MOLECULAR CLOUDS AND CO EMISSION IN LOW–METALLICITY GALAXIES

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1. Introduction

Irregular and dwarf galaxies are probably the most numerous actively star-forming galaxies. They are generally gas-rich (in neutral hydrogen) and metal-poor, with gas-phase metallicity $Z \lesssim 0.25$ solar and similarly low dust-to-gas ratios. The nearest examples are the Large and Small Magellanic Clouds, but there are many others within a few Mpc (*e.g.*, NGC 1569, NGC 4449). Irregular and dwarf galaxies are notoriously poor in CO emission and the resulting high ratios of infrared to CO luminosities have been interpreted as a high star formation efficiency. Here we show that CO emission is not generally a reliable tracer of molecular mass in low-Z objects, and discuss alternative tracers of the molecular gas content.

2. Low–Metallicity Cloud Models

The key parameter controlling the physical and chemical state of gas exposed to FUV photons is G_o/n, where G_o is the scaling factor for the FUV radiation field (relative to the solar neighborhood value) and n is the total hydrogen density. If G_o/n is high, then attenuation of the FUV photons by dust determines where molecules survive; if G_o/n is low, molecular survival is determined by self-shielding. The transition between these regimes (for H_2) occurs at $(G_o/n)_{cr} \sim 10^{-2} Z^{1/2}$ (assuming that the H_2 formation

Figure 1. H_2 and carbon species column densities for $G_o = 1$ models.

rate on grains scales with grain surface area $\propto Z$). We have constructed chemical and physical models (including thermal balance) for a series of cloud models, all with $n = 10^3\,\mathrm{cm}^{-3}$. These include models with parameters appropriate to Galactic molecular clouds and models that approximate the physical conditions in the LMC and SMC, with the gas-phase metallicity and dust-to-gas ratios reduced by factors of 4 and 15, respectively, compared to the Galactic model.

$G_o = 1$ *Models.* These are appropriate to quiescent molecular clouds exposed only to the ambient FUV flux. Figure 1a shows the cumulative molecular hydrogen and CO column densities as functions of total hydrogen column density N_{H}. The differences in H_2 between the different models are small. The differences in carbon chemistry, however, are pronounced, as these models are all in the self-shielding regime. Figure 1b shows the C and C^+ columns as functions of N_{H}. The column density of CO drops by more than three orders of magnitude as Z declines from 1 to 1/15 (relative to solar), while the C^+ column is nearly constant, *increasing* by about a factor of 3. Neutral carbon is also roughly constant, with $N_{\mathrm{C}} \sim 6 \times 10^{17}\,\mathrm{cm}^{-2}$ for $Z = 1$ and $Z = 1/4$, and about a factor of 6 smaller for $Z = 1/15$ (here C^+ is the dominant carbon species). The observable consequences for CO are dramatic: for the LMC ($Z = 1/4$) model, the emergent intensity is smaller than in the Galactic model by about 35% (due to the smaller CO column), but the size of the optically thick CO core has decreased by more than a factor of two, leading to a drop in the CO luminosity of more than a factor of six. CO in the SMC model would be undetectable. For realistic (clumpy) cloud models, the effects on the CO luminosity depend on the clump column density spectrum, but are generally severe.

Figure 2. (a) H_2 and CO column densities for $G_o = 10^3$ models. (b) Ratio of emergent integrated intensities in the C^+ 158μm and CO $J = 1 - -0$ lines for the same models.

$G_o = 1000$ *Models.* These are appropriate to star-forming molecular clouds exposed to intense FUV fluxes from OB stars, *e.g.,* photodissociation regions or PDRs. Here the survival of molecules is determined by dust; due to the lower dust-to-gas ratios in the low-Z models, formation of H_2 and CO requires a larger N_H to reach the same extinction. The dramatic differences between $Z = 1$ and low-Z PDRs are shown in Figure 2a. At the end of the integration (to $N_H = 10^{23}\,cm^{-2}$, or $A_v \approx 60$ for the Galactic model) the CO column in the SMC model is still only $N_{CO} \approx 2 \times 10^{15}\,cm^{-2}$, while the C^+ column is nearly constant in all three models at $N_{C+} \approx 2 \times 10^{18}\,cm^{-2}$. As shown in Figure 2b, this leads to enormous differences in the C^+ 158μm to CO $J = 1 - 0$ line ratio, with the observed ratio for the low-Z models depending strongly on the total column through the PDR. This is in agreement with observations of low-Z galaxies, which show $I_{[CII]}/I_{CO} \sim 5 - 15$ times larger than typical for IR-bright galactic nuclei or Galactic HII regions.

3. Conclusions

Clouds in low metallicity galaxies, such as irregular and dwarf galaxies, can have most of their hydrogen in molecular form with little or no CO.

The 158μm/CO $J = 1 - 0$ ratio in low-Z PDRs depends on the total column through the PDR and the degree of clumping and is in general considerably higher than in $Z \sim 1$ PDRs.

On global (kpc) scales, photodissociation processes dominate the ISM of low metallicity galaxies. Neutral carbon and C^+ emission will be more useful as a tracer of molecular gas mass than CO.