Chemical Complexity in Galaxies

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Abstract ALMA will be able to detect a broad spectrum of molecular lines in galaxies. Current observations indicate that the molecular line emission from galaxies is remarkably variable, even on kpc scales. Imaging spectroscopy at resolutions of an arcsecond or better will reduce the chemical complexity by allowing regions of physical conditions to be defined and classified.

Keywords galaxies: ISM · astrochemistry · galaxies: individual (IC 342, M 82)

1 Introduction

A rich spectrum of molecular lines is available at millimeter and submillimeter wavelengths for the study of molecular clouds in galaxies. A recent single dish survey in the $\lambda = 2$ mm band of the starburst Sc galaxy NGC 253 revealed lines from 25\cite{1} of the over 35 molecular species detected to date in external galaxies (see contribution by S. Martín in this volume). Within the reach of ALMA will be thousands of transitions of over a hundred molecules, bringing a vast set of potential diagnostics of molecular gas and physical conditions within galaxies.

With such chemical riches comes complexity. Existing observations of the most commonly used molecular tracers, such as CO, HCN, $H_2$, and ammonia, often give conflicting results for the properties of molecular gas in galaxies. Mean densities inferred over decaparsec scales of $\sim 10^3$ cm$^{-3}$ to $\sim 10^5$ cm$^{-5}$, depending on which molecular tracer is used. Temperatures inferred from molecular lines can also vary, from $\sim 10$–900 K. While CO emission, particularly in spiral arms, appears to be optically thick, as expected from observations of Galactic clouds, there appears to be a widespread diffuse and emissive optically thin CO component in the interarm regions of spiral galaxies, mixed in with the thick gas\cite{2,3}.

Spatial resolution can provide key information to resolve the complexity and confusion in molecular spectra of galaxies, by isolating areas of common physical conditions. Arcsecond imaging of molecular line emission with millimeter arrays gives resolutions comparable to individual giant molecular clouds in the nearest galaxies. Dense cloud tracers identify where the dense cloud cores are\cite{4}, and their gas properties should be very different from those of diffuse molecular gas found between spiral arms\cite{4}. Nuclear activity can affect relative molecular abundances\cite{5} on these sizescales (see the contribution by S. García-Burillo in this volume). These small-scale variations in molecular emission properties are of interest to astrophysicists, since these are potential diagnostics of physical processes such as shocks or irradiation. The variations are also of interest to astrochemists, since where molecules are found within galaxies may provide clues toward solving the mystery of how they form. ALMA will be a tool for both astrophysicists and astrochemists, with exquisite sensitivity to many different molecules and transitions.
An example of the imaging spectroscopy of a nearby normal spiral galaxy, IC 342, with data from the Owens Valley Millimeter Array, is presented in the next section. This example illustrates that with a sufficiently large number of spectral lines and the appropriate statistical analysis, the imaging of the line emission of many molecules can reduce the complexity of the interpretation of the physical and chemical processes in the molecular clouds.

2 Principal Component Analysis of the Center of a Normal Spiral Galaxy: Imaging Chemistry in IC 342

IC 342 is a nearby Scd galaxy, nearly face-on, and at a distance of 3 Mpc (1″=15 pc). An intense episode of nuclear star formation is indicated by a bright infrared and radio continuum source of luminosity $L_{IR} \sim 10^8 L_\odot$ [7-8], which is offset by ~50 pc from the dynamical center and nuclear star cluster [9]. Molecular gas in the center of IC 342 forms a barlike structure [10,11] within the central 300 pc. A schematic of the stellar $x_1$ and $x_2$ bar orbits and other dynamical features of this central molecular bar are shown in Figure 1 [12]. Streaming of the gas along the bar [10] leads to strong shearing motion, corresponding to a velocity differential of 50 km s$^{-1}$ [13] across the arms. The current burst of star formation is found at the southwestern intersection of the $x_1$ and $x_2$ bar orbits, where the stellar orbits change from parallel to perpendicular to the bar [12,14].

IC 342 has many faces, depending on which molecules are used to observe it. Careful analysis of CO and its isotopologues indicate that the bulk of the molecular gas in the center of IC 342 tends to be cool, 20 K or less [13]. Dust temperatures measured to 160µm with the KAO are ~40 K [15]. There is evidence for an extremely warm component of molecular gas, ranging from 50–150 K as indicated by the lower inversion lines of ammonia, CO(7–6) and the H$_2$ rotational lines [16,17,18,19]. Gas temperatures as high as 800–900 K are inferred from the higher inversion lines of ammonia [19] within the same general region as the cooler CO gas. However, the velocity of the CO(7–6) emission suggests that it originates in the clouds to the northeast of the dynamical center [17], a preliminary indication that CO alone gives an incomplete view of the spatial distribution of molecular line emission in IC 342.

How can higher resolution and more molecules refine our understanding of the molecular gas in the center of IC 342? Images were made of the central kpc of IC 342 in eight molecules with the Owens Valley Millimeter Array: C$_2$H, C$_3$4S, N$_2$H$^+$, CH$_3$OH, HNCO, HNC, HC$_3$N, and SO by Meier & Turner [12]. Results were combined with existing observations of the CO and CO isotopologues of the 2–1 and 1–0 transitions [14] and HCN [4] maps. The seven images (SO was not detected) are shown in Figure 2. The 5″ resolution maps reveal a re-
Fig. 2 Images of 3mm transitions of molecules in the center of IC 342. Data from the Owens Valley Millimeter Array at a resolution of 4″. Contours of the 3mm emission of 12C18O are shown in each panel, showing where the molecular clouds are found. From [12].

A remarkable degree of chemical variation across the central kpc. These lines arise from molecules with similar upper level energies and critical densities; the differences appear to be due to molecular abundance variations within the nuclear region [12].

The combination of nearly a dozen different molecular lines with an image containing ∼ 220 independent resolution elements is a dataset sufficiently large that one can study the statistical correlations among the molecules as a function of location. Following the methods of Ungerechts et al. for the Orion Ridge [20], a principal component analysis was done of the molecular line intensities across the nucleus of IC 342. The principal component analysis extracts an unbiased set of correlations from the data by choosing independent axes that maximize variance. Strong correlations are apparent in the first two principal components; a third component seems to indicate weak radial variations.

The spatial map of principal component axis 1 is shown in Figure 3. With a resemblance to the CO map of Figure 1, it represents the best “average” map for this set of molecules, which trace a slightly denser gas component than CO. This first axis simply tells us that the molecular lines arise in molecular clouds. More precisely, principal component axis 1 appears to be the density-weighted mean column density. The molecules with the highest projections (i.e., best correlation with density-weighted mean column density) along PC axis 1 are C18O, N2H+, HNC, and HCN. In fact the PC 1 map appears to be an effective average of the C18O and HNC maps. These 3mm lines appear to be the best general tracers of quiescent clouds and the overall denser molecular gas component characteristic of the nuclear region of a spiral galaxy.

Principal component axis 2 distinguishes two further major correlations, which are roughly anticorrelated here (modulo the requirement of PC axis 1 that molecules are found in molecular clouds.) With positive projections along PC axis 2 are the emission of HNCO and CH3OH (methanol). These molecules are found
preferentially along the molecular bar arms. Observed Galactic abundances of methanol are very difficult to produce through gas-phase chemistry, so methanol is believed to be a tracer of grain chemistry. That methanol lies along the bar arm in IC 342 suggests that it is produced by the processing of grain mantles in the shocks along the bar arms. The SiO image of IC 342 of Usero et al. (2002) looks very much like the CH$_3$OH image [21], which would also support this interpretation. The chemistry of HNCO has been less certain from Galactic studies; both gas or grain chemistry have been suggested for it. Based on the IC 342 image, and the very good correlation with methanol and SiO, we suggest that it is also a product of grain chemistry (the excellent correlation of HNCO and methanol is also seen in the barred galaxy Maffei 2, Meier et al. in prep.) It is interesting that these putative shock tracers are found most strongly along the northern bar arm, which also has less active star formation.

The second correlation evident in PC axis 2 of Figure 3 is that of C$_2$H and C$^{34}$S. Both of these molecules are restricted to the central 100 pc of IC 342. The emission from these lines is distinctive in that they are not found along the bar arms where the other species are found nor are they coincident with the bulk of the youngest embedded star formation. These molecules are likely to be tracers of highly irradiated molecular gas on the inner faces of the central ring, which contains a bright nuclear star cluster, presumably located at the dynamical center of the galaxy (or a combination of many star clusters, C. Max private communication).

The fact that these two lines appear to be more closely associated with the visible nuclear cluster, estimated to be 60 Myr in age [9], than with the IR and radio source of the current starburst, suggests that this gas may be more closely correlated with a B star population than the young O stars. A similar result has been found for PAHs in galaxies [22].

Another view of the results of the principal component analysis is the correlation matrix, shown in Table 1. This matrix represents the correlations between individual pairs of molecules and the 3 mm continuum. Of particular interest are the unusually low correlations and high correlations. The spatial anti-correlation of the molecular bar arm molecules and the nuclear “PDR” molecules of PC axis 2 described above is evident in unusually low values of the correlation coefficient. The correlation between HNC and HCN is very high, and perhaps this is not surprising since they are isomers. But the very highest correlation, and it is remarkably high at 0.94, is between HNC and the 3 mm continuum. This is closely followed by a correlation between HCN and 3 mm continuum, which at 0.91 is nearly as tight. The 3 mm continuum in IC 342 is free-free emission, with little contribution from dust [14]. Thus the dense gas tracers HNC and HCN are extremely well-correlated with free-free emission. This result suggests that the correlation found by Gao & Solomon [23] based on global HCN fluxes (mostly) holds down to the scales of individual giant molecular clouds.

While it is encouraging that the ability to resolve features such as bar arms, orbital intersections, and
nuclear star cluster appears to simplify the chemical analysis, there is still more to learn about the molecular clouds in IC 342. The transitions here all trace the cool and relatively dense molecular gas component. While there are indications that the warmer molecular cloud component at 50-150 K traced by ammonia, H$_2$, and upper J levels of CO, and the hot component above 500 K traced by the upper ammonia inversion levels, are found in different parts of the nucleus than the lower energy gas traced by CO $^{[17,24]}$, the hot molecular gas chemistry remains as yet relatively unexplored in the imaging domain.

### 3 A Different Kind of Chemistry: M82

A different situation is represented by the dwarf starburst galaxy, M82. At L$_{IR}$ $\sim 3 - 4 \times 10^9$ L$_\odot$, M82 is one of the most energetic local starbursts. Since it is a dwarf galaxy, processes associated with the starburst might be expected to dominate the physical processes in the molecular gas of this galaxy, including the chemistry. These processes would include high radiation fields and shocks associated with the many supernova remnants within the nucleus.

In Figure 4 are shown the same set of molecules mapped in M82 as were mapped in IC 342, observed with the Berkeley-Illinois-Maryland Association array. Emission from C$_2$H is particularly bright in M82, which reflects chemistry in the presence of strong radiation fields. HNC is also bright. Based on our analysis of IC 342, we infer this is because HNC traces the regions of free-free emission within the starburst, which are extensive in M82. Methanol and HNCO, tracers of grain chemistry, are relatively weak in M82 compared to the dense gas tracer molecules and the PDR molecules. This suggests that either the many supernova remnants observed in M82 either do not have as great an impact on the molecular gas as do the bar arms in IC 342 or that the harsh interstellar radiation field has chemically processed these species even further. This set of images is consistent with the characterization of M82 as a “giant PDR” in terms of its chemistry $^{[25,26]}$.

### 4 Summary

High spatial resolution observations of millimeter-wave emission from molecules indicates that the chemical structure of nearby galaxies is variable and complex, but that it is possible to spatially isolate clouds with particular characteristics, such as clouds experiencing shocks within spiral arms, or clouds near high radiation fields. However, this work is at the limits of the feasibility of today’s interferometers, requiring long integration times and multiple spectral tunings. ALMA will revolutionize the study of chemistry in external galaxies due to its dramatic increase in resolution, sensitivity, and instantaneous bandwidth. At Band 6, ALMA will be able to achieve similar sensitivities to the current IC 342 dataset ($\sim 20$ mK) in a few minutes over 8 GHz simultaneous bandwidth, with six times the spatial resolution. With this degree of improvement, mapping significant fractions of nearby galaxies at resolutions of a few pc in an extensive set of molecular species becomes possible, permitting the study of astrochemistry in different local galactic environments in much the fashion as large scale surveys do in our Galaxy today.

Pushing out beyond the local neighborhood of galaxies, ALMA will be able to detect IC 342-like GMCs in the brighter lines (eg. HNC and CH$_3$OH, $^{[27]}$; see contribution by S. Aalto in this volume) out to 75 Mpc in 1 hour on source; the fainter lines to Virgo distances at least. Arp 220-like systems will be detectable in species like HNC and HC$_3$N to $z \sim 0.1$ in an 8 hr track. This will open up an array of galaxy types—dwarfs, ULIRGs, mergers, and potentially even ellipticals—to astrochemical scrutiny. The recent detections of HCN(3-2) and HCO$^+$(1-0) towards the Cloverleaf galaxy at $z = 2.56$ $^{[28,29]}$ demonstrate that for the most luminous sys-

|          | $^{12}$CO | C$^{18}$O | 3 mm | C$_2$H | C$^{34}$S | CH$_3$OH | HC$_3$N | HCN | HNC | HNCO |
|----------|-----------|-----------|------|-------|---------|---------|--------|-----|-----|------|
| $^{12}$CO | 1.0       | ...       | ...  | ...   | ...     | ...     | ...    | ...  | ...  | ...  |
| C$^{18}$O | 0.82      | ...       | ...  | ...   | ...     | ...     | ...    | ...  | ...  | ...  |
| 3 mm     | 0.65      | 0.76      | 1.0  | ...   | ...     | ...     | ...    | ...  | ...  | ...  |
| C$_2$H   | 0.53      | 0.62      | 0.76 | 1.0   | ...     | ...     | ...    | ...  | ...  | ...  |
| C$^{34}$S| 0.38      | 0.39      | 0.48 | 0.50  | 1.0     | ...     | ...    | ...  | ...  | ...  |
| CH$_3$OH | 0.75      | 0.80      | 0.67 | 0.49  | 0.21    | 1.0     | ...    | ...  | ...  | ...  |
| HC$_3$N  | 0.60      | 0.71      | 0.85 | 0.57  | 0.30    | 0.68    | 1.0    | ...  | ...  | ...  |
| HCN      | 0.65      | 0.75      | 0.90 | 0.74  | 0.49    | 0.64    | 0.77   | 1.0  | ...  | ...  |
| HNC      | 0.76      | 0.85      | 0.94 | 0.79  | 0.49    | 0.72    | 0.81   | 0.91 | 1.0  | ...  |
| HNCO     | 0.67      | 0.75      | 0.58 | 0.42  | 0.19    | 0.78    | 0.57   | 0.57 | 0.66 | 1.0  |
| N$_2$H$^+$| 0.73      | 0.81      | 0.75 | 0.59  | 0.42    | 0.71    | 0.68   | 0.74 | 0.82 | 0.69 |
tems chemistry is within reach across the observable universe.

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