Resolving Gas Chemistry at Arcsecond Scales in Nearby Spiral Nuclei

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Abstract. Astrochemistry is rapidly becoming one of the most powerful tools to study the structure and evolution of the central kiloparsec in spiral nuclei. Imagining the distribution of quiescent ion-molecule, photon-dominated region (PDR) and shock chemistry permits the triggers of nuclear starbursts to be identified and the bursts subsequent feedback to be constrained. Two new chemical methods for identifying the evolutionary phase of the starbursts in IC 342, NGC 6946 and Maffei 2 are discussed. The first method is to use the HCO⁺/N₂H⁺ ratio to constrain the degree of penetration of dense clumps by UV radiation. The second determines the evolutionary phase by mapping the amount and physical conditions of the densest molecular component via multi-transition HC₃N observations. With the full capabilities of radio facilities such as the VLA and ALMA, probing the changing gas chemistry on sub arcsecond scales in external galaxies will very soon be routine.

1. Introduction

Centers of galaxies are characterized by short dynamical times, strong tidal forces, nuclear bars and outflows, both ionized and molecular. This makes for a tumultuous interstellar medium (ISM). Systems that harbor active galactic nuclei (AGN) or are in the midst of episodes of intense star formation have ISMs that are further altered by strong UV and X-ray radiation fields. These in turn influence the physical and chemical conditions of the ISM and therefore the future evolution of star formation, AGN feeding and nuclear dynamics. With recent advances in millimeter interferometry it is now possible to follow this evolution directly in the molecular component at scales smaller than an individual giant molecular cloud (GMC).

2. Astrochemistry in an extragalactic context

Astrochemistry provides a direct probe of the physical state of the ISM. In Galactic studies much attention has been focussed on the chemistry present at small scales in the vicinity of localized areas of activity, such as young stellar objects and their outflows, hot/dark cores, individual massive star/supernovae (SNe) molecular cloud interfaces, circumstellar envelopes and comets [1]. Given the difficulties of surveying a number of faint molecular lines over large angular sizes, less work has been done on the large scale chemistry that dominates a galaxy’s volume [2-4]. Observations of chemistry in nearby galaxies have the sensitivity, resolution and field of view to permit the study of the chemistry across scales of hundreds of parsecs.
From a theoretical point of view, away from extreme environments, interstellar chemistry is fairly well formulated [5-8]. The low average densities and temperatures make most neutral-neutral reactions inefficient throughout the large volumes averaged over in extragalactic observations. Allowing for some approximation, we can characterize much of astrochemistry on these scales as the result of grain or ion catalyzed molecule formation. Ions induce dipolar attractive forces in neutrals. The attraction between the ion and neutral drives a rapid nearly temperature-independent chemistry. In quiescent clouds, cosmic ray ionization of H$_2$, leading immediately to H$_3^+$, is the main catalytic ion. Molecules formed primarily in this quiescent ‘ion-molecule’ chemistry include CO, HCN, HNC, N$_2$H$^+$ and OH.

When intense UV radiation fields are present C$^+$ takes over the role as the dominant catalytic ion. In these regions, so-called photon-dominated regions (PDRs), molecules formed from C$^+$ + H$_2$, including CH, C$_2$H, CN and c-C$_3$H$_2$ are particularly important [9].

Certain large organic molecules, such as CH$_3$OH, have no known gas-phase formation pathway capable of explaining the abundances observed in both the Galactic and extragalactic ISM. High abundances of these species are observed in cool grains’ ice mantles [10]; where the grain surfaces catalyze reactions between atoms, neutral radicals and hydrogen [11-13]. Liberating these mantles can readily explain the observed gas-phase abundances. However, in all but the most extreme starbursts, liberation of mantles by star formation heating (hot cores) occur in regions too compact to be detected with current telescopes. Liberation mechanisms need to operate coherently on scales greater than 10 pc to explain observed abundances in nearby galaxies. The prime mechanism for liberating these large organic species appears to be shocked molecular gas in bars and spirals or starburst winds [14-16].

3. Spatially resolved chemical maps in spiral nuclei

By imaging representative species from the separate categories of quiescent ion-molecule, PDR and shock chemistries it is possible to deconstruct the dynamical structure and evolution of starbursts in external galaxies. Figure 1 shows five representative species, including at least one from each of the three above chemistries, mapped across the central 0.5 kpc of the nearby starbursts, IC 342, Maffei 2 and NGC 6946, along with CO and millimeter continuum. The IC 342 data was imaged with the OVRO interferometer at ~6” resolution (80 pc) [16], the Maffei 2 data with the BIMA interferometer at ~8” (110 pc) [17] and the NGC 6946 data with the Plateau de Bure Interferometer at ~2” resolution (50 pc).

The most striking feature of the maps is how much the morphologies differ amongst the tracer molecules, and from CO and the 3 mm continuum (star formation intensity). For example, C$_2$H and CH$_3$OH are nearly anti-correlated in all three nuclei. Therefore the PDR and shock chemistries are distributed very differently. Comparing C$_2$H with millimeter continuum in Figure 1 demonstrates that PDRs are more intimately associated with star formation than regions emitting in CH$_3$OH. This is further evidence that CH$_3$OH does not trace ice mantles evaporated by star formation. Towards IC 342, CH$_3$OH spans the entire molecular arms, with some emphasis towards the outer ends of the bar/spiral. In Maffei 2 and NGC 6946 the outer ends of the (nuclear) bar are even more strongly pronounced. In [16] a consistent picture for the mutual evolution of star formation and gas chemistry is laid out. Shocks in the outer bar arms cause dissipation of energy and angular momentum. Gas flows inward. Just before it reaches the intersection of the arms with the central ring, gas collides with existing ring gas, piling up and triggering starbursts. Inertia causes the star formation and remaining residual gas to continue inward, settling onto the small nuclear ring. The starbursts just outside the ring-intersection are young and the ring star formation is expected to somewhat more evolved. With little modification this chemical picture carries over to the other two nuclei.

No starbursts are perfectly coeval. It is expected that individual star forming regions in the nuclear of spirals manifest a spread in burst phase. The burst begins with a ’proto-starburst’ (in
**Figure 1.** The integrated intensities of six molecular transitions towards the nuclei of the nearby starbursts, IC 342 [16], Maffei 2 [17] and NGC 6946. For each nucleus the leftmost plane shows the molecular gas distribution traced by $^{13}$CO(1–0) [except for NGC 6946 which is CO(1–0)] in grayscale. For IC 342 and Maffei 2, the grayscale ranges from 1 - 10 Jy beam$^{-1}$ km s$^{-1}$, while for NGC 6946 it ranges from 1.5 - 15 Jy beam$^{-1}$ km s$^{-1}$. The contours are 7 or 3 mm continuum which traces star formation. Contours are 1.0, 0.25 and 1.2 mJy beam$^{-1}$ for IC 342, NGC 6946 and Maffei 2, respectively. The remaining planes are HNC(1–0), HC$_3$N(10–9), C$_2$H(1–0; 3/2–1/2), N$_2$H$^+$(1–0) and CH$_3$OH(2$K$–1$K$) as labeled. For IC 342 the contours and resolution are the same as in Figure 2 of [16]. For NGC 6946 contours are 0.125, 0.11, 0.15, 0.125 and 0.125 Jy beam$^{-1}$ km s$^{-1}$ for the five trace species (left to right). Beamsizes for these maps are $\sim 2.5'' \times 2''$. For Maffei 2 contours are 1.0, 0.60, 1.1, 0.75 and 1.5 Jy beam$^{-1}$ km s$^{-1}$. Beamsizes for these maps are $\sim 8'' \times 7''$ except HC$_3$N which is $\sim 10'' \times 8.5''$.

analogy with a protostar) having high columns of cool, dense gas with faint, perhaps optically thick radio continuum emission. The burst matures, large numbers of massive stars form, bathing the surrounding dense clumps in dissociative UV radiation, creating dense PDRs, an expanding HII region and bright thermal radio continuum. As an individual burst ages the dense molecular gas is consumed or dispersed, HII regions fade and the radio continuum spectrum steepens with the generation of synchrotron emission after the onset of SNe. For an instantaneous burst all three phases typically last $\sim 10^7$ yrs or less. Short, but longer than chemical equilibrium timescales, so we expect to be able discriminate them with chemistry.
Averaged over the nucleus it is quite difficult to separate such phases but with the high angular resolution molecular spectroscopy now available, evidence of this evolution is now being observed in the most nearby systems. This is particularly true in the three nuclei discussed here. All three systems have organized kinematics consistent with inflow driven along the nuclear bar arms followed by star formation triggered at the arm-inner ring intersection regions. Therefore a connection between the location of gas and star formation relative to the arm-inner ring intersection and its age is expected. This connection suggests that changing starburst phases should be morphologically separated and their chemical signatures resolvable.

4. Localized changes in dense gas chemistry: the HCO$^+$/N$_2$H$^+$ ratio
C$_2$H has a modest critical density and so is more sensitive to PDR gas at low to moderate densities. In IC 342, C$_2$H tracers the cloud interfaces oriented towards the evolved nuclear cluster not the embedded, young bursts [16]. This tendency to avoid the dense clumps is more pronounced in the outskirts of Maffei 2, while in NGC 6946 we do not have the spatial resolution to tell for sure. In fact in Maffei 2 and to a lesser extent IC 342, C$_2$H critical densities are such that it the presumably modest density molecular outflows along the minor axis of the nuclear disk are sampled. To investigate whether the gas chemistry in a particular starburst has transitioned from the ‘proto-burst’ phase to the phase when the PDRs permeate the bulk of the dense cores, we need a high density probe that is PDR sensitive.

We propose that the HCO$^+$(1–0)/N$_2$H$^+$(1–0) integrated intensity ratio could be just such a probe [17]. In quiescent gas, proton transfer reactions of H$_3^+$ with CO and N$_2$ form HCO$^+$ and N$_2$H$^+$ respectively:

\begin{align}
H_3^+ + CO & \rightarrow HCO^+ + H_2, \\
H_3^+ + N_2 & \rightarrow N_2H^+ + H_2,
\end{align}

(1)

(2)

However, in PDR gas only HCO$^+$ maintains a relatively rapid formation route:

\begin{align}
C^+ + OH & \rightarrow CO^+ + H \\
H_2 + CO^+ & \rightarrow HCO^+ + H.
\end{align}

(3)

(4)

No corresponding route exists for N$_2$H$^+$ in PDRs [18]. So toward the PDR regions associated with the starbursts, HCO$^+$ can maintain appreciable abundances while N$_2$H$^+$ is readily destroyed. Therefore, for irradiated gas we expect a precipitous drop in N$_2$H$^+$ intensity that is not matched in HCO$^+$. Since both HCO$^+$ and N$_2$H$^+$ have high critical densities this ratio is more strongly sensitive to the properties of the dense clumps than is C$_2$H. Hence we predict that as a starburst strengthens or evolves we should see a dramatic, localized increase in the HCO$^+$/N$_2$H$^+$ ratio.

Consistent with the fact that in IC 342 PDRs appear primarily as surface features, the strong decrease of N$_2$H$^+$ relative to HCO$^+$ is not seen [16]. But the above predicted behavior is observed in Maffei 2 and NGC 6946 (Figure 2). For Maffei 2, the starbursts at the ring intersection region exhibit slightly elevated HCO$^+$/N$_2$H$^+$ ratios but not as extreme as found toward the burst on the ring.

5. Dense gas evolution: towards high angular resolution chemistry
The HCO$^+$/N$_2$H$^+$ ratio suggests that gas chemistry evolves with starburst strength and evolutionary phase. Unlike Maffei 2 and NGC 6946, N$_2$H$^+$ remains bright towards both arm-ring intersection starbursts in IC 342. This hints that the gas at these locations remain relatively unprocessed and possibly quite young. To pursue this further we investigate the excitation of very dense molecular component in IC 342 at much higher spatial resolutions (~25 pc).
Figure 2. The HCO$^+$/N$_2$H$^+$(1–0) integrated intensity ratio toward Maffei 2 [17] and NGC 6946. The grayscale ranges from 1 - 6 for Maffei 2 and 1 - 9 for NGC 6946, with dark being large values. Contours are in steps of 1 for Maffei 2 and steps of 2 for NGC 6946. The beam size of each map is displayed in the bottom left corner of each image.

On 100 pc scales HC$_3$N was the molecule found to be morphologically most closely connected to the starburst [16]. Therefore studies of this molecule are excellent for characterizing the physical conditions of the gas out of which the starburst directly forms. Not only do we improve the spatial resolution but we map multiple transitions to constrain gas densities, excitation temperatures and thermal pressure.

Figure 3 displays the J =5–4 transition of HC$_3$N imaged in the center of IC 342 with the Very Large Array at 45 GHz [19]. At this resolution, the cloud towards the main starburst, marked by the bright 45 GHz continuum source in the grayscale, breaks up into a small collections of barely detectable sub-GMC clumps. By contrast, the cloud at the corresponding dynamical location of the other side of the ring remains an extremely bright, coherent emission source. Total fluxes were measured over a 2" aperture in J=10–9 and J=16–15 (from the Plateau de Bure interferometer) towards the two arm-ring intersection regions [19]. Figure 3 also shows the corresponding spectral line energy distributions for the three transitions.

The amount and excitation of the dense gas differs signification at the two locations. Toward the main starburst total fluxes are surprisingly low but excitation is not ($T_{ex} \approx 40$ K). The low absolute brightness together with high excitation implies that the total column of dense gas towards the burst is small. The location of the strongest star formation in the nucleus of IC 342 is not a source of abundant dense gas. On the eastern side of the ring, where the star formation indicators are less intense, dense gas columns are high, but excitation remains low ($T_{ex} < 15$ K), implying large amounts of dense gas.

We generate a multi-component, large velocity gradient model that can simultaneously explain the excitation of six low energy transitions of the CO isotopologues [20,21] and the three
transitions of HC$_3$N. For an adopted abundance of HC$_3$N, solutions are obtained for kinetic temperatures ranging from 5 - 100 K. A subset of these solutions are displayed with different lines in Figure 3. The degeneracy between high kinetic temperatures and high densities means that it is not possible to separately constrain both precisely. However the gas thermal pressure is tightly constrained, with $n_{H_2}T_k$ being $\approx 6 \times 10^6$ cm$^{-3}$ K. From the size and ionization rate of the associated starburst nebula [22], we estimate the thermal pressure of the HII region to be the same within uncertainties.

Toward the main IR/radio continuum source, temperatures and densities of the dense gas are high enough to be in pressure equilibrium with the HII region. The eastern region has lower thermal pressure and large total dense gas masses ($\sim 10^6$ M$_\odot$), despite the much weaker instantaneous star formation. This dichotomy is interesting in the context of the well established global dense gas versus star formation rates relationships [23]. If such simple relations apply universally we would expect the behavior of the dense component of the two star forming regions to be reversed. We interpret this breakdown as a manifestation of the evolution of the starburst across the nucleus. The currently dominant starburst near the bright IR/mm continuum source (Figure 3) has reached an evolutionary phase where it has consumed, or dispersed much of its natal dense gas. The dense gas that remains is remnant detritus embedded in, and in pressure equilibrium with, the expanding HII region. The younger non-dispersed location appears to be a ‘proto-starburst’ just beginning an active phase.

6. Conclusions
Astrochemistry is rapidly becoming one of the most powerful tools to study the structure and evolution of the central kiloparsec in galactic nuclei. Here we have used it to map the locations of dense, quiescent ion-molecule, PDR and shock-liberated grain mantle chemistries across the
nuclei of three nearby spirals. The chemistry in these nuclei are observed to be quiet variable. Here we present two new methods for watching dense molecular gas properties evolve with starburst phase — the degree of PDR penetration by comparison of $\text{C}_2\text{H}$ versus the $\text{HCO}^+/\text{N}_2\text{H}^+$ ratio and the evolution of dense gas clouds near the starburst through $\text{HC}_3\text{N}$ modeling of the gas density at arcsecond scales. The high spatial resolution and wide simultaneous spectral bandwidths available with the upgraded Karl G. Jansky Very Large Array and the newly arrived Atacama Large Millimeter/Submillimeter Array implies that these two diagnostics are only the beginning of what should become possible in the next decade.

Acknowledgments

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