The IRAM-30m EMPIRE Nearby Galaxy Dense Gas Survey

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Abstract. This work presents an overview of the main results from the EMIR Multi-Line Probe of the ISM Regulating Galaxy Evolution (EMPIRE) survey, an IRAM-30m Large Program (~ 500 h) which observed tracers of high density molecular gas across the disks of nine nearby, star-forming galaxies. EMPIRE is the first comprehensive and systematic study mapping high-density tracers including HCN, HCO^+ and HNC, as well as optically thin $J = 1-0$ transitions of ^{13}CO and $C^{18}O$. Such a combination of spectroscopic tracers offers the best way to study cold, immediately star-forming gas to address how dense gas fractions and star formation efficiencies vary across and among galaxies. The extensive and sensitive data collected from EMPIRE has allowed us to relate the fraction of star-forming gas and its ability to form stars to local interstellar medium (ISM) and dynamical conditions, such as stellar surface densities, ISM dynamical pressure or molecular gas surface densities. The main results from EMPIRE show that the star formation efficiency in the dense gas varies systematically in all galactic disks. Therefore, this provides support for a context-dependent role of gas density, where dense gas fractions follow interstellar pressure, but star formation only takes place in local over-densities. The EMPIRE survey has successfully turned into a stepping stone for on-going and future projects, aiming to link the large-scale EMPIRE extragalactic results to high-resolution measurements, accessible from our Milky Way.

1 Introduction

Only a few decades ago a rigorous study of the processes that lead to star formation could only be performed in detail in our Galaxy. From the extragalactic point of view, it was only possible to study entire star-forming regions or whole, averaged galaxies. At these large scales, most of our knowledge consists of scaling relations between the total gas mass forming stars, and the rate at which this is converted into stars. The pioneer work from [1] and [2, 3] on integrated galaxies found a tight relation between the disk-averaged gas surface density and the averaged star-formation rate in the form of a power-law.

Many observational studies started mapping high-resolution CO as a tracer for the bulk molecular gas, with the goal of exploring variability in this so-called *Kennicutt-Schmidt* relation. One of these pioneer studies was carried by [4], who combined H I maps with new ^{12}CO (2-1) from the IRAM-30m telescope in M51 and derived star formation rates (SFR) from radio-continuum at 20cm wavelength.

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Building up on these efforts, the Very Large Array large program THINGS (The H I Nearby Galaxy Survey, [5]) mapped 34 galaxies in the 21 cm line with high angular resolution and sensitivity. Later on, the IRAM large program HERACLES (Heterodyne Receiver Array CO Line Extragalactic Survey, [6]) mapped 48 galaxies in the CO (2-1) line. This was the first time that a wide, sensitive and high-resolution dataset was available to study the diversity of physical conditions in a large sample of nearby galaxies.

However, tracing easily accessible molecules such as CO emission, only allows us to probe the low-density regime in extragalactic systems. High-density tracers, such as hydrogen cyanide (HCN), have much higher dipole moments and larger critical densities, which allow us to probe the cold, dense sites of star formation. Triggered by the pioneer work by [7] in galaxy integrated measurements using HCN and HCO^+, the IRAM-30m Large program EMPIRE (PI Bigiel) was developed with a clear motivation: to map a suite of lines sensitive to different critical densities in diverse galactic environments . This allows to immediately:

- Look at empirical line ratios between different spectroscopic tracers, and analyze them across galaxies.
- Understand how the density distribution responds to galactic environment, as a function of molecular gas fractions, different stellar and SFR surface densities.
- Employ these lines for radiative transfer modeling, to better understand the underlying physical conditions of the gas.
- Link these measurements to high-z results, where the EMPIRE observed lines can also be detected. In addition, it allows us to provide more environment and context to the Galactic work, at lower resolution.

2 Survey and observations

The Large Program EMPIRE was designed to use the IRAM-30m telescope to systematically map the star-forming disks of a representative sample of nearby galaxies. With almost 500h of observing time, it provided full maps of a suite of high critical density lines, such as HCN (1-0), HCO^+ (1-0) and HNC (1-0), as well as carbon isotopologues such as ^{13}CO (1-0) and $C^{18}O$ (1-0) (see Table 1 for a complete overview of emission lines included in the bandpass). Complementary to EMPIRE, we obtained deep and homogeneous CO (1-0) maps for the entire sample (PI Jiménez-Donaire).

The EMPIRE sample consists of 9 well-resolved galaxies at $d \sim 10$ Mpc, and nearly face-on. All the galaxies were chosen to span a broad range of physical properties, morphological and dynamical features, representing strong spiral structures (e.g., NGC 628), heavily barred galaxies (e.g., NGC 3627), flocculent sources (e.g., NGC 5055), strong nuclear bursts (e.g., NGC 6946) and cluster galaxies (e.g., NGC 4321). Therefore this constitutes an excellent sample to study the dense gas emission as a function of environment across entire galaxy disks, with more than ~600 independent lines of sight across the sample, a major improvement over any previous observations.

Figure 1 displays the integrated intensity maps of HCN (1-0), HCO^+ (1-0), and HNC (1-0) in the galaxy M51, the pilot target for the Large Program. It is clear that the dense gas emission is detected across the disk of the galaxy, with the brightest emission in its center and along the spiral arms.

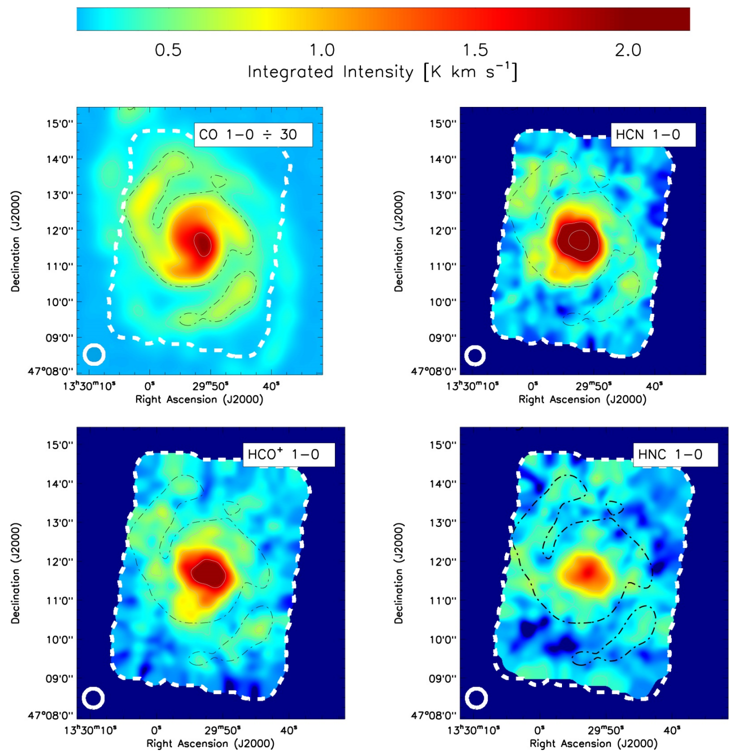

Figure 1. Integrated intensity maps from the EMPIRE survey of HCN (1-0) (top right), HCO^+ (1-0) (bottom left) and HNC (1-0) (bottom right) in the pilot galaxy M51, adapted from [8]. The ^{12}CO (1-0) emission map from the PAWS survey [9] is shown for comparison in the upper left panel, convolved to a matching 30¨ resolution.

3 Main Survey Results

3.1 Global correlations

Figure 2 shows the correlation between the IR luminosity, an indicator of the star-formation rate, as a function of the HCN luminosity tracing the dense gas content. The high signal-to-noise ratio measurements of HCN from EMPIRE are shown in comparison to literature measurements probing Galactic-scale cores out to unresolved entire galaxies. At a resolution of ~ 1 kpc, EMPIRE populates the intermediate regime corresponding to large parts of galaxy disks, between Giant Molecular Clouds and observations of entire galaxies.

This compilation shows that EMPIRE clearly follows the same relation found by [7] between, and it extends across almost ten orders of magnitude with a scatter of a factor of two. The large scatter is therefore an indication that the observed IR-to-HCN ratios are quite different from region to region, which suggests an environment-dependent efficiency of star formation in dense gas.

3.2 Galaxy-to-galaxy correlations

The left panel of Figure 3 shows the HCN-to-CO ratio for each EMPIRE galaxy, which is a good proxy for dense gas fractions, as a function of stellar surface density, one of several

Table 1. Main spectral lines covered by the EMPIRE setup.

Species	Frequency GHz	E_{up} K	n_{crit} cm^{-3}
SiO 2-1	86.45	6.25	1×10^5
C_2H 1-0	87.32	4.19	1×10^5
HNCO 4-3	87.93	10.55	1×10^4
HCN 1-0	88.63	4.25	2×10^5
HCO^+ 1-0	89.19	4.28	3×10^4
HNC 1-0	90.66	4.35	1×10^5
N_2H^+ 1-0	93.20	4.47	4×10^4
$C^{18}O$ 1-0	109.78	5.27	4×10^2
HNCO 5-4	109.90	15.8	1×10^7
^{13}CO 1-0	110.20	5.29	4×10^2
^{12}CO 1-0	115.27	5.53	4×10^2

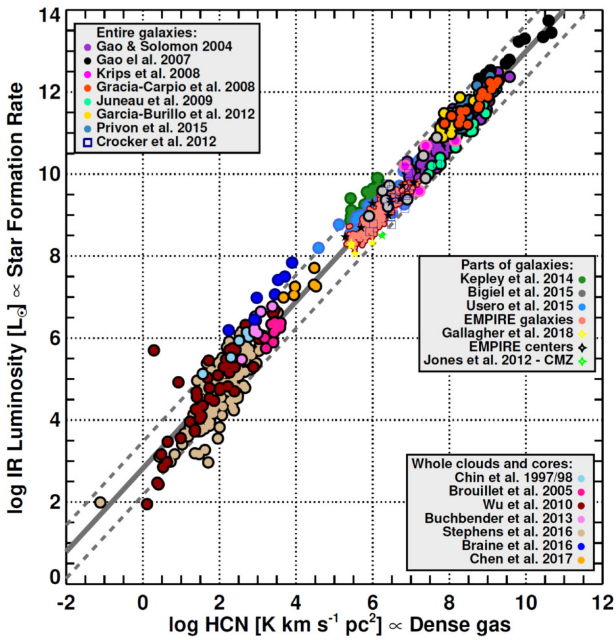

Figure 2. Figure adapted from [10]. Correlation between the measured luminosities of our tracers of the recent SFR and dense gas mass in EMPIRE, as well as a major literature compilation probing distinct scales and environments. The mean IR-to-HCN ratio is represented by the solid gray line, while the RMS scatter is indicated by the dashed gray lines.

physical quantities explored in [10]. EMPIRE indicates that there is more dense gas towards the centers of galaxies, an intuitive result since many physical quantities that facilitate the formation of dense gas (e.g., dust content, turbulence, mean gas density) also increase towards inner disk. The right panel of Figure 3 shows the IR-to-HCN ratio as a tracer for star formation efficiency in dense gas. The plot suggests a completely different behavior, where dense gas becomes more inefficient in those regions where there is more dense gas per unit mass. These findings appear to be the same for all galaxies in EMPIRE, leading to the same trends when using HCO^+ and HNC as dense gas tracers.

These interesting results directly match previous research in the center of our own Galaxy [11], where observations have shown abundant dense gas but no enhanced star formation efficiency. It is important to note, however, that these observational constraints are sensitive to the conversion factors needed to translate line emission into masses of dense molecular gas. In particular, it is well known that very different factors can be responsible for varying the emissivity of a given dense gas tracer (e.g., UV, X-rays, cosmic rays, and mechanical heating), which are linked to the chemistry of the region where this emission emerges. Taking all these factors into account is, therefore, an extremely complex task.

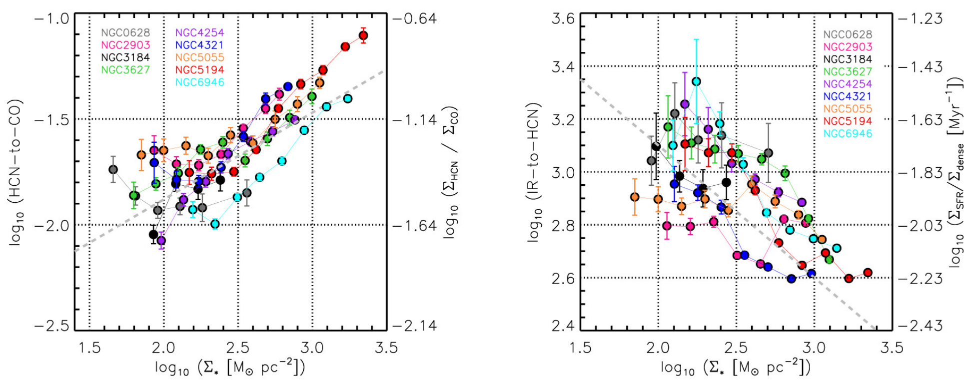

Figure 3. Figure adapted from [10]. The left panel shows the HCN-to-CO ratio as a proxy for the dense gas fraction, while the right panel shows the TIR-to-HCN ratio, tracing the efficiency of star formation in dense gas. Both quantities are plotted as a function of the stellar surface densities, for each galaxy. The gray dashed line indicates the fit to all EMPIRE data.

4 Conclusions and follow-up work

The EMPIRE survey results have constituted a major step forward into the characterization of the dense ISM in extragalactic sources. Systematic, resolved measurements of a set of dense gas tracers across disks of normal, nearby galaxies was a regime never explored before. The main results from this large program are:

- EMPIRE provided for the first time complete maps of high gas density tracers and CO isotopologues across 9 entire galaxy disks.
- Extends previous dense gas-star formation relations and finds systematic trends in IR-to-HCN (tracing star formation efficiency) and HCN-to-CO (tracing dense gas fraction) as a function of environment.
- The role of any particular gas density in star formation appears to be context dependent. However, environment alone is not sufficient to explain the variations seen in the star formation efficiency of dense gas.

In addition to the results presented in this work, EMPIRE has allowed us to constrain the optical depths of the commonly used dense gas tracers [12] as well as derive relative abundance variations of the main carbon isotopologues [13, 14]. Furthermore, the work led by [15] has allowed us to derive new constraints on the ^{12}CO (2-1)/(1-0) line ratio across nearby disk galaxies.

Building up on EMPIRE grounds, much progress is currently being made in bridging the local and extragalactic scales, a key next step to build a complete picture of the interplay between ISM and star formation across a variety of environments. Our recent IRAM-NOEMA project is the perfect example to achieve this synergy. The work in [16] presents very high resolution and sensitivity interferometric measurements of dense gas tracers in NGC 3627, pushing the EMPIRE results to almost individual cloud scales. One of the main results of this research is that dense gas line ratios vary systematically with radius, and they show clear differences in distinct dynamic environments of the galaxy (e.g., center, bar, bar ends and spiral arms).

Linking the central galaxy environment to the ISM properties of galaxies is the focus of another EMPIRE follow-up project using the former IRAM-PdBI. As shown in [17], the center of NGC 6946 is extremely bright and rich in complex molecular emission. Several canonical line ratios targeted at high resolution can help us distinguish photon-dominated regions from X-ray dominated regions, and compare these environments to the many centers available from the EMPIRE survey.

This line of research has the advantage that it is also very important for studies of distant galaxies, therefore observation, analysis and theoretical modeling of many molecular lines and their correlations at high resolution are fundamental next steps.

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