The HCN/HNC Ratio as a Tracer of Mechanical Energy in NGC 253

HCN, HNC, and HCO^+ as Tracers of Dense Gas and Heating Processes

Measurements of HCN, HNC, and HCO^+ are traditional tracers of dense gas in both galactic and extragalactic star formation regions. For high-spatial resolution studies of the dense gas in protostars, the recent study of the J=3-2 transitions of HCN, HCO^+, and $HC^{18}O^+$ toward IRS43 (Brinch et. al. 2016; http://adsabs.harvard.edu/abs/2016ApJ...830L..16B) exemplifies the use of these molecular tracers for studies of dense gas in protostellar disks. Brinch et. al. imaged these transitions with a spatial resolution of 24 AU with a goal to characterize the disk/YSO associations in this multi-component system. It appears that these investigators chose to measure the $HC^{18}O^+$ J=3-2 transition at 255.5 GHz rather than the more-abundant $H^{13}CO$+ transition at 260.55 GHz due to the current IF limitations of the ALMA Band 6 receivers. With the proposed receiver upgrade, the HCN, HCO^+, and $H^{13}CO^+$ J=3-2 transitions would be measurable simultaneously. Noteworthy in this regard is the recent investigation of the theoretical utility of using the J=3-2 transitions of HCO^+ and $H^{13}CO^+$ in studies of protostellar disk dynamics by Seifried et. al. (2016; http://adsabs.harvard.edu/abs/2016MNRAS.459.1892S).

In the extragalactic context, the J=3-2 transitions of HCN and HCO^+ in the ground (v=0) and first-excited (v_2=1) vibrational states have been used extensively to study both starburst/AGN evolution and the deeply-embedded nuclei of galaxies. For example, Imanishi et. al. (2016; https://arxiv.org/abs/1609.01291) made simultaneous measurements of these J=3-2 transitions toward a sample of luminous infrared galaxies, with a goal toward a better characterization of the dominance of AGN or starburst processes in these objects.

Starburst Galaxy Heating

An understanding of how high kinetic temperatures are produced, and what role they play in the evolution of starburst galaxies, is crucial to a global view of the extragalactic starburst process. Recent theoretical studies of the environment in starburst galaxies suggest that either photon-dominated regions (PDR) or cosmic ray dominated regions (CRDR) could enhance the average kinetic temperature to extremely high values (T_K > 80 K in CRDRs; Papadopoulos 2010). Significant cosmic ray (CR) flux, in turn, influences the chemistry in starburst environments (Bayet etal. 2011). The contribution due to mechanical heating (Meijerink et. al. 2010), such as that produced by supernovae within an environment where the star formation rate is $\geq$ 100 solar masses per year, is clearly an important potential source of heating in these systems.

The chemical models of PDRs/CRDRs which include mechanical heating suggest that the HCN/HNC ratio can be used to track the relative contribution of these two heating mechanisms in starburst environments. The HCN and HNC abundances do not show a strong dependence upon the incident CR rate, but they do show a strong dependence upon the mechanical heating rate. The temperature-dependent chemistry of these two molecules is the reason for this dependence: (1) At kinetic temperatures less than 24 K ion-neutral chemical processes will cause $HCNH^+$ to recombine and produce either HCN or HNC in roughly equal amounts. (2) At higher kinetic temperatures, the neutral-neutral reaction HNC + H $\rightarrow$ HCN + H is dominant. Since it has a temperature barrier of ~200 K, higher kinetic temperatures process HNC into HCN, enhancing the abundance of HCN relative to HNC. (3) At increasing CR ionization rates at high spatial densities He^+ destroys both HCN and HNC effectively, leading to a decrease in the abundances of both, with a slightly larger effect on the HCN abundance. Figure 1 shows results from the modified PDR models of Meijerink etal 2010 which include cosmic ray and mechanical heating contributions. With no mechanical heating (Λ_{mech}) the HCN/HNC ratio is ~2, while for increasing Λ_{mech} HCN/HNC can get as high as 100. *Clearly the HCN/HNC ratio can be used as a very sensitive diagnostic of the importance of mechanical heating in starburst galaxies.*

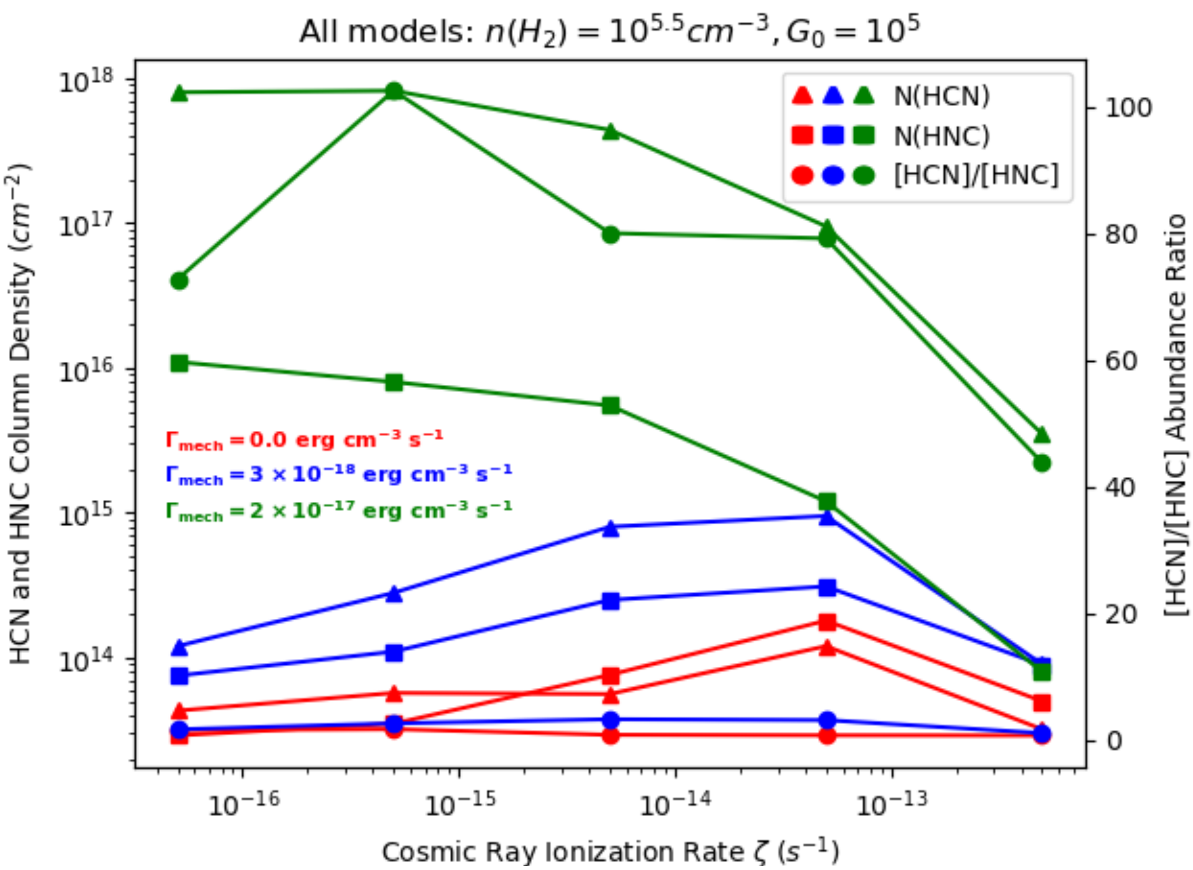

Figure 1: Modified PDR model (Meijerink et. al. 2010) predictions of the HCN and HNC abundances (left axis) and HCN/HNC abundance ratio (right axis) as a function of CR ionization rate and mechanical heating. For Λ_{mech} = 3.0x10^{-18} and 2.0x10^{-17} erg cm^{-3} s^{-1} the star formation rates are 140 and 950 solar masses per year, while the gas kinetic temperatures are ~250 and ~400 K, respectively.

The ALMA Comprehensive High-resolution Extragalactic Molecular Inventory (ALCHEMI)

The molecular composition of the dense star-forming gas in galaxies varies dramatically, a likely product of the complex interplay between chemistry and the physical environment within each galaxy. Before ALMA, we could only sample this complexity using relatively low spatial and spectral resolution toward a few relatively nearby galaxies. ALMA now allows us to study the chemical complexity of the molecular interstellar medium beyond the Milky Way on size scales which are analogs to giant molecular clouds in our Galaxy. To provide a template for the star formation process in a galaxy outside the Milky Way, with a multi-transition multi-species database measured with uniform sensitivity and spatial resolution, ALCHEMI was conceived. This ALMA Cycle 5 Large Programme images the NGC 253 circumnuclear zone (the central bar in this nearby starburst galaxy), a region approximately 850x340 pc in extent, with a spatial resolution of about 1 arcsec (17 pc) at ALMA Bands 3 (84 to 116 GHz), 4 (125 to 163 GHz), 6 (211 to 275 GHz), and 7 (275 to 368 GHz). For ALMA Cycle 6, we have also been granted time to observe Band 5 (163 to 211 GHz) with the same measurement parameters, and which we will add to our existing ALCHEMI data products. These observations will result in the most complete extragalactic molecular inventory ever obtained and will provide the extragalactic community with reliable templates of chemistry and excitation in a starburst galaxy at GMC size scales. These data will be used to benchmark molecular diagnostics and chemical models, and will serve as a guide for future observations in the near and distant Universe.

Outline of the HCN/HNC Isotopomer Ratio Project

ALCHEMI is comprised of ~1.6 arcsec resolution mosaics of the central molecular zone of NGC 253 in the HCN, HNC, $H^{13}CN$, $HN^{13}C$, $HC^{15}N$, and $H^{15}NC$ 1-0, 2-1, 3-2, and 4-3 transitions. Table 1 lists the transitions and frequencies for all isotopomers.

Transition/Band	HCN	HNC	H13CN	HN13C	HC15N	H15NC
1-0 / B3	88.632	90.664	86.340	87.091	86.055	88.866
2-1 / B5	177.261	181.325	172.678	174.179	172.108	177.729
3-2 / B6	265.886	271.981	259.012	261.263	258.157	266.588
4-3 / B7	354.505	362.630	345.340	348.340	344.200	355.439

Table 1: HCN isotopomer frequencies in GHz

The project will likely proceed as follows:

1. Inspection of Science Ready Data Products (SRDPs) delivered by ALCHEMI collaboration. This will include 12m+7m and 7m-only image cubes. Goal here will be to spend some time looking over the image cubes and trying to identify spectral lines of interest, including HCN and isotopomers.
2. Investigate any blending with target HCN isotopomers. This will involve inspecting spectra toward GMCs in NGC 253 and identifying potential blends using a spectral line list.
3. Extra moment maps of HCN isotopomers. This will entail use of the CubeLineMoment script.
4. With integrated intensities (moment 0) images in-hand, proceed to Large Velocity Gradiant (LVG) modeling of HCN isotopomers. Start by running online RADEX (http://var.sron.nl/radex/radex.php) by-hand to get a feel for the range of LVG solutions

allowed by your data sets. Final modeling will be done using a python interface to RADEX.

5. With good spatial density, kinetic temperature, and column density fits to your HCN isotopomer measurements, you can now derive HCN/HNC and isotopomer column density ratio images of NGC 253. These column density ratios (equivalent to abundance ratios) can then be compared to models which include varying amounts of mechanical energy (see above).
6. Once you get an idea of what the distribution of mechanical energy "demand" is in NGC 253, you can investigate what other diagnostics of the heating processes in NGC 253 can tell you. For example, what does the distribution of radio sources look like in comparison to your HCN/HNC ratio.
7. Quite a few "odds-and-ends" to investigate:
    a. TH2 (Region 5) absorption
    b. Given the possible connection to kinetic temperature monitoring sensitivity, a deep-dive into the chemical reactions underpinning the assertion that HCN/HNC is a mechanical energy probe might be interesting (and useful)
    c. Are the modified PDR models (Meijerink, Kazandijian, Bayet, etc.) really applicable to our problem? In other words, are the GMCs embedded within the CMZ of NGC253 really appropriately described by the modified PDR models of the chemistry?

Reading Material

- What Every Millimeter Spectroscopist Should Know:
    1. Mangum, J. G. & Shirley, Y. L. 2015, PASP, 127, 266, "How to Calculate Molecular Column Density" (https://ui.adsabs.harvard.edu/link_gateway/2015PASP..127..266M/EPRINT_PDF).
        a. Basic discussion of molecular spectroscopy and how to use molecular spectral line measurements to derive molecular column density.
    2. Shirley, Y. L. 2015, PASP, 127, 299, "The Critical Density and the Effective Excitation Density of Commonly Observed Molecular Dense Gas Tracers" (https://ui.adsabs.harvard.edu/link_gateway/2015PASP..127..299S/EPRINT_PDF)
        a. Really important to understand this fundamental aspect of molecular collisional excitation.
- Starburst Modeling:
    1. Meijerink, R., Spaans, M., Loenen, A. F., & van der Werf, P. P. 2011, A&A, 525, A119, "Star Formation in Extreme Environments: The Effects of Cosmic Rays and Mechanical Heating" (https://ui.adsabs.harvard.edu/link_gateway/2011A&A...525A.119M/PUB_PDF).
        a. This is the theoretical model of starbursts used to compare to our HCN/HNC (and other molecular probe) measurements.

2. Kazandjian, M. V., Meijerink, R., Pelupessy, I., Israel, F. P., & Spaans, M. 2012, A&A, 542, A65 "Diagnostics of the Molecular Component of Photon-Dominated Regions with Mechanical Heating" (https://ui.adsabs.harvard.edu/abs/2012A%26A...542A..65K/abstract)
    a. Very similar model to Meijerink, but interestingly different…
3. Bayet, E., Williams, D. A., Hartquist, T. W., & Viti, S. 2011, MNRAS, 414, 1583, "Chemistry in Cosmic Ray Dominated Regions" (https://ui.adsabs.harvard.edu/link_gateway/2011MNRAS.414.1583B/PUB_PDF)
    a. Similar starburst physio/chemical model to Meijerink etal, but without mechanical heating. Good for comparison to the Meijerink no-mechanical heating models.

- NGC 253:
    1. Leroy, A. K., Bolatto, A. D., Ostriker, E. C., etal. 2015, ApJ, 801, A25, "ALMA Reveals the Molecular Medium Fueling the Nearest Nuclear Starburst" (https://ui.adsabs.harvard.edu/link_gateway/2015ApJ...801...25L/PUB_PDF).
        a. Excellent overview of the physical properties of the NGC 253 circumnuclear zone (CMZ…which is where all of the star formation is happening).
    2. Leroy, A. K., Bolatto, A. D., Ostriker, E. C., etal. 2018, ApJ, in press, "Forming Super Star Clusters Power the Central Starburst in NGC 253 (https://ui.adsabs.harvard.edu/link_gateway/2018arXiv180402083L/EPRINT_PDF).
        a. This article is basically a high-resolution follow-up to article 4 above. Yet another excellent overall study of the star formation process in NGC 253.