Properties of CO Molecular Gas in IR Luminous Galaxies

Lihong Yao

*Department of Astronomy & Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada*

**Abstract.** We present the properties of the $^{12}\text{CO}(1-0)$ and (3-2) line emission from the nuclei of 60 IR luminous SLUGS galaxies. This sub-sample is flux limited at $S_{60\mu m} \geq 5.24$ Jy with FIR luminosities mostly at $L_{FIR} > 10^{10} \, L_{\odot}$. The emission line strengths of $^{12}\text{CO}(1-0)$ and (3-2) transitions were compared at a common resolution of $\sim 15''$, and the line ratios $r_{31}$ vary from 0.22 to 1.72 with a mean value of 0.66 for the sources observed, indicating a large spread of the degree of excitation of CO in the sample. Our analysis shows that (1) there is a non-linear relation between CO and FIR luminosities, such that their ratio $L_{CO}/L_{FIR}$ decreases linearly with increasing $L_{FIR}$, (2) we find a possible dependence of the degree of CO gas excitation on the efficiency of star forming activity, (3) using the large velocity gradient (LVG) approximation to model the observed data, the results show that the mean value of the CO-to-$H_2$ conversion factor $X$ for the SLUGS sample is lower by a factor of 10 compared to the conventional value derived for the Galaxy, assuming that the abundance of CO relative to $H_2$ is $10^{-4}$, (4) due to a contribution to the SCUBA brightness measurement by $^{12}\text{CO}(3-2)$ emission, the average dust mass is reduced by 25-38%, and the mean global gas-to-dust mass ratio is reduced from 430 to 360, but is further reduced to 100 when applied to the nuclear regions of the SLUGS galaxies, (5) for a subset of 12 galaxies with $H\ I$ maps, we derive a mean total face-on surface density of $H_2+H\ I$ of about $42 \, M_\odot \, pc^{-2}$ within $\sim 2$ kpc of the nucleus, which is intermediate between that in galaxies like our own and those with strong star formation.

1. Introduction

Understanding the properties and evolution of the gas and dust content in nearby IR luminous galaxies is essential for understanding the cause and temporal evolution of starburst activity and its role in the cosmic evolution of galaxies. Therefore, there is a need to investigate large statistical samples of IR luminous galaxies using a multitude of different types of data, including CO, $H\ I$, and continuum in the submillimeter (sub-mm), FIR and radio, in order to constrain theories of how the interstellar medium (ISM) evolves. Millimeter and submillimeter CO rotational lines are often used as tracers of molecular hydrogen. The ratio of $^{12}\text{CO}(3-2)$ to (1-0) line emission provides more sensitive measure of gas temperature and density than the ratio of $^{12}\text{CO}(2-1)$ to (1-0) lines. Recently,
we have presented the largest statistical CO survey (Yao et al. 2003) for the nearby universe by investigating the properties of CO molecular gas in a nearly complete subsample of 60 IR luminous galaxies selected from the SLUGS Survey (Dunne et al. 2000). The SLUGS survey containing 104 galaxies is based on the Revised Bright Galaxy Sample of IRAS galaxies (Soifer et al. 1987) within -10° ≤ δ ≤ +50° and with cz ≥ 1900 km s⁻¹, a flux limit of S_{60μm} ≥ 5.24 Jy, and the FIR luminosity L_{FIR} ≥ 10^{10} L_{⊙}.

2. Properties of Molecular Gas and Dust

A study of molecular gas of a complete flux-limited subsample is important to complement the study of the dust. The angular resolution of the $^{12}$CO(1-0) and (3-2) point observations presented in our CO survey are nearly identical ($\sim 15''$). A complete discussion of the observations, the CO line spectra, and the data analysis is contained in Yao et al. (2003) and references therein. Together with the sub-mm fluxes (Dunne et al. 2000), plus existing data on H I (Thomas et al. 2002), radio continuum (Condon et al. 1990), and FIR (Dunne et al. 2000; NED\(^1\)), we are able to search for a relationship between the degree of excitation of the CO in this sample and the star forming properties.

2.1. CO and FIR Luminosities

Figure 1(a) shows a comparison between the CO and FIR luminosities for two different FIR color regimes. A linear fit to the 1-0 data in the log-log plane yields log_{10}L_{^{12}CO(1-0)} = (0.2 ± 0.7) + (0.57 ± 0.07) log_{10}L_{FIR}. The nonlinear variation of L_{CO} with L_{FIR} implies a decrease in the ratio L_{CO}/L_{FIR} with increasing L_{FIR}, so that more IR luminous galaxies have higher dust temperatures and star formation efficiency. No correlation with the projected beam size on the galaxies is evident. The ratio depends intrinsically on the total FIR luminosity. This implies that for high-z objects where L_{FIR} is exceedingly high, the corresponding L_{CO} will be seriously overestimated if a linear relation between L_{CO} and L_{FIR} is assumed.

2.2. Star Formation Efficiency

We examined the excitation of CO and its relation with the properties of gas/dust and star formation in the the central starburst regions in the SLUGS sample. There are no significant correlations between the $^{12}$CO(3-2) to (1-0) line ratio r_{31} and the distance of galaxies, star formation rate, T_{dust} and M_{dust}, H$_2$ gas mass, and the color indices. This might reflect a range of localized conditions in the molecular clouds. But the degree of CO excitation measured by r_{31} varies greatly from galaxy to galaxy. There is a trend for the r_{31} to increase with increasing concentration and efficiency of star-forming activity (see Figure 1 (b)). The saturation of r_{31} seen at higher SFE implies that the gas is denser and warmer in regions of higher SFE, which is consistent with the nonlinearity between L_{CO} and L_{FIR}.

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Figure 1. (a) CO luminosity vs. FIR luminosity applicable to the 15″ beam, (b) the $r_{31}$ ratio vs. star formation efficiency; the line represents a linear regression fit to the data with SFE $\leq 200 \, L_\odot/M_\odot$, the $M(H_2)$ is computed using our derived X-factor, i.e. $2.7 \times 10^{19} \, \text{cm}^{-2} (K \, \text{km s}^{-1})^{-1}$, (c) $r_{31}$ vs. $T_{\text{dust}}$ for different $H_2$ gas densities $\log_{10} n(H_2)$ based on LVG model for $\Lambda = 10^{-5} \, (\text{km s}^{-1} \, \text{pc}^{-1})$, assuming $T_{\text{kin}} = T_{\text{dust}}$, the $^{12}\text{CO}$ abundance is $10^{-4}$, and the isotope abundance ratio $^{12}\text{CO}/^{13}\text{CO} = 40$, (d) a comparison between the distributions of computed (dotted line) and observed isotope $^{12}\text{CO}(1-0)/^{13}\text{CO}(1-0)$ ratios (solid line) for the best agreement regime of $\Lambda = 10^{-5}$, (e) SCUBA equivalent flux $S(V)$ produced by $^{12}\text{CO}(3-2)$ line vs. SCUBA flux at the central pixel for SLUGS sources for $v < 10,000 \, \text{km s}^{-1}$ (filled circles) and $v > 10,000 \, \text{km s}^{-1}$ (open circles), the slope for the linear regression fit is $0.26 \pm 0.01$, and (f) histogram of $S(V)$, the dash curve
2.3. The CO-to-H$_2$ Conversion Factor $X$

Our CO line measurements, together with dust and CO isotope data taken from the literature (Dunne et al. 2000; Aalto et al. 1995; Taniguchi et al. 1999), are modeled using the LVG approximation yielding $X = \frac{n(H_2)_{\Lambda}}{X_{CO,T_{rad}}}$ (see Figure 1 (c) and (d)) to estimate that the controversial $X$ lies between $1.3 \times 10^{19}$ and $6.7 \times 10^{19}$ cm$^{-2}$(K km s$^{-1}$)$^{-1}$ for SLUGS galaxies, which is about 4-20 times lower than the conventional $X$ factor derived from the Galaxy. The mean value $2.7 \times 10^{19}$ is comparable to that estimated from diffuse clouds in the Galaxy and with that found for extreme starbursts in nearby galaxies.

2.4. Virial Stability of the Molecular Clouds

Using virial analysis, we show that the molecular clouds in starburst regions are not gravitationally bound, confirming the suggestion recently made by Zhu et al. (2003) for the Antennae galaxies, unless one is willing to accept a 9-90 times lower [CO/H$_2$] abundance ratio. The cause could be the destruction by the stellar winds and expanding shells of newborn massive stars. Most of the CO line emission originates from the nonvirialized warm and diffuse gas clouds.

2.5. Revised Masses of Dust and Gas of SLUGS Galaxies

Our $^{12}$CO(3-2) observations provide an important database for correcting the SCUBA 850 $\mu$m data in the SLUGS sample (see Figure 1 (e) and (f)), thus permitting a revised characterization of the masses of dust and gas (see Seaquist et al. 2003). The average downward correction of dust mass is 25-38%, which has no bearing on earlier conclusions concerning the shapes of the dust mass-luminosity function derived from SLUGS survey. Using the $^{12}$CO(3-2)/(1-0) ratios in Yao et al. (2003), we estimate that it is unlikely that any correction is required for the contribution by $^{12}$CO(6-5) to 450 $\mu$m fluxes of the SLUGS galaxies measured with SCUBA. The revised mean gas-to-dust ratio (g/d) is reduced from 310 to 100, which is significantly lower than those reported for the global g/d ratios for IR luminous galaxies.

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