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SPATIAL VARIATION OF THE PHYSICAL CONDITIONS OF MOLECULAR GAS IN GALAXIES

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Introduction

Multi-line studies of ^{12}CO, ^{13}CO, $C^{18}O$, HCN, and HCO^+ at 3 mm, 1.3 mm, and 0.8 mm using the IRAM 30 m telescope, with the IRAM SIS receivers and the MPE 350 GHz SIS receiver, show that the denisities and temperatures of molecular gas in external galaxies change significantly with position. ^{12}CO measures the densities and temperatures of diffuse interclump molecular gas, but not the bulk of the molecular gas. Simple one-component models, with or without external heating, cannot account for the weakness of the ^{12}CO $J = 3 \rightarrow 2$ line relative to $J = 2 \rightarrow 1$ and $J = 1 \rightarrow 0$. ^{12}CO does not trace the bulk of the molecular gas, and optical depth effects obviate a straightforward interpretation of ^{12}CO data. Instead, we have turned to the optically thin CO isotopes and other molecular species. Isotopic CO lines measure the bulk of the moleular gas, and HCN and HCO^+ pick out denser regions. We find a warm ridge of gas in IC342 (Eckart et al. 1989), denser gas in the starburst nucleus of IC342, and a possible hot-spot in NGC2903. In IC342, NGC2146, and NGC6764, the ^{13}CO $J = 2 \rightarrow 1$ line is subthermally populated, implying gas densities $\lesssim 10^4$ cm^{-3}.

^{12}CO Studies

Recent IRAM 30 m observations of ^{12}CO $J = 1 \rightarrow 0$, $J = 2 \rightarrow 1$, and $J = 3 \rightarrow 2$ toward M82 (see Wild *et al.*, this volume) and IC342, as well as toward several Galactic high mass star-forming regions, show that simple models cannot account for the ^{12}CO data. In each of these regions, the ^{12}CO $J = 2 \rightarrow 1$ line is as bright as or brighter than the $J = 1 \rightarrow 0$ line, but the $J = 3 \rightarrow 2$ line is weaker than $J = 2 \rightarrow 1$, typically by a factor of two. This cannot be explained by simple one-component models, nor by externally heated clouds. Furthermore, self-absorbed features are evident in the ^{12}CO spectra, often associated with peaks in the isotopic lines. It seems clear that ^{12}CO suffers in a complicated way from optical depth effects, and that one must turn to optically thin species to trace the bulk of the interstellar medium. Global properties such as mass or temperature derived from ^{12}CO must be treated with extreme caution.

CO Isotopic Studies

We have used the IRAM 30 m to observe ^{13}CO $J = 1 \rightarrow 0$ (22″ beam) and $J = 2 \rightarrow 1$ (14″ beam) emission in IC342, NGC2146, and NGC6764. When both maps are convolved to the same angular resolution, in each case the ratio $T(2 \rightarrow 1)/T(1 \rightarrow 0)$ is ~ 1.0. In the nucleus of IC342, the corresponding $C^{18}O$ ratio is ~ 1.8. These ratios are much smaller than the value of 4.0 produced by warm, thermalized, optically thin gas. Since the large $CO/^{13}CO$ and $CO/C^{18}O$ brightness temperature ratios suggest optically thin emission in the isotopic lines, we conclude that the $J = 2 \rightarrow 1$ isotopic lines are subthermally excited. This constrains the densities to be near the CO critical density. If subthermal excitation occurs in all galaxies, then the ^{13}CO and $C^{18}O$ $J = 1 \rightarrow 0$ lines trace total column density and may be used to estimate mass.

NGC2903

VLA 21 cm radio continuum, Lick $H\alpha$, and IRAM 30 m $J = 1 \rightarrow 0$ and $2 \rightarrow 1$ CO observations of the hot-spot galaxy NGC2903 show them all to be distributed nearly identically in a central bar. Thus synchrotron emission, H II regions, and molecular gas all accompany star formation. There is an unresolved "hot-spot" at the northern end of the bar that has a ^{12}CO $T(2 \rightarrow 1)/T(1 \rightarrow 0)$ ratio ~ 1.0, which may indicate substantially warmer or thinner CO emission. Otherwise, this ratio is typically ~ 0.7, consistent with emission from molecular clouds with properties typical of those found in the Milky Way, that is, with large optical depths, excitation temperatures near 10 K, and sizes about 100 to 200 pc. Star formation extends throughout the bar, but the star formation rate per unit area is enhanced by an order of magnitude in the nucleus. A comparison with resolved IRAS ADDSCAN and CPC images shows that the far infrared to CO luminosity ratio, which is often interpreted as a measure of star formation efficiency, is typical of normal spirals and does not vary with position at 1.4 arcminute resolution. The nuclear starburst may then result from a large amount of molecular gas with normal star formation efficiency collected into a small nuclear region due to streaming motions induced by the bar.

IC342

Eckart *et al.* (1989, preprint) have mapped IC342 in the ^{12}CO and ^{13}CO $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ lines and also obtained $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ $C^{18}O$ spectra toward the nucleus. The $T(2 \rightarrow 1)/T(1 \rightarrow 0)$ ratio varies with position for both ^{12}CO and ^{13}CO. The CO isotopic $J = 2 \rightarrow 1$ lines are subthermally excited. Molecular gas temperatures and densities were derived using a radiative transfer code with a clumpy cloud model. The gas in the nucleus is substantially warmer (~ 30 K) than in the disk (~ 13 K). Further, a ridge to the east of the nucleus shows elevated temperatures. New ^{12}CO $J = 3 \rightarrow 2$ observations at the IRAM 30 m with the MPE 350 GHz receiver show that this line is weaker than $J = 2 \rightarrow 1$ by about a factor of two. Simple one-component models, or externally heated cloud models, cannot account for the weak $J = 3 \rightarrow 2$ line. New HCN and HCO^+ $J = 3 \rightarrow 2$ data show that dense molecular gas ($n \gtrsim 10^5$ cm^{-3}) is found only in the nuclear starburst region.