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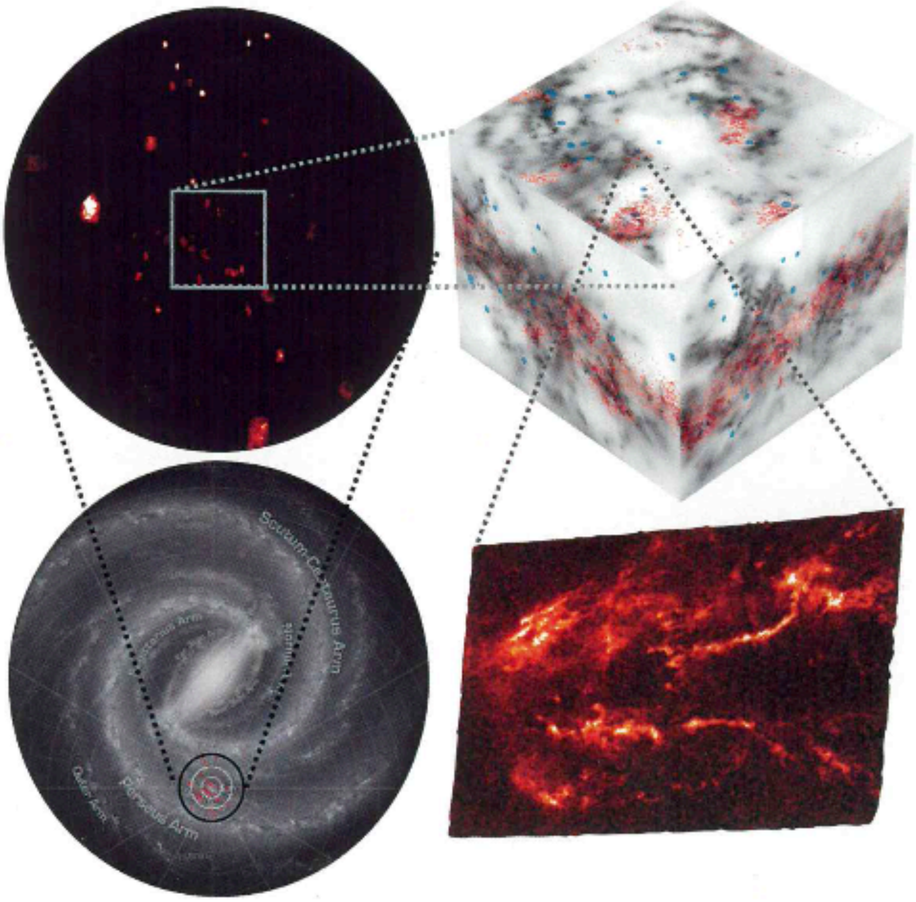

Bird's eye view of star formation in the local Milky Way

How perspective changes with scale, time and viewing angle

ANDRI KAROLINE LUNØE SPILKER

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THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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I've looked at clouds from both sides now
From up and down, and still somehow
It's cloud illusions I recall
I really don't know clouds at all
— Joni Mitchell

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, velocity and star formation statistics of the dust and molecular gas in the Solar neighbourhood and determine how it appears when viewed through apertures of various sizes. First, we employ sub-pc resolution dust 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. Second, we study a complete three dimensional volume of the Milky Way between the scales of $\sim 2 - 800$ pc, taking advantage of three dimensional dust maps and young stars from recent advances made using *Gaia* satellite data. This second dataset gives the possibility to study not only the scale dependency of star formation, but also the dependence on age and orientation angle in the Milky Way. In these two ways, we connect the average properties of the gas in the local Galactic environment to the resolved properties at cloud scales. Our results provide observational constraints for star formation models. They can also 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.

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: I. Column density and star formation from subparsec to kiloparsec scales". Astronomy & Astrophysics, Volume 653 (2021): A63.

[B] **Andri Spilker**, Jouni Kainulainen, Jan Orkisz, "Bird's-eye view of molecular clouds in the Milky Way: II. Cloud kinematics from subparsec to kiloparsec scales". Astronomy & Astrophysics, Volume 667 (2022): A110.

[C] Jouni Kainulainen, Sara Rezaei Kh., **Andri Spilker**, Jan Orkisz, "The effect of viewing angle on the Kennicutt-Schmidt relation of the local molecular clouds". Astronomy & Astrophysics, Volume 659 (2022): L6.

[D] **Andri Spilker**, Jouni Kainulainen, Sara Rezaei Kh., "The volumetric Kennicutt-Schmidt relation in the local Milky Way: Model for the scale and age dependency". Submitted to Astronomy & Astrophysics.

Acknowledgments

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I also want to thank all my colleagues at the Astronomy and Plasmaphysics division, who have contributed to a nice work environment. I am happy to have shared the PhD journey with you, and thank you for the encouragements and support that have helped me through this PhD. I am also happy to have made good memories outside of work, with nice walks, conversations, dinners, bookclub, yoga, camping, games and gatherings. Thank you to all who have been a part of enriching my life in Gothenburg!

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Acronyms

2D:	Two-dimensional
3D:	Three-dimensional
ISM:	Interstellar medium
YSO:	Young stellar object
IMF:	Initial stellar mass function
SFR:	Star formation rate
SFE:	Star formation efficiency
UV:	Ultraviolet
IR:	Infrared
N-PDF:	Column density probability distribution function
AU:	Astronomical Unit, 1.496×10^{11} m
(k)pc:	(kilo)parsec, $(1000\times)$ 3.086×10^{16} m
(M)yr:	(Mega)year, Million years
Gaia:	Global Astrometric Interferometer for Astrophysics
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 how stars form, through studying how star formation and gas properties related to it depend on size-scale. This is done through a new approach: an experiment of viewing molecular gas 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 an important 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). The spiral arms swipe through the gas in the ISM, creating spiral waves of increased density. In this process flows of gas can collide, inducing

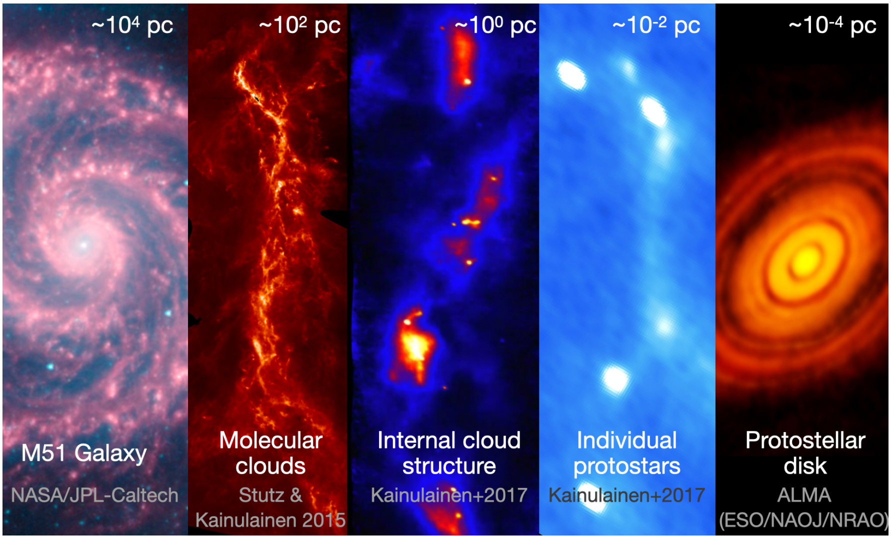

Figure 1.1: The scales of star formation include 8 orders of magnitude, from galaxy disks ($\sim 10^4$pc) to protostellar disks ($\sim 10^{-4}$pc). The left panel shows the M51 galaxy in infrared 3.6-8μm light by the *Spitzer* telescope, credit: NASA/JPL-Caltech. The second panel shows the Orion A molecular 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 (3 arcsec) 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; Padoan et al. 2014). 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 composed of molecules, the most abundant one in the Universe being molecular hydrogen, H_2. But H_2 is difficult to detect, and astronomers therefore commonly 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 gas is arranged in 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 derived by Goldsmith et al. (2008) and figure 1.5 showing a snapshot from a hydrodynamical simulation of star cluster formation by Bate (2009). Major factors that contribute to the complex structure in figures 1.4 and 1.5 are gravity, turbulence, magnetic fields, thermal physics and feedback (more in section 3.1). 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. They also dictate how many stars will form, how fast star formation happens, and how massive the stars become. But how does this interplay work, and how are the efficiency, rate and mass distribution of stars determined? 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 star formation and molecular cloud structure can get us one step closer to solving them.

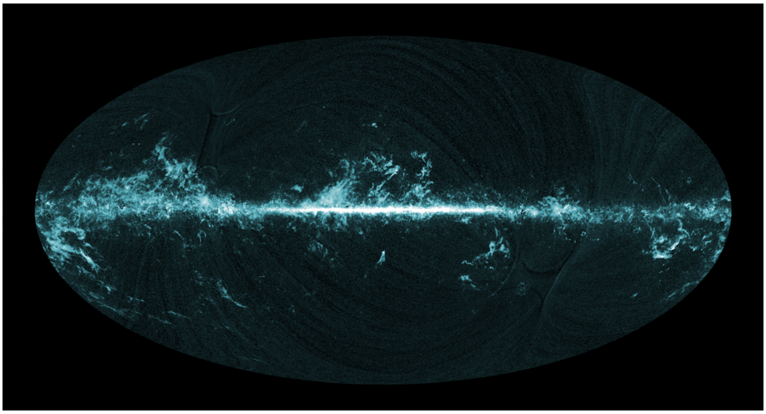

Figure 1.2: The Milky Way seen in CO by the Planck satellite. Credit: ESA/Planck Collaboration.

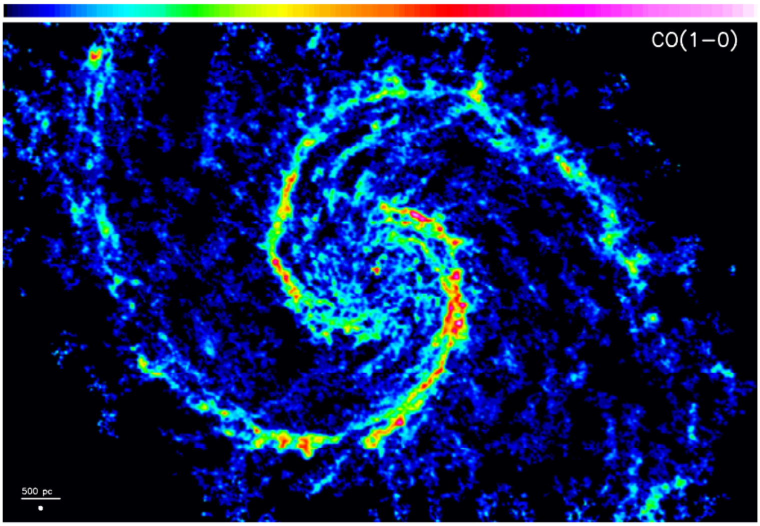

Figure 1.3: M51 the Whirlpool galaxy in CO, seen by the IRAM telescope. Credit: PAWS team, Schinnerer et al. (2013). The physical size of the region is 7 x 11 kpc.

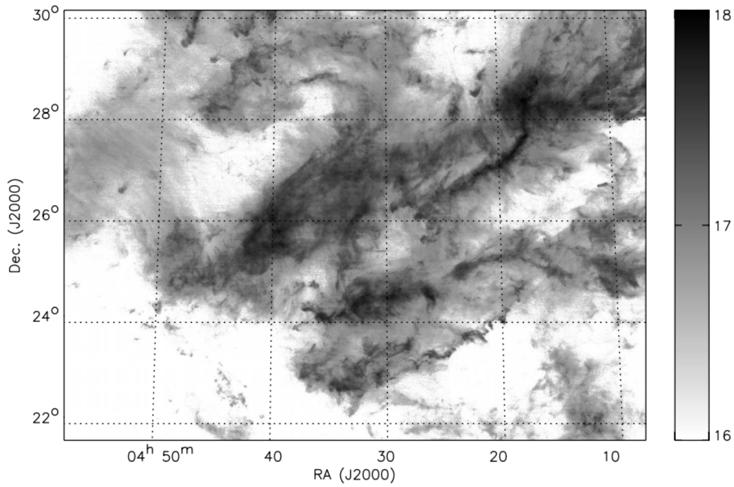

Figure 1.4: Taurus molecular cloud in CO column density at 20" (0.014 pc) resolution from Goldsmith et al. (2008). The physical size of this region is 21 x 28 pc.

Figure 1.5: Snapshot from a hydrodynamical simulation of star cluster formation by Matthew Bate, University of Exeter (Bate 2009). The black-red-yellow colours show the gas distribution with lighter colours for higher densities, and the little white dots represent 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, high resolution can be achieved, enabling studies of sub-parsec-sized regions within molecular clouds and even planets forming in protostellar disks at AU scales (figure 1.1). 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 gas 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 scale structure. 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 (Schinnerer et al. 2013; Goldsmith et al. 2008). 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 new observing programs in the Milky Way and other galaxies, complemented by improved methods, theories and simulations. The Physics at High Angular resolution in Nearby GalaxieS (PHANGS) program with the Atacama Large Millimetre Array (ALMA) is dedicated to observing nearby galaxies at the smallest scales possible today. These data achieve 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, e.g. Sawada et al. 2018). In the

Milky Way, the Global Astrometric Interferometer for Astrophysics, *Gaia*, is currently mapping more than a billion stars, revolutionising our knowledge of the large scale structure of both gas and stars in the Galaxy (more in section 4.2).

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. A relevant study on this is Leroy et al. (2016), where the scale dependency of ISM properties in five nearby galaxies is studied. They found that the molecular ISM in those 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) do 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, there have been several studies working on getting a better overview of the gas in the Milky Way, to understand the large scale structure of our own Galaxy. 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 sub-millimetre 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. And last but certainly not least, the *Gaia* satellite is creating an accurate three dimensional map of over a billion stars in the Milky Way, which we elaborate on in chapter 4. Understanding the gas distribution and structure of our own galaxy is crucial if we want to connect it to external galaxies. With a clear picture of the geometry of the Milky Way, one can take advantage of the high spatial resolution data available, 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, shedding light on how observed star formation relations and laws change with scale, time and angle or dimension. 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; Leroy et al. 2021). 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 an overlap in the scales can be achieved is by studying the Milky Way on scales comparable to extragalactic works. This is what is done in this thesis. I use (sub-)parsec resolution observations to describe the internal structure of the dense ISM from the sub-pc scale to kpc scales. I study the densities and velocities within the gas, and how they relate to the newly formed stars at different scales, times and angles. The scales involved are illustrated in figure 1.6.

This broad range of scales is studied in two ways. First, 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 sample of clouds is studied in papers A (Spilker

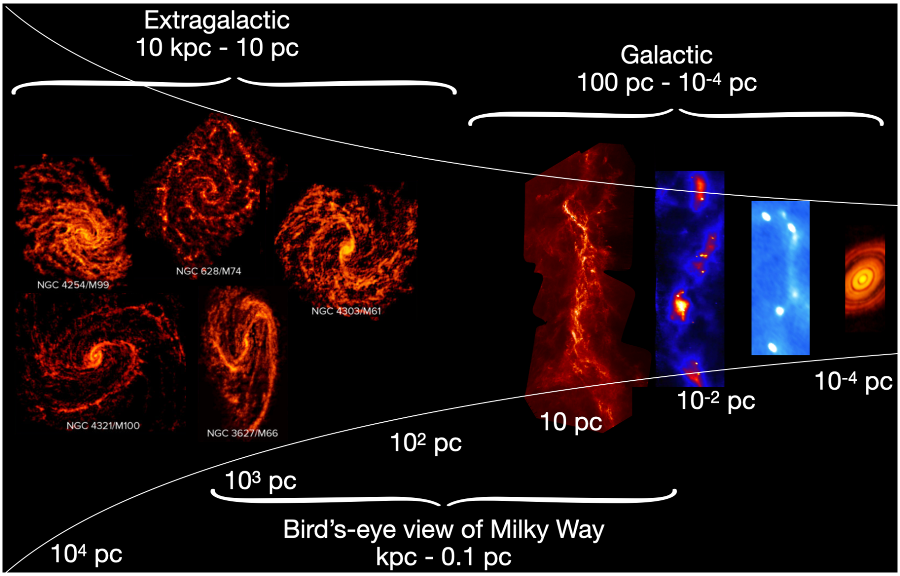

Figure 1.6: The scales of star formation covered by extragalactic and Galactic communities, and the range covered by this work. The figures are not to scale. Credits: galaxies: PHANGS, ALMA (ESO/NAOJ/NRAO); NRAO/AUI/NSF, B. Saxton, molecular cloud: Stutz and Kainulainen (2015), internal structure+protostars: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

et al. 2021) & B (Spilker et al. 2022). Second, we use a recently derived 3D dust map from Leike et al. (2020) to study star formation within 400 pc distance. This three dimensional dust map is based on accurate distances from *Gaia* (see Sect. 4.2), and achieves a resolution of 2 pc. The map is used to study star formation in three dimensions in papers C (Kainulainen et al. 2022) & D (Spilker et al. subm).

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 studies of nearby galaxies, at the same time as it probes the small scales not accessible outside the Milky Way. This study also utilises the newly available three dimensional (3D) data of our local neighbourhood in the Milky Way together with young stars of different ages. Together, the datasets enable us to describe how the statistical structure of the dense ISM changes with size-scale in two and three dimensions, and how this connects to star formation. This represents a step forward in understanding how star formation is controlled at different scales, 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 three chapters, I will go through some of the relevant theoretical background. This includes chapter 2: Observations of the interstellar medium and star formation, chapter 3: Structure and characteristics of the ISM, and chapter 4: The ISM in three dimensions. I will then describe the idea and methodology of this thesis in a bit more detail in chapter 5: Bird's eye view of molecular clouds in the Milky Way. In chapter 6 I introduce and summarise the results of the appended papers, and finally chapter 7 contains some conclusive remarks and future outlook. The papers on which this thesis is based are 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 it 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 requiring high temperatures have been observed, 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

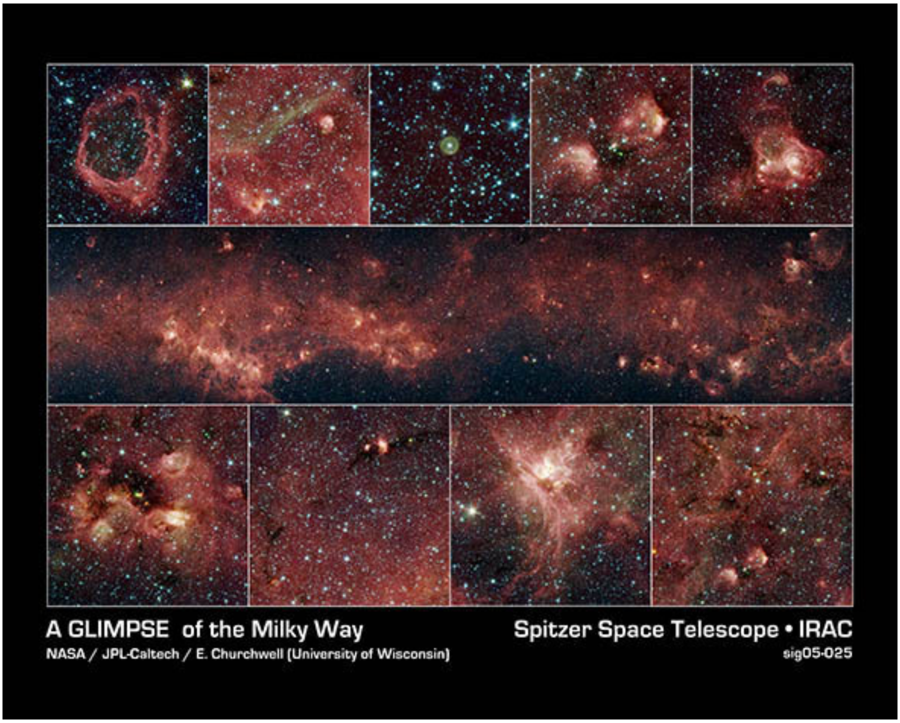

Figure 2.1: A GLIMPSE of the Milky Way in the infrared covering ca 6 degrees of the outer Galaxy. Credit: NASA/JPL-Caltech/E. Churchwell (University of Wisconsin-Madison) and the GLIMPSE Team, 2005.

the *Spitzer* telescope (figure 2.1). 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" (i.e. 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.

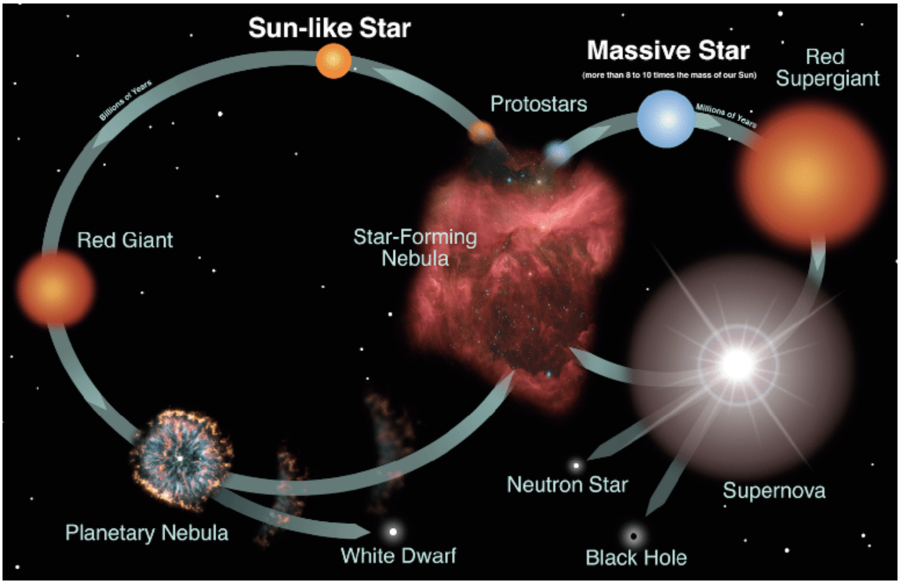

Figure 2.2: Illustration of the cycles of the ISM, and the lifecycle of stars. Credits: NASA/JPL, Astronomical Society of the Pacific.

The cycles of the ISM

The ISM is both 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 (e.g. Morison 2013). When the gas is blown away it can get dispersed, preventing further star formation, or moving gas flows can collide with each other and cause collisions and 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 in various "phases", at different 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 H II 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 H I , 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. 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 mass 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. Dust and gas are generally considered correlated and well mixed, 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 and gas, 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).

However, the clouds are part of the hierarchical and fractal structure of the ISM, and their boundaries are not so straight forward to define. Higher resolution and sensitivity observations within the Milky Way have revealed more complex structure and less well defined boundaries of molecular clouds, and there are no clear physical motivation for the boundaries (see review by Chevance et al. 2022). The CO clouds we observe reside in pockets of CO dark gas, where CO is not abundant due to insufficient shielding, but H_2 can still be present. There is also a significant amount of molecular gas that is more diffuse and not necessarily distributed in clouds (e.g. Roman-Duval et al. 2016), and the cloud properties change with the CO threshold used. Cloud properties also change when traced by other molecules.

For the above reasons, it is interesting to study the full range of gas densities rather than defining cloud "boundaries" that are somewhat arbitrary. This has been done in nearby galaxies (e.g. Leroy et al. 2016; Sun et al. 2018; Pessa et al. 2021), but is more difficult in the Milky Way. When we view Galactic molecular gas in the plane of the sky, nearby gas and dust is superimposed on gas and dust at further distances, and it is difficult to pinpoint the distances to the different components. However, molecular gas is gathered in more or less coherent regions, especially outside the central plane of the Galaxy (see Figure 1.2). It is possible to estimate distances to these regions, by studying the velocities of the gas or the positions of associated stars (see Section 4.1). This is why molecular cloud definitions have been very useful to understand our Milky Way, and why we study the gas structures using segmented clouds in papers A, B & C.

Figure 2.3 shows molecular clouds traced by CO in six nearby galaxies. Only very recently have the resolutions required to see the molecular gas in nearby galaxies at such a level of detail been achieved. The data in the figure are from the PHANGS survey with the ALMA telescope. PHANGS has mapped ~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 CO from Dame et al. (2001) is shown 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 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 $\sim 5\times10^6$ M$_\odot$ (Heyer and Dame 2015). The CO observations have also 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, more in section 3.2). Observations also indicate that molecular

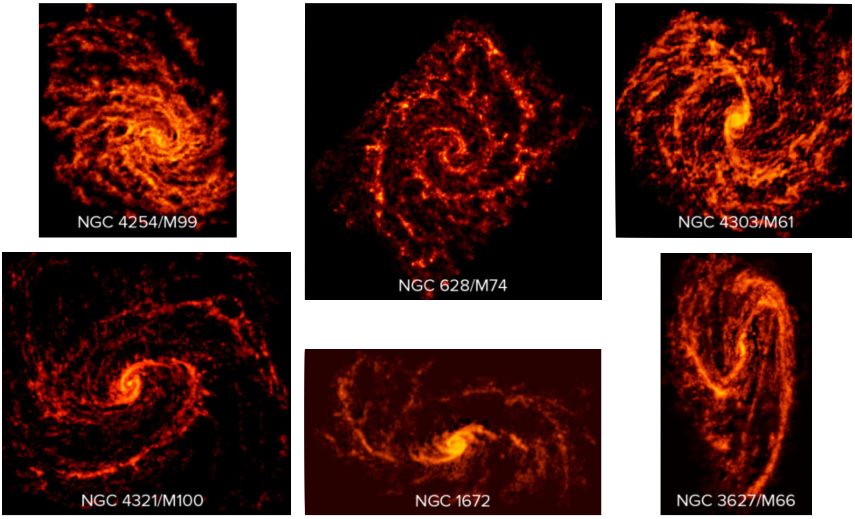

Figure 2.3: Six of the galaxies in the PHANGS sample mapped in CO. Credit: ALMA (ESO/NAOJ/NRAO); NRAO/AUI/NSF, B. Saxton.

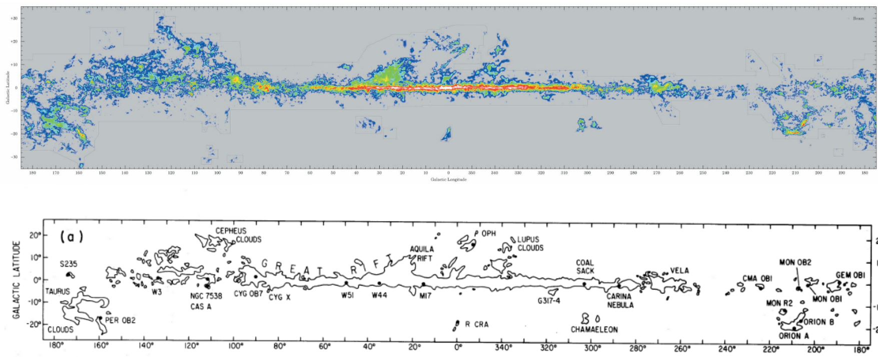

Figure 2.4: **Top:** The Milky Way in CO from Dame et al. (2001), the most recent complete survey of our Galaxy in CO. **Bottom:** Names of clouds in the Milky Way with CO contour, from Dame et al. (1987).

clouds are gravitationally bound, and have approximately constant surface density in a given galactic environment. These properties are captured by the Larson (1981) relations, described in section 3.2.

2.3 Mapping molecular clouds

Star formation depends on the mass distribution within 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; Heyer and Dame 2015), with extinction being well calibrated to low column densities, and emission tracing high column density regions well. In paper A, we use dust extinction to map molecular clouds in the Milky Way, and for a few clouds we also use dust emission. In paper B, we use molecular (CO) line mapping to study velocity information. In papers C & D we use a three dimensional dust map that is also based on extinction. In the following sections I provide an overview of the three tracers used to map molecular clouds.

Molecular line mapping

The transitions between molecular energy levels result in emission of radiation at specific 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 radiation from a given transition depends on the number of molecules, 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 the radiation field). An additional level of complexity is caused by 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 (see for example Draine 2011, for a textbook description of line emission).

This means that molecular lines observed by telescopes can be complicated to interpret in terms of physical quantities, 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 ∼30K, we 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 ∼200 K to be thermally excited, and the higher transitions are widely spaced (Bolatto et al. 2013). 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. The recommended conversion factor by Bolatto et al. (2013) for the Milky Way is:

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

with an uncertainty of ∼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 mass of 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. Other used isotopologue of CO are ^{13}CO and C^{18}O, which are much less abundant and therefore harder to detect and mostly optically thin. This means that the emission from these isotopologues is not strong enough to trace diffuse regions, but 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 from paper A and B 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 is in paper B used to study dynamical properties of the 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. In low density regions the dust emission is weak, and dust emission therefore works best for mapping high density regions. 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. Far-infrared observations require space-based telescopes, which makes it more difficult to observe than for example CO emission.

To infer the corresponding gas column density from the thermal dust emission, one needs to make assumptions for the temperature, emissivity/absorption of the dust grains and the gas to dust ratio. The H_2 column density can then be estimated from the dust emission as

$$N_{H_2} = \frac{F_\nu R}{B_\nu(T_D)\Omega\kappa_\nu\mu m_H}, \tag{2.2}$$

where F_ν is the received flux density from the dust emission, R is the gas to dust ratio ($\sim$ 100 in the Milky Way), $B_\nu(T_D)$ is the Planck function for a dust temperature T_D, Ω is the solid angle of the beam, κ_ν is the dust absorption coefficient, μ the mean molecular weight and m_H is the mass of an hydrogen atom (Hildebrand 1983; Schuller et al. 2009). The absorption coefficient depends on the grain composition, which can to some degree be 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 paper A, where we use dust emission to compute 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 (Wolf 1923; Bok 1937). 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 empirical 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:

$$I_i^{\mathrm{obs}} = I_i^0 \times e^{-\tau_i}, \tag{2.3}$$

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:

$$(m_i - m_j)_{\mathrm{obs}} = -2.5 \log \frac{I_i^{\mathrm{obs}}}{I_j^{\mathrm{obs}}}, \tag{2.4}$$

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:

$$E_{i-j} = (m_i - m_j)_{\mathrm{obs}} - (m_i - m_j)_0 \,. \tag{2.5}$$

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

$$A_{\mathrm{V}} = R_V \cdot E_{B-V}. \tag{2.6}$$

R_V is ~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):

$$N_{\mathrm{H}} \left[\mathrm{cm}^{-2}\right] = (2.21 \pm 0.09) \times 10^{21} A_{\mathrm{V}}[\mathrm{mag}]. \tag{2.7}$$

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). A wide range of related methods have also been developed (e.g. Lombardi and Alves 2001; Lombardi 2009; Butler and Tan 2009; Ragan et al. 2009; Vasyunina et al. 2009; Kainulainen et al. 2011; Kainulainen and Tan 2013; Planck Collaboration et al. 2014, 2016; Zhang and Kainulainen 2022). In this thesis, we use the extinction mapping methods NICER (Lombardi and Alves 2001) and NICEST (Lombardi 2009) to produce the extinction maps used in paper A. The three dimensional dust mapping used in papers C & D is also based on extinction, more on this in section 4.3.

2.4 Tracing star formation

The molecular clouds and gas described in the previous sections are the nurseries of stars, but how can we find out how many stars these clouds are producing, and how fast it happens? There are several ways of tracing star formation, and the most suitable method depends on the distance. In the local Milky Way it is possible to count the individual precursors to stars, the young stellar objects (YSOs). This is what we do in this thesis: YSOs are used in papers A, C and D, and we provide more detailed information about YSOs in the next section. YSOs are relatively small and faint, and become very challenging to detect at larger distances. Since a goal of this thesis is to also bridge the gap towards star formation studies in external galaxies, we also briefly outline how star formation is measured in extragalactic studies.

In external galaxies one cannot count individual YSOs, instead it is possible to measure star formation rates from brighter tracers. Such tracers include massive O and B stars, infrared (IR) radiation or ionised gas traced by Hα emission or ultraviolet (UV) radiation. These are less direct tracers of star formation, as they only detect the radiation from the massive stars. To estimate a total star formation rate, it is then necessary to assume that the number of smaller stars is relatively the same as in other, more nearby places where whole populations of stars can be detected. This relative number of stars as a function of mass is called the initial stellar mass function (IMF). Observations indicate that this IMF is quite universal, but some studies indicate that the IMF might vary across different star-forming regions, galactic environments or galaxy types (Offner et al. 2014; Cappellari et al. 2012; Martín-Navarro et al. 2015). Commonly used IMFs include the ones by Kroupa (2001) and Chabrier (2003). Another issue with the more indirect tracers of star formation is that they often trace stars that are somewhat evolved. Hα emission traces very young massive stars with ages 0-10 Myr, while UV and IR can trace stars that are up to 200 Myr old (Kennicutt and Evans 2012). Stars can move from their birthplace as they evolve, and older stars are therefore less likely to be located in the region where they formed. Different tracers of star formation therefore probe different stages in the star formation process, and studying star formation at different scales and with tracers of different ages can provide insight to the timescales of star formation and the lifetime of star-forming regions (e.g. Chevance et al. 2022).

Young stellar objects

YSOs, the precursors to stars, provide a crucial link between the interstellar medium and star formation. 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 can be computed as:

$$\mathrm{SFR} = \frac{M_{\mathrm{YSOs}}}{t_{\mathrm{YSO}}}, \tag{2.8}$$

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 comes from the IMF. One of the most commonly used IMFs is Chabrier (2003) and has the mean mass of $0.5\mathrm{M}_{\odot}$. The mean lifetime of YSOs is $t_{\mathrm{YSO}} \sim 2$ Myr, but 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:

$$\mathrm{SFE} = \frac{M_{\mathrm{YSOs}}}{M_{\mathrm{cloud}} + M_{\mathrm{YSOs}}}. \tag{2.9}$$

The star formation rate and efficiency vary between molecular clouds, and a long standing aim of ISM research has been to understand which physical processes determine these numbers. A step towards this goal is 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. Schematically, 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 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

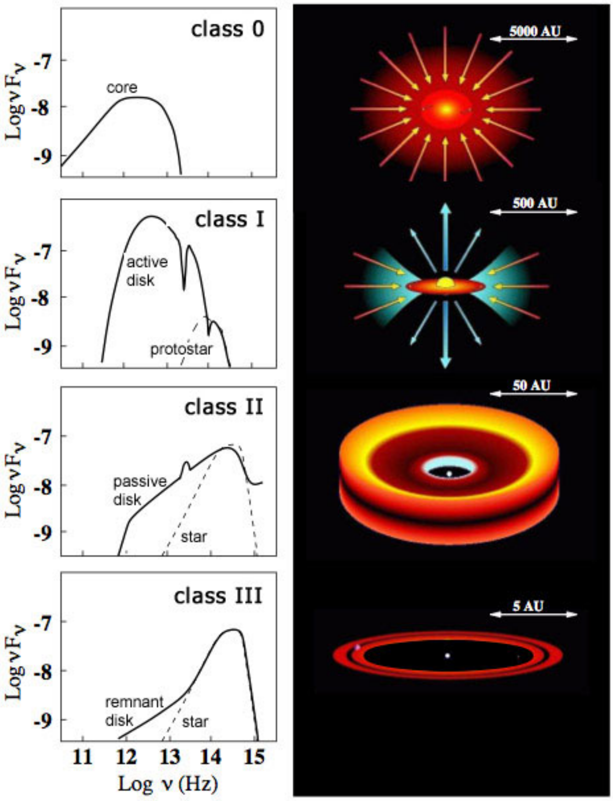

Figure 2.5: The spectrum (left) and structure (right) of the four classes of YSOs. Credit: Andrea Isella.

stars out to 1 kpc distance. 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. More recently, YSOs have also been identified using data from the *Gaia* mission (e.g. Zari et al. 2018; Großschedl et al. 2018; Zucker et al. 2022), which covers wavelengths from the near ultraviolet to the near infrared ($\sim 330 - 1050$ nm, Gaia Collaboration et al. 2018, more in chapter 4).

In paper A we investigate how star formation, measured by YSO counts, depends on the scale on which it is studied. For this we used YSOs found by several surveys of clouds within 2 kpc, mostly targeting class I and II objects. In paper C we use YSOs for nine nearby clouds compiled by Lada et al. (2010) to study whether the star formation relation (see Sect. 3.2) depends on viewing angle. In the final paper of this thesis, paper D, we use young *Gaia* stars from Zari et al. (2018) to study how the star formation relation depends on scale and age. The stars in the Zari et al. (2018) sample are mostly older than the YSOs in the other samples, as they are pre-main sequence stars with ages up to 20 Myr. In paper D we also study how the correlation between the stars and gas density change with the age of the stars used. This relates to how studies of star formation change when observed with different star formation tracers (for example in external galaxies), and to the lifetime of star-forming clouds and regions.

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), velocity distributions, 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 equipartition between collapse and expansion, i.e. when gravitational forces inwards balance the kinetic energy outwards. This is expressed through the virial theorem, which states that the potential (gravitational) energy is equal to two times the kinetic energy ($E_{\text{potential}} = 2 \times E_{\text{kinetic}}$). For a spherical homogeneous cloud in isolation this becomes:

$$\frac{GMm}{r^2} = 2 \times \frac{mv^2}{2} \tag{3.1}$$

$$\frac{GM}{r^2} = v^2, \tag{3.2}$$

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:

$$M_J \approx \left(\frac{5k_B T}{G\mu m_H}\right)^{3/2} \left(\frac{3}{4\pi\rho_o}\right)^{1/2}. \tag{3.3}$$

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. The recent review by Chevance et al. (2022) tentatively favour a scenario where the collapse is local rather than global, so that entire clouds are not collapsing, but regions within them are. If molecular clouds collapsed due to gravity only, stars would form 100 times faster than we observe (Ballesteros-Paredes et al. 2011). It could be that clouds are collapsing relatively quickly, but that feedback destroys the clouds before significant amounts of the gas has been converted to stars, or that something supports the clouds against gravity. The most likely mechanisms to uphold the clouds against gravity are turbulence or magnetic fields, which we describe in the next sections.

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. A medium is said to be turbulent if the Reynolds number is large, $R_e >> 1$. $R_e = \frac{vL\rho}{\eta}$, where v is the velocity in the medium, L is the size-scale, 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 properties of turbulence might contribute to setting the time, mass and size scales of star formation (Mac Low and Klessen 2004; Elmegreen and Scalo 2004; 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.

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 $k = 2\pi/L$ is the wavenumber 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. The turbulence in the ISM is supersonic (velocities exceed the local speed of sound), and supersonic turbulence is not well understood. However, also supersonic turbulence is thought to show signatures in the energy spectrum and scaling between velocity and scale (Ballesteros-Paredes et al. 2006).

The origins of the turbulent motions in the ISM are not certain. Turbu-

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.

lence 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 increasing mixing 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 paper A, and the velocity distribution in paper B. I will come back to the signature of turbulence in the density and velocity distributions in section 3.2.

Magnetic fields

Observations have shown that magnetic fields are oriented along the spiral arms of galaxies, where the molecular clouds are located and star formation occurs (e.g. Fletcher et al. 2011; Li and Henning 2011). Magnetic fields are also seen on smaller scales, in individual molecular clouds (e.g. 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 the role of magnetic fields in the ISM and star formation.

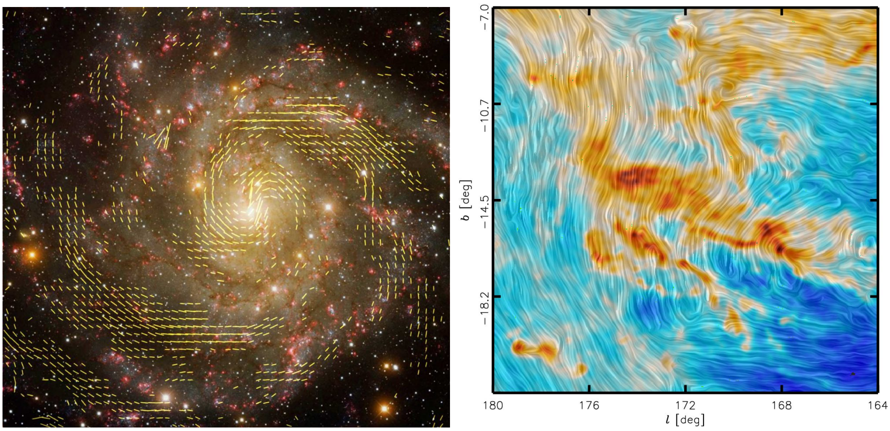

Figure 3.2: Left: Magnetic field orientation in galaxy IC342, shown on a combined radio/optical image from the Very Large Array and the Effelsberg telescope. Credit: R. Beck, MPIfR; NRAO/AUI/NSF; graphics: U. Klein, AIfA; Background image: T.A. Rector, University of Alaska Anchorage and H. Schweiker,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

Much of the debate regarding 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 (e.g. Crutcher 2012). The strength of the magnetic fields is difficult to measure, and we therefore still do not known how important the magnetic fields are at different scales. Observations of the Zeeman effect indicate that magnetic energy is comparable to turbulent energy, but has a wide range of values (Crutcher 2012; Pattle et al. 2022). 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).

It is possible to observe the orientation of magnetic fields in the ISM through dust polarisation, as seen in figure 3.2. 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 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 (e.g. Crutcher 2012), while within clouds it can contribute to regulate the contraction and fragmentation of gas along filamentary structures (e.g. Planck Collaboration et al. 2016).

In a recent review, Pattle et al. (2022) concludes that magnetic fields cannot be uncoupled from turbulence, and that the two effects need to be considered simultaneously, as they together dominate over gravity on large scales in the ISM. They also argue that magnetic fields can contribute to direct gas flows towards star-forming regions, and probably play an important role in regulating protostellar feedback (see also Tsukamoto et al. 2022). Hennebelle and

Inutsuka (2019) agrees that magnetic fields affect the distribution of gas in molecular clouds by influencing the gas to organise into filaments rather than clumps and cores, by this reducing the star formation rate. They argue that relatively strong magnetic fields can significantly affect the star formation process, especially by inducing formation of more massive stars. The signature of magnetic fields in ISM density distributions seems to be less clear than the turbulence signature (Molina et al. 2012; Hennebelle and Inutsuka 2019). However, Soler (2019) find that the distribution of gas is different in regions where the field is perpendicular to the density structures, and future observations of magnetic field directions and strengths in the coming years can give new insight to the signature and effect of magnetic fields in distributing ISM gas.

Other physical processes

There are also other physical processes at work in the interstellar medium. Some important ones are radiative processes, chemistry, galaxy dynamics, feedback and galactic potential. 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. 3.3). The cooling and formation of molecules are affected by the ISM chemistry, the balance between elements and molecules play important roles in determining shielding and cooling. 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 influencing cloud orientations, and they might increase the densities in clouds and trigger shocks and star formation (Elmegreen 1998). Recent observations of nearby galaxies indicate that properties of molecular clouds depend on their surrounding galactic environment (e.g. Sun et al. 2018, 2020; Rosolowsky et al. 2021; Chevance et al. 2022), and 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). Galactic potential and shear can cause elongated clouds and maybe a preferred axis of flattening of clouds in the plane of the galaxy. 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), and feedback probably plays an important role in regulating the lifetimes of molecular clouds and hence the timeline for star formation (e.g. Chevance et al. 2022). This indicates that feedback and galaxy dynamics have to be taken into account in a complete theory of star formation.

These processes affect the ISM in various ways at different scales, and understanding the scale dependence of ISM properties can help shed light on which processes are most important at which scales. Viewing the ISM and molecular clouds in three dimensions and at different angles can give insight to cloud orientations. We study scale dependence in papers A, B and D, and in paper C and D we study how molecular clouds and the ISM look at different angles and in three dimensions.

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 give an overview of density probability distribution functions used in paper A, and velocity distributions used in paper B. Then follows a description of the most important scaling relations related to the ISM and star formation: Larson's relations (studied in paper B) and the Kennicutt-Schmidt relation (studied in paper A, C and D).

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. It can also be related to the effects of gravity, turbulence and magnetic fields, because 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. We can only observe 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 paper A 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 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. Figure 3.3 from Ward et al. (2014) shows how the shape of the N-PDF changes with time from turbulence dominated with lognormal shape to gravity dominated with power law shape.

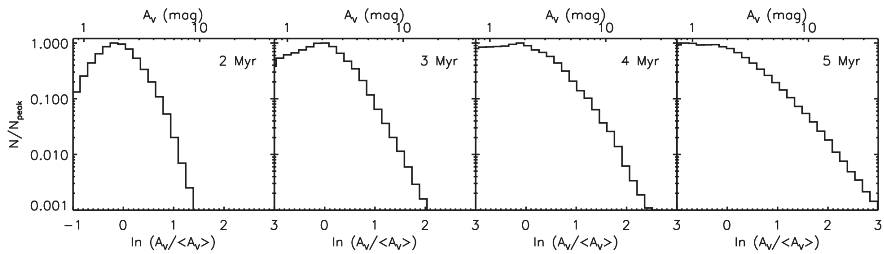

Figure 3.3: Evolution of an N-PDF from turbulence dominated to gravity dominated, from Ward et al. (2014).

Inspired by these predictions, the observed N-PDFs have commonly been analysed with lognormals, power laws, or the combination of the two. The 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:

$$\sigma_s^2 = \ln(1 + b^2 M_s^2 \frac{\beta}{1+\beta}), \tag{3.4}$$

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. 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 the density structures in molecular clouds.

The N-PDFs can then be used as a tool to characterise the structure of the clouds and infer the physical conditions within. The shapes 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; Padoan et al. 2014). 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 still 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, but as we saw in section 2.3 the CO line does not cover the highest density gas.

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 paper A we start 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.

Velocity dispersions

The dynamics of the gas can be inferred from the velocity structure of molecular lines. This is because when gas is moving towards us the emitted light gets slightly blue-shifted, and when it is moving away the light gets slightly red-shifted. When gas in a cloud is moving both towards us and away from us, this causes broadening of the observed spectral line. The broadening is described by the standard deviations of the emission lines, the velocity dispersions σ_v. Observations of molecular clouds in CO have revealed broad lines, with σ_v around $1 - 5$ km/s (Heyer and Dame 2015). Temperature is one of the physical conditions that causes gas to move and lines to broaden, but the temperatures of molecular clouds are $\sim 10 - 20$ K, which is not sufficient to produce the observed width. There then needs to be some other physical process causing the gas in the clouds to move, and possibilities include magnetic fields, gravitational collapse and supersonic turbulence (Ballesteros-Paredes et al. 2011; Dobbs et al. 2014; Heyer and Dame 2015).

The strengths of magnetic fields is not certain, and their relative role in producing the linewidths and other properties of the ISM is therefore also largely unknown. The velocity dispersions of molecular clouds can together with polarisation angles be used to estimate the magnetic field strengths (Tsukamoto et al. 2022). A problem with clouds undergoing free-fall like gravitational collapse is that it would cause a much higher star formation rate than what is observed, unless feedback from young stars disperses the cloud at an early stage (Vázquez-Semadeni et al. 2007). The wide velocity dispersions of molecular gas is most often attributed to turbulence, and studying the velocity distributions can shed light on the turbulent properties of the ISM. How the velocity dispersion varies with size-scale is especially interesting, as we saw in section 3.1 that an important characteristic of turbulence is that most of the velocity is at the larger scales, while the smaller scales have more vorticity. Kolmogorov turbulence predicts that velocity decreases with scale as $v \propto L^{1/3}$. This is studied with an important scaling relation in molecular cloud research, the Larson size-line width relation, which I introduce in the next section. We study the velocity distributions of our molecular cloud sample and how it varies from sub-pc to kpc scales in Paper B.

Larson's relations

Three relations found by Larson (1981) have been crucial 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 by 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 has been interpreted to imply that molecular clouds are turbulent. A characteristic of turbulence is that velocity dispersion is dependant of scale, which is what the first relation imples. 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. It is also possible that the line widths are caused by another mechanism than turbulence, for example gravitational collapse or magnetic fields (Ballesteros-Paredes et al. 2011; Heyer and Dame 2015). Later studies have found exponents closer to 0.5 in supersonic molecular clouds (Miville-Deschênes et al. 2017; Heyer and Dame 2015), and that line widths of clouds of the same size tend to be higher in regions of galaxies that have higher surface densities (Miville-Deschênes et al. 2017; Rosolowsky et al. 2021; Chevance et al. 2022).

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, i.e. 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. Theories of gravitational collapse and fragmentation alone give star formation rates and efficiencies much higher than what is observed, which indicates that clouds are generally not collapsing on the large scales. It is still not clear at which scales and under which conditions gas becomes gravitationally bound and collapses, as the process is also affected by the larger scale gravitational potential, shear, turbulence and magnetic fields (Chevance et al. 2022).

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 inner parts of galaxies and in spiral arms tend to have higher surface densities than the ones in outer parts of galaxies and between arms (Heyer and Dame 2015; Querejeta et al. 2019; Chevance et al. 2022).

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. Recent results from observations of nearby galaxies indicate that molecular cloud properties depend on their galactic environment (Chevance et al. 2022), which could be manifested in scale dependencies. In paper B we study the scale dependencies of the Larson relations for Milky Way clouds within 2 kpc distance, at scales from sub-pc to kiloparsec.

The Kennicutt-Schmidt relation

There is a clear correlation between the gas surface density of the interstellar medium and the star formation rate surface density. 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 broad 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 is correlated with higher star formation rates. The relation as observed by Kennicutt (1998) is shown in figure 3.4, and reads:

$$\Sigma_{SFR} \propto \Sigma_{gas}^{1.4}. \tag{3.5}$$

Σ_{SFR} is the surface density of stars born per year and Σ_{gas} is the surface density of gas. 1.40 is the exponent from Kennicutt (1998). Originally, the relation was studied using averages of entire 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; Pessa et al. 2021). 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 confined to the densest gas than in extragalactic works (Kennicutt and Evans 2012). However, the star formation relation is not seen between clouds in the Solar neighbourhood (Heiderman et al. 2010; Lada et al. 2013). 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. It also relates to the timescales of star formation and the lifetime of star-forming regions (Kruijssen and Longmore 2014; Kruijssen et al. 2018; Chevance et al. 2022). Recent results for nearby PHANGS galaxies studied at scales between 1 kpc and 100 pc find exponents to be quite constant and close to 1, but some variation with galactic environment (Pessa et al. 2021; Pessa et al. 2022). The KS relation measured

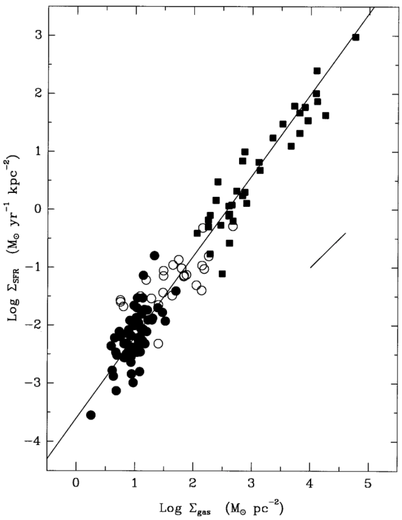

Figure 3.4: The star formation relation as observed by Kennicutt (1998).

at three scales across 18 galaxies from Pessa et al. (2021) is shown in figure 3.5.

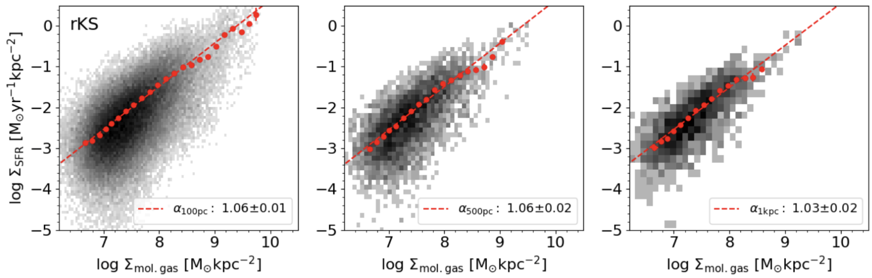

Figure 3.5: KS relation in 18 PHANGS galaxies, from Pessa et al. (2021). The relation is shown at three different scales, 100 pc (left), 500 pc (middle) and 1 kpc (right).

The vast majority of studies of the KS relation focus on surface densities, but the original relation proposed by Schmidt (1959) was with volumetric densities, which in Schmidt (1959) were calculated using estimations of the thickness of the Milky Way disk. The volumetric KS relation has the form

$$\rho_{SFR} \propto \rho_{gas}^{\alpha}. \tag{3.6}$$

Volumetric densities are not directly observable, and so this volumetric star formation relation has been more difficult to study, but may be more directly linked to underlying theories of star formation physics (Krumholz et al. 2012; Padoan et al. 2014). Evans et al. (2014) estimated the volumetric KS relation for nearby clouds modelling their volume as sets of spherical nested shells, and using approximations of the thickness and flaring of galaxy disks Bacchini et al. (2019a,b) have found the volumetric KS relation to be tighter in three dimensions than the classical two dimensional relation, both for external disk galaxies and for the Milky Way.

The KS relation and its dependency on scale is studied in paper A, C and D. In paper A, we study the relation for the most complete sample of molecular clouds in the local Galactic environment (d< 2kpc) to date. We also examine how the relation changes when the clouds are observed "from the outside of the Milky Way" through apertures at scales comparable to extragalactic studies.

In paper C we study how the 2D KS relation depends on the viewing angle of 9 nearby clouds, and in paper D we study the volumetric KS relation in the Solar neighbourhood (d$<$ 400pc). The results of the papers are summarised in chapter 6.

The three dimensional information needed to study clouds from other viewing angles (paper C) and to study the volumetric KS relation (paper D) is available due to recent advances by the *Gaia* satellite. The next chapter describes the difficulties in attaining such a three dimensional perspective, and how the *Gaia* satellite is revolutionising the volumetric understanding of our home galaxy.

CHAPTER 4

The ISM in three dimensions

We view the sky in two dimensions, and recovering a three dimensional universe from the two dimensional sky is difficult as the depth is not easy to perceive. It is only one hundred years ago since we learned that there are other galaxies, and the structure of our own Milky Way is still not well constrained. Our perspective from inside the disk makes it difficult to measure distances accurately and to reconstruct the geometry of our Galaxy. Uncertain distances also lead to uncertainties in physical properties such as mass and size. In this chapter I outline some of the challenges and paths to recovering the three dimensional structure of the Milky Way ISM (section 4.1), explain how the understanding of our home Galaxy is currently being revolutionised due to the *Gaia* satellite (section 4.2), and finally give some background to the three dimensional dust maps derived from *Gaia* data, which are used in papers C & D (section 4.3).

4.1 Recovering the three dimensional structure of the Milky Way ISM

The geometry of our home Galaxy is a long standing puzzle in Astronomy, and has been studied in various ways. One way to infer distances in the Milky Way is through velocities: if we have a model for the rotation of the Galaxy and assume that stars and gas follow that rotation, we can estimate the distances. 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 of the molecular clouds from Miville-Deschênes et al. (2017) is shown in figure 4.1. This view is very interesting because it covers almost all the CO in the galaxy and gives an overview of the molecular clouds. The figure also shows some of the 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. This is caused by the higher resolution at near distances, making it possible to separate the structures into smaller clouds. The figure also shows that 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. Another way to measure accurate distances is through parallaxes. Parallax is the difference in direction/angle to a star or celestial object as seen by an observer from Earth's position at two opposing

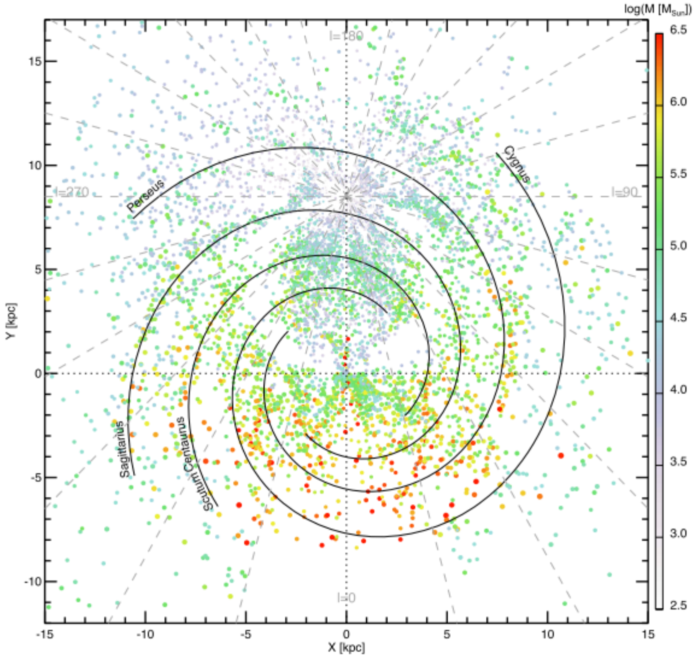

Figure 4.1: Bird's-eye view of molecular clouds in the Milky Way from Miville-Deschênes et al. (2017). Colour corresponds to mass of cloud and size corresponds to size. The approximate positions of the spiral arms are shown in black, from Vallée (2008).

sides of the Sun. Astrophysical objects that can be observed at large distances and have recognisable emission signatures are masers; microwave amplification by stimulated emission of radiation. Masers give accurate distances, but are limited to the relatively few regions where the physical conditions allow such emission. It is also possible to measure parallaxes of stars, and when the Hipparcos satellite measured parallaxes to more than a million stars in the Milky Way in the nineties, this greatly improved our understanding of the Galaxy. Now the *Gaia* satellite is taking the next leap towards an overview of the Milky Way structure.

4.2 The *Gaia* revolution

Gaia was launched in December 2013. It is the follow up for the Hipparcos satellite, and the goal of the mission is to create the largest, most precise three-dimensional map of the Milky Way by surveying over a billion stars in the Galaxy (Gaia Collaboration et al. 2016). *Gaia* is measuring positions, velocities, extinction, luminosities and chemical abundances of stars. So far the mission has covered roughly half a billion stars with their third data release (Gaia Collaboration et al. 2022), and the data are revolutionising our understanding of the Galaxy, especially the Solar neighbourhood (reviewed in Zucker et al. 2022). An artist impression of *Gaia* in the Milky Way is shown in figure 4.2.

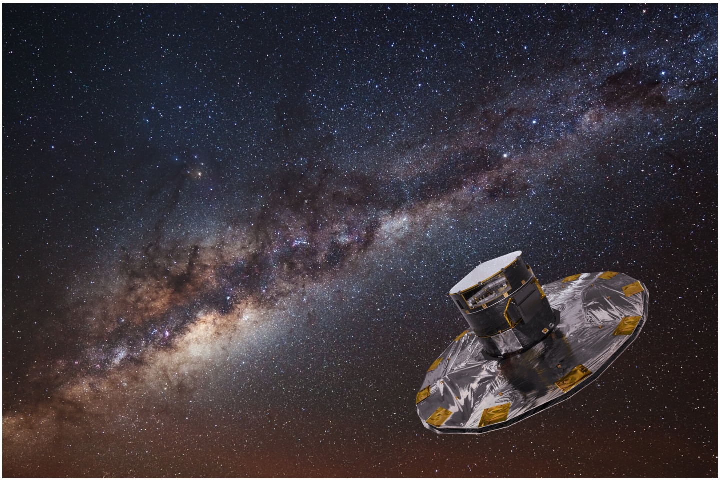

Figure 4.2: Artist impression of the *Gaia* satellite mapping the Milky Way. Credit: ESA/ATG medialab; background: ESO/S. Brunier. (2013).

Gaia is observing approximately 1% of the stars in the Galaxy, and is limited by brightness. This means that faint objects such as young, low-mass stars can only be detected relatively nearby, while brighter objects are included out to larger distances, some all the way towards the Galactic centre. In this thesis we want to get a complete picture of the star formation in the local Milky Way, and in the Solar neighbourhood *Gaia* includes class II and III protostars (e.g. Großschedl et al. 2018). We do however note that the *Gaia* mission operates at optical wavelengths, and therefore does not include the more obscured (and often younger) YSOs detected in infrared surveys (see section 2.4). The young stars from the second *Gaia* data release within ∼500 pc are included in the Zari et al. (2018) catalogue, which we use to study star formation in the Solar neighbourhood in paper D.

The accurate 3D positions and other properties of the millions of stars released by *Gaia* so far have improved our understanding of the Milky Way in several ways. The data have for instance been used to trace stars back in time and look at the evolution of star clusters, accretion of dwarf galaxies and the evolution of the Milky Way (reviewed in Gallart et al. 2019; Helmi 2020). The data have also been used to determine accurate distances to extinction features such as molecular clouds. Zucker et al. (2019, 2020) determined distances to the molecular clouds in the Solar vicinity using *Gaia*, improving their distance uncertainties from $20-30\%$ to ∼5% (Zucker et al. 2022). These accurate distances are essential for placing local clouds in their rightful place in the Milky Way disk, enabling the bird's-eye view of molecular clouds in our Galactic surroundings that is used in papers A & B.

The *Gaia* data have also been used to construct three dimensional maps of stars and dust in the Galaxy, and has through this revealed new structures in the Solar neighbourhood, such as bubbles and large elongated features which are probably related to nearby spiral arms (Zucker et al. 2022). We use one such three dimensional map in papers C & D, and include more about 3D dust maps below.

4.3 3D dust maps

The data from the *Gaia* mission have recently been exploited to construct three dimensional dust maps of local regions of the Milky Way disk (Rezaei Kh. et al. 2018; Lallement et al. 2018, 2019; Chen et al. 2019; Green et al. 2019; Leike et al. 2020; Vergely et al. 2022). The mapping is done using accurate measurements of extinction, stellar types and distances of *Gaia* stars. In 3D dust maps, the dust is not assumed to be a foreground screen (as in 2D dust extinction mapping, section 2.3). Instead, the dust is modelled as a field in which the stars are embedded, at the same time as the spectral type and distances to stars are modelled (Green 2016). 3D mappings of dust have also been done before *Gaia* (see Green 2016, for references and summary),

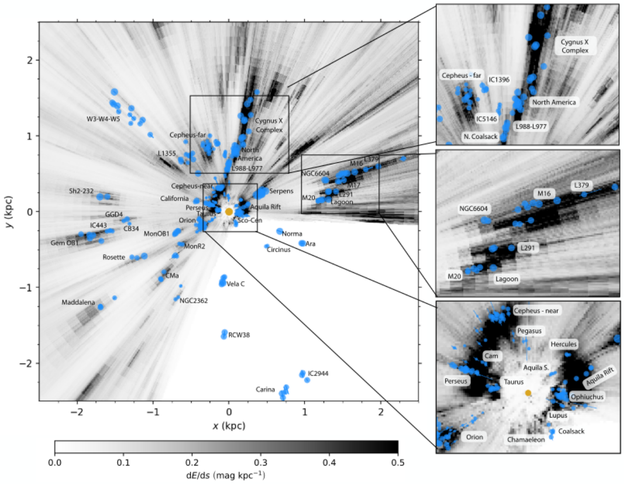

Figure 4.3: Bird's-eye view of molecular clouds within $\sim$ 2.5 kpc distance from Zucker et al. (2020). The background black and white map is from the three dimensional dust map from Green et al. (2019).

but the large number of stars covered by *Gaia*, together with the accurate distances, spectroscopy and extinction measurements, now enable superior resolution and substantially lower uncertainties. This is radically changing our understanding of our local Galactic environment and the Solar neighbourhood (see review by Zucker et al. 2022).

Figure 4.3 shows a face-on view of the three dimensional dust map within $\sim$ 2.5 kpc distance from Green et al. (2019), with positions of molecular clouds from Zucker et al. (2020). This map shows that we are beginning to get an overview of the distribution of dust in our local Galactic neighbourhood. The cloud positions in the figure are from Zucker et al. (2019, 2020), and are used in papers A & B. In those papers, we combine accurate distances to clouds with sub-pc resolution column density maps of the clouds, to probe an as wide range of scales as possible, from the kpc scale Galactic surroundings to the sub-pc internal structure of clouds.

Recently, Leike et al. (2020) have used *Gaia* data combined with other Milky Way stars and Gaussian process methods to construct a three dimensional dust map of the nearest $\sim$400 pc of the Milky Way. This map achieves a resolution of 2 pc, and for the first time provides an overview of a significant part of

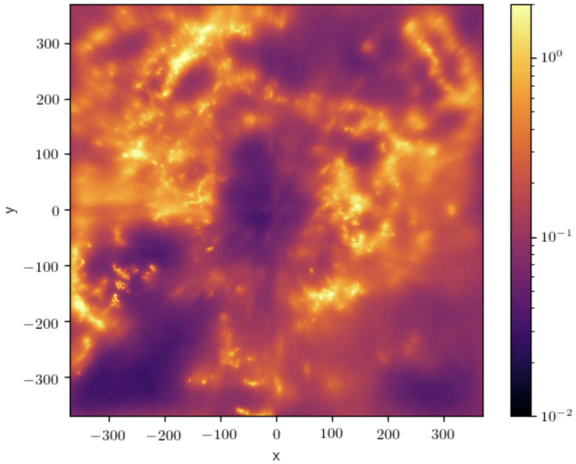

Figure 4.4: Bird's-eye view of molecular gas within ∼ 400 pc distance from Leike et al. (2020). The colour shows differential dust extinction in e-folds per parsec, which is related to column density of gas.

our Galaxy with such small scales included. It is also the first time we get an overview of the pc scales of any large part of a galaxy in three dimensions, enabling volumetric studies of star-forming gas which are more intimately linked to star formation theories. The face-on view of the Leike et al. (2020) dust map is shown in figure 4.4. In paper C we use this map to study how molecular clouds and their star-forming properties depend on the angle we view them from, and in paper D we use the whole map to study the KS relation in three dimensions and how it depends on scale and age. Compared to the approach used in papers A & B we then probe a narrower range of scales ($\sim 2 - 800$ pc versus ~ 0.1 pc-4 kpc), but gain the third dimension and a more complete view of the gas and young stars in the region. In the next chapter the idea and approach used in the papers is further explained.

CHAPTER 5

Bird's-eye view of molecular gas 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, and discussed some of the difficulties and progress in connecting the large (kpc) scales seen in external galaxies with the small (sub-pc) scales accessible in the Solar neighbourhood of the Milky Way. In this chapter I give an introduction to the "bird's eye view" idea and approach used in the appended papers to study 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. We combine the large (kpc) scale picture of the Milky Way with the high resolution (sub-pc) observations of molecular clouds and gas. We take advantage of the recent improvements in distance determination in the local Milky Way to place stars and gas in their rightful place in a face-on view of the Galaxy disk, making it possible to study star formation in a bird's-eye perspective. We combine this with (sub-)pc maps of the gas from CO and dust, enabling a study of star formation across a broad range of scales.

In papers A & B we study molecular clouds in the Milky Way within a 2 kpc radius circle of the Galaxy disk. Within this circle, all major molecular clouds, their column density maps, CO velocity distributions and YSO counts are collected from the literature. The dataset is used to study the scale dependency of N-PDFs and star formation (paper A) and the scale dependency of velocity distributions and the Larson relations (paper B). The scale dependency is studied through defining apertures with a range of scales within our survey area, and examining different quantities within the apertures and the individual clouds that fall within them. Figure 5.1 shows the range of scales involved, and an illustration of the two ways the sample is analysed is shown in figure 5.2. We note that this approach only includes the high density material composed in identifiable cloud-like structures. In section 2.2 we saw that molecular clouds do not have well-defined boundaries, and that there also exists a more diffuse molecular component within the apertures. These aspects are not captured with our cloud-based analysis. However, this new approach captures a broad range of scales. It 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 a galaxy disk.

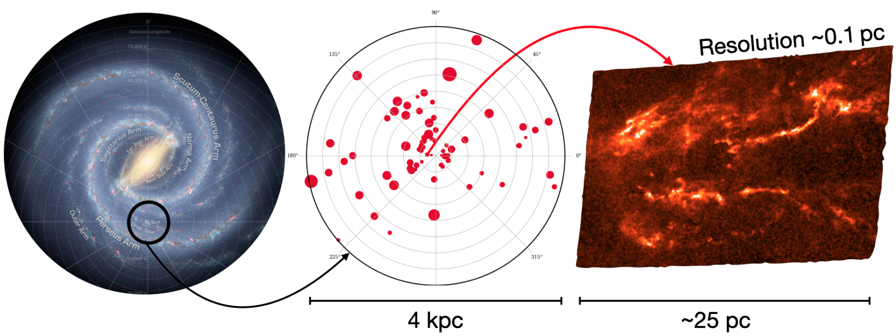

Figure 5.1: Illustration of the scales involved in papers A and B: scales from 4 kpc to $\sim$ 0.1 pc are studied. Milky Way image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech).

In papers C & D, we use the recently derived 3D dust map from Leike et al. (2020) to study star formation within $\sim$400 pc distance. This three dimensional map of dust tracing star-forming gas is based on accurate distances from *Gaia* (see Sect. 4.2), and achieves a resolution of $\sim$ 2 pc. While not

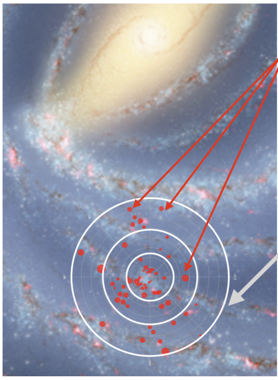

Figure 5.2: Illustration of the survey area in a bird's eye perspective, and the two ways in which the sample is analysed. The picture shows the molecular cloud sample with red filled circles, while the white unfilled circles represent apertures of various sizes. The figure is from paper A, but we analyse the velocity distributions from CO in the same two ways in paper B. Background image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech).

sensitive to the sub-pc internal structure of the clouds, the advantage of this map is that we get a more complete picture of the gas in the survey area, and the possibility to study how the gas and star formation behaves in all three dimensions. The picture is more complete because all the dust in the extinction range accessible by *Gaia* is included in the full survey area. In paper C we use this to study how the third dimension of clouds affects our conclusions about physical properties and star formation within the clouds. In paper D, we turn away from the cloud definitions, and instead study the full range of densities covered by the Leike et al. (2020) map, together with young *Gaia* stars from Zari et al. (2018). We then do not only study the high density molecular clouds, but also their lower density surroundings. This makes the face-on or bird's eye view more realistic, and more comparable to what is seen external galaxies. The young stars from Zari et al. (2018) are divided into three age groups, which also makes it possible to study how conclusions on star formation properties depend on the age of the star formation tracer used.

The papers on which this thesis is based take some first steps towards reconciling the studies of molecular gas and star formation in the Milky Way with studies of molecular gas and star formation in external galaxies. The full range of scales studied in this thesis are illustrated in figure 5.3, which is the same as the front page. Paper summaries follow in the next chapter, and the papers are appended at the end of the thesis.

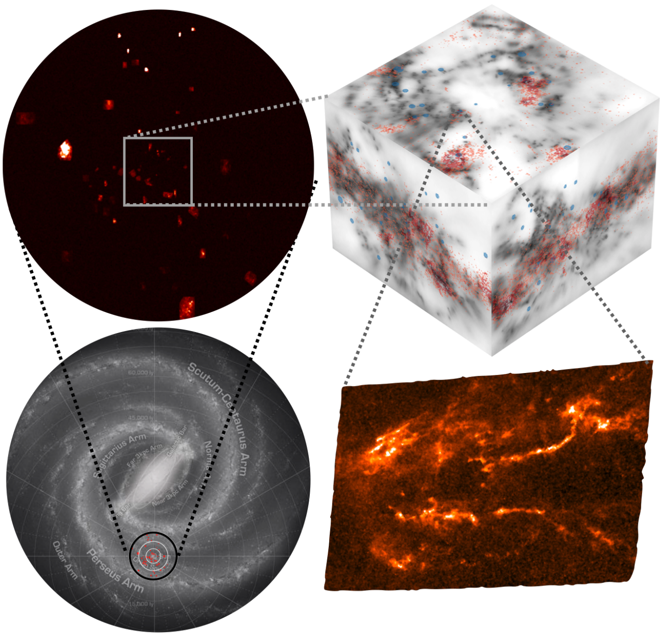

Figure 5.3: Illustration of the scales involved in this study of molecular gas in the Milky Way. The bottom left panel shows the survey area in the Milky Way disk, with molecular the molecular cloud sample in red. We then zoom in to the survey area used in papers A & B, showing column density maps of the 72 clouds within 2 kpc distance (top left). The top right panel shows the three dimensional region studied in papers C & D, with the dust map from Leike et al. (2020) in greyscale, the young stars from Zari et al. (2018) in red contours, and the locations of the molecular clouds from the larger scale sample in blue. The final panel shows the column density map of the Taurus molecular cloud from dust extinction used in paper A. Milky Way image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech).

CHAPTER 6

Paper summaries

6.1 Paper A

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

I. Column density and star formation from sub-parsec to kiloparsec scales

The goal of this paper was to create an overview of the molecular clouds in a significant region within the Milky Way, and use it to study gas density distribution and star formation across a wide range of scales. In the paper we present the most complete sample of molecular clouds within 2 kpc to date. We also present our Bird's Eye view experiment and analyse the column density and star formation statistics of the sample at various scales. We explain how the sample of clouds was gathered, and how column density maps, distances and star formation tracers were obtained. We first analysed the sample as individual clouds, and fitted all N-PDFs with lognormal, power-law and a combination of the two models. This provided 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, we analysed the sample from a bird's-eye perspective, through apertures with radii from 250 pc – 2 kpc. The shape of the N-PDFs, their relation to star formation and their dependency on scale are studied on the largest scales so far within the Milky Way. Finally, we used the clouds and the apertures to look into the scale dependency of the Kennicutt-Schmidt relation.

From the analysis we found a number of interesting results. The N-PDFs of individual clouds (at scales of sub-pc to $\sim$100 pc) are not well described by any single simple shape, and the common way of describing N-PDFs as log-normals, 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 properties within apertures might be different towards this region, with higher mean surface densities and more top-heavy N-PDFs. This is important, because it indicates that different physical processes may be shaping the distribution of density in the clouds in different galactic environments. We caution that the data-set used is heterogeneous, with several of the clouds in the spiral arm environment being 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 data-set and inclusion of more spiral arm clouds would be needed for definite evidence on this difference.

We also studied how the N-PDFs and star formation measures change with size scale, and found 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 show 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.

I lead the work for this paper guided by my supervisor Jouni Kainulainen, and I did the majority of the analysis, all the plots and the majority of the writing of the paper. Jouni Kainulainen defined the density contrast and dense gas fractions (Sect. 3.2.2 in the paper), and Jouni Kainulainen and Jan Orkisz helped with discussions of results in group meetings, and by going through and giving me feedback on the manuscript in several iterations.

6.2 Paper B

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

II. Cloud kinematics from sub-parsec to kiloparsec scales

The goal of this paper was to continue the work of paper A, by bringing in cloud kinematics. Cloud kinematics and the velocity dispersion are, in addition to density, among the most important parameters characterising the ISM physics. In the paper we compute the velocity dispersions (standard deviations of the CO spectra) and CO masses for the clouds, and use this to study the Larson linewidth-size and mass-size relations. As in paper A, we study the properties and relations of individual clouds, and how these appear when viewed through apertures with radii from 250 pc – 2 kpc.

For this most complete sample of nearby molecular clouds to date, we reproduce the Larson linewidth-size and mass-size relations, with significant scatter. When the clouds are viewed through apertures of various sizes, we see that the linewidth and mass continue to increase with scale, increasing the range of the Larson relations. We also see a suggestive dependence on Galactic environment, with linewidths being slightly higher towards the Galactic centre and the Sagittarius spiral arm.

In the discussion section we show that the data in this paper to first order agree with high resolution extragalactic data, even though there are significant differences between the data. We also consider how the inclusion of a diffuse molecular gas component would affect the results, and find that such a component would likely widen the linewidths and flatten the linewidth-size relation.

I lead the work for this paper guided by my supervisor Jouni Kainulainen, and I did the analysis, all the plots and the majority of the writing of the paper. Jouni Kainulainen and Jan Orkisz helped with discussions of results in group meetings, and by filling in on some paragraphs and giving me feedback on the manuscript.

6.3 Paper C
The effect of viewing angle on the Kennicutt-Schmidt relation of the local molecular clouds

The goal of this paper was to use newly available three dimensional data to study how cloud properties change with viewing angle and how this affects the KS relation. The paper utilises the 3D dust map from Leike et al. (2020) (see chapter 4) to study how the viewing angle affects the observed area, mass and ultimately the Kennicutt-Schmidt relation of nine nearby molecular clouds. We used the 3D cloud definitions from Zucker et al. (2021), and rotated the clouds to see how the observed area, mass and KS relation would change if we were viewing the clouds from another angle.

We found that both the cloud area and therefore also the estimated mass varies significantly with viewing angle, and that it also changes with the threshold we use to define the clouds. This demonstrates the limited, or sometimes even erroneous, knowledge we get from projected 2D quantities. This is also clear from a related work by Rezaei Kh. and Kainulainen (2022), where they show that the difference in star formation rate between California and Orion molecular clouds can be attributed to their 3D structure and density.

Paper C also demonstrates that the area and mass are dependant on each other, so that the relation between them is relatively constant. This makes the changes in surface density of the clouds with viewing angle less prominent than the changes in mass and area, although still present. We find that at lower thresholds (corresponding to larger scales), the observed surface density is more dependant on viewing angle. As the surface density is used in the KS relation, this also means that the KS relation varies with viewing angle, and more so for lower thresholds and larger scales. However, the variation in the KS relation with viewing angle is relatively minor, and the result of no observed KS relation between these clouds would hold also if the clouds were observed from any other angle.

My contribution to this paper was participation in discussions about the goals, analysis, and interpretations of the work. I participated in the analyses of the joint probability distributions and produced figures 2, 3, C.2, and C.3. I also provided comments on the manuscript.

6.4 Paper D

The volumetric Kennicutt-Schmidt relation in the local Milky Way:

Model for the scale and age dependency

The goal of this paper was to study the volumetric and classical KS relation in a complete volume within the Milky Way disk, and determine how the relations depend on physical scale and the age of the star formation tracer. We used the 3D dust map from Leike et al. (2020) together with young stars identified with the help of *Gaia* from Zari et al. (2018) to study how the KS relation depends on scale and age in two and three dimensions. We did not define molecular clouds, but rather studied the total amount of gas (inferred from the dust) and stars within 400 pc distance. We studied the KS relation at scales from 25 pc to 250 pc, and with stars in three age groups; 0-5 Myr, 5-10 Myr and 10-20 Myr. We also studied the three dimensional volumetric version of the KS relation.

The paper provides one of the first constraints for the age and scale dependency of the KS relation in this parameter space, and the first three dimensional KS relation derived from a three dimensional map. We find that the KS relation in this sample becomes steeper and tighter at larger scales, and with younger stars. We derive a model for the KS slope as a function of scale and age, so that the expected slope can be calculated by providing the scale of the observations and the age of the star formation tracer used. The three dimensional version of the KS relation is found to be tighter than the 2D relation, indicating that this relation is more fundamental than the projected 2D version. In the paper we also give information about how the underlying 3D relation is related to the projected 2D relation. These results in this paper show that one needs to take caution with interpreting observations of the KS relation: the resolution of the data and the star formation tracer used matters. The models provided in the paper can be used to understand first order differences between studies at different scales and ages, and relate the 2D relation to 3D properties.

I lead the work for this paper guided by my supervisor Jouni Kainulainen, and did the analysis, all the plots and the majority of the writing of the paper. Jouni Kainulainen and Sara Rezaei Kh. helped with discussions of results, and by filling in on some paragraphs and giving me feedback on the manuscript. The paper has been submitted to Astronomy & Astrophysics, and is currently under review.

CHAPTER 7

Conclusion and outlook

In this PhD thesis I have worked to bridge the gap between Galactic and extragalactic studies of star formation, by examining the star formation scaling relations and key parameters linked to the properties of star-forming gas. The main focus has been to obtain an overview of a significant volume of our own Galaxy, and reveal how the relations relevant to star formation change when observed at different scales. We also studied how the KS relation depends on time, and the effect of a three dimensional perspective.

The work of this PhD thesis lead to many interesting results which hopefully can bring the Galactic and extragalactic communities closer to each other. In paper A we saw that the dependency of cloud N-PDFs on star formation content is best captured by relative measures such as the density contrast or the dense gas fraction, and that the N-PDFs get wider at larger scales. We also saw that the KS relation is not present between the clouds, but arises when larger apertures cover the clouds. The KS relation in this sample does not seem to arise from underlying physics, but rather as a combination of sampling effects and the inclusion of potentially different environments. The KS relation is used widely in star formation research, and if it is not representative of underlying physics this would be important for star formation research. However, as discussed in Paper A, our study is not enough to claim that the KS relation is unphysical in all cases, and further research should be done on this.

We start to see indications of environmental dependence of molecular clouds in papers A and B, with clouds closer to the Galactic centre and the Sagittarius spiral arm having higher surface densities, dense gas fractions and velocity dispersions. Similar results have been seen in other galaxies (e.g. Chevance et al. 2022), but it would be interesting to study this further within the Milky Way, as this is the only place where we can access the small scale internal structure of the clouds. It would be possible to expand the study of Galactic molecular clouds by for example including 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. It does however become very challenging to detect YSOs at larger distances, and one might then need to use brighter stars for that, for example O and B stars. Adding O and B stars could also provide an interesting comparison between the star formation tracers used in Galactic and extragalactic works, and one could look more into the timeline of star formation by studying star formation tracers of different ages.

In paper B, we also show that the Larson relations still seems to hold for this relatively complete sample of molecular clouds within 2 kpc. We study the CO spectra at various scales in this region of the Milky Way, and see that the spectra widen at larger scales. We also consider the effect of a diffuse component, and find that such a component would widen the spectra and likely flatten the linewidth-size relation. This could be further developed into more direct comparisons with external galaxies, especially in the next years when the distances and structures of the Milky Way will be better constrained due to the advances arising from *Gaia* data.

In paper C and D we take advantage of the recent three dimensional dust map by Leike et al. (2020) based on data from *Gaia*. In paper C we show that the area and mass of clouds can change significantly with viewing angle, but that the KS relation is only slightly affected. In paper D we study how the KS relation depends on the scale on which it is measured and the age of the star formation tracer used, and also study a three dimensional version of the KS relation. The slope of the KS relation becomes steeper and more tightly constrained at larger scales, and with younger stars. This again points to the need for caution when studying the KS relation. We provide a model for how the slope of the relation depends on scale and age, so that one can insert the scale studied and the age of the star formation tracer used to predict the slope of the relation as it would be in our local Galactic neighbourhood. We also very interestingly show that the KS relation is better constrained in three dimensions with volume densities than in two with surface densities, so that the three dimensional relation is likely more fundamental, although it also depends on scale and age.

The papers in this thesis provide an overview of star formation in the local neighbourhood of our Milky Way, and of the star formation scaling relations. I have studied scale dependencies and tried to bring the work of Galactic and extragalactic communities to more common ground. The results from my PhD work show that properties of star-forming gas tend to depend on the scale on which it is studied, and that this should be considered with caution. The Kennicutt-Schmidt relation may not be as universal as it seems, and I hope future studies can further reveal its properties and with that cast light on the physical processes important for the formation of stars. I also look forward to the day when we have an accurate bird's-eye view of the molecular gas in the entire Milky Way disk, and believe that the coming releases from *Gaia* will lead us closer to such an overview. This can then be combined with the advancing studies of external galaxies to deepen the understanding of the interstellar medium and its role in star formation across the full range of scales.

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PAPER A

Bird's-eye view of molecular clouds in the Milky Way: I. Column density and star formation from sub-parsec to kiloparsec scales

Andri Spilker, Jouni Kainulainen, Jan Orkisz

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PAPER B

Bird's-eye view of molecular clouds in the Milky Way: II. Cloud kinematics from subparsec to kiloparsec scales

Andri Spilker, Jouni Kainulainen, Jan Orkisz

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PAPER C

The effect of viewing angle on the Kennicutt-Schmidt relation of the local molecular clouds

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PAPER D

The volumetric Kennicutt-Schmidt relation in the local Milky Way: Model for the scale and age dependency

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