ABSTRACT. We combine beam-matched $^{13}\text{CO}$, $^{12}\text{CO}$ $J = 3 \rightarrow 2$ 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: NGC253, IC 342, M 83, Maffei 2, and NGC6946. 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 (NGC253, IC 342, M 83, Maffei 2, and NGC6946), 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 ~ 20" beamsizes, or ~ 200-500 pc at the adopted distances (i.e. 1.8-5.5 Mpc). Larger beam (i.e. ~ 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 $n(\text{H}_2) \lesssim 10^4 \text{ cm}^{-3}$ to $n(\text{H}_2) \gtrsim 10^5 \text{ cm}^{-3}$) 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 ($n(\text{H}_2) \lesssim 10^4 \text{ cm}^{-3}$). The $^{12}R_{32}$ values imply molecular gas kinetic...
temperatures at least as warm as that in our Galaxy (i.e. $T_K \approx 5-20$ K, Sanders et al. 1985).

The $^{15}$O $J = 1 \rightarrow 0$ and $^{13}$CO $J = 1 \rightarrow 0$ data imply appreciable optical depth in the $^{13}$CO $J = 1 \rightarrow 0$ line (i.e. $\tau \approx 1-5$, assuming Galactic abundances, see Wannier 1989) over the central 60'' (720 pc) of NGC253. Similarly high optical depths have been inferred for $^{13}$CO $J = 1 \rightarrow 0$ in IC 342 (Wall & Jaffe 1990). It is possible that optically thick $^{13}$CO $J = 1 \rightarrow 0$ is common, even over $10^2-10^3$ pc scales.

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

References