Astrochemistry in Galaxies of the Local Universe

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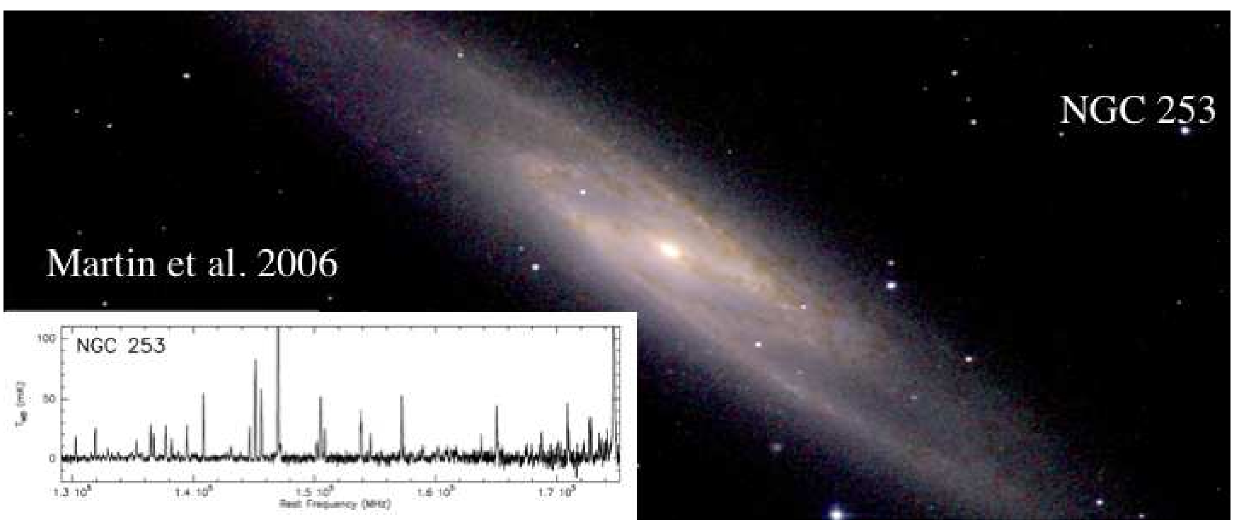
Science Frontier Area: Galactic Neighborhood

Abstract

To understand star formation in galaxies we must know the molecular fuel out of which the stars form. Telescopes coming online in the upcoming decade will enable us to understand the molecular ISM from a new and powerful global perspective. In this white paper we focus on the use of astrochemistry—the observation, analysis and theoretical modeling of many molecular lines and their correlations—to answer some of the outstanding questions regarding the evolution of star formation and galactic structure in nearby galaxies.



The 2 mm spectral line survey of the nearby starburst spiral, NGC 253 (Martin et al. 2006), overlaid on the 2 MASS near infrared JHK color image. The spectrum shows the richness of the millimeter spectrum.

1 Introduction

Galactic structure and its evolution across cosmic time is driven by the gaseous component of galaxies. Our knowledge of the gaseous universe beyond the Milky Way is sketchy at present. Least studied of all is molecular gas, the component most closely linked to star formation. How has the gaseous structure of galaxies changed through cosmic time? What is the nature of intergalactic gas and its interaction with galaxies? How do galaxies accrete gas to form disks, giant molecular clouds (GMCs), stars and star clusters? How are GMCs affected by their environment? What is the relative importance of secular evolution and impulsive dynamical interactions in the histories of different kinds of galaxies? In this white paper we focus on how to concretely address these questions through astrochemistry. Astrochemistry means studying the correlations of molecules and the physical states of molecular clouds through observations and analysis of their lines. It can tell us the physical states of molecular clouds and their readiness to form stars. Astrochemistry has been used successfully in the Galaxy to infer the morphology, irradiation, and density structure of protostellar disks. Now, with new high resolution submillimeter and millimeter arrays, astrochemistry has great potential for revealing similar physical processes in the gas of nearby galaxies.

2 Chemistry in Nearby Star-Forming Galaxies

Galactic astronomers have a long history of using the power of chemical studies to trace the evolutionary stages of the molecular gas (van Dishoeck & Blake 1998), but only very recently have such detailed studies become feasible for extragalactic systems. Historically, the 3mm line of CO has been the workhorse for mapping the ISM in external galaxies because it is bright, abundant, and easily excited (Young & Scoville 1991), but these same properties limit its usefulness as a probe of the internal structures of molecular clouds. Other molecules are better tracers of specific conditions. New wide band cm/millimeter surveys are finding unexpectedly rich molecular spectra in external galaxies (Martin et al 2006; Narayanan et al. 2008); subsequently, many different molecular probes are available. For example HCN, with a high dipole moment, is excited only in high density clouds. Unlike CO, HCN is linearly related to IR luminosity (Figure 1; Gao & Solomon 2004); this indicates that the dense gas, not the total molecular gas, determines the star formation rate. There are molecules for tracing quiescent gas (N_2H^+); grain chemistry in shocks or photo-warmed gas (CH_3OH, HNCO); shock tracers (SiO); dense gas tracers (HCN, HC_3N), and high temperature gas (upper J levels of CO, NH_3). Although the currently available single dish spectra have low spatial resolution, averaging nearly a kiloparsec of ISM into a single beam, they show a complex and varied chemistry, sensitive to a wide range of cloud conditions.

To characterize what influences gas chemistry locally within a galaxy, we must be able to resolve GMCs, the building blocks of the extragalactic ISM. Surveys with current millimeter interferometers are just beginning to sample GMC scales in the nearest galaxies (e.g., Garcia-Burrillo et al. 2001; Meier & Turner 2005, Usero et al. 2006, Turner & Meier 2008). The

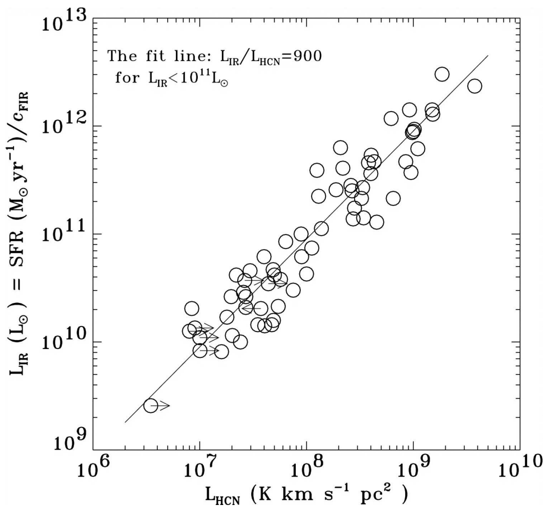


Figure 1: The correlation between HCN and IR luminosity of 65 local universe galaxies from Gao & Solomon (2004). The solid line is of slope unity, indicating that the star formation rate is directly correlated with the amount of dense gas available.

degree of chemical differentiation on these smaller scales is remarkable; relative abundances frequently vary by more than orders of magnitude between GMCs. Figure 2 illustrates the morphological variations seen among different molecules in the central 300 pc of the spiral galaxy, IC 342, where 4″ (60 pc) beams can just resolve individual GMCs (Meier & Turner 2005). The correlated morphologies separate species into groups according to their preferred physical or chemical environment. C_2H and $C^{34}S$ are confined to the innermost part of the nucleus tracing out the photon-dominated regions (PDRs) of the inner molecular ring, which is illuminated by the central nuclear cluster. Widespread, bright emission from CH_3OH, SiO and HNCO indicate that grain chemistry is important across the nucleus, especially along the nuclear bar arms. Other chemical surprises include the ubiquity, even in the starburst region, of the dense, quiescent gas tracer, N_2H^+. This suggests that the starburst hasn't had enough time to disrupt the surrounding gas clouds. Only high-resolution molecular spectra can provide such insights into the evolutionary history of the dusty core of IC 342.

3 Chemistry as a Diagnostic of Galactic Structure and Environment

The molecular ISM is the agent that transmits macroscopic changes in the structure and environment of a galaxy to the local star formation process. The goal of this research is to use gas chemistry to identify the regulating mechanisms of galaxy evolution in the ISM directly. The importance of the spectral region from centimeter to submillimeter wavelengths lies in the great richness of molecular species found there and in the range of excitation properties

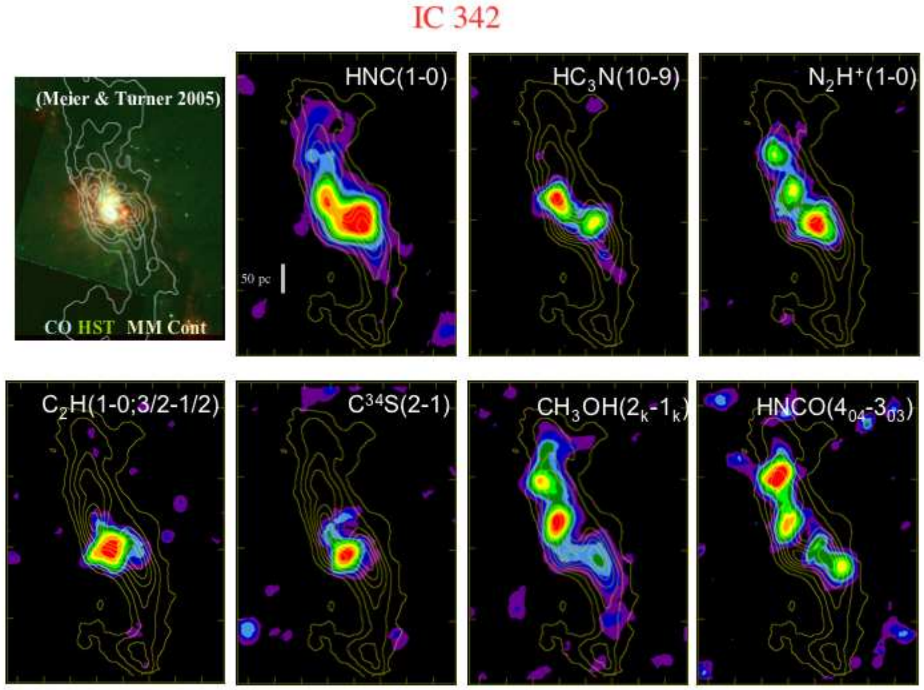


Figure 2: A survey of seven astrochemical important species across the nucleus of the nearby spiral, IC 342 (Meier & Turner 2005). These species are all dense gas tracers. The differences reflect the strong sensitivity of the different chemical species to changes in their dynamic and radiative environment.

they probe. In the gas-rich environments of extreme starbursts and AGN the brightest lines such as CO and HCN can lose their diagnostic usefullness because of high opacity, and the less abundant chemical tracers become the preferred probes of the inner workings of the most deeply embedded regions. New arrays becoming available during the upcoming decade, such as ALMA and the EVLA, promise simultaneous subarcsecond imaging in many molecular transitions, and thus of a wide range of excitation and density conditions. This is a relatively new field, but it is actively developing, and with the recent commissioning of the CARMA and SMA arrays, and the advent of the ALMA array, we expect rapid progress in this area in the next decade. We identify four questions below that we expect to be key areas during this period.

3.1 Just how good is HCN as a star formation tracer?

The 3 mm rotational transition of HCN appears to be an excellent tracer of star formation in galaxies. Gao & Solomon (2004) found that HCN is more linearly correlated with total far-IR emission on global scales in galaxies than is CO. This correlation holds between the radio free-free emission and HCN down to GMC sizescales (e.g. Meier & Turner 2005; Meier

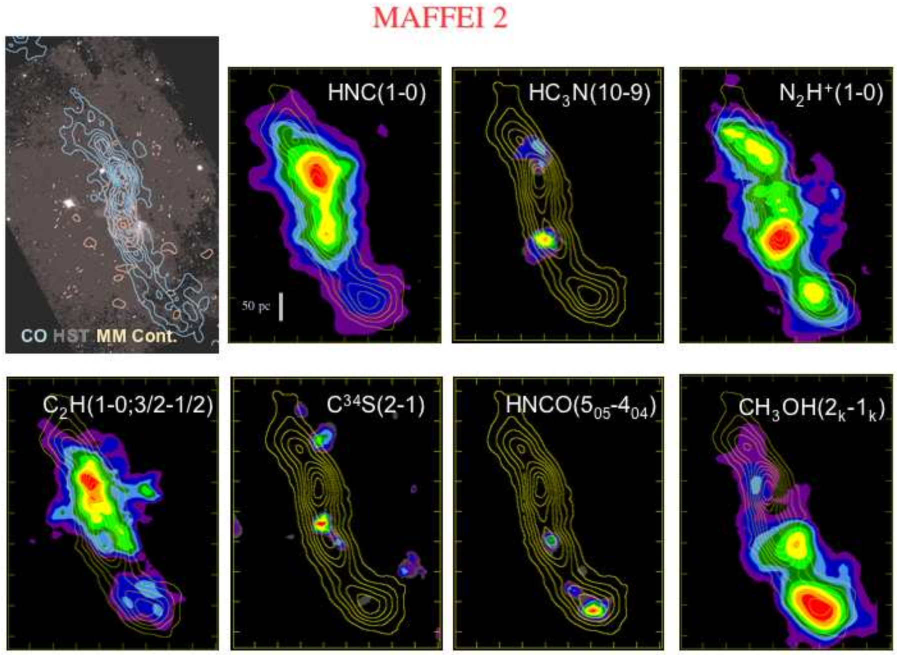


Figure 3: A survey of the same seven species as in Figure 2 towards the nearby nuclear bar, Maffei 2 (Meier & Turner 2009, in prep.). Here the observed chemical differentiation follows the same patterns as IC 342, only much or dramatically.

et al. 2008). The correlation may be because star formation occurs in the denser gas traced by HCN (critical density of $\sim 10^6$ cm^{-3}), or because HCN emission is enhanced by high X-ray radiation and IR pumping (Aalto et al. 2008). In either case, HCN is one of the brightest molecular lines after CO and could be a terrific, extinction-free star formation tracer to z of 1-2, farther if lensed, with the potential to also give kinematic information on star forming regions at the 10 km/s level or better. But we first have to understand the physics of this relation in nearby systems to be confident of its use in more distant and extreme systems, and this is the contribution of astrochemistry. How strongly does the HCN vs star formation correlation depend on local environment, radiation field, density? Are the excellent correlations of HCN with L_{IR} and free-free emission due to IR pumping or the presence of dense gas? Correlations with other dense gas tracers could answer this. Down to what spatial scale does the HCN-IR relation hold within individual galaxies?

3.2 Can chemistry be used to distinguish AGN from starburst luminosity?

The intense X-ray radiation from the AGN central engine is expected to have distinctive influences on the chemical state of molecular gas in its vicinity (Lepp & Dalgarno 1996;

Meijerink & Spaans 2005). These regions, known as X-ray Dominated Regions (XDRs), are characterized by the presence of enhanced OH, CN, HCN and the absence of larger, more fragile species like HC_3N. As the ionization increases further molecular ions like HCO^+ and N_2H^+ are predicted to drop in abundance. Anomalously high HCN/CO and HCN/HCO^+ line ratios are indeed a common feature of molecular gas surrounding AGNs (Usero et al. 2004; Kohno 2005). Detailed studies of the molecular ISM close to nearby AGN such as NGC 1068 will be important in identifying AGN-specific chemical fingerprints, which can then be extended to more distant active galaxies. Over what physical scales do AGN influence the physics of their surroundings? — in both the AGN phase and potentially even the quasar phase? The black hole vs. bulge mass relationship (Magorrian et al. 1998) argues that AGN (QSO) must effectively regulate star formation well beyond their direct dynamical influence, possibly via jets or winds interacting with inner bulge gas. If this is true then imaging surveys of these AGN-dominated chemicals should resolve this extended influence during the SMBH's most active phases.

3.3 What is the global chemical structure of galaxies and do they relate to the galaxies' overall dynamical history?

The structures of galaxies continually evolve, both violently in mergers and interactions, and more peacefully under slow steady, secular evolution. Little is known of how chemical properties of the gas evolve during these different dynamical states. Because of dissipation, interactions result in complete and violent redistribution of the ISM in a galaxy. Almost certainly the ISM will experience significant and widespread shocking due to colliding gas flows. What is the impact of these shocks on the ISM? On the triggered star formation that follows the interaction? Observations of those species most closely associated with grain chemistry (CH_3OH, HNCO, and SiO) trace out the large scale orbital dynamics, presumably because grains are heated or sputtered during shock passage. Mapping of these species can isolate the location of dynamic shocks throughout different evolutionary phases and constrain the type and strength of shocks present. How do these impacts compare to the milder shocks associated with spiral arms or bars, drivers of secular evolution? At high spatial resolution the anatomy of the shock fronts may be chemically resolved, providing valuable tests of shock models. For those disks that remain relatively undisturbed there are often strong radial gradients in metallicity. Investigating the chemistry that result from the changes in metallicity will be of great importance for understanding the ISM at high redshift.

3.4 What are the effects of starburst feedback on GMCs and how might that regulate future star formation?

Massive star formation in starbursts can inject momentum and energy into the surrounding molecular ISM, changing gas excitation, generating PDRs and SNe and wind shocks. The chemical state of the molecular gas reacts profoundly to these stimuli. This can be seen clearly by comparing the state of the ISM in the prototypical starburst, M 82, with that seen in the milder starbursts, IC 342 and Maffei 2 (Fig. 3). The ISM in M 82 is effectively a giant PDR, with a preponderance of simple radicals such as C_2H and CN. This reflects a vigorous ion-molecule chemistry that is stimulated by the enhanced C^+ abundances arising from the high UV radiation fields (Fig. 4, Turner & Meier 2008; Garcia-Burillo et al. 2001). How does this altered molecular phase take part in future star formation? This gas is expected to have higher temperatures, ionization fractions and different gas heating vs. cooling routes than a normal ISM. Each of these influence how cores collapse to form stars. Do these changing physical conditions result in different IMFs? Control the interburst timescale? And how do the conclusions change with both starburst strength and evolutionary state?

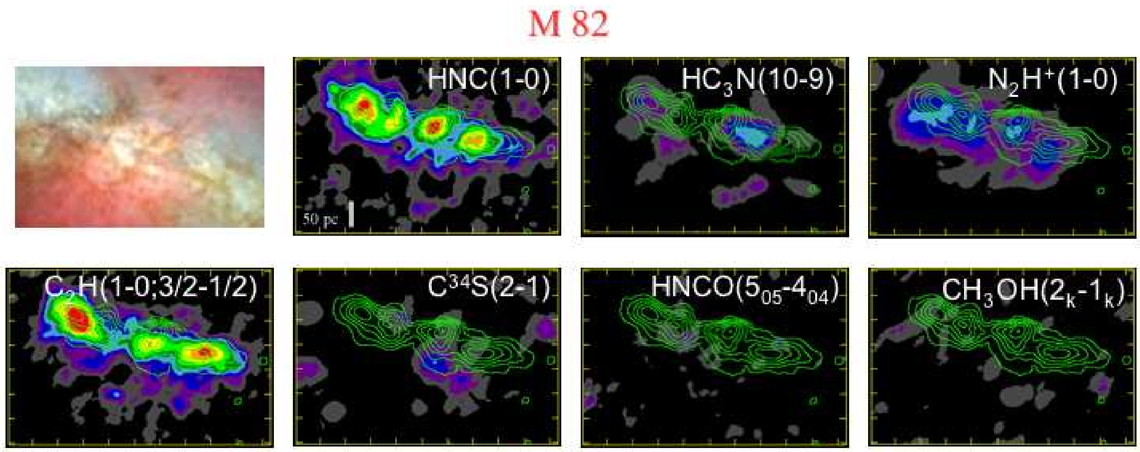


Figure 4: Same as in Figures 2-3 except for the much stronger starburst, M 82. Here the PDR species dominate, penetrating the entire ISM (Turner & Meier 2008).

4 Technical Requirements for Astrochemistry beyond the Milky Way

The next decade brings the ALMA /EVLA revolution. ALMA will cover the low energy states of simple molecules and the higher energy states of heavier species in the submillimeter and millimeter. With large instantaneous bandwidth and high sensitivity ALMA will make every observation of local galaxies an astrochemical one. Astrochemistry is currently possible in ∼10 galaxies. Extrapolating from the FCRAO Survey CO brightness (Young et al. 1995), the sensitivity increase of ALMA will extend this number to ∼150 galaxies of all Hubble types with full 1 km s^{-1} velocity resolution. The EVLA will complement ALMA by covering the vital low excitation transitions of heavier molecules in the cooler disk ISM. This is the frequency range most likely to constrain the degree of molecular complexity reached in the ambient ISM. To move astrochemistry out of the nucleus it will be important to extend EVLA's surface brightness sensitivity to faint spectral lines. Construction of an E configuration for the EVLA would be of particular value for astrochemistry beyond the Milky Way.

Right now work is focused primarily on a few workhorse molecular transitions. Searches to identify new line diagnostics are equally important. Single-dish telescopes, such as the LMT, GBT and CCAT, equipped with extremely wide band spectrometers will be vital for species identification. Moreover, the virtually unexplored THz regime is rapidly going to become important. This is the portion of the spectra containing both the light hydrides, which represent the first, poorly understood, steps in the build up of complex molecules and many fundamental atomic transitions, useful for studying the chemistry of the atomic - molecular gas interface. ALMA observations of high redshift galaxies will be sampling this part of the spectrum, so local galaxy comparisons are imperative. For the unexplored THz regime observations from SOFIA are the only way to observe galaxies with sufficient resolution to study processes on GMC scales.

While the upcoming instrumentation for this area is superb, the theoretical picture requires attention. Existing chemical models will need to be updated, and in particular, the role of IR radiative excitation will need to be explored more fully. The great sensitivity of ALMA means that distinguishing lines from the many "weeds" (species with many lines) in the submillimeter part of the spectrum requires determining the line frequencies of many species. Theoretical modeling and laboratory astrochemistry support will be of key importance to fully mine such rich observational datasets.

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