Probing the Physical Conditions of Dense Molecular Gas in (U)LIRGs with LVG modeling*

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1. Introduction

The gas-rich content of (U)LIRGs constitutes a great laboratory in characterizing the physical processes occurring in molecular gas while at the same time it put constrains on their excitation conditions. In particular, molecules with large dipole moments (such as CS, HCN, HCO^+) present high critical densities ($n_{crit} > 10^4$ cm^{-3}) and therefore can be used to probe dense, UV shielded, regions. At the same time and since these molecules are the fuel of star formation, they can reveal the physical/excitation conditions of molecular gas phases in galaxies and hence probe star formation properties.
One of the most successful modeling techniques is the Large Velocity Gradient (LVG), which well interprets molecular rotational lines, taking into account the decoupling of radiative transfer equations and level population calculations by the introduction of a photon escape probability (Papadopoulos et al. 2007). It provides a unique method for ignoring the detailed structure of gas but retaining its general properties. However, such approaches are prone to degeneracies, most notably the degeneracy between the gas kinetic temperature and the density of the collisional exciting species (almost exclusively H_2) (Sobolev 1960). If multiple lines for each molecule are available, accurate excitation modeling can occur, able to break this density/temperature degeneracy, and probe the physical properties and the state of the gas.

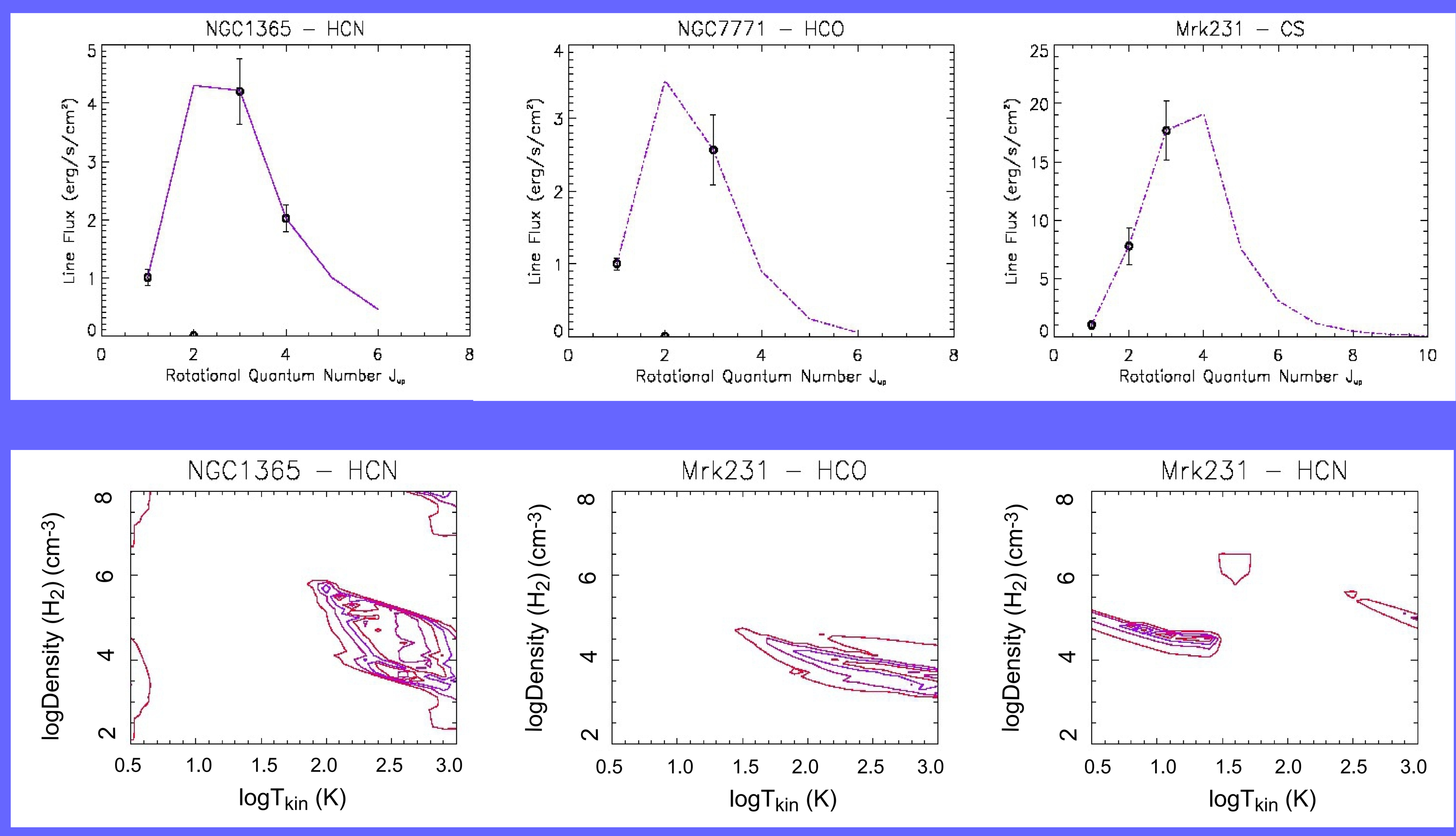

Fig. 1: *Top panel:* Minimum chi-squared SLEDs (normalized to J=1-0) of HCN, HCO^+ and CS for NGC1365, NGC7771 and Mrk231 respectively. *Bottom panel:* Probability density functions (pdfs) of the [n,Tkin] LVG parameters (in steps of 0.2), as constrained by the HCO^+, HCN SLEDs in NGC1365 and Mrk231.

2. Sample

The sample in use consists of 29 galaxies all observed within the framework of the Herschel Comprehensive (U)LIRG Emission Survey (HerCULES, PI: van der Werf). For the whole sample, the entire CO rotational ladder (J=1-0 up to J=13-12) 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 ground-based observations (performed and reduced by the DeMoGas 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.

3. Results

Based on the aforementioned data-set, we have embarked on radiative transfer modeling for the HerCULES sample, using the LVG code RADEX (van der Tak et al. 2007) in order to map a wide parameter space [n(H_2), T_{kin}, dv/dr/abundance]. In Fig. 1 (bottom panel) we show as indicative examples, the probability density functions (pdfs) for NGC1365 and Mrk231, as constrained by various heavy rotor lines (e.g. HCO^+, HCN). After concluding the modeling for all 29 galaxies, which is well underway, 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 Arp193; Papadopoulos et al. 2014, see Fig. 2), 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.

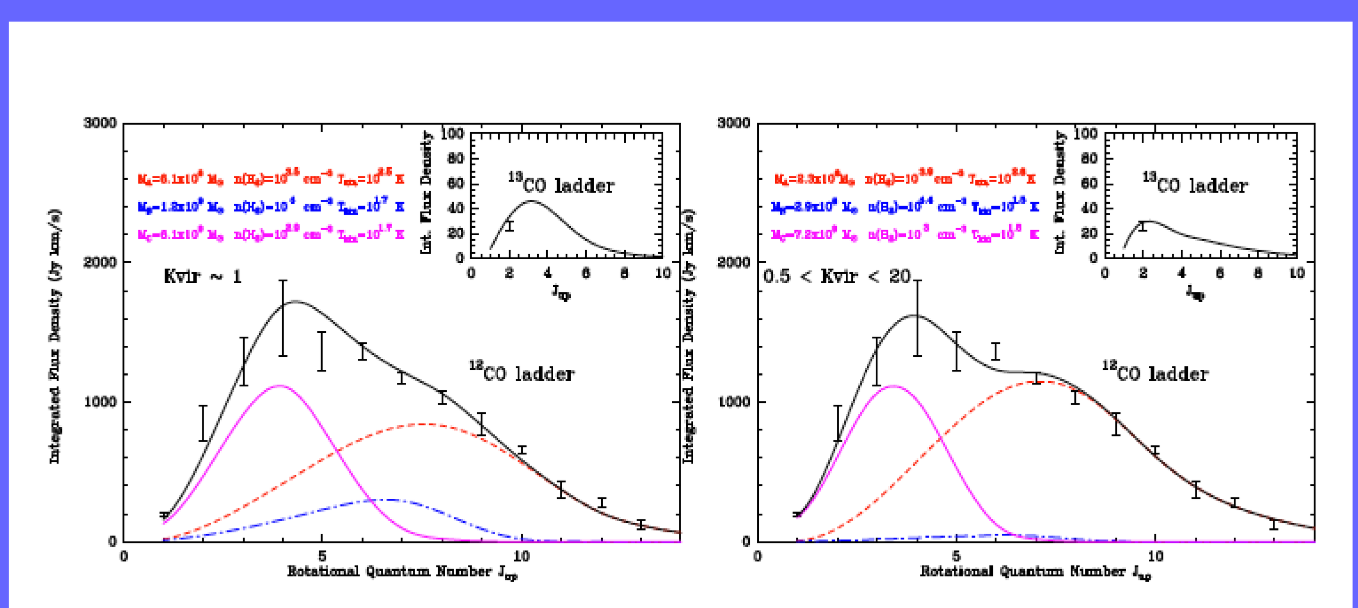

Fig. 2: The two CO SLEDs for Arp193. The dense components (red, blue dotted lines) are drawn from LVG solution space compatible with the HCN, HCO^+ and CS SLEDs of this system while the pink line shows a lower-density and lower-temperature component, which accounts for most of the gas mass.

REFERENCES:

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•Sobolev, 1960, Moving Envelopes of Stars, HUP
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