MOLECULAR GAS AND STAR FORMATION IN GALAXIES

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1. Introduction

Using the 14m millimeter telescope of the Five College Radio Astronomy Observatory (HPBW=45″), we have observed the CO J=1–0 emission at 1412 positions in 300 galaxies. These observations, which comprise the *FCRAO Extragalactic CO Survey*, are the most extensive and uniform database on the content and large-scale distribution of molecular gas content in galaxies (Young et al. 1995). Since stars form in molecular clouds, these observations enable us to investigate galaxy evolution through a determination of the star formation efficiency and the molecular-to-atomic-gas ratio within and among galaxies.

The galaxies observed as part of the *Survey* were selected at optical and infrared wavelengths to cover a wide range of morphological type, luminosity, and environment; 260 of the 300 galaxies are classified as spiral (S0 – Sm). Among galaxies that are either brighter than 11th magnitude in the blue or brighter than 15 Jy at 100 μm, the *Survey* is 80% complete. CO was detected in 236 galaxies (79%) and observations were made along the major axis in 193 galaxies. Since many of the galaxies in the *Survey* are at distances of $\sim$20 Mpc, the regions we are observing are at least a few kiloparsecs across.

The H_2 masses used in this work were derived from CO observations assuming a constant CO$\rightarrow H_2$ proportionality (Bloemen et al. 1986). The global H_2 masses derived for luminous spirals have been shown to be statistically accurate to $\sim$ 30% (Devereux and Young 1990) and the absolute value of the CO$\rightarrow H_2$ proportionality for the MiLky Way has been confirmed in the Local Group spirals M31 (Sb) and M33 (Scd) by observations which resolve individual molecular clouds (cf. Figure 1 in Young and Scoville 1991).

2. Molecular Gas Distributions

Since both the Milky Way and Andromeda have molecular rings with radii $\sim$5 kpc, it is of interest to determine the frequency of such large molecular rings in other spiral galaxies. In fact, among the galaxies whose CO distributions were determined in the *Survey*, large-scale molecular rings are very unusual. Only 7 out of the 193 galaxies that were mapped exhibit CO rings with radii $\geq$ 5 kpc. The galaxies with molecular rings are primarily early-type unbarred spirals.

For $\sim$150 of the galaxies in the *Survey*, we have characterized the extent of the CO in the disk by determining CO isophotal diameters (for details, see Young et al. 1995). Among these galaxies, we find the mean ratio of CO-to-optical isophotal diameters is 0.52 ± 0.02; that is, the CO typically extends over half of the optical disk. Additionally, we find a trend along the Hubble sequence such that the CO extends over a smaller fraction of the optical disk for the early-type spiral galaxies while it extends over a larger fraction of the optical disk among Sc galaxies.

With regard to the form of the CO radial distributions in galaxies, it has been known for over a decade that the CO, blue light, Hα, far-infrared, and radio continuum emission all display similar exponentials in Sc galaxies, while the HI distribution is typically flat across the disk (Young and Scoville 1982, 1991). Thus, the ratio of molecular to atomic gas decreases as a function of radius in these galaxies.

3. The Star Formation Efficiency (SFE)

One of the most fundamental parameters describing the star formation activity in a galaxy is the ratio of the current star formation rate to the mass of molecular gas available to form stars, which we call the star formation efficiency. We have used both the luminosity in the far-infrared, from IRAS data, and the luminosity in Hα, from CCD imaging (Young et al. 1996), as measures of the star formation rate and we find similar results using both tracers.

To date, of all the investigations of the star formation efficiency in galaxies, the largest effect that has been found is the factor of $\sim$7 to 10 elevated star formation efficiency in interacting galaxies relative to isolated galaxies (Young et al. 1986; Sanders et al. 1986; Solomon and Sage 1988).

Another global property that appears to correlate with an elevated star formation efficiency is the bar morphology of a galaxy. Among 219 of the *Survey* galaxies for which bar classifications are available in the literature, 141 are barred or mixed, and 78 are unbarred. The mean value of the star formation efficiency for the barred galaxies is a factor of $\sim$2 higher than

for the unbarred galaxies, a trend that is present in both the early- and late-type spiral galaxies, independently (Young 1993).

Finally, investigations of the star formation efficiency in galaxies along the Hubble sequence indicate that there is no variation in the mean SFE with Hubble type among spiral galaxies of types Sa-Sc. That is, the mean global star formation efficiency is independent of the spiral morphology of a galaxy (using L(IR) to trace the star formation rate—Rengarajan and Verma 1986; Devereux and Young 1991; using L(Hα) to trace the star formation rate—Young et al. 1996). Therefore, it appears that spiral disks are similar and that disk morphology has little to do with the global rate at which molecular gas is converted into stars.

4. Molecular and Atomic Gas

Since stars form from molecular clouds, and molecular clouds form from atomic gas, both processes are of fundamental importance in the evolution of galaxies. The above results indicate that the star formation rate in spiral disks is proportional to the available mass of molecular gas, independent of Hubble type. The situation is very different for the comparison of the molecular and atomic gas masses in galaxies.

For 178 galaxies of types Sa-Sc, we find that the dominant neutral gas phase in spiral galaxies changes smoothly along the Hubble sequence, with the mean ratio of molecular to atomic gas ranging from 2 ± 1 among Sa galaxies to 0.4 ± 0.2 for the Sc galaxies, as suggested by Young and Knezek (1989). Additionally, the mean neutral gas surface density (molecular+atomic) increases only a factor of 2 from Sa to Sc galaxies. Thus, it appears that the dominant neutral gas phase changes along the Hubble sequence, with more molecular gas in the early type spirals and more atomic gas in the late type spirals.

5. Summary and Conclusions

The trends revealed with regard to the star formation efficiency and the molecular-to-atomic-gas ratio in galaxies as a function of morphology and environment provide important constraints for theories of the evolution of galaxies.

First, it is clear that the SFE in spiral galaxies is independent of morphology, so that the global rate of star formation depends primarily on the global quantity of molecular gas. Apparently, once molecular clouds are formed, star formation proceeds in a way that is similar from one galactic disk to another. However, forming the molecular clouds is another matter entirely and there is a significant difference in the molecular-to- atomic-gas ratio as a function of morphology—early-type spirals are predominantly

molecular, while late-type spirals are predominantly atomic. In other words, the dominant phase of the neutral gas in galaxies changes with the degree of central mass concentration, or the depth of the central potential.

These results can be simply understood in terms of the effects of gravity in cloud and star formation and the size scale on which gravity must operate. In order for molecular clouds to form from atomic gas, it is not surprising that gravity on the large scale should be important. This is reflected in the H_2/HI ratio changing with type or, equivalently, with the mass distribution of the galaxy. In contrast, it appears that star formation in unbarred, isolated, spiral galaxies occurs with the same mean efficiency independent of morphological type. This suggests that once the molecular clouds are formed, star formation within them is a local process, due to gravity on the small scale. These results suggest that spiral disks are similar and that the Hubble sequence is primarily a sequence of changing bulge-to-disk ratio. Only when a large scale perturbation is present, such as a bar or a tidal encounter with another galaxy, does the global star formation rate per unit mass of molecular gas become elevated.

In the galaxies surveyed, the global gas cycling times range between 10^8 and 10^{10} years, although this can vary dramatically with position within individual galaxies as well. In M82, for example, the gas in the center will be cycled into stars in less than 10^9 years, while the outer parts can sustain star formation for $\sim 10^{11}$ years. Thus, gas depletion may not occur everywhere in a galaxy and may not occur at all if only high mass stars form.

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