A Cloud-Scale View of the Molecular Gas Disk in the Whirlpool Galaxy and Beyond

Eva Schinnerer[1,*], *Jérôme* Pety[2], *Ivana* Bešlić[3], *Cosima* Eibensteiner[3], *Sophia* Stuber[1], *Adam* Leroy[4], *Annie* Hughes[5], *Antonio* Usero[6], *Frank* Bigiel[3], and *PAWS & PHANGS* Collaborations

[1]Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany
[2]IRAM, 300 rue de la Piscine, 38406 Saint-Martin d'Hères, France
[3]Argelander-Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
[4]Ohio State University, 140 West 18th Ave, Columbus, OH 43210, USA
[5]CNRS, IRAP, 9 Av. du Colonel Roche, BP 44346, 31028 Toulouse cedex 4, France
[6]Observatorio Astronómico Nacional (IGN), C/ Alfonso XII, 3, 28014 Madrid, Spain

Abstract. The nearby galaxy M51 (also known as the Whirlpool galaxy) hosts an iconic grand-design spiral pattern and both IRAM facilities conducted the first cloud-scale (~50 pc resolution) survey of the molecular gas reservoir across a the disk of a massive star-forming galaxy (PAWS, PdBI+30m Arcsecond Whirlpool galaxy Survey) using the CO(1-0) line emission. PAWS showed that the various properties of the giant molecular cloud (GMC) population vary with galactic environment (center/bar, spiral arms, inter-arm). Recent observations of a ~1000 pointing mosaic of the nearby late-type spiral galaxy IC342 using NOEMA resolved its GMC population at ~70 pc resolution and find consistent trends. Investigation of the dense molecular gas phase at cloud-scales using tracers such as HCN(1-0) confirms the trends seen in kpc-scale surveys, namely that the dense gas star formation efficiency inn general apparently anti-correlates with the inferred dense gas fraction. Multi-line studies of the molecular gas in the galactic disks of nearby galaxies such as the ongoing large NOEMA+30m program to map the dense molecular gas phase in GMCs in the central part of M51 will allow for gaining new insights of the properties of this important molecular gas phase.

1 Introduction

Observations of molecular gas disks of nearby galaxies can provide key insights for our understanding of the physics driving the star formation process. In particular reaching resolutions of 100 pc or better allows to resolve the gas disks into giant molecular clouds (GMCs) and thus the study of their properties as a function of environment across the disks. While the low transitions of CO are excellent tracers of the bulk molecular, molecular emission lines of, e.g., HCN or HCO+, give access to the more dense molecular phase (e.g. [12]). IRAM facilities have been fundamental in progress in this area by enabling surveys such as HERACLES [11], PAWS [22], and EMPIRE [3] which have substantially increased our understanding of the molecular gas, its intrinsic properties and how these relate to the star formation process.

*e-mail: schinner@mpia.de

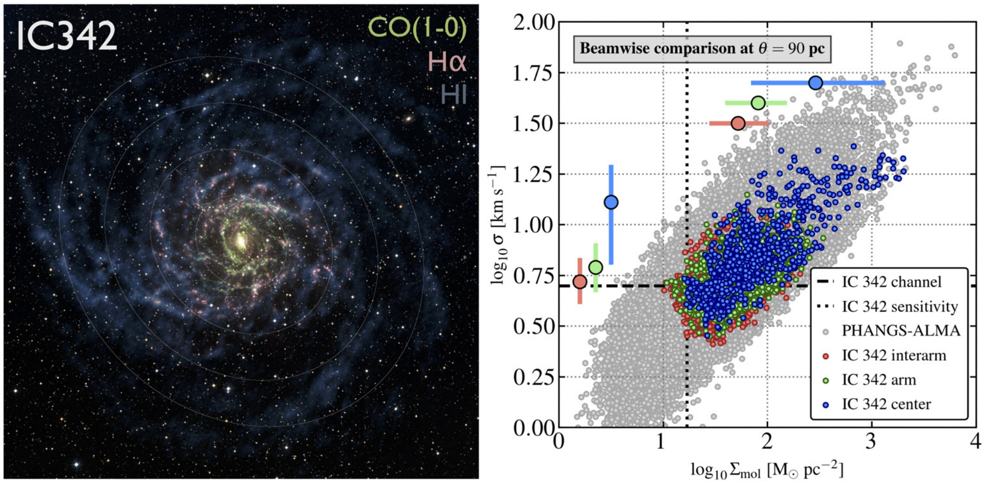

Figure 1. *L*eft: Distribution of the atomic (*blue*), molecular (*green*), and ionized gas (*red*). Ellipses show galactocentric radii at 5, 10, 15, and 20 kpc. *R*ight: Measurements of line width versus gas surface density at a fixed 90 pc resolution for each independent sight-line. IC 342 data are similar to the large sample of PHANGS–ALMA galaxies [14] with the center environment (*blue points*) scattering towards larger line widths and higher surface densities. Adopted from [19].

2 Resolving the GMC population in nearby galaxies

2.1 PAWS – Molecular clouds in the disk of M 51

The PdBI Arcsecond Whirlpool Survey (PAWS) by [22] provided the first complete ~40pc resolution imaging of the molecular gas disk in the nearby spiral galaxy M51 and allowed for the detection of about 1,500 individual GMCs [4]. PAWS has shown that (i) a significant fraction (~50%) of the molecular material is in a thick, diffuse disk component [18], (ii) the 3D distribution of the atomic and molecular gas phase is not identical [5], (iii) galactic structures (spiral arms, bar) strongly impact the organization of the molecular gas phase [4, 8], (iv) a GMC's ability to form stars depends on its exact location in the galactic disk [15], and (v) the typical lifetime of a GMC is about 20-30 Myr [16]. Taken together these results have challenged previous assumptions of molecular gas properties and the subsequent star formation, and imply that local conditions can have a significant impact on the star process (including the central AGN, [20]). Moreover, a low overall efficiency of star formation relative to the gravitational collapse time (~0.7%; [13]) has been inferred for M 51 – similar to theoretical expectations [10] where stellar feedback into the ISM plays a central role in regulating star formation in galaxies.

2.2 The molecular cloud population in the late-type galaxy IC 342

Using 941 pointings with NOEMA, we resolved the CO(1-0) emission from the very nearby (d = 3.45 Mpc) spiral galaxy IC 342 (Fig. 1; [19]) into >600 individual giant molecular clouds and associations over 10.75×10.75 arcmin^2 ($\approx 11 \times 11$ kpc^2) with high resolution ($\theta = 4'' \approx 70$ pc) covering more than 1.5 effective radii. Overall the clouds show approximate virial balance, with typical virial parameters of $\alpha_{\rm vir} = 1\text{–}2$. The typical surface density and line width of molecular gas increase from the inter-arm region to the arm region and reach

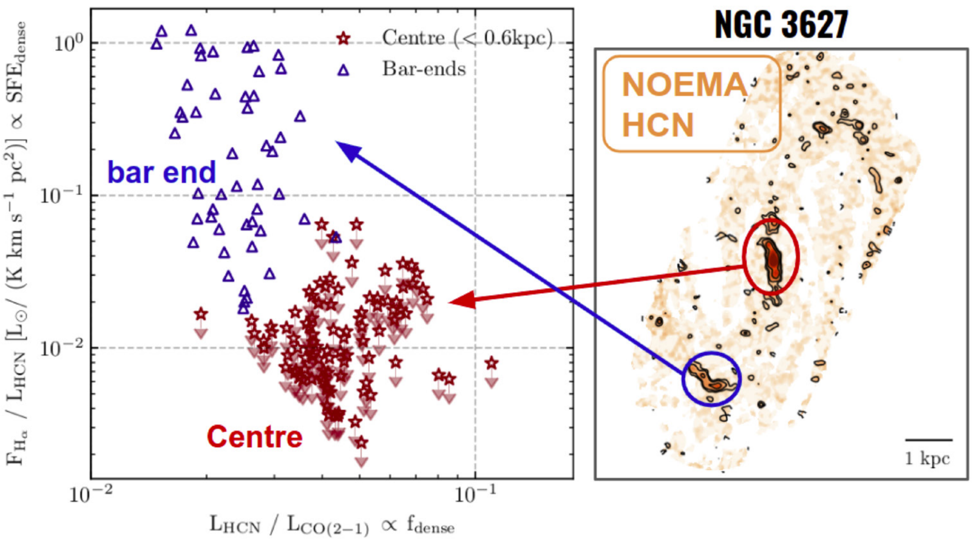

Figure 2. *R*ight: Distribution of the dense molecular gas as traced by HCN(1-0) across the inner disk of NGC 3627. *L*eft: Dense gas star formation efficiency (SFE_{dense}) versus dense molecular gas fraction (f_{dense}). Adopted from [1].

their highest values in the inner 3 kpc disk. Clouds in the central part of the galaxy show enhanced line width relative to their surface densities and evidence of additional sources of dynamical broadening (Fig. 1). This is in agreement with studies of clouds in more distant galaxies at similar physical resolution. This wide-area CO map of the closest face-on massive spiral galaxy demonstrates the current mapping power of NOEMA, the intriguing similarity between atomic, molecular, and ionized gas' large-scale distributions and the scientific potential of such large-scale maps of the molecular gas reservoir.

3 Toward the dense gas phase in GMC populations

3.1 Dense molecular gas at 100 pc across NGC 3627

It is still poorly constrained how the densest phase of the interstellar medium varies across galactic environments. This is partly because probing high (critical) density molecular tracers within extragalactic sources at high spatial resolution and covering a wide range of scales is challenging due to the extensive observing time required to achieve significant detections. In [1], we presented new IRAM NOrthern Extended Millimeter Array (NOEMA) observations of a range of dense molecular gas tracers (HCN, HNC, HCO+) and CO isotopologues (^{13}CO, C^{18}O) towards the nearby (11.3 Mpc), strongly barred galaxy NGC 3627. These data represent some of the highest resolution ($1.85'' \approx 100$ pc), large-scale mapping of the dense molecular phase across a nearby spiral galaxy. We find that the HCN/CO integrated intensity ratio, at face value tracing the dense gas fraction, does not correlate with the amount of recent star formation, yet it depends on the galactic environment (Fig. 2). In addition, stars appear to be forming less efficiently in the inner 600 pc of the galaxy than in the bar ends, despite the latter containing a lower fraction of denser molecular gas. The bar end regions show complex gas dynamics, seen as multiple velocity components of HCN emission, which were previously observed in CO(2-1) by [2]. This detection indicates that these regions are places

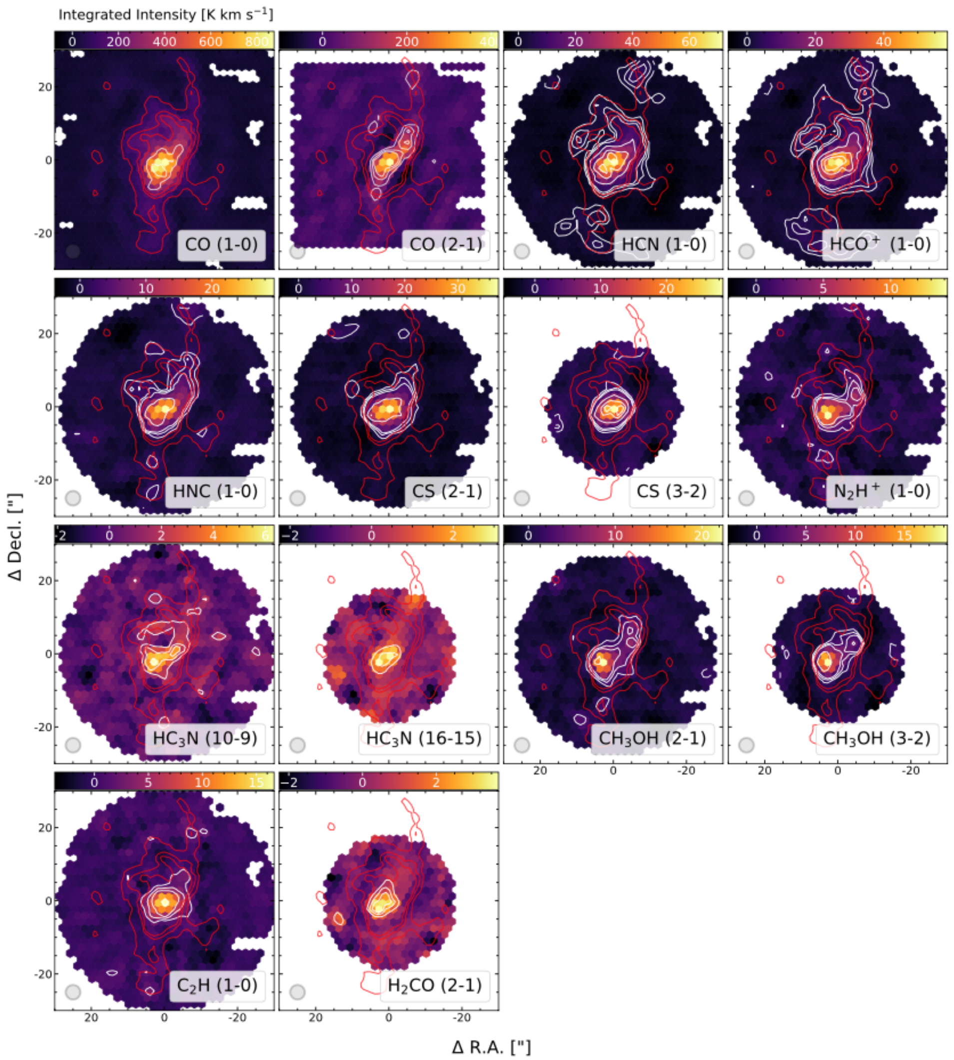

Figure 3. The central region of the "Fireworks" galaxy, NGC 6946, observed with the IRAM Plateau de Bure Interferometer (see [7]). Integrated intensity maps for 14 molecular emission lines at 4″ ≈ 150 pc resolution.

with colliding gas flows and possible cloud-cloud collisions, which can further enhance local star formation.

3.2 Molecular Fireworks: The high angular resolution 2-3 mm molecular line survey covering the central arc minute of the Fireworks Galaxy NGC 6946

NGC 6946 is a nearby, gas-rich, very actively star-forming double-barred spiral galaxy. We have observed a suite of 1−3 mm lines with the IRAM Plateau de Bure Interferometer (PdBI) [PI: Schinnerer] to assess the physical and chemical structure of the inner ∼50″ of this galaxy. This gives us one of the most comprehensive, high resolution (2–4″ ≈ 75−150 pc) molecular

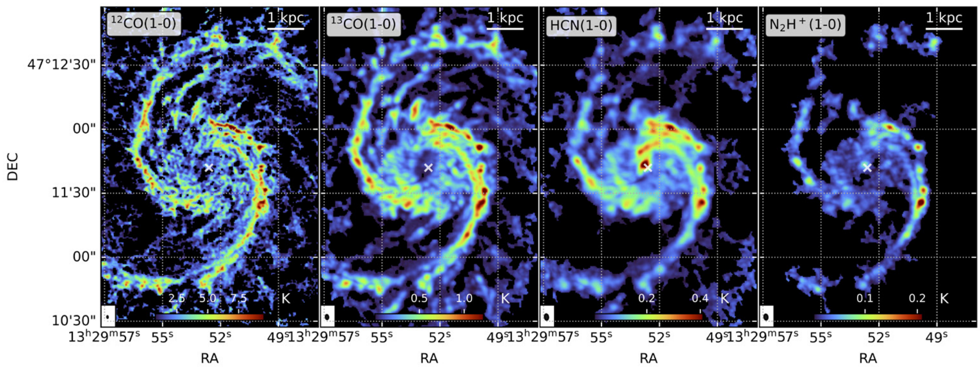

Figure 4. Peak temperature maps of dense gas tracers in the central ~5kpc of M51 at ~3″ resolution. From left to right: ^{12}CO(1-0) high-resolution data from PAWS and preliminary (NOEMA-only) data from selected dense gas tracers (^{13}CO(1-0), HCN(1-0), and N_2H^+(1-0)).

line dataset for a nearby galaxy center in the northern hemisphere ([7]; see Fig. 3). In this work, we identify three distinct regions of prominent line emission in the inner small scale bar (based on the work of [21]): the nuclear region and the northern/southern inner bar ends. Our analysis suggests that the presence of this inner bar has a strong effect on the observed line emission. For example, higher molecular mean density and higher star formation rates correlate with the shock tracers in the southern bar end. The star formation efficiency of the dense gas (SFE_{dense}) shows a different behavior than expected from large-scale disk observations; SFE_{dense} increases with increasing integrated intensity of CO(2-1). Adding 8 nearby galaxies (EMPIRE dense gas observations [9]; and high-resolution observations of M51 [20] and NGC3627 [1]) to our analysis, we speculate that (i) HCN/HNC is not an accurate probe for kinetic temperatures for sub-kpc and kpc sized extragalactic regions, and (ii) HCO+/HCN ratio might not be a unique indicator for AGN activity in galaxies at these scales.

3.3 A first cloud-by-cloud multi-wavelength view of M 51

IRAM's large program PAWS was the first to resolve the GMC population in a massive star-forming external spiral galaxy. With ~50pc resolution observations of the molecular gas reservoir in the inner ~8kpc in its CO(1-0) transition in the nearby galaxy M51, this allowed for a better understanding of the ongoing star formation processes (see 2.1). While ^{12}CO is one of the most commonly used tracers of the dense molecular medium in external galaxies, other studies have shown how CO isotopologues (CLAWS, [6]) and additional tracers of the molecular medium such as HCN and N_2H+ (EMPIRE, [3]) are a key ingredient for understanding SF regulation. These studies, however, lack the spatial resolution and sensitivity for cloud-scale conclusions. The necessity for a high-resolution, high-sensitivity multi-wavelength view of M51 has led to a NOEMA+30m large program mapping emission from dense gas tracers in the 3mm window (e.g. ^{13}CO, $C^{18}O$, HCN, HCO+, HNC, N_2H^+). We present the first results from the ongoing observations in comparison to the PAWS CO(1-0) map in Fig. 4. Using the resulting ~2" resolution dense-gas maps, we will expand the cloud-by-cloud analysis from PAWS to a set of important dense gas tracers which will bring critical insights into current models of star-formation theory by studying the dense gas properties of GMCs, their relation to the local star formation activity, and galactic environment of the morphologically rich central 5 kpc of M 51.

4 Conclusion

The IRAM facilities have been pioneering the study of the molecular gas reservoir of nearby galaxies over the past decade by providing information on molecular emission lines at the scales of GMCs and thus the properties of resolved cloud populations. Variations in GMC populations with galactic environment seen in M 51 by PAWS has resulted in a major ALMA effort [14] and motivated studies to measure the properties of the dense molecular gas phase at cloud scales. Recent observations are pointing to a more complex behavior of key emission lines – either due to fundamental changes in the star formation process or the behavior of the tracer molecules, i.e. HCN, HCO+. Combining NOEMA's large multiplexing capability with an efficient mapping mode (i.e. interferometric on-the-fly mapping) is a very promising way to better understand the conditions and excitation mechanisms in nearby galaxy disks.

References

[1] Bešlic, I.,et al., MNRAS, 506, 963 (2021)
[2] Beuther H., et al., A&A, 597, A85
[3] Bigiel , F., et al., Ap.J., 822, L26 (2016)
[4] Colombo, D., et al., ApJ, 784, 3 (2014)
[5] Colombo, D., et al., ApJ, 784, 4 (2014)
[6] den Brok, J., et al., A&A, (2022)
[7] Eibensteiner, C. et al., A&A, Volume 659, id.A173, 37 pp. (2022)
[8] Hughes, A., et al., Ap.J., 779, 46 (2013)
[9] Jiménez-Donaire, M. J. et al., ApJ, 880, 127 (2019)
[10] Krumholz, M.R., Tan, J.C., Ap.J., 654, 304 (2007)
[11] Leroy, A., et al., AJ, 137, 4670 (2009)
[12] Leroy, A., et al., Ap.J., 835, 217 (2017)
[13] Leroy, A., et al., Ap.J., 849, 71 (2017)
[14] Leroy, A., et al., Ap.J.S., 257, 43 (2021)
[15] Meidt, S.E., et al., Ap.J., 779, 45 (2013)
[16] Meidt, S.E., et al., Ap.J., 788, 144 (2014)
[17] Meidt, S.E., et al., Ap.J., 806, 72 (2015)
[18] Pety, J., et al., Ap.J., 779, 43 (2013)
[19] Pety et al., A&A, subm. (2022)
[20] Querejeta, M., et al., A&A, 593, A118 (2016)
[21] Schinnerer, E. et al., Ap.J., 649, 181 (2006)
[22] Schinnerer, E., et al., Ap.J., 779, 42 (2013)