THE MOLECULAR CLOUD CONTENT OF SPIRAL AND DWARF GALAXIES

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ABSTRACT. This paper concentrates on the molecular cloud component in its role as the site of current star formation - especially massive star formation. It is further restricted to the molecular component as traced by CO, the preeminent tracer of molecular gas in galaxies despite the problems discussed here. The basic topics addressed are (1) the variation of CO properties with galactic environment and type; (2) the problems involved in the inference of H_2 distributions for individual galaxies from CO observations; and (3) the particular question of the presence of spiral structure in the CO component.

1. DEPENDENCE OF CO CONTENT ON GALAXY CHARACTERISTICS

1.1. Environment

The HI in cluster spirals is systematically removed from the outer disks of the spirals closer in to the cluster center (e.g., Gorkom and Kotanyi 1985). Stark *et al.* (1986) and Kenney and Young (1986) searched for a similar effect in the CO disks of Virgo spirals, and found a clear increase of the ratio of integrated CO line flux to integrated HI line flux, CO/HI, with decreasing angular separation from M87. Both concluded that the effect is wholly accounted for by the variation in HI alone. Apparently, the bulk of the CO is sufficiently deep within the galactic potential, and in the form of sufficiently dense molecular clouds, that it is unaffected by the processes removing HI.

1.2. Morphological Type

Early attempts to assess the relative abundance of CO in Magellanic-type irregulars indicated clear deficiencies relative to late-type spirals (Elmegreen *et al.* 1980). Possible explanations were underabundance of CO relative to hydrogen, reflecting overall low metallicities; rapid destruction of GMCs due to higher than normal star formation efficiencies; or lower CO excitation temperatures due to lower cosmic-ray heating rates. Israel *et al.* (1986) have confirmed the general weakness in

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CO emission of the Magellanic Clouds themselves. They suggest that the combination of lower metallicity with a lower dust-to-gas ratio and a stronger ambient ultraviolet radiation field leads to an enhanced rate of dissociation of CO clouds. The underabundances in CO implied by their analysis are factors of 4 for the LMC and 20 for the SMC, and do not necessarily mean comparable underabundances in H_2 content.

Among spirals, it has been difficult to isolate dependencies on subtype because of the considerable nonuniformities in the samples and sensitivities of early searches. Two searches of fairly uniform sensitivity for the Virgo cluster (Young *et al.* 1985; Stark *et al.* 1986), and an attempt to put all previous observations on a uniform statistical footing (Verter 1983; 1986, in preparation) allow reconsideration. Young *et al.* detected the centers of 18 of 25 spirals in the Virgo cluster; Stark *et al.* detected 25 of 47 spirals, making partial maps of most to estimate total CO brightnesses. Binning types into earlier or later than Sb, neither found differences in CO content based on type alone. Verter, on the other hand, working with 40 detections and 47 upper limits drawn from 283 reported observations, and also using model distributions to estimate total fluxes, chose three morphological bins: E-Sab, Sb-Sbc, and Sc-Irr. She found a clear peak for the Sb-Sbc galaxies both in L(CO) and <CO/HI>, the latter running roughly from 55 to 70 to 20 for detected galaxies alone. The Young *et al.* and Stark *et al.* data apparently also show such a peak when binned similarly. Verter suggests that the peak represents the competition between earlier types tending to be larger and later types tending to have larger fractional gas contents.

1.3. Luminosity

Verter also determined a CO luminosity function by applying a maximum-likelihood technique to the sample of detections and upper limits. The distribution is strongly peaked at low luminosities (to be expected, as the upper limits weight the lower flux levels) with a long high luminosity tail. In CO/HI, the distribution peaks at a line flux ratio of 13, corresponding to a total mass in H_2 roughly half that of the mass in HI. The high-luminosity tail extends out to CO/HI $\simeq$ 500.

A strong correlation has been reported between the integrated CO line flux and the blue stellar luminosity - both from point to point within galaxies (Young and Scoville 1982a), from galactic center to galactic center (Young and Scoville 1982b). The Virgo data (Young *et al.* 1985) appear to confirm this effect, with different correlations appearing for early and late types presumably because of different central bulge contributions. The correlation with blue light within galaxies has been questioned (Rickard 1982, Rickard and Palmer 1985), but the correlation from galaxy to galaxy has appeared to hold over a considerable range in luminosity (e.g., Young *et al.* 1984).

Stark *et al.* (1986), however, disagreed with both forms of the correlation, at least within Virgo. Their models compared fits for different forms of CO distributions; for 13 mapped galaxies with well-fit models, none could be characterized as exponential disks with scale lengths identical to the blue light disks. They found little correlation between integrated CO flux and total blue magnitude for the whole Virgo sample. Over less than three magnitudes in blue magnitude, the scatter in integrated CO line fluxes was two orders of magnitude. Verter's analysis tends to confirm the Young *et al.* correlation, but again with considerable scatter and a strong domination by the brightest members of the sample. Resolution of these differences will probably have to await larger samples and better assessments of systematic effects.

1.4. Activity

The correlation of CO line flux with infrared emission (Rickard *et al.* 1977a, Telesco and Harper 1980) has been well confirmed through observations of the far-infrared from detected CO galaxies (Rickard and Harvey 1984) and observations of the CO from IRAS detections (e.g., Young *et al.* 1984). The effect is not primarily one of brighter CO lines being associated with hotter clouds (Rickard and Harvey 1984), although such an effect may contribute to scatter in the correlation. Rather, it represents the correlation of increasing amounts of massive star formation with the presence of more CO clouds to support that star formation. At very high far-infrared luminosities, Sanders and Mirabel (1985) found excess IR emission for the apparent L(CO); this may represent enhanced massive star formation rates due to unusual conditions in these highly active galaxies, together with the consequent enhanced destruction of the CO.

The correlation of CO with nonthermal radio continuum emission (Rickard *et al.* 1977b, Morris and Rickard 1982), has been well established through observations of CO itself (Rickard *et al.* 1985; Stark *et al.* 1986) and through observations of the associated far-IR emission (Rickard and Harvey 1984; de Jong *et al.* 1985; Sanders and Mirabel 1985) and Hα emission (Kennicutt 1983). This correlation is striking, because the CO or IR emission of the central arc-minute is so well linked to the mean continuum emission of the disk. Somehow, the activity of the central regions is tied to that of the galaxy as a whole. Among suggestions proferred to account for this are a dominant role for massive stars in determining the nonthermal disk emission (de Jong *et al.*), global independence of the IMF for massive stars and the star formation rate (Sanders and Mirabel), or the common dependence of central star formation activity and the strength of the disk spiral shock on some structural feature like a central bar (Rickard *et al.* 1985, Ball *et al.* 1985).

2. DETERMINATION OF H_2 DISTRIBUTIONS FROM CO MAPS

Extragalactic CO papers usually report an integrated intensity of ^{12}CO emission, P(CO) = $\int T_R^* dV$ [K km s^{-1}], and convert directly to the column density of H_2, N(H_2) [cm^{-2}]. The original justification for this was the apparent proportionality of CO and, presumably optically-thin, ^{13}CO emission along many lines of sight in Galactic surveys (Solomon *et al.* 1979). Considerable effort has gone into justifying particular values of $N(H_2)/P(CO)$ (e.g., Sanders *et al.* 1984), with currently popular values falling near 3×10^{20} molecules cm^{-2} $(K\ km\ sec^{-1})^{-1}$ (cf. summary by Kutner and Leung 1985).

There is much evidence now to suggest caution in applying a single $N(H_2)/P(CO)$ value, especially in mapping galaxies. Liszt *et al.* (1984) reported differences in the ^{12}CO to ^{13}CO ratio at the level of a factor of two across the Galactic disk. Observations of bright CO galaxies (Rickard and Blitz 1985; Young and Sanders 1986) show clear variations in the apparent integrated line ratios, both from galaxy to galaxy and within individual galaxies, with differences up to a factor of 5. All three studies suggested that changing mean properties of the cloud ensemble, particularly temperature, may be responsible. Detailed cloud models by Kutner and Leung (1985) show that $N(H_2)/P(CO)$ scales roughly as the -4/3 power of the gas temperature.

Gamma-ray studies also suggest that $N(H_2)/P(CO)$ is neither constant nor well-determined. COS-B and SAS-2 satellite results yield values lower than the Sanders *et al.* (1984) number by one-half to one-sixth (Lebrun *et al.* 1983, Bhat *et al.* 1985). An order of magnitude difference may be required to explain the apparent absence of gamma-ray emission from the Galactic center (Blitz *et al.* 1985).

Metallicity variations also obscure the desired value of $N(H_2)/P(CO)$ (Blitz and Shu 1980, Talbot 1980, Blitz 1985). Such effects have been studied with detailed cloud models by Kutner and Leung (1985), and chemical evolution models by Tosi and Diaz (1985). Also, Williams (1985) has noted that the high atomic carbon abundances in dense CO clouds (Phillips and Huggins 1981, Keene *et al.* 1986) imply deviations from chemical equilibrium. Thus, the $[CO]:[H_2]$ ratio may change as a function of cloud age and internal activity, characteristics that could vary across galactic disks.

3. SPIRAL STRUCTURE

By determining the degree to which the molecular cloud component is confined to the optical spiral pattern, one hopes to understand the extent to which the pattern of the young stellar distribution is determined by the structure of the star-forming gas as opposed to the presence of some structured star-formation trigger. Until recently, only the studies of M31 have had sufficient angular resolution for useful results.

Work has focussed on the dense clouds of M31's SW arms (Stark *et al.* 1981, Boulanger *et al.* 1984, Stark 1985, Ichikawa *et al.* 1985) where the apparent arm-interarm contrast is 25:1, and on an extensive arm region to the NE (Ryden and Stark 1986) where the contrast is 10:1. Both regions show narrow features that appear to be GMCs distributed along the arm, roughly correlated with HII regions, dust, and peaks of IR emission. There is also a smooth component of emission filling the velocity width of the rotation curve within the beam, apparently representing many smaller clouds. The CO velocity structure of the NE arm tends to follow the rotation curve along the inner edge, but deviates toward the outer edge by a gradient of roughly 25 km s^{-1} kpc^{-1}. This apparent streaming motion is consistent density wave predictions.

However, a stronger anomalous velocity structure is seen in the innermost NW arm along the minor axis (Stark 1985).

M31 is not representative of bright CO galaxies, having only 10% of its gas surface mass density in the form of H_2 (Stark 1985). Among galaxies with richer H_2 components, most work has been done on M51. At 1′ resolution, it is effectively impossible to separate out the optical arm structure (Rickard and Palmer 1981, Rickard 1982, Scoville and Young 1983). At Onsala, Rydbeck *et al.* (1985) have made an extensive J=1-0 map with 33" resolution that, after subtraction of a smooth axisymmetric component, yields spiral features at a level of roughly 20% of the disk. The presence of these features is better revealed by their velocity structures, which show large (≃ 70 km $\sec^{-1}$) radial streaming motions. The central regions have been mapped interferometrically at 7" resolution (Lo *et al.* 1986) to show individual GMC complexes distributed along the innermost dust lanes, presumably superposed on a smoother distribution as less than half of the zero-spacing flux density is detected. These clumps appear in high contrast in J=2-1 maps made at 30" resolution (Rickard and Turner, in preparation).

Other galaxies with reported evidence of CO enhancements associated with the optical spiral pattern are IC 342 (Rickard and Palmer 1985) and M83 (Lord, in preparation).

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