12th Hel.A.S Conference
Thessaloniki, 28 June - 2 July, 2015
CONTRIBUTED LECTURE

Probing the physical conditions of dense molecular gas in (U)LIRGs with LVG modeling

I. Leonidaki[1], *M. Xilouris*[1], *Z.-Y. Zhang*[2] *and T. Greve*[3]
[1]IAASARS, National Observatory of Athens
[2]IfA, University of Edinburgh/ESO
[3] UCL

Abstract:

The gas-rich content of Ultra Luminous Infrared Galaxies (ULIRGs) constitutes a great laboratory in characterising the physical processes occuring in molecular gas and hence probing star formation properties. In particular, molecules with large dipole moments such as CS, HCN, HCO^+, which are the fuel of star formation, can reveal the physical/excitation conditions of molecular gas phases in galaxies. For that reason, we compiled the aforementioned dense gas tracers in a sample of local (U)LIRGs in order to investigate the physical properties of the gas while at the same time put constrains on their excitation conditions. The sample in use consists of 29 galaxies all observed within the framework of the Herschel Comprehensive (U)LIRG Emission Survey (HerCULES). For all galaxies, we compiled our ground-based spectral line observations as well as all available data from the literature. Using Large Velocity Gradient (LVG) radiative transfer models in these spectral lines and in a wide parameter space [n_{H2}, T_{kin}, N_{mol}], and combining multiple molecules and multiple excitation components, it is possible to break the degeneracy between different parameters and to probe molecular gas physical conditions ranging from the cold and low-density average states in giant molecular clouds all the way up to the state of the gas found only near their star-forming regions. We then analyse the best LVG solution ranges to match the observed SLEDs (using more than one excitation components where necessary) in order to disentangle different molecular gas phases and possibly different molecular gas heating mechanisms.

1 Introduction

Intsrestellar Medium (ISM) is comprised of a multitude of constituents, both in composition (ionized, atomic, molecular) and in physical conditions (densities, temperatures). In this talk, we are going to focus on the interplay between molecular gas and ISM.

The molecular gas in galaxies is dominated by H_2. However, all low-lying energy levels have small transition probabilities and relatively high-excitation energies (the first lies 500K above the ground level) due to the lack of permanent dipole moment, hence only a very smal fraction can be studied through H_2 emission in the infrared. On the other hand CO, which is ubiquitous in the ISM (second most abundant molecule), is easily excited through collisions with H_2 (5K for the 1st excitation level) and the CO ladder spans the entire density regime encountered in the ISM. That makes it an excellent tracer of the total mas of the molecular gas (especially the CO J=1-0, 2-1 transitions). Furthermore, we have the so-called dense gas molecules (e.g. HCN, HCO^+, CS) which present high dipole moments and therefore high critical densities, and that makes them excellent tracers of the dense gas in galaxies. Dense molecular gas in galaxies is of great importance since this is the gas that forms stars. Infrared and millimeter studies in Giant Molecular Clouds (GMCs) in our Galaxy have shown that stars form in dense cores (e.g. [1], [6]). The dense gas residing in these cores is best traced by molecules with high critical densities. Therefore, the presence of dense gas and its physical conditions correlate with Star Formation Rate (SFR).

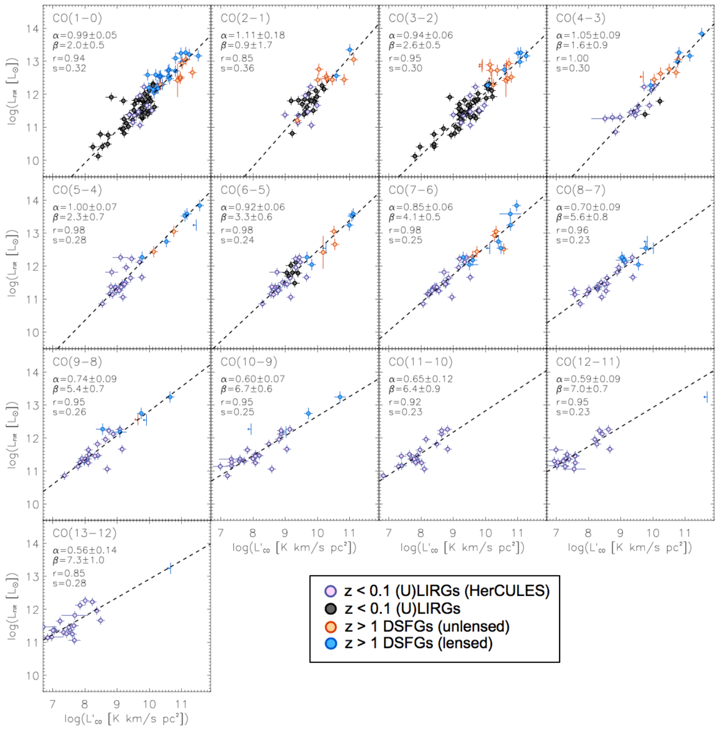

Fig. 1: log L$_{FIR}$ - log L$_{CO}$

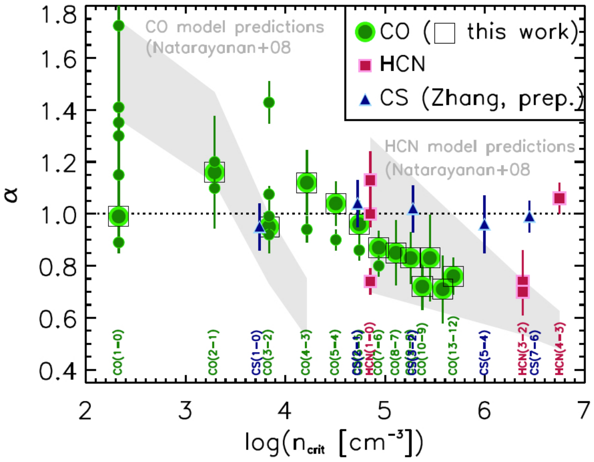

Fig. 2: α - n$_{crit}$

Long discussions within the scientific community have also been made the last decades regarding Star Formation (SF) laws in galaxies. Since the pioneering Kennicutt-Schmidt law, many other studies have been conducted in order to define laws that govern SF in galaxies. However, these studies differentiate in various ways: For example, they use galaxy samples with different characteristics (disks, mergers or both), they investigate the efficiency of different molecules in different transitions or use constant/varying CO-to-H$_2$ conversion factors.

Taking into account the aforementioned, a few intriguing challenges arise: Are SF laws universal i.e. are the same for local/high-z galaxies or different types of galaxies (disks, starbursts)? Can we tie the observed SF laws to physical mechanisms governing/regulating star formation, and if so what are they? In order to address these challenges, the aim of this work is to probe the densest regions in galaxies (where star formation occurs) and derive the physical properties of the dense gas, *using well-sampled high-J CO SLEDs and/or multi-J observations of heavy rotor molecules*. This way we will be able to investigate the nature of the SF laws in the dense gas as well as the heating mechanisms occurring within dense gas (n$_{crit}$ $> 10^4$ cm^{-3}).

2 SAMPLE

(Ultra) Luminous Infrared Galaxies (ULIRGs) are an excellent laboratory to study molecular gas. They are enshrouded by copious amounts of gas and dust which makes them obscured, exhibiting 90-95% of their energy in the infrared (LIRGs $\geq 10^{11}$ $L_{\odot}$, ULIRGs $\geq 10^{12}$ L$_{\odot}$). They host intense starbursts and/or AGNs while they are often part of a merging galaxy group. They are an intermediate stage in the merger-driven process that gives rise to elliptical galaxies. Due to their transitional nature, they are also ideal for studies of the heating mechanisms within the ISM.

The sample in use is the so-called HeRCULES sample which consists of 29 local (U)LIRGs (z$<$ 0.1), all observed within the framework of the Herschel Comprehensive (U)LIRG Emission Survey (PI: van der Werf). The galaxies were chosen from the IRAS BGS (Bright Galaxy Sample) and fulfill the following criteria: S$_{60}$>11.65 Jy for LIRGs and S$_{60}$>16.4 Jy for ULIRGs while we have in hand the entire CO ladder, either from ground-based observations (CO J=1-0 to J=4-3) or from Herschel observations (CO J=5-4 up to CO=13-12).

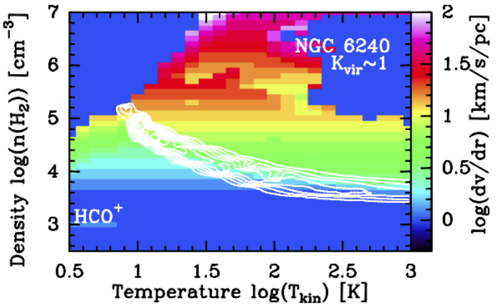

Fig. 3: Probability density function (pdf) for NGC 6240 (as constrained by the HCO$^+$ line ratios)

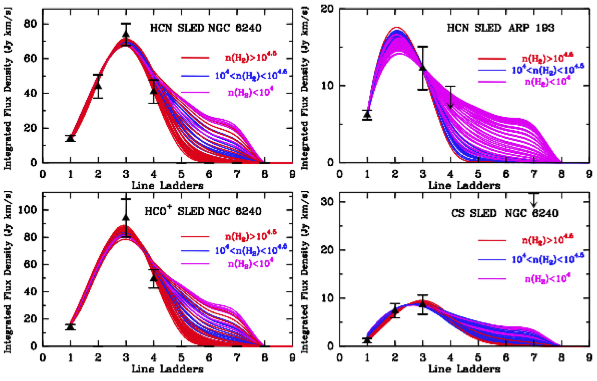

Fig. 4: Molecular SLEDs parametrized by their density ranges

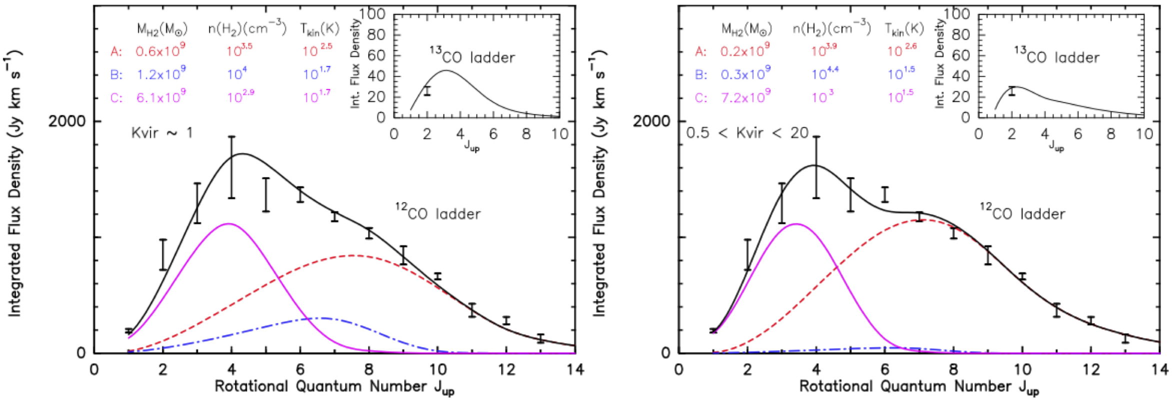

Fig. 5: Arp 193: Two CO SLED decompositions. The dense components (A) and (B) (red, blue dotted lines) are drawn from the LVG solution space compatible with the HCN SLED of this galaxy, while a lower-density component (C) (pink) accounts for the low-J CO line emission [4].

3 RESULTS

3.1 Observing the CO ladder in local (U)LIRGs

As a first step in the investigation of molecular gas in (U)LIRGs, we studied the Star Formation laws for the entire CO rotational ladder up to J=13-12 for a large, well-defined sample of local (U)LIRGs as well as high-z dusty star forming galaxies (DSFGs) ([2]). Functionals of the form $L_{FIR} = \alpha\, L_{CO} + \beta$ were fitted to the data. As can be seen in Fig. 1, low to mid J CO transitions (up to J=5-4) present slopes equal to unity (α ~1) while for CO J=6-5 and beyond the slopes become sublinear ($\alpha < 1$). This can be more easily seen in Fig. 2 where the slope of each CO transition is correlated with critical density. For low to mid-J CO lines, our (U)LIRG sample has nearly constant $f_{dense} = M_{dense}/M_{total}$ ($df_{dense}/dL_{IR} \sim 0$) where for the predicted model or some previous studies (where the used sample contains disks and mergers) we see that $df_{dense}/dL_{IR} > 0$. On the other hand, we see that high-J CO lines require high densities (and also high kinetic temperatures) to be excited. Therefore, these lines are effectively being detached from the star formation since they trace gas that is dense ($n > 10^4 cm^{-3}$) but also radically warmer (T_{kin} >100K) than what is typical for star forming gas. At the same time, FUV radiation at these high temperatures dissociate CO molecules and make them no longer tied to UV heating. This is suggestive of alternative heating mechanisms (cosmic rays, mechanical heating via SN turbulence/shocks).

In order to further investigate the molecular gas behavior in relation to its efficiency in forming stars and the heating mechanisms that take place, a detailed analysis of the CO SLEDs *in conjunction with the multi-J HCN, CS and HCO$^+$ line data-sets* is necessary.

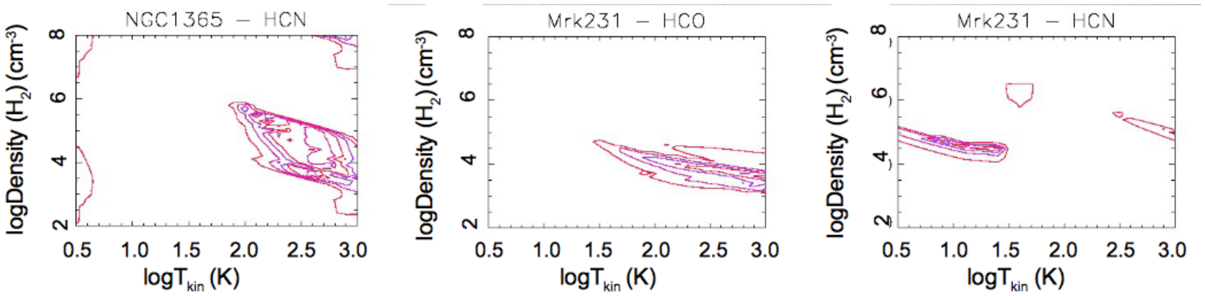

Fig. 6: Probability density functions (pdfs) for NGC 1365 and Mrk 231, as constrained by various heavy rotor lines (e.g. HCO^+, HCN).

3.2 NGC 6240 and Arp 193 as case studies

In this context, two galaxies (NGC 6240 and Arp193) were selected to be investigated as case studies [4]. The main selection criterion for these galaxies to start with was that their CO SLEDs strongly diverge from J=3 - 2 onwards, with NGC 6240 having a much higher CO line excitation than Arp 193, despite their similar low-J CO SLEDs ([4]; their Fig.4). In this work, probability density functions (pdfs) were created in a wide parameter space [n(H2), T_{kin}, dv/dr/abundance], constrained by available heavy rotor molecules (e.g. HCO^+, HCN, CS; see Fig. 3) . Based on these pdfs, the heavy rotor molecular SLEDs of the [n,Tkin,dV/dR] solutions were constructed for the galaxies (Fig. 4), parametrized by their density ranges. The best solutions were then matched with the complete CO SLEDs of the galaxies, combining multiple molecules and multiple excitation components where necessary (Fig. 5).

3.3 HeRCULES sample

The entire CO rotational ladder (J=1-0 up to J=13-12) for the whole HerCULES sample is in hand, covered both from ground-based (up to J=4-3) to Herschel/SPIRE-FTS (up to J=13-12) observations. In addition and for the same sample of galaxies, we used all available molecular spectral lines that are good dense gas tracers (e.g. CS, HCN, HCO^+, HNC, CN).

After a meticulous search, we collected all data of dense gas molecule transitions that are available for the HerCULES sample, coming either from our ground-based observations (performed and reduced by our group members) or from the literature. Since the collection of these dense gas tracers arises from different telescopes, we applied various corrections in order to be used in a uniform manner through LVG modeling. This comprehensive data-set, in conjunction with the complete CO ladder coverage, provides to date a complete census of the molecular Interstellar Medium (ISM) in a large, homogeneous sample of local (U)LIRGs. The uniqueness of this data base will evoke a strong utilization from the majority of the ISM/(U)LIRG community.

Based on the aforementioned data-set, we have embarked on radiative transfer modeling for the HerCULES sample, using the LVG code RADEX ([5]) in order to map a wide parameter space [n(H2), T_{kin}, dv/dr/abundance]. In Fig. 6 we show as indicative examples, the probability density functions (pdfs) for NGC 1365 and Mrk 231, as constrained by various heavy rotor lines (e.g. HCO^+, HCN). After concluding the modeling for all 29 galaxies ([3]), the best LVG solution ranges will be analyzed and based on them we will construct their Spectral Energy Distributions (SEDs). These will be matched with the complete CO SLEDs of the galaxies from J=1-0 to J=13-12 (as in the case of [4], see Figs 4, 5), combining multiple molecules and multiple excitation components where necessary.

This way, it is possible to disentangle different molecular gas phases and possibly different molecular gas heating mechanisms. It will break the degeneracy between different parameters and will probe molecular gas physical conditions ranging from the cold and low-density average states in giant molecular clouds all the way up to the state of the gas found only near their star-forming regions.

References

[1] Evans, N.J. 1999, ARA&A, 37, 311
[2] Greve, T.R., Leonidaki, I., Xilouris, E.M. et al. 2014, ApJ, 794, 142
[3] Leonidaki, I., Zhang, Z.-Y., Greve, T.R., Xilouris, M. 2015, in preparation
[4] Papadopoulos, P., Zhang, Z.-Y., Xilouris, E.M. et al. 2014, ApJ, 788, 153
[5] Van der Tak et al. 2007, A&A, 468, 627
[6] Wu, J., Evans, N.J. et al. 2010, ApJS, 188, 313