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Molecular Gas Temperature and Density in Spiral Galaxies

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ABSTRACT. We combine beam-matched ^{13}CO, ^{12}CO $J = 3 \rightarrow 2$ and $J = 2 \rightarrow 1$ line data to infer the molecular gas excitation conditions in the central 500 to 1600 pc diameters of a small sample of infrared-bright external galaxies: NGC 253, IC 342, M 83, Maffei 2, and NGC 6946. Additional observations of the $J = 1 \rightarrow 0$ lines of $C^{18}O$ and ^{13}CO set limits on the opacity of the ^{13}CO $J = 1 \rightarrow 0$ line averaged over the central kiloparsec of these spiral galaxies.

1. Introduction

The large-scale physical conditions of molecular gas can lead to understanding large-scale star formation in galaxies. To probe the molecular gas temperature and density on hundred or thousand parsec scales in a sample of 5 spiral galaxies (NGC 253, IC 342, M 83, Maffei 2, and NGC 6946), we compare the strengths of the $J = 3 \rightarrow 2$ rotational lines of ^{13}CO and ^{12}CO with those of the corresponding $J = 2 \rightarrow 1$ lines, observed at the Caltech Submillimeter Observatory, James Clerk Maxwell Telescope, and the Swedish ESO Submillimetre Telescope. All $J = 3 \rightarrow 2$ and $J = 2 \rightarrow 1$ observations had $\sim 20''$ beamsizes, or $\sim$ 200-500 pc at the adopted distances (i.e. 1.8-5.5 Mpc). Larger beam (i.e. $\sim 60''$) observations of the $J = 1 \rightarrow 0$ lines of $C^{18}O$ and ^{13}CO were carried out at the National Radio Astronomy Observatory 12-meter telescope.

2. Results

The observed ratios of the integrated main-beam radiation temperature of the ^{13}CO $J = 3 \rightarrow 2$ line to that of the ^{13}CO $J = 2 \rightarrow 1$ line – abbreviated by $^{13}R_{32}$ – implies that the physical conditions of the molecular gas in the central $20''$ (170-530 pc) diameter varies strongly from galaxy to galaxy. Figure 1 shows that the $^{13}R_{32}$ values range from 0.2 (in M 83) to 2.0 (in NGC253), suggesting that the molecular gas density can change by at least an order of magnitude (from $n(H_2) \lesssim 10^4\,cm^{-3}$ to $n(H_2) \gtrsim 10^5\,cm^{-3}$) from galaxy to galaxy. The corresponding ^{12}CO line ratio, $^{12}R_{32}$, lies in the narrow range 1.1-1.3 (except in IC 342, see Wall & Jaffe 1990, Eckart *et al.* 1990), so that molecular gas temperature differences between galaxies cannot totally account for the $^{13}R_{32}$ variation.

Outside the central $20''$, $^{13}R_{32}$ is small (i.e. $^{13}R_{32} \lesssim 0.1$) in M 83 and NGC253, requiring low molecular gas densities ($n(H_2) \lesssim 10^4\,cm^{-3}$). The $^{12}R_{32}$ values imply molecular gas kinetic

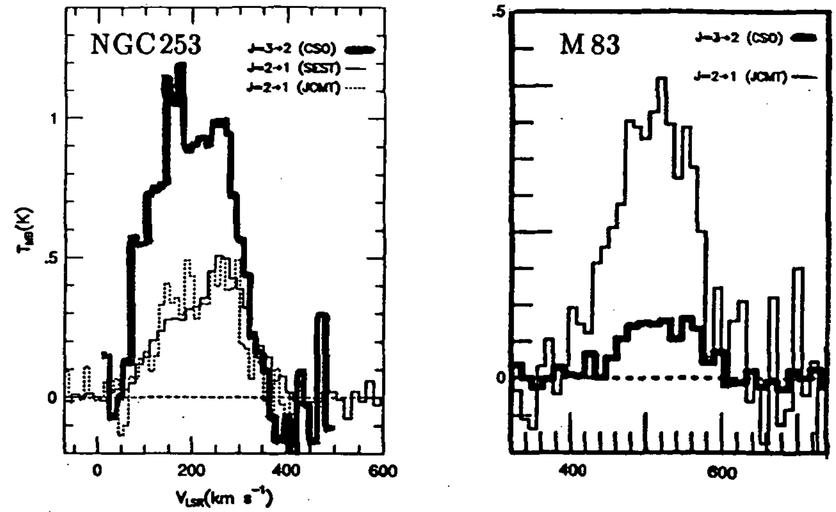

Figure 1 — The ^{13}CO J=3⟶2 (thick line) and ^{13}CO J=2⟶1 (thin and dashed lines) spectra are shown above in units of main-beam radiation temperature versus LSR velocity. Note the contrast between the NGC253 and M83 J=3⟶2/J=2⟶1 ratios.

temperatures at least as warm as that in our Galaxy (i.e. $T_K \simeq$ 5-20 K, Sanders *et al.* 1985).

The $C^{18}O$ J = 1 → 0 and ^{13}CO J = 1 → 0 data imply appreciable optical depth in the ^{13}CO J = 1 → 0 line (i.e. $\tau \simeq$ 1-5, assuming Galactic abundances, see Wannier 1989) over the central 60″ (720 pc) of NGC253. Similarly high optical depths have been inferred for ^{13}CO J = 1 → 0 in IC 342 (Wall & Jaffe 1990). It is possible that optically thick ^{13}CO J = 1 → 0 is common, even over 10^2-10^3 pc scales.

The total luminosity of CO over its entire rotational ladder from the central 60″ (∼ 0.5-1.6 kpc) of these galaxies is estimated from the ^{12}CO J = 3 → 2 line strength and radiative transfer models. The total CO luminosity is ∼ 10^5-10^6 $L_\odot$, which is within an order of magnitude of that of the important [C II] 158 μm cooling line (Crawford *et al.* 1985, Wolfire *et al.* 1989, Stacey *et al.* 1991).

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