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Dissertation Summary

Physical Properties of Giant Molecular Clouds in Nearby Starburst Galaxies

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In this dissertation, I have explored the properties of molecular gas in the nuclei of four nearby, gas-rich, actively star forming galaxies. Three barred galaxies (IC 342, Maffei 2, and NGC 6946) and one possible merger remnant (NGC 4826) have been mapped at high spatial resolution (∼3″, or 30–100 pc) in ^{12}CO, ^{13}CO, C^{18}O, 3 mm, and 1 mm continuum using the Owens Valley Millimeter Array. The two closest and brightest galaxies of the sample, IC 342 and Maffei 2, have been mapped in the $J = 2–1$ and $J = 1–0$ transitions of each isotopomer. Comparisons between the $J = 2–1$ and $J = 1–0$ transitions provide the first determination of the physical conditions of individual giant molecular clouds (GMCs) in the centers of large spiral galaxies other than our own. Variations in physical properties of the clouds are related to their spatial locations within these galactic centers and to the star formation.

The ΔJ line ratios in IC 342 paradoxically imply optically thin ^{12}CO and optically thick ^{13}CO. The assuredly optically thin C^{18}O gives yet another picture. A model is developed in which strong external radiation fields create photodissociation regions (PDRs), with high kinetic temperatures in the outer, UV-illuminated cloud surfaces and progressively cooler gas toward the centers of the clouds. Because ^{13}CO and C^{18}O have lower abundances and optical depths, they sample most of the molecular gas in the GMCs and hence are less influenced by the highly emissive outer edges of the molecular clouds compared to ^{12}CO. These isotopomers yield a more robust measure of the true temperatures and densities of the molecular gas in these starburst regions than does the overluminous ^{12}CO (D. S. Meier, J. L. Turner, & R. L. Hurt 2000, ApJ, 531, 200).

The isotopic line ratios, such as ^{12}CO(1–0)/^{13}CO(1–0), vary by as much as a factor of 4 over ∼100 pc scales in these galaxies. The isotopic ratio minima (^{12}CO/^{13}CO ∼ 3–4) tend to trace the locations of dense GMCs seen in HCN(1–0). In the three barred galaxies, there are large off-arm regions having very high isotopic line ratios (^{12}CO/^{13}CO > 20), best explained by the presence of an extended low-density molecular gas component. For the conditions prevalent in these galactic centers ($T_{\rm kin} \sim 10–40$ K and $n_{\rm H_2} \sim 10^{2.5}–10^{4.5}$ cm^{-3}), ^{12}CO is warm and thermalized while the rarer isotopomers are subthermally excited.

Measurements of molecular cloud masses are derived from four independent methods—optically thin CO isotopomers, 1.3 mm dust continuum emission, near-IR dust extinction, and virial sizes and line widths—have been made in an effort to constrain the true gas column density in each galaxy. Masses obtained by three of the four methods generally agree. The exception is the estimated virial masses. The virial masses are always the largest; this may indicate that the line widths are dominated by systematic orbital motions and that the GMCs are in fact not virialized. At no location in any of the four galaxies is the Galactic conversion factor obtained. In IC 342 and Maffei 2, $X_{\rm CO}$ appears to be lower than the Galactic value by factors of 3–4 toward the dense gas peaks and higher elsewhere. Similar values are derived for NGC 6946 and NGC 4826. Evidently, molecular masses in the centers of galaxies have been significantly overestimated by the use of the Galactic $X_{\rm CO}$ (D. S. Meier & J. L. Turner 2001, ApJ, 551, 687).

Active star formation occurs at the sites of the densest gas. However, a significant amount of dense gas is currently sterile. The main governor of physical conditions, particularly density, appears to be dynamical in nature. In all three barred galaxies, the molecular gas closely follows the predicted orbits found in barred potentials. The observed barlike features are 0.3–1.0 kpc in scale, smaller than any large-scale (galaxy class defining) bar, and are typically confined to the large-scale inner Lindblad resonance of each galaxy. ^{13}CO and C^{18}O tend to be brighter relative to ^{12}CO on the leading sides of the arms traced out by the x_1 orbitals. Toward the center of the three barred galaxies, the gas appears to pile up into a ring, presumably associated with the perpendicular x_2 bar orbits. Comparisons with HCN show that the densest gas (and star formation) picks out the intersections of the two orbital families. Modeled gas inflow rates of each nucleus match the observed star formation rates. Moreover, the theoretically predicted “spray regions” in barred potentials naturally explain the presence and locations of the extended low-density gas component inferred from the regions of high ^{12}CO(1–0)/^{13}CO(1–0). These results suggest that these small nuclear bars are driving inflows of gas toward the centers of the galaxies, triggering the starburst. By contrast, in NGC 4826, the lone unbarred galaxy in the sample, there is no current starburst, and no noncircular motions or rapidly varying physical conditions are seen. The physical properties of both molecular clouds and star formation appear to be highly sensitive to the presence of radial gas motions in the centers of galaxies.

The nucleus of IC 342 has also been surveyed at high spatial resolution in a collection of astrochemically important species. The molecules HNC, HC_3N, C_2H, $C^{34}S$, HNCO, CH_3OH, and N_2H^+ have been imaged at 3″ resolution. These chemical species exhibit significantly stronger spatial variation than seen among the CO lines and from what would be expected for these molecules based on Galactic work. This differentiation appears to be correlated with gas physical conditions and dynamics, with, for example, HC_3N tracing the highest density gas, C_2H tracing PDR surfaces, and HNCO tracing large-scale dynamical shocks.

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