THESIS FOR THE DEGREE OF LICENTIATE OF ASTRONOMY

Bird's-eye view of molecular clouds in the Milky Way

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Abstract

A crucial aspect in interpreting the scaling relations relevant for star formation—the Kennicutt-Schmidt relation and the Larson relations—is how those relations depend on size-scale. This is especially so when comparing relations derived from unresolved, extragalactic data to those derived from resolved, Galactic data. We present an experiment in which the Solar neighbourhood (distance < 2 kpc) is examined from the outside, with an aim to unveil the connection between the true, "resolved" properties of star-forming regions and their beam-averaged, "unresolved" properties. To do so, we examine the density and star formation statistics in the Solar neighbourhood and determine how they appear when viewed through apertures of various sizes. We employ sub-pc resolution column density maps and star formation rates of individual molecular clouds from the literature to study the scale dependencies of molecular cloud structure from sub-pc to kpc scales. In this way, we connect the average properties of the gas in the Solar neighbourhood to the resolved properties of individual clouds. Our results will aid the interpretation of on-going and upcoming extragalactic observations, especially by shedding light on the sub-beam properties of the structures detected by them.

Keywords: Interstellar medium, star formation, column density statistics.

List of Publications

This thesis is based on the following publications:

[A] **Andri Spilker**, Jouni Kainulainen, Jan Orkisz, "Bird's-eye view of molecular clouds in the Milky Way: Column density and star formation from sub-pc to kpc scales". Submitted to Astronomy & Astrophysics.

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I am also happy to be part of Astronomy on Tap and the Onsala space observatory outreach team lead by Robert Cumming. It is fun to work with all of you, and I am grateful for the opportunity of seeing the Universe from the perspective of non-astronomers, because it always brings back the wonder and curiosity that motivates me to study astronomy.

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Acronyms

ISM:	Interstellar medium
YSO:	Young stellar object
N-PDF:	Column density probability distribution function
(k)pc:	(kilo)parsec, (1000$\times$) 3.086×10^{16} m
ALMA:	Atacama Large Millimetre Array
PHANGS:	Physics at High Angular resolution in Nearby GalaxieS

Contents

CHAPTER 1

Introduction

Star formation is one of the key processes in the formation of structures in the Universe, essential to the formation of galaxies, planets and life. This project aims to improve the understanding of star formation, through studying how star formation and density distribution depends on scale. This is done through a new approach: an experiment of viewing molecular clouds and star formation in a portion of the Milky Way from a "bird's-eye" perspective. This experiment probes a broad range of scales, and takes a first step towards bridging the gap between studies based on observations within the Milky Way and observations of external galaxies.

1.1 Star formation in galaxies

Stars mainly form in the gaseous arms of spiral galaxies, out of dense clouds of molecular gas (e.g. Kennicutt and Evans 2012). The gas is likely accreted from the extended, low density circumgalactic medium, before it enters the interstellar medium (ISM) of spiral galaxy disks (Kereš et al. 2005; Dekel et al. 2009). There the spiral arms swipe through the gas, creating spiral waves of increased density. In this process clouds of gas and dust can collide, inducing

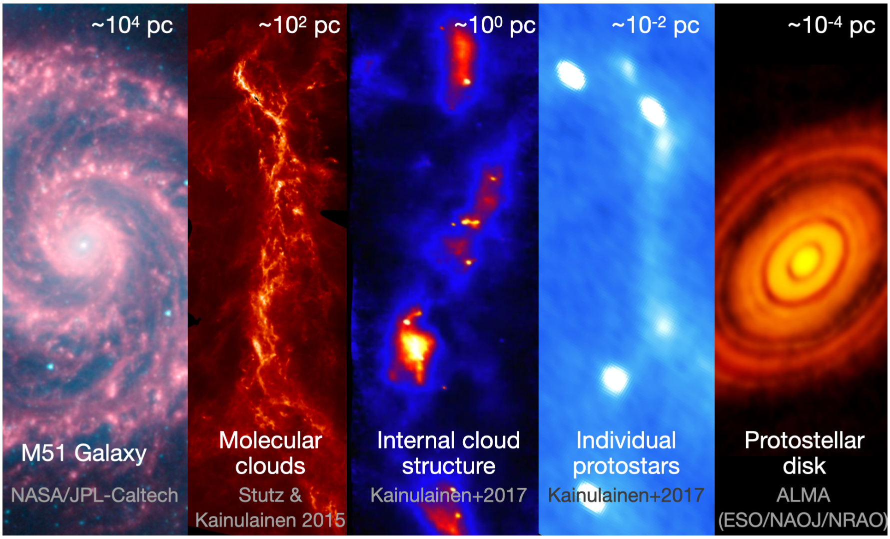

Figure 1.1: The scales of star formation include 8 orders of magnitude, from galaxy disks ($\sim 10^4$pc) to protostellar disks ($\sim 10^{-4}$pc). The left panel shows the M51 galaxy in infrared 3.6-8μm light by the *Spitzer* telescope, credit: NASA/JPL-Caltech. The second panel shows the Orion A molecular cloud, from *Herschel* 160-500μm Stutz and Kainulainen (2015). The third and fourth panel of internal cloud structure and individual protostars also show the Orion A molecular cloud, but now a smaller part at higher resolution (3arcsec) with the ALMA telescope at 3mm wavelength (Kainulainen et al. 2017). Finally, the last panel portrays a protostellar/protoplanetary disk, also with the ALMA telescope, but now at 1.3mm wavelength and an extended configuration of the array achieving a resolution of a few AU (Brogan et al. 2015), credit: ALMA (ESO/NAOJ/NRAO).

shocks, cooling and enhanced densities. In some regions of the spiral arms the gas is cooled enough to become molecular. In these molecular clouds, the conditions are such that gas is dense and cold enough for gravity to compress the highest density regions so that stars can ignite. The physical conditions deep within the clouds have important roles in deciding exactly how often stars are formed, how massive the stars are and how much gas is turned into stars (e.g. McKee and Ostriker 2007). Star formation in galaxies then involves a wide range of scales, from entire galaxy disks (tens of kpc) down to protostellar disks (small fractions of a pc). Figure 1.1 shows the wide range of scales involved.

As star formation happens in molecular clouds, we need to understand these clouds in order to understand how stars form. Molecular clouds are made up of molecules, the most abundant one in the Universe being molecular hydrogen, H_2. But H_2 is difficult to detect, and astronomers therefore tend to use the second most abundant molecule, carbon monoxide, CO, to study molecular clouds (Heyer and Dame 2015) (more in section 2.2). This molecule emits radiation at radio wavelengths, that can be detected by telescopes. Molecular clouds are often defined as regions above a threshold of CO emission (Heyer and Dame 2015). The Milky Way in CO is shown in figure 1.2, while an external galaxy, M51 the Whirlpool galaxy, is shown in figure 1.3. In these figures we see that molecular clouds are complex structures residing in the dynamical environment of galaxy disks. In spiral galaxies, they are mainly located in the thin disk (scale height $\sim$100 pc) and they follow the spiral arms (e.g. Kennicutt and Evans 2012). The distribution of CO and other molecules is much more clumpy/cloudlike than for example atomic gas.

In addition to residing in an intricate environment, molecular clouds have complex internal structures. This has been seen in observations and simulations, see figure 1.4 of the nearby Taurus molecular cloud in CO column density as observed by Goldsmith et al. (2008) and figure 1.5 showing a snapshot from a hydrodynamical simulation of star cluster formation by Bate (2009). Factors that probably contribute to the complex structure in figures 1.4 and 1.5 are gravity, turbulence, magnetic fields, thermal physics and feedback. These physical processes generate fluctuations in pressure leading to compressed gas in some regions and dispersed gas in others. The interplay between the physical processes determine the structure and distribution of molecular clouds in galaxies, and dictate how many stars are made, how fast star formation happens, and how massive the stars become. But how does this interplay work, how is the efficiency, rate and mass distribution of stars determined? And what is the effect of the galaxy structure and dynamics? How do different processes act and regulate the star formation process at different scales? These are still unsolved questions in the theory of star formation. An improved understanding of the scale dependency of molecular cloud structure can potentially get us one step closer to a solution.

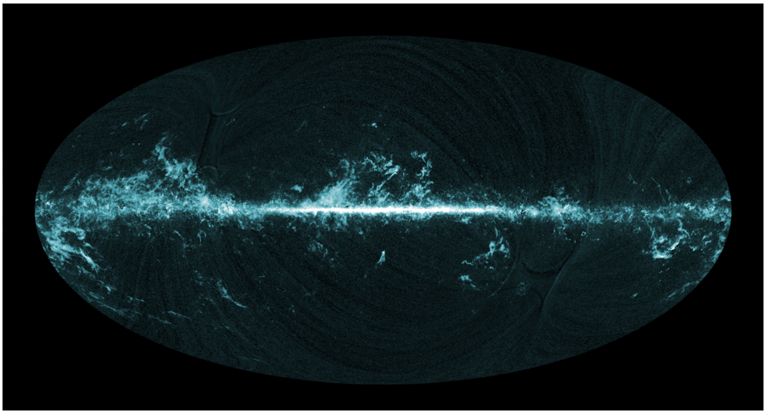

Figure 1.2: The Milky Way seen in CO by the Planck satellite.
Credit: ESA/Planck Collaboration.

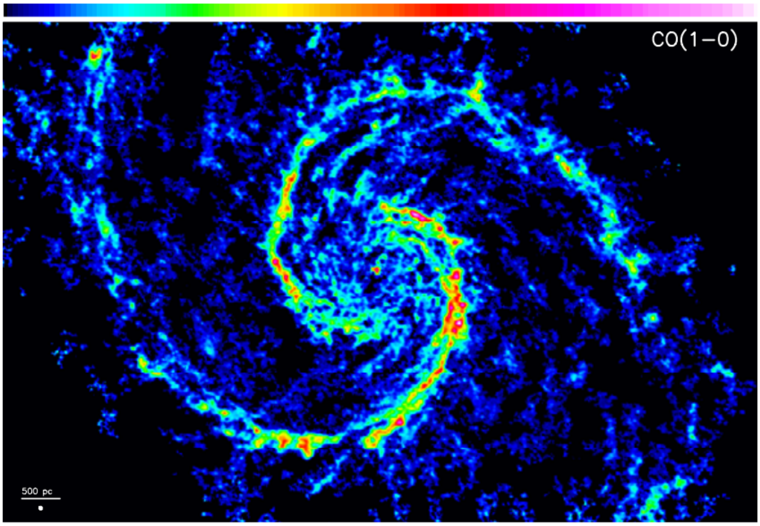

Figure 1.3: M51 the Whirlpool galaxy in CO, seen by the IRAM telescope. Credit: PAWS team, Schinnerer et al. (2013). The physical size of the region is 7 x 11 kpc.

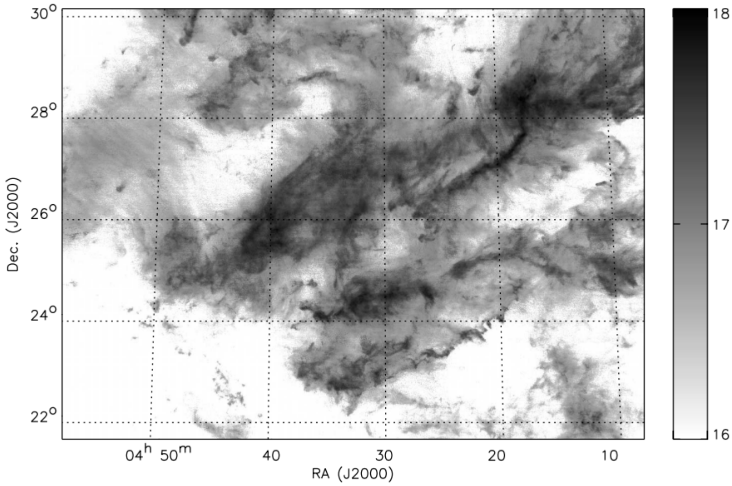

Figure 1.4: Taurus molecular cloud in CO column density at 20" (0.014 pc) resolution from Goldsmith et al. (2008). The physical size of this region is 21 x 28 pc.

Figure 1.5: Snapshot from a hydrodynamical simulation of star cluster formation by Matthew Bate, University of Exeter (Bate 2009). The little white dots are newly formed stars.

1.2 The gap between Galactic and extragalactic works

Star formation has been an active field within astronomy for decades, and a lot of research has gone in to answering some of the questions posed in the previous section. For the most part the questions have been studied by two separate camps of astronomers: the ones studying our own Galaxy and the ones studying other galaxies. The reason for this is the very different techniques and data available. Within the Milky Way, very high resolution can be achieved, enabling studies of sub-parsec regions within molecular clouds. However, observations of the Milky Way are complicated by our point of view from within the disk. This makes it difficult to assign accurate distances, which means that we still only have a broad picture of the geometry of our own Galaxy. A crucial consequence of this is that we do not have a complete view of any specific part of the Galaxy, prohibiting us from reliably probing the large scales. In extragalactic observations entire galaxies are seen face and edge on, with their structure and geometry immediately visible in the data. However, these galaxies are far away, making small scale structures invisible. For an idea of the difference in data, one can compare the CO map of M51 in figure 1.3 with the CO map of the Taurus molecular cloud in figure 1.4. The map of M51 covers 11 kpc and the map of Taurus covers 28 pc, while the resolution in the M51 map is 37 pc and the resolution in the Taurus map is 0.014 pc. This means that the entire map of Taurus is smaller than one pixel in the map of M51.

There is then a gap between the scales that are possible to study with extragalactic and Galactic data. The gap is currently becoming smaller, thanks to the Physics at High Angular resolution in Nearby GalaxieS (PHANGS) program with the Atacama Large Millimetre Array (ALMA). The PHANGS program is dedicated to observing nearby galaxies at the smallest scales possible, and ALMA is able to resolve individual molecular clouds in external galaxies, achieving physical resolutions down to a few tens of pc (Sun et al. 2018, 2020; Leroy et al. 2021). This brings extragalactic works closer to Galactic resolutions, but the sub-pc internal structure of molecular clouds is still only accessible within the Milky Way (and a handful of clouds in the Large Magellanic Cloud (Sawada et al. 2018)).

In order to understand star formation across the full range of spatial scales involved, we need to understand how star formation properties depend on scale and fill the gap between Galactic and extragalactic works. Few people have worked on this so far, but among them are Leroy et al. (2016) who studied the scale dependency of ISM properties in five nearby galaxies. They found that the molecular ISM in the galaxies has higher surface densities, lower line widths, and more self-gravity at smaller scales (the scales they studied were from several kpc to 60 pc). This scale dependency is potentially important for star formation theories, and needs to be studied further. Another project which has worked towards reconciling star formation studies between Galactic and extragalactic works is LEGO (Kauffmann et al. 2017; Barnes et al. 2020). They found that the dense gas tracers often used in extragalactic works (especially HCN) does not trace as dense gas as previously thought, and thus is not equivalent to Galactic studies of dense gas. Another group working on interpreting molecular lines and line ratios used in extragalactic works by analysing Galactic data is the Orion-B collaboration (Pety et al. 2017). They have found that the relationships between line ratios and mass, density, temperature and radiation fields are more complicated than often assumed in extragalactic works (Pety et al. 2017).

Meanwhile, several groups are working on getting a better overview of the gas in the Milky Way. Molecular gas is among other tracers studied with CO surveys, the most widely used survey being the full Milky Way survey by Dame et al. (2001). This has been decomposed into molecular clouds by Miville-Deschênes et al. (2017), giving new insight to the distribution and properties of molecular clouds in the Galaxy. More recent CO surveys cover smaller portions of the Milky Way, among others GRS (Jackson et al. 2006) and SEDIGISM (Schuller et al. 2017, 2021). The Milky Way has also been mapped in the infrared by the *Herschel* telescope HIGAL survey (Molinari et al. 2010b,a), revealing a wealth of interesting small scale filamentary structure within molecular clouds. The Galaxy has also been mapped in the submillimetre with the ATLASGAL survey, covering ∼10 000 dense, high-mass clumps (Schuller et al. 2009; Beuther et al. 2012). The THOR project (Beuther et al. 2016; Wang et al. 2018) has been surveying the kpc scale gas distribution in the Galaxy with multiple tracers, and they have constructed a face-on view of the HI gas in a large portion of the Milky Way disk. Understanding the gas distribution and structure of our own galaxy is crucial if we want to take advantage of the high spatial resolution data available in the Milky Way to reconcile with extragalactic works and understand how the gas in galaxies is converted to stars across the full range of scales.

1.3 This thesis

This thesis presents a new approach to bridging the gap between Galactic and extragalactic works on molecular clouds and star formation. The resolution elements of extragalactic studies range from whole galaxies (tens of kpc) down to individual molecular clouds (tens of pc, Hughes et al. 2013; Sun et al. 2018, 2020). In the Milky Way, sub-parsec scales within molecular clouds can be studied across several kpc of the Galaxy, but the molecular clouds are commonly studied individually. To bridge the gap and study the ISM across the full range of scales relevant to star formation, an overlap in the spatial scales is needed. One way to achieve this would be to improve the resolution of extragalactic sources, but the attainable physical resolution will always be smaller within the Milky Way. Another way, which is possible, is to study the Milky Way on scales comparable to extragalactic works. This is what is done in this thesis. I use sub-parsec resolution observations available for nearby molecular clouds to describe the internal structure of the dense ISM from the sub-pc scale to kpc scales. The scales involved are illustrated in figure 1.6.

This broad range of scales is studied by assembling the most complete census of the molecular clouds to date in a significant portion of our own Galaxy. The portion used is a 2 kpc radius circle of the Milky Way disk, centred on the Sun. This is the first time the molecular cloud density structure and star formation in such a large region of the Milky Way has been studied in a complete manner. The range of spatial scales probed by our survey overlaps significantly with ISM studies of nearby galaxies. In addition, it probes the sub-parsec scales not accessible outside the Milky Way. This enables us to describe how the statistical structure of the dense ISM changes with size-scale, and how this connects to star formation. This represents a step forward in understanding which scales are most important in star formation theories, and it gives clues to what substructure might be present within the beam/resolution element of extragalactic observations.

The structure of this thesis is as follows. In the next two chapters, I will go through some of the relevant theoretical background. This includes chapter 2: Observations of the interstellar medium and star formation, and chapter

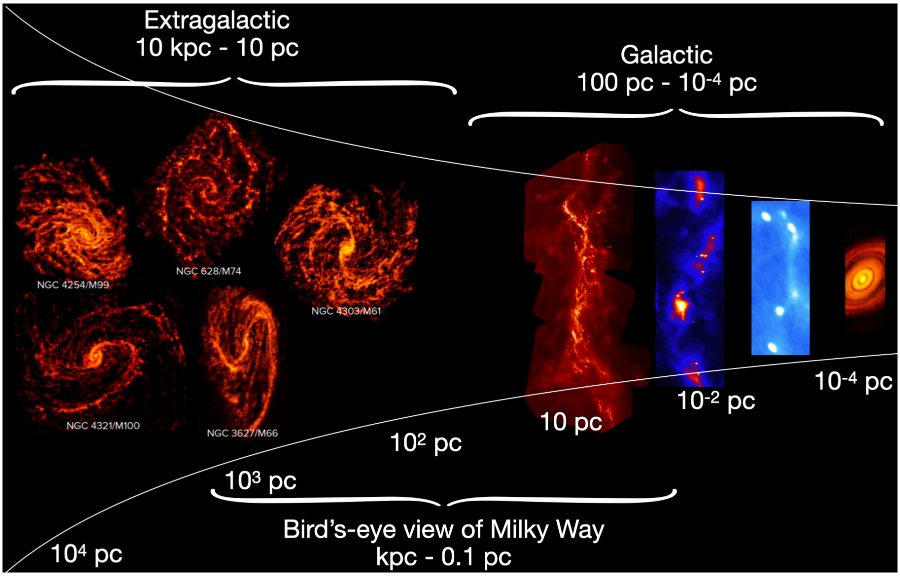

Figure 1.6: The scales of star formation covered by extragalactic and Galactic communities, and the range covered by this work. The figures are not to scale. Credits: galaxies: PHANGS, ALMA (ESO/NAOJ/NRAO); NRAO/AUI/NSF, B. Saxton, molecular cloud: Stutz and Kainulainen (2015), internal structure+protostars: Kainulainen et al. (2017) and protostellar disk: ALMA (ESO/NAOJ/NRAO).

3: Structure and characteristics of the ISM. I will then describe the idea and methodology of this thesis in a bit more detail in chapter 4: Bird's eye view of molecular clouds in the Milky Way. In chapter 5 I introduce and summarise the results of the appended paper, and finally chapter 6 contains a future outlook. The paper on which this thesis is based is appended at the end of the thesis.

CHAPTER 2

Observations of the interstellar medium and star formation

2.1 The interstellar medium

The space between stars, the interstellar medium (ISM), was first thought to be empty. Then, just over 100 years ago, in the early 1900s, absorption lines were seen in the light passing through this medium, revealing the presence of atoms and later molecules (Hartmann 1904; Swings and Rosenfeld 1937). Trumpler (1930) found that all starlight from clusters of stars was "dimmed" with distance. This dimming is now called extinction, and is caused by absorption and scattering of light by dust in the ISM. As observations have advanced, the ISM has been found to be interesting and diverse. Absorption lines from ionised gas present at high temperatures have been seen, emission from neutral hydrogen has been found to fill the disks of the Milky Way and other galaxies, and emission from molecules which require very low temperatures to form is observed in "clouds" following spiral arms of galaxies. Thus, the ISM is far from empty and images now reveal that it is rich in structure and stunningly beautiful, as shown for example by infrared images taken by the *Spitzer* telescope (figure 2.1).

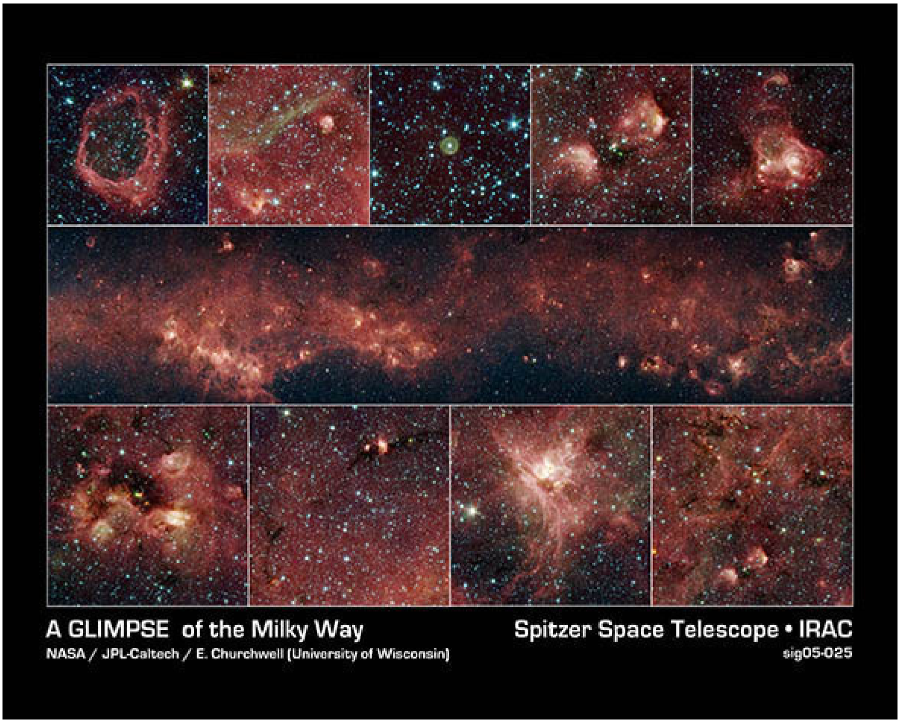

Figure 2.1: A GLIMPSE of the Milky Way in the infrared covering ca 6 degrees of the outer Galaxy. Credit: NASA/JPL-Caltech/E. Churchwell (University of Wisconsin-Madison) and the GLIMPSE Team, 2005.

The red clouds here show molecules and dust, heated and made bright by nearby star formation. The white regions are locations of massive star formation, the circular "bubbles" (ie. top left) are formed by groups of forming stars, and the planetary nebula (top middle) is the leftovers of a dying sunlike star (NASA/JPL-Caltech/E. Churchwell and the GLIMPSE Team 2005). The structure of the interstellar medium is in observations such as these revealed to be intimately tied to the birth and death of stars. This is one of the main reasons why studying the ISM is important for understanding the Universe and our cosmic origins.

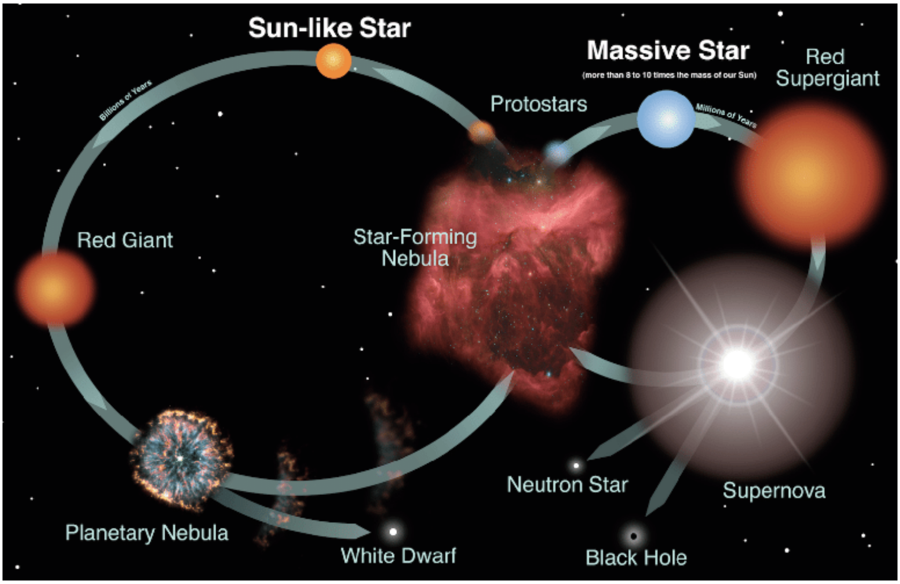

Figure 2.2: Illustration of the cycles of the ISM, and the lifecycle of stars. Credits: NASA/JPL, Astronomical Society of the Pacific.

The cycles of the ISM

The ISM is the fuel and the product of star formation, and it undergoes cycles illustrated in figure 2.2. Stars are born from the ISM, their formation ionises and disperses it, and their evolution and death enriches and redistributes it such that the process can begin again. Sun-like stars live long and eventually evolve to red giants and die to become planetary nebulae and white dwarfs. Massive stars ($M > 8\mathrm{M}_{\odot}$) have much shorter lifetimes, become red supergiants and die in powerful supernova explosions which enriches the ISM in heavy elements and can blow away the star forming gas (Morison 2013). When the gas is blown away it can get dispersed, preventing further star formation, or the gas can be thrown into other gas causing collisions and/or compression of gas. Such collisions may trigger the formation of new high density regions and new cycles of star formation (e.g. Elmegreen 1998).

The components of the ISM

The ISM has been found to consist of gas and dust at various temperatures and densities. The main components are listed below, following Draine (2011).

- **Ionised gas:** The ISM contains ionised gas, due to high temperatures or nearby radiation fields. The "hot ionised medium" has temperatures of 10^5 K or above, and the gas is generally diffuse ($n_{\rm H} \sim 0.004$ cm^{-3}). There is also a colder ionised component, the "warm ionised medium", which is mainly traced by ionised hydrogen HII and has densities of $\sim 0.2 - 10^4$ cm^{-3}.

- **Neutral gas:** The neutral gas in the ISM is mainly observed through neutral hydrogen HI , which quite smoothly fills the disks of galaxies and even extends beyond it. This gas has temperatures of ca $10^3 - 10^2$ K, and densities of ca $n_{\rm H} = 0.6 - 30$ cm^{-3}.

- **Molecular gas:** The molecular gas is the component of the ISM which is most interesting for studying star formation, as it is the coldest and densest part of the ISM, and is where star formation happens. The molecular ISM has temperatures of $\sim 50 - 10$ K and densities of $n_{\rm H} \sim 10^2 - 10^6$ cm^{-3}. The molecular ISM is mostly composed of H_2, but as this is difficult to observe, we instead tend to observe the second most abundant molecule CO. The ISM traced by CO is much more clumpy than the ionised and neutral gas, and star formation occurs in the densest parts of it. These dense molecular clouds are the subject of this thesis. There is also a more diffuse molecular component, in the higher temperature and lower density of the range given above.

- **Dust:** The ISM also contains dust. Dust grains are composed of an agglomeration of molecules, with sizes up to $\sim 1\mu$m (Draine 2011). The dust comes from red giant stars, AGB stars and previous supernovae, and makes up $\sim 1\%$ of the ISM in the Milky Way (Draine 2003). Dust emits light in infrared wavelengths when it is heated (as was seen in figure 2.1), and dust blocks light, causing extinction and reddening in optical observations. There is more dust in regions of high gas density, dust can shield molecules from destruction by high energy radiation and dust is needed for some molecules to form. The emission and extinction by dust can therefore be used to trace molecular clouds, as will be done in this thesis.

2.2 Molecular clouds

As seen in the previous section, the interstellar medium has a wide range of temperatures and densities. The colder and denser gas is generally embedded in the warmer more diffuse gas. Most of the gas in a galaxy is probably somehow involved in the cycles of star formation, but the colder gas is more directly involved as star formation occurs in the coldest and densest regions, the molecular clouds. But how are molecular clouds defined? At which densities and temperatures does the gas become star forming?

Historically, the concept of molecular clouds is intertwined with observations of CO. CO was first detected towards the Orion nebula by Wilson et al. (1970), and not long after, astronomers started mapping the CO in the sky through various surveys. The first full map of the Milky Way was completed in 1987, establishing CO to be clumpy and cloudlike (Dame et al. 1987). Other surveys followed, reviewed in Heyer and Dame (2015). Catalogues of molecular clouds as discrete units of CO emission became a product of such surveys, and most molecular clouds have been located in that way. A molecular cloud is generally defined as a coherent structure in position-position-velocity space with CO emission above some threshold (Heyer and Dame 2015). CO requires shielding from radiation to not dissociate, and the gas density at which this shielding becomes effective provides a natural boundary to the cloud (Heyer and Dame 2015).

Figure 2.3 shows molecular/CO clouds in six nearby galaxies. It is very recently that the resolutions required to see the molecular gas in nearby galaxies at such a level of detail have been achieved. The data in the figure are from the PHANGS survey with ALMA telescope. PHANGS is mapping $\sim$90 nearby galaxies in CO(2-1) at $1 - 1.5$ arcsec resolution, corresponding to a physical resolution of 20-130 pc (Sun et al. 2018, 2020; Leroy et al. 2021). In these data it is clear that molecular clouds follow the spiral arms of galaxies (e.g. Rosolowsky et al. 2021). The Milky Way in molecular clouds/CO from Dame et al. (2001) is seen in figure 2.4. This is the most recent complete survey of CO in the Milky Way, and has been important for Galactic studies of molecular clouds. It is challenging to disentangle the clouds in the Milky Way and to

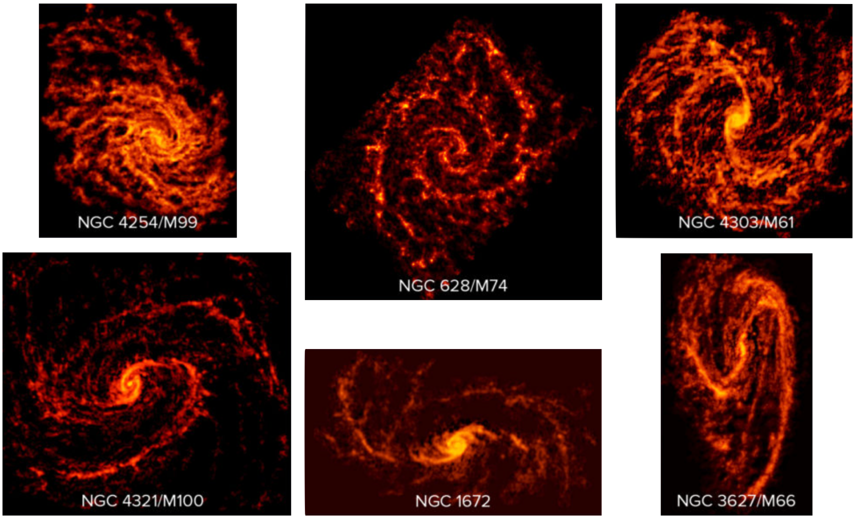

Figure 2.3: Six of the galaxies in the PHANGS sample mapped in CO. Credit: ALMA (ESO/NAOJ/NRAO); NRAO/AUI/NSF, B. Saxton.

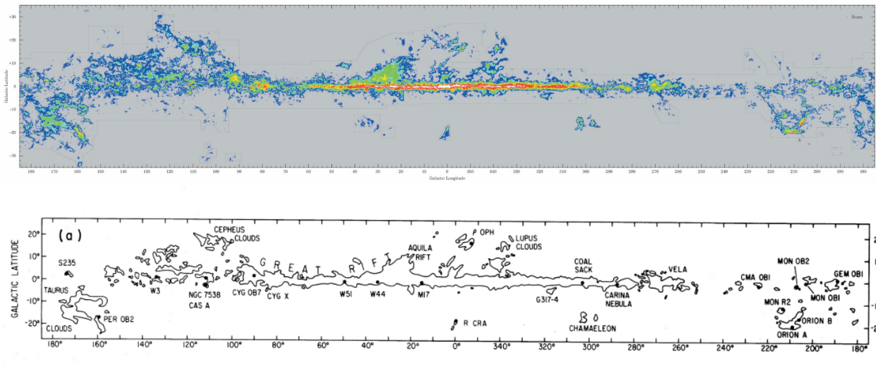

Figure 2.4: **Top:** The Milky Way in CO from Dame et al. (2001), the most recent complete survey of our Galaxy in CO. **Bottom:** Names of clouds in the Milky Way with CO contour, from Dame et al. (1987).

determine their distances, as the geometry of our Galaxy is still not certain. But for nearby clouds we have the ability to resolve their substructures down to fractions of a parsec (see figure 1.4), and such observations have revealed important properties of molecular clouds.

From observations of Galactic molecular clouds it has been found that the majority of clouds are small with low masses, but that most of the molecular mass in the Milky Way resides within clouds with masses greater than 10^5 $M_\odot$, and there is an upper mass limit of $\sim 5 \times 10^6$ $M_\odot$ (Heyer and Dame 2015). The CO observations have revealed large velocity dispersions in molecular clouds. This may be due to the clouds undergoing gravitational collapse and/or due to supersonic turbulence (Ballesteros-Paredes et al. 2011; Dobbs et al. 2014). Observations also indicate that molecular clouds are gravitationally bound, and have approximately constant surface density. These properties are captured by the Larson (1981) relations, described in section 3.2. How many stars form within a cloud seems to depend on the distribution of the cloud's internal structure (Kainulainen et al. 2009, 2014). This structure can be studied with the help of column density maps, which will be done in this thesis and described in the next section.

2.3 Mapping molecular clouds

Star formation depends on the mass distribution of molecular clouds, and this mass distribution can be studied by mapping the clouds using molecular emission, dust emission or dust extinction. Dust traces a wider range of densities than molecular lines do (Goodman et al. 2009), with extinction being very sensitive to low column densities, and emission tracing high column density regions well. In this work, we mostly use dust extinction to map molecular clouds in the Milky Way, and for a few clouds we also use dust emission. We plan to use molecular (CO) line mapping in a future paper to include velocity information. In the following sections I provide an overview of the three tracers used to map molecular clouds.

Molecular line mapping

The transitions between energy levels in molecules emit photons with known wavelengths. Different molecules and different transitions are observed at different gas densities and temperatures and in different radiation fields (e.g. Pety et al. 2017). The intensity of a given transition received by a telescope depends on the number of molecules present in the source, at the upper energy level of the transition. This number depends on the overall number of molecules (and therefore the gas density in the source) and the excitation conditions of the molecules (and therefore the gas temperature and/or the radiation field). An additional level of complexity is owed to the chemical networks through which molecules are formed and destroyed, and therefore control the abundance of each molecule as a function of the gas density, temperature and radiation field. This means that molecular lines observed by telescopes can be complicated to analyse, but contain crucial information about the physical conditions in the observed region. From the velocity structure of the molecular lines one can infer the dynamics of the region in question, which is one of the major advantages of molecular line mapping compared to dust mapping. Molecular line mapping is also the main way molecular clouds in external galaxies are studied. The major disadvantage of molecular line mapping compared to dust mapping is the limited range in density and temperature which a single transition probes (Goodman et al. 2009).

To observe the cold molecular phase of the ISM, with temperatures generally less than $\sim$ 30K, we therefore need to use molecular transitions with low energy levels. This is one of the main reasons why it is difficult to observe H_2 directly: the lowest transition requires temperatures of $\sim$200 K to be thermally excited, and the higher transitions are widely spaced. The second most abundant molecule CO is much less abundant than H_2, but can be used to infer the amount of H_2 using a conversion factor. Bolatto et al. (2013) recommend this conversion factor for the Milky Way:

$$X_{\rm CO} = 2 \times 10^{20}\ {\rm cm}^{-2}({\rm K\ km\ s}^{-1})^{-1}, \tag{2.1}$$

with an uncertainty of $\sim$ 30%. Tracing the most abundant molecule in the universe (H_2) with one that is a factor of 4000-7000 less abundant (CO) poses some risks (Bolatto et al. 2013). The relative abundance of the two molecules varies with metallicity, and is different in the central regions of galaxies (Bolatto et al. 2013).

Several works have shown that there is some H_2 gas that is "CO dark" (Heyer and Dame 2015). At high densities the CO molecules can "freeze out" onto dust grains and at low densities they require shielding in order to not be disassociated by UV radiation. However, CO has a major advantage: it has conveniently spaced rotational energy levels, low enough to emit in the cold ISM. The three lowest transitions lie only 4-22 K above the ground state, and the molecules can therefore emit in the coldest regions of the ISM (Heyer and Dame 2015). The wavelengths of the transitions are in sub-millimetre and millimetre wavelengths, which are accessible to ground based telescopes. Because of the high abundance relative to other molecules, the low energy transitions and the convenient wavelengths, CO is the molecule most used for mapping molecular clouds (Heyer and Dame 2015). There are also many other molecules that can and have been used to study the ISM, but none have been studied and used as extensively as CO, and none seem to trace the total molecular gas as well.

CO has several isotopologues, the most abundant one being ^{12}CO. ^{12}CO is mostly optically thick, which means that the radiation we see from this molecule mainly comes from the "surface" of molecular clouds. Another commonly used isotopologue of CO is ^{13}CO, which is much less abundant and therefore harder to detect and mostly optically thin. This means that the ^{13}CO emission is not strong enough to trace diffuse regions, but it has the advantage of being able to probe not only the surface of the molecular clouds, but also the interior.

In this thesis, most of the molecular cloud sample comes from identification of coherent structures in the whole Milky Way position-position-velocity ^{12}CO survey from Dame et al. (2001). This survey contains velocity information for the clouds, and will in a further work be used to study dynamical properties of molecular clouds and their dependency on scales.

Dust emission mapping

As opposed to molecules, dust is not subject to complex phase changes, chemistry and excitation conditions, and is therefore a more stable tracer of the ISM (Molinari et al. 2010b). Dust particles heated by interstellar starlight emit thermal radiation according to the Planck law. The temperature of molecular clouds is around 10-15 K, and so the emission from the dust grains peak in the far infrared, but can also be observed at infrared and (sub-)millimetre wavelengths. In low density regions the dust emission is weak, and dust emission therefore works best for mapping high density regions. To infer the corresponding gas column density from the thermal dust emission, one needs to make assumptions for the temperature, emissivity of the dust grains and the gas to dust ratio. The gas to dust ratio is usually assumed to be ~ 100 in the Milky Way, and the emissivity depends on the grain composition, which is relatively tightly constrained by the infrared spectrum (Draine 2011). The temperature can vary significantly along a line of sight, and to take this into account Marsh et al. (2015, 2017) developed a procedure to constrain the temperature along the line of sight using observations at several different wavelengths. This point process mapping method (PPMAP) is applied for the emission maps used in this work. In this thesis dust emission is used to get column density maps for a handful of molecular clouds in the galactic plane.

Dust extinction mapping

Extinction is caused when dust absorbs and scatters background light. This can be mapped by considering many lines of sight towards background stars. The way this was first done was by star counting, as fewer stars are visible in regions with foreground clouds due to extinction. Now it is more common to use reddening or colour excess to study the clouds, as the amount of reddening is related to the amount of dust along the line of sight (Draine 2011). We usually assume that the dust is well mixed with the gas, and the amount of extinction/reddening can then be used to infer the amount of gas present (Boulanger et al. 1985; Heyer and Dame 2015). This is done through the well-established relation between extinction and hydrogen column density (Bohlin et al. 1978; Güver and Özel 2009).

The way extinction/reddening is related to the amount of dust present is described by radiative transfer. The radiative transfer equation describes how the intensity of light changes when travelling through a medium. With no emission the equation reads:

$$I_i^{\mathrm{obs}} = I_i^0 \times e^{-\tau_i}, \tag{2.2}$$

where I_i^{obs} is the observed intensity of light from a star in wavelength band i and I_i^0 is the initial/intrinsic intensity. τ is the optical depth, and is related to the density and absorption properties of the foreground medium. The colour of a star is defined as the ratio of the intensity in two different bands:

$$(m_i - m_j)_{\mathrm{obs}} = -2.5 \log \frac{I_i^{\mathrm{obs}}}{I_j^{\mathrm{obs}}}, \tag{2.3}$$

where m_i is the apparent magnitude in band i. The colour excess is then defined as the difference between the observed and intrinsic colour of a star:

$$E_{i-j} = (m_i - m_j)_{\mathrm{obs}} - (m_i - m_j)_0 \,. \tag{2.4}$$

The colour excess in the visual band is related to the extinction A_{V} with a proportionality constant R_V:

$$A_{\mathrm{V}} = R_V \cdot E_{B-V}. \tag{2.5}$$

R_V is $\sim$ 3.1 in the Milky Way, but varies between regions (Kreckel et al. 2013; Schlafly et al. 2016). The extinction in the visible band is related to the hydrogen column density N_{H} (Bohlin et al. 1978). We use the relation from Güver and Özel (2009):

$$N_{\mathrm{H}} \left[\mathrm{cm}^{-2}\right] = (2.21 \pm 0.09) \times 10^{21} A_{\mathrm{V}}[\mathrm{mag}]. \tag{2.6}$$

These equations describe how we can use the colours of background stars to find the column density of the foreground clouds.

To measure the extinction along a line of sight to a star we need to know the intrinsic colour of the star. This can be found by spectroscopic analysis and determination of the spectral class of individual stars, but it requires expensive observations and it is time consuming. Lada et al. (1994) developed a method where intrinsic colour is inferred from the mean of a large sample of stars in a nearby field assumed to be free of extinction. This method facilitates measuring extinction towards many lines of sight and thus mapping extended regions. The pixels in the maps are assigned weighted mean extinction values. The method got the name NICE (Near Infrared Colour Excess method), and was later further developed into NICER (Lombardi and Alves 2001) and NICEST (Lombardi 2009). The main difference from NICE to NICER is that the method was optimised and generalised to multi-band observations, and errors and scatter were taken into account. NICEST adjusts for contamination from foreground stars and corrects for possible substructure below the smoothing length/pixel scale. The NICER and NICEST extinction mapping methods were used to produce the extinction maps used in this work.

2.4 Young stellar objects

A key component to understand the link between the interstellar medium and star formation is young stellar objects (YSOs), the precursors to stars. YSOs are born in the high density parts of molecular clouds, and the numbers and masses of them can tell us about the star formation activity of their parent cloud. The star formation rate of a cloud is computed as:

$$\mathrm{SFR} = \frac{M_{\mathrm{YSOs}}}{t_{\mathrm{YSO}}}, \tag{2.7}$$

where M_{YSOs} is the mass of YSOs in the cloud and t_{YSO} is their age/lifetime. The mass of YSOs is calculated as the number of YSOs times the mean mass of a YSO, and the mean mass of YSOs come from the initial stellar mass function (IMF). The most commonly used IMF comes from Chabrier (2003) and has a mean mass of $0.5\mathrm{M}_{\odot}$. It is however possible that the mass distribution of stars varies between star forming regions, galactic environments and/or galaxy types (Kennicutt and Evans 2012; Cappellari et al. 2012; Martín-Navarro et al. 2015). The mean lifetime of YSOs is $t_{\mathrm{YSO}} \sim 2 \cdot 10^6$ yr, but varies between YSO classes and is uncertain by a factor of $\sim$2 (Padoan et al. 2014). The star formation efficiency is the fraction of the cloud mass which is forming stars:

$$\mathrm{SFE} = \frac{M_{\mathrm{YSOs}}}{M_{\mathrm{cloud}} + M_{\mathrm{YSOs}}}. \tag{2.8}$$

The star formation rate and efficiency varies between molecular clouds, and a long standing aim of ISM research has been to understand which physical processes determine these numbers. Therefore, we wish to get an as complete picture as possible of where YSOs are found. YSOs are small and faint, and they can be obscured by their dense and dusty natal environment. This means that YSOs can be difficult to detect even in nearby clouds, and this difficulty increases with distance.

YSOs are divided into classes based on their spectral energy distribution. The classes correspond to stages in their evolution from a core to a main sequence star, as illustrated in figure 2.5. The different classes are observed at

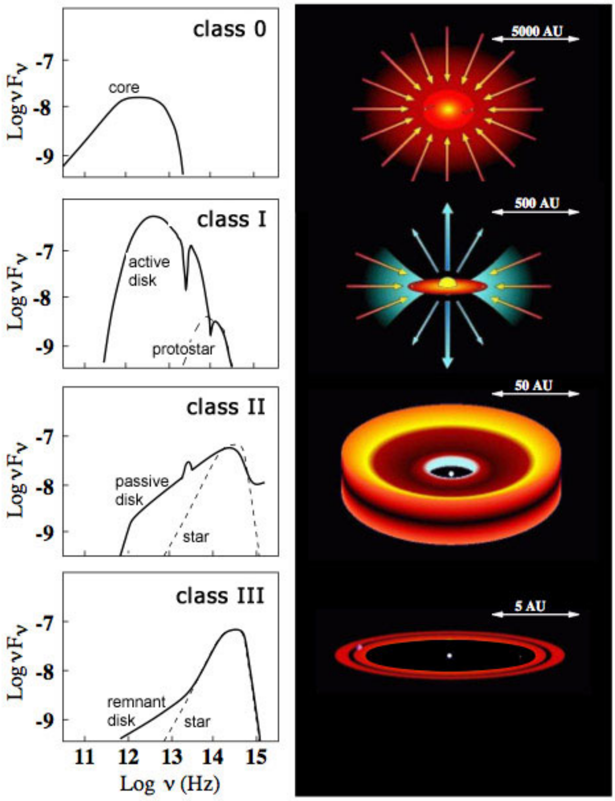

Figure 2.5: The spectrum (left) and structure (right) of the four classes of YSOs. Credit: Andrea Isella.

different wavelengths, the emission of class 0 YSOs peaks at sub-millimetre, class 1 peaks at far infrared, class 2 peaks at near infrared and class 3 peaks in the visible. Several surveys have searched for YSOs in nearby clouds and in the Milky Way disk. Most of the molecular clouds within 500 pc have been surveyed for YSOs with the *Spitzer* infrared telescope (Evans II et al. 2003; Dunham et al. 2015). A full sky infrared survey was done by Wright et al. (2010), enabling detection of optically thick disk emission for solar-type stars out to 1 kpc distance. More recently, YSOs have also been found in data from the *Gaia* mission (e.g. Zari et al. 2018). For more distant clouds several individual surveys have been done with various telescopes, leading to variations in completeness and which classes of YSOs that are targeted.

In this thesis and appended paper, I investigate how star formation, measured by YSO counts, depends on the scale on which it is studied. This could provide clues to the physical processes responsible for setting the numbers and masses of the generations of stars in galaxies. In order to study star formation in molecular clouds across a large range of scales, a goal of this work is to gather a complete census of YSOs in molecular clouds within 2 kpc distance.

CHAPTER 3

Structure and characteristics of the ISM

In this chapter I summarise some relevant background theory to this thesis, on the structure and characteristics of the ISM. Section 3.1 describes the main physical processes acting in the ISM: gravity, turbulence and magnetic fields. Then, section 3.2 contains an overview of the relevant diagnostics used to describe and characterise the ISM in this work: Column density probability distribution functions (N-PDFs), Larson's relations and the Kennicutt-Schmidt relation.

3.1 Shapers of the ISM

This section gives a short summary of the most important physical processes shaping molecular clouds and the interstellar medium, and hence also contributing to set the stage for star formation. The most important physical processes are gravity, turbulence and magnetic fields. I will also briefly discuss the role of some other physical processes.

Gravity

Gravity is one of the lead actors in the physics of molecular clouds and star formation, but it is not yet clear whether clouds as a whole are undergoing gravitational collapse or are virialised (Ballesteros-Paredes et al. 2011; Dobbs et al. 2014). A cloud is said to be virialised when it is in equilibrium between collapse and expansion, ie. when gravitational forces inwards balance the kinetic energy outwards. In mathematical form, this is expressed through the virial theorem:

$$Potential = 2 \times Kinetic \tag{3.1}$$

$$\frac{GMm}{r^2} = 2 \times \frac{mv^2}{2} \tag{3.2}$$

$$\frac{GM}{r^2} = v^2, \tag{3.3}$$

where G is the gravitational constant, M is the mass of the cloud, m is the mass of a particle/molecule, r is the radius of the cloud and v is the velocity of the particle. From this, one can derive that when the cloud reaches a certain mass the equilibrium no longer holds, and the cloud collapses. This critical mass is called the Jeans mass, and is expressed as:

$$M_J \approx \left(\frac{5k_BT}{G\mu m_H}\right)^{3/2} \left(\frac{3}{4\pi\rho_o}\right)^{1/2}. \tag{3.4}$$

Here, the particle's kinetic energy is expressed through the temperature, and density is substituted for size. It should be noted that the Jeans mass above applies to spherical objects, and molecular clouds are far from spherical (see figures 1.4 and 1.5). However, the form of the Jeans mass illustrates that the mass scale that can undergo collapse depends on temperature/velocity and size/density. Such a critical mass leads to fragmentation: when the cloud is collapsing, regions within the cloud can reach the Jeans mass and start collapsing in on themselves. The mass where this fragmentation and collapse happens can determine the masses of stars, and is therefore of key importance. However, if gas collapsed due to gravity only, stars would form 100 times faster than we observe (Ballesteros-Paredes et al. 2011). This implies that something supports the clouds against gravity, and the most likely mechanisms to uphold the clouds against gravity are turbulence or magnetic fields.

Turbulence

Turbulence can be described as a cascade of motions from large to small scales, or small eddies super-imposed on larger ones. This was nicely illustrated by da Vinci, see figure 3.1. Turbulence leads to energy being transported from larger to smaller scales, before it dissipates at the scale of the smallest eddies. Turbulence arises when the velocity of a flow becomes so large that the inertial forces become large compared to viscous forces, which often happens in the interstellar medium. The properties of turbulence might contribute to setting the time, mass and size scales of star formation (Ballesteros-Paredes et al. 2006; Hennebelle and Falgarone 2012). How the masses of stars are set and how this varies is still an open question in astrophysics, and understanding the turbulence in molecular clouds could help solve this.

Figure 3.1: Illustration of turbulence in water. Credit: Leonardo da Vinci, Studies of Turbulent Water, Royal Collection Trust/© Her Majesty Queen Elizabeth II 2021.

The statistics of subsonic turbulence were described by Kolmogorov (1941), who showed that the energy cascade through the scales in a medium with subsonic turbulence is characterised by an energy spectrum $E(k) \propto k^{5/3}$, where k is the wavenumber $2\pi/L$ for each scale L. This leads to a relation between velocity and scale: $v \propto L^{1/3}$. In a turbulent medium the largest scales then carry the most velocity, while the smallest carry most of the vorticity. A medium is said to be turbulent if the Reynolds number is large, $R_e >> 1$, where $R_e = \frac{vL\rho}{\eta}$. ρ is the density of the medium and η the viscosity. In molecular clouds the Reynolds number is observed to be $\sim 10^6$–10^7, and thus they are definitely in the realm of turbulence (Hennebelle and Falgarone 2012). The turbulence in the ISM is supersonic (velocities exceed the local speed of sound), and supersonic turbulence is not well understood, but probably has some similarities with subsonic turbulence (Ballesteros-Paredes et al. 2006).

The origins of the turbulent motions in the ISM are not certain. Turbulence decays, so we need something to power and maintain the turbulence. The powering mechanism could be gravitational collapse, or the turbulence could be driven internally or externally by some other physical process. Phenomena that could drive turbulence externally are the spiral density waves in the galactic disk, or feedback from relatively nearby supernovae. Possible internal drivers of turbulence include protostellar jets, stellar winds, radiation pressure and photoionisation (Dobbs et al. 2014). Brunt et al. (2009) point to the dominant processes driving molecular cloud velocity structures working on scales larger than the clouds, and hence the source of the turbulence is likely external to the clouds. It may also be that the drivers of turbulence varies between clouds, with different conditions and environments (Dobbs et al. 2014).

Turbulence sets its signature in the distribution of gas in the ISM, by making the distribution more chaotic and preventing some of the gas to collapse to high densities by distributing the gas across a range of densities. It seems to help prevent collapse on large scales, but contribute to the formation of filaments and cores on small scales (Mac Low and Klessen 2004; Ballesteros-Paredes et al. 2006). It is also thought to make the ISM structure fractal and hierarchical (Vazquez-Semadeni 1994). The density distribution of the dense ISM is studied in this thesis and the appended paper, and I will come back to the signature of turbulence in section 3.2.

Magnetic fields

Observations have shown that magnetic fields trace the spiral arms of galaxies, where the molecular clouds are located and star formation occurs (Fletcher et al. 2011; Li and Henning 2011). Magnetic fields are also seen on smaller scales, in individual molecular clouds (i.e. Planck Collaboration et al. 2016) and strong fields are seen in protostars and stars (e.g. Bouvier et al. 2007; Donati and Landstreet 2009). Magnetic fields on the scales of a galaxy and a cloud are shown in figure 3.2. Although magnetic fields are not directly related to the work of this thesis, it is one of the shapers of the interstellar medium, so I give a brief summary of what is known of the role of magnetic fields in the ISM and star formation.

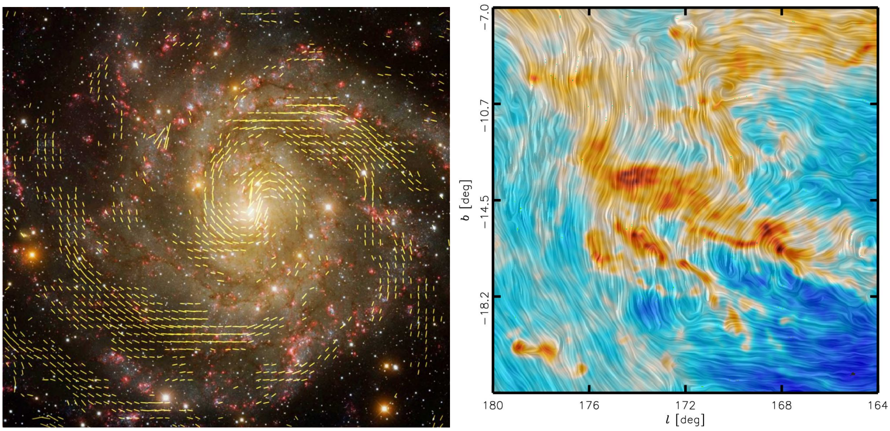

Figure 3.2: Left: Magnetic field orientation in galaxy IC342, shown on a combined radio/optical image from the Very Large Array and the Effelsberg telescope. Credit: R. Beck, MPIfR; NRAO/AUI/NSF; graphics: U. Klein, AIfA; Background image: T.A. Rector, University of Alaska Anchorage and H. Schweiker, WIYN; NOAO/AURA/NSF. **Right:** The magnetic fields in the Taurus molecular cloud from Planck Collaboration et al. (2016).

Much of the debate in the role and importance of magnetic fields in shaping the ISM and star formation has been about the relative strength of the interstellar magnetic fields, and if they are strong enough to be the main support against gravitational collapse of molecular clouds and strong enough to dominate over turbulence (Crutcher 2012). The strength of the magnetic fields is difficult to measure, and we therefore have not known how important the magnetic fields are at different scales. Observations of the Zeeman effect now indicate that magnetic energy is of comparable strength to turbulent energy, but has a wide range of values (Crutcher 2012). Magnetic fields have been proposed to contribute to the formation of molecular clouds, through what is known as Parker instabilities (Parker 1966). This theory suggests that magnetic fields in the ISM of galaxy disks could build up large low density reservoirs of gas due to buoyancy. These could collapse and fragment by gravitational instability or local converging flows to form molecular clouds.

However, it is not known if this would be possible in the turbulent ISM (Dobbs et al. 2014).

Recently, it has become possible to observe the orientation of magnetic fields through dust polarisation. Since dust particles are generally not spherical, their orientation is affected by the magnetic fields. When background starlight then passes through the dust it becomes polarised. The dust can also thermally emit polarised radiation. Magnetic fields in molecular clouds are observed both parallel and perpendicular to filamentary/cloud structures (Li et al. 2013; Planck Collaboration et al. 2016; Soler 2019) (both cases can be seen in the right panel of figure 3.2). Parallel fields may indicate contraction along magnetic field lines, while perpendicular fields may "trap" matter in magnetic flux tubes (Crutcher 2012). Planck Collaboration et al. (2016) studied the alignment of density structure and magnetic fields in ten nearby molecular clouds using dust emission. They conclude that magnetic fields are significant, and that the field lines tend to be more perpendicular to the high density structures. It then seems that magnetic fields may be strong enough to prevent gravitational collapse on large scales in some cases (Crutcher 2012), while within clouds it can contribute to regulate the contraction and fragmentation of gas along filamentary structures (Planck Collaboration et al. 2016).

In a recent review, Hennebelle and Inutsuka (2019) conclude that relatively strong magnetic fields can significantly affect the star formation process, especially by inducing formation of more massive stars. They also affect the distribution of gas in molecular clouds, and seem to influence the gas to organise into filaments rather than clumps and cores, by this reducing the star formation rate (Hennebelle and Inutsuka 2019). The signature of magnetic fields in ISM density distributions seem to be less clear than the turbulence signature (Molina et al. 2012; Hennebelle and Inutsuka 2019), but Soler (2019) find that the distribution of gas is different in regions where the field is perpendicular to the density structures.

Other physical processes

There are also other physical processes at work in the interstellar medium. Some important ones are radiative processes, galaxy dynamics, galactic potential and feedback. Radiative processes lead to heating and cooling of gas, which influences the densities in the ISM. Cooling is essential to the build up of high density structures and star formation, as small scale and high density structures are unable to form at high temperatures (see Jeans mass eq. 3.4). Galaxy dynamics influence the ISM by making it constantly changing, and might help drive turbulence on large scales. The density in the spiral arms of galaxies is higher than in between the arms, and these spiral density waves might induce cloud-cloud collisions, increase the densities in clouds and trigger shocks and star formation (Elmegreen 1998). The global gravitational potential of the galaxy is believed to play a significant role at scales $\gtrsim$ 100 pc (c.f. Meidt et al. 2020). Feedback from supernovae, expanding HII regions, protostellar jets, stellar winds and ionising radiation from young stars can halt star formation and disperse clouds as well as power turbulence. Implementing feedback in galaxy simulations is essential to produce galaxies with realistic star formation histories and efficiencies (Naab and Ostriker 2017). This indicates that feedback and galaxy dynamics have to be taken into account in a complete theory of star formation.

3.2 ISM diagnostics

This section describes some of the diagnostics used to characterise and understand the structure and physical processes in the ISM. First I will give an overview of density probability distribution functions, and then follows a description of the most important scaling relations related to the ISM and star formation: Larson's relations and the Kennicutt-Schmidt relation.

Density probability distribution functions

The density probability distribution function (PDF) is a statistical representation of the amount of gas present at different densities. Density PDFs are a fundamental measure of molecular cloud structure, and can tell us about how much gas is dense enough to form stars and about the contribution from gravity, turbulence and magnetic fields. The reason is that the shape of density PDFs depends on the physical processes in the clouds (reviewed in Hennebelle and Falgarone 2012; Padoan et al. 2014). It is not possible to observe the volume density of molecular clouds directly, what we observe is the surface or column density N. PDFs of column density (N-PDFs) can also be related to the physical processes within the clouds, and it is the diagnostic used in this thesis to study the scale dependency of the density distribution of molecular clouds.

The link between the PDF shape and physical processes has been studied widely with numerical simulations. Simulations of molecular clouds dominated by supersonic turbulence and not significantly affected by gravity predict lognormal N-PDFs, while self-gravitating gas is expected to develop PDFs with power law shapes at high densities (Federrath and Klessen 2013; Klessen et al. 2000; Federrath et al. 2008; Ballesteros-Paredes et al. 2009; Kritsuk et al. 2011). The evolution of N-PDFs as a function time can be studied, e.g., via simulations in which the physical processes change as a function of time. A common way to do this is to start from a gas reservoir that has only been shaped by turbulence, and then follow the evolution of that gas under self-gravity. In this kind of simulations, the gas then transits from turbulence dominated phase to a gravity dominated phase, as shown in figure 3.3 from Ward et al. (2014). This figure clearly shows how the shape of the N-PDF changes with time from turbulence dominated with lognormal shape to gravity dominated with power law shape.

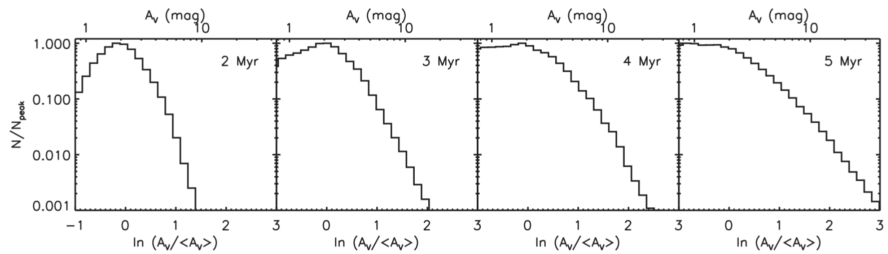

Figure 3.3: Evolution of an N-PDF from turbulence dominated to gravity dominated, from Ward et al. (2014).

Inspired by these predictions, the observed N-PDFs have commonly been analysed with log-normals, power-laws, or the combination of the two. These observed shapes can then provide clues to the evolutionary stage of the cloud and the contribution from turbulence, gravity and magnetic fields. The width of the lognormal part of the N-PDF is from simulations predicted to be related to the strength of turbulence and the magnetic field (at intermediate magnetic field strengths) as:

$$\sigma_s^2 = \ln(1 + b^2 M_s^2 \frac{\beta}{1+\beta}), \tag{3.5}$$

where σ_s is the standard deviation of the lognormal part of the N-PDF, b is the forcing parameter related to the turbulence driving, M_s is the sonic Mach number related to turbulence strength and β is the ratio of thermal to magnetic pressure (Molina et al. 2012).

The width of N-PDFs can then be used to infer the physical conditions in molecular clouds, and Burkhart et al. (2017) argues that the transition point and slope can too. The authors argue that these shape parameters are related to the amount of gas undergoing gravitational collapse, and also find that they likely depend on the magnetic field. The effect of the magnetic field is also studied by e.g. Auddy et al. (2018), and observations by Soler (2019) show that N-PDF slopes are steepest in regions where the magnetic field is close to perpendicular to density structures in molecular clouds.

The N-PDFs can then be used as a tool to characterise the structure of the cloud and infer the physical conditions in the cloud. The shape of N-PDFs are also proposed to affect the initial mass function of stars and the star formation rates of clouds (Krumholz and McKee 2005; Federrath and Klessen 2013). Together with the roles of gravity, turbulence and magnetic fields these are crucial aspects in the theory of star formation and highlight the utility of N-PDFs as a tool to quantify the internal structure of clouds and relate it to star formation.

N-PDFs have so far been observed using mostly small samples or individual clouds in the Solar neighbourhood (Kainulainen et al. 2009, 2014; Schneider et al. 2013; de Oliveira et al. 2014; Lombardi et al. 2015), or covering large portions of external galaxy disks (Hughes et al. 2013). Within the Milky Way, there is some debate as to what is the most common shape of N-PDFs. Previous works have established a habit of describing them with lognormal functions, power-laws, or a combination of the two (e.g., Kainulainen et al. 2009, 2013; Schneider et al. 2013; Chen et al. 2018). Some studies argue that all N-PDFs are power-laws (i.e. Lombardi et al. 2015), while others argue that when field selection is tightly constrained to the cold, molecular zone, N-PDFs are best described by log-normals (Brunt 2015). Outside the Milky Way, Hughes et al. (2013) find that the CO N-PDFs of kpc regions of M51, M33 and the LMC are best described by lognormals.

Extragalactic studies cover entire galaxies (several of kpc), while Galactic studies so far only cover an area of some hundred pc; only the Solar neighbourhood closer than ~250 pc has been studied in a complete manner so far

(Kainulainen et al. 2009, 2014). As a result, it is not yet possible to understand the connection between the statistics describing the internal cloud structure and those describing the galactic-scale gas distribution. To tie these together, an overlap in the scales between the Galactic and extragalactic works is needed. In this thesis and the appended paper we attempt to bridge this gap by studying the shapes of N-PDFs in a portion of the Milky Way and their relation to star formation from sub-pc to kpc scales.

Larson's relations

Three relations found by Larson (1981) have been very important for the understanding of molecular clouds and star formation and have influenced the field for 40 years. The relations provide simple ways to characterise the structure of molecular clouds, and can be used as probes of scale-dependent phenomena. The three relations imply that molecular clouds are turbulent, gravitationally bound and have approximately constant column/surface density. The relations were found through studying nearby Galactic molecular clouds with various tracers, but have also been observed in nearby galaxies (Bolatto et al. 2008; Fukui and Kawamura 2010; Sun et al. 2018, 2020). The relations are not independent, any two can be used to derive the third. The relations are:

1. The **size - line width** relation: $\sigma_v \propto L^{0.38}$. This relation implies that molecular clouds are turbulent. A characteristic of turbulence is that variance is dependant of scale, which is what we have here. The exponent 0.38 is from Larson (1981), and is similar to the Kolmogorov (1941) law for subsonic turbulence which has an exponent of 1/3. Later studies have found exponents closer to 0.5 in supersonic molecular clouds (Heyer and Dame 2015).

2. The **mass - line width** relation: $\sigma_v \propto M^{0.2}$. This relation implies that molecular clouds are in approximate virial equilibrium between gravity and internal velocities, ie. they are gravitationally bound. Some clouds and regions within clouds have higher masses compared to internal velocities and can then undergo gravitational collapse leading to star formation. But theories of gravitational collapse and fragmentation alone give star formation rates and efficiencies much higher than what is

observed, and hence most clouds seem to not be collapsing, but rather exist in equilibrium.

3. The **density - size** relation: $n(H_2) \propto L^{-1.1}$. This relation implies approximately constant column density of molecular clouds. This might be due to the shielding required for molecules to survive in radiation fields, but could also be partly caused by observational detection limits. Later studies have found that the surface density of molecular clouds depends on the position of the cloud in the galaxy; clouds in the inner galaxy tend to have higher surface densities than the ones in the outer galaxy (Heyer and Dame 2015).

Given the strong influence of these relations on the field of star formation and ISM studies, it is important to understand how the relations depend on the scale on which they are studied. This is something I am planning to study in a forthcoming paper.

The Kennicutt-Schmidt relation

There is a clear correlation between gas surface density of the interstellar medium and star formation rate. This relation is so important in the study of star formation in galaxies that it is often called "The star formation relation". The relation was first observed by Schmidt (1959), and later expanded by Kennicutt (1998). It is therefore also called the Schmidt-Kennicutt or Kennicutt-Schmidt (KS) relation. There has been some debate to the exact exponent of the KS relation, whether the correlation is tightest with all gas or molecular gas only, and to the range and globality of it. But it is clear that higher surface density of gas in galaxies leads

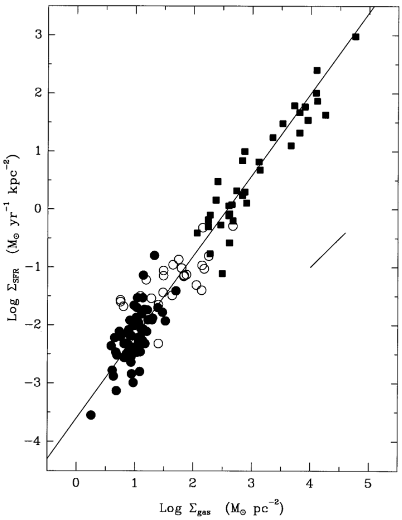

Figure 3.4: The star formation relation as observed by Kennicutt (1998).

to higher star formation rates. The relation as observed by Kennicutt (1998) is shown in figure 3.4.

The relation reads:

$$\Sigma_{gas} \propto \Sigma_{SFR}^{1.4}, \tag{3.6}$$

where Σ_{gas} is the surface density of gas and Σ_{SFR} is the surface density of stars born per year. 1.40 is the exponent from Kennicutt (1998). The original points in the KS relation came from galaxies, but the relation has also been studied within galaxies and within the Milky Way.

For whole galaxies and large areas within, the correlation is clearly present down to 100-200 pc scales (Bigiel et al. 2008; Kennicutt and Evans 2012). For nearby ($d < 500$ pc) clouds the correlation is seen within clouds on $0.3 - 2$ pc scales (Lada et al. 2010; Gutermuth et al. 2011), and is found to be more localised to the densest gas than in extragalactic works (Kennicutt and Evans 2012). However, the star formation relation is not seen between clouds (Lada et al. 2013), and the authors argue that the extragalactic KS relation therefore arises due to unresolved molecular clouds. This breakdown of the star formation relation between some size-scales is interesting and might have important implications for star formation theories and understanding which physical processes dictate the star formation rate. This relation and its dependency on scale is studied in the appended paper, and the results are summarised in chapter 5.

CHAPTER 4

Bird's-eye view of molecular clouds in the Milky Way

In the previous chapters I have provided an overview of observations, structure and characteristics of the interstellar medium and star formation. As was seen already in section 1.1, the scales involved in the process of transforming gas to new stars are diverse, from galaxy disks (tens of kpc) to protostars (small fractions of a pc). In such a broad span of scales the way we study the ISM varies significantly. The differences between Galactic and extragalactic studies of the ISM are especially prominent, and the scales studied by the two camps of astronomers are difficult to reconcile. To deepen our knowledge and come closer to understanding the complete process of star formation, the variation of the ISM and star formation needs to be studied and understood across the full range of scales. This could lead to answers on how the different processes act on different scales, and what sets the star formation rates, efficiencies and masses of stars. Therefore, the aim of this thesis is to study the scale dependencies in the ISM.

To study the scale dependencies of star formation diagnostics and physical properties across a broad range of scales, the approach used in this thesis is to gather observations of the Milky Way covering a significant portion of the Galaxy disk into a bird's-eye view. For this the positions of molecular clouds within the disk are needed. Our perspective from inside the disk makes it difficult to measure distances accurately and to reconstruct the geometry of the Galaxy. Therefore it is not straightforward to construct a bird's eye view from observations of molecular clouds. However, several works have looked into this, and we are getting a little closer to an overview of the Galaxy. In the next few paragraphs some of the most relevant advances are described.

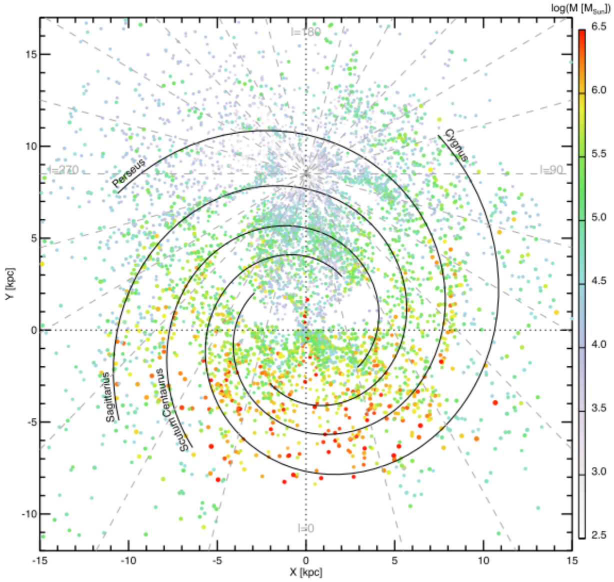

Figure 4.1: Bird's-eye view of molecular clouds in the Milky Way from Miville-Deschênes et al. (2017). Colour corresponds to mass of cloud and size corresponds to size. The approximate positions of the spiral arms are shown in black, from Vallée (2008).

The entire Dame et al. (2001) CO survey of the Milky Way has been decomposed into molecular clouds by Miville-Deschênes et al. (2017), and the velocities of the clouds were used to estimate distances. The resulting face on view is shown in figure 4.1. This view is very interesting because it covers almost all the CO in the galaxy and gives a nice overview of the molecular clouds, but the figure also shows some artefacts that come from the challenges of determining the positions of molecular clouds in the disk using velocities. Kinematic distances rely on rotation models of the Galaxy, and the velocities of the clouds are assumed to be only due to the rotation of the disk. But the velocities of the clouds are not always following the disk perfectly, and this leads to uncertainties in the kinematic distances. Kinematic distance also has the problem that it gives two solutions for the distances in the inner Galaxy $R_{\mathrm{Gal}} < R_0$. This is the reason for the shortage of molecular clouds in the circle between the Sun and the Galactic centre. Another artefact is that many small clouds are identified in the solar vicinity, while on the far side of the Galaxy the identified clouds are much more massive. And finally the cloud distribution does not trace the spiral arms anywhere near as well as in external galaxies. The Milky Way is thought to be a typical spiral galaxy, and the weak spiral arms seen in this picture is not likely to mean that the molecular clouds in our Galaxy follow the spiral arms less than in other galaxies. It rather points to uncertainties in distance measurements for the clouds, and in the spiral arm model.

Luckily, there are also other ways of determining distances than using the velocities of molecular clouds. When using parallaxes of stars rather than the radial velocities of CO gas, distances are generally more tightly constrained. Using parallaxes to get distances to molecular clouds is easier when using dust extinction rather than CO to trace the molecular clouds, because the stars are already involved in the extinction mapping. The *Gaia* satellite is currently determining accurate distances to over a billion stars in the Milky Way (Gaia Collaboration et al. 2016). This has recently been exploited to construct three dimensional dust maps of portions of the Milky Way disk by Rezaei Kh. et al. (2018), Lallement et al. (2018, 2019) and Green et al. (2019). Zucker et al. (2019, 2020) have used *Gaia* distances to accurately determine distances to the molecular clouds in the Solar vicinity. These works are leading to an improved bird's-eye view of our Galactic surroundings. Figure 4.2 shows the molecular clouds within ~ 2.5 kpc distance from Zucker et al. (2020). The background is the dust map from Green et al. (2019), showing that molecular clouds are beginning to be resolved in the disk of the Galaxy. However, also this map has some artefacts and the resolution is orders of magnitude lower than in extinction maps of the individual clouds, making internal cloud structure inaccessible.

In order to study the scale dependencies of the high density interstellar medium across a wide range of scales, it is possible to combine the large (kpc) scale picture of the Milky Way disk with the high resolution (sub-pc)

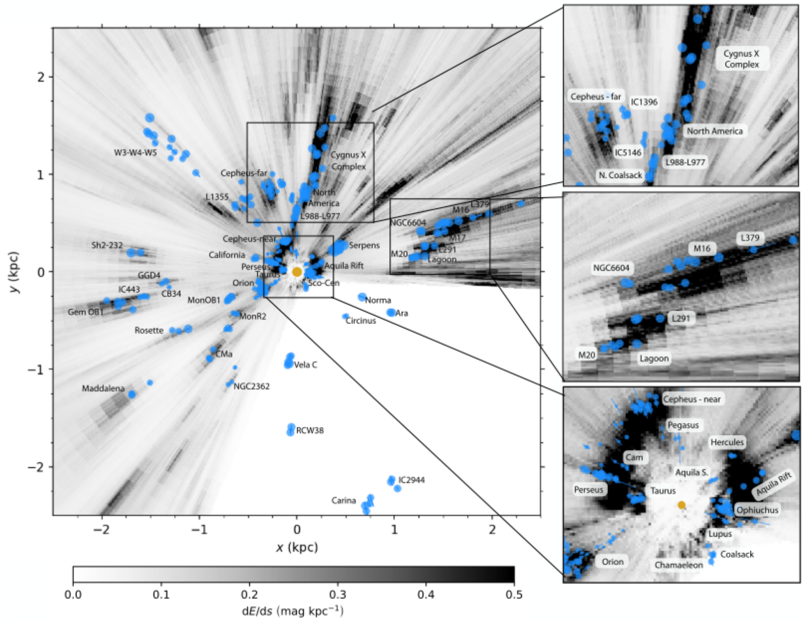

Figure 4.2: Bird's-eye view of molecular clouds within ~ 2.5 kpc distance from Zucker et al. (2020). The background black and white map is from the three dimensional dust map from Green et al. (2019).

observations of molecular clouds. This is what is done in this thesis. We take advantage of the recent improvements in distance determination of nearby clouds to look at the clouds in a bird's-eye perspective, and combine this with sub-pc column density maps of the clouds from dust extinction and emission. The portion of the Milky Way that is studied is a 2 kpc radius circle of the Galaxy disk, centred on the Sun. Within this circle, all major molecular clouds, their column density maps and YSO counts are collected from the literature. In the appended paper, the dataset is used to study the scale dependency of N-PDFs and star formation. The scale dependency is studied through defining apertures with a range of scales within our survey area, and examining the N-PDFs and star formation measures of the apertures and the individual clouds which compose them. Figure 4.3 shows the range of scales involved and an illustration of the two ways the sample is analysed is shown in figure 4.4. This new approach leads to the most complete picture to date of molecular clouds and star formation down to sub-pc scales in a significant (several kpc) portion of the disk of our own galaxy. This is a first step towards reconciling the studies of molecular clouds in the Milky Way with studies of molecular clouds in external galaxies.

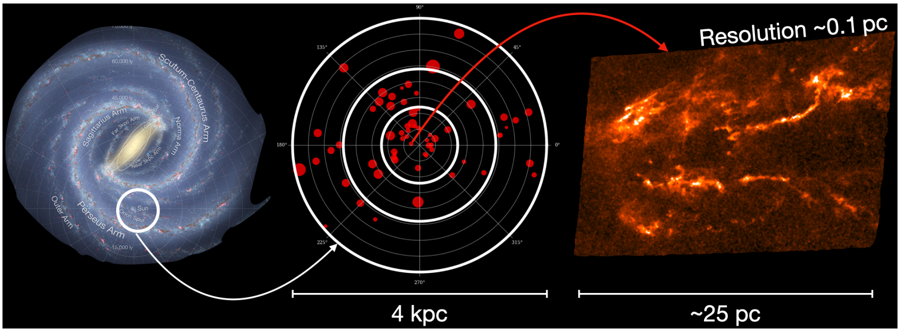

Figure 4.3: Illustration of the scales involved in this study of molecular clouds in the Milky Way: scales from 4 kpc to $\sim$ 0.1 pc are studied. Milky Way image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech).

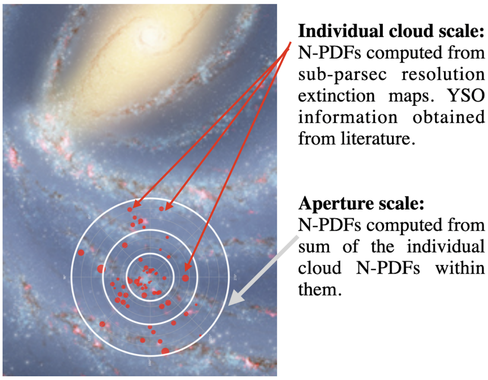

Figure 4.4: Illustration of the survey area in a bird's eye perspective, and the two ways in which the sample is analysed. The picture shows the molecular cloud sample with red filled circles, while the white unfilled circles represent apertures of various sizes. Background image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech).

CHAPTER 5

Paper summary

5.1 Paper A

In the appended paper the most complete sample to date of molecular clouds within 2 kpc is presented, our bird's-eye view experiment is explained and the column density and star formation statistics of the sample are analysed. We explain how the sample of clouds was gathered, and how column density maps, distances and star formation tracers were obtained. The sample is first analysed as individual clouds, and all N-PDFs are fitted with lognormal, power-law and a combination of the two models. This provides a chance to study the occurrence of the shapes of N-PDFs and their relation to star formation for a larger sample of molecular clouds than has been done before. Then the sample is analysed from the bird's-eye perspective, through apertures with radii from 200 pc – 2 kpc. The shape of the N-PDFs, their relation to star formation and their dependency on scale are then studied on the largest scales so far within the Milky Way. We then use the clouds and the apertures to look into the scale dependency of the Kennicutt-Schmidt relation.

From the analysis we find a number of interesting results. We find that the N-PDFs of individual clouds (at scales of sub-pc $-\sim$100 pc) are not well described by any single simple shape, and that the common way of describing N-PDFs as lognormals, power-laws or combinations of the two (see section 3.2) might lead to biases in the interpretation of them. We also find that the star formation rates and efficiencies of the clouds depend on the "top-heaviness" of the N-PDFs, as measured by dense gas fraction or density contrast. This agrees with previous works on the topic (Kainulainen et al. 2009, 2014), with the change from describing N-PDF shapes with power-law slopes to using empirical descriptions.

The portion of the Milky Way studied includes potentially different galactic environments, as the Sagittarius spiral arm most likely enters the survey area on the side of the Galactic centre. The paper results indicate that clouds and apertures might be different towards this region, with higher mean surface densities and more top-heavy N-PDFs. This is potentially very interesting, and might point toward different physical processes shaping the distribution of density in the clouds in different galactic environments. We do however have a heterogeneous data set, where several of the clouds in the spiral arm environment are mapped in dust emission, while most of the other clouds are mapped in extinction. In the paper we argue that the difference most likely exists despite of this, but a homogeneous dataset and inclusion of more spiral arm clouds would be needed for definite evidence on this difference.

We also study how the N-PDFs and star formation measures change with size scale, and find that the N-PDFs in our sample do change with scale. The N-PDFs of larger apertures are shallower and have higher dense gas fractions and density contrasts. Finally, we see how the Kennicutt-Schmidt relation is born from our data; even though there is no relation for the cloud sample, the relation appears for the apertures as a combination of sampling effects and the inclusion of different Galactic environments.

CHAPTER 6

Outlook and future work

After taking a first step towards understanding molecular clouds and star formation in our own galaxy on scales comparable to studies of external galaxies, several interesting paths forward are emerging. A path that was already identified in the beginning of the work, and indeed might have been the topic of the first paper, is to look into velocity statistics of the sample of clouds. The Dame et al. (2001) survey of CO in the Milky Way includes velocity information for the clouds in our sample, and this could be analysed in a similar manner to the density statistics in paper A, giving insight to the scale dependency of the Larson relations. This work has already started, and most likely will become a follow up paper to paper A. Another work in progress that emerged during an online conference towards the end of 2020 is a study of the timescales of star formation, utilising the uncertainty principle of star formation from Kruijssen and Longmore (2014).

A possible way forward would be to continue and expand the study of Galactic molecular clouds. I could for example extend our sample to include more clouds toward spiral arm areas and cover a larger portion of the Milky Way disk, to further study the dependency of scale and environment on N-PDFs and star formation. I would also like to get some observational expertise, and an opportunity to do this would be to work with some newly acquired data from the Onsala 20m telescope on the AFGL490 molecular cloud.

It would also be very interesting to work more directly in comparisons of the Milky Way and extragalactic studies. To do this, the data should be brought to a more similar ground. This could include adding a diffuse component to our survey area, and/or studying the emission from O and B stars, which are more common tracers of star formation in external galaxies. Adding O and B stars could also provide an interesting comparison between the star formation tracers used in Galactic and extragalactic works. Another interesting avenue would be to start direct comparisons with new PHANGS results that are probing the same relations that we are down to about 100 pc scales (Pessa et al. 2021).

In the second half of my PhD I hope to contribute to the field of interstellar medium and star formation studies through continuing the study of scale dependencies and the work of bringing Galactic and extragalactic communities a little closer. I hope that in not too long an accurate bird's-eye view of the molecular clouds in the entire Milky Way disk will be available, and that this can be combined with the advancing studies of external galaxies to understand the interstellar medium and its role in star formation across the full range of scales.

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