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The Properties of Dense Molecular Gas in the Milky Way and Galaxies

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Abstract. We review the evidence for a constant star formation rate per unit mass in dense molecular gas in the Milky Way and the extragalactic correlations of L_{IR} with L$'$ from observations of dense molecular gas. We discuss the connection between the constant SFR/M interpretation in dense gas and the global Schmidt-Kennicutt star formation law.

1. SFR/M in the Milky Way

The connection between star formation studied in the Milky Way and in galaxies is important for understanding the global evolution of stars in the universe. Lessons learned locally, where angular resolution permits detailed studies of high-mass star forming regions, may be applied to star formation regions that are unresolved in other galaxies. Star formation occurs in dense molecular gas (Evans 1999); therefore, it is necessary to study the properties of dense molecular gas to understand the conditions in the material actively involved in forming protostars. An important aspect of this study is the efficiency of star formation or how effectively dense gas is converted into stars.

One method for determining the star formation efficiency in Milky Way molecular clouds is to calculate the ratio of the bolometric luminosity to the mass of a star-forming clump within a giant molecular cloud (L/M). Within high-mass star forming regions in the Milky Way, submillimeter single-dish telescopes can resolve individual cluster-forming clumps ($\theta_{mb} <\approx 30''$). Higher resolution interferometric observations resolve the clumps into individual star-forming cores (e.g. Brogan et al. 2007). Only a few high-mass clumps have been observed at high resolution. Since several systematic single-dish surveys of clumps have been made (e.g., Plume et al. 1997; Zinchenko et al. 2000; Sridharan et al. 2002), we focus on the properties of the cluster-forming clumps. If we assume a universal stellar Initial Mass Function (IMF) for all star-forming regions within the Milky Way, then the bolometric luminosity is directly proportion to the star formation rate ($L_{bol} \propto SFR$). The virial mass of a molecular clump is calculated from

$$M_{\rm virial} = \frac{5R\Delta v^2}{G\ln 2}\frac{a_{\rm density}}{a_{shape}} \,, \qquad (1)$$

where R is the size of the clump, Δv is the FWHM linewidth, $a_{density} = (1 - 2p/5)/(1-p/3)$ (for $p < 2.5$) is the correction factor for a power-law density of the form $n \propto r^{-p}$, and a_{shape} is the correction factor for an ellipsoidal shape (Bertoldi & McKee 1989). The size and shape are determined from the FWHM intensity contour of the clump (see Shirley et al. 2003). An optically thin linewidth must be determined from observations of isotopomers (e.g. $H^{13}CN$, $C^{34}S$, $H^{13}CO^+$) since the linewidth of common dense gas tracers can be significantly broadened due to large optical depths (Philips et al. 1979). Radiative transfer modeling of optically thin dust continuum emission indicates that the average large scale structure of dense molecular clumps follows a single power-law density $n \propto r^{-p}$ (Mueller et al. 2002; Williams et al. 2005), for which the correction to M_{vir} can be substantial ($a_{density} = 0.6$ for a r^{-2} power-law).

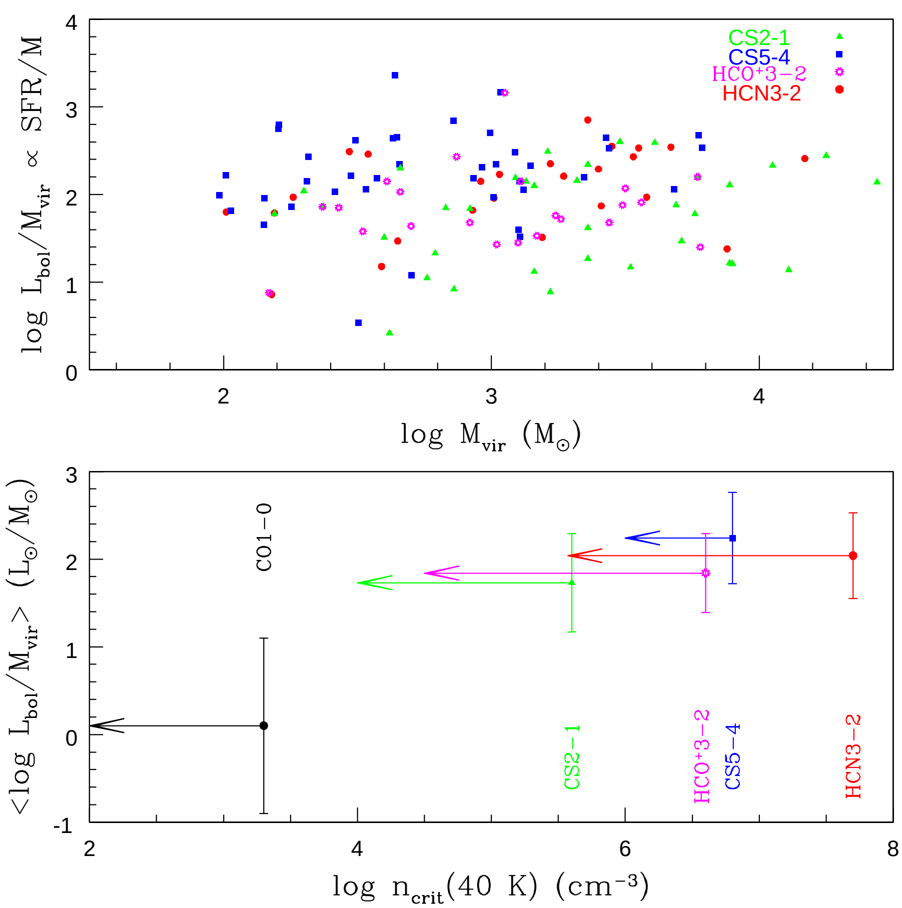

Figure 1. L_{bol}/M_{vir} is plotted for high-mass star forming clumps observed in various dense molecular gas tracers (top panel). The average $\log L/M$ is plotted versus the critical density of the molecular tracer calculated at 40 K (bottom panel). The arrows in density correspond to the effective density for which a 1 K line may be observed in a typical clump (see Evans 1999). Notice that $\langle \log L_{bol}/M_{vir} \rangle$ is nearly constant for all molecular tracers above 10^4 cm^{-3}.

The ratio of L_{bol}/M_{vir} versus M_{vir} is plotted in Figure 1 for mapping surveys of CS J=2-1 and J=5-4 (Wu et al. 2008, in prep.; Plume et al. 1992; Shirley et al. 2003), HCN J=3-2 (Wu & Evans 2005), and HCO^+ J=3-2 (Shirley et al. 2008, in prep.). All of these dense gas tracers display a remarkable lack of correlation. When all of these tracers are considered together, this result is consistent with a constant SFR per unit mass of dense gas. The average star forming efficiency traced by dense gas is constant among high-mass star forming regions in the Milky Way and this result appears to be independent of the dense gas tracer observed (bottom panel, Figure 1). The critical density of a transition ($n_{crit} = A_{ul}/\gamma_{ul}$) is crude approximation for determining the density at which a particular transition is excited. In reality, radiative transfer effects can significantly lower the density at which a particular line may be easily detected ($n_{eff} < n_{crit}$) by up to an order of magnitude (see Evans 1999). The observed $\langle \log(L_{bol}/M_{vir}) \rangle$ is nearly constant for all tracers with $n_{eff} > 10^4$ cm^{-3}.

The result from molecular line observations is confirmed by making L_{bol}/M_{dust} comparisons from dust continuum observations. Since the dust emission on large scales is optically thin at (sub)millimeter wavelengths, the dust mass may be calculated with assumptions of the average dust temperature and the dust opacity (Hildebrand 1983). For instance, the 350μm radiative transfer modeling survey of Mueller et al. (2002) find a constant $\log(L_{bol}/M_{dust})$ that is within a factor of two of the $\log(L_{bol}/M_{vir})$ calculated from dense molecular gas (Shirley et al. 2003). A factor of two is within the uncertainty in dust opacity at long wavelengths in high-mass star forming regions. Thus, there is strong evidence that, regardless of tracer, the SFR/M is constant in dense molecular gas within the Milky Way.

2. Dense Molecular Gas in Galaxies

Observations of other galaxies are not currently able to resolve individual cluster-forming molecular clumps; since we cannot calculate M_{vir} directly, we must instead interpret global averages of the molecular luminosity. As a result, we calculate L', or the source-integrated surface brightness

$$L' = 3.256 \times 10^{-7} (D_L/\mathrm{Mpc})^2 (\nu_{\mathrm{rest}}/\mathrm{GHz})^{-2} (1+\mathrm{z})^{-1} \int \mathrm{S}_\nu \, \mathrm{dv} \mathrm{Jy\,km/s\,pc}^2 \quad (2)$$

where D_L is the luminosity distance and ν_{rest} is the rest frequency (see Mangum et al. 2007 for a derivation; Solomon et al. 1997). The physical conditions in molecular gas may be probed by comparison of L' for tracers with the same spatial extent.

Recent extragalactic surveys have found very strong correlations between the globally integrated L' and the galactic infrared luminosity (L_{IR}, $\lambda \in [8, 1000]$ μm). The HCN 1-0 survey of Gao & Solomon (2004a,b) found a remarkable, tight linear correlation between L'(HCN1-0) and L_{IR} over three orders of magnitude in L_{IR}. This relationship is significantly different from the super-linear correlation between L' and L_{IR} observed for CO 1-0 (Figure 2). Linear correlations are also observed in other dense gas tracers including CO J=3-2 (Narayanan et al. 2005), HNC J=1-0, HCO^+ J=1-0, and CN N=1-0 and N=2-1 (Baan et al. 2007; see Figure 2). Furthermore, the extragalactic linear HCN $1-0$ correlation directly extends, without an offset, to L' versus L_{IR} for galactic high-mass star-forming clumps (Wu et al. 2005). If $L_{IR} \propto SFR$ and $L' \propto M$, then the linear correlation would indicate that the SFR in dense molecular gas is also constant in other star-forming galaxies ($L_{IR}/L' \approx$ constant, analogous with the galactic $L_{bol}/M_{vir} \approx$ constant result). One interpretation of these results is that the general star formation law in other galaxies is a simple extension of the constant SFR/M observed in the Milky Way with the dense molecular clumps greater than a few hundred $M_\odot$ comprising a fundamental unit of star formation (see Wu et al. 2005). In this interpretation, the main difference between the Milky Way and an extreme starburst galaxy is that the a larger fraction of the molecular ISM is in a dense molecular phase in the the starburst galaxy compared to the Milky Way. Observationally, a larger ratio of HCN to CO 1-0 emission is observed with larger L_{IR} (Gao & Solomon 2004b; see Figure 2) possibly indicating a higher dense gas fraction in more luminous galaxies (cf. Riechers et al. 2007 for a flattening of the ratio for high z galaxies).

There are several caveats to the constant SFR/M interpretation. L$'$ is determined globally and contains contributions from both low density and high density molecular gas with a wide range of excitation conditions along each line-of-sight. L' may not be linearly proportional to mass; therefore, proper interpretation of L$'$ may required radiative transfer modeling of excitation conditions in gas on galactic scales. The observational study of Mangum et al. (2007) attempts to circumvent this problem by calculated the total molecular mass from LVG models of the absorption spectra of the centimeter K-doublet H_2CO transitions. This pilot survey detected more than a dozen galaxies and was able to determine the L_{IR}/M_{H_2} ratio globally for an assumed formaldehyde abundance. The considerable scatter precludes strong conclusions, but the observed relationship may be consistent with a constant SFR/M (see Figure 2).

Theoretical calculations of L' must couple galactic hydrodynamics with radiative transfer. Two initial studies have provided an alternative explanation to the observed linear correlations for L'(HCN1-0) and L_{IR} and the super-linear correlation of L'(CO1-0) and L_{IR}. Krumholz & Thompson (2007) model the radiative transfer for an ensemble of clumps with a lognormal distribution in density, as expected from turbulent ISM simulations, and a SFR $\propto n^{1.5}$ based upon free-fall arguments. They find that the slope of the L_{IR} versus L' correlation depends on whether the mean density of the gas is above or below the critical density of the tracer: L_{IR} correlates super-linearly with L' if $\langle n\rangle > n_{crit}$ while L_{IR} correlates linearly with L' if $\langle n\rangle < n_{crit}$. Similar results were found with the more sophisticated 3D coupled hydrodynamic-radiative transfer models of Narayanan et al. (2007) with the main difference being that Narayanan et al. also predict sub-linear correlations for the higher J transitions of dense molecular gas tracers (e.g. HCN 3-2). This theoretical prediction is testable by current extragalactic surveys of higher excitation lines of HCN and HCO^+ (e.g., Padelis et al. 2007; HHT survey of Bussmann et al. 2008, in prep.). In both sets of models, L'(HCN 1-0) is significantly affected by sub-thermal excitation of large quantities of low density gas along lines-of-sight through the galaxy. Thus, the naive assumption that L' faithfully traces mass may be incorrect. Furthermore, both of these model assume an underlying star formation law that is similar to the Kennicutt-Schmidt law of $SFR \propto n^{1.5}$ (Kennicutt 1998; Kennicutt et al. 2007) and not a constant SFR/M.

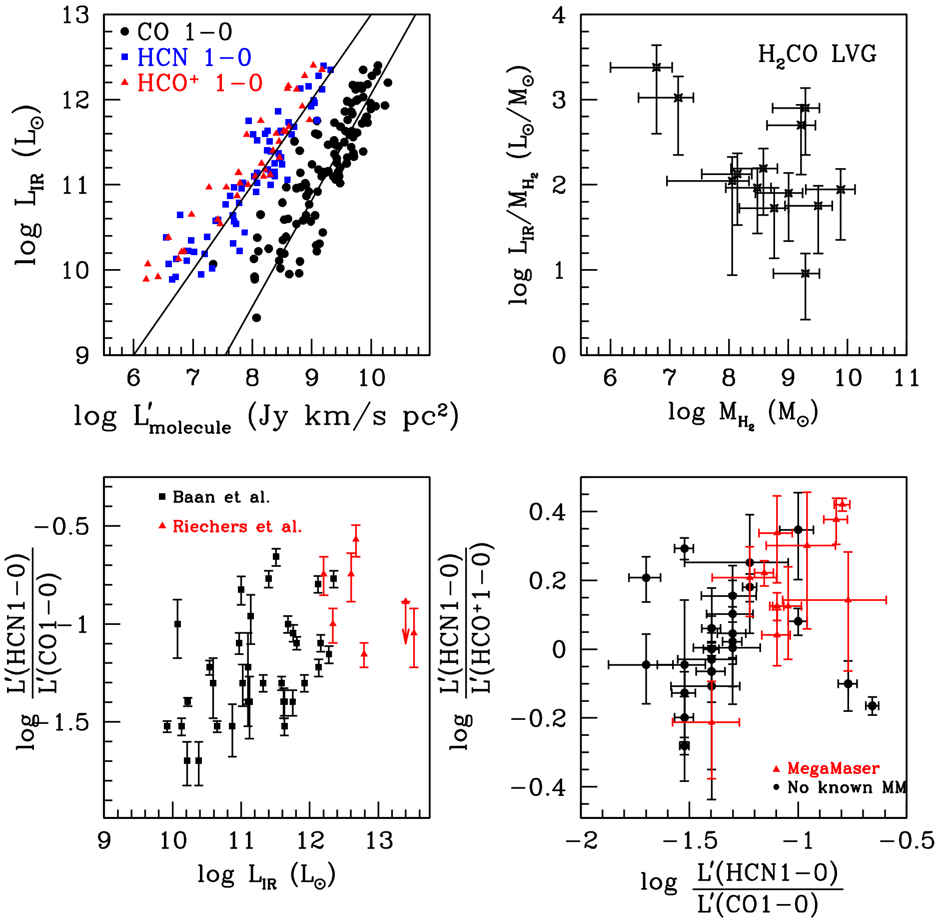

Figure 2. Top left: L_{IR} vs. L' for CO, HCN, and HCO^+ 1-0 (L' calculated from data in Baan et al. 2007). The solid lines have slopes of 1.0 and 1.4 to illustrate the difference between dense gas tracers (HCN and HCO^+) and CO. Top right: L_{IR}/M_{H_2} vs. M_{H_2} determined from LVG models of the lowest K-doublet transitions of H_2CO observed by Mangum et al. 2007. Bottom left: The ratio of HCN to CO 1-0 emission vs. L_{IR} for galaxies compiled in Baan et al. (2007) and Riechers et al. (2007; high-z detections). Bottom right: The ratio of HCN to HCO+ 1-0 emission vs. HCN to CO 1-0 emission (data compiled in Baan et al. 2007). Source with known megamasers (OH or H_2O), usually indicative of AGN activity, are at the higher end of the correlation.

L' may also be affected by the chemical or excitation effects on the dense molecular gas via processes not related to star formation such as the effects from an AGN (see Combes 2007 for a chemical review). AGN generate a substantial infrared radiation field that may contribute to L_{IR} (violating the $L_{IR} \propto$ SFR assumption) and also may enhance (sub)millimeter molecular transitions through absorption of IR photons in mid-infrared vibrational bands (e.g., the 21μm bending mode of HNC; Aalto et al. 2007). Active AGNs generate harder X-ray radiation fields (X-ray Dominated Regions, XDRs) than star forming regions and may effect global ionization balance and the chemistry in dense molecular gas. For instance, a purported chemical trend has been observed in the ratio of HCN to HCO^+ emission versus the ratio of HCN to CO emission that may be due to the effects of AGN (see Figure 2; Graciá-Carpio et al. 2007; Bann et al. 2007). Comparison of the properties of the galaxies with these higher molecular ratios tend to have evidence for strong AGN activity (either via optical, x-ray, or megamaser identification). In one case, the Seyfert 2 galaxy NGC 1068 was imaged with an interferometer and an enhancement in the HCN to CO ratio is seen toward the central molecular torus (Krips et al. 2007). Great care must be taken in the interpretation of these results since theoretical prediction of the abundances in XDRs is inchoate (e.g. Lintott et al. 2006; cf. Meijerink et al. 2007). Multi-transition interferometric studies with spatially resolved SED modeling are needed to fully understand the excitation and abundance effects of the AGN on L_{IR} and L'.

3. Summary

Galactic observations indicate that the SFR per unit mass traced by dense molecular transitions is constant, independent of tracer above $n_{eff} > 10^4$ cm^{-3}. In contrast, extragalactic observations of HI, CO, and optical and near-infrared emission lines indicate that the SFR follows a super-linear Schmidt-Kennicutt law with $SFR \propto n^{1.5}$. Recent radiative transfer models of molecular emission on galactic scales indicate that the observed linear correlations observed between L_{IR} and L' for dense gas tracers may be related to an underlying Schmidt-Kennicutt law. Indeed, within the Milky Way, accounting of the gas content (HI + CO) and cluster populations within 1 kpc of the sun reveal that the Schmidt-Kennicutt relationship predicts the observed star formation surface density (Evans 2007).

How do we reconcile the two possibilities for the SFR law (constant vs. super-linear or both)? In the absence of direct observations of molecular clumps in other galaxies, the problem presents a difficult theoretical hydrodynamic-radiative transfer challenge which we have only begun to explore. Within the Milky Way, it is still a theoretical challenge to understand which process mitigate the observed constant SFR/M in dense gas (see article by Mac Low in this volume). On galactic scales, one intriguing possibility is that the local Schmidt-Kennicutt law may flatten at high densities such that the SFR $\propto n$. This possibility should be explored theoretically. Also, observation of higher excitation lines at high spatial resolution with interferometers (e.g., PdBI, CARMA, and ALMA) are needed to resolve issues of excitation and abundance variations within galaxies.

The synthesis of current observational and theoretical studies of dense molecular gas in the Milky Way and other galaxies is beginning to reveal the global properties of star formation in the gas that is actively involved in star formation.

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