$\text{ii}$](1–0) with those of [C$\text{ii}$] and HI, carried out from observational data.

[C$\text{ii}$] emission arises from almost all phases of the ISM, such as molecular clouds, the CNM, the diffuse WNM and the HIMxviii. The vertical distribution of [C$\text{ii}$] is a result of the emission from the different phases. In contrast, the vertical distribution of the CO and [C$\text{ii}$](1–0) emission (as shown in this chapter) reflects exclusively the distribution of molecular gas. Therefore it is expected that the scale height of [C$\text{ii}$] emission is higher than those of CO and [C$\text{ii}$](1–0).

The scale height of [C$\text{ii}$] in the Milky Way is discussed in Langer, Pineda & Velusamy (2014a). This study calculated the average [C$\text{ii}$] scale height between $5^\circ<l<25^\circ$. The calculation is based on observations carried out with BICExix and IRTS/FILMxx. The BICE and FILM observations have a low spectral resolution, $\Delta v>175$ km/s. Therefore, the radial distribution of the [C$\text{ii}$] scale height could not be analysed. For the analysis all [C$\text{ii}$] emissions between $5^\circ<l<25^\circ$ was averaged to a single vertical profile. The profile is shown in 6.20. This profile almost have a Gaussian shape. The

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xviii see section 2.1
xix The Balloon-borne Infrared Carbon Explorer, BICE, (Nakagawa et al. 1998) mapped the [C$\text{ii}$] emission between $b=\pm3^\circ$ and $350^\circ<l<25^\circ$ with an angular resolution of 15 $^\prime$ and low velocity resolution of $\Delta v=175$ km/s
xx The Far-Infrared Line Mapper (FILM) onboard the Infrared Telescope in Space (IRTS) (Shibai et al. 1991; Makiuti et al. 2002) observed the [C$\text{ii}$]emission in a circle, that crossed the galactic plane at $l=50^\circ$ and 230$^\circ$ with a velocity resolution of $\Delta v=750$ km/s
Table 6.6: $D_\odot$ and $R_{GC}$ used to determine the vertical profiles as shown by the red boxes in Figure 6.17. Note that the uncertainties of $z_c$ are equal to $z_c/2$.

<table>
<thead>
<tr>
<th>$n$</th>
<th>$D_\odot$</th>
<th>$R_{GC}$</th>
<th>$R_{GC}-R_{GC,u}$</th>
<th>$R_{GC}-R_{GC,l}$</th>
<th>$R_{GC}$</th>
<th>$\pm$</th>
<th>$R_{GC}$</th>
<th>$\pm$</th>
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<th>$\pm$</th>
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<td>0.5–0.7</td>
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<td>0.119</td>
<td>0.119</td>
<td>0.119</td>
<td>0.04</td>
<td>0.119</td>
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<td>0.119</td>
<td>0.04</td>
<td>0.119</td>
<td>0.04</td>
</tr>
<tr>
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<td>0.7–2.0</td>
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<td>0.250</td>
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<td>0.450</td>
<td>0.450</td>
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<td>1.250</td>
<td>0.28</td>
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</table>

Note that the uncertainties of $z_c$ are equal to $z_c/2$. 

$[\Delta z] = \sqrt{\sum (z_c - z_c)^2}$.

Heliocentric radius $R_{GC}$ is used to determine the vertical profiles as shown by the red boxes in Figure 6.17.
6.4 Vertical and Radial Distribution of the Emission Around the Galactic Midplane

Figure 6.19: Radial distribution of $z_c$ (upper image) and $z_{1/2}$ (lower image) as function of the distance to the Galactic Centre $R_{GC}$ of $^{13}$CO(1–0) ($\bullet$), $^{12}$CO(1–0) ($\square$), CO(2–1) ($\triangledown$), CO(4–3) ($\triangleright$) and [CII](1–0) ($\blacklozenge$). The scale heights for $R_{GC} < 4.3$ kpc are fitted with the function $z_{1/2}(R_{GC}) = A \times R_{GC}^B$, illustrated by the dashed lines. The fit parameters are listed in table 6.5. The position of the sun is marked by the solid grey line.
shape results from the integral over the large number of clouds within these 20°. The BCIE+FILM data were combined to spectrally resolved [CII] data at $b=0^\circ$xxi, to estimate the distance of the mean emission from the sun. Langer, Pineda & Velusamy (2014a) calculated a [CII] scale height of $z_{1/2}$([CII])=73 pc as a mean value for $R_{GC}=3$ to 7 kpc. Note that the [CII] scale height is effected by the warping of the galactic disc. Therefore it is an upper limit.

The fit of equation 6.16 give average scale heights of $\sim$50 pc for CO and [CII](1–0)xxii, for the galactic distances of $R_{GC}=3$ to 7 kpc. The average scale height of [CII], as estimated by Langer, Pineda & Velusamy (2014a), is higher than the average scale heights of CO and [CII](1–0) at the same galactic distances. The differences can be presumably (at least partially) explained by [CII] emission which arises from the WNM and HIM. This emission increases the scale height of [CII], compared to the $z_{1/2}$([CII]) that is based on [CII] emission from molecular clouds and the CNM. The scale height of the [CII] emission, that is associated with molecular clouds and the CNM could be similar to those of CO and [CII](1–0).

The scale height of HI and its radial distribution has been discussed for more than five decades (cf. Schmidt 1957; Woltjer 1962). Neutral atomic hydrogen is associated with the cold neutral medium as well as with the warm neutral mediumxxiii. Therefore different HI scale heights for different phases are found. The scale height of HI in the CNM is $z_{1/2}$($H_I$)$\sim$110 pc (Schmidt 1957; Baker & Burton 1979; Dickey & Lockman 1990), and $\sim$ 250 pc in the WNM (Lockman 1984; Dickey & Lockman 1990). This scale height of HI in the CNM shows no radial distribution within the inner 8.5 kpc (Schmidt 1957; Woltjer 1962; Boulares & Cox 1990; Dickey & Lockman 1990; Narayan & Jog 2002). It remains almost constant at $z_{1/2}$($H_I$)$\approx$110pc. This coincidence is explained by the combined gravitational potential of the $H^0$, $H_2$ and of the stars (Narayan & Jog 2002). So the scale height of atomic hydrogen of the CNM exceeds those of CO and [CII](1–0) by a factor $\sim$5 at $R_{GC}\sim$2 kpc and $\sim$2 at the location of the sun.

xxi Spectrally resolved [CII] data at $b=0^\circ$ is provided by the Herschel/HIFI observations within the GOT C+ project (Pineda et al. 2013)
xxii The fit gives scale heights of 48±5 pc for CO(1–0), 56±6 pc for CO(2–1) and 52±12 pc for [CII](1–0), as mean values for 3 kpc$<R_{GC}<7$ kpc
xxiii For further details see Section 2.1.
6.4.5 Comparison with Simulated [CII] Maps

The comparison of the shape of the profiles, as presented here, with numerical simulations can shed light onto the evolution of the gas and allow statements about the dominant dynamical processes within galactic discs. Turbulences, shocks from supernovae and the local gravitational clumping of clouds dominates.

Recently, simulations of pieces of galactic discs were carried out within the SILCC project. (SILCC: Simulating the Life Cycle of molecular clouds, Walch et al. 2015; Girichidis et al. 2016; Franck et al. 2016 submitted). Within this project the evolution of the ISM is simulated in boxes of $0.5 \times 0.5 \times \pm 5$ kpc, by using the mesh hydrodynamic code FLASH 4 (Fryxell et al. 2000). The simulations are based on physical conditions similar to those found in the solar neighbourhood. The simulations are based on self gravitating clumps with a gas surface density of $10 \, M_\odot/pc^2$. A simplified chemical network is provided, consisting of $H_2$, $H^0$, $H^+$, CO, $C^+$, O and $e^-$. The feedback of supernovae is to the ISM is simulated. A constant supernova rate is assumed. The positions of the supernovae relative to the density of the gas vary for the different runs. Further an interstellar radiation field is assumed. The feedback by stellar-winds is not simulated.

In a post-processing step simulated [CII] emission maps were carried out based on these simulations, using the RADMC–3D code$^{\text{xxiv}}$ (Dullemond & Dominik 2004). Vertical profiles of the [CII] emission were calculated from these map (Franck et al. submitted). The shape of the profiles is generally complex and cannot be described by a single Gaussian. Commonly they have an asymmetrical shape and show several local peaks with diameter of $\sim 10^1$ pc around the galactic midplane. Faint emission is observed towards higher latitudes. An example of such a profile is shown in figure 6.21.

The shape of the profiles is influenced highly by the distribution of the supernovae. The emission around the galactic midplane arises form $C^+$ that is associated with molecular clouds and the CNM. The [CII] emission towards higher latitudes arising from the $C^+$ in the WNM and HIM. These simulation find [CII] scale heights of $\gtrsim 70$ pc for the CNM. The simulations are in good agreement with the observations of CO and [CII](1–0) presented in this chapter. The concordance between the simulated [CII] emission in the CNM and the CO and [CII](1–0) observation might indicate that vertical distribution of the ISM in the Milky Way is influenced by supernovae which locally disrupt or compress the ISM.

For a further analysis, velocity resolved [CII] data would be required, complementary to the here presented observations$^{\text{xxv}}$.

6.5 Discussion and Summary

This chapter analysed the distribution of [CII](1–0), $^{12/13}$CO(1–0), CO(2–1) and CO(4–3) perpendicular to the galactic disc ($b=\pm 2^\circ$) of eight galactic longitudes within the fourth quadrant of the Milky Way.

$^{\text{xxiv}}$ http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/

$^{\text{xxv}}$ Recently, SOFIA/UPGREAT observations are planned to provide complementary data for the $b$-strips, as analysed in this thesis.
Figure 6.21: Profile of a synthetic [C\textsc{ii}] emission map based on a simulation of a piece of a galactic disc, in a volume of 500 pc $\times$ 500 pc $\times$ $\pm$0.5 kpc, carried out within the SILCC Project. Supernovae were implemented for these simulation. The supernovae are positioned randomly around the galactic plane, with a Gaussian probability for a certain position. This plot is based on a constant supernovae rate of 15 supernovae per Myr. The major fraction of the [C\textsc{ii}] emission arises from molecular clouds around the galactic midplane. Faint [C\textsc{ii}] emission is detected at larger distances to the midplane. Note that the shape of the profile is complex and has no Gaussian shape.

The observed emission arises preliminary from the galactic spiral arms. The observations show no significant differences between [C\textsc{i}](1–0), CO(1–0) and CO(2–1) at least in the inner galaxy ($R_{GC}<$8.5 kpc) neither radial from the Galactic Centre nor vertical from the galactic midplane. The [C\textsc{i}](1–0) emission shows a good match with $^{12}$CO(2–1) and $^{12}$CO(1–0). The observations show that on average only $\sim$1% to 2% of the detected [C\textsc{i}](1–0) is not associated with CO. That might indicate that most C\textsuperscript{0} within the Milky Way arises from the surface of the CO photodissociation layer and that these lines arise from the same star forming matter. It indicates also that [C\textsc{i}](1–0) is no good tracer for CO dark H\textsubscript{2} in the Milky Way, at least for a large fraction of the positions in the Milky Way. This study is based on a relatively small sample of thin vertical strips. Therefore, it can not be excluded that there are other regions in the Milky Way, that show [C\textsc{i}](1–0) in the absence CO\textsuperscript{xxvi}. The observations show asymmetrical latitudinal profiles with local features, having diameters of 5 to 30 pc. They can not be described by a single Gaussian. The scale height of [C\textsc{i}](1–0), $^{12}$CO(1–0) and CO(2–1) rises from $z_{1/2}$$\sim$25–30 pc at $R_{GC}$$\approx$2 kpc to $z_{1/2}$$\sim$50 to 55 pc at $R_{GC}$$\approx$4 kpc. The scale heights of the observed transitions can be fitted with power law functions. Within the uncertainties $z_{1/2}$$\propto$R\textsubscript{GC}\textsuperscript{0.5}, which is consistent with the function found by Sanders, Solomon & Scoville (1984) and Clemens et al. (1988) for $^{12}$CO(1–0). The extrapolation gives a $z_{1/2}(R_0)$=62$\pm$7 for [C\textsc{i}](1–0) and $z_{1/2}(R_0)$=71$\pm$12 for CO(2–1) at the location of the sun.

\textsuperscript{xxvi} An example for detected C\textsuperscript{0} that is not associated with CO is M17 SW (Pérez-Beaupuits et al. 2015).
Simulation within the SILCC-project give [C II] profiles that are similar to those of CO and [C I](1–0). Assuming that the [C II] has a similar distribution as CO and C O, these simulations imply that major parts of the local structure of the Milky Way are triggered by supernova, which locally disrupt or compress the ISM.
Chapter 7

The distribution of carbon in M33

The following chapter investigates the distribution of carbon and hydrogen in the nearby galaxy M33. The investigations are focused on five representative major GMCs located on a $\sim 5$ kpc long strip along the major axis of the galaxy, for which I present new [C\textsc{i}](1–0) observations. Combined with complementary $^{12}/^{13}$CO(1–0), $^{12}$CO(2–1) and [C\textsc{ii}] data, from IRAM and Herschel, I am able to discuss the spectral and radial distribution of CO, C\textsc{0}, and C\textsc{+} in M33. Additional complementary data, particular H\textsc{i}, [N\textsc{ii}]122\mu m and FIR-emission, allows to estimate the fraction of molecular hydrogen in the discussed positions, particularly the fraction of CO dark H\textsc{2} traced by the neutral atomic and ionised carbon lines. The fraction of CO dark H\textsc{2}, derived from the observations, is compared with those predicted by the PDR-model by Wolfire, Hollenbach & McKee (2010), for a half solar metallicity. The effect of different excitation temperatures within the different gas phases is also tested and discussed.

7.1 OBSERVATIONAL DATA OF M33

This Section describes the [C\textsc{i}](1–0) observations, which were performed with the CSO, APEX and Nanten2 telescopes. The data reduction process is also described. (Section 7.1.1). The complementary data used in the following analysis is described as well (Section 7.1.2).

7.1.1 [C\textsc{i}](1–0) OBSERVATIONS AND DATA PROCESSING

Between August 2012 and June 2015 we\textsuperscript{1} observed the [C\textsc{i}](1–0) transition in the five prominent giant molecular clouds in M33, BCLMP691, GMC91, BCLMP302, GMC01 and GMCno06. The observations were performed with the Caltech Submillimeter Observatory, CSO (GMC01 and GMCno06), the Apex Pathfinder Experiment, APEX, (BCLMP691 and BCLMP302) and Nanten2 telescope (GMC91)\textsuperscript{2}. These five GMCs are located on a strip along the major axis of M33 at distances up to $\sim 3.3$ kpc from the galactic centre (cf. Table 7.1 & Fig. 7.1). This observing strategy provides a sample from major structural elements of M33 along its major axis, as the galactic centre (GMC01), the main spiral arms (GMC91, 

\textsuperscript{1} These observations were carried out by Ed Chamber, Marc J. Royster and myself.

\textsuperscript{2} GMC01 and GMCno06 were observed in August 2012 with the CSO. BCLMP691 and BCLMP302 were observed in November 2013 and October 2014 with APEX. GMC91 was observed during several nights between July 2014 to June 2015 with the Nanten2 telescope.
BCLMP302, GMCno06) and a faint outer spiral arm (BCLMP691). A detailed description of the individual clouds is given in Section 7.1.3.

The observed positions were chosen, as a large amount of complementary data is available for these position, particular Herschel/Spire/PACS and HIFI data, and their bright [CII] emission and/or strong CO(2–1) emission (Kramer et al. 2010; Boquien et al. 2011; Gratier et al. 2010; Mookerjea et al. 2012; Xilouris et al. 2012; Braine et al. 2012a;b; Buchbender et al. 2013; Buchbender 2013; Druard et al. 2014; Mookerjea et al. 2016; Nikola et al. in prep.; Kramer et al. in prep).

Due to the faint [CII](1–0) emission ($I([\text{CII}](1–0)) \lesssim 2 \times 10^{-7}$ erg cm$^{-2}$s$^{-1}$) only a single position was observed in all sources except GMC01, in which an additional position was observed. In the GMCs BCLMP691, BCLMP302 and GMC01 (alias GMC01 Peak) the [CII](1–0) observations were centred on the [CII] peak of the individual GMCs (cf. Fig. 7.22, 7.26 and 7.25). The second position in GMC01 (alias GMC01 Flank) was observed at $\approx 11'' \approx 45$pc to the northwest of the [CII]-peak of GMC01. The [CII] peak of GMCno06 is within the beam of the [CII](1–0) observations. Nevertheless, the beam centre of the [CII](1–0) observations does not match the [CII] peak. It lies $\approx 7''$ to the north-east of the beam centre (Fig. 7.28). The GMC91 shows no distinct [CII] emission. Therefore, the observations were centred at the CO(2–1) peak (Fig. 7.23). Due to its missing [CII]-emission in GMC91, the [CII](1–0) observations were centred at the CO(2–1) peak (Fig. 7.23).

The [CII](1–0) observations in the GMCs BCLMP691 and BCLMP302 were performed with the 12m Atacama Pathfinder Experiment (APEX, Güsten et al. 2006). The positions of GMC01 and GMCno06 were observed

Table 7.1: Coordinates and radial distances of the observed positions. The positions are shown in Figure 7.1 as well.

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<tbody>
<tr>
<td>BCLMP691$^a$</td>
<td>GMCno01$^b$, #300$^c$</td>
<td>01:34:16.4</td>
<td>30:51:54.6</td>
<td>30.54.6</td>
<td>+3.29</td>
</tr>
<tr>
<td>GMC91$^b$</td>
<td>600N$^d$, #245$^c$</td>
<td>01:34:09.4</td>
<td>30:49:07.1</td>
<td>30.49:1</td>
<td>+2.52</td>
</tr>
<tr>
<td>BCLMP302$^a$</td>
<td>GMCno03$^b$, #256$^c$</td>
<td>01:34:06.6</td>
<td>30:47:26.0</td>
<td>30.47:26</td>
<td>+2.08</td>
</tr>
<tr>
<td>GMC01$^b$ [CII] Peak</td>
<td>#108$^c$</td>
<td>01:33:52.2</td>
<td>30:39:15.8</td>
<td>30.39:15</td>
<td>-0.11</td>
</tr>
<tr>
<td>GMC01$^b$ [CII] Flank</td>
<td>#108$^c$</td>
<td>01:33:52.9</td>
<td>30:39:25.1</td>
<td>30.39:25</td>
<td>-0.12</td>
</tr>
<tr>
<td>GMCno06$^b$</td>
<td>500S$^d$, #42$^c$</td>
<td>01:33:34.1</td>
<td>30:32:06.3</td>
<td>30.32:06</td>
<td>-2.03</td>
</tr>
<tr>
<td>Centre of M33</td>
<td></td>
<td>01:33:51.02</td>
<td>30:39:36.7</td>
<td>30.39:36</td>
<td>0.00</td>
</tr>
</tbody>
</table>

(1) Name of the GMC used in this paper.
(2) Alternative names of the GMC, (a) from Mookerjea et al. (2012), (b) from Rosolowsky et al. (2007); Buchbender et al. (2013), (c) CO(2–1) clump number from Gratier et al. (2012), (d) Nikola et al. in prep..
(3) Coordinates of the observed positions.
(4) lists the distance of the observing position centres to the galactic centre. The reference point for the centre of M33 is at Ra: 01:33:51.02, Dec: 30:39:36.7 (J2000). Positive values conform to distances north of the centre while negative values to distances south of the centre.
(5) Beam-size of the [CII](1–0) observations in arc-seconds. The super-scripted letters mark the telescope used for the observation; A=Apex, C=CSO and N=Nanten2.
with the 10.4m antenna of the Caltech Submillimeter Observatory (CSO, Phillips 1996). The observations of GMC91 were performed with the 4m antenna Nanten2 (Kawamura et al. 2005). The FWHM $\Theta_B$ of the [Cl](1–0) observations are 12.7″ for APEX, 17″ for the CSO and 37″ for Nanten2.

The APEX observations were performed with the single pixel dual-sideband SHIFI/APEX-3 receiver (Vassilev et al. 2008). The backend consists of two partially overlapping eXtended bandwidth Fast Fourier Transform Spectrometer (XFFTS), each with an individual bandwidth of 2.5 GHz and 32768 spectral channels, providing a total bandwidth of 4 GHz and a spectral resolution of 76 kHz (Klein et al. 2012).

The CSO observations were performed with the wide band 492 GHz low noise sis waveguide receiver using a FFTS with 8192 channels and a bandwidth of 4 GHz as backend (Kooi et al. 1998; Kooi 2009; Kooi et al. 2010).

The Nanten2 observations were performed with the 460–490 GHz channel of the 2×8 pixel SMART receiver (Graf et al. 2002; 2008). The backends of SMART consist of sixteen eXtended bandwidth Fast Fourier Transfer Spectrometer (XFFTS; Klein et al. 2012) with a used bandwidth of 1 GHz and a spectral resolution of 76 kHz.

All [Cl](1–0) observations were performed during very good weather conditions, pwv $\lesssim 0.5$ mm. The system temperature ($T_{\text{sys}}$) varies between

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{350 µm Herschel-SPIRE map of M33 (Xilouris et al. 2012). This wavelengths shows the prominent northern and southern spiral arms of M33 as well as the GMCs discussed here. The white crosses mark the positions of the [Cl](1–0) observations. The black cross displays the centre of M33. The angular distance between the two observed positions in GMC01 is 11″ (∼45 pc). For the sake of a better clarity GMC01 is therefore marked by a single cross. The coordinates of the positions are listed in Table 7.1.}
\end{figure}
$T_{\text{sys}} \sim 900 - 1200$ K for the CSO, $T_{\text{sys}} \sim 900 - 2100$ K for APEX and $T_{\text{sys}} \sim 420 - 1100$ K for the Nanten2 observations. The observations of M33 from the APEX and Nanten2\textsuperscript{iii} side, both located in the southern hemisphere, required excellent weather conditions ($\text{pwv} \lesssim 0.5$ mm) and relatively long integration time, as the source elevation is $\lesssim 36^\circ$. For example the summed on-source integration time on the position BCLMP302 was $\approx 5$ hours. The integration time for the positions observed with the CSO, located in the northern hemisphere on Mauna Kea\textsuperscript{iv}, were significantly shorter. For example the on-source integration time at the $[\text{CII}]$ peak position of GMC01 was 16 minutes.

The data was reduced with the program CLASS, version: jan14a\textsuperscript{v}. A fifth order baseline was fitted and subtracted from all data. Spectra that showed sinusoidal standing wave patterns, sinusoidal baselines with standing wave periods between 8 and 27 km/s were fitted to the spectra, similar as for the $[\text{CII}]$ observations described in chapter 5. If the fit improved the RMS by more than 1/5 compared to a linear baseline fit, the fitted sinusoidal pattern was subtracted from the spectrum.

All data was converted to the main beam temperature scale via $T_{\text{mb}} = T^* A / \eta_{\text{mb}}$, using a main beam efficiency $\eta_{\text{mb}} = 0.60$ for APEX, $\eta_{\text{mb}} = 0.5$ for the CSO and $\eta_{\text{mb}} = 0.5$ for the Nanten2. Afterwards all the spectral data was regridded to have the same grid in velocity, and convolved to a velocity resolution of 2 km/s. The RMS of the APEX and CSO data varies between 0.009K (in GMC01 Flank) and 0.024K (in BCLMP691). The RMS of GMC91 is 0.061K. As uncertainties for the $[\text{CII}](1-0)$ data I assume standard calibration uncertainties of 10%.

$[\text{CII}](1-0)$ emission was detected in all positions, except in GMC91, with a signal to noise ratio better than or equal to $S/N \geq 3.4$.

7.1.2 COMPLEMENTARY DATA

Within the framework of the Herschel key program HERM33ES (Kramer et al. 2010) a large set of complementary data is provided, thus as $[\text{CII}]$, $[\text{OI}]63\mu m$, $[\text{NII}]122\mu m$, $^{12}/^{13}\text{CO}(1-0)$, $^{12}\text{CO}(2-1)$ and $\text{H}\text{i}$. The combination of these data allows to study the distribution of the different carbon species and to determine the total amount of $H_2$ in the GMCs, discussed here. Furthermore, the data allows to determine the fraction of $[\text{CII}]$ arising from the different gas phases. The fraction of CO dark $H_2$ can be determined as well.

High spectrally resolved $\text{CO}(2-1)$ and $\text{H}\text{i}$ maps are available for all positions. $\text{CO}(1-0)$ spectra are provided for all positions but GMC01 Flank. The $[\text{CII}]$, $[\text{NII}]122\mu m$ and $[\text{OI}]63\mu m$ was mapped in all positions with Herschel/PACS with a low spectral resolution $\Delta v > 100$ km/s. Spectral resolved $[\text{CII}]$ data is provided for all positions, but GMC91 and GMC01

\textsuperscript{iii} APEX is located at the coordinates 22.97\textdegree S, 67.70\textdegree W. The location of Nanten 2 is roughly 10 km north of Apex (Coordinates: 23.01\textdegree S, 67.76\textdegree W).
\textsuperscript{iv} Coordinates: 19.82\textdegree N, 155.48\textdegree W
\textsuperscript{v} available at http://www.iram.fr/IRAMFR/GILDAS
peak by Herschel/HIFI\textsuperscript{vi} observations. The complementary data is discuss in detail in the following paragraph.

High spectrally resolved [CI] data ($\theta_B=12''$) was obtained from Herschel/HIFI observations (Mookerjea et al. 2012; Braine et al. 2012b; Mookerjea et al. 2016; Kramer et al. in prep.)\textsuperscript{vii}. GMC91 and GMC01 Peak were not observed with Herschel/HIFI. Therefore no velocity resolved [CI] spectra are available for these positions\textsuperscript{viii}. The centre position of the [CI](1–0) observations in BCLMP302 is located between the centre positions of three [CI] HIFI observations (cf. Fig 7.2). The [CI] spectra used for the analysis of this position was therefore composed by the average of the three spectra, weighted by the distances of their beam-centre to the centre of the [CI](1–0) observations.

The velocity integrated distribution of [CI], [OI]63\textmu m and [NI]122\textmu m emission was mapped with Herschel/PACS, in all positions. (Mookerjea et al. 2012; 2016; Nikola et al. in prep.). For the analysis I used the [NI]122\textmu m data of the [CI] peak positions smoothed to a 12'' beam (Nikola et al. in prep.). In the position GMC01 Flank and GMCno06 the [NI]122\textmu m data of the respective [CI] peak was used.

$^{12/13}\text{CO}(1–0)$ data at a resolution of 21'' was observed with the EMIRreceiver at the IRAM 30m observatory (Rosolowsky et al. 2011; Buchbender et al. 2013).

$^{12}\text{CO}(2–1)$ maps of M33 with $\theta_B=10.7''$ were obtained from IRAM 30m observations using the HERA receiver (Gratier et al. 2010; Druard et al. 2014).

Neutral hydrogen H\textsc{i} was mapped in the whole galaxy with the VLA at a resolution of $\theta_B=12''$ (Gratier et al. 2010).

H\textalpha emission data ($\theta_B\approx0.3''$) was obtained from observation with the 60cm Burrel-Schmidt telescope of the Kitt Peak National Observatory by Hoopes & Walterbos (2000).

Continuum maps at 24\textmu m, 70\textmu m (Spitzer, Tabatabaei et al. 2007) and 100\textmu m to 500\textmu m (Herschel/PACS and Spire Boquien et al. 2011; Xilouris et al. 2012) are provided as well.

The complementary H\textsc{i} and CO(2–1) data was convolved to the respective beamsize of [CI](1–0), to compare the data. The Herschel/HIFI [CI] spectra have not been convolved as only single positions with $\theta_B\approx12''$ were observed. In BCLMP302 and BCLMP691 the beam sizes of [CI](1-0) and [CI] are almost equal, $\theta_B=12''$. In GMC01 and GMCno06 the beam of [CI](1–0) ($\theta_B=17''$) exceeds those of [CI] ($\theta_B=17''$ and $\theta_B=12''$). PACS maps show distinctive [CI] peaks in these position (Fig. 7.28. 7.26). As a consequence the integrated [CI] intensities and peak temperatures are

\textsuperscript{vi} The PACS receiver was a Bolometer while HIFI was a Heterodyne instrument. Bolometer are used for sensitive continuum observations. They do not provide spectral information. Heterodyne receivers are used to for observations with a high spectral resolution. See appendix A for further details.

\textsuperscript{vii} Mookerjea et al. (2012) and Mookerjea et al. (2016) discusses the distribution of [CI] in BCLMP302 and around the centre of M33 (GMC01). [CI] in BCLMP691 is discussed in Braine et al. (2012b). Kramer et al. in prep. will discuss the [CI] distribution of the southern main spiral arm, including the position GMCno06.

\textsuperscript{viii} Future observations with SOFIA/upGREAT can provide [CI]-spectra of GMC01 Peak.
presumably higher and the line widths are presumably narrower compared to a [CII] beam that would be equal to the [Cl](1–0) observations.

7.1.3 OVERVIEW OF THE OBSERVED CLOUDS

The following paragraph gives a brief overview of the observed GMC. Their precise physical properties are described in Section 7.6.

7.1.3.1 BCLMP691

BCLMP691 (alias GMCno01 in Rosolowsky et al. 2007, #300 in Gratier et al. 2012) is an Hα region (Hoopes & Walterbos 2000) located in the northern region of M33 in a distance of 3.3 kpc from the nucleus. This GMC is the major star forming region on a faint spiral arm or spur with a moderate SF-rate of $12.2 \pm 1.7 \, M_\odot \, \text{Gyr}^{-1} \, \text{pc}^{-2}$ (Buchbender et al. 2013). This arm or spur is primarily visible at 350 & 500 μm. BCLMP691 is associated with a O–B star accumulation (#38 in Humphreys & Sandage (1980)), in the optical. For a detailed further description I recommend Braine et al. (2012a) and Braine et al. (2012b).

7.1.3.2 GMC91

GMC91 (Rosolowsky et al. 2007, alias #245 in Gratier et al. 2012) is located at the northern main spiral arm. At the position of GMC91 the arm changes its orientation from north-west to west (cf. Figure 7.1). The northern arm also hosts the prominent GMC NGC604, the second brightest Hα region in the local group which is also located at a prominent knee point of this spiral arm. GMC91 lies in a distance of $\approx 2.5\, \text{kpc}$ to the galactic centre.

GMC91 shows the most intense low J–CO emission in the sample of positions discussed in the present paper, and is one of the brightest CO emitters in the whole galaxy M33. [CII] PACS-map show only diffuse emission, that cannot be associated with the CO-emission.

IR continuum dust emission maps from 24 μm to 500μm show no distinguishable emission, which is associated with the CO peak (cf. Boquien...
et al. 2011; Xilouris et al. 2012; Buchbender et al. 2013; Boquien et al. 2014). The emission indicates a low star formation rate of $\sim 4 \, M_{\odot} \, \text{Gyr}^{-1} \, \text{pc}^{-2}$ (Buchbender et al. 2013).

7.1.4 BCLMP302

*BCLMP302* (alias GMCno03 in Rosolowsky et al. 2007 and #256 in Gratier et al. 2012) is the seconds largest and brightest GMC in the northern arm of M33 in a distance of $\approx 2.1$ kpc to the galactic centre. It is located at the southern end of the same knee point of the northern spiral arm in which also GMC91 is located. The distance between these two GMCs is $\approx 450$ pc.

The morphology of BCLMP302 is complex. The majority of CO and dust emission is observed in an elongated bow–like structure with a total length of $\sim 250$ pc (cf. Fig. 7.25). This structure can be roughly divided into an elongated northern complex and compact southern complex. The majority of the CO emission arises from the northern complex. The dust emission (Spitzer 8 $\mu$m, 24 $\mu$m & 100 $\mu$m) arises from both complexes with a focus at the southern CO-structure. The 8 $\mu$m & 24 $\mu$m dust emission might indicate embedded star formation in this complex (Buchbender 2013). A bright young optical star cluster, with O and B–type stars, is observed between these two complexes. Its age is set to $\sim 3$-10 Myr (Murphy et al. 2011). For a detailed description of the main molecular zone I recommend Buchbender (2013).

Herschel/PACS maps (Mookerjea et al. 2012) show that the [C$^\text{ii}$] emission arises $\sim 40$pc east of the main molecular zone. Furthermore, these maps show that the spatial morphology of [O$^\text{I}$]63$\mu$m is very similar to the [C$^\text{ii}$] morphology (Mookerjea et al. 2012).

7.1.5 GMC01

*GMC01* (alias #108 in Gratier et al. 2012, ID#106 in Gordon et al. 1999a) is a bright H$\alpha$ region (Gordon et al. 1999b) with a distance of $\sim 27'' \simeq 110$ pc to the centre of M33. The high H$\alpha$, FUV ($G_0=50$ Habing units) and NIR emission indicate the highest star formation rate ($65 \, M_{\odot} \, \text{Gyr}^{-1} \, \text{pc}^{-2}$) of the sources, discussed here (Gordon et al. 1999a; Calzetti et al. 2007; Buchbender 2013). The FUV and [C$^\text{ii}$] emission reach their highest value within the discussed GMCs as well.

7.1.6 GMCno06

*GMCno06* (alias #42 in Rosolowsky et al. 2007) is a the major star forming region and most massive GMC on the prominent inner southern arm, in a radial distance of 2.0 kpc from the centre of M33. GMCno06 has the second highest star formation rate ($\text{SFR} = 36 \, M_{\odot} \, \text{Gyr}^{-1} \, \text{pc}^{-2}$, Buchbender 2013) and hydrogen column density of the positions discussed here. It is also associated with a bright O–B star accumulation (#13 in Humphreys & Sandage 1980). The cloud complex hosts the most luminous X-ray binary

ix The star cluster is denoted as #71 in Humphreys & Sandage (1980). It was observed in detail with the HST by Bedin et al. (2005)
Figure 7.3: $^3P_1 \rightarrow ^3P_0$[Cl] spectra for the individual GMCs are shown by the black solid line. The beam of the [Cl](1–0) data is 12.7′′ for BCLMP691 and BCLMP302, 17′′ for GMC01 and GMCno06 and 37′′ for GMC91. The spectra of H\textsc{i} (blue dotted) and $^{12}$CO(2–1) (green dashed) are superimposed. They are scaled to the respective beam-size of [Cl](1–0). All [Cl] spectra refer to data with a beam size of 12′′ (red, dotted-dashed). For a better understanding the H\textsc{i}, CO(2–1) and [Cl] spectra were multiplied with a scale factor. The scale-factors are shown in the individual plots.

M33 X-7 (Ra: 1:33:34.12, Dec: 30:32:11.6 (J2000)) known so far (Valsecchi et al. 2010) with an average luminosity of $5 \times 10^{37}$ erg s$^{-1}$ (Pietsch et al. 2004).

7.1.7 OVERVIEW OF THE OBSERVATIONAL RESULTS

The [Cl](1–0) spectra are shown in Figure 7.3. The complementary H\textsc{i}, $^{12}$CO(2–1) and [Cl] spectra are superimposed.

All regions, but GMC91, show H\textsc{i}, [Cl], [Cl](1–0), $^{12/13}$CO(1–0) and $^{12}$CO(1–0) emission. No [Cl](1–0) and [Cl] emission has been detected in GMC91.

To determine the precise line parameters, Gaussian were fitted to these lines. All the line–parameters (line widths $\Delta v$, central velocities $v_{\text{LSR}}$, and the velocity integrated line intensities $I$, in K km s$^{-1}$) are listed in Table 7.2. The integrated intensity of [Cl] in the position GMC01 Peak as well as the integrated intensities of [N\textsc{ii}]122\(\mu\)m were determined from the fluxes of the Herschel/PACS data. The fluxes of [N\textsc{ii}]122\(\mu\)m, [Cl] as well as for [Cl](1–0), CO(2–1) and H\textsc{i} are listed in Table 7.3.

The observed fluxes emphasize the importance of [Cl] as a cooling line for the ISM, and particular for the molecular gas phase (cf. Table 7.3). [N\textsc{ii}]122\(\mu\)m emission is exclusively associated with the ionised phase. As shown in the following (Section 7.2.4) $\gtrsim 25\%$ of the [Cl] emission arises from the molecular phase. In this phase the majority of the energy is
<table>
<thead>
<tr>
<th>Position</th>
<th>Line</th>
<th>$\nu_{\text{LSR}}$</th>
<th>$\Delta v$</th>
<th>$\int T_{\text{mb}} , dv$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>[km/s]</td>
<td>[km/s]</td>
<td>[K km/s]</td>
</tr>
<tr>
<td>BCLMP901</td>
<td>[Cl] (1–0)</td>
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<td>6.3±0.8</td>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>$^{12}$CO (2–1)</td>
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<td>7.4±0.2</td>
<td>3.2±0.4</td>
</tr>
<tr>
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<td>[CII]</td>
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<td>9.9±1.0</td>
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<tr>
<td></td>
<td>H$^i$</td>
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<td>1085±112</td>
</tr>
<tr>
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<td>[NII]122$\mu$m</td>
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<td></td>
<td>0.49±0.09</td>
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<td>-</td>
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</tr>
<tr>
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</tr>
<tr>
<td>GMC01</td>
<td>[CII] Peak</td>
<td>[CII] (1–0)</td>
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<tr>
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<tr>
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<td>-</td>
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</tr>
<tr>
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<td>H$^i$</td>
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<tr>
<td>GMC01</td>
<td>[CII] Flank</td>
<td>[CII] (1–0)</td>
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<td>8.4±1.3</td>
</tr>
<tr>
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<td>$^{12}$CO (1–0)</td>
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<tr>
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<td>$^{12}$CO (2–1)</td>
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<tr>
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<td>H$^i$</td>
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<td>GMCno06 A</td>
<td>[CII] (1–0)</td>
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</tr>
<tr>
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<td>4.34±0.4</td>
</tr>
<tr>
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<td>H$^i$$^a$</td>
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<td>[NII]122$\mu$m</td>
<td></td>
<td></td>
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<tr>
<td>GMCno06 B</td>
<td>[CII] (1–0)</td>
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<td>$^{12}$CO (1–0)</td>
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<td>1.45±0.27</td>
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<tr>
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<td>$^{13}$CO (1–0)</td>
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<td>4.2±2.9</td>
<td>0.19±0.06</td>
</tr>
<tr>
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<td>2.53±0.30</td>
</tr>
<tr>
<td></td>
<td>[CII]</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>H$^i$$^a$</td>
<td>-119.8±0.1</td>
<td>21.0±0.2</td>
<td>1854±187</td>
</tr>
</tbody>
</table>

Table 7.2: Parameters of single Gaussian fits to the [CII], [Cl] (1–0), CO(2–1) and H$^i$ spectra. The integrated line intensities of [NII]122$\mu$m intensities as well as of [CII] intensities in the position GMC01 Peak were calculated from their fluxes (cf. Table 7.3, Nikola et al. in prep.) via Equation (4.16).

* The CO(1–0) data refer to a beam of 21$''$.

** The H$^i$ spectra shows no double peak in GMCno06. The H$^i$ values in GMCno06 A and GMCno06 B refer to a fit with a single Gaussian. They are identical for both clouds.
radiated by \([\text{C}^\text{II}]\). It radites \(\sim 50\) to \(100\) times the energy that is radiated by \([\text{C}^\text{I}](1–0)\) and \(\text{CO}(2–1)\). Furthermore, these fluxes reveal that the \([\text{C}^\text{I}](1–0)\) transitions radiates more energy than \(\text{CO}(2–1)\) in the majority of the positions (up to \(\sim 5\) times more).

In general \([\text{C}^\text{II}]\) is the broadest carbon line, with an average line width of \(\sim 10–20\) km/s. The line widths of \(\text{CO}(2–1)\) are relative constant in all positions, with a typically \(\Delta v(\text{CO}(2–1))\sim 7\) to \(12\) km/s. The line width of \(\text{CO}(2–1)\) exceeds the one of of \([\text{C}^\text{I}](1–0)\) or is of similar width within the uncertanties, \(\Delta v([\text{C}^\text{I}])\sim 5–10\), in all positions but BCLMP302. \([\text{C}^\text{I}]\) and \([\text{C}^\text{I}](1–0)\) have similar line width \(\sim 15\) K km/s in BCLMP302, while \(\text{CO}(2–1)\) has the narrowest line.

The central velocities of the individual lines match within the uncertanties, in almost all the positions. An exception is the GMCno06, in which two \(\text{CO}(2–1)\) and \([\text{C}^\text{I}](1–0)\) velocity components were observed (component \(A\) and \(B\); cf. Fig. 7.3, and Table 7.2) while the \([\text{C}^\text{II}]\) emission is only associated with the component \(A\). These two \(\text{CO}\) and \([\text{C}^\text{I}](1–0)\) velocity components are associated with two nearby GMCs, cloud \(A\) and \(B\). These clouds overlap partially spatially within the beam (cf. Fig 7.28). Therefore the spectra arises from tow different clouds, not from a \(\text{CO}\) and \([\text{C}^\text{I}](1–0)\) selfabsorption.

The observations indicate that \([\text{C}^\text{II}]\) , \([\text{C}^\text{I}](1–0)\) and \(\text{CO}\) emissions arise from different regions within the GMCs. The different transitions trace different phases of the gas, otherwise the lines would have the same widths and central velocity. In general, the observations are consistent with a \(\text{C}^+\)/\(\text{C}^0\)/\(\text{CO}\) layer structure, as described in Section 2.2.1 and proposed by Tielens & Hollenbach (1985a). All the molecular clouds (except GMC91) have the characteristic of a PDR. \(\text{CO}\) and \(\text{C}^0\) are associated exclusively with molecular gas. In this cases \([\text{C}^\text{I}](1–0)\) arises from the photodissocation layer of \(\text{CO}\). The widths of the \([\text{C}^\text{II}]\)–lines can be explained by \(\text{C}^+\) that is associated with the ionised, neutral and molecular phase. Hence its line width is broader compared to \(\text{CO}\) and \([\text{C}^\text{I}](1–0)\). The GMC BCLMP302 is an exception, as \([\text{C}^\text{I}](1–0)\) and \([\text{C}^\text{II}]\) have similar line widths. This indicates a phase where \([\text{C}^\text{II}]\) and \(\text{C}^0\) trace the same \(\text{H}_2\), while \(\text{CO}\) is absent. This meets the expectations of the model proposed by Hollenbach, Takahashi & Tielens (1991), Wolfire et al. (2003) and Wolfire, Hollenbach & McKee (2010).

The following sections will determine the column densities of \(\text{C}^+\), \(\text{C}^0\) and \(\text{CO}\) in the molecular phase. The calculations are based on an assumed \(\text{C}^+\)/\(\text{C}^0\)/\(\text{CO}\) layer structure of the PDRs. Based on these column densities I will determine the fraction of \(\text{H}_2\) traced by the different carbon species. As \(\text{C}^+\) is associated with the ionised, neutral and molecular phase it is necessary to determine the fraction of \([\text{C}^\text{II}]\) that arises from the different phases.
Table 7.3: Fluxes of [C\textsc{ii}], [C\textsc{i}](1–0), \(^{12}\text{CO}(2–1)\) and \([\text{N}\textsc{ii}]122\text{\textmu m}\) The fluxes of \([\text{N}\textsc{ii}]122\text{\textmu m}\) as well as the [C\textsc{ii}] flux in the position GMC01 Peak are obtained from Nikola et al. in prep.. Almost all other fluxes were derived via Equation (4.16). The used integrated velocity integrated line intensities are listed in Table 7.2.

<table>
<thead>
<tr>
<th>Position</th>
<th>(I([\text{C}\textsc{ii}])) (^{10^{-5}})</th>
<th>(I(<a href="1%E2%80%930">\text{C}\textsc{i}</a>)) (^{10^{-8}})</th>
<th>(I(X(2–1))) (^{10^{-8}})</th>
<th>(I([\text{N}\textsc{ii}]122\text{\textmu m})) (^{10^{-6}})</th>
<th>(I(\text{H}i)) (^{10^{-30}})</th>
</tr>
</thead>
<tbody>
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<td>BCLMP691</td>
<td>6.97±0.14</td>
<td>6.60±1.59</td>
<td>12.02±0.10</td>
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<td>&lt;2.2</td>
<td>23.88±0.15</td>
<td>3.4±0.7</td>
<td>4.5±0.5</td>
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<tr>
<td>BCLMP302</td>
<td>5.18±0.13</td>
<td>19.06±2.44</td>
<td>4.59±0.21</td>
<td>3.6±1.4</td>
<td>4.5±0.5</td>
</tr>
<tr>
<td>GMC01 Peak</td>
<td>9.34±0.21</td>
<td>11.97±1.95</td>
<td>10.10±0.15</td>
<td>7.8±0.8</td>
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<tr>
<td>GMC01 Flank</td>
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<td>13.81±1.47</td>
<td>7.56±0.18</td>
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<td>5.49±0.24</td>
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</table>
7.2 CARBON AND HYDROGEN COLUMN DENSITIES IN M33

The following section is dedicated to the column densities of hydrogen CO, C\(^0\) and C\(^+\). These column densities will be calculated via the observed \(^{12}/^{13}\)CO(1–0), CO(2–1), [C\(i\)](1–0), [C\(ii\)] and H\(i\) line intensities. The column densities of H\(^0\), CO, C\(^0\) and C\(^+\) allow the calculation of the molecular hydrogen column densities and the total hydrogen column densities (Section 7.2.6 and 7.2.7). Based on these column densities I will derive the relative fraction of CO dark H\(_2\) relative to the total contribution of H\(_2\) (Section 7.2.8).

First I will discuss the column densities of H\(_i\), CO, C\(^0\) and C\(^+\).

7.2.1 NEUTRAL ATOMIC HYDROGEN COLUMN DENSITIES

The H\(^0\) column densities are calculated via Equation (A.11) \(x\), for an assumed optically thin case. The \(N(H^0)\) derived by this means varies vary between \(\sim 1.5\) to 3\(\times\)10\(^{21}\) cm\(^{-2}\). The H\(_i\) emission exceeds the beam of [C\(i\)](1–0) observations. Therefore the calculations of \(N(H^0)\) are based on an assumed beam filling factor of \(\Phi_B = 1\). The derived \(N(H^0)\) for the individual positions are summarised Table 7.13.

7.2.2 CO COLUMN DENSITIES IN LTE

The following section describes the calculation of the total CO column densities, \(N(CO)\) for clouds in an assumed local thermal equilibrium\(xii\). All available CO transitions (\(^{13}\)CO(1–0), \(^{12}\)CO(1–0) and \(^{12}\)CO(2–1)) in the observed positions were used for these calculations. I will investigate two different approaches.

i: The first approach uses the \(^{13}\)CO(1–0), \(^{12}\)CO(1–0) and \(^{12}\)CO(2–1) data to derive the optical depth, excitation temperature as well as of the beam filling factor needed for the CO column density calculations.

ii: The first approach gives to CO excitation temperatures below the ambient dust temperature of (\(\sim 6\) K versus \(\sim 20\) K)\(xii\). This discrepancy might have its origin in different regions in which the dust emission and the low–J CO transitions arises. Low–J CO transitions arise from the cold central regions of molecular clouds. This gas is almost completely shielded against the penetrating radiation field, which has not to be the case for dust. Dust can be observed also in region in which the radiation field is higher, and also the temperature. The second approach calculates the CO column densities in the case that the CO excitation temperatures are equal to the dust temperatures.

At first I will discuss approach I. The three CO transitions (\(^{12}/^{13}\)CO(1–0) and \(^{12}\)CO(2–1)) allows the determination of all parameters needed for

---

\(x\) \(N(H^0) = 1.823 \times 10^{18} \int T_{mb}(Hi)dv\)

\(xi\) This method is described in detail in Section 4.2.

\(xii\) Approach I gives \(T_{ex}(CO(2–1)) = 6\) K. Buchbender (2013) calculated dust temperatures of \(T(Dust) = 20\) K. Note that the excitation temperatures of CO(2–1), \(T_{ex}(CO(2–1)) = 6\) K, are consistent with the \(T_{ex}\) derived for other sources (e.g. Liszt & Lucas 1998)
the CO column density calculations: the optical depth $\tau$, excitation temperature $T_{\text{ex}}$ as well as of the beam filling factor in the observed clouds $\Phi_B$. The optical depth of $^{13}$CO(1–0), $\tau_{13}$, is numerically calculated via relation 4.15. A $^{12}$C/$^{13}$C ratio of $x_{12}=56$ is assumed. This ratio was found as the mean ratio of the integrated line intensities of $^{12}$CII and $^{13}$CII in BCLMP691 (Braine et al. 2012b). This approach assumes that both lines are optically thin. If the lines are optically thin the ratio of $^{12}$C and $^{13}$C is equal to those of the integrated intensities. In the case of optically thick $^{12}$CII, the used $^{12}$CII/$^{13}$CII ratio would underestimate the real $^{12}$C/$^{13}$C ratio by a factor $\tau_{12}/(1-\exp(-\tau_{12}))$. It was further assumed that the isotope ratio is constant for all discussed positions. That does not necessarily has to be the case. The $^{12}$C/$^{13}$C isotope ratio has a radial gradient within the Milky Way, from $\sim30$ at the galactic centre to $\sim90$ at the sun (Clayton 2003). Note that the $x_{12}=56$ is similar to the value used in Buchbender (2013) of $x_{12}=60$.

The value found for $\tau_{13}$ varies between 0.1 to 0.3, which corresponds to an optical depths of $\tau_{12}=6$ to 17 for $^{12}$CO(1–0). These values indicate that the low–$J$ $^{12}$CO transitions are optically thick in all positions, discussed here.

The excitation temperatures for the different transitions were calculated with Equation (4.6). The beam filling factor $\Phi_B$ was preliminary kept as an open variable at this stage, and was determined at the end of these calculations. The column density of $^{13}$CO, $N_{\text{tot}}$(CO) are calculated with Equation (4.14). The total column density of $^{12}$CO, $N_{\text{tot}}(CO)$ is calculated by the multiplication of $N_{\text{tot}}$(CO) with the isotope ratio $x_{12}$. Note that $\Phi_B$ is still undetermined. These calculations are based on an assumed local thermal equilibrium, that means that the excitation temperatures are equal for all the transitions discussed here. Hence, the CO column densities can be calculated from the CO(2–1) observations, as described in the following section. The following calculations are based on the assumption that $^{12}$CO(2–1) and $^{12}$CO(1–0) have identical excitation temperature, $T_{\text{ex}}$, and beam filling factors, $\Phi_B$). The CO(2–1) data was in addition convolved to the same spatial resolution as the CO(1–0) data ($\Phi_B$(CO(1–0))=21.4$^{+4}_{-0}$), for the sake of consistency. In the position GMC01 Flank no complementary CO(1–0) data is available. Therefore it was assumed that the optical depths, excitation temperature and beam filling factor in this position are equal to the values in GMC01 Peak. The total CO column densities $N_{\text{tot}}$(CO) should be equal, regardless of the CO

\[ \frac{N_{\text{tot}}(^{13}CO)}{N_{\text{tot}}(^{12}CO)} = \frac{1-e^{-x_{12} \tau_{13}}}{1-e^{-\tau_{13}}} \]

\[ T_{\text{ex}} = \frac{h \nu}{k_B} \times \left[ \ln \left( \frac{1}{1-e^{-\tau_{13}}}) \Phi_B \frac{h \nu}{k_B} \frac{1}{T_{\text{CMB}}} \right) + 1 \right]^{-1} \]

\[ N = \frac{\tau_{13}}{1-e^{-\tau_{13}}} \times \frac{2.8}{3.3} \times \frac{2}{3} \times \frac{Q^4}{4} \times \frac{1}{\sqrt{\sigma_A}} \times \frac{\frac{h \nu}{k_B}}{1-e^{-\tau_{13}}} \times \frac{1}{\Phi_B} \int T_{\text{mb}} d\nu \]

\[ \tau_{13} \text{ is Braine et al. (2012b) search for } [^{13}\text{CII}] \text{ emission on the 'blue'shoulder of five } [^{12}\text{CII}] \text{ spectra near/at the centre of BCLMP691. } [^{13}\text{CII}] \text{ has a frequency equivalent offset of } +11 \text{ km/s relative to the centre of the } [^{12}\text{CII}] \text{ transition. They fit the } [^{12}\text{CII}] \text{ spectra with a Gaussian. The fit gives an excess of [CII]--emission on the blue side of the spectra. This excess is explained by the additional emission of } [^{13}\text{CII}], \text{ resulting in a ratio of } I([^{12}\text{CII}])/I([^{13}\text{CII}]) \approx 56 \pm 41. \]

\[ T_{\text{ex}} = \frac{h \nu}{k_B} \times \left[ \ln \left( \frac{1}{1-e^{-\tau_{13}}}) \Phi_B \frac{h \nu}{k_B} \frac{1}{T_{\text{CMB}}} \right) + 1 \right]^{-1} \]

\[ N = \frac{\tau_{13}}{1-e^{-\tau_{13}}} \times \frac{2.8}{3.3} \times \frac{2}{3} \times \frac{Q^4}{4} \times \frac{1}{\sqrt{\sigma_A}} \times \frac{\frac{h \nu}{k_B}}{1-e^{-\tau_{13}}} \times \frac{1}{\Phi_B} \int T_{\text{mb}} d\nu \]
transition used. The beam filling factor and thus the excitation temperature can be now numerically calculated by equating the total CO column densities based on the observed \(I(^{12}\text{CO}(1-0))\) and \(I(^{12}\text{CO}(1-0))\).

This method gives optical depth of \(\tau_{12} \sim 6\) to 17 and beam filling factors between \(\Phi_B \sim 0.1\) (GMcno06 B) to 0.7 (GMC91). The beam filling factor average over all positions is \(\langle \Phi_B \rangle 0.3 \pm 0.2\). The excitation temperatures have typical values between \(T_{\text{ex}} \sim 5\) to 8 K with a mean of \(\langle T_{\text{ex}} \rangle = 6\pm1\) K. The GMCs have CO column densities between \(N(\text{CO}) \sim 33 \times 10^{17}\) cm\(^{-2}\) with a mean of \(\langle N(\text{CO}) \rangle = 13 \pm 6 \times 10^{17}\) cm\(^{-2}\). Note that these column densities are average over the beam. The total column densities in the clouds is given by dividing the beam average column densities with the beam filling factors. The \(T_{\text{ex}}, \Phi_B\) and \(N(\text{CO})\) for the individual positions are summarised in Table 7.5.

Now I will will discuss the approach II.

The excitation temperatures of \(\sim 6\) K, derived in the previous paragraph, are in the order of the ground level energy of the CO(1–0) transition \(E(\text{CO}(1-0))/k_B \approx 5.5\) K. cf. Section 4.1). These temperatures are expected in the cold cores of molecular clouds, in which the CO(1–0) transition dominates (e.g. Parikka et al. 2015), but not as mean temperatures of the molecular gas in a GMC. Higher excitation temperatures are expected and derived for higher \(J\) CO transitions. For example Okada et al. (2015) estimated \(T_{\text{ex}} \sim 20\) to 150 K for N159 based on CO(3–2) data. Buchbender (2013) derived cold dust\(^{xvii}\) temperatures of \(\sim 20\) K for the positions, discussed here (cf. Table 7.5). If the gas is thermalised\(^{xviii}\), the dust temperature can be equal to the gas temperatures (e.g. Goldsmith 2001). CO(1–0) has a critical density of \(\sim 3000\) cm\(^{-3}\) for collisions with \(\text{H}_2\) in the optically thin limit. The critical density is reduced in the optically thick regime, as \(n_{\text{crit}} \propto \tau^{-1xix}\). This, the critical densities is reduce to \(\sim 600\) cm\(^{-3}\) for a \(\tau=5\) and to \(\sim 300\) cm\(^{-3}\) for a \(\tau=10\).

The following calculations assume that the CO excitation temperatures are equal to the cold dust temperatures. This approach gives optical depths of \(\tau_{12} \sim 5\) to 30, beam filling factors of 1 to 6% and beam average

\(^{xvii}\) Cold dust is typically associated with CO gas (Braine et al. 2010; Xilouris et al. 2012; Buchbender 2013). Warm dust has higher temperatures of \(T \sim 50-60\) K and is typically associated with \([\text{C}\text{ii}]\) emission.

\(^{xviii}\) For details see Section 4.2. Note that the term \(1-e^{-\tau}\) in Equation (4.2) can be approximated by \((1-e^{-\tau}) \times \tau^{-1} \xrightarrow{\tau \to \infty} \tau^{-1}\) in the optical thick case.
7.2 Carbon and Hydrogen Column Densities in M33

Figure 7.5: CO column densities for the different transitions modelled with RADEX.

CO column densities of $\sim 2$ (GMC06 B) to $34$ (GMC91) $\times 10^{17}$ cm$^{-2}$ with a mean of $\langle N(CO)\rangle = 12 \pm 10 \times 10^{17}$ cm$^{-2}$. The beam average CO column densities are thus of similar order for both approaches.

The following paragraph discusses the different beam filling factors of both approaches.

Approach I gives $\Phi_B = 0.4$ for BCLMP302. This beam filling factor is consistent with high angular resolved $^{12}$CO(1–0) maps of BCLMP302$^{xx}$, $\Theta_B \approx 4'' \approx 15$ pc, as shown in Fig. 11.3 in Buchbender (2013). The beam filling factors of Approach II are also consistent with beam filling factors found in other nearby extragalactic sources as for example the LMC (e.g. Okada et al. 2015), in which $\Phi_B \approx 0.3$ to 0.4 were derived.

The beam filling factors of approach II are roughly one order below those of approach I ($\Phi_B \approx 0.03$ v.s. $\Phi_B \approx 0.3$). The beam filling factors of approach II are hard to reconcile with the size of the clouds. If the depths of the GMCs is equal to its diameter ($d_C \sim 50$ pc), the surfaces of the individual clumps within the beam should superimpose and roughly fill the surface the beam.

On the other hand, an ensemble of CO clumps could explain the low beam filling factor. A beam filling of 3% would imply small bright dense CO–clumps that emit all the observed CO emission. Such a beam filling factor is hard to reconcile with dense gas tracers as HCO$^+$ and HCN, which were observed by Buchbender (2013) in all positions, discussed here. These tracers require a shielding from the penetrating FUV field. Small clump sizes can hardly provide this shielding.

$^{xx}$ This map was observed with the Plateau de Bure interferometer (PdB)
The ratio of the observed CO(1–0) and CO(2–1) line intensities were modelled with the statistical equilibrium radiative transfer code RADEX\textsuperscript{xxi} (van der Tak et al. 2007) (cf. Fig. 7.5. The simulations give similar $T_{\text{ex}}$, $\tau_{12}$ and $N$(CO) as derived for Approach I, in the majority of the positions 7.2.2. The simulations give CO(1–0) excitation temperatures between $T_{\text{ex}} = 4.2$ to 13.6 K and optical depths of $^{12}$CO(1–0) $\tau_{12}=1.3$ to 10.4. One exception is the cloud GMCno06 B in which the observations imply an CO(2–1) excitation temperatures of $\sim 100$ K and an optical depth $\tau_{12}=10^{-1}$.

In summary it can be concluded that the approach I ($T_{\text{ex}} \sim 6$ K, $\Phi_B \sim 0.3$) presumably reflects the real conditions within the clouds, also approach I and II give similar $N$(CO) in the end. Nevertheless, I will consider the column densities of approach I and II in the following discussions. It allows to compare the impact of the different approaches to the total carbon column densities and in the end to the amount and distribution of $\text{H}_2$.

### 7.2.3 Column Densities of Neutral Atomic Carbon

The following paragraphs are dedicated to the calculation of the neutral atomic carbon column density $N$(C\textsuperscript{0}). The calculations are based on an assumed thermal equilibrium in the observed clouds.

The calculations are based exclusively on the [C\textsuperscript{i}](1–0) observations, due to the lack of [C\textsuperscript{i}](2–1) data. This lack of [C\textsuperscript{i}](2–1) data prevents the direct calculation of its excitation temperature (cf. e.g. Stutzki et al. 1998; Schneider et al. 2003; Glover et al. 2015). If both transitions were available, the $T_{\text{ex}}$ could be calculated directly from the ratio of their integrated line intensities\textsuperscript{xxii}.

Lo et al. (2014) proposed that the lower limit of the [C\textsuperscript{i}](1–0) excitation temperature is given by the CO excitation temperatures. This approach gives an absolute lower limit, but higher $T_{\text{ex}}$ are likely as discussed below. Excitation temperatures of $\sim 6$ K, as derived for CO (see previous section), are uncommon for C\textsuperscript{0} in PDRs. The ground level energy of the [C\textsuperscript{i}](1–0) transition is $E/k_B=23.6$ K. For a significant excitation of C\textsuperscript{0} $\text{C}^0$ has only two transitions (cf. Section 4.1). The excitation temperature of neutral atomic carbon is directly given by the relative population of the different energy levels, and hence by the ratio of their integrated line intensities:

\[
T_{\text{ex}} = 38.8 \times \left[ \ln \left( \frac{I_{\text{C}[1-0]}}{I_{\text{C}[2-1]}} \right) \right]^{-1} \text{[K]} \quad \text{(e.g. Schneider et al. 2003)}.
\]

\textsuperscript{xxi} http://var.sron.nl/radex/radex.php

\textsuperscript{xxii} http://var.sron.nl/radex/radex.php

---

<table>
<thead>
<tr>
<th></th>
<th>$T_{\text{ex}}$(CO(1–0))</th>
<th>$\tau_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCLMP691</td>
<td>7.5</td>
<td>7.3</td>
</tr>
<tr>
<td>GMC91</td>
<td>4.4</td>
<td>10.0</td>
</tr>
<tr>
<td>BCLMP302</td>
<td>4.2</td>
<td>4.6</td>
</tr>
<tr>
<td>GMC01 Peak</td>
<td>13.7</td>
<td>1.3</td>
</tr>
<tr>
<td>GMCno06 A</td>
<td>7.6</td>
<td>4.3</td>
</tr>
<tr>
<td>GMCno06 B</td>
<td>100.</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Table 7.4: Optical depth and excitation temperatures of $^{12}$CO(1–0) from RADEX-simulations
7.2 Carbon and Hydrogen Column Densities in M33

Table 7.5: Derived beam average CO column densities for different excitation temperatures.

<table>
<thead>
<tr>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\tau_{12})</td>
<td>(\Phi_B)</td>
<td>(T_{\text{ex}})</td>
<td>(N(^{12}\text{CO}))</td>
</tr>
<tr>
<td></td>
<td>([K])</td>
<td></td>
<td></td>
<td>(10^{16}\text{cm}^{-2})</td>
</tr>
</tbody>
</table>

Approach I:

\(T_{\text{ex}}\) derived from \(^{13}/^{12}\text{CO}(1–0)\) and \(^{12}\text{CO}(2–1)\) data

<table>
<thead>
<tr>
<th>Cloud</th>
<th>(\tau_{12})</th>
<th>(\Phi_B)</th>
<th>(T_{\text{ex}})</th>
<th>(N(^{12}\text{CO}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCLMP691</td>
<td>6.9</td>
<td>0.2</td>
<td>5.1±0.1</td>
<td>11.6±1.2</td>
</tr>
<tr>
<td>GMC91</td>
<td>6.2</td>
<td>0.7</td>
<td>6.1±0.8</td>
<td>14.4±1.5</td>
</tr>
<tr>
<td>BCLMP302</td>
<td>9.1</td>
<td>0.4</td>
<td>5.6±0.3</td>
<td>4.9±0.5</td>
</tr>
<tr>
<td>GMC01 Peak</td>
<td>8.4</td>
<td>0.2</td>
<td>8.1±0.6</td>
<td>15.0±1.5</td>
</tr>
<tr>
<td>GMC01 Flank(^a)</td>
<td>8.4</td>
<td>0.2</td>
<td>8.1±0.6</td>
<td>9.2±0.9</td>
</tr>
<tr>
<td>GMCno06 A</td>
<td>7.8</td>
<td>0.2</td>
<td>5.2±0.1</td>
<td>20.5±2.1</td>
</tr>
<tr>
<td>GMCno06 B</td>
<td>16.9</td>
<td>0.1</td>
<td>6.6±0.1</td>
<td>5.2±0.5</td>
</tr>
<tr>
<td>Mean</td>
<td>9.2±3.6</td>
<td>0.3±0.2</td>
<td>6.2±1.0</td>
<td>13.1±5.7</td>
</tr>
</tbody>
</table>

Approach II:

\(T_{\text{ex}}\) equal to \(T_{\text{Dust}}\)

<table>
<thead>
<tr>
<th>Cloud</th>
<th>(\tau_{12})</th>
<th>(\Phi_B)</th>
<th>(T_{\text{ex}})</th>
<th>(N(^{12}\text{CO}))</th>
</tr>
</thead>
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<tr>
<td>BCLMP691</td>
<td>13.6</td>
<td>0.02</td>
<td>23±1</td>
<td>5.9±1.1</td>
</tr>
<tr>
<td>GMC91</td>
<td>19.2</td>
<td>0.06</td>
<td>20±1</td>
<td>24.4±3.9</td>
</tr>
<tr>
<td>BCLMP302</td>
<td>28.1</td>
<td>0.03</td>
<td>20±1</td>
<td>5.7±1.1</td>
</tr>
<tr>
<td>GMC01 Peak</td>
<td>11.3</td>
<td>0.04</td>
<td>25±1</td>
<td>14.5±2.5</td>
</tr>
<tr>
<td>GMC01 Flank(^a)</td>
<td>11.3</td>
<td>0.04</td>
<td>25±1</td>
<td>11.5±1.9</td>
</tr>
<tr>
<td>GMCno06 A</td>
<td>6.8</td>
<td>0.02</td>
<td>23±1</td>
<td>4.8±0.4</td>
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<tr>
<td>GMCno06 B</td>
<td>4.7</td>
<td>0.01</td>
<td>23±1</td>
<td>2.0±0.3</td>
</tr>
<tr>
<td>Mean</td>
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<td>0.03±0.01</td>
<td>22±2</td>
<td>12.1±9.6</td>
</tr>
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(2), (3) & (4) Derived optical depth \(\tau\), beam filling factors \(\Phi_B\) and excitation temperatures. The dust temperatures are obtained from Buchbender (2013)

(5) Beam average CO column densities estimated from the CO(2–1).

\(^a\) For GMC01 Flank it was assumed that \(\tau\), \(T_{\text{ex}}\) and \(\Phi_B\) are equal to the corresponding values in GMC01 Peak.

the excitation temperatures must be at least in the order of this ground level energy. Schneider et al. (2003) derived, for example, \(T_{\text{ex}}\) of \(\gtrsim 60\) K in S106 IR based on [CI](2–1) and [CI](1–0) observations. Okada et al. (2015) derived median excitation temperatures of \(T_{\text{ex}}\)70-80 K in N159 in the LMC and Pérez-Beaupuits et al. (2015) found \(T_{\text{ex}}\)~40 to 100 K in M17. Furthermore, equal [CI](1–0) and CO excitation temperatures (and equal beam filling factors) gives negative values within the logarithm of Equation (4.7)xxiii in three clouds, and consequently to an infinite optical depth, which is non-physical (cf. Table 7.6) Therefore, the excitation temperatures of [CI](1–0) must be higher, to be consistent with the observations.

Neural atomic carbon column densities for different \(T_{\text{ex}}\) are listed in Table 7.6. At lower temperature I assume a \(T_{\text{ex}}\)~10 K. This temperature is close to the calculated CO excitation temperatures and gives \(\tau<\infty\) for all positions. The C\(^{1}\) column densities were calculated for temperatures talht are equal to the dust temperatures \(T_{\text{ex}}\)~25 K, for \(T_{\text{ex}}\)~50 K and for \(T_{\text{ex}}\)~75 K. It was further assumed that the beam filling factors of [CI](1–0) are equal to those of CO \((\Phi_B = 0.1\) to \(0.4\)).

xxiii \(\tau = -\ln\left(1 - \frac{k_B}{\Phi_B h \nu} (T_{\text{mb}} + \mathcal{J}(T_{\text{CMB}})) e^{\frac{h \nu}{k_B T_{\text{ex}}}} - 1\right)\)
<table>
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<td>$N(C^0)$</td>
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<td>BCLMP691</td>
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<td>GMC91</td>
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<td>1.1±0.2</td>
</tr>
<tr>
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<td>&lt;0.1</td>
</tr>
<tr>
<td>GMCno06 B</td>
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<td>$T_{\text{ex}}=10$ K</td>
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</tr>
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<td>10</td>
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<td>0.7</td>
<td>10</td>
<td>&lt;0.2</td>
</tr>
<tr>
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<td>10</td>
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</tr>
<tr>
<td>Mean</td>
<td>0.3±0.2</td>
<td>10</td>
<td>0.8±0.3</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{ex}}=25$ K</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BCLMP691</td>
<td>0.03</td>
<td>0.2</td>
<td>25</td>
<td>0.8±0.2</td>
</tr>
<tr>
<td>GMC91</td>
<td>&lt;0.1</td>
<td>0.7</td>
<td>25</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>BCLMP302</td>
<td>0.01</td>
<td>0.2</td>
<td>25</td>
<td>1.6±0.3</td>
</tr>
<tr>
<td>GMC01 Peak</td>
<td>0.05</td>
<td>0.2</td>
<td>25</td>
<td>1.5±0.3</td>
</tr>
<tr>
<td>GMC01 Flank</td>
<td>0.04</td>
<td>0.2</td>
<td>25</td>
<td>1.7±0.3</td>
</tr>
<tr>
<td>GMCno06 A</td>
<td>0.04</td>
<td>0.2</td>
<td>25</td>
<td>2.0±0.3</td>
</tr>
<tr>
<td>GMCno06 B</td>
<td>0.07</td>
<td>0.1</td>
<td>25</td>
<td>0.9±0.2</td>
</tr>
<tr>
<td>Mean</td>
<td>0.3±0.2</td>
<td>25</td>
<td>1.2±0.7</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{ex}}=50$ K</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BCLMP691</td>
<td>0.01</td>
<td>0.2</td>
<td>50</td>
<td>1.2±0.3</td>
</tr>
<tr>
<td>GMC91</td>
<td>&lt;0.1</td>
<td>0.7</td>
<td>50</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>BCLMP302</td>
<td>0.004</td>
<td>0.2</td>
<td>50</td>
<td>2.3±0.45</td>
</tr>
<tr>
<td>GMC01 Peak</td>
<td>0.02</td>
<td>0.2</td>
<td>50</td>
<td>2.1±0.4</td>
</tr>
<tr>
<td>GMC01 Flank</td>
<td>0.02</td>
<td>0.2</td>
<td>50</td>
<td>2.5±0.4</td>
</tr>
<tr>
<td>GMCno06 A</td>
<td>0.02</td>
<td>0.2</td>
<td>50</td>
<td>2.9±0.5</td>
</tr>
<tr>
<td>GMCno06 B</td>
<td>0.03</td>
<td>0.1</td>
<td>50</td>
<td>1.3±0.3</td>
</tr>
<tr>
<td>Mean</td>
<td>0.3±0.2</td>
<td>50</td>
<td>2.0±0.7</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{ex}}=75$ K</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BCLMP691</td>
<td>0.006</td>
<td>0.2</td>
<td>75</td>
<td>1.4±0.4</td>
</tr>
<tr>
<td>GMC91</td>
<td>&lt;0.1</td>
<td>0.7</td>
<td>75</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>BCLMP302</td>
<td>0.003</td>
<td>0.2</td>
<td>75</td>
<td>2.6±0.5</td>
</tr>
<tr>
<td>GMC01 Peak</td>
<td>0.011</td>
<td>0.2</td>
<td>75</td>
<td>2.5±0.5</td>
</tr>
<tr>
<td>GMC01 Flank</td>
<td>0.010</td>
<td>0.2</td>
<td>75</td>
<td>2.8±0.4</td>
</tr>
<tr>
<td>GMCno06 A</td>
<td>0.010</td>
<td>0.2</td>
<td>75</td>
<td>3.3±0.5</td>
</tr>
<tr>
<td>GMCno06 B</td>
<td>0.016</td>
<td>0.1</td>
<td>75</td>
<td>1.5±0.4</td>
</tr>
<tr>
<td>Mean</td>
<td>0.3±0.2</td>
<td>75</td>
<td>2.3±0.8</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.6: Derived beam average $C^0$ column densities for different excitation temperatures.

(2), (3) & (4) Derived optical depth $\tau$, beam filling factors $\Phi_B$ and excitation temperatures. The dust temperatures are obtained from Buchbender (2013). (5) Beam average $C^0$ column densities. The mean values are based on the positions where a clear $N(C^0)$ was calculated (GM91 is excluded in all cases).
The optical depth of $|\text{[CII]}(1-0)|$, $\tau_{\text{[CII]}(1-0)}$, are calculated for all positions with Equation (4.7) xxiv. For all excitation temperatures in all positions the optical depths below 1 were derived. The highest optical depths are found for a $T_{\text{ex}} \sim 10$ K where $\tau_{\text{[CII]}(1-0)} \sim 0.1$ to 0.5. Therefore, $|\text{CII}|(1-0)$ is optically thin in all the positions. These optical depths are consistent with the results of other studies, for example Okada et al. (2015), Lo et al. (2014) and Pérez-Beaupuits et al. (2015).

The total $C^0$ column densities were derived with Equation (A.4) xxv. For GMC91 an upper limit $N(C^0)$ is listed, as no $|\text{CII}|(1-0)$ emission has been detected. The lowest beam average $N(C^0)$ are derived for $T_{\text{ex}} \sim 10$ K, where $N(C^0) \sim 0.5$ to $1.2 \times 10^{16}$ cm$^{-2}$. The $N(C^0)$ almost doubles to $N(C^0) \sim 0.8$ to $2 \times 10^{16}$ cm$^{-2}$ for $T_{\text{ex}} = 25$ K. Excitation temperatures of $T_{\text{ex}} = 50$ K and 75 K give almost similar $C^0$ column densities of $N(C^0) \sim 1$ to $3 \times 10^{16}$ cm$^{-2}$.

The derived $C^0$ column densities are thus lower than the CO column densities for $T_{\text{ex}} \sim 6$ K in all cases. The $N(C^0)/N(\text{CO})$ ratio does never exceed 3/4 (GMCh006 B for $T_{\text{ex}} = 75$ K).

### 7.2.4 Column Densities of Ionised Carbon

This Section aims to calculate and discuss the column densities of ionised carbon.

The emission of singly ionised carbon can arise from the ionised, neutral and molecular gas phase. In contrast, CO and $C^0$ are associated exclusively with molecular gas xxvi. The observed total integrated $[\text{CII}]$ line intensity, $I([\text{CII}])_{\text{tot}}$, is a composition of the $[\text{CII}]$ emission that is associated with the ionised, neutral atomic and molecular hydrogen gas;

$$I([\text{CII}])_{\text{tot}} = I([\text{CII}])_{\text{H}^+} + I([\text{CII}])_{\text{H}_0} + I([\text{CII}])_{\text{H}_2} \quad (7.1)$$

All these gas phases have different physical properties, in particular different temperatures and densities (cf. Section 2.1). These different properties have to be considered when the total column density of ionised carbon, $N(\text{C}^+)_{\text{tot}}$, is calculated. The total column density of $\text{C}^+$ is given by the sum of the column densities of the individual gas phases;

$$N(\text{C}^+)_{\text{tot}} = N(\text{C}^+)_{\text{H}^+} + N(\text{C}^+)_{\text{H}_0} + N(\text{C}^+)_{\text{H}_2} \quad (7.2)$$

with $N(\text{C}^+)_{\text{H}^+}$ being the $\text{C}^+$ column density in the ionised phase. $N(\text{C}^+)_{\text{H}_0}$ is the column density in the neutral phase and $N(\text{C}^+)_{\text{H}_2}$ is those in molecular gas. The $\text{C}^+$ column densities within a phase can be in general calculated from the integrated $[\text{CII}]$ intensities via equation (A.7) xxvii.

To determine the total $\text{C}^+$ column density, it is necessary to calculate the $N(\text{C}^+)_{\text{H}^+}$ and $I([\text{CII}])$ within the different gas phases. In the following paragraphs there will be discussed a method to determine $N(\text{C}^+)_{\text{H}^+}$ and $I([\text{CII}])$ within the different gas phases. The argumentation is inspired

---

xxiv see previous footnote

xxv $N(C^0) = 5.94 \times 10^{15} \times \frac{\nu \sigma(|\text{[CII]}(1-0)|)}{1/e - 1} \tau_{\text{[CII]}(1-0)} \int T_{\text{mb}}(|\text{[CII]}(1-0)|) \, \text{d}v$ ; cf. Section A

xxvi See Section 2.2.1 for further details.

xxvii $N(\text{C}^+) = 2.9 \times 10^{15} \left(1 + 0.5 e^{\frac{E_{\text{vib}}}{kT_{\text{ex}}}} \left(1 + \frac{n_{\text{H}_2}}{n_{\text{H}_2}^0}\right)\right) \frac{\Phi}{1 - e^{-\tau}} I([\text{CII}])$

See Section 4.2 and Appendix A in particular for further details.
by Langer et al. (2014b). They investigated the [CII] emission and C\(^+\) column densities in the neutral atomic and in the molecular phase. The fraction of [CII] emission that arises from the ionised hydrogen gas was not considered. The approach by Langer et al. (2014b) is elaborated in the following by including the [CII] emission from HII gas.

### 7.2.4.1 C\(^+\) in ionised hydrogen

The fraction of the total [CII] emission that arises from the ionised gas can be estimated via the transitions of single ionised nitrogen at \([\text{[NI]}]_{122}\mu\text{m}\) and \([\text{[NI]}]_{205}\mu\text{m}\). Both transitions arise almost exclusively from HII regions (Malhotra et al. 2001; Abel 2006). The emissions of [CII] and [NI]205\(\mu\text{m}\) show a power law in HII regions Abel (2006):

\[
\text{log} \left( \frac{I([\text{CII}])}{\text{[CII]} \text{[HII]}} \left[ \frac{\text{erg}}{\text{cm}^2 \text{s}^{-1}} \right] \right) = 0.937 \times \text{log} \left( \frac{I([\text{[NI]}]_{205}\mu\text{m}}}{[\text{[NI]}]_{205}\mu\text{m}} \left[ \frac{\text{erg}^{-1}}{\text{cm}^2 \text{s}^{-1}} \right] \right) + 0.689
\]

(7.3)

This correlation allows in general the estimation of \(I([\text{CII}])_{\text{HII}}\). Equation (7.3) has to be adopted for [NI]122\(\mu\text{m}\) as only [NI]122\(\mu\text{m}\) but no [NI]205\(\mu\text{m}\) data is available for the observed positions.

In HII regions it can be assumed that the proton density is equal to the electron density, \(n_{\text{HII}}=n_e\) (e.g. Lang 2013), as all hydrogen is ionised. A study of 25 HII regions in M33 found an almost constant electron density of \(n_e=100\) cm\(^3\) in all these regions (Rubin et al. 2008). Therefore the following calculation assume that this density represents the \(n_e\) in the positions discussed here as well. The integrated intensities of [NI]122\(\mu\text{m}\) and [NI]205\(\mu\text{m}\) show an almost constant ratio \(I([\text{[NI]}]_{122}\mu\text{m}\)/I([NI]205\(\mu\text{m}\)= 3, for an electron density of \(n_e=100\) cm\(^{-2}\) (Rubin 1985; Malhotra et al. 2001).

The ratio of \(I([\text{[NI]}]_{122}\mu\text{m}\)/I([NI]205\(\mu\text{m}\)= 3 combined with Equation (7.3), allows the calculation of the [CII] emission that arises from the ionised gas, \(I([\text{CII}])_{\text{HII}}\):

\[
\frac{I([\text{CII}])_{\text{HII} \left[ \frac{\text{erg}}{\text{cm}^2 \text{s}^{-1}} \right]} = 1.75 \times \left( \frac{I([\text{[NI]}]_{122}\mu\text{m}]}{[\text{[NI]}]_{122}\mu\text{m}]} \left[ \frac{\text{erg}}{\text{cm}^2 \text{s}^{-1}} \right] \right)^{0.937}
\]

\[
\Rightarrow I([\text{CII}])_{\text{HII} \left[ \frac{\text{K}}{\text{km s}^{-1}} \right]} = 2.48 \times 10^5 \left( \frac{I([\text{[NI]}]_{122}\mu\text{m}]}{[\text{[NI]}]_{122}\mu\text{m}]} \left[ \frac{\text{erg}}{\text{cm}^2 \text{s}^{-1}} \right] \right)^{0.937}
\]

(7.4)

The [NI]122\(\mu\text{m}\) fluxes combined with Equation (7.4) gives \(I([\text{CII}])_{\text{HII}}\) ~2 to 4 K km/s for the positions discussed here. This corresponds to ~10 to 40 % of the total [CII] emission. The \(I([\text{CII}])_{\text{HII}}\) for the different positions are listed in Table 7.8.

This approach assumes that the C\(^+\) and N\(^+\) gas in the ionised phase are mixed in the discussed positions. In that case the line width and central velocity of [CII] and [NI]122\(\mu\text{m}\) should be similar. Based on the available data it is not possible to justify this assumption, as the spectral resolution of the [NI]122\(\mu\text{m}\) PACS data is not sufficient enough xxviii. In the positions GMC01 Flank and GMC06 [NI]122 \(\mu\text{m}\) data from the specific [CII] peak is used. PACS maps of GMC01 (Nikola et al. in prep.) show a similar spatial distribution of [NI]122\(\mu\text{m}\) and [CII]. Therefore, the amount of [CII] from the ionised gas is presumably overestimated in the

xxviii PACS has a spectral resolution of ~290 km/s for [NI]122\(\mu\text{m}\) (PACS Observer’s Manual (http://herschel.esac.esa.int/Docs/PACS/html/pacs_om.html), Poglitsch et al. 2010.
position GMC01 Flank and in consequence also \( N([\text{CII}]_{\text{HIII}}) \). The calculated \( I([\text{CII}]_{\text{HIII}}) \) represent the lower limits, as the ratio of \( I([\text{CII}]_{\text{HIII}}) \) to the total \([\text{CII}]\) emission increases in a low metallicity environment (cf. Section 2.2.3).

The following paragraph is dedicated to the calculation of the \( \text{C}^+ \) column densities in the ionised phase.

Rubin et al. (2008) derived electron excitation temperatures of \( T_{\text{ex}}(e^-) \approx 8000 \) to 10000 K for the 25 \( \text{HII} \) regions in M33. The following calculations are based on an assumed medium excitation temperature of \( T_{\text{ex}}=9000 \) K. Furthermore, it is assumed that the gas is optically thin. This results in critical densities of \( n_{\text{crit}}=48 \text{ cm}^{-3} \) for collisions of \( \text{C}^+ \) with electrons\(^{xxix}\). Variations of the used excitation temperatures of \( \sim 10\% \) lead to minor changes of the critical density. A variation of \( \pm 1000 \) K changes the critical density by \( \sim \pm 2 \text{ cm}^{-3} \). A critical density of \( 48 \text{ cm}^{-3} \) and an excitation temperature of \( T_{\text{ex}}=9000 \) K results in \( \text{C}^+ \) column densities of \( N(\text{C}^+)_{\text{HII}} \approx 1 \) to \( 2 \times 10^{16} \text{ cm}^{-2} \) in the ionised phase. All column densities are listed in Table 7.9. Variations of \( T_{\text{ex}} \pm 1000 \) K change the calculated \( \text{C}^+ \) column densities in the ionised phase by less than \( \lesssim 1\% \). These values are based on a beam filling factor of 1, \( \Phi_B=1 \), as \( \text{HII} \) gas commonly fills a large volume\(^{xxx}\).

The following section deals with the \( \text{C}^+ \) column densities in the neutral phase.
Table 7.7: Hydrogen volume densities derived from the ambient FUV field.

<table>
<thead>
<tr>
<th>Source</th>
<th>L_{TIR} (10^7 L_{sun})</th>
<th>G_{0}</th>
<th>\rho(H) (10^{-26} \text{g cm}^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMC01</td>
<td>5.9</td>
<td>2.4</td>
<td>1.0 \pm 0.3</td>
</tr>
<tr>
<td>GMC03</td>
<td>1.1</td>
<td>1.2</td>
<td>0.5 \pm 0.2</td>
</tr>
<tr>
<td>GMC02</td>
<td>1.4</td>
<td>1.0</td>
<td>0.3 \pm 0.1</td>
</tr>
<tr>
<td>BCLMP691</td>
<td>1.7</td>
<td>1.0</td>
<td>0.9 \pm 0.3</td>
</tr>
<tr>
<td>BCLMP302</td>
<td>2.0</td>
<td>1.1</td>
<td>0.8 \pm 0.2</td>
</tr>
<tr>
<td>GMCno06</td>
<td>3.1</td>
<td>1.5</td>
<td>0.7 \pm 0.2</td>
</tr>
</tbody>
</table>

Note: \( \rho(H) \) via thermal pressure for \( T = 100 \) K

The used \( L_{TIR} \) of the observed regions were obtained from Boquien et al. (2011), the far-infrared surface brightness \( L_{TIR} \) via Equation (4.19) (Braine et al. 2012). The used \( G_{0} \) of the observed regions were obtained from Habing et al. (2012).

The thermal pressure derived from Equation (4.21) calculated lower limits of the hydrogen column density for gas surface temperatures of 75, 100, and 200 K via Equation (4.21) calculated lower limits of the hydrogen column density for gas surface temperatures of 75, 100, and 200 K.
7.2.4.2 [C\text{II}] from the neutral phase

The C$^+$ column density and the [C\text{II}] emission from the neutral atomic gas phase can be estimated from the column density of neutral atomic carbon. In H$^0$ regions it can be assumed that the entire carbon is present in ionised form. In principle, the C$^+$ column density can be, therefore, estimated via the carbon-hydrogen abundance $X_C$. It needs to be considered, however, that not all carbon is gaseous in the neutral and molecular phase. A fraction of the carbon is depleted by dust grains. This depletion has to be considered when $N(C^+)$ is calculated. From Figure 3 in Garnett et al. (1999) I have calculated a hydrogen-carbon abundance of $X_C=8.5\times10^{-5}$ for a half solar metallicity of $Z=0.5$ Z$_\odot$. This value is $\sim$60% of the abundance found in the Milky Way of $X_{CMW}=1.4\times10^{-4}$ (Sofia et al. 1997). Approximately $\sim$40% (Cardelli et al. 1996) to $\sim$60% (Sofia et al. 1994; Snow & Witt 1996) of the total amount of carbon is present in this gas phase. Mookerjea et al. (2016) assumes a medium fraction of 50%. Along the same line of reasoning, the following calculations assume that 50% of the carbon is depleted on dust grains, which results in an adopted carbon-hydrogen abundance of $X_C^*=X_C/2=4.25\times10^{-5}$. Hence, the C$^+$ column density in the neutral phase is given by

$$N(C^+)_H^0 = X_C^* \times NH^0$$

Equation (7.5) gives C$^+$ column densities in the neutral phase of $N(C^+)_H^0 \sim 0.6$ to $1.2\times10^{-17}$ cm$^{-2}$. All these column densities are listed in Table 7.9.

The integrated [C\text{II}] emission in the neutral phase can be calculated by solving Equation (A.7) for $I([\text{CII}])_H^0$,

$$I([\text{CII}])_H^0 = \frac{N(C^+)_H^0 (1 - e^\tau)}{2.9 \times 10^{15} \left(1 + 0.5 e^{\Delta E / kT} \left(1 + \frac{A_{ul}[\text{CII}]}{C_{ul}[\text{H}^0] n[\text{HI}]} \right)\right)}$$

The optical depth of [C\text{II}] is unknown in the observed positions. Studies of [C\text{III}] and [C\text{I}] observations have found optical depths of $\tau \geq 1$ for [C\text{I}] in various GMCs (Stacey et al. 1991; Graf et al. 2012; Ossenkopf et al. 2013). Hence, a possible contribution of the optical depth is to consider, when $I([\text{CII}])_H^0$ is calculated. Therefore, the C$^+$ column densities are calculated for an assumed optical depth of $\tau=1$ and, in addition, for the optically thin limit. A lower limit for hydrogen volume density in the neutral phase $n(H^0)$ can be estimated by the hydrogen volume density at a PDR–surface for a given FUV-field $G_0$ and an assumed PDR surface gas temperatures via the thermal pressure (cf. Section 4.6, Equation xxix).

Equation (4.2) is used to calculate the critical densities, $n_{crit} = (1 - e^{-\tau}) / \tau \times A_{ul} / C_{ul}$. The de-excitation collision rate coefficient is calculated with Equation (A.10).

Compact H\text{II} regions are observed as well. For examples see the catalogue by (Wood & Churchwell 1989) and Garay & Lizano (1999) for a discussion of the physical properties in compact H\text{II} regions.

see Section 2.2.1 and Langer et al. 2014b).

I.a. a fraction of the dust particles consists

$N(H^0)$ is calculated in Section 7.2.1.

$\tau$ is calculated. From Figure 3 in Garnett et al. (1999) I have calculated a hydrogen-carbon abundance of $X_C=8.5\times10^{-5}$ for a half solar metallicity of $Z=0.5$ Z$_\odot$. This value is $\sim$60% of the abundance found in the Milky Way of $X_{CMW}=1.4\times10^{-4}$ (Sofia et al. 1997). Approximately $\sim$40% (Cardelli et al. 1996) to $\sim$60% (Sofia et al. 1994; Snow & Witt 1996) of the total amount of carbon is present in this gas phase. Mookerjea et al. (2016) assumes a medium fraction of 50%. Along the same line of reasoning, the following calculations assume that 50% of the carbon is depleted on dust grains, which results in an adopted carbon-hydrogen abundance of $X_C^*=X_C/2=4.25\times10^{-5}$. Hence, the C$^+$ column density in the neutral phase is given by

$$N(C^+)_H^0 = X_C^* \times NH^0$$

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The optical depth of [C\text{II}] is unknown in the observed positions. Studies of [C\text{III}] and [C\text{I}] observations have found optical depths of $\tau \geq 1$ for [C\text{I}] in various GMCs (Stacey et al. 1991; Graf et al. 2012; Ossenkopf et al. 2013). Hence, a possible contribution of the optical depth is to consider, when $I([\text{CII}])_H^0$ is calculated. Therefore, the C$^+$ column densities are calculated for an assumed optical depth of $\tau=1$ and, in addition, for the optically thin limit. A lower limit for hydrogen volume density in the neutral phase $n(H^0)$ can be estimated by the hydrogen volume density at a PDR–surface for a given FUV-field $G_0$ and an assumed PDR surface gas temperatures via the thermal pressure (cf. Section 4.6, Equation xxix).

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Compact H\text{II} regions are observed as well. For examples see the catalogue by (Wood & Churchwell 1989) and Garay & Lizano (1999) for a discussion of the physical properties in compact H\text{II} regions.

see Section 2.2.1 and Langer et al. 2014b).

I.a. a fraction of the dust particles consists

$N(H^0)$ is calculated in Section 7.2.1.
The distribution of carbon in M33

Figure 7.7: Simulations of the plane parallel homogeneous PDR-model by Kaufman, Wolfire & Hollenbach (2006). The colours show the $[\text{C} \text{II}]$ emission at the PDR surface as function of the FUV field and the hydrogen volume density. The black isolines show the corresponding PDR surface gas temperature between 50 to 300 K. The dashed gray lines mark the derived FUV field strengths in the discussed positions.

The strength of the ambient FUV field can be calculated from the far-infrared surface brightness $L_{\text{TIR}}$ via Equation (4.17) (e.g. Mookerjea et al. 2012; Buchbinder 2013). The $L_{\text{TIR}}$ in the individual positions were obtained from the dust continuum data observed by Spitzer and Herschel between 3.6$\mu$m to 500$\mu$m. The data was fitted by Boquien et al. (2011) by use of of the the Silicate-Graphite-PAH model from Draine & Li (2007) and as well as by Buchbinder (2013) (cf. Figure 7.6). The derived $G_0$ values are in the order 15-50 Habing units. The $L_{\text{TIR}}$ as well as the precise $G_0$ values for the individual positions are listed in Table 7.7. The gas temperatures and the $[\text{C} \text{II}]$ excitation temperature in the neutral phase can not be directly calculated from the observations Mookerjea et al. (2016) has assumed an excitation temperatures of 100 K for BCLMP302 and GMC01. The same temperature was assumed by Langer et al. (2014b) as mean gas temperature for the neutral phase in the Milky Way. Braine et al. (2012b) estimated $[\text{C} \text{II}]$ excitation temperatures between $\sim 90$ K based on 24$\mu$m and 70$\mu$m SPIRE data and $\sim 200$ K based on the plane parallel PDR-model by Kaufman et al. (1999) in BCLMP691. In order to consider the uncertain $[\text{C} \text{II}]$ excitation tem-

\[
\begin{align*}
n(H^+) &\approx \frac{8500 G_0 \frac{G_0}{G_H}}{(1+3.1 \left( \frac{G_0}{G_H} \right)^{0.365})} \times 1.1 T \left[ \text{cm}^{-3} \right] \\
G_0 &\approx 4\pi 0.5 L_{\text{TIR}}
\end{align*}
\]
temperatures, the $[\text{CII}]$ emission and $\text{C}^+$ column densities will be calculated for $T_{\text{ex}}([\text{CII}]) = 200$ K, 100 K and 75 K. Furthermore, it is assumed that the dust/PAH and gas metal abundances are equal, $Z_f^d = Z_f^g$. The fraction of dust compared the gas is lower in a low metallicity environment, and therefore the shielding of the radiation within the GMCs is less effective. Thus the gas ionisation rate, $\zeta_t$, in a low metallicity environment is higher compared to the Milky Way. Dalgarno (2006) discusses different models and observations of the gas ionisation rate. He concludes that the $\zeta_t$ range from $10^{-16}$ s$^{-1}$ to $10^{-15}$ s$^{-1}$ between the dense cores in molecular clouds to the inter-cloud medium (Dalgarno 2006). A gas ionisation rate of $\zeta_t = 3$ $\times$ $10^{-16}$ s$^{-1}$ is assumed in the following section (Geballe et al. 1999; 2007; Indriolo et al. 2007). Lower gas ionisation rates would result in lower $n$(H). Equation (4.21) gives $n$(H$^0$) between $n$(H$^0$)$\sim$50 to 100 cm$^{-3}$ for 200 K, $n$(H$^0$)$\sim$90 to 200 cm$^{-3}$ for a gas temperature of 100 K and $n$(H$^0$)$\sim$120 to 300 cm$^{-3}$ for 75 K. All volume densities for the individual positions and temperatures are listed in Table 7.7. The assumed gas temperatures are upper limits and the volume densities are lower limits as they represent the values on the surface of a PDR. Note that the derived lower limits for the H$^0$ volume densities are below the critical densities for collisions of C$^+$ with H$^0$, $n$(H$^0$)$\ll n_{\text{crit}}$(H$^0$). This might indicate that C$^+$ gas is not thermalised. Thus, the assumption that the gas surface temperature is equal to the excitation temperature is not stringent.

Simulations with the plane parallel homogeneous PDR-model by Kaufman, Wolfire & Hollenbach (2006) of the PDR surface support the derived H$^0$ volume densities of a few $10^2$ cm$^{-3}$ and gas temperatures between around 100 to 200 K for the calculated $G_0$ and the remaining $[\text{CII}]$ emission (cf. Fig. 7.7).

Equation (7.6) gives for $\tau=1 I([\text{CII}])_{\text{HI}}$ of $\sim 4$ to 12 K km/s for $T_{\text{ex}}=75$ K, $I([\text{CII}])_{\text{HI}}$ $\sim$2.5 to 8 K km/s for 100 K and $I([\text{CII}])_{\text{HI}}$ of $\sim 1$ to 3 K km/s for 200 K. The integrated $[\text{CII}]$ intensities at $\tau=75$ K correspond to $\sim$40 to 85% of the total $[\text{CII}]$ emission, while the $[\text{CII}]$ at 200 K correspond to 10 to 20% of the total $[\text{CII}]$ emission. In the optically thin limit, the contribution of the $[\text{CII}]$ emission is roughly higher by a factor of 1.5. The differences between $I([\text{CII}])_{\text{H0}}$ at different $T_{\text{ex}}$ have their origin in the high uncertainties of the temperature and the volume density. This has a significant impact on the $[\text{CII}]$ emission from the molecular phase as elaborated in the following section.

7.2.4.3 $[\text{CII}]$ from the molecular phase

The $[\text{CII}]$ emission from the molecular phase can be calculated via

$$I([\text{CII}])_{\text{H2}} = I([\text{CII}])_{\text{tot}} - I([\text{CII}])_{\text{HI}} - I([\text{CII}])_{\text{H0}}.$$  \hspace{1cm} (7.7)

This term gives the $[\text{CII}]$ emission that arises from the regions in which the molecular hydrogen is predominant. The derived $I([\text{CII}])_{\text{H2}}$ are listed in Table 7.8. $I([\text{CII}])_{\text{H2}}$ is a function of the assumed excitation temperature in the neutral phase as $I([\text{CII}])_{\text{H0}}$ depends on this temperature. The majority of the $[\text{CII}]$ emission arises from the neutral phase at low temperatures while the $I([\text{CII}])_{\text{H2}}$ is minimal. In the opposite case, the $I([\text{CII}])_{\text{H0}}$ are minimal and the $I([\text{CII}])_{\text{H2}}$ are maximal. Equation (7.7) gives a mean $[\text{CII}]$ emission from the molecular phase of $\sim 7$ for an excitation temperature of 75 K and an assumed $\tau=1$. On average, this is $\sim 40\%$ of the total $[\text{CII}]$
emission. For a $T_{\text{ex}}=200$ K, on average $\sim 70\%$ of the [CII] emission arises from the molecular phase with a mean [CII] emission of $I([\text{CII}])_{\text{H}_2}$ of $\sim 10$ K km/s. In the optical thin case, these $I([\text{CII}])_{\text{H}_2}$ are roughly lower by a factor of 2 for $T_{\text{ex}}=75$ K and remain almost constant for $T_{\text{ex}}=200$ K compared to a $\tau=1$.

I will now discuss the C$^+$ column densities in the molecular gas phase. The main obstruction for its determination is the unknown excitation temperature in the atomic and molecular phases. It can be assumed, that the temperatures of the molecular gas phase are lower than those of the neutral phase. The upper limit of the gas temperature in the molecular phase is thus given by the temperature of the neutral phase. Its lower limit is given by the gas temperature of the H$_2$ traced by C$^0$. In the following, it is assumed that the gas temperature for H$_2$ traced by C$^+$ is equal to the medium temperature between these upper and lower limits. As gas temperature for the H$_2$ traced by C$^0$, I assume 75 K. Furthermore, it is assumed that the derived gas temperature is equal to the excitation temperature. The $T_{\text{ex}}([\text{CII}])_{\text{H}_2}$ is thus given by $T_{\text{ex}}([\text{CII}])_{\text{H}_2}=(T_{\text{ex}}([\text{CII}])_{\text{H}_2}+75$K$)/2$ ($T_{\text{ex}}([\text{CII}])_{\text{H}_2}=75$ K, 88 K and 138 K).

The density within the molecular phase is higher than in the neutral phase. Therefore, it is assumed that the optical depth is $\tau=1$ and that $n(H_2)=n_{\text{crit}}(H_2)$.

The critical densities for C$^+$ in the molecular phase $n_{\text{crit}}(H_2)$ are of the order of 2 to 3 $\times 10^3$ cm$^{-3}$ for the discussed temperatures. They were calculated by use of the deexcitation rates for collisions of C$^+$ with H$_2$ (Equation (A.9)).

The column density of C$^+$ in the molecular phase is calculated with Equation (A.7). All derived $N(C^+)_\text{H}_2$ are listed in Table 7.9. The $N(C^+)_\text{H}_2$ have values between $\sim 7$ cm$^{-2}$ for $\tau \to 0$ and $T_{\text{ex}}([\text{CII}])_{\text{H}_2}=75$ K to $\sim 25$ cm$^{-2}$ for $\tau=1$ and $T_{\text{ex}}([\text{CII}])_{\text{H}_2}=138$ K, which is between $\sim 20\%$ and $\sim 35\%$ of the total calculated C$^+$ column density. The fraction of C$^+$ ions in the molecular phase increases for high excitation temperatures. This can be explained by the method, chosen to calculate $N(C^+)_\text{H}_2$ (cf. Section 7.2.4.2). $N(C^+)_\text{H}_2$ is constant for all temperatures- therefore, $I([\text{CII}])_{\text{H}_2}$ lowers towards higher temperatures in the neutral phase. The remaining [CII] emission arises from the molecular phase. Its intensity increases with the an increasing temperature. Therefore, $N(C^+)_\text{H}_2$ and $N(C^+)_\text{tot}$ are increased towards higher temperatures.

The $N(C^+)_\text{H}_2$ and $N(C^+)_\text{H}_2$ in the position GMCn006 A needs to be taken with caution. The peak of the H$\alpha$ spectra in GMCn006 (Fig 7.3) is located almost in the middle between the CO and [CII] peaks of the clouds GMCn006 A and B, while [CII] is only associated with GMCn006 A. Therefore, the calculated C$^+$ column densities are, at least partially, based on the H$\alpha$ emission that is not associated with the [CII] emission.

xxxvii see Section 2.2.1
xxxviii The critical densities are $n_{\text{crit}}(H_2)\sim 2.2 \times 10^3$ cm$^{-3}$ for $T([\text{CII}])_{\text{H}_2}=75$ K, $\sim 2.5 \times 10^3$ cm$^{-3}$ for $T([\text{CII}])_{\text{H}_2}=88$ K and $\sim 3.0 \times 10^3$ cm$^{-3}$ for $T([\text{CII}])_{\text{H}_2}=138$ K
xxxix $C_{\text{tot}}(H_2) = (4.55 + 1.6 \times e^{100K/T}) \times 10^{-10}$ cm$^3$s$^{-1}$
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<tr>
<th></th>
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<th>(\text{H}^0) phase</th>
<th>(\text{H}_2) phase</th>
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<td>17</td>
<td>7.8 ± 0.8</td>
</tr>
<tr>
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<td>6.9 ± 0.7</td>
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<tr>
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<td>6.0 ± 0.7</td>
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<td>12.0 ± 1.2</td>
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<tr>
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<tr>
<td>Mean</td>
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<td>23±10</td>
<td>4.7 ± 1.7</td>
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<td>Mean</td>
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Table 7.8: [CII] emission in the three gas phases for different temperatures in the neutral phase and molecular phase for optically thin case and an optical depth of \(\tau = 1\).
in GMCno06 A. The calculated \(N(C^+)_H^0\) in GMCno06 A are thus upper limits and the \(N(C^+)_H^2\) are lower limits.

7.2.4.4 Conclusion to C\(^+\) in the different gas phases

The previous sections have dealt with the C\(^+\) distribution in the ionised, neutral and molecular phase for different excitation temperatures and optical depths. The derived \([\text{CII}]\) intensities for the different gas phases are listed in Table 7.8. The C\(^+\) column densities are listed in Table 7.9.

The sum of the C\(^+\) column densities over all the phases gives the total C\(^+\) column density, \(N(C^+)_\text{tot}\), (cf. Equation (7.2)xli). The beam averaged total mean C\(^+\) column density varies between \(\sim2 \times 10^{17}\) cm\(^{-2}\) for gas temperature of 75 K in the optically thin limit and \(\sim3.5 \times 10^{17}\) cm\(^{-2}\) for high temperatures and \(\tau=1\). Within the individual GMCs, the total column density varies around a factor \(\sim2\) to 3, in which GMC01 has in general the highest \(N(C^+)_\text{tot}\) and BCLMP091 has the lowest the lowest \(N(C^+)_\text{tot}\).

Roughly 1/4 of the \([\text{CII}]\) emission arises from the ionised phase, regardless of the ambient gas temperature in the neutral and the molecular phase. The fraction of \(I([\text{CII}])\) from the neutral and molecular phase depends on the assumed gas temperatures and the optical depth. The \([\text{CII}]\) emission from the molecular phase is higher for higher gas temperatures, while the contribution from the neutral phase is lower. In general, the contribution of \([\text{CII}]\) emission from the molecular phase is higher compared to the emission from the neutral and ionised phase. The derived fractions of the \([\text{CII}]\) emission are similar to the fractions found in other studies. Pérez-Beaupuits et al. (2015) derived relative fractions of the \([\text{CII}]\) emission of \(\sim39\%\), 18\% and 46\% for the ionised, neutral and molecular phase in M17. Pineda et al. (2013) found out that the majority of the \([\text{CII}]\) emission arises from the molecular phase (\(\sim50\%\)) followed by the ionised and neutral phase where \(\sim30\%\) and 20\% of the \([\text{CII}]\) emission arises.

The main obstruction for a precise determination of the \(N(C^+)\) is an unknown excitation temperature in the different gas phases. Tracer for these temperatures are required. A possible tracer is the linear molecule CH\(^+\). This molecule can be used to estimate the excitation temperature of \([\text{CII}]\) in the neutral atomic phasexlii (Guacinski, Krogulec & Krelowski 2007; Menten et al. 2011). Unfortunately a bright atmospheric ozone line harms the observation of \(^{12}\text{CH}^+\) from the groundxlii. Therefore this line can be only observed from space. \(^{13}\text{CH}^+\) can be in general observed from the ground based observatoriesxliii, but this line is relatively faint (Menten et al. 2011).

\[N(C^+)_{\text{tot}} = N(C^+_H^0) + N(C^+_H^2) + N(C^+_H^2)\]

xli CH\(^+\) is commonly associated with the reaction C\(^+\) + H\(_2\) → CH\(^+\) + H. Therefore it is expected to arise in the neutral atomic phase.

xlii \(^{12}\text{CH}^+\) has rotational transitions at \(\nu=835.1\) (\(J=1-0\)), 1609.3 GHz (\(J=2-1\)), 2501.4 GHz (\(J=3-2\))...

xliii \(^{13}\text{CH}^+\) is observed with the APEX telescope (Menten et al. 2011)
Table 7.9: C\(^+\) column densities in the three gas phases and their relative fraction for excitation different temperatures in the optically thin case ($\tau=0$) as well as for a optical depth $\tau=1$ in the neutral and molecular phase.

The column densities in the positions GMCno06 A are based on the [C\textsc{ii}]$_{\text{H}_2}$ emission calculated from the total H\textsc{i} emission in GMCno06.
Table 7.10: Used $C^+$, $C^0$ and CO column densities for $(N(C)\text{H}_2$ in the Cases I, II, III and IV. The specific column densities are defined by their excitation temperature. The used column densities are listed in the upper and lower columns of the tables 7.9($N(C)$), Table 7.6 ($N(C^+)$) and Table 7.5 ($N(CO)$).

$^*$ The $T_{\text{ex}} \approx 6\text{ K}$ represent the mean excitation temperatures of the CO column densities in the upper half of Table 7.5.

7.2.5 TOTAL CARBON COLUMN DENSITIES IN THE MOLECULAR PHASE

The following section aims to determine the total contribution of carbon in the molecular phase. The total hydrogen column densities are calculated and discussed in the following section.

The total carbon column density in the molecular phase is given by the sum of the column densities of CO, $C^0$ and $C^+$ in the $\text{H}_2$ phase in the observed positions

$$N(C)\text{H}_2 = N(C^+)\text{H}_2 + N(C^0) + N(CO) \quad (7.8)$$

It was assumed that all CO and $C^0$ are located in the molecular phase.

The CO, $C^0$ and $C^+$ column densities are dependent on the assumptions made for the calculations. It is hard to get a precise estimate of the parameters needed to calculate the different carbon column densities as shown in the previous sections. Different total carbon column densities can be calculated for the different assumptions.

Different possible total carbon column densities will be discussed in the following. This is necessary to reflect and study the different possible carbon compositions. The four cases are chosen to study the maximal and minimal $N(C)\text{H}_2$ as well as to study the upper and lower limits the CO dark $\text{H}_2$ fraction.

CASE I: In this case, the total carbon column density is composed of the $C^+$ and $C^0$ column densities which show the highest values in Table 7.9 and 7.6. These are the $C^+$ column densities $N(C^+)\text{H}_2$ calculated for $T_{\text{ex}}([\text{C}^+])\text{H}_2= 200\text{K}$ and $T_{\text{ex}}([\text{C}^+])\text{H}_2=138\text{ K}$ for an optical depth $\tau=1$ (Table 7.9) and the $N(C^0)$ calculated for a $T_{\text{ex}}=75\text{ K}$. I choose the CO column densities that were calculated for $T_{\text{ex}}\sim 6\text{ K}$ (Approach I Table 7.5).

CASE II: In this case, the $N(C)\text{H}_2$ is composed of the lower $C^+$ and $C^0$ column densities. The CO column densities are calculated for
Table 7.11: The total carbon column densities in the different discussed cases. Mean: Average over all positions
Mean*: Average over positions in which [C\textsubscript{i}](1–0) was detected (all positions but GMC91)
Mean**: Average over positions in which [C\textsubscript{i}](1–0) and [C\textsubscript{ii}] were detected (all positions but GMC91 and GMCno06 B)

The different column densities used for the different cases are illustrated in Table 7.10. The total carbon column densities calculated for the different cases are summarised in Table 7.11. The total \( N(\text{C}) \text{H}_2 \) have mean values between \( \sim 18 \times 10^{16} \text{cm}^{-2} \) (Case II and IV) and \( \sim 30 \times 10^{16} \text{cm}^{-2} \) (Case I and III).

The fraction of the column densities of the different carbon species relative to the total \( N(\text{C}) \text{H}_2 \) are summarised in Table 7.12.

The mean fraction of \( N(\text{C}^+) \) to the \( N(\text{C}) \text{H}_2 \) varies between \( \sim 69\% \) (CASE I). These values refer to the positions in which \( \text{C}^+ \) was detected, the GMC91 and BCLMP691 B are excluded. The fraction of the mean \( \text{C}^0 \) fraction varies between \( \sim 8\% \) (Case IV) and \( \sim 5\% \) (Case II). The mean fraction of \( N(\text{CO}) \) to the total \( N(\text{C}) \text{H}_2 \) varies between \( \sim 24\% \) (Case I) and \( \sim 62\% \) (Case II).

The relative fraction of \( \text{C}^+ \) and CO to the total carbon column densities in the cases I and III are similar to the ones found in other studies.

For example, the study of Okada et al. (2015) found out that \( \sim 20\% \) to \( 25\% \) of the carbon is CO and \( \sim 60\% \) to \( 70\% \) of the carbon is \( \text{C}^+ \) in the
the distribution of carbon in M33. The fraction of C$^0$ varies between $\sim$10 and 20%. Note that this study does not consider any [CII] emission from the neutral and ionised phase.

These $N$(C)$_{H_2}$ allow the calculation of the column densities of H$_2$ and, thus, of the total hydrogen column density as described in the following section.

### 7.2.6 Molecular Hydrogen Column Densities

The column density of molecular hydrogen can be estimated from the amount of carbon in the molecular phase. Each carbon species traces a particular fraction of the molecular gas. Molecular hydrogen consists of two protons. Therefore, total molecular hydrogen column densities can be calculated via

$$N(H_2)_{\text{tot}} = N(H_2)_{C^+} + N(H_2)_{C^0} + N(H_2)_{CO}\quad (7.9)$$

$$= \frac{1}{2} \frac{N(C^+)_{H_2} + N(C^0) + N(CO)}{X_C^*} \quad (7.10)$$

These calculations assume that half of the carbon in the molecular zones is depleted on dust grains, $X_C^*=X_C/2 = 4.25 \times 10^{-5}$ (cf. Section 7.2.4.4).

The derived beam average H$_2$ column densities have mean values of $\sim 4 \times 10^{21}$ cm$^{-2}$ (Case II and IV) to $\sim 7 \times 10^{21}$ cm$^{-2}$ (Case I and III). The $N$(H$_2$) of the different cases are summarised in Table 7.13. These molecular hydrogen column densities were calculated from the beam average carbon column densities and were not divided by the uncertain beam filling factors. Hence, these column densities are in fact lower limits.

The fraction of H$_2$ traced by CO, C$^0$ and C$^+$ is equal to the relative distribution of the carbon species to the total amount of carbon (Table 7.12). C$^+$ traces $\sim 1/3$ (cases II and IV) to 2/3 (cases I and II) of all molecular hydrogen. Roughly $\sim 1/4$–$1/3$ (case II and IV) to 3/5 (case I and III) of the H$_2$ is traced by CO. On average, C$^0$ traces less than 1/10 of the H$_2$.

Now, it is possible to calculate the total hydrogen column density (Section 7.2.7), the fraction of CO dark H$_2$ (Section 7.2.8) and the that one molecular hydrogen to the total amount of hydrogen (Section 7.2.9).

### 7.2.7 Total Hydrogen Column Densities

The total hydrogen column density is given by the sum of the hydrogen column densities of the ionised, neutral and molecular phase.

$$N(H)_{\text{tot}} = N(H^+) + N(H^0) + 2 \times N(H_2)_{\text{tot}}^{xlv} \quad (7.11)$$

The ionised phase contains no dust grains in a first approximation (e.g. Mookerjea et al. 2016). Therefore, it can be assumed that all the carbon is gaseous in this phase. Hence, the hydrogen column density in the ionised phase can be estimated via $N(H^+)=N(C^+)_{H^+}/X_C$. When $N(H)_{\text{tot}}$ is

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$xlv$ Molecular hydrogen consists of 2 protons. Therefore, the molecular hydrogen column density is multiplied by a factor two
<table>
<thead>
<tr>
<th></th>
<th>Case I</th>
<th>Case II</th>
<th>Case III</th>
<th>Case IV</th>
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<tr>
<td>BCLMP69I</td>
<td>64±17</td>
<td>6±2</td>
<td>20±8</td>
<td>49±12</td>
</tr>
<tr>
<td>GMC91</td>
<td>&lt;8</td>
<td>&lt;2</td>
<td>&lt;100±24</td>
<td>&lt;100±28</td>
</tr>
<tr>
<td>BCLMP302</td>
<td>70±18</td>
<td>9±1</td>
<td>31±12</td>
<td>72±18</td>
</tr>
<tr>
<td>GMC01 Peak</td>
<td>71±17</td>
<td>4±1</td>
<td>25±17</td>
<td>33±9</td>
</tr>
<tr>
<td>GMC01 Flank</td>
<td>62±15</td>
<td>7±2</td>
<td>31±8</td>
<td>50±12</td>
</tr>
<tr>
<td>GMCno06 A</td>
<td>76±20</td>
<td>9±3</td>
<td>3±4</td>
<td>49±12</td>
</tr>
<tr>
<td>GMCno06 B</td>
<td>&lt;57</td>
<td>38±24</td>
<td>62±37</td>
<td>90±31</td>
</tr>
</tbody>
</table>

<p>| | | | | |</p>
<table>
<thead>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>49±31</td>
<td>10±12</td>
<td>23±23</td>
<td>72±23</td>
</tr>
<tr>
<td>Mean*</td>
<td>57±26</td>
<td>12±12</td>
<td>31±15</td>
<td>67±21</td>
</tr>
<tr>
<td>Mean**</td>
<td>69±5</td>
<td>7±2</td>
<td>24±6</td>
<td>62±21</td>
</tr>
</tbody>
</table>

Table 7.12: The total carbon column densities in the different cases discussed here. Mean: Average over all positions
Mean*: Average over positions in which [C\text{i}](1–0) was detected (all positions but GMC91)
Mean**: Average over positions in which [C\text{i}](1–0) and [C\text{ii}] were detected (all positions but GMC91 and GMCno06 B)
calculated, \( N(H^+) \) is commonly neglected (e.g. Langer et al. 2014b) as it participates \( \lesssim 5\% \) to the \( N(H)_{\text{tot}} \) (cf. Table 7.13).

The hydrogen column densities for the ionised, neutral and molecular phase as well as the total hydrogen column density \( N(H) \) in the different cases are listed in Table 7.13. The total hydrogen column densities have mean values of \( \sim 15 \times 10^{21} \text{ cm}^{-2} \) in the cases I and III. The mean values of the cases II and IV are roughly 1/3 lower compared to the cases I and II with mean values of \( \sim 10 \times 10^{21} \text{ cm}^{-2} \). GMC01 has the highest hydrogen column density of all discussed clouds, GMCno06 B has the lowest \( N(H)_{\text{tot}}. \)

7.2.8 CO dark \( \text{H}_2 \) in M33

The previous calculations allow the estimation of the CO-dark \( \text{H}_2 \) gas fraction, \( f(DG) \), in M33. The derived \( f(DG) \) will be compared to the results from the Milky Way and to theoretical predictions by Wolfire, Hollenbach & McKee (2010).

CO dark \( \text{H}_2 \) gas means all gas that is not directly associated with CO emission, according to the definition of Leroy et al. (2011). The column density of CO dark \( \text{H}_2 \) can be calculated from \( N(H^2) \) that is calculated from \( C_0 \) and \( C^+ \) column densities.

\[
N(DG) = N(H^2)_{C^+} + N(H^2)_{C_0} \quad (7.12)
\]

The fraction of CO dark \( \text{H}_2 \) gas, \( f(DG) \), is given by the ratio of \( N(DG) \) to the total hydrogen column density\(^{xlv}\),

\[
f(DG) = \frac{N(DG)}{N(H^2)_{\text{tot}}} \quad (7.13)
\]

As the hydrogen column densities are directly calculated from the specific carbon column densities Equation (7.13) can be expressed by

\[
f(DG) = \frac{N(C^+)_{\text{H}_2} + N(C^0)}{N(C^+)_{\text{H}_2} + N(C^0) + N(CO)} \quad (7.14)
\]

The fractions of CO dark \( \text{H}_2 \) for the different cases are summarised in Table 7.14. The calculated mean fraction varies between \( \sim 40\% \) (case IV) and \( \sim 80\% \) (case I). The largest share of the CO dark \( \text{H}_2 \) fraction is traced by \([\text{CII}] \) emission (\( \sim 80 \) to 90 \%) , while only a minor fraction is traced by \([\text{CI}](1-0) \) (\( \sim 10 \) to 20 \%). The position GMCno06 B is an exception as all CO dark \( \text{H}_2 \) gas is traced by the \([\text{CI}](1-0) \) in this position.

The fraction of CO dark \( \text{H}_2 \) in the Milky Way is derived by Langer et al. (2014b) based \([\text{CII}] \) observations carried out with Herschel/HIFI. The \( C^0 \) transitions are not considered in this study. They derived a mean

---

\(^{xlv}\) I use the same definition for \( f(DG) \) as given by equation (1) in Wolfire, Hollenbach & McKee (2010). This definition defines the relative fraction of CO dark \( \text{H}_2 \) to the total amount of molecular hydrogen. It does not give the fraction of CO dark \( \text{H}_2 \) to the total amount of hydrogen, which includes the contribution of \( H^0 \) as well (cf. Section 7.2.9).
<table>
<thead>
<tr>
<th></th>
<th>(N(\text{H}^0))</th>
<th>(N(\text{H}_2))</th>
<th>(N(\text{H}^0))</th>
<th>(N(\text{H}_2))</th>
<th>(N(\text{H}))</th>
<th>(N(\text{H}))</th>
<th>(N(\text{H}))</th>
<th>(N(\text{H}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(10^{21}) cm(^{-2})</td>
<td>(10^{21}) cm(^{-2})</td>
<td>(10^{21}) cm(^{-2})</td>
<td>(10^{21}) cm(^{-2})</td>
<td>(10^{21}) cm(^{-2})</td>
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<td>(10^{21}) cm(^{-2})</td>
<td>(10^{21}) cm(^{-2})</td>
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<tr>
<td>BCLMP691</td>
<td>0.24±0.01</td>
<td>1.97±0.05</td>
<td>4.5±1.0</td>
<td>3.5±0.5</td>
<td>5.9±1.0</td>
<td>2.2±0.5</td>
<td>11.1±2.1</td>
<td>9.1±1.0</td>
</tr>
<tr>
<td>GMC91</td>
<td>--</td>
<td>2.83±0.05</td>
<td>5.7±0.14</td>
<td>3.4±0.6</td>
<td>3.4±1.4</td>
<td>5.7±1.4</td>
<td>14.3±2.8</td>
<td>9.6±1.3</td>
</tr>
<tr>
<td>BCLMP302</td>
<td>0.18±0.01</td>
<td>2.77±0.05</td>
<td>6.3±1.5</td>
<td>2.0±0.3</td>
<td>6.1±1.5</td>
<td>2.2±0.5</td>
<td>15.3±2.9</td>
<td>6.7±0.8</td>
</tr>
<tr>
<td>GMC01 Peak</td>
<td>0.24±0.01</td>
<td>1.67±0.06</td>
<td>13.6±3.1</td>
<td>10.6±2.2</td>
<td>13.7±3.1</td>
<td>10.5±2.3</td>
<td>28.8±6.2</td>
<td>22.9±4.4</td>
</tr>
<tr>
<td>GMC01 Flank</td>
<td>0.24±0.01</td>
<td>1.45±0.05</td>
<td>8.6±1.8</td>
<td>4.3±0.8</td>
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<td>4.9±0.9</td>
<td>18.7±3.7</td>
<td>10.1±1.6</td>
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<tr>
<td>GMCno06 A</td>
<td>0.11±0.01</td>
<td>1.69±0.15</td>
<td>7.5±1.9</td>
<td>5.7±0.7</td>
<td>11.6±1.9</td>
<td>1.6±0.4</td>
<td>16.7±3.8</td>
<td>13.1±1.3</td>
</tr>
<tr>
<td>GMCno06 B</td>
<td>0.11±0.01</td>
<td>1.69±0.15</td>
<td>0.8±0.5</td>
<td>2.4±0.5</td>
<td>1.5±0.5</td>
<td>0.6±0.5</td>
<td>3.3±1.0</td>
<td>4.5±1.0</td>
</tr>
<tr>
<td>Mean</td>
<td>0.16±0.08</td>
<td>2.0±0.5</td>
<td>7.2±4.0</td>
<td>4.4±2.9</td>
<td>7.2±4.0</td>
<td>3.9±3.2</td>
<td>15.4±7.2</td>
<td>10.8±5.5</td>
</tr>
<tr>
<td>Mean(^\ast)</td>
<td>0.19±0.06</td>
<td>1.9±0.4</td>
<td>7.8±4.0</td>
<td>4.6±3.1</td>
<td>7.8±4.0</td>
<td>3.7±3.3</td>
<td>15.6±7.7</td>
<td>11.0±5.9</td>
</tr>
<tr>
<td>Mean(^{\ast\ast})</td>
<td>0.20±0.05</td>
<td>1.9±0.5</td>
<td>9.1±3.1</td>
<td>5.2±3.0</td>
<td>9.2±3.1</td>
<td>4.3±3.3</td>
<td>18.1±5.9</td>
<td>12.4±5.7</td>
</tr>
</tbody>
</table>

Table 7.13: Ionised, neutral, molecular and total hydrogen column densities in the different cases. The mean values show the average over all positions. Mean\(^\ast\) is the average over all positions in which [C\(\text{i}\)](1–0) was observed (all positions but GMC91) Mean\(^{\ast\ast}\) is the mean value over all positions in which [C\(\text{ii}\)] was detected (all positions but GMC91 and GMCno06 B)
Relative fraction of CO dark H$_2$, f(DG)

<table>
<thead>
<tr>
<th>Case</th>
<th>Case I</th>
<th>Case II</th>
<th>Case III</th>
<th>Case IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCLMP091</td>
<td>0.70±0.10</td>
<td>0.23±0.09</td>
<td>0.54±0.08</td>
<td>0.37±0.11</td>
</tr>
<tr>
<td>GMC91</td>
<td>&lt;0.08</td>
<td>0.013</td>
<td>&lt;0.14</td>
<td>&lt;0.08</td>
</tr>
<tr>
<td>BCLMP302</td>
<td>0.79±0.11</td>
<td>0.41±0.12</td>
<td>0.81±0.12</td>
<td>0.38±0.11</td>
</tr>
<tr>
<td>GMC01 Peak</td>
<td>0.75±0.10</td>
<td>0.67±0.10</td>
<td>0.74±0.10</td>
<td>0.68±0.10</td>
</tr>
<tr>
<td>GMC01 Flank</td>
<td>0.69±0.10</td>
<td>0.50±0.10</td>
<td>0.73±0.10</td>
<td>0.44±0.09</td>
</tr>
<tr>
<td>GMCno06 A</td>
<td>0.85±0.11</td>
<td>0.08±0.07</td>
<td>0.55±0.08</td>
<td>0.28±0.16</td>
</tr>
<tr>
<td>GMCno06 B</td>
<td>0.38±0.59</td>
<td>0.10±0.36</td>
<td>0.19±0.30</td>
<td>0.22±0.75</td>
</tr>
<tr>
<td>Mean*</td>
<td>0.69±0.16</td>
<td>0.43±0.25</td>
<td>0.59±0.21</td>
<td>0.36±0.12</td>
</tr>
<tr>
<td>Mean**</td>
<td>0.77±0.06</td>
<td>0.51±0.21</td>
<td>0.67±0.12</td>
<td>0.40±0.10</td>
</tr>
</tbody>
</table>

Table 7.14: Fraction of CO dark H$_2$ relative to the total H$_2$ column densities. For GMC01 I applied the mean value of both positions.

Mean* represents the mean value of all positions in which [C$^\text{ii}$](1–0) was detected, i.a all positions but GMC91.

Mean** represents the mean value of the positions in which [C$^\text{ii}$] emission was observed. GMC91 and GMCno06 B are not considered in this case.

\( \text{f(DG)} = \sim 20\% \) for dense molecular clouds\[\text{xlvi}\] in the Milky Way. Averaged over all sources with [C$^\text{ii}$] emission (sources with CO and no CO) the \( \text{f(DG)} \) is 44%±28% in the Milky Way (Langer et al. 2014b). The \( \text{f(DG)} \) in M33 are calculated for clouds that show an emission of $^{13}$CO(1–0) and $^{12}$CO(1–0) as well. The derived \( \text{f(DG)} \) in M33 are \( \sim 2 \) to 4 times higher compared to the mean values in dense molecular clouds in Milky Way. They are even one to two times higher compared to the mean \( \text{f(DG)} \) in the Milky Way. The observations are consistent with the expectations. Due to metallicity effects (as for example an increased photodissociation rate of CO at low \( Z \)), it is expected that the \( \text{f(DG)} \) is higher in M33 compared to the Milky Way.\[\text{xlvii}\].

In the following, I will compare the derived \( \text{f(DG)} \) with the predictions of the PDR model of Wolfire, Hollenbach & McKee (2010). This model estimated the fraction of CO dark H$_2$ as a function of the metallicity and the total hydrogen column density via Equation (2.1)\[\text{xlviii}\].

Figure 7.8 shows the \( \text{f(DG)} \) discussed here as a function of the specific total hydrogen column density. The predictions by the Wolfire, Hollenbach & McKee (2010)–model are superimposed. The \( \text{f(DG)}_{\text{W10}} \) are plotted for the same parameters as used in Langer et al. (2014b) for the sake of a better comparability. These parameters are: \( k_\text{e}=2.0 \) and \( \Delta A_{V,\text{DG}}=2.0 \) for \( Z=0.5Z_\odot \), and \( k_\text{e}=0.8 \), \( \Delta A_{V,\text{DG}}=0.8 \) for \( Z=Z_\odot \). They give a \( \text{f(DG)}_{\text{W10}} \) of \( \sim 0.95 \) to 0.5 for a hydrogen column density between \( N(\text{H})_{\text{tot}}=0.1 \) and \( 3 \times 10^{22} \text{ cm}^{-2} \) in the case of \( Z=0.5Z_\odot \) and \( \text{f(DG)}_{\text{W10}} \) of \( \sim 0.9 \) to 0.15 for \( Z=Z_\odot \).

The CO dark H$_2$ fraction in M33 meets the expectations of the model by Wolfire, Hollenbach & McKee (2010) for \( Z=0.5Z_\odot \) in the cases I and III. A slope of \( \text{f(DG)}/N(\text{H})_{\text{tot}} \) towards higher \( N(\text{H})_{\text{tot}} \) could not be observed but can also not be excluded within the uncertainties. The mean fractions

\[\text{xlvi}\] Dense molecular clouds were defined as clouds that show $^{13}$CO(1–0) and $^{12}$CO(1–0) emission (Langer et al. 2014b)

\[\text{xlvii}\] See Section 2.2.3

\[\text{xlviii}\] \( \text{f(DG)}_{\text{W10}} = 1 - \left[ 1 + \left( \frac{k_\text{e}-1}{3k_\text{e}} \right) \frac{0.76 \Delta A_{V,\text{DG}}}{Z'N_{22}(\text{H})} \right]^{\frac{3-k_\text{e}}{k_\text{e}-1}} \)
Figure 7.8: Relative fraction of CO dark H\textsubscript{2} \((f(DG))\) as function of \(N(H)\)\textsubscript{tot} in the studied Case I (black •), Case II (■) Case III (blue ♦) and Case IV (▲). The lines show the CO dark H\textsubscript{2} fractions calculated with Equation (2.1) for a \(k_{\text{g}}=2.5\) and \(A_{V,DG}=2.5\) for a metallicity of \(Z=0.5Z_\odot\) (cyan—) and \(Z=Z_\odot\) (violet—).
remains almost constant at $f(DG) \sim 80\%$ and 70\% along $N(H)_{\text{tot}}$ in these two cases.

The calculated CO dark $H_2$ fractions are below the expectation for $Z=0.5Z_\odot$ in the cases II and IV. They are roughly in the order of the expectations for $Z=Z_\odot$. The slope of $f(DG)(N(H)_{\text{tot}})$ increases towards higher hydrogen column densities which is counter-intuitive. Lower $f(DG)$ are expected towards higher $N(H)_{\text{tot}}$ as the size of the CO zone shrinks towards lower clump sizes, while the widths of the $C^+$ and $C^0$ stay almost constant\textsuperscript{xlix}.

The comparison indicates that a $[CII]$ excitation temperatures of 75 K (Cases II and IV) does not represent the real conditions in the positions discussed here. $[CII]$ excitation temperatures of 200 K (Cases I and III) give similar $f(DG)$ as expected by Wolfire, Hollenbach & McKee (2010). Therefore these $T_{\text{ex}}([CII])$ might be a better estimation for the clouds in M33. In this case, the fraction of CO dark $H_2$ increases towards lower metallicities. Furthermore, the study indicates that the major fraction of CO dark $H_2$ in M33, $\sim 90\%$, is traced by $C^+$, while $C^0$ traces only a minor fraction. These values relate to the total emission. The spectral distribution of CO dark $H_2$ will be discussed in Section 7.5.2.

### 7.2.9 Fraction of Molecular Gas in M33

The fraction of the molecular hydrogen is defined via

$$f(H_2) = \frac{2 \times N(H_2)}{2 \times N(H_2)_{\text{tot}} + N(H^0)}$$

(7.15)

$$= 1 - \frac{N(H^0)}{N(H)_{\text{tot}}}$$

(7.16)

The $H_2$ fractions are listed in table 7.15. The calculations show that the major fraction of the hydrogen in the positions discussed here is molecular. The $H_2$ fraction is on average $\gtrsim 70\%$ in all cases with the lowest $f(H_2)$ (case IV, $f(H_2) \sim 0.7$). The highest $f(H_2)$ are derived for the cases I and III with an average $f(H_2) \sim 0.90$ over the positions in which $[CII]$ was detected. The $N(H^0)$ are roughly constant for the all clouds\textsuperscript{1}. Therefore, the total hydrogen column densities and, hence, the fraction of $H_2$ are directly correlated to the total molecular hydrogen column densities (c.f Equation (7.16)). Hence, the position GMC01 peak has the highest $f(H_2)$ in all cases ($f(H_2) \sim 0.95$), while the position GMCno06 B has the lowest $f(H_2)$ of $\sim 0.5$ to 0.65.

\textsuperscript{xlix} For further details see Section 2.2.3.

\textsuperscript{1} see Section 7.2.1
### 7.3 H$_2$ Conversion Factors

H$_2$–CO conversion factors are a common tool to estimate the H$_2$ column density from the observed integrated $^{12}$CO line intensities. H$_2$–[Cl](1–0) conversion factor are proposed as an alternative for the H$_2$–CO conversion factors (Offner et al. 2014; Lo et al. 2014; Glover et al. 2015; Glover & Clark 2015). This section aims to calculate H$_2$–CO(2–1) and H$_2$–[Cl](1–0) conversion factors ($X_{CO(2-1)}$ and $X_{Cl}$) based on the derived total molecular hydrogen column densities and the observed integrated line intensities. H$_2$–[Cl] conversion factors based on the total integrated [Cl] emission and the $I([Cl])_{H_2}$ from the molecular phase will be also be calculated (Section 7.3.1). These conversion factors will be compared to established conversion factors as well as to theoretical predictions (Section 7.3.2). I would like to refer to Section 4.8 for the the explanation of the theoretical background of the H$_2$ conversion factors.

#### 7.3.1 H$_2$ Conversion Factors of the Observed Integrated Line Intensities of CO(2–1), [Cl](1–0) and [CII]

The H$_2$–line conversion factor can be calculated from the derived total molecular hydrogen column density and the integrated line intensity via\(^{li}\)

$$X_{line} = \frac{N(H_2)_{tot}}{I(line)} \quad (7.17)$$

I also consider the upper and lower H$_2$ column densities of the discussed cases in the observed clouds, to determine the upper and lower limits of the conversion factors.

\(^{li}\) Derived from Equation (4.24); $N(H_2) := X_{CO} \times I(CO(1-0))$
The $H_2$–CO(2–1) conversion factors vary between $X_{CO(2−1)}=1$ and $20 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1}$ with a mean value of $\langle X_{CO(2−1)}\rangle \sim 3$ as lower limit and $\sim 15 \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1}$ as an upper limit.

The $H_2$–[Cl](1–0) conversion factor vary between $X_{Cl}=0.5$ to $14 \times 10^{21} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1}$ with a mean between $\langle X_{Cl}\rangle \sim 2$ to $9 \times 10^{21} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1}$

The [Cl] emission arises from different gas phases, not only from molecular gas. Therefore, two $H_2$–[Cl] conversion factors are calculated. One conversion factor is based on the total observed integrated [Cl] intensity, $X_{Cl_{tot}}$. The other one is based on the [Cl] emission that arises from the molecular phase $X_{ClH_2}$. The $H_2$–[Cl]$_{tot}$ conversion factors based on the total integrated [Cl] intensity varies between $X_{Cl_{tot}}=0.6$ and $6 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1}$ with a mean between $\langle X_{Cl_{tot}}\rangle \sim 1.3$ and $5.5 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1}$. The [Cl] emission that arises from the molecular phase gives $X_{ClH_2}$ between $5$ and $15 \times 10^{21} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1}$ with a mean of $\sim 7$ to $8 \times 10^{21} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1}$.

The upper and lower limits of the conversion factors for the individual positions as well as the average over all positions are listed in Table 7.16. An illustration of the different $H_2$ conversion factors is shown in Figure 7.9.

The derived conversion factors will be compared with established and proposed conversion factors in the following section.

### 7.3.2 Established $H_2$ Conversion Factors

The following paragraphs discuss established $H_2$ conversion factors. I will give a summary of the $H_2$ conversion factors for CO discussed by Wilson (1995), Bolatto et al. (2013) and Israel (1997) as well as $H_2$–[Cl] (1–0) conversion factors proposed by Offner et al. (2014) and Glover & Clark (2015) for a half solar metallicity, $Z=0.5Z_\odot$. Afterwards, I will determine these conversion factors for the positions discussed here. For further details on these conversion factors, please refer to Section 4.8.

#### 7.3.2.1 $H_2$–CO conversion factors

Within uncertainties of $\sim 30\%$, a $X_{CO(1−0)}=2 \times 10^{20} \text{ cm}^{-2} \text{ K km s}^{-1}$ is established for the $^{12}$CO(1–0) line in the Milky Way (Bolatto, Wolfire & Leroy 2013; cf. Section 4.8). In a low metallicity environment such as M33, the $H_2$–CO conversion factor is, in general, higher compared to the value found in the Milky Way. In the first place, the $H_2$–CO conversion at different metallicities can be approximated via equation (4.25)\textsuperscript{iii}. In the case of M33, this equation gives a conversion factor of $X_{CO}=4 \times 10^{20} \text{ cm}^{-2}$, a factor two times higher compared to the value in the Milky Way. Equation 4.25 gives, thus, a constant $X_{CO(1−0)}$ of $4 \times 10^{20} \text{ cm}^{-2}$ for $^{12}$CO(1–0) in a half solar metallicity environment.

It is adequate to adopt a $H_2$–CO(1–0) conversion factor for the $^{12}$CO(2–1) transition. CO(2–1) observations are available for all positions discussed here. In addition its beam size matches roughly those of the [Cl](1–0) and [Cl] observations. The $H_2$–CO(1–0) conversion factor can be transformed

\begin{equation}
X_{CO} Z = \frac{X_{CO(1−0)}}{Z}
\end{equation}

\textsuperscript{iii} $X_{CO} Z = \frac{X_{CO(1−0)}}{Z}$
Table 7.16: H₂ conversion factors for the integrated line intensities of CO(2−1), [C\textsc{i}] (1−0) and [C\textsc{ii}]. The values are based on the molecular hydrogen column densities that are listed in Table 7.13. The mean values of the conversion factors at the end of the list refer to all positions in which the specific line was detected. The mean* considers all positions in which [C\textsc{ii}] was detected, the position GMC91 and GMCno06 B are excluded.

<table>
<thead>
<tr>
<th>Position</th>
<th>(X_{\text{CII tot}})</th>
<th>(X_{\text{H₂ tot}})</th>
<th>(X_{\text{CI}})</th>
<th>(X_{\text{CO}})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(10^{20})</td>
<td>(10^{20})</td>
<td>(10^{21})</td>
<td>(10^{20})</td>
</tr>
<tr>
<td></td>
<td>(K \text{ km s}^{-1})</td>
<td>(K \text{ km s}^{-1})</td>
<td>(K \text{ km s}^{-1})</td>
<td>(K \text{ km s}^{-1})</td>
</tr>
<tr>
<td>BCLMP691</td>
<td>4.6±1.1</td>
<td>1.1±0.3</td>
<td>8.3±1.9</td>
<td>6.1±1.3</td>
</tr>
<tr>
<td>GMC91</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>BCLMP302</td>
<td>5.6±1.3</td>
<td>1.0±0.2</td>
<td>7.6±1.8</td>
<td>6.8±1.4</td>
</tr>
<tr>
<td>GMC01 Peak</td>
<td>5.8±1.3</td>
<td>2.3±0.5</td>
<td>7.5±1.7</td>
<td>4.2±0.9</td>
</tr>
<tr>
<td>GMC01 Flank</td>
<td>5.8±1.2</td>
<td>1.6±0.3</td>
<td>8.6±1.8</td>
<td>4.9±0.9</td>
</tr>
<tr>
<td>GMCno06 A</td>
<td>5.3±1.4</td>
<td>0.6±1</td>
<td>7.4±1.9</td>
<td>15.7±3.7</td>
</tr>
<tr>
<td>GMCno06 B</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>mean</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>mean*</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>8.3±2.9</td>
</tr>
<tr>
<td>mean**</td>
<td>5.4±0.5</td>
<td>1.3±0.6</td>
<td>7.9±0.5</td>
<td>7.2±4.5</td>
</tr>
</tbody>
</table>
Table 7.17: Mean \( I(CO(2–1)), I([CII](1–0)), I([CII]) \) and \( I([CII])_{H_2} \) conversion factors

<table>
<thead>
<tr>
<th>( X_{CO, L_{TIR}} )</th>
<th>( L_{TIR} )</th>
<th>( X_{CO(2–1)} )</th>
<th>( L_\odot )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \times 10^{20} )</td>
<td>( \times 10^{21} )</td>
<td>( \times 10^{20} )</td>
<td>( \times 10^{20} )</td>
</tr>
<tr>
<td>( \text{K km cm}^{-2} )</td>
<td>( \text{K km cm}^{-2} )</td>
<td>( \text{K km cm}^{-2} )</td>
<td>( \text{K km cm}^{-2} )</td>
</tr>
<tr>
<td>BCLMP691</td>
<td>1.7</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>GMC91</td>
<td>1.3</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>BCLMP302</td>
<td>2.0</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>GMC01 Peak</td>
<td>5.9</td>
<td>8.6</td>
<td></td>
</tr>
<tr>
<td>GMC01 Flank</td>
<td>5.9</td>
<td>8.6</td>
<td></td>
</tr>
<tr>
<td>GMCno06 A</td>
<td>3.1</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>GMCno06 B</td>
<td>3.1</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Mean*</td>
<td>4.1±2.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.18: \( L_{TIR}, X_{CO(2–1)} \) and \( H_2 \) column densities derived from \( CO(2–1) \). The Mean* represents the mean value of the conversion factor as function of \( L_{TIR} \) whereby the conversion factors of the positions GMC01 Flank and GMCno06 B have not been considered. The conversion factor at these positions are based on the same \( L_{TIR} \) as used in GMC01 Peak and GMCno06 A therefore are no independent variables.

to a \( H_2–CO(2–1) \) via the ratio of the integrated \( CO(2–1) \) and \(^{12}CO(1–0) \) line intensities, \( I(CO(2–1))/I(CO(1–0)) \). Druard et al. (2014) observed an almost constant \( CO(2–1)/CO(1–0) \) integrated line intensity ratio of 0.80 in M33\( ^{liii} \) This \( I(CO(2–1))/I(CO(1–0)) \) ratio gives a \( X_{CO(2–1)} = 5.0 \times 10^{20} \text{ cm}^{-2} \) for M33.

7.3.2.2 \( H_2–CO \) conversion factor as a function of \( L_{TIR} \)

Israel (1997) proposed to use a \( CO-H_2 \) conversion factor that correlates with the far-infrared surface brightness in a low metallicity environment (cf. Section 4.8).

According to Israel (1997), the \( H_2-{^{12}CO(1–0)} \) conversion factor in a half solar metallicity environment is given by\( ^{liv} \)

\[
X_{CO} = 1.17 \times 10^{20} \frac{L_{TIR}}{10^6 \times L_\odot} \left[ \text{cm}^{-2} \text{K}^{-1} \text{km}^{-1} \right] \quad (7.18)
\]

\( ^{liii} \) The mean \( CO(2–1) \) v.s \( CO(1–0) \) integrated line intensity ratio is 0.85±0.38, in the positions.

\( ^{liv} \) See Section 4.7 as well.
Equation (7.18) can be adopted to a $H_2$–CO(2–1) conversion factor by the use of an assumed constant $I(\text{CO}(2–1))/I(\text{CO}(1–0))=0.8$ (Druard et al. 2014) (cf. Section 7.3.2.1)

$$X_{\text{CO}(2–1)} = 1.46 \times 10^{20} \frac{L_{\text{TIR}}}{10^6 \times L_{\odot}}$$

The used far–infrared surface brightness $L_{\text{TIR}}$ for the individual positions regions were obtained from Boquien et al. (2011). The used $L_{\text{TIR}}$ and the derived $X_{\text{CO}(2–1)}$ are listed in Table 7.18. The derived conversion factors vary between $X_{\text{CO}(2–1)} \sim 2 \times 9 \times 10^{20}$ s cm$^{-2}$ K$^{-1}$ km$^{-1}$ with a mean value of $(X_{\text{CO}(2–1)})=4.2\pm2.4$. Within the uncertainties, the derived $(X_{\text{CO TIR}})$ is identical to the 'constant' conversion factor derived in Section 7.3.2.1.

7.3.2.3 $H_2$–[Cl]$(1–0)$ conversion from simulations

$H_2$–[Cl]$(1–0)$ conversion factors for M33 are already discussed in Section 4.8.

Glover & Clark (2015) calculated $H_2$–[Cl]$(1–0)$ conversion factor of $X_{\text{Cl}0.5Z} \sim 0.3 \times 10^{22}$ s cm$^{-2}$ K$^{-1}$ km$^{-1}$ for $G_0=10$ and a $X_{\text{Cl}0.5Z} \sim 0.5 \times 10^{22}$ s cm$^{-2}$ K$^{-1}$ km$^{-1}$ for $G_0=100$. Note that the sources in M33 are penetrated by radiation fields of $G_0 \sim 15$ to 50. (cf. Table 7.7).

7.3.3 Comparison of the $H_2$ conversion factors and summary

This section compares the different $H_2$ conversion factors that were calculated in the previous sections. The $H_2$ conversion factors and their mean values for the individual positions are illustrated in Figure 7.9.

As demonstrated in Figure 7.9, the derived $X_{\text{CO}(2–1)}$ and $X_{\text{Cl}}$ match the 'established' conversion factors within the uncertainties.

The $H_2$–CO(2–1) conversion factors ($X_{\text{CO}(2–1)} \sim 4 \times 10^{20}$ K$^{-1}$ km$^{-1}$ cm$^{-2}$) are at the lower edge of the CO(2–1) conversion factors derived from the line observations presented here. This corresponds to the conversion factors derived from the cases II and IV ($X_{\text{CO}(2–1)} \sim 3 \times 10^{20}$ K$^{-1}$ km$^{-1}$ cm$^{-2}$). In these cases, the carbon in the molecular phase is dominated by CO in the majority of the positions (cf. Table 7.12). The conversion factors derived for the upper column densities ($X_{\text{CO}(2–1)} \sim 15 \times 10^{20}$ K$^{-1}$ km$^{-1}$ cm$^{-2}$) are almost 2 to 4 times higher than the mean values from literature. In these cases, the carbon in the molecular phase is dominated by $C^+$ (Table 7.12). This could indicate that the $N(\text{H}_2)$ are overestimated in the cases I and III, or vice versa that the established $H_2$ conversion factors tend to underestimate the $H_2$ column densities at low metallicities.

The averaged CO(2–1)–$H_2$ conversion factors by Israel (1997) are equal to the conversion factor derived in Section 7.3.2.1. Both $H_2$–CO(2–1) conversion factors have mean values of $\sim 4 \times 10^{20}$ s K$^{-1}$ km$^{-1}$ cm$^{-2}$ in M33. The individual CO(2–1) conversion factors based on Israel (1997) have a higher correlation with the $X_{\text{CO}(2–1)}$ derived from the observations, compared to the constant conversion factors. In the positions GMC91 and GMC01 Peak, the conversion factor based on Israel (1997) lies within the
limits of the conversion factors derived from the observations which does not apply for the constant conversion factor from Section 7.3.2.1.

The $\text{H}_2$—[C\textsc{i}](1–0) conversion factors by Glover & Clark (2015) for $G_0=10$ to $G_0=100$ are consistent with the conversion factors derived from the observed integrated [C\textsc{i}](1–0) line intensities of $X_{\text{C\textsc{i}}}$~2 to $9 \times 10^{21}$ s K$^{-1}$ km$^{-1}$ cm$^{-2}$. This indicates that a $\text{H}_2$—[C\textsc{i}](1–0) conversion factor could be a reliable tool to calculate the amount of $\text{H}_2$ at $Z=0.5Z_{\odot}$.

The $\text{H}_2$—[C\textsc{ii}] conversion factors are relatively constant in all positions. I derived a $X_{\text{C\textsc{ii}}}=5.5 \times 10^{20}$ s K$^{-1}$ km$^{-1}$ cm$^{-2}$ based on the total integrated [C\textsc{ii}] emission and a $X_{\text{C\textsc{ii}}}=1.3 \times 10^{20}$ s K$^{-1}$ km$^{-1}$ cm$^{-2}$. It
would be worth to investigate if similar \([\text{CI}]\) conversion factors can be found in other sources as well. If this is the case, a \([\text{CI}]_{\text{tot}}-\text{H}_2\) conversion factor, or at least a \([\text{CI}]_{\text{H}_2}-\text{H}_2\) could be an additional, reliable tool to estimate the amount of \(\text{H}_2\) in galaxies. This idea is similar as those of Madden et al. (e.g. 2011) who proposed a \(\text{H}_2\) to \((\text{CO}+\text{[CI]})\) conversion factor for low metallicity galaxies.

7.4 RADIAL DISTRIBUTION OF THE HYDROGEN AND CARBON COLUMN DENSITIES AND OF THE RADIATION FIELD

This section investigates the radial distribution of carbon and hydrogen as function of the distance to the galactic centre of M33, \(R_{\text{M33}}\). The radial distribution of CO dark \(\text{H}_2\) is studied as well. The distances of the sources vary between \(R_{\text{M33}} \sim 0.1\) kpc (GMC01) an \(\sim 3.5\) kpc (BLMCP691). All the distances are listed in Table 7.1. The observed radial distributions will be compared with results from Druard et al. (2014) and Tosaki et al. (2011). Additional \(\text{Nii}\) or \(\text{[Nii]}\) or at least \(\text{Hii}\) and \(\text{Hii}\) data would be required to calculate \(X_{\text{[CI]}-\text{H}_2}\) conversion factor.

7.4.1 RADIAL DISTRIBUTION OF HYDROGEN COLUMN DENSITIES

Figure 7.10 illustrates the \(N(\text{H})\), \(N(\text{H}^0)\) and \(N(\text{H}_2)\) as function of \(R_{\text{M33}}\) for the different cases. The neutral hydrogen column densities remain almost constant over \(R_{\text{M33}}\). The fit of \(N(\text{H}^0)\) with an exponential decay function\(^\text{lv}\) as function of \(R_{\text{M33}}\) implies a slight increase towards higher \(R_{\text{M33}}\) (cf. Table 7.19 and Figure 7.10). The fit gives a negative scale length of \(l_e \approx -5.8 \pm 4.7\) kpc. These observations can be explained by an almost constant amount of \(\text{H}^0\) in the neutral phase between the ionised and molecular phase. The result is consistent with previous studies by Druard et al. (2014) and Tosaki et al. (2011). They haven’t found any significant radial distribution for \(\text{Hii}\).

The molecular hydrogen column densities become lower along \(R_{\text{M33}}\) in all the cases and, therefore, the total hydrogen column densities \(N(\text{H})\) lowers as well. The fit to \(N(\text{H}_2)\) with an exponential decay function gives an exponential scale lengths of \(l_e \approx 2.4 \pm 1.5\) kpc in case III to 1.4\(\pm 0.7\) kpc in case IV. The fit to \(N(\text{H})\) gives exponential scale length between \(l_e \approx 2.9 \pm 1.9\) kpc (case III) and 1.9\(\pm 1.0\) (case IV). The precise fit results are summarised in Table 7.19. The scale length of the total hydrogen column densities are of the order of the scale length found by Druard et al. (2014). They found a scale lengths of \(\langle l_e(N(\text{H})) \rangle \approx 2.2\) kpc for the inner 3.5 kpc of M33. The calculations imply that the overall mass of the GMCs decreases towards larger distances to the galactic centre of M33, in particular the mass and the size of the inner regions of the GMCs, in which the hydrogen is molecular.

\(^{lv}\) Druard et al. (2014) and Tosaki et al. (2011) investigated the radial distribution of \(\text{H}^0\) and \(\text{H}_2\) based on \(\text{Hii}\), CO maps \((J=1-0\) and 2-1 respectively).

\(^{lvii}\) \(N(\text{H}^0)=a \times e^{-64R_{\text{M33}}}\)
Figure 7.10: Derived fraction of molecular hydrogen as function of the radial distance to the centre of M33, \( R_{\text{M33}} \) in the Cases I, II, III and IV. Southern positions (negative distances in Table 7.1) are plotted at positive distances as well. The magenta dashed lines (\( \cdots \cdots \)) illustrate the radial distribution of \( N(\text{H}^0) \). The yellow \( \cdots \cdots \) show the \( N(\text{H}_2) \) and the blue \( \cdots \cdots \) show the radial distribution of the total hydrogen column densities \( N(\text{H}) = N(\text{H}^0) + 2 \times N(\text{H}_2) \).
7.4 Radial Distribution of the Hydrogen and Carbon Column Densities and of the Radiation Field

The radial distribution of the hydrogen and carbon column densities and of the radiation field can be described using an exponential decay function:

\[ N(H^0, H_2, H) = a \times e^{-\rho_d R_{M33}}. \]

where \( \rho_d \) is the specific scale length calculated from the exponential decay constant. The specific scale lengths are calculated via \( l_e = \ln(0.5)/(-\rho_d) \).

<table>
<thead>
<tr>
<th>Case I</th>
<th>Case II</th>
<th>Case III</th>
<th>Case IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N(H^0) )</td>
<td>1.6±0.2</td>
<td>-0.12±0.10</td>
<td>-5.8±4.7</td>
</tr>
<tr>
<td>( N(H_2) )</td>
<td>11.4±1.8</td>
<td>0.35±0.13</td>
<td>2.0±0.8</td>
</tr>
<tr>
<td>( N(H) )</td>
<td>24.1±3.6</td>
<td>0.29±0.17</td>
<td>2.4±1.4</td>
</tr>
</tbody>
</table>

Table 7.19: Fit parameters of for the radial distribution of \( N(H^0), N(H_2) \) and \( N(H) \). These column densities were fitted with an exponential decay function, \( N(H) = a \times e^{-\rho_d R_{M33}} \). The specific scale lengths \( l_e \) is calculated from the exponential decay constant \( \rho_d \) via \( l_e = \ln(0.5)/(-\rho_d) \).

<table>
<thead>
<tr>
<th>Case I</th>
<th>Case II</th>
<th>Case III</th>
<th>Case IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N(C^+)/N(C)_{tot} )</td>
<td>0.70±0.06</td>
<td>0.00±0.03</td>
<td>0.48±0.04</td>
</tr>
<tr>
<td>( N(C^0)/N(C)_{tot} )</td>
<td>0.07±0.07</td>
<td>0.00±0.01</td>
<td>0.06±0.01</td>
</tr>
<tr>
<td>( N(CO)/N(C)_{tot} )</td>
<td>0.24±0.08</td>
<td>0.00±0.04</td>
<td>0.45±0.19</td>
</tr>
</tbody>
</table>

Table 7.20: Parameters from fitting the relative fractions of the \( C^+, C^0 \) and CO column densities to the total carbon column density as function of \( R_{M33} \) in the Cases I, II, III and IV. The fractions in which fitted with a linear function \( N(X)/N(C)_{tot} = a + m \times R_{M33} \). Positions which show no \([CII]\) emission were not considered in the fit (positions GMC91 and GMCno06 B).

7.4.2 Radial Distribution of Relative Carbon Fractions

Figure 7.11 shows the radial distribution of the fraction of the specific carbon column densities in the molecular phase to the total carbon column densities in the molecular phase, \( N(CO/C^0/C^+)/H_2/N(C)_{H_2} \).

The fractions of all lines do not show any favorable gradient along \( R_{M33} \) in case I. The fraction of all species stays almost constant. In all other cases, the fraction of CO shows a trend to higher relative fraction towards higher \( R_{M33} \), while the fraction of \( C^+ \) decreases. In case II, a constant distribution of \( C^+ \) is possible within the uncertainties. The fraction of \( C^0 \) doesn’t show any significant gradient along \( R_{M33} \) in all the cases. Linear fits to the relative carbon fractions are listed in table 7.20.

The results will be discussed in detail at the end of this section. At first, I will discuss the radial distribution of CO dark H2.
Figure 7.11: Derived relative fractions of the $C^+$, $C^0$ and CO column densities to the total $N(C)$ in all discussed cases plotted as function the radial distance to the centre of M33, $R_{M33}$. Southern positions (negative distances in Table 7.1) are plotted at positive distances as well. The solid line shows the linear fit though the positions in which [CII], [CI](1–0) and CO(2–1) were detected.
7.4.3 Radial Distribution of the CO Dark \( \text{H}_2 \)

In general, the radial distribution of \( f(DG) \) is similar to distribution of \( \text{C}^+ \). \( \text{C}^+ \) traces most of it. The radial distributions of CO dark \( \text{H}_2 \) fractions relative to the total amount of \( \text{H}_2 \) are shown in Figure 7.12. The \( f(DG) \) shows no distinctive radial gradient in case I, within the uncertainties. In all other cases, the \( f(DG) \) decreases towards larger \( R_{\text{M33}} \). A positive gradient can not be excluded for the case III within the uncertainties. The \( f(DG) \) has a scale lengths of \( l_e \approx 21 \) in case I. The scale lengths is \( \sim 1.5 \) in the cases II and IV, and \( \sim 7 \) in the case III.

7.4.4 Discussion of the Radial Distributions

The decrease of \( N(\text{H}_2) \) and \( N(\text{H})_{\text{tot}} \) as well as the relative constancy of \( N(\text{H}^0) \) found along the galactic radius of M33 is expected. In a galactic disc, the average mass surface density decreases towards higher galactic distances (e.g. Schmidt 1985). On the other hand, the radial distribution of the carbon species is surprising. The \( \text{C}^+ \) fraction shows a decrease towards larger \( R_{\text{M33}} \) while the fraction of CO increases (cases II, III and IV) (or both fractions stay constant, case I). The radial distributions in the cases II, III and IV are hard to reconcile with the standard picture of PDRs and the mass distribution of molecular gas in galaxies. The size of the CO core should lower towards a lower clump mass surface densities, while the size of the \( \text{C}^+ \) layers in the molecular phase should almost stay constant\textsuperscript{lviii}. Therefore, an increase of the \( \text{C}^+ \) and CO dark \( \text{H}_2 \) fraction as well as a decrease of the CO fraction would have been expected. Such a distribution was found in the Milk Way by the GOT \( \text{C}^+ \) project Langer et al. (2014b). They found an increase of the CO dark \( \text{H}_2 \) fraction towards larger distances to the galactic centre. The increase can be described by a linear fit with a slope of \( \sim 0.03 \frac{f(DG)}{\text{kpc}} \).

The observed radial distribution of the carbon species allow two different explanations.

A possible explanation is, that the case I (and maybe case III) provides a reliable description of the physical conditions in the positions, discussed here. The amount of \( \text{C}^+ \) is underestimated in the cases II and IV. This explanation is consistent with the conclusion drawn in Section 7.2.8\textsuperscript{lix}.

On the other hand, the observations could be explained by a gradient of the ambient radiation field along \( R_{\text{M33}} \). The penetration depth of the FUV radiation into a clump is lower at a fainter UV radiation. This gives a a narrower \( \text{C}^+ \) layer in the molecular phase. Finally this leads to a higher fraction of CO towards larger distances to the centre of M33. Observations show a decrease of the \( L_{\text{TIR}} \) towards higher \( R_{\text{M33}} \) (cf. Figure 7.6; Boquien et al. 2011). \( L_{\text{TIR}} \) is proportional to the ambient FUV field, in a first approximation\textsuperscript{lx}. Therefore, the ambient radiation field lowers towards larger \( R_{\text{M33}} \) as well. The radial distribution of \( G_0 \) is illustrated in Figure 7.13. The radial distribution of \( G_0 \) has a scale lengths of \( l_e(G_0) \approx 1.7 \) kpc. This scale lengths are lower than the scale lengths of\textsuperscript{lviii} The effect of different clump sizes and mass surface densities is described in Section 2.2.3 and is illustrated in Figure 2.7.

\textsuperscript{lix} I compared the CO dark \( \text{H}_2 \) fraction with the predictions of the PDR-model by Wolfire, Hollenbach & McKee (2010)

\textsuperscript{lx} cf. Section 4.5; \( G_0 = 4 \pi 0.5L_{\text{TIR}} \)
Figure 7.12: Derived CO dark H$_2$ fraction as function of the radial distance to the centre of M33, $R_{M33}$. Southern positions (negative distances in Table 7.1) are plotted at positive distances as well. The solid line shows the linear fit to the $f$(CO dark H$_2$).
7.4 Radial Distribution of the Hydrogen and Carbon Column Densities and of the Radiation Field

Figure 7.13: Radial distribution of $G_0$ in the observed positions as function of $R_{M33}$. The $G_0$ were calculated from the $L_{TIR}$ (Boquien et al. 2011) via the relation $G_0 = 4 \pi 0.5 L_{TIR}$. The red dotted line shows the exponential fit to the $G_0$.

Figure 7.14: $N(C^+)$ as function of $G_0$ in the Cases I (●), II (■), III (blue ♦) and IV (▲). The dashed lines show the linear fits to $N(C^+)$. $N(H)$ (Table 7.19). This means that the strength of the ambient UV-field decreases more along $R_{M33}$ compared to the total hydrogen column densities. Therefore, the FUV radiation has a lower penetration depths at higher $R_{M33}$. The width of the C$^+$ layer in the molecular phase lowers faster than the size of the CO core towards higher $R_{M33}$ and, thus, the fraction of C$^+$ relative to those of CO as well. This might be another explanation for the observed radial distributions of the carbon species. The fraction of C$^+$ as function of $G_0$ is illustrated in Figure 7.14.

In summary, the molecular hydrogen densities decrease towards larger distances to the galactic centre. The fraction of C$^0$ shows no radial distribution in M33. The radial distributions of C$^+$ (in the molecular phase) and CO and $f(DG)$ in case I, are roughly consistent with the expectations for GMCs with a decreasing column density towards larger $R_{M33}$. The fraction of C$^+$ and CO remains constant along $R_{M33}$ in this case. This distribution is consistent with observations in the Milky Way by Langer et al. (2014b) as well. The fraction of C$^+$ decreases while the fraction of CO increases towards larger distances to the galactic centre. In general, this can be explained by the decrease of the ambient radiation field towards larger $R_{M33}$. 
7.5 SPECTRAL DISTRIBUTION CARBON AND HYDROGEN

The calculations in the previous sections were based on line intensities that were integrated over the full velocity range of the lines. These intensities allowed to determine the total column densities of \( \text{C}^+ \), \( \text{C}^0 \), CO, \( \text{H}_2 \) and \( \text{H}_2 \), the total fraction of CO dark \( \text{H}_2 \) in the clouds. They also allowed to calculate \( \text{H}_2 \) conversion factors and to study the radial distribution of the gas. Spectral informations were not directly needed for these calculation.

The following section deals with the spectral distribution of \( \text{C}^+ \), \( \text{C}^0 \), CO in the molecular phase, as well as of the CO dark \( \text{H}_2 \). Spectral informations allow to study the kinematics within the clouds. They allow to investigate gas that arises from different regions within the clouds. Spectral informations allow to distinguish between different sources along the line of sight, which was for example the case in GMCno06. The spectral information allowed to distinguish between GMCno06 A and GMCno06 B. Spectral data allow to study the distribution of the different carbon species, and to allocate the position of CO dark \( \text{H}_2 \) in the clouds.

The following section discusses the velocity resolved distribution of the \( \text{C}^+ \), \( \text{C}^0 \) and CO column densities in the molecular phase of the Cases I, II, III and IV. The velocity resolved distribution of the CO dark \( \text{H}_2 \) gas, its relative fraction to the total \( \text{H}_2 \) column densities and the fraction of molecular hydrogen in the observed positions is discussed as well. The discussion is restricted to the positions BCLMP691, BCLMP302, GMC01 Flank and GMCno06. For these positions, spectral resolved data for all carbon species is available.

The following analysis is based on spectra that are smoothed to velocity bins of \( dv=2 \) km/s width. This width provides an adequate signal to noise ratio and allows to study the spectral distribution of the different lines. The column densities of \( \text{C}^+ \), \( \text{C}^0 \), CO and \( \text{H}_2 \) are calculated with the same initial parameters (gas temperature, excitation temperature, critical densities etc.) as used for the Cases I, II, III, and IV (cf. Section 7.2). The specific lines trace from different regions in the clouds. I assume that the physical conditions within these regions are roughly constant, as otherwise different line transitions would be observed. In the following analysis, only velocity bins with a S/N \( \geq 1 \) were considered. A problem of this method is the quality of the individual line spectra. The \([\text{C}i](1–0)\) spectra have a higher RMS compared to the \([\text{C}ii] \) and CO observations. Therefore, the spectral distribution of \( \text{C}^0 \) is concentrated on the bins around the specific line peak of the \([\text{C}i](1–0)\) observations.

At first I will discuss the spectral distribution of the \( \text{C}^+ \), \( \text{C}^0 \) and CO column densities (Section 7.5.1). The velocity resolved distribution of CO dark \( \text{H}_2 \) is described in Section 7.5.2. The distribution of the \( \text{H}_2 \) gas fraction relative to the total amount of hydrogen is discussed in Section 7.5.3.

7.5.1 SPECTRAL DISTRIBUTION OF CARBON

The spectral distribution of the \( \text{C}^+ \) (red), \( \text{C}^0 \) (black), and CO (green) column densities are illustrated in Figure 7.15 (Cases I and II) and 7.16 (Cases III and IV).
The spectral distribution of $N$(CO) and $N$(C$^0$) have a similar shape as the spectra of $^{13}$CO(2–1) and [C$^{}$	extsc{i}](1–0) as these column densities are directly proportional to the observed main beam brightness temperatures.

The spectral distribution of CO(2–1) is broader compared to [C$^{}$	extsc{i}](1–0) in the majority of the positions (BCLMP691, GMC01 and GMCno06 A&B), and therefore also the column densities of CO to C$^0$. BCLMP302 is an exception. In this position, the [C$^{}$	extsc{i}](1–0) line is broader than CO(2–1) and [C$^{}$	extsc{i}]. The same applies for the C$^0$ column density.

The velocity resolved distribution of the [C$^{}$	extsc{i}] emission in the molecular phase and, thus, of the C$^+$ column densities arise from the specific velocity bins in which $T_{mb}([C^{}$	extsc{i}])$_{H_2} = T_{mb}([C^{}$	extsc{i}])$_{tot} - T_{mb}([C^{}$	extsc{i}])$_{H^+} - T_{mb}([C^{}$	extsc{i}])$_{H^0} >0$. It is assumed that the velocity distribution of the H$^0$ emission is equal to the one of H$^1$. In the Cases I and III $T_{mb}([C^{}$	extsc{i}])$_{H_2} >0$ in almost all velocity bins. In these two cases, the spectral distribution of $N$(C$^+$)$_{H_2}$ is roughly similar to the observed [C$^{}$	extsc{i}] spectra. In the Cases II and IV, the [C$^{}$	extsc{i}] emission in the molecular phase is narrower than those of [C$^{}$	extsc{i}] and CO. In these cases, the [C$^{}$	extsc{i}] emission from the molecular phase is concentrated on the velocity bins around the [C$^{}$	extsc{i}]peak (BCLMP691, GMC01 and GMCno06 A) or to the red side of the spectra (BCLMP302).

Differences between the column densities are highlighted by the spectral distribution of the relative carbon fractions. The spectral distribution of the relative carbon fractions in the molecular phase is illustrated in Figure 7.17 (Cases I and II) and 7.18 (Cases III and IV). The relative fraction of the carbon species in the velocity bins around the line centres are roughly equal to the relative carbon fractions averaged over the full spectrum as listed in Table 7.12. The carbon at the sides of the spectra is dominated by C$^+$ in the majority of the positions in the Cases I and III. Expectations are the red wing of BCLMP302 and GMCno06 A as well as both wings of GMCno06 B. A significant faction of carbon is C$^0$ at these positions.

The carbon at the spectral edges is dominated by CO in the Cases II and IV. An exception is BCLMP302, once more where, in which C$^0$ and C$^+$ dominates, and the red wing of BCLMP691 where roughly 1/4 to 1/2 of the carbon is C$^+$.

### 7.5.2 SPECTRAL DISTRIBUTION OF CO DARK H$_2$ GAS

Now, I will discuss the spectral distribution of the CO dark H$_2$ fraction, $f$(DG). The spectral distribution of the CO dark H$_2$ fraction (Section 7.2.8) is shown in the Figures 7.17 (Cases I and II) and 7.18 (Cases III and IV).

The fraction of CO dark H$_2$ shows a characteristical shape in the majority of the positions in the cases I and III. Around the centre of the spectra the $f$(DG) is minimal with a typical $f$(DG) of $\sim$60% to 80%. Almost all H$_2$ is CO dark ($f$(DG)$\simeq$1) towards the wings of the spectra. In BCLMP691, GMC01 and GMCno06 A the CO dark gas is commonly associated with C$^+$. C$^0$ traces a significant fraction of the CO dark H$_2$ at the edges in BCLMP302 as well ($\sim$30% up to 100%). The GMCno06 A and B are an

\[ N = \frac{\tau}{1-e^{-\tau}} \times \frac{8\pi v^3}{9u} A_{ul} \frac{h\nu}{k T_{mb}(1-e^{-h\nu/k T_{mb}})} \frac{1}{J_v(T_{ex})-J_v(T_{BG})} \Phi_B \int T_{mb} dv \]
Figure 7.15: Distribution of the C\(^+\), C\(^0\) and CO column densities for the carbon column density compositions 'case I and II' in the clouds at the positions BCLMP691, BCLMP302, GMC01 Flank and GMCn006 along the velocity axis in velocity bins with a width of 2 km s\(^{-1}\).
Figure 7.16: Distribution of the C$^+$, C$^0$ and CO column densities for the carbon column density compositions ‘case III and IV’ in the clouds at the positions BCLMP691, BCLMP302, GMC01 Flank and GMCno06 along the velocity axis in velocity bins with a width of 2 km s$^{-1}$. 
Figure 7.17: Relative fraction of the C$^+$, C$^0$ and CO column densities relative to the total carbon column densities for the carbon column density compositions Case I and II.
Figure 7.18: Relative fraction of the C$^+$, C$^0$, and CO column densities relative to the total carbon column densities for the carbon column density compositions Case III and IV.
exception. The $f(DG)$ remains almost constant over their entire width at $f(DG)\approx 0.5$ to 0.75 (cloud A) and $f(DG)\approx 0.6$ (cloud B) and decreases to 0 at the blue wing.

In the cases II and IV the $f(DG)$ are generally lower compared to the case III and IV, with a $f(DG)\sim 0.1$ to 0.5. In these cases the CO dark $H_2$ fractions decrease towards the edges, except for BCLMP302, in which $f(DG)=1$. The decrease of the $f(DG)$ is induced by narrow spectral distribution of $C^+H_2$ and $C^0$ compared to CO.

### 7.5.3 Spectral distribution of the molecular gas fraction

The spectral distribution of molecular hydrogen to the total amount of hydrogen are illustrated in the figures 7.19 and 7.20. $H_2$ is expected to be located towards the centre of clouds, surrounded by a layer of atomic neutral (and ionised) hydrogen.

The $H_2$ fraction reaches its maximum roughly around the centre of the spectra and decreases towards the edges. This spectral distribution is pronounced in the cases II and IV as well as in clouds with a low total hydrogen column density (GMCno06 B). The $H_2$ fraction is $\sim 70\%$ to $90\%$ at the line centres and decreases to $\sim 20$ to $40\%$ towards the edges.

In general the fraction of molecular hydrogen is higher in the cases I and III compared to the cases II and IV. In the cases I and III the differences of $f(H_2)$ between the centre and the edges of the spectra are less pronounced. $H_2$ has a peak fraction of $\sim 95\%$ in all positions in these two cases. Towards the flanks the fraction decreases to $\sim 50$ to $60\%$. 

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**Figure 7.19:** Distribution of the $H_2$ fraction in the clouds at the positions BCLMP691, BCLMP302, GMC01 Flank and GMCno06 along the velocity axis in velocity bins with a width of 2 km s$^{-1}$ for the $N(C)$ compositions case I and II.
7.5.4 Discussion of the Spectral Distribution

The observations show that carbon in the molecular phase has no uniform distribution in the positions discussed here. C\(^+\), C\(^0\) and CO are present at different velocities and thus in different regions of the GMCs.

The spectral distribution of the cases I and III can be explained by a C\(^+\)/C\(^0\)/CO layer structure. C\(^+\) traces the H\(_2\) of the outer layer of the molecular hydrogen and CO the H\(_2\) in the centre of the cloud. The molecular hydrogen is surrounded by a layer of neutral hydrogen. H\(_2\) is almost exclusively associated with C\(^+\) towards the wings of the spectra, BCLMP302 is an exception. A significant fraction of the H\(_2\) is associated with C\(^0\) at the red edge of BCLMP302 as well. These observations indicate a gas phase in which the H\(_2\) is associated C\(^+\) and C\(^0\) in the absence CO, as it was proposed by Hollenbach, Takahashi & Tielens (1991), Wolfire, McKee, Hollenbach & Tielens (2003) and Wolfire, Hollenbach & McKee (2010).\(^{lxii}\) The distribution of C\(^0\) is relatively narrow, compared to CO and C\(^+\), in all other clouds. This indicates that C\(^0\) is located at the surface of the CO photodissociation layer in these clouds, and that CO and C\(^0\) are associated with the same star forming matter in most of the positions.

The spectral distribution of the C\(^+\) column densities and the f(DG) in the cases II and IV, are hard to reconcile with a C\(^+\)/C\(^0\)/CO layer structure. The observations might indicate narrow C\(^+\) and C\(^0\) layers in the molecular phase, or even H\(_2\) that is associated with C\(^+\) in the inner regions of the molecular phase while CO is associated with the outer regions. This might indicate that the N(C\(^+\))H\(_2\) are underestimated in the the cases II and IV. Vice versa the assumptions in the cases I and III lead to spectral distributions which are in agreement with the assumptions for a molecular phase.

\(^{lxii}\) See also Section 2.2.1. Possible causes for the spectral distribution of C\(^+\), C\(^0\) and CO in BCLMP302 will be discussed in Section 7.6.3.
clouds.

The discussions in the previous sections indicate, that the cases I and III represent the real composition of the gas in the molecular clouds, discussed here. The fraction of CO dark H$_2$, the radial distribution and the spectral distribution of the different gas species in the cases II and IV are hard to reconcile the standard picture of molecular clouds. That is not the case for the cases I and III.

The individual positions will be discussed in detail, in the following section. I will use the column densities that were calculated for the cases I and III in the following discussion.
7.6 THE OBSERVED REGION IN DETAIL

The previous discussion was focused on the general distribution of carbon and hydrogen in M33. The observations in the individual clouds are worth to be discussed, as they allows to study the local conditions in a broader context and to gain an impression of the variety of the different GMCs and their environment.

7.6.1 BCLMP691

![Figure 7.22: Grey image [C ii] image of BCLMP691 (Nikola et al. in prep.). Green contours show the CO(2–1) emission, blue contours show H i. The red circle marks the intrinsic Beam size of the APEX [C i](1–0) observations.](image)

The BCLMP691 can be described as the most 'standard'–like GMCs in the sample of discussed positions. The distribution of carbon is consistent with a $C^+ / C^0 / CO$ layer structure. Within the uncertainties all discussed carbon lines peak at the same velocity. The broadest line is [C ii]while [C i](1–0) is the most narrow line. Roughly 80% of the hydrogen is molecular form. Almost 2/3 of the $H_2$ is traced by $C^+$ while $\sim$1/3 by CO. The fraction of $H_2$ traced by $C^0$ of 6% is the lowest value of the discussed clouds. Roughly $\sim$70% of the $H_2$ is not associated with CO and is thus CO dark $H_2$.

7.6.2 GMC91

In GMC91 is characterised by a strong and broad CO emission, while no $[C i](1–0)$ and $[C i]$ is observed. The observed CO(2–1) line has a widths of $\Delta v \sim 12$ km/s. This is the broadest CO(2–1) line in the current sample of sources discussed here. The integrated $[C ii]$ line intensity has a upper
Figure 7.23: Grey image [C\textsc{ii}] image of GMC91 (Nikola et al. in prep.). Green contours show the CO(2–1) emission, blue contours show H\textsc{i}. The red circle marks the intrinsic Beam size of the Nanten2 [C\textsc{i}](1–0) observations

limit of $\lesssim 0.72$ K km/s (Nikola et al. in prep.). $I([\text{C\textsc{ii}}](1–0))$ has an upper limit of $\sim 0.2$ K km/s. The H\textsc{i} emission is widely spread around the point like CO peak.

The GMC91 has a total hydrogen column density of $N(\text{H})_{\text{tot}} \sim 14 \times 10^{21}$ cm$^{-2}$, with $\sim 80\%$ of the hydrogen being H$_2$. All molecular hydrogen is traced by CO.

The following paragraph gives a possible explanation for the observed bright and broad CO lines, as well as the absence of [C\textsc{ii}] and [C\textsc{i}](1–0)

In general the observations can be explained by the kinematic within the northern spiral arm of M33, as shown in the following.

Observation in M51 found clouds with bright and broad low $J$-CO lines but no or faint [C\textsc{ii}] and H$\alpha$ emission (Schinnerer et al. 2013; Pety et al. 2013). Meidt et al. (2013) explained these observations by the dynamical environment of the GMCs. Strong streaming motions can stabilise GMCs by their high dynamical pressure and prevent a collapse of these clouds. Strong streaming motions can be found at the edges of spiral arms (Meidt et al. 2013). Therefore, those GMCs have only faint or even no star formation. Due to the low number of stars within these GMCs, the ambient radiation field is faint. As a consequence, CO is not photodissociated and carbon can hardly be ionised. Therefore almost all carbon is CO, in these clouds.

The shape of the northern spiral arm indicates strong streaming motions in this GMC. The northern spiral arm of M33 has a kneed structure as well. This structure is illustrated and emphasised in Figure 7.24. A kneed spiral structure indicates spirals shock waves in the spiral arms (Chernin 1999; Efremov 2010). The dynamical pressure is at its highest level in the kneeing points.

GMC91 is situated directly at a kneeing point of the northern spiral arm\textsuperscript{lxiii}. Furthermore, the optical depth of the $^{12}$CO(1–0) line of $\tau_{12}=6$ is

\textsuperscript{lxiii} NGC604 is also situated at a kneeling of the northern spiral arm. NGC604 is the second most massive GMC in the local group.
the lowest in this sample of clouds, while the $N(H_2)$ is of similar order as found in the other clouds. This indicates a low volume density in GMC91, which can be explained by a high dynamical pressure.

The model by Meidt et al. (2013) gives thus a possible explanation for the observed bright CO lines and missing ionised and neutral carbon lines in GMC91.

7.6.3 BCLMP302

$[\text{Cl}\,(1-0)]$ was observed at the $[\text{Cu}]$ peak of BCLMCP302. The $[\text{Cu}]$ peak is located $\sim 40$ pc to the east of the CO emission regions (cf. Figure 7.25).

A distinctive characteristic at the observed position is the line-width of $[\text{Cl}\,(1-0)]$, $\Delta v_{[\text{Cl}]}$. The line-width of $\Delta v_{[\text{Cl}]}=15.1 \pm 1$ km/s is the broadest $[\text{Cl}\,(1-0)]$ line within the sample of here presented observations. The width clearly exceeds the line width of the CO line of $\Delta v_{\text{CO}}=8.4 \pm 0.4$ km/s. Within the uncertainties $\Delta v_{[\text{Cl}]}$ could have a similar line-width as $[\text{Cu}]$ ($\Delta v_{[\text{Cu}]}=14.6 \pm 0.5$ km/s) and $\text{HI}$ ($\Delta v_{\text{HI}}=17.8 \pm 0.4$ km/s) (cf. Table 7.2).

Within the observed beam I derived a $N(H)_{\text{tot}} \sim 13$ cm$^{-2}$, in which $\sim 80 \pm 22$% is molecular gas. CO traces $\sim 20$% of the $H_2$, while $C^0 \sim 10$% and $C^+ \sim 70$%. Roughly 80% of the $H_2$ is CO dark.

As consequence of the broad $[\text{Cl}]$ and $[\text{Cl}](1-0)$ lines all $H_2$ at the left spectral wing of BCLMP302 is CO dark (cf. Figure 7.17). The excess of
[CII] emission in the molecular phase, and thus of CO dark H$_2$, at this position is consistent with the study by Mookerjea et al. (2016). At the left wing of BCLMP302 the $N(C^0)/N(C)_{\text{tot}}$ rises to $\sim 80\%$.

The line-width and the central velocity of the CO(2–1) line at the observed position and at the peak of the southern CO complex are almost identical ($\Delta v = 8.7\pm0.3$, $v_{\text{LSR}}=252.8\pm0.2$ compared to $\Delta v = 8.4\pm0.4$, $v_{\text{LSR}}=252.8\pm0.2$). This might be that the observed CO(2–1) emission arises from the flank of the southern CO complex which lies within the beam. In that case the observed CO(2–1) emission has an other spatial origin as the [CII] emission (cf. Fig. 7.25).

The almost identical widths of the [CII](1–0) and [CII] lines and their similar spectral shape indicates that the [CII](1–0) arises from the same region as [CII], in a distance of $\sim 40$ pc from the central molecular zone.

### 7.6.3.1 Possible origin of the broad [CII](1–0) line in BCLMP302

I will now discuss possible origins of the broad [CII](1–0) line in BCLMP302 and the excess of C$^0$ and C$^+$ at the left spectral.

The observations might indicate a diffuse cloud in the stage in which the diffuse ionised gas recombines to neutral gas (cf. e.g. Beuther et al. (2014)) while only few carbon monoxide has jet been formed. Oxygen might have not yet bounded to carbon, which causes the bright [OII]63$n\mu$m line and the faint CO(2–1) emission at the left wing. The clouds density has to become denser to recombine ionised carbon to neutral atomic carbon and finally to form CO. HI and [CII] peak emission shows a slight shift of $\sim 3$km/s and $\sim 1$km/s relative to [CII](1–0). This velocity shift could be accompanied by a density gradient between the more diffuse C$^+$ and H$^0$ and the more dense C$^0$ and CO. A possible origin for the velocity (and density) might be a slow collision of diffuse clouds. No double peak structure or an asymmetrical line structure can be observed in HI and [CII]. That might indicate that the velocity of the collision would be relatively slow $\lesssim 3$km/s. In that case the spatial distribution of [CII](1–0) and [CII]
might be different. For a further analysis a [CI](1–0) map is needed.

Also a temporary UV shadowing of the cloud could cause the broad [CI](1–0) line. The formation of C\(^0\) is more efficient in clouds that are cooled down compared to clouds which are in thermal equilibrium (Störzer, Stutzki & Sternberg 1997). Ionised carbon recombines to C\(^0\) rapidly in the absence of UV radiation (within few 10\(^4\) years, Stutzki et al. 1997). The timescale to from CO from C\(^0\) is higher; a few 10\(^5\)–6 years (Stöerzer, Stutzki & Sternberg 1997; Stutzki et al. 1997). This mechanism in non-equilibrium regions leads to an enhanced [CI] abundance in a PDR for \(~10^5–6\) years. As [CI] had just formed from [CII], both lines should have similar spectra and a similar spatial distribution. This scenario would require a UV-shadowing of a cloud with a diameter of few 10 pc for \(~\)few 10\(^4\) – 5 years.

Another scenario is the dissolution of the cloud by the nearby bright star cluster. The UV radiation arising from the star cluster could have photodissociated almost all the CO in the observed position. The remnants of the photodissociation, oxygen and neutral carbon, are further penetrated by UV. C\(^0\) ionises and forms C\(^+\). Hence, the line widths of [CII] and [CI](1–0) would have their origin in the formation of C\(^+\) out of C\(^0\). The fraction of [CII] compared to [CI](1–0) could shows an gradient in direction to the star cluster in that case. The carbon nearby the star cluster would ionise first. The velocity shift between [CII] and [CI](1–0) could be interpreted this way.

Maps of neutral carbon transitions would be required to test these scenarios.
7.6.4 GMC01

GMC01 has hydrogen column density of $\sim 30 \times 10^{21}$ cm$^{-2}$ at the [Cii] Peak and $\sim 20 \times 10^{21}$ at the position GMC Flank. In both positions, the fraction of molecular hydrogen is almost equal with $f(H_2) \sim 0.99$ to 0.95. Almost 75% of the H$_2$ is CO dark in the [Cii]-peak position and $\sim 70\%$ in GMC01 Flank. In both positions, the majority of the H$_2$ is traced by C$^+$ ($\sim 70\%$ and 60%). Only $\sim 5\%$ of the H$_2$ is associated with C$^0$. CO traces $\sim 25\%$ to $\sim 30\%$ of the H$_2$. In a simple spherical cloud with a C$^+$/C$^0$/CO layer structure (e.g. Sternberg & Dalgarno 1995) the opposite $f(DG)$ distribution would be expected. The $f(DG)$ should be higher at the flanks of a GMC and lower in their centre. The difference can be explained by the (spatial) distribution of the gas species. CO(2–1) peaks $\approx 7'' \sim 30$ pc north-east of the [Cii] peak. Noticeable is distribution of the integrated [Cii](1–0) line intensities. The $I$([Cii](1–0)), and thus the calculated $N$(C$^0$), is higher in GMC01 Flank than in the [Cii]peak position. [Cii] and CO(2–1) have their highest emission in GMC01 peak (cf. Figure 7.27). This indicates, that the structure of the carbon is complex in GMC01. The distribution of [Cii](1–0) is unlike the distribution CO(2–1) and [Cii]. For a further investigation, maps of the C$^0$ transition are needed.

7.6.5 GMCNo06

The CO and [Cii](1–0) spectra in GMCNo06 show two velocity components at $v_{LSR} \approx -128$ and -113 km/s. These two velocity components are associated with two nearby GMCs, cloud A and B. These clouds overlap partially spatially in the beam (cf. Fig 7.28). This creates the double peak in the spectra spectra. Hence, the observed 'dip' is no selfabsorption. The CO peaks of cloud A and B have a projected spatially distance of $\sim 85$ pc. [Cii] peaks $\sim 10$ pc south of the CO peak of cloud A. The [Cii](1–0) observations were performed roughly in the middle between the CO peaks of these GMCs. The beam of the [Cii](1–0) includes the CO peak of cloud A as well as the [Cii] peak. [Cii] is spectrally associated with cloud A ($v_{LSR} \approx -125$ km/s). CO(2–1) and [Cii](1–0) have a
7.7 Summary and Conclusion

I presented [C\textsc{i}](1–0) observations of five prominent GMCs (BCLMP691, GMC91, BCLMP302, GMC01 and GMCno06) along the galactic radius of M33. The observations were set directly at, or close to, the [C\textsc{i}] peak of these GMCs. Based on complementary [C\textsc{ii}], [N\textsc{ii}]122\mu m, 12/13CO(1–0), 12CO(2–1) and H\textsc{i} data I was able to derived the beam average column...
densities of CO, C$^0$, C$^+$ and H$^0$. Combined with H$\text{I}$ and [Nii]122$\mu$m data I have determined the C$^+$ column density and the [CII] emission from the molecular, neutral atomic and the ionised phase. The molecular hydrogen column densities were determined from the carbon column densities in the molecular phase. I also derived the fraction of CO dark H$_2$. The radial and spectral distribution of the different gas species was discussed. The H$_2$ column densities and the observed integrated intensities allowed to determine H$_2$ conversion factors for the integrated intensities of CO(2–1), [CII](1–0), [CII] as well as the [CII] emission from the molecular phase. The individual position were discussed in detail as well.

The C$^0$ and C$^+$ column densities were calculated for different excitation temperatures. I have calculated $N$(C$^+$) for assumed [CII] excitation temperatures between 75 K to 200 K in the atomic phase and 75 K to 138 K in the molecular phase in the optically thin limit and for a $\tau$=1. I can conclude, that the uncertainties of the [CII] excitation temperatures are the main obstacle to calculate the C$^+$ column densities. The total column densities are on average $N$(CO)$\sim$12$\times$10$^{16}$cm$^{-2}$, $N$(C$^0)\sim$12$\times$10$^{16}$cm$^{-2}$ and $N$(C$^+)$\sim$20$\times$10$^{16}$cm$^{-2}$ ($T_{\text{ex}}$=75K, $\tau$→0) to $\sim$35$\times$10$^{16}$cm$^{-2}$ ($T_{\text{ex}}$=200K, $\tau$=1). Roughly $\sim$2/3 of the C$^+$ column density and 25% ($T_{\text{ex}}$=75K, $\tau$→0) to 70% ($T_{\text{ex}}$=200K, $\tau$=1) of the [CII] emission is associated with H$_2$.

I have studied four different carbon compositions. These compositions allowed to study the maximal and minimal amount of H$_2$ in the different positions. The cases I and III were based on an [CII] excitation temperature of 200 K in the the atomic phase and a $\tau$=1 in the molecular phase. The cases II and IV were based on an assumed optically thin limit and [CII] excitation temperature of 75 K in the the atomic phase. C$^+$ is associated with $\sim$25% (cases II and IV) to $\sim$70% (cases I and III) of the molecular hydrogen, CO traces in average between $\sim$70% and 25% of the H$_2$. C$^0$ is associated with $\sim$5 to 10% of the H$_2$. The average fraction of CO dark H$_2$ is $\sim$40% (cases II and IV) to 80% (cases I and III) in M33. The first fraction is roughly equal to the f(DG) found in the Milky Way. The second is roughly twice this value. These fraction of CO dark H$_2$ was compared with the prediction of the PDR model of Wolfire, Hollenbach & McKee (2010) for a $Z$=0.5$Z_\odot$. The cases I and III are in good agreement with the theoretical predictions.

I have calculated maximal and minimal H$_2$ conversion factors. The derived H$_2$ conversion factors have lower and upper limits of $X_{\text{CO}(2–1)}$\sim3.5 to 15$\times$10$^{20}$ s K$^{-1}$km$^{-1}$cm$^{-2}$, $X_{\text{CI}}$\sim2 to 9$\times$10$^{21}$ s K$^{-1}$km$^{-1}$cm$^{-2}$, $X_{\text{CII}}$\sim1 to 8$\times$10$^{20}$ s K$^{-1}$km$^{-1}$cm$^{-2}$ and $X_{\text{CIIH}_2}$\sim7 to 8$\times$10$^{20}$ s K$^{-1}$km$^{-1}$cm$^{-2}$ These conversion factors are roughly consistent with the H$_2$–CO conversion factors by Bolatto, Wolfire & Leroy (2013) (adapted for $Z$=0.5$Z_\odot$) and Israel (1997) as well as H$_2$–[CII](1–0) conversion factors based on numerical simulations for a half solar metallicity.

Towards larger distances to the galactic centre of M33 the total and molecular hydrogen column densities decrease. They have a scale lengths of $\sim$2 to 3 kpc. The radial distribution of the carbon species either showed no gradient (case I) or the amount of C$^+$ decreases towards larger $R_{M33}$, while the amount of CO increases (cases II, III and IV). A significant radial gradient was not observed for C$^0$ in all the cases. These radial distribution can be in general explained by the radial gradient of the ambient radiation.
field. The scale lengths of the ambient radiation field are less than the scale lengths of $N$(H) and $N$(H$_2$), thus that the size of the C$^+$ layer shrinks faster compared to the size of the CO core.

C$^+$, C$^0$, CO and the fraction of CO dark H$_2$ have different spectral distributions in the molecular phase (C$^+$ from the neutral atomic and the ionised phased are excluded in the comparison). In the cases I and II the majority of the carbon at the edges of the spectra is C$^+$. CO and C$^0$ are located preliminary the centre of the spectra, which is consistent with a C$^+$/C$^0$/CO layer structure. In the cases II and IV the carbon at edges of the spectra is dominated by CO. In these cases C$^0$ and C$^+$ are allocated towards the centre of the spectra. CO dark H$_2$ has almost a similar distribution as C$^+$ in most of the cases and the positions. Exceptions are the GMC91, BCLMP302 and GMCno06. GMC91 shows no [CII] and CO emission, such that no CO dark H$_2$ was detected. A significant fraction of the H$_2$ at the red wing of BCLMP302 is associated with C$^0$, while CO is absent. These observations presumably indicate a gas phase in which the H$_2$ is associated C$^+$ and C$^0$ in the absence CO, as it was proposed by Hollenbach, Takahashi & Tielens (1991), Wolfire, McKee, Hollenbach & Tielens (2003) and Wolfire, Hollenbach & McKee (2010). The cloud GMCno06 B shows no [CII] emission. Therefore all the CO dark H$_2$ is associated with C$^0$.

In summary it can be concluded that the C$^+$ column densities are deeply affected by the assumed excitation temperatures within the different gas phases. This uncertainty affects all the calculation that are based on these values, such as the amount of H$_2$, the fraction of CO dark H$_2$ as well as their radial and spectral distribution. Furthermore the study shows that most of the CO dark H$_2$ is traced by [CII]. [CII](1–0) traces only a minor fraction of this gas, in most of the positions.
Part IV

CONCLUSION AND OUTLOOK
Chapter 8

Summery, Conclusion and Outlook

This thesis serves a study of distribution of carbon in the nearby universe. It was motivated by the overall question 'What is distribution of carbon in the ISM and what conclusions can be drawn for the ISM in general?' In order to shed light on this question, I have investigated the distribution and the composition of C$^+$, C$^0$ and CO based on representative samples of sources in the Milky Way and M33. Three major samples were analysed, each providing an insight into different aspects of the ISM.

At first, I have investigated the nature and composition of clouds along the line of sight towards the quasars B0355+508 and B0212+735 (chapter 5). These clouds were originally observed by the absorption of mm-waves towards these quasars. CO(1–0) and CO(2–1) emission was observed around the line of sight towards the quasars and identified to be associated with these clouds because of their matching velocity characteristics with the mm-wave absorption spectra (Liszt & Lucas 1998; Liszt & Pety 2012). These clouds were identified as warm non-LTE diffuse clouds with a temperature of $T \gtrsim 30$ K and subthermal excited CO lines. In diffuse clouds, the photo-electric heating efficiency is maximal and the cooling is dominated by [C$^\text{ii}$]. If the clouds were indeed diffuse, [C$^\text{ii}$] emission lines with an integrated line intensity of a few $\sim 10^0$ K km/s were expected. Observations, carried out with SOFIA/GREAT, did not found such [C$^\text{ii}$] emission. [C$^\text{ii}$(1–0) observations (carried out with Nanten2/SMART) of an other similar cloud also show no detection. Due to the lack of alternative cooling mechanisms of diffuse clouds, it is concluded that the clouds towards the line–of–sight of B0355+508 and B0212+735 are not diffuse clouds. Furthermore, this thesis also provided an alternative explanation. The observed CO line intensities, the ratio of CO(2–1) to CO(1–0) and of $^{13}$CO to $^{12}$CO, the calculated molecular hydrogen column densities, the size of the clouds and the upper limits for [C$^\text{ii}$] are fully consistent with an ensemble of cold dense clumps with temperatures of $\sim 15$ K and volume densities of $n(^{12}\text{H})\sim 10^{4.5}$ cm$^{-3}$ to $10^{4}$ cm$^{-3}$. This explanation was developed by analytical calculations of the expected [C$^\text{ii}$] line intensities for a kinetic gas temperature of 15 K (this temperature is implied by the CO(2–1) to CO(1–0) ratio) and by simulations of clumps with the KOSMA–$\tau$ PDR model.

The large scale latitudinal and radial distribution of carbon in the fourth quadrant of the Milky Way was tackled in chapter 6. The study was based on the analysis of spectrally resolved latitudinal observations of
$^{12/13}$CO(1–0), CO(2–1), CO(4–3) and [C{\textsc{i}}](1–0), at eight galactic longitudes between $l=306^\circ$ and 354$^\circ$ and $b=\pm 2^\circ$. Kinematic distances from the sun and from the Galactic Centre were determined by the velocity and longitudinal information within the datasets. The vertical distribution of the lines was determined based on the distances. The observations were set in relation to the spiral arms as well. The observations do not show any significant differences between [C{\textsc{i}}](1–0), CO(1–0) and CO(2–1) within in the inner galaxy ($R_{GC} < 8.5$ kpc) neither radial from the Galactic Centre nor vertical from the galactic midplane. This might indicate that most of the [C{\textsc{i}}](1–0) emission within the Milky Way arises from the surface of the CO photodissociation layer and that these lines arise from the same star forming matter.

The observed latitudinal profiles have an asymmetrical shape with local features with diameters of 5 to 30 pc. The profile can not be described by a single Gaussian. The scale height of [C{\textsc{i}}] rises from $z_{1/2} \sim 25-30$ pc at $R_{GC} \approx 2$ kpc to $z_{1/2} \sim 50$ to 55 pc at $R_{GC} \approx 4$ kpc. The scale heights of the observed transitions can be fitted with power law functions, $z_{1/2} \propto R_{GC}^{0.5}$. The calculations give $z_{1/2}(R_0) = 62\pm 7$ pc for [C{\textsc{i}}](1–0) and $z_{1/2}(R_0) = 71\pm 12$ pc for CO(2–1) at the location of the sun.

The observed profiles were compared with simulated [C{\textsc{i}}] profiles carried out within the SILCC-project. The observed CO and [C{\textsc{i}}](1–0) profiles show strong similarities to the simulations. In conclusion, this might indicate that major parts of the local structure of the Milky Way are triggered by supernovae, which locally disrupts or compresses the ISM.

The distribution of carbon and hydrogen in the nearby galaxy M33 was investigated in the case study of five GMCs situated on the major axis of this galaxy. M33 has a half solar metallicity, $Z = 0.5Z_{\odot}$. I have presented [C{\textsc{i}}](1–0) observations of these GMCs. The observations were set directly at, or close to, the [C{\textsc{i}}] peak of these GMCs. With the use of complementary [C{\textsc{ii}}], $^{12/13}$CO(1–0), $^{12}$CO(2–1), H{\textsc{i}} and [N{\textsc{ii}}]122$\mu$m data, I was able to determine the column densities of all major carbon species, CO, C{\textsc{ii}} and C{\textsc{i}} as well as the column densities of neutral atomic hydrogen. The amount of molecular hydrogen could be directly determined from the carbon column densities. In addition, the data allowed to derive the fraction of CO dark H{\textsc{ii}}. Furthermore, I have discussed the radial and spectral distribution of the different gas species. H{\textsc{ii}} conversion factors for the observed line transitions were also calculated. Finally, the individual position were discussed in detail.

CO and C{\textsc{i}} are associated exclusively with H{\textsc{ii}}. C{\textsc{i}} is situated in all gas phases. I have determined the column densities of the C{\textsc{i}} in the different gas phases as well as the fraction of the [C{\textsc{i}}] emission that arises from the different phases, for assumed [C{\textsc{i}}] exception temperature between 75 K and 200 K in the optically thin limit and for an assumed $\tau = 1$. The uncertainty of the [C{\textsc{i}}] excitation temperature is the main obstacle for the calculation of the C{\textsc{i}} column densities. The total column densities of the different carbon species, found in the GMCs are on average $N$(CO)$\sim 12 \times 10^{16}$cm$^{-2}$, $N$(C{\textsc{ii}})$\sim 12 \times 10^{16}$cm$^{-2}$ and $N$(C{\textsc{i}})$\sim 20 \times 10^{16}$cm$^{-2}$ ($T_{ex} = 75$ K, $\tau \to 0$) to $\sim 35 \times 10^{16}$cm$^{-2}$ ($T_{ex} = 200$ K, $\tau = 1$). Roughly $2/3$ of the C{\textsc{i}} column density and 25% ($T_{ex} = 75$ K, $\tau \to 0$) to 70% ($T_{ex} = 200$ K, $\tau = 1$) of the [C{\textsc{i}}] emission is associated with H{\textsc{ii}}. The
column densities of molecular hydrogen, $N$(H$_2$), and the fractions of CO dark H$_2$, $f$(DG), were calculated from the carbon column densities. Different possible total carbon column densities were discussed. This approach allowed to investigate the maximal and minimal $N$(H$_2$) and $f$(DG) of the individual positions.

C$^+$ can be associated with $\sim$25% ($T_{ex}$=75 K, $\tau$→0) to $\sim$70% ($T_{ex}$=200 K, $\tau$=1) of the molecular hydrogen, CO can be associated in average with $\sim$70% to 25% of the H$_2$. C$^0$ is associated with $\sim$5 to 10% of the H$_2$. The average fraction of CO dark H$_2$ is $\sim$40% to 80% in M33. These $f$(DG) fractions for the cases with an $T_{ex}$=200 K and $\tau$→1 are in good agreement with the theoretical predictions by the PDR model of Wolfire, Hollenbach & McKee (2010) for a Z=0.5Z$_\odot$. This fraction roughly twice the $f$(DG) in the Milky Way.

H$_2$ conversion factors were derived from calculated $N$(H$_2$) and the observed integrated line intensities of CO(2–1), [C$\text{ii}$](1–0) and [C$\text{ii}$]. A H$_2$ conversion factor based on the [C$\text{ii}$] emission that arise from the molecular phase was calculated as well. The derived H$_2$ conversion factors have lower and upper limits of $X_{CO(2–1)}$$\sim$3.5 to 15 $\times$10$^{20}$ s K$^{-1}$ km$^{-1}$ cm$^{-2}$, $X_{\text{CII}}$$\sim$2 to 9 $\times$10$^{21}$ s K$^{-1}$ km$^{-1}$ cm$^{-2}$, $X_{\text{CH}}$$\sim$1 to 8 $\times$10$^{20}$ s K$^{-1}$ km$^{-1}$ cm$^{-2}$ and $X_{\text{CH}_{2}H_2}$$\sim$7 to 8 $\times$10$^{20}$ s K$^{-1}$ km$^{-1}$ cm$^{-2}$ These conversion factors are roughly consistent with established H$_2$–CO conversion factors and H$_2$–[C$\text{ii}$](1–0) conversion factors based on numerical simulations.

The total and molecular hydrogen column densities decrease towards larger distances to the galactic centre of M33, with a scale lengths of $\sim$2 to 3 kpc. The radial distribution of the carbon species in the different cases was surprising. Either they do not show any gradient or the amount of C$^+$ decreases towards larger distances to the centre of M33, while the amount of CO increases. The amount of C$^0$ is almost constant in all cases. In general, this radial distribution could be explained by the radial gradient of the ambient radiation field. The scale lengths of the ambient radiation field are less than the scale lengths of $N$(H) and $N$(H$_2$).

C$^+$, C$^0$ and CO are present at different velocities within the clouds. The spectral distributions of C$^+$ (in the molecular phase), C$^0$, CO and the fraction of CO dark H$_2$ shows major differences in the different cases. In the cases of an assumed [C$\text{ii}$] excitation temperature of 200 K and $\tau$=1, the majority of the carbon at the edges of the spectra is C$^+$. CO and C$^0$ are located in preliminary the centre of the spectra. This distribution is consistent with the existence of a C$^+$/C$^0$/CO layer structure. In the cases with a [C$\text{ii}$] excitation temperature of 75 K and $\tau$=0 the carbon at the edges is dominated by CO. C$^+$ is only at the centre in these cases. The fraction of CO dark H$_2$ has an almost similar distribution as C$^+$. An exception is the C$^0$ distribution the GMC BCLMP302. In this position, a significant fraction of H$_2$ at the red edge is associated with C$^0$ while CO is absent.

The study shows that the calculated C$^+$ column densities are deeply affected by the assumed (as unknown) excitation temperatures within the different gas phases. This uncertainty affects the amount of H$_2$, the fraction of CO dark H$_2$ and their radial and spectral distribution.

In general it can be concluded that the cases with an assumed [C$\text{ii}$] excitation temperature of 200 K and $\tau$=1 are probably a better estimate for the conditions within the clouds. The majority of the CO dark H$_2$ is
associated with C⁺. C⁰ has a lower spectral distribution than CO. That indicates that C⁰ is associated with the CO photodissociation layer in M33, similar as in the Milky Way. [Cl](1–0) in the absence of CO is only been observed in a single position.

This thesis studied various aspects of the ISM in the Milky Way and M33. Many conclusions were drawn, that were already mentioned above. Nevertheless I would like to point out the following conclusions as the essence of this thesis:

- The gas towards the line of sight to B0355+508 and B0212+735 is seen as warm diffuse gas with subthermal excited CO lines with temperatures of $T \gtrsim 30$ K, for roughly two decades. This study has shown that this can not be case. This study indicates that the clouds along the line of sight consist of an ensemble of cold dense clumps with $T \sim 15$ K and $n \sim 10^{3.5}$ cm$^{-3}$ to $10^{4}$ cm$^{-3}$.

- [Cl](1–0) has not been observed in the absence of CO(1–0) and CO(2–1) in most of the positions analysed in this thesis. This is the case for the Milky Way and for M33. This indicates that most of the C⁰ arises from the surface of the CO photodissociation layer in the Milky Way and in M33. Nevertheless, there are a few positions that show [Cl](1–0) in the absence of CO. This study found a single position (BCLMP302 in M33) in which C⁰ and C⁺ are present while CO is not.

- This study indicates, that the majority of H₂ can be traced by low–J CO transitions and [Cii]. [Cl](1–0) was not observed in the absence of CO transitions or [Cii].

- The observed vertical profiles of CO and [Cl](1–0) have an asymmetrical shape and can not be described by a single Gaussian. The profiles have a similar shape, such as the [Cu] profiles carried out within the SILCC–project. This might indicate that the local structure of the Milky Way is triggered by supernovae to a large degree.

- The CO dark H₂ fraction is presumably higher towards a lower metallicity. Probably up to $\sim 2/3$ of the H₂ is CO dark in M33. The majority of this gas is traced by [Cii], not by [Cl](1–0).

- I would also like to point out that the calculations of the C⁺ column density and the [Cii] intensities are dominated by the assumed [Cii] excitation temperatures in the different gas phases. The assumption deeply affect the estimated total amount of carbon and hydrogen in the positions of interest.

- Furthermore, this thesis highlights the importance of spectral resolved line observations in order to study the ISM. A large fraction of the study would have been impossible without the spectral information.

This thesis is based on relatively small samples of positions. The significance of all the different aspects discussed here could be highly improved, if the number of studied positions were increased.
The study of the clouds towards the line of sight to the B0355+508 and B0212+738 was based in total on four positions with a relatively short integration time. A [CII] mapping of these sources would significantly increase the statistical representativeness of the study. Furthermore, it would be worth to investigate if the emission from other clouds which have been identified as diffuse are also consistent with a cold and dense clump scenario, once the [CII] intensity is observed and taken into account.

[CII] observations of the $b$–strips, complementary to [CII](1–0) and the CO transitions, would allow to determine the radial and vertical distribution of C$^+\!$ in the fourth quadrant in the Milky Way and to provide an overall picture of carbon in the fourth quadrant of the Milky Way. Its vertical could be compared with the results, presented here. The vertical distribution of CO dark H$_2$ could be determined. The compassion of [CII] observations with the SILCC simulations would allow further statements about the main mechanisms that trigger the local distribution of matter in the ISM. These observations are already planed to be performed with SOFIA/upGREAT. It would be worth to determine the column densities of CO, C$^0$ and C$^+\!$ in the $b$–strips. This would allow to determine the amount of molecular hydrogen within these strips, and to study its vertical and radial distribution.

Nevertheless, it is interesting to study distribution of CO, C$^0$ and C$^+\!$ based on additional positions. The distribution of [CII](1–0) (and partially [CII](2–1)) was recently mapped at $b=0^\circ$ between the galactic longitudes $l=323.6^\circ$ to $341.4^\circ$ with Nanten2/SMART. These observations were carried out within the framework of this thesis. Complementary [CII] and CO observations are provided by Herschel/HIFI observations of GOT C$^+$ project and the Mopra Southern Galactic Plane CO Survey.

It would be also worth to study the [CII](2–1) transition at 809.3 GHz in the Milky Way and in M33. This transition might have an other distribution compared to [CII](1–0) and, therefore, might trace other regions of the ISM. Complementary [CII](2–1) would allow to determine precise excitation temperatures for the C$^0$ transitions as well. A map of the [CII](1–0) and [CII](2–1) emission of the GMC BCLMP302 would allow to investigate the origin of C$^0$ in the absence of CO. I would also like to mention that the present allocation of telescopes harms the observations of the frequencies above $\nu \gtrsim 350$ GHz in the northern hemisphere from ground based observatories.

Calculations of the C$^+$ column densities require a reliable estimate of the [CII] excitation temperatures in the different gas phases. In future it could be useful to observe tracers for these temperatures. For example CH$^+$ could be a tracer for the temperatures within the neutral atomic phase.

In summery this thesis had shed light on many aspects of the distribution of carbon in the nearby universe and had suggested many possible explanations for various questions. Nevertheless many aspects remain open and require a further investigations. I dare to say that the combination large scale spectral resolved CO, [CII], [CII](1–0) and [CII](2–1) maps, combined with tracers for the gas temperatures of C$^+$, provide a reliable tool to study major aspects of the ISM as, for example, the distribution of molecular hydrogen.
Part V

APPENDIX
Appendix A

Column densities of CO, C\(^0\), C\(^+\) and H\(^0\)

The following chapter contains a brief discussion concrete Einstein \(A\) \(_{ul}\) coefficients and partition functions \(Q\) of carbon monoxide, neutral atomic carbon and atomic ionised carbon. Equations used to derive the column densities of these carbon species and of neutral atomic hydrogen are also discussed.

A.1 COLUMN DENSITIES OF CO

Carbon monoxide is a dipolar linear molecule. The rate coefficient for the spontaneous emission \(A\) \(_{ul}\) of a dipole molecule as CO for a specific \(J\) is given by

\[
A\_{ul} = \frac{64 \pi^4 \nu^3}{3h\epsilon_0^3} |\mu|^2 \frac{J}{J+1} \tag{A.1}
\]

with \(|\mu|^2\) being the matrix element of permanent electronic dipole moment. \(^{12}\)CO and \(^{13}\)CO have a permanent magnetic dipole moment of \(|\mu| \approx 0.11\) Debye\(^i\).

For rotational transitions, the statistical weights are equal to the degeneracy, \(g_J = 2J + 1\). The rotational partition function of a linear molecule with a dipole is, in consequence given by

\[
Q = \sum_{J=0}^{\infty} (2J+1) e^{\frac{hB_J(J+1)}{kT_{ex}}} \approx \frac{kT_{ex}}{hB_0} + \frac{1}{3} \tag{A.2}
\]

\[
B \text{ is the rotational constant with } B = \nu/(2 J_u). \text{ Column densities as function of the excitation temperature at the example of }^{13}\text{CO are shown in Figure A.1.}
\]

A.2 COLUMN DENSITIES OF C\(^0\)

The column density of neutral atomic carbon \(N(C^0)\) can be calculated from the observed \([\text{C}] (1-0)\) line intensity via (c.f. Schneider et al. (2003))

\[
N(C^0) = 5.94 \times 10^{15} \times \frac{Q \tau ([\text{C}](1-0))}{1 - e^{-\tau ([\text{C}](1-0))}} \int T_{mb} ([\text{C}](1-0)) d\nu \tag{A.4}
\]

\(^i 1\) Debey=10\(^{-18}\) erg\(^{1/2}\) cm\(^{3/2}\)
Figure A.1: Column densities of $^{13}$CO in cm$^{-2}$ as function of $T_{ex}$ for an integrated $^{13}$CO(2–1) line intensity of $\int T_{mb}(\text{[CII]}) d\nu = 1$ K km/s in the optically thin limit.

with $E_1 / k_B = 23.62$ K and $E_2 / k_B = 62.4$ K. The partition function is given by

$$Q = \frac{1 + 3 e^{-E_1 / k_B T_{ex}} + 5 e^{-E_2 / k_B T_{ex}}}{3 e^{-E_1 / k_B T_{ex}}}$$

(A.5)

The optical depth of [CII] (1–0) is given by

$$\tau([\text{CII}](1-0)) = -\ln \left( 1 - T_{mb} e^{E_1 / k_B T_{ex}} \right)$$

(A.6)

Figure A.2 shows the calculated $N(\text{C}^0)$ as function of the excitation temperature for a $\int T_{mb}(\text{[CII]}(1-0)) d\nu = 1$ K km/s

A.3 COLUMN DENSITIES OF C$^+$

The C$^+$ column density can be approximated via (Goldsmith et al. 2012)

$$N(\text{C}^+) = 2.9 \times 10^{15} \left( 1 + 0.5 e^{E / k_B T_{ex}} \left( 1 + \frac{n_{\text{crit}}}{n(\text{H}_2)} \right) \right)$$

$$\frac{\tau}{1 - e^{-\tau}} \frac{1}{\Phi_B} \int T_{mb}(\text{[CII]}) d\nu$$

(A.7)

with $E / k_B = 91.2$ K.

The specific critical density can be calculated with Equation 4.2, $n_{\text{crit}} = (1 - e^{-\tau}) / \tau \times A_{u1} / C_{u1}$. C$^+$ is present in almost all gas phases of the ISM (c.f. Section 2.1). Neutral atomic carbon in the main collision partner of C$^+$ in the WNM and CNM. In the molecular gas phase collisions with H$_2$ dominate.
Figure A.2: Column densities of neutral atomic carbon in cm$^{-2}$ as function of $T_{ex}$ for an integrated [C]1(–0) line intensity of $\int T_{mb} \, dv = 1$ K km/s in the optically thin limit.

The collisional rate coefficient of C$^+$ for collisions with H$^0$, $C_{ul}(H^0)$, can be fitted by (Goldsmith et al. 2012)

$$C_{ul}(H^0) = 7.6 \times 10^{-10} \left( \frac{T}{100} \right)^{0.14} \text{cm}^3\text{s}^{-1} \quad (A.8)$$

This fit is valid for temperatures between $20 \, K \leq T \leq 2000 \, K$. Equation (A.8) gives, for example, $n_{crit}(H^0)=3.1 \times 10^3$ cm$^3$ for $T=100$ and $n_{crit}(H^0)\approx 2.8 \times 10^3$ cm$^3$ for $T=200 \, K$ in the optically thin limit.

The collisional rate coefficient for collisions of C$^+$ with H$_2$ (Wiesenfeld & Goldsmith 2014) can be fitted by

$$C_{ul}(H_2) = \left( 4.55 + 1.6 \times e^{100K/T} \right) \times 10^{-10} \text{ cm}^3\text{s}^{-1} \quad (A.9)$$

This expression is valid for clouds in LTE and temperature between $\sim 20 \, K$ to $\sim 400 \, K$. This equation gives, for example, $n_{crit}(H_2)=4.41 \times 10^3$ cm$^{-3}$ for $T_{ex}=100 \, K$, and $4.15 \times 10^3$ cm$^{-3}$ for $T_{ex}=200 \, K$ in the optically thin limit.

The collisional rate coefficient of C$^+$ for collisions with electrons can be estimated via (Goldsmith et al. 2012)

$$C_{ul}(e^-) = 8.7 \times 10^{-8} \left( \frac{T}{2000} \right)^{-0.37} \text{cm}^3\text{s}^{-1} \quad (A.10)$$

Figure A.3 shows the C$^+$ column densities for different excitation temperatures and hydrogen volume densities at the example of lines with an integrated intensity of $\int T_{mb}([C\alpha])=1$ K km/s. The plot shows the solution for collisions with H$^0$ and H$_2$. 
Figure A.3: Column densities of $^{12}$C$\text{ii}$ in cm$^{-2}$ for different neutral (left) and molecular (right) hydrogen volume densities as function of $T_{\text{ex}}$ for an integrated [C$\text{ii}$] line intensity of $\int T_{\text{mb}} \, dv = 1$ K km/s in the optically thin limit. The main collision partners are H$^0$ (left) and H$_2$(right), respectively.

A.4 COLUMN DENSITY OF NEUTRAL ATOMIC HYDROGEN

The column density of optically thin neutral atomic hydrogen in a local thermal equilibrium can be approximated via (e.g. Rohlfs & Wilson 2000)

$$N(\text{H}^0) = 1.823 \times 10^{18} \int T_{\text{mb}}(\text{HI}) \, dv$$  \hspace{1cm} (A.11)

This approximation is valid for brightness temperatures that are lower than the kinetic temperature.

It has to be considered that H$^0$ is the most abundant species in the ISM. Hence the HI transition may become optically thick. This can be accompanied by H$^0$-self absorption (HISA; e.g. Burton, Liszt & Baker 1978). The strength of HISA can be used to calculate $N(\text{HI})$ as well. For further details, I recommend Dickey (2002).
Appendix B

Observation techniques in Radio Astronomy

The following section will give a brief overview of the technical background of radio telescopes and radio observations. The following section is based on the description in Wilson, Rohlfs & Hüttemeister (2009), Carlhoff (2013) and Guan (2013). For details of a theoretical background of telescopes and observing techniques I recommend Wilson, Rohlfs & Hüttemeister (2009). The influence of the atmosphere to the observations are elaborated in Guan (2013).

B.1 OBSERVATIONS WITH SINGLE DISH TELESCOPES

This thesis is based on data from single dish telescopes. These telescopes are the most common type in the millimetre and sub-millimetre astronomy. They consist of a system of mirrors, commonly a circular parabolic primary mirror and a secondary mirror (sometimes more mirrors are needed) that directs and focuses the incoming radiation into the optics of the receivers. This telescope design aims to reach a high directivity. The angular extent of the received radiation is called beam pattern. The beam pattern is the Fourier transform of the aperture. It depends on the precise geometry and the observed frequency. The beam pattern of a parabolic single dish telescope is approximately described by a sinc function, with a maxima at its centre. As the function is cut-off at the edges it shows additional smaller maxima beside the beam centre, the so called side lobes. Further deviations are caused by the precise telescope geometry, as for example the position of the secondary mirror. Nevertheless the main beam almost have a Gaussian shape. Its full widths half maximum defines the resolution of the telescope. It can be approximated by

$$\Theta_{\text{FWHM}} \approx 1.22 \times \frac{c}{\nu D} \quad (B.1)$$

with \(c\) being the speed of light, \(D\) the diameter of the primary mirror and \(\nu\) the frequency of the observed line.

The incoming radio signal is converted to an electrical signal by receivers. Different receivers are in use, depending on requirements. I will describe Bolometers and Heterodyne receivers in the following, as these are of relevance for this thesis.

Bolometers are widely used for broad band and sensitive continuum observations. The incoming photons heats an absorber. This heating is measured and can be used to calculate the amount of the incoming energy.
This technique is highly sensitive to incoming the energy, but is does not provide any spectral informations. Velocity informations can be provided by the use of filters. PACS and SPIRE\(^\text{ii}\) are prominent receiver, that used the bolometer technique.

Spectra with a high spectral resolution are often observed with Heterodyne receivers in radio astronomy. The receiver mixes the incoming radiation with a sinus wave of a local oscillator (LO) and converts the signal to a lower frequency. The mixed signal contains still the spectral information of the incoming radiation. For example HIFI, GREAT and SMART use the Heterodyne technique.

The spectral information is observed via spectrometers, the so called back ends of the receiver. There are different types of spectrometers. The data used in this thesis was observed with accusto-optical spectrometers (AOSs) and Fast Fourier–transform spectrometers (FFTSs)\(^\text{iii}\). AOSs convert the signal into an acoustical signal which creates sound waves in a so called Bragg-cell\(^\text{iii}\). The sound waves change the refraction of the cell, which changes the deflation of laser beam, that shines to the cell. Finally the position change of the laser beam is detected by a CCD. AOSs are more and more replaced by FFTSs in the modern time, as they have less stringent temperature requirements and have higher resolutions. The time dependent signal is directly digitised by the FFTSs and transformed into a spectrum.

The observed intensity \(I_\nu\) is commonly expressed by the brightness temperature \(T_B\) in radio astronomy, as mentioned in section 4.2. The brightness temperature is the black body equivalent temperature of the source with a temperature \(T\). In the Rayleigh-Jeans approximation \(T_B\) is proportional to \(I_\nu\)

\[
T_B = \frac{c^2}{2kB\nu^2} I_\nu
\]

The receiver does not measure the brightness temperature. It detects the antenna temperature, \(T_A\) instead. The antenna temperature reflects external influences to the source signals as the attenuation by the atmosphere or a possible shielding of the antenna by a membrane\(^\text{iv}\). The detected emission that arises exclusively from the sky can be calculated by the division of \(T_A\) with the forward efficiency, \(\eta_{fw}\)

\[
T_A^* = \frac{T_A}{\eta_{fw}}
\]

\(T_A^*\) contains all the emission observed that is detected from the sky. Commonly astronomers are interested in the temperature that is detected within the main-beam, the so called main-beam brightness temperature \(T_{mb}\). The fraction of emission that arises from the main-beam is given by

---

\(^{i}\) Both receiver were allocated at the Herschel space observatory

\(^{ii}\) The AST/RO data was observed with used AOSs. The other observations analysed in this thesis are based on FFTs.

\(^{iii}\) The Bragg-cell consist of a special crystal, such as tellurium dioxide (TeO\(_2\)), lead molybdate (PbMoO\(_4\)) or crystalline quartz.

\(^{iv}\) The Nanten2 telescope, for example, is protected by a membrane against the environmental conditions.
so called the main-beam efficiency $\eta_{mb}$. Now, the main-beam brightness temperature is defined via

$$T_{mb} = \frac{T^*}{\eta_{mb}}$$  \hspace{1cm} (B.4)

S. Alexander. On the origin of the forms and the present condition of some of the clusters of stars, and several of the nebulae. AJ, 2:97–103, April 1852. doi: 10.1086/100231.


M. G. Burton, C. Braiding, C. Glueck, P. Goldsmith, J. Hawkes, D. J. Hollenbach, C. Kulesa, C. L. Martin, J. L. Pineda, G. Rowell, R. Simon,


Publications

SOFIA/GREAT [CII] observations in nearby clouds near the lines of sight towards B0355+508 and B0212+735

The Mopra Southern Galactic Plane CO Survey - Data Release 1

The Carbon Inventory in a Quiescent, Filamentary Molecular Cloud in G328

The Mopra Southern Galactic Plane CO Survey

Full SED fitting with the KOSMA-τ PDR code. I. Dust modelling

The Mopra-STO-Nanten2 Atomic and Molecular Gas Survey: The Formation of Giant Molecular Clouds
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<td>ATCA</td>
<td>Australia Telescope Compact Array</td>
</tr>
<tr>
<td>AOS</td>
<td>Acusto-optical spectrometer</td>
</tr>
<tr>
<td>APEX</td>
<td>Atacama Pathfinder Experiment</td>
</tr>
<tr>
<td>AST/RO</td>
<td>Antarctic Submillimeter Telescope and Remote Observatory</td>
</tr>
<tr>
<td>$b$</td>
<td>galactic latitude</td>
</tr>
<tr>
<td>CLASS</td>
<td>Continuum and Line Analysis Single-dish Software</td>
</tr>
<tr>
<td>CNM</td>
<td>cold neutral medium</td>
</tr>
<tr>
<td>CSO</td>
<td>Caltech Submillimetre Observatory</td>
</tr>
<tr>
<td>DFG</td>
<td>Deutsche Forschungsgemeinschaft</td>
</tr>
<tr>
<td>ESO</td>
<td>European Southern Observatory</td>
</tr>
<tr>
<td>FFTS</td>
<td>Fast Fourier-transform spectrometer</td>
</tr>
<tr>
<td>FWHM</td>
<td>full width at half maximum</td>
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<td>GMC</td>
<td>Giant Molecular Cloud</td>
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<td>GOT C$^+$</td>
<td>Galactic Observations of the Terahertz C$^+$ Line</td>
</tr>
<tr>
<td>GREAT</td>
<td>German REceiver for Astronomy at Terahertz Frequencies</td>
</tr>
<tr>
<td>HERM3ES</td>
<td>Herschel M33 extended survey</td>
</tr>
<tr>
<td>HIFI</td>
<td>Heterodyne Instrument for the Far Infrared</td>
</tr>
<tr>
<td>HIM</td>
<td>Hot ionized medium</td>
</tr>
<tr>
<td>IRAM</td>
<td>Institut de Radioastronomie Millimétrique</td>
</tr>
<tr>
<td>ISRF</td>
<td>interstellar radiation field</td>
</tr>
<tr>
<td>JCMT</td>
<td>James Clerk Maxwell Telescope</td>
</tr>
<tr>
<td>$l$</td>
<td>galactic longitude</td>
</tr>
<tr>
<td>LTE</td>
<td>local thermal equilibrium</td>
</tr>
<tr>
<td>ISM</td>
<td>Interstellar Medium</td>
</tr>
<tr>
<td>PACS</td>
<td>Photodetecting Array Camera and Spectrometer</td>
</tr>
<tr>
<td>PAH</td>
<td>Polycyclic aromatic hydrocarbon</td>
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</table>
RMS  root mean square
pv   position velocity
pwv  precipitable water vapour
SED  Spectral Energy Distribution
SIS  superconductor–insulator–superconductor
S/N  signal to noise
SOFIA Stratospheric Observatory For Infrared Astronomy
SPIRE Spectral and Photometric Imaging Receiver
STO  Stratospheric Terahertz Observatory
WIM  warm ionized medium
WNM  warn neutral medium
List of Constants and Units

List of the constants and units used in this thesis.

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<th>Description</th>
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<td><strong>c</strong></td>
<td>2.9979</td>
<td>m/s</td>
<td>speed of light in vacuum</td>
</tr>
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<td><strong>k_B</strong></td>
<td>1.2807</td>
<td>J/K</td>
<td>Boltzmann Constant</td>
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<td><strong>G</strong></td>
<td>6.674</td>
<td>N/m²</td>
<td>Gravitational constant</td>
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<td><strong>h</strong></td>
<td>6.6262</td>
<td>J·s</td>
<td>Planck constant</td>
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<tr>
<td><strong>pc</strong></td>
<td>3.086</td>
<td>m</td>
<td>Parsec</td>
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<td><strong>M☉</strong></td>
<td>1.989</td>
<td>kg</td>
<td>Mass of the sun</td>
</tr>
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<td><strong>L☉</strong></td>
<td>3.85</td>
<td>L</td>
<td>Luminosity of the sun</td>
</tr>
<tr>
<td><strong>R☉</strong></td>
<td>8.5</td>
<td>kpc</td>
<td>Distance Sun–Galactic Centre</td>
</tr>
<tr>
<td><strong>T</strong></td>
<td>K</td>
<td></td>
<td>Temperature</td>
</tr>
<tr>
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<td>m</td>
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<td>Frequency</td>
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<td><strong>v</strong></td>
<td>m/s</td>
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<td>Velocity</td>
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<td><strong>n_x</strong></td>
<td>cm⁻³</td>
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<td>Volume density of x</td>
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<td><strong>N_x</strong></td>
<td>cm⁻²</td>
<td></td>
<td>Column density of x</td>
</tr>
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<td>Degree</td>
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<td><strong>′</strong></td>
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<td>Arcsecond</td>
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<tr>
<td><strong>eV</strong></td>
<td>6.242×10¹¹</td>
<td>erg</td>
<td>electron Volt</td>
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Acknowledgements

First of all, I would like to thank my principal supervisor and first referee of this thesis, Prof. Dr. Jürgen Stutzki, for his support and all the various opportunities he had opened up for me. I also like to thank him for all his useful suggestions and comments.

I like thank Prof. Dr. Joachim Hemberger for being the second referee of this thesis. Also I like to thank Prof. Dr. Uwe Ruschewitz for taking over the chairmanship of the PhD–committee. My thanks go also to Volker Okada–Ossenkopf for being the reporter at the defense.

I also like to thank Prof. Dr. Michael J. Burton for his supervision, suggestions and comments. I like to thank him for the opportunity to support the Mopra Southern Galactic Plane CO Survey in Sydney and from the ATCA side. We also had several very interesting, productive and nice stays in Chile.

My special thanks goes to Jérôme Pety and Harvey Liszt for their dedicated support and their helpful and critical comments concerning the project of the SOFIA \(^{[\text{CI}]}\) observations in B0355+508 and B0212+735. I also like to give special thanks to Markus Röllig for his support and help.

My special thanks goes to the whole HERM33ES team for the dedicated support and useful comments. In particular I would like to mention Bhaswati Mookerjea for her dedicated help concerning the M33 chapter. I also like to thank Carsten Krammer, Jonathan Braine and Frank Israel for their comments and support.
My special thanks goes also to Marc J. Royster (Northwestern University) and Ed Chambers for their essential help in obtaining the CSO data.

I like to thank Annika Franeck for here comments and the discussions concerning the vertical distribution of carbon in the Milky Way.

My thanks go to the whole working group for their support, comments and the nice atmosphere. Even it is hard to pick out special persons I would like to specially mention Ronan Higgins, Markus Röllig, Yoko Okada, Robert Simon, Christoph Buchbender, Philipp Carlhoff, Anna Parikka, Volker Okada-Ossenkopf, Silke Andree-Labsch, Nikola Schneider and Ed Chambers for their support, help and taking their time for my questions.

Thanks again to Ronan Higgins, Anna Parikka and Yoko Okada for the proof–reading.
Thanks to the operators and teams of the telescopes for carrying out the specific observations.

I also like to thank our secretaries for their support, in particular Bettina Krause and Steffi Krämer.

I want to thank my parents, my brother, and all my family and friends who supported me in all that time. In particular I like to thank Corinna Glück and Nadine Khayat for the proof-reading.

Last but not least my special thanks goes to my beloved wife Theresa. You are my inspiration.

This thesis work is carried out within the Collaborative Research Centre 956, sub-project A3, funded by the Deutsche Forschungsgemeinschaft (DFG).
Erklärung


Teilpublikationen:
SOFIA/GREAT [C11] observations in nearby clouds near the lines of sight towards B0355+508 and B0212+735

Ich versichere, dass ich alle Angaben wahrheitsgemäß nach bestem Wissen und Gewissen gemacht habe und verpflichte mich, jedmögliche, die obigen Angaben betreffenden Veränderungen, dem Dekanat unverzüglich mitzuteilen.

Köln, 3. Mai 2017

Christian Björn Glück