Molecular Gas, Dust, and Star Formation in Galaxies
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Diagnostics of the ISM in star formation regions

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Abstract. Line emissions of high- and low-density molecular tracers serve as powerful diagnostic tools for the ISM in both Galactic and extragalactic star formation environments. The emission line strengths and line ratios may be interpreted using detailed modeling of both the dominant physics and the chemistry of the molecular constituents. Observed molecular line ratios will thus reveal the signatures of dominant UV, X-ray, and CR radiation fields and of mechanical heating and feedback from the star formation process. In addition, certain line ratios reflect the physical and chemical changes resulting from the time-evolution of a star formation region. In this paper, we present results of Galactic sources and extragalactic starbursts covering a large range of FIR luminosities and illustrate the similarities between the diagnostics of these environments.

Keywords. line: formation — ISM: molecules — ISM: evolution — galaxies: ISM — stars: formation

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1. Introduction

Molecular line emissions serve as a diagnostic tool of the physical and chemical environment in the interstellar medium in the Galaxy and in extragalactic sources. Understanding star formation processes depends strongly upon understanding the excitation and chemical processes in the molecular gas. Many of these excitation studies use transitions along molecular ladders to determine the excitation temperature or density (or both) of the molecule. In this manner multiple temperature and density regimes can be identified in the ISM. However, different molecular species react differently to environmental influences and together they provide a more accurate description of the physical and chemical environment. The line intensities provide information about the geometry of the source, while the molecular line ratios illustrate its physics and chemistry.

Physical and chemical modeling networks may be used to interpret the line ratios and the evolutionary variation of these line ratios. Modeling codes have been developed for interpreting line strengths and ratios (Meijerink & Spaans 2005, Meijerink, Spaans & Israel 2006). These codes incorporate many molecular species, many chemical reactions, as well as radiation transfer. In this paper we present some results of coherent multi-molecule modeling in order to provide diagnostics of the medium and information about the density, temperature, radiation fields, and mechanical heating.

The diagnostic studies of regions in the Galaxy and nearby galaxies, where star formation regions can be resolved, serve as a benchmark for the phenomenology and evolution of ISM in distant sources with only integrated line emission profiles. This allows the extrapolation of Galactic results to nearby galaxies and more distant galaxies.

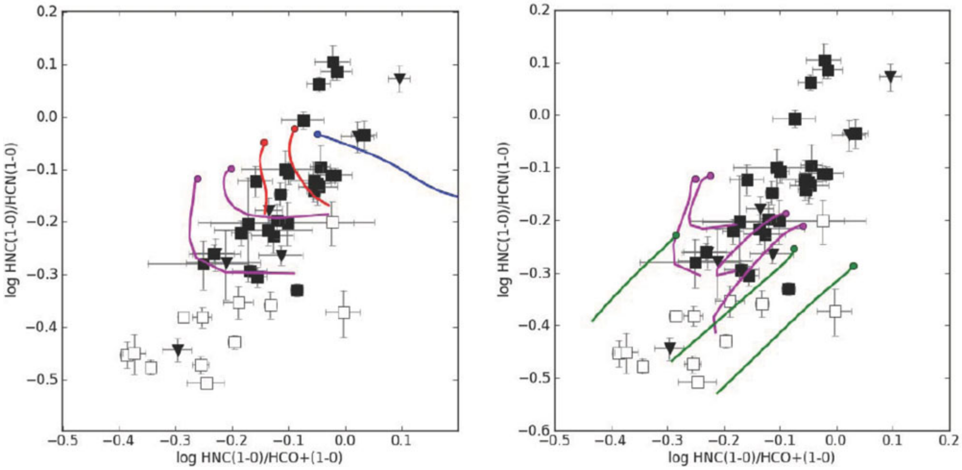

Figure 1. Line ratios of high-density tracers for Galactic star formation regions at 7 positions in the CMZ (filled triangles), 28 in the GMC complex G333 (filled squares), and 12 IRAS sources associated with UCHII regions (open squares). *Left:* Colored tracks of PDR modeling results with increasing density from left to right. *Right:* IRAS sources with low HNC/HCN values are explained as lower density PDRs with varying rates of mechanical feedback heating.

2. Galactic Studies

Molecular line ratios for a sample of southern Galactic star formation regions have been obtained with the Mopra 22m telescope (Baan, Lian & Loenen 2013), representing a wide variety of star formation environments. The characteristic line ratios of ground state transitions of the high-density tracer molecules HCN, HNC, and HCO^+ show a large range of values, indicating strongly varying physical/chemical conditions (Fig. 1).

Modeling of observed ratios shows that the regions can be explained as PDR regions with a density range of $10^{4.5-5}$ cm^{-3} and a UV flux of 10^3 Habing units. In the diagrams the model density increases towards the right. Regions with HNC(1-0)/HCN(1-0) > 1 may be explained as PDR-regions with additional X-ray heating. Although there is redundancy between density, UV-heating, and column density, satisfactory solutions can be found for each data point. IRAS sources with a HNC/HCN ratio lower than predicted for standard PDRs may be explained with slightly lower densities of $10^{4-4.5}$ cm^{-3} and additional mechanical feedback, which raises the temperature and enhances the conversion of HNC to HCN. Similar results are found for a sample of northern IRAS sources observed with the Onsala 20m telescope (Loenen, Baan & Spaans 2012).

Large variations in the line ratios have also been found for other molecular tracers HCO, N_2H^+, HC_3N, HNCO, and CN, all depending differently on the physical and chemical environment. Modeling of the molecular ensemble will provide a more detailed and more accurate description of the environment. For instance, a single CS(2-1) emission line can already determine the sulfur depletion (Loenen, Baan & Spaans 2012).

3. Extragalactic Studies

Modeling studies of high-density tracers have also been done for a sample of (mostly unresolved) extragalactic nuclear star formation regions (Fig. 2) (Baan *et al.* 2008, Loenen *et al.* 2008). The distribution of these data points resembles strongly the distribution in Galactic sources, but with a larger width in HNC/HCO^+.

Modeling shows that the extragalactic environmental conditions have similar densi-

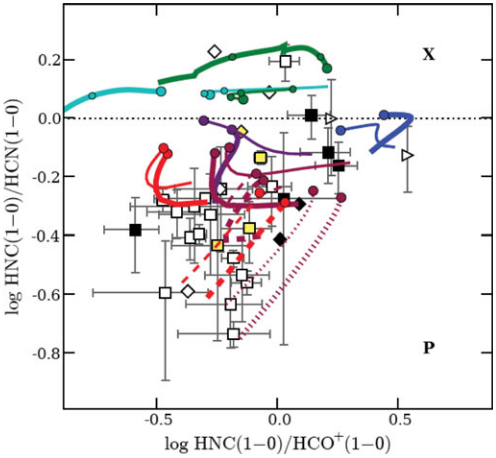

Figure 2. HNC(1-0)/HCN(1-0) versus HCN(1-0)/HCO$^+$(1-0) line ratios for an extragalactic sample of ULIRGs and starburst galaxies. ULIRGs and OH Megamaser galaxies are indicated with filled symbols and M82 and Arp220 are indicated in yellow. Solid (green, light-blue) tracks for log (HNC/HCN) $\geqslant 0$ relate to possible XDR models. Solid (red, magenta, blue) tracks for log (HNC/HCN) $\leqslant 0$ represent pure PDR models, and dotted (red, magenta) tracks for log (HNC/HCN) $\leqslant 0.2$ are PDR models with additional mechanical feedback heating.

ties of 10^{4-5} cm^{-3} for pure PDR modeling (with varying UV-fluxes) and densities of $10^{4-4.5}$ cm^{-3} for sources with added mechanical feedback heating. The few sources with HNC(1-0)/HCN(1-0) > 1 may be explained with XDR models for densities $10^{5.5-6}$ cm^{-3}, although these are likely extreme PDRs with additional X-ray heating.

Galactic and extragalactic star formation regions show slightly different sample distributions but very similar model environments. For the current samples, the extragalactic PDR density range is slightly lower than that of Galactic sources. Mechanical feedback (heating) is required for sources with low HNC/HCN ratios for both samples.

4. Molecular evolution

The Galactic and extragalactic HCO$^+$/HCN versus HCN/CO diagrams both show a gradient from low density to high density environments (Fig. 3). The distribution of extragalactic sources show a variation from high-luminosity ULIRG/OH megamaser sources with high environmental densities to low-luminosity evolved starbursts (right to left) (Baan, Loenen & Spaans 2010). Extragalactic sources affected by feedback move away from the main distribution, while such sources in the Galaxy remain in the distribution. The dashed line in Figure 3(left) indicates the similarity of the two samples.

As star formation activity depends on evolutionary time as well, older star formation regions will have different ISM characteristics than younger regions, a fact that will be reflected in their molecular line ratios. The HCN(1-0)/CO(1-0) ratio (high-density tracer versus low-density tracer) may serve as an evolution or age indicator, assuming that the ongoing star formation depletes, relatively, the high-density component. This relative depletion may apply to large-scale extragalactic environments with a nuclear starburst; however, it is less clearly valid for Galactic sources.

The evolutionary trends as a function of the HCN/CO ratio are very similar for Galactic and extragalactic environments, which may indicate that density evolution and evolutionary time are important factors for interpreting their line ratios.

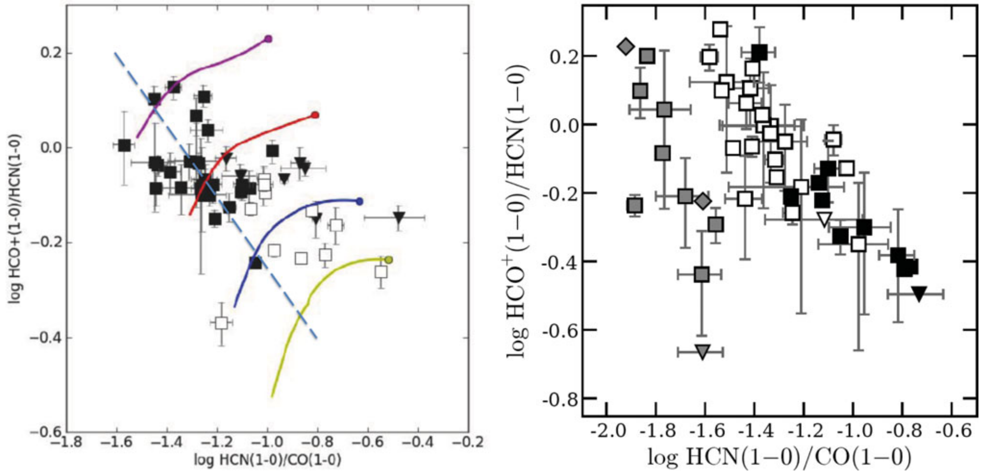

Figure 3. The variation of HCO$^+$(1-0)/HCN(1-0) versus HCN(1-0)/CO(1-0) for the southern Galactic sample and the extragalactic sample. *Left:* The PDR modeling results for the Galactic sample show a variation from low (purple) to high density (yellow) (left to right). A dashed line indicates the centroid distribution for the extragalactic sample. *Right:* The main distribution of extragalactic sources has a similar density gradient between high-density PDRs in ULIRGs (black) and low-density evolved PDRs (open symbols). Evolved starburst sources (grey symbols) with low HCN/CO ratios have additional mechanical feedback. Note the different axis scaling.

5. Implications

Multi-molecule and multi-transition modeling of the ISM in Galactic and extragalactic environments provides a powerful diagnostic tool for probing their physical and chemical properties and their evolutionary status. Line ratios provide significant differentiation between the effects of density, temperature, UV-flux, X-ray flux, CR flux, and mechanical feedback heating.

Galactic regions may be interpreted as simple PDRs in a certain density range, while some require additional local X-ray heating or envelopes affected by feedback heating.

Nearby starburst galaxies and powerful (U)LIRGs provide a broad range of parameters and may be modeled as nuclear PDRs, some of which having additional X-ray heating. PDR models of evolved galaxies with older starbursts and lower HNC/HCN ratios require additional mechanical heating from feedback as well.

The evolutionary trends observed as a function of the HCN/CO ratio are very similar in Galactic and extragalactic environments, a fact that may indicate that evolutionary time is an important factor for both Galactic and extragalactic star formation.

The inclusion of more molecules and multiple molecular transitions augments the modeling accuracy and is part of ongoing research.

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