MOLECULAR CLOUDS IN EXTERNAL GALAXIES AND THE EFFICIENCY OF STAR FORMATION

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ABSTRACT. Observations of the molecular cloud distributions in spiral galaxies are reviewed. For the luminous, relatively face-on Sc galaxies, the azimuthally averaged CO distributions are centrally peaked, with H_2 surface densities which decrease as a function of radius. For the Sb and Sa galaxies, the CO distributions exhibit central CO holes up to 5 kpc across in a significant fraction of the galaxies studied. In galaxies with this CO morphology, the central hole is coincident with the nuclear bulge of the galaxy. Additionally, the radial distributions of CO and ^{13}CO emission are similar in 10 Sb and Sc galaxies.

The shapes of the CO distributions in the face-on Sc galaxies are similar to those observed in Hα, radio continuum, and blue light, and markedly different from the flat, extended distributions of atomic gas. In these high luminosity galaxies, there is significantly more H_2 than HI in the inner disks, while the HI surface density exceeds that of the H_2 in the outer parts. The relative constancy of the Hα/CO ratio as a function of radius suggests that the massive star formation rate is proportional to the mass of molecular clouds present, or that the star formation efficiency is constant as a function of radius in these galaxies. In contrast, the radial behavior of the H_2/HI ratio suggests that the efficiency of molecular cloud formation decreases with radius.

In large samples of galaxies, the CO and far-IR luminosities show a rough correlation over 4 orders of magnitude. The inferred star formation efficiencies, deduced from the ratios of Hα/CO or IR/CO luminosities, are not constant from galaxy to galaxy, but range over 2 orders of magnitude. Furthermore, the IR/CO luminosity ratio is correlated with the dust temperature from galaxy to galaxy, with the highest values found in merging and interacting systems. Clearly, the galaxian environment influences both the rate <u>and</u> the efficiency of star formation.

CO studies of the galaxies in the Virgo cluster provide a measure of the effect of the cluster environment on the dense component of the ISM. While the atomic gas associated with the galaxies near the center of the cluster appears to have been stripped, the CO extents and luminosities of the galaxies throughout the cluster appear normal.

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1. INTRODUCTION

Studies of the distribution and abundance of molecular clouds in external galaxies provide fundamental information for understanding galactic structure and evolution, since molecular clouds are the birthplaces for stars. The evolution of a galaxy can be described as the star formation history of a galaxy; the distribution of blue light from the disk indicates the past sites of star formation, the distribution of far-infrared emission indicates the currently forming stellar population, the distribution of molecular clouds indicates the underlying potential for star formation, and the distribution of atomic gas delineates the potential sites for molecular cloud formation. A synthesis of the details of the distributions of past, present, and future sites of star formation is one key to expanding our picture of the evolution of galaxies.

Since the first detection of CO in external galaxies (Rickard et al. 1975), there have been a large number of CO studies of galaxies conducted. These have included both detailed studies of nearby galaxies, and comparisons of the global properties of selected samples of galaxies. Each of these approaches has been fruitful, and provided illuminating results regarding the CO content of galaxies. Tables 1 and 2 list those individual galaxies for which radial distributions have been measured and statistical surveys for which CO observations have been published. Using galaxy types from Sandage and Tammann (1981, hereafter RSA), there are now radial CO distributions measured in 8 Sa/Sab galaxies, 19 Sb/Sbc galaxies, 23 Sc/Scd galaxies, and 1 Amorphous galaxy (M82).

From a combination of galaxies whose CO distributions have been mapped, and those whose total CO content have been determined with a single measurement, there are more than 100 galaxies for which the total CO luminosity is known. Thus, we are beginning to have sufficient statistics to determine the global CO properties of galaxies as a function of morphological type, luminosity, and galaxian environment. The most interesting questions which can now be addressed relate to the efficiency of star formation and molecular cloud formation in galaxies. The questions which I will pay particular attention to in this review are:

1) What is the star formation efficiency in individual galaxies, and from galaxy to galaxy ?

2) What is the molecular cloud formation efficiency, and how does it vary in individual galaxies ?

3) What causes variations in the star formation and molecular cloud formation efficiencies ?

The answers to these and similar questions involve the comparison of data over a wide range of wavelengths. In particular, the CO observations will be used to deduce the distributions and masses of molecular hydrogen in galaxies; it is these masses and mass surface densities which are critical for interpreting the star formation histories of galaxies. Before discussing the results of the CO observations of galaxies, I will first justify the use of CO as a tracer of the mass of molecular clouds in external galaxies.

Table 1
CO Distributions in Galaxies

Galaxy	Type[a]	Telescope[b]	Resolution (arcsec)	Reference
CO Radial Distributions[c]				
NGC 224 (M31)	SbI-II	BTL	100	Stark (1979)
NGC 253	Sc(s)	NRAO	67	Rickard et al. (1977)
		FCRAO	45	Scoville et al. (1985)
NGC 598 (M33)	Sc(s)II-III	FCRAO	45	Young (1986)
NGC 891	Sb on edge	FCRAO	45	Solomon (1982)
		FCRAO	45	Sanders and Young (1986)
NGC 1068	Sb(rs)II	FCRAO	45	Scoville et al. (1983)
NGC 2403	Sc(s)III	FCRAO	45	Young (1986)
NGC 2841	Sb	FCRAO	45	Young and Scoville (1982b)
NGC 3034	Amorphous	NRAO	67	Rickard et al. (1977)
(M82)		FCRAO	45	Young and Scoville (1984)
		OSO	33	Olofsson and Rydbeck (1984)
NGC 3079	Sc pec	FCRAO	45	Young et al. (1986)
NGC 3147	Sb(s)I.8	FCRAO	45	Young et al. (1986)
NGC 3623	Sa(s)II	FCRAO	50	Young et al. (1983)
NGC 3627	Sb(s)II.2	FCRAO	50	Young et al. (1983)
NGC 3628	Sbc	FCRAO	50	Young et al. (1983)
Virgo		FCRAO	45	Kenney and Young (1986) -- 23 galaxies
NGC 4565	Sb	BTL	100	Richmond and Knapp (1986)
NGC 4631	Sc on edge	FCRAO	45	Young (1986)
NGC 4736	RSab(s)	FCRAO	45	Garman and Young (1986)
NGC 4826	Sab(s)II	FCRAO	45	Young (1986)
NGC 5005	Sb(s)II	FCRAO	45	Young et al. (1986)
NGC 5055	Sbc(s)II-III	OSO	33	Johansson and Booth (1986)
NGC 5194/5	Sbc(s)I-II	NRAO	67	Rickard and Palmer (1981)
(M51)		FCRAO	45	Scoville and Young (1983)
		FCRAO	45	Lord and Young (1986)
		OSO	33	Rydbeck et al. (1984)
NGC 5236 (M83)	SBc(s)II	NRAO	67	Combes et al. (1978)
NGC 5457 (M101)	Sc(s)I	NRAO	67	Solomon et al. (1983)
NGC 6946	Sc(s)II	NRAO	67	Morris and Lo (1978)
		NRAO	67	Rickard and Palmer (1981)
		FCRAO	50	Young and Scoville (1982a)
		FCRAO	45	Tacconi and Young (1986)
NGC 7331	Sb(rs)I-II	FCRAO	50	Young and Scoville (1982b)
NGC 7479	SBbc(s)I-II	FCRAO	45	Young et al. (1986)

Table 1 (continued)
CO Distributions in Galaxies

Galaxy	Type[a]	Telescope[b]	Resolution (arcsec)	Reference
CO Radial Distributions[c]				
NGC 7814	S(ab)	FCRAO	50	Young (1986)
IC 342	Sc	NRAO	67	Morris and Lo (1978)
		NRAO	67	Rickard and Palmer (1981)
		FCRAO	50	Young and Scoville (1982a)
Maffei II	Sb	NRAO	67	Rickard et al. (1977)
High Resolution CO Observations[d]				
NGC 224 (M31)		NRO	15	Ichikawa et al. (1987)
		OSO	33	Boulanger et al. (1984)
		BTL	100	Ryden and Stark (1986)
NGC 3034 (M82)		NRO	15	Nakai et al. (1987)
		OVRO	7	Lo et al. (1987)
NGC 5194/5 (M51)		OVRO	7	Lo et al. (1984b)
NGC 5236 (M83)		NRO	15	Handa et al. (1987)
NGC 6946		OVRO	7	Ball et al. (1985)
IC 342		OVRO	7	Lo et al. (1984a)
		NRO	15	Hayashi et al. (1987)

[a] Galaxy type from Revised Shapley Ames Catalogue (Sandage and Tammann 1981, hereafter RSA).

[b] Key for telescopes:
BTL = Bell Telephone Laboratories
FCRAO = Five College Radio Astronomy Observatory
NRAO = National Radio Astronomy Observatory
NRO = Nobeyama Radio Observatory
OSO = Onsala Space Observatory
OVRO = Owens Valley Radio Observatory

[c] Galaxies whose major or minor axis CO radial distributions have been measured in > 5 points.

[d] Observations with resolution of better than 15 arcsec or 300 pc.

Table 2
Published Surveys of CO in Galaxies

Galaxy Class	Sample Size	No. Detected	Telescope[a]	Reference
IR Bright				
Centers	20	10	FCRAO	Young et al. (1984)
Maps	14	14	FCRAO	Young et al. (1986)
High z	15	15	FCRAO	Sanders et al. (1986)
Irregulars				
Magellanic	6	1	NRAO	Elmegreen et al. (1980)
Active	4	4	FCRAO	Young et al. (1984), Tacconi and Young (1985)
Radio Bright	21	20	FCRAO/NRAO	Sanders and Mirabel (1985)
Seyferts	9	2	NRAO/BTL	Bieging et al. (1981)
	9	0	NRAO	Wilson et al. (1979)
Spirals				
Gas-rich	29	5	NRAO	Rickard et al. (1977)
Nearby	81	5	NRAO	Rowan-Robinson et al. (1980)
	75	65	FCRAO	Young (1986)
Range of Types	19	6	BTL	Verter (1983)
SAB	23	5	NRAO	Elmegreen and Elmegreen (1982)
Sc	9	9	FCRAO	Young and Scoville (1982b)
Virgo Cluster				
Centers	25	18	FCRAO	Young et al. (1985)
Major Axis Maps	23	21	FCRAO	Kenney and Young (1986)
Total CO	47	25	BTL	Stark et al. (1986)
^{13}CO Observations				
Centers	8	5	BTL	Encrenaz et al. (1979)
Disks	6	6	NRAO	Rickard and Blitz (1985)
Disks	6	6	FCRAO	Young and Sanders (1986)

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BTL = Bell Telephone Laboratories
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2. CO AS A TRACER OF MOLECULAR HYDROGEN

2.1. Theoretical Arguments

Although molecular hydrogen is the dominant component of the interstellar medium over the inner disk of the Milky Way galaxy (Scoville and Solomon 1975; Burton et al. 1975), it is difficult to determine its abundance in cold, dense clouds. Because of its brightness and widespread distribution, CO is generally used as a tracer of the molecular hydrogen gas. Several simple arguments have been proposed to describe why the optically thick CO line can be used as a tracer of the mass of molecular clouds. Starting from the definition of the CO integrated intensity, and assuming a uniform population of molecular clouds that are virialized, Dickman, Snell, and Schloerb (1986), Young et al. (1986) and Solomon (1986) have shown that the CO luminosity is given by

$$L_{CO} = C\ T_g\ M\ \rho^{-1/2} \tag{1}$$

where M is the mass of molecular clouds in the telescope beam, T_g is the gas radiation temperature averaged over the beam, ρ is the mean gas density, and C is a constant. Similarly, the CO integrated intensity is proportional to the mass surface density of molecular clouds within the beam. This dependence of the CO luminosity on the mass of molecular clouds is precisely the justification for using CO observations to trace the distribution of H_2 in galaxies.

2.2. Empirical Arguments

There have been a number of studies in which an empirical correlation between CO integrated intensities, I_{CO}, and H_2 column densities, $N(H_2)$, has been derived (Young and Scoville 1982a; Liszt 1982; Sanders, Solomon, and Scoville 1984; Lebrun et al. 1983; Bloemen et al. 1984). The essence of such correlations is that for regions several hundred parsecs to several kiloparsecs across, the CO integrated intensity is a measure of the mean cloud properties over the region. From an analysis of ^{12}CO and visual extinction data for dark clouds along with virial theorem masses for giant molecular clouds, Young and Scoville (1982a) derived a conversion factor from CO integrated intensities to H_2 column densities of $N(H_2)/I_{CO} = (4 \pm 2)\times10^{20}\ H_2\ cm^{-2}/(K\ km\ s^{-1})$. Sanders, Solomon, and Scoville (1984) find a value for the inner galaxy conversion factor of $(3.6 \pm 1)\times10^{20}\ H_2\ cm^{-2}/(K\ km\ s^{-1})$ from ^{13}CO observations compared with visual extinction data and virial theorem masses. Finally, comparisons of the distribution of γ-rays and CO emission in the Milky Way give an independent value for the I_{CO}-$N(H_2)$ conversion factor of $2.6\times10^{20}\ H_2\ cm^{-2}/(K\ km\ s^{-1})$ (Lebrun et al. 1983; Bloemen et al. 1984).

Thus, different studies have yielded similar values for the empirical correlation between CO integrated intensities and H_2 column densities. The physical basis for such a correlation is the virial theorem, and the fact that the line width of an individual cloud is a

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measure of its mass. Throughout this work, I will use the value of $N(H_2)/I_{CO} = (4\pm2)\times10^{20}$ H_2 $cm^{-2}/(K\ km\ s^{-1})$ derived by Young and Scoville in order to estimate H_2 surface densities and masses in galaxies.

2.3. ^{13}CO Radial Distributions in Galaxies

One test of the accuracy with which the distributions of ^{12}CO emission in galaxies trace that of H_2 is to make observations of the more optically thin ^{13}CO molecule. The first ^{13}CO observations of external galaxies were made by Encrenaz et al. (1979) in 8 systems, with subsequent observations in individual galaxies by Young and Scoville (1982a; 1984), Stark and Carlson (1984), and Rydbeck et al. (1985). If we define R to be the ratio of ^{12}CO to ^{13}CO integrated intensities, then

$$R = I(^{12}CO)/I(^{13}CO). \quad (2)$$

From ^{13}CO detections of 5 galaxies, Encrenaz et al. (1979) found that R has a value of ~ 12, or twice the value typical of regions on the molecular annulus in our Galaxy (Solomon, Scoville, and Sanders 1979).

More recently, Rickard and Blitz (1985) and Young and Sanders (1986) have measured the ^{13}CO emission from the disks of nearby luminous spiral galaxies. Overall, the value of R was found to range between 6 and 20 for individual galaxies, with the Milky Way at the lower end of the range, similar to NGC 891 (see Figure 1). The most peculiar value

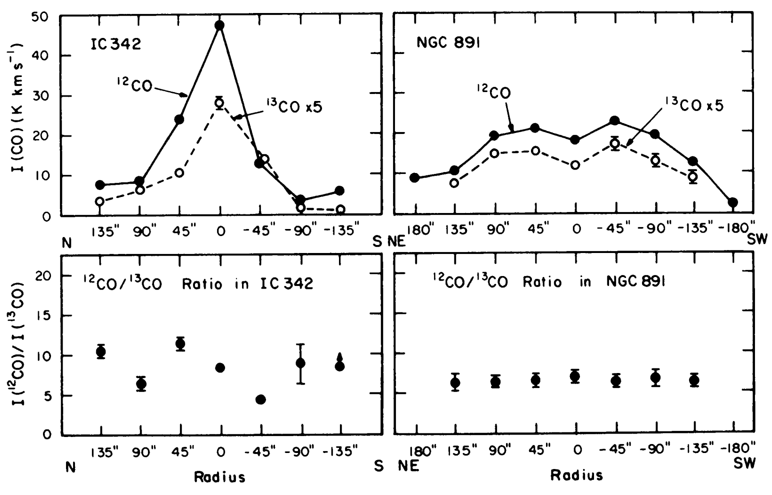


Figure 1. The upper panels illustrate the ^{12}CO and ^{13}CO distributions in the face-on Sc galaxy IC 342 (Young and Sanders 1986), and the edge-on Sb galaxy NGC 891 (Sanders and Young 1986); the solid dots represent the ^{12}CO distributions and the open circles represent the ^{13}CO distributions scaled up by a factor of 5. The center of the galaxy is plotted in the center of the panel. The lower panels show the ratio of $^{12}CO/^{13}CO$ integrated intensities at each position in each of these galaxies.

of R was found in the center of M82 (Stark and Carlson 1984; Young and Scoville 1984), where the integrated intensity ratio is greater than 20. Within individual galaxies, Rickard and Blitz (1985) and Young and Sanders (1986) found that the value of R varies by a factor of two on the scale of 1 to 2 kpc in the most nearby objects. These variations may be related to the differences in the distributions of hot and cold cloud cores found in the disk of the Milky Way (Solomon, Sanders, and Rivolo 1985).

From observations of 6 galaxies, Young and Sanders (1986) find that the shapes of the azimuthally averaged radial distributions of ^{12}CO and ^{13}CO emission are similar (see Figure 1), suggesting that the surface density distribution of H_2 is adequately traced by observations of either ^{12}CO or the weaker ^{13}CO species. In the remainder of this paper, the H_2 masses and distributions in galaxies will be inferred from ^{12}CO observations, with an adopted constant of proportionality for determining H_2 surface densities from CO integrated intensities as described above in section 2.2.

3. CO RADIAL DISTRIBUTIONS IN NEARBY SPIRAL GALAXIES

In this section, I will summarize the results of observations of the CO radial distributions in galaxies for those galaxies whose major or minor axis CO distributions have been measured in 5 or more positions.

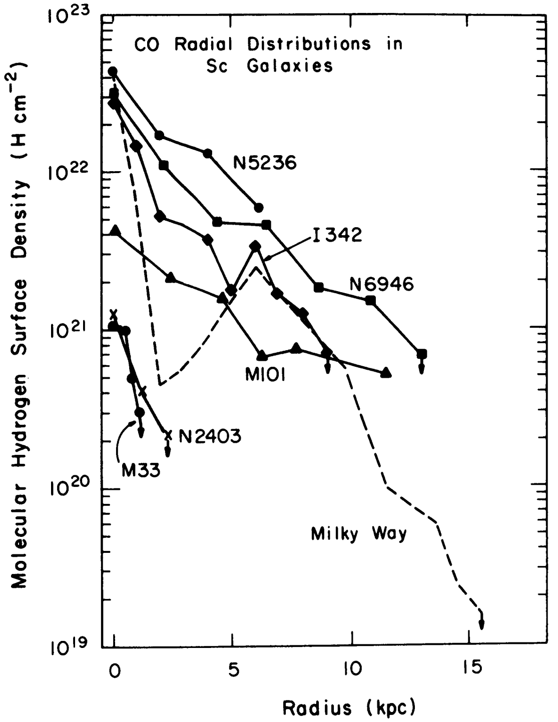
3.1. Sc Galaxies

There are 23 Sc galaxies for which the major axis CO distributions have been measured, 14 of which are in the Virgo cluster (Kenney and Young 1986), and 9 of which are non-Virgo galaxies listed in Table 1. These 9 non-Virgo galaxies --- NGC 253, NGC 598 (M33), NGC 2403, NGC 3079, NGC 4631, NGC 5236 (M83), NGC 5457 (M101), NGC 6946, and IC 342 -- are almost all more nearby than the Virgo cluster, so that the CO observations have a resolution of ~ 2.5 kpc or better (see Table 1 for references). Two of the Sc galaxies, NGC 3079 and NGC 4631, are edge on and it is therefore difficult to determine the true H_2 surface densities as a function of radius. The other 7 galaxies are sufficiently nearby or face-on that the radial CO distributions can be inferred directly from the observations.

In the face-on galaxies, the azimuthally averaged distribution of CO integrated intensities peaks in the center and decreases with radius in the disk. Figure 2 shows the CO integrated intensity distributions corrected to the plane of the galaxy (i.e. corrected for inclination) for the 6 most face-on Sc galaxies. Also shown in Figure 2 is the Milky Way CO distribution at 1 kpc resolution, which has a central peak, an absence of gas between 1 and 4 kpc, and a molecular annulus between 4 and 8 kpc (Scoville and Solomon 1975; Burton et al. 1975; Sanders, Solomon, and Scoville 1984). None of the Sc galaxies have distributions which resemble that in the Milky Way.

While the dominant feature in the Sc galaxy CO radial distributions is the central peak and intensity decrease with radius, it has been pointed out a number of times (Rickard 1982; Solomon et al. 1983; Scoville and Young 1983; Tacconi and Young 1986) that there is a scatter of a factor of two in the CO integrated intensities at a particular radius, relative to the mean value measured at that radius. This conclusion applies to all of the Sc galaxies whose disks have been fully sampled. In the Sc galaxies, this scatter has not yet been obviously correlated with spiral arm structures.

Figure 2. Radial distributions of CO integrated intensity, corrected to face-on, for 6 relatively face-on Sc galaxies (solid lines) and the Milky Way (dashed line; Sanders, Solomon, and Scoville 1984). Galaxy types and references for the CO distributions are found in Table 1.



3.2. Sb and Sbc Galaxies

The total number of Sb/Sbc galaxies whose major axis CO distributions have been determined is 19, of which 14 are non-Virgo galaxies; 4 of these 14 are classified Sbc, while the remaining 10 are type Sb (RSA). The CO morphologies of the Sb and Sbc galaxies are distinctly different from those of the Sc galaxies. In order to investigate the CO morphologies of the Sb/Sbc galaxies, it is necessary to exclude the 2 Sb/Sbc galaxies, NGC 3147 and NGC 5005, which are at distances greater than 50 Mpc (1' corresponds to 15 kpc for H_o = 50 km s^{-1} Mpc^{-1}).

Of the 12 nearby Sb/Sbc galaxies, 5 have been observed to exhibit central CO depressions. These are NGC 224 (M31; Stark 1979), NGC 891 (^{12}CO by Solomon et al. 1982, ^{13}CO and ^{12}CO by Sanders and Young 1986), NGC 2841 and NGC 7331 (Young and Scoville 1982c), and in NGC 5194/5 (M51) at 33" resolution (Rydbeck et al. 1985). Additionally, it has been suggested that NGC 1068 also has a central CO minimum (Scoville, Young, and Lucy 1983), based on a deconvolution of the CO intensity distribution with the assumption that the CO velocity field mimics that of Hα. Thus, 6 out of 12, or 50% of the intermediate type galaxies have central CO depressions.

Figure 3 illustrates the CO integrated intensity distributions for the 8 Sb/Sbc galaxies which are not edge-on; the intensities plotted have again been corrected to the plane of the galaxy. In 5 of these 8 galaxies the central CO depressions are evident. In the case of NGC 7331, the observed CO integrated intensity distribution is similar to what would be observed for the Milky Way at the distance and inclination of NGC 7331. Obviously, higher resolution CO observations may reveal central CO depressions in more of the Sb/Sbc galaxies.

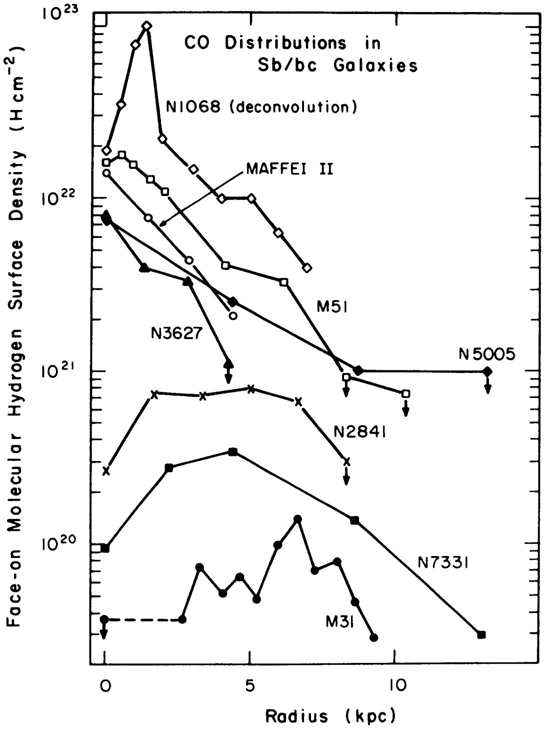


Figure 3. Radial distributions of CO integrated intensity, corrected to face-on, for 8 Sb/Sbc galaxies which are not edge-on. Galaxy types and references for the CO distributions are given in Table 1. Five of these galaxies exhibit central CO depressions.

3.3. Sa and Sab Galaxies

Major axis observations of the CO distributions in early type galaxies have been published for only 8 systems. While CO was detected in all 4 of the Virgo galaxies observed, detections in the non-Virgo galaxies were made in only 2 out of the 4 galaxies mapped. The detections were in NGC 4736 and NGC 4826, both Sab galaxies, while the nondetections were in NGC 3623 and NGC 7814. The CO radial distribution in NGC 4736 exhibits a central CO depression similar to many of the Sb/Sbc galaxies described above, while that in NGC 4826 exhibits a central peak. Clearly, more observations of the CO distributions in early type spiral galaxies are needed to address the question of the shapes of the CO radial profiles in galaxies as a function of morphological type.

3.4. Galaxies with CO Bars, and CO in Barred Spiral Galaxies

Recent high resolution observations of IC 342 and NGC 6946 using the OVRO millimeter interferometer indicate that each of these galaxies has a CO bar in the central arcminute (Lo et al. 1984; Ball et al. 1985). Optically, these galaxies do not have strong bar morphologies, but the central CO structures have distinctly elongated appearances. These observations have prompted the suggestion that the bar serves as the mechanism which feeds gas into the center of the galaxy, thus providing interstellar matter out of which large numbers of stars may form.

The best example of a barred spiral galaxy in which CO has been mapped is NGC 5236 (M83). This galaxy has strong CO emission (Combes et al. 1978; Lord 1986), and has an optical bar morphology (RC2). The fully mapped CO disk of this galaxy indicates that the CO emission is stronger along the bar rather than perpendicular to it. Thus, M83 provides an excellent example of the CO distribution following the large scale structural features in a galaxy. Certainly more studies of the molecular clouds in barred spiral galaxies will be useful in determining the roles of bars in the centers of galaxies.

3.5. The Star Formation History of an Individual Galaxy: NGC 6946

Measurement of the CO distribution in a galaxy provides not only a measure of the H_2 surface density as a function of radius, but also enables the determination of the star formation history of the galaxy through a comparison of past, present, and future sites of star formation. In the case of NGC 6946, observations have been made of Hα (DeGioia-Eastwood et al. 1984), HI (Rogstad, Shostak and Rots 1973; Tacconi and Young 1986), CO (Morris and Lo 1978; Rickard and Palmer 1981; Young and Scoville 1982a; Ball et al. 1985; Tacconi and Young 1986), radio continuum (van der Kruit, Allen and Rots 1977; Klein et al. 1982), and in the blue (Ables 1971; Elmegreen and Elmegreen 1984). The blue light traces the past sites of star formation, the Hα traces the present sites of massive star formation, the CO traces the distribution of molecular clouds or potential sites of star formation, and the HI indicates the medium out of which molecular clouds may form.

Figure 4 is a schematic illustration of NGC 6946, and indicates the regions in the galaxy in which different components are dominant. The CO bar is present in the central arcminute (Ball et al. 1985), the optical disk or inner disk is coincident with the region in which CO emission is strongest, and the HI disk extends out to a radius of 30 kpc (Rogstad, Shostak, and Rots 1973; Tacconi and Young 1986), well beyond the optical edge of the galaxy. Figure 5 shows the radial distributions of H_2, HI, Hα, blue light and radio continuum emission in NGC 6946. It is striking that all distributions show similar radial behavior except that of the atomic gas.

The fact that the CO, blue light, and Hα distributions in NGC 6946 all show similar radial behavior has important implications for the evolution of this galaxy. If the blue light from a late-type spiral galaxy is a measure of the star formation which has occurred over the last 2×10^9 years (cf. Searle, Sargent and Bagnuolo 1973), the proportionality

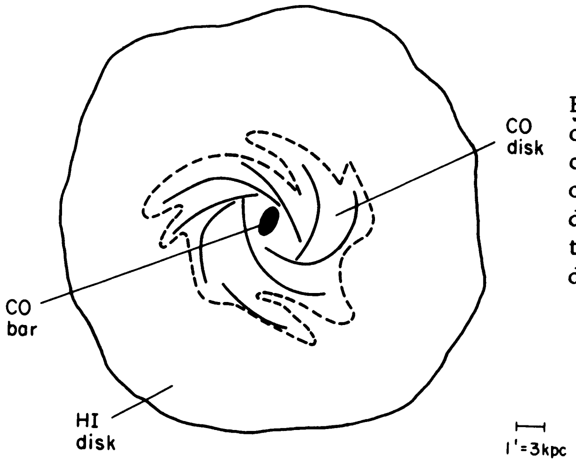


Figure 4. Schematic illustration of the Sc galaxy NGC 6946, indicating the central CO bar, the optical disk (outlined with dashes) which is coincident with the CO disk, and the outer HI disk.

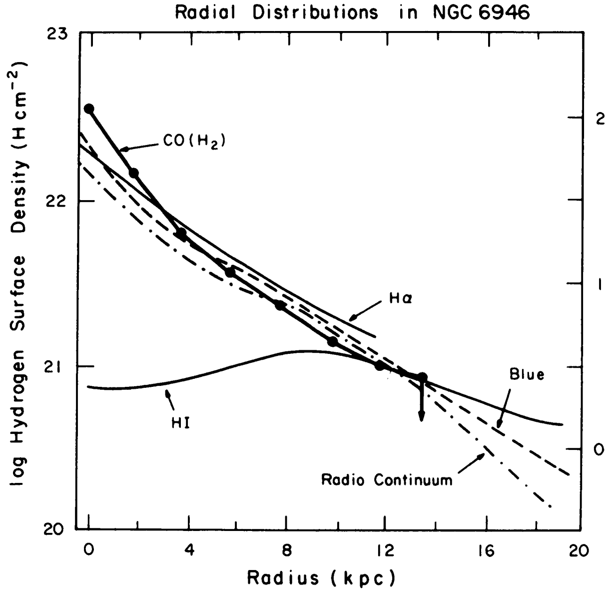


Figure 5. Comparison of the CO (H_2), HI, Hα, blue, and radio continuum radial distributions in NGC 6946 (see text for references). All intensity scales are relative except that for the HI, which is plotted relative to H_2, assuming the H_2 surface densities are derived as in §2.2.

between the CO and blue light in NGC 6946 indicates that the amount of star formation which occurs is proportional to the available supply of molecular gas (Young and Scoville 1982a). Additionally, the correspondence between the CO and Hα distributions indicates that the current massive star formation rate depends on the available supply of molecular gas as well (DeGioia-Eastwood et al. 1984). Taken together, these results suggest that the star formation efficiency is constant as a function of radius in NGC 6946.

From a comparison of the ISM surface density distributions, it is apparent that the azimuthally averaged distribution of H_2 has a central peak and decreases monotonically with radius, while the distribution of HI has a central depression, a peak at 8 kpc, and a shallow decrease out

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to 30 kpc radius. The ratio of H_2 to HI surface densities decreases from a central value of 30, to approximately 1 at a radius of 10 kpc. This behavior in the H_2 and HI surface density distributions in NGC 6946 is typical of other luminous late type spiral galaxies such as IC 342, NGC 5194/5 (M51), and NGC 5236 (M83) (cf. Rogstad and Shostak 1972; Rogstad, Lockart, and Wright 1974; Shane 1975; Combes et al. 1978; Young and Scoville 1982a; Morris and Rickard 1982; Scoville and Young 1983; Lord 1986). If the ratio of H_2 to HI surface densities is a measure of the efficiency with which molecular clouds form, the radial behavior of the H_2 to HI ratio indicates that the molecular cloud formation efficiency decreases with radius in NGC 6946 (Tacconi and Young 1986). Certainly, higher resolution observations of CO, HI and Hα are necessary to investigate the variations in the star and molecular cloud formation efficiencies in both spiral arm and interarm regions in galaxies.

Elmegreen (1986) has shown that galaxies with grand design spiral patterns and those with flocculent spiral arms both have similar Hα fluxes per unit surface area. He uses this result to argue that the density wave does not enhance star formation in galaxies, but may enhance cloud formation. However, there is no evidence for this conclusion based on observations within individual galaxies.

Following the arguments of Schmidt (1959), let us assume that the star formation rate (SFR) depends on some power n of the gas volume density ρ, or

$$SFR = c\ \rho^n \tag{3}$$

where c is a constant. From a comparison of the HI with stellar scale heights and distributions in the Milky Way, Schmidt concluded that n has a value of ~ 2. However, we can now decompose equation (3) into 2 separate processes: that of star formation from molecular clouds, and that of molecular cloud formation from atomic clouds. We then have

$$SFR = a_1\ \rho(H_2)^n = a_1\ [\sigma(H_2)/z(H_2)]^n \tag{4a}$$

and

$$CFR = a_2\ \rho(H_2)^m = a_2\ [\sigma(HI)/z(HI)]^m \tag{4b}$$

where CFR is the molecular cloud formation rate, $\rho(H_2)$, $\rho(HI)$, $\sigma(H_2)$, and $\sigma(HI)$ are the H_2 and HI volume and surface densities, respectively, and $z(H_2)$ and $z(HI)$ are the molecular and atomic gas scale heights. The correspondence between the CO, blue light, and Hα surface density distributions in NGC 6946 indicates that the exponent n has a value of 1, and that this value does not change with radius. In contrast, the decreasing H_2/HI ratio with radius indicates that the value of the exponent m decreases with radius, so that molecular cloud formation is least efficient in the outer parts of the galaxy. Tacconi and Young (1986) suggest that this may in part be due to an increase in the HI scale height and a corresponding decrease in the HI volume density in the outer parts of the galaxy. Furthermore, they suggest that the optical edges of galaxies may reflect the edges of molecular disks where the efficiency of formation of molecular clouds from atomic clouds is reduced. However, once formed, the molecular clouds in NGC 6946 appear to form stars in proportion to the available mass of H_2.

4. THE STAR FORMATION EFFICIENCY FROM GALAXY TO GALAXY

4.1. Correlation of CO and Blue Light

In order to understand the star formation histories of large samples of galaxies, it is necessary to compare the global CO luminosities of galaxies with tracers of ongoing star formation. Ideally, it would be most useful to compare the CO fluxes of galaxies with a measure of the currently forming stellar population, such as that provided by Hα emission. However, Hα data are just becoming available for large samples of galaxies, and such a comparison must await further observations. Another important measure of the past star formation which has occurred in a galaxy is provided by observations of the blue luminosities of galaxies. There are several correlations which have been found between CO and blue light, both within an individual galaxy and from galaxy to galaxy. In this section, those correlations will be presented, along with an interpretation of the results in terms of on the origin of the blue light in a galaxy.

In several high luminosity, relatively nearby and face-on late-type spiral galaxies, the exponential profiles of blue luminosity have been shown to follow the CO distributions in the disk (IC 342 and NGC 6946 -- Young and Scoville 1982a; M101 -- Solomon et al. 1983) out to radii of ~ 10 kpc. Additionally, from a comparison of the central CO and blue luminosities in a 5 kpc aperture, the blue luminosity was found to be proportional to roughly the first power of the CO luminosity in the same region for 19 late-type spiral galaxies in the Virgo cluster and in the field (Young and Scoville 1982a; Young, Scoville, and Brady 1985), or

$$L_B(5\ \text{kpc}) \quad \alpha \quad L_{CO}(5\ \text{kpc})^{0.8\pm0.2}\ . \tag{5}$$

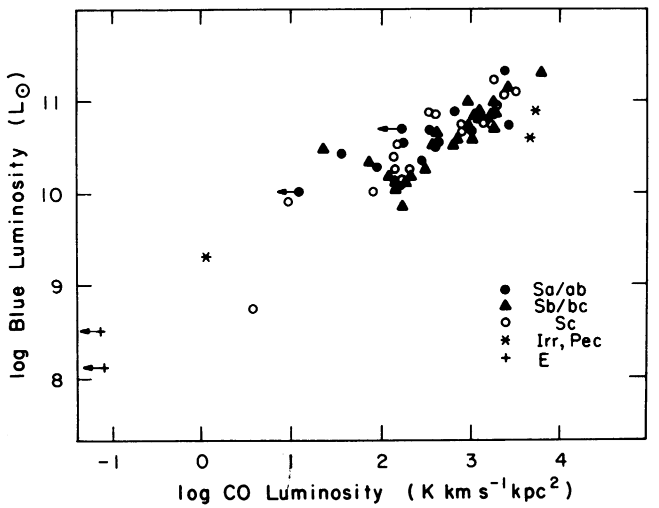
The above results apply to measurements of the CO and blue luminosities in the same region, either as a function of radius in a particular galaxy or from galaxy to galaxy.

The interpretation of these results depends upon the origin of the blue light in the disk of a galaxy. Based on the modeling study of Searle, Sargent, and Bagnuolo (1973), it is possible to compute the fraction of the blue light which originates from stars younger than a given age in the disk of a late-type spiral; approximately 50% of the blue light in the disk of a late-type spiral galaxy is produced by stars younger than ~ $2\text{x}10^9$ years old (cf. Young, Scoville, and Brady 1985). Thus, the blue light in the disk of a galaxy may be thought of as the integrated star formation which has occurred over the last several billion years, and originates from the objects classified as Disk Population I.

The correlations found between the CO and blue luminosities in individual galaxies and from galaxy to galaxy may be interpreted as follows. If the blue light indicates the integrated star formation which has occurred over ~ $2x10^9$ years, and if the CO integrated intensity is a measure of the H_2 surface density, then the fact that the blue and CO profiles are similar in individual galaxies indicates that the amount of star formation which can occur is directly proportional to the available supply of molecular gas, as concluded in §3.5. for NGC 6946. Furthermore, the one-to-one proportionality between the central 5 kpc blue and CO luminosities from galaxy to galaxy indicates that the proportionality between star formation and the molecular reservoir is present in this sample as well. Thus, within a uniform sample of Sc galaxies, where the primary difference from galaxy to galaxy is luminosity (or mass or size), the efficiency of star formation appears constant from galaxy to galaxy.

While there are no published comparisons of the total blue and total CO luminosities which cover several orders of magnitude in luminosity, in the course of preparing this review I have compiled data for the galaxies whose total CO luminosities are known. Figure 6 shows the comparison of total blue and CO luminosities for 63 galaxies in a range of environments, where different symbols are used to represent different galaxy types. While the scatter in Figure 6 is significantly larger than the scatter found in the blue-CO comparisons for the central 5 kpc in Sc galaxies, this is probably because we are no longer considering emission in the blue and in CO from the same regions or from galaxies of the same type.

Figure 6. Comparison of the total blue and total CO luminosities for 63 galaxies. Blue luminosities were computed using values of $B_T{}^o$ taken from RC2, and the distances derived from heliocentric redshifts corrected to the Local Group (assuming H_o = 50 km s^{-1} Mpc^{-1}). CO luminosities are primarily from maps for the nearby galaxies, and from single observations for a few more distant galaxies. References are listed in Table 1.



Overall, there is a general correlation in Figure 6 between the blue and CO luminosities, such that

$$L_B(\text{total}) \ \alpha \ L_{CO}(\text{total})^{0.6\pm0.2} \qquad (6)$$

for the entire range of blue luminosity. More statistics as a function of galaxy type, luminosity, and environment will be needed to determine the power relating the total blue and CO luminosities for each subclass of galaxies. Stark et al. (1986) have compared the total CO and blue luminosities for Virgo spirals and find no correlation such as that illustrated in Figure 6. However, the galaxies in their sample cover only one order of magnitude in blue luminosity, so that the trend shown in Figure 6 is not readily apparent in their data.

4.2. Correlation of Total CO and IR Luminosities

With the success of the IRAS mission, the IR flux densities and color temperatures have now been measured for galaxies over the entire sky. These observations provide an independent measure of the star formation occurring within a galaxy, since the far infrared (far-IR) emission is believed to arise from dust heated by young stars embedded in molecular clouds (cf. Rieke et al. 1980; Telesco and Harper 1980). It is the comparison of the IR luminosity, which provides a measure of the currently forming stellar population, with the CO luminosity, which traces the molecular content, that enables us to deduce the star formation efficiency as a function of radius in individual galaxies or from galaxy to galaxy.

Only a handful of CO-IR comparisons have been made in galaxies due to the small amount of IR data previously available. Smith (1982) made observations at 170 μm of the Sbc galaxy M51; Scoville and Young (1983) compared this map with their CO observations and found a one-to-one correspondence between the azimuthally averaged radial distributions of CO and far-IR emission. They concluded that there is a roughly constant yield of stars per unit molecular mass as a function of radius in the disk of M51.

Several CO-IR studies have been conducted for small samples of galaxies. From observations between 40 and 160 μm, Rickard and Harvey (1984) found a rough correlation between CO and IR fluxes in the central 1' for 30 galaxies. Young et al. (1984) searched for CO emission in 20 galaxies reported during 1983-4 in the IRAS Circulars and for which radial velocities were available in the literature. CO emission was detected in 10 of these galaxies, including Arp 220 and NGC 6240, and a rough correlation between CO and 100 μm luminosities was found, although a wide scatter was observed in this relation. Sanders and Mirabel (1985) compared the central 1' CO luminosities and 40 to 120 μm IR luminosities for a sample of galaxies chosen on the basis of their strong radio continuum emission, and found a similar correlation. All of the above CO-IR comparisons exhibit more scatter than would be expected based on a constant efficiency of star formation from galaxy to galaxy as suggested in §4.1. However, the galaxy samples investigated were too inhomogeneous to determine which parameters were primarily responsible for this scatter.

Young et al. (1986) compared the total CO luminosities for 27 galaxies with the IR luminosities measured by IRAS. The CO luminosities, L_{CO}, were determined from the major axis CO distributions for galaxies with CO maps; the IR luminosities, L_{IR}, were computed using both the 60 and 100 μm flux densities and assuming a single temperature component, following the method described in the Appendix of Lonsdale et al. (1985). Only those galaxies which were point sources at both 60 and 100 μm were included in the analysis (cf. IRAS Point Source Catalogue; Joint IRAS Science Working Group 1985). Young et al. (1986) find a general correlation between the total IR and CO luminosities from galaxy to galaxy, as noted previously by Rickard and Harvey (1984), Young et al. (1984), and Sanders and Mirabel (1985). Their data set extends over almost 4 orders of magnitude in luminosity, with a scatter of more than an order of magnitude in L_{IR} at a given L_{CO}. However, this scatter is highly correlated with dust temperature, in that there is a tight correlation between the IR and CO luminosities within each distinct range of dust temperature.

Figure 7 is a plot of the IR and CO luminosities for galaxies from several studies. IR and CO data for the central 1' in galaxies are included from the work of Rickard and Harvey (1984) and Young (1986), respectively. The total CO and IR luminosities are taken from the work of Young et al. (1984, 1986) and Sanders et al. (1986). The galaxies shown in Figure 7 are coded by dust temperature, following the analysis of Young et al. (1986), and a fit yields

$$L_{IR} \propto L_{CO}^{0.8\pm0.2} \quad . \qquad (7)$$

For each dust temperature bin, the IR luminosity is proportional to roughly the first power of the CO luminosity, independent of whether one considers the total CO and IR luminosities or the centers only.

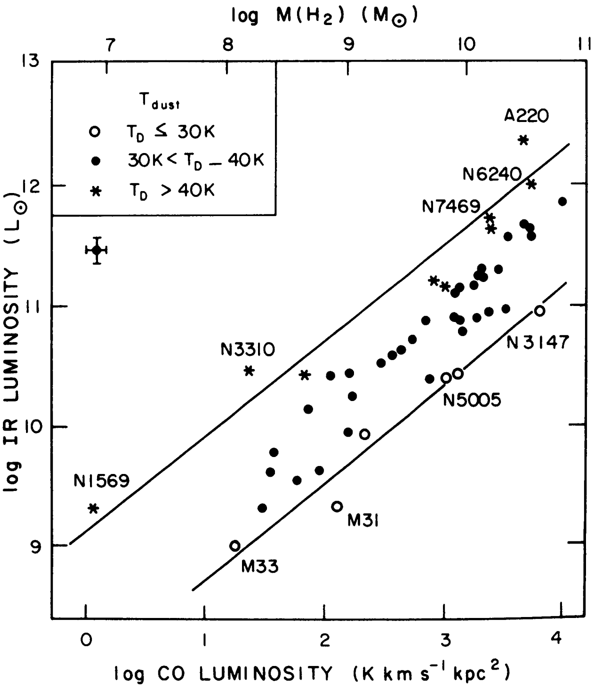


Figure 7. Comparison of the CO and IR luminosities in the same region in galaxies, where the 3 different symbols plotted represent three different ranges of dust temperature. The solid lines plotted are fits to the hottest and coldest dust temperature bins, where $L_{IR} \propto L_{CO}^{0.8\pm0.2}$. Data plotted include total CO luminosities from major axis maps and single CO observations (Young et al. 1984, 1986; Sanders et al. 1986; Young 1986). IR luminosities are from the IRAS Point Source Catalogue (JISWG 1985) for 41 galaxies which are point sources to IRAS, and from 50 and 100 μm flux densities measured in a 1' aperture for 8 galaxies (Rickard and Harvey 1984).

The data in Figure 7 can alternatively be illustrated as in Figure 8, where the ratio of L_{IR}/L_{CO} for each galaxy is plotted against the ratio of 60/100 μm flux densities, or the dust temperature. The ratio of the IR/CO luminosities is observed to depend on roughly the fourth power of the dust temperature, which is what one expects if the infrared emission is thermal emission related to dust in molecular clouds. This is further emphasized by the fact that Young et al. (1986) find no correlation of the IR luminosities with HI masses.

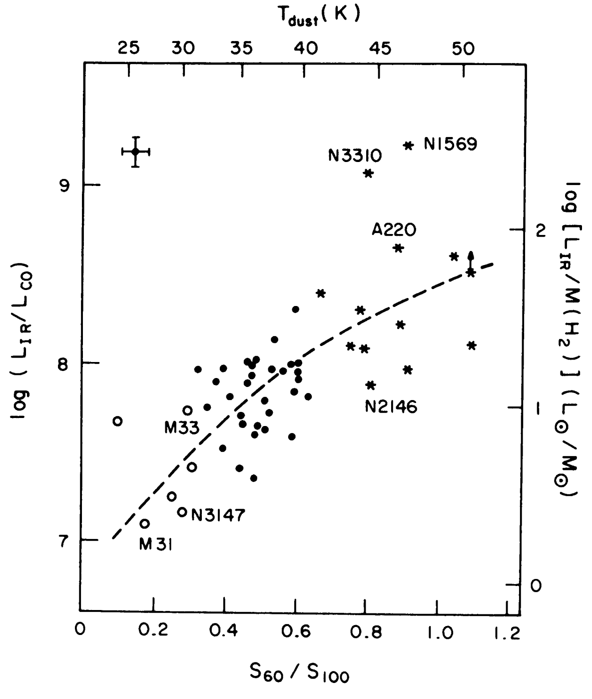


Figure 8. Ratio of IR to CO luminosities versus the ratio of 60/100 μm flux densities for all of the galaxies plotted in Figure 7. The dust temperatures indicated at the top of the figure were derived from the ratio of 60/100 μm flux densities, assuming a λ^{-1} emissivity law. The dashed line superposed on the data is not a fit, but represents a T^4 dependence of the L_{IR}/L_{CO} ratio, which is what one expects if the IR luminosity has a T^5 dependence, and the CO luminosity has a T^1 dependence (cf. equation (1)). The different symbols represent the same three different dust temperature bins as in Figure 7. The typical 1σ uncertainty is indicated in the upper left corner.

Young et al. (1986) interpret the ratio L_{IR}/L_{CO} as the reradiated stellar luminosity per unit molecular mass, or the galaxy-wide star formation efficiency (SFE). Thus, the SFE varies by almost 2 orders of magnitude from one galaxy to another, with higher SFEs in galaxies with higher dust temperatures. Furthermore, the galaxies previously identified as mergers (cf. Joseph and Wright 1985) which are common to the study of Young et al. (1984; 1986) -- Arp 220, NGC 6240, and NGC 3310 -- are among the galaxies with the highest SFEs. They suggest that efficient star formation is responsible for the high dust temperatures observed, through the formation of more stars per unit molecular mass. Thus, this study indicates that the interacting galaxies which are luminous in the IR and therefore have high rates of star formation (Lonsdale, Persson, and Matthews 1984) also have high efficiencies of star formation. However, even if the rate of star formation is low, as for the merging galaxy NGC 3310, the efficiency of using the molecular gas in that system is high as well.

Additionally, Young et al. (1986) find that the dust mass is well correlated with the molecular gas mass from galaxy to galaxy even though IRAS is only sensitive to that fraction of the dust which is warmer than 25 K and emitting at 100 μm. If the gas to dust ratios in the external galaxies are the same as that in the Milky Way, we are observing as little as 20% of the dust mass with IRAS. However, due to the strong temperature dependence of the IR luminosity, IRAS is sensitive to the majority of the dust luminosity in a galaxy.

Sanders et al. (1986) have recently surveyed CO emission in 15 high luminosity IRAS galaxies. They have detected CO in a close interacting pair with a redshift of 0.052, the CO detection with the highest redshift thus far. They find that the galaxies with the highest IR luminosities also have high efficiencies of star formation, comparable to the efficiencies observed in the nearby galaxies NGC 253 and M82. They also point out that the systems with the highest H_2 masses and highest star formation efficiencies are mergers or close galaxy pairs.

Thus, one of the most important results of the CO-IR comparisons is the conclusion that the efficiency of star formation is higher for galaxies undergoing interactions. This result indicates that galaxy dynamics are important in determining the evolution of a galaxy, and that star formation does depend on global factors as well as on the available supply of molecular gas. How is this result consistent with the conclusion (cf. §4.1.) that the star formation efficiency is constant from galaxy to galaxy for late-type spiral galaxies ? The answer is probably that IRAS has pinpointed the merging galaxies and galaxies which are luminous in the IR. Without these galaxies, the range in observed star formation efficiencies would be a factor of 10, rather than a factor of 100. The blue-CO luminosity comparisons did not include the galaxies in these extreme environments, and the conclusion of a constant star formation efficiency from galaxy to galaxy applies primarily to late-type spiral galaxies which are not mergers. Thus, while IRAS observations have selected those galaxies with high rates of star formation, the combination of IRAS and CO data in galaxies has indicated those galaxies with high efficiencies of star formation. It is the understanding of how merging galaxies produce high efficiencies of star formation which will be an important step in understanding the evolution of galaxies.

4.3. Gas Depletion Timescales

Assuming that the observed IR and blue luminosities are produced primarily by O, B, and A stars, one can estimate the inferred global rates of star formation in galaxies. Assuming that early type stars produce energy using the CNO cycle, and that they process 13% of their mass while on the main sequence, Scoville and Young (1983) have shown that the star formation rates are given by

$$\dot{M}_{O,B,A} = 7.7\mathrm{x}10^{-11}\ L_{tot}/L_{o} \qquad (8)$$

where L_{tot} is the sum of the IR and blue luminosities, and $\dot{M}_{O,B,A}$ is in

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$M_\odot$ yr^{-1}. Figure 9 is a plot of the total luminosities (L_{IR} + L_B) and total ISM gas masses (H_2 + HI) for the sample of galaxies studied by Young et al. (1986). Also shown are lines which represent the times in which the present gas masses will be depleted at the current rates of star formation implied by the total luminosities.

For the galaxies illustrated in Figure 9, the timescales for gas depletion range from 10^8 years to $6x10^9$ years, with a mean value of $2x10^9$ years for this sample. However, the galaxies with the highest star formation efficiencies (as discussed in §4.2.) and highest dust temperatures have an average gas depletion timescale of $1x10^9$ years, while those with lower efficiencies and dust temperatures have an average gas depletion timescale of $4x10^9$ years. Certainly, if the episodes of intense star formation in merging galaxies are relatively short-lived compared to 10^8 years, then the gas depletion timescales for these objects could in fact be considerably longer.

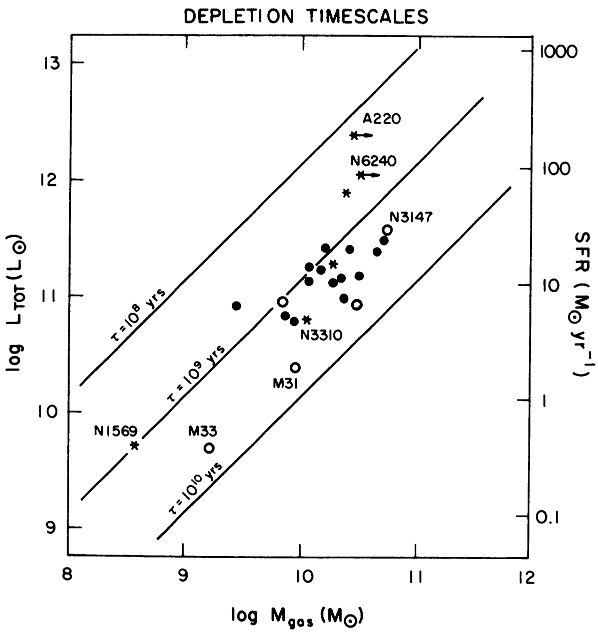

Figure 9. Comparison of the total luminosity (L_{IR} + L_B) with the gas mass in the interstellar medium (H_2 + HI) for the galaxies studied by Young et al. (1986). For both Arp 220 and NGC 6240, there is no measure of the HI mass due to the strong HI absorption seen toward the centers of the galaxies; the gas masses for these galaxies are lower limits. Assuming that the star formation rates are given by equation 8, the ISM gas masses will be depleted in times indicated on the solid lines.

5. THE VIRGO CLUSTER AND THE EFFECT OF ENVIRONMENT ON STAR FORMATION

In an effort to understand the effect of environment on star formation for nearby galaxies, there have been several CO studies of the galaxies in the Virgo cluster (Young, Scoville, and Brady 1985; Kenney and Young 1986; Stark et al. 1986). The Virgo cluster environment is important because it appears to be altering the atomic gas content of some of the member galaxies (cf. Giovanelli and Haynes 1983). Additionally, the star formation rates of Virgo spiral galaxies seem to have been reduced (Kennicutt 1983). Therefore, the Virgo cluster provides a unique environment for investigating the histories of star formation and molecular cloud formation in galaxies.

HI observations of large samples of galaxies indicate that the atomic gas content of spiral galaxies in the Virgo cluster is lower by a factor of 2 in the mean, with some galaxies deficient by more than a factor of 10, based on comparisons with isolated galaxies of the same type and optical size (cf. Haynes, Giovanelli, and Chincarini 1984). The currently favored explanation for the HI deficiency is stripping of the HI as the galaxies move through the intracluster medium. Recent maps of the HI disks of Virgo spirals indicate that the HI radial extents are reduced in the HI deficient galaxies (Giovanelli and Haynes 1983; van Gorkom and Kotanyi 1985; Warmels 1985), and that therefore, the stripping occurs primarily in the outer parts of the disk. CO observations of galaxies in the Virgo cluster are of interest to determine whether the molecular gas is stripped as well.

The two CO studies of Virgo cluster spirals which involve mapping of the CO emission are those of Kenney and Young (1986), in which the major axis CO distributions were mapped in 23 Virgo spirals, and Stark et al. (1986), in which 47 galaxies were observed in 1 to 5 points. Kenney and Young (1986) have shown that the ratio of H_2/HI masses is lower in the HI-normal galaxies and higher in the HI-deficient galaxies, consistent with stripping of the HI and not the CO. Additionally, they find that the ratio of CO diameters to HI diameters decreases with distance from M87 (see Figure 10), providing further evidence for the conclusion that only HI is stripped from the galactic disks. The observations of Stark et al. in a larger sample of galaxies also indicate that the CO is probably not stripped from the disks of the Virgo cluster spiral galaxies.

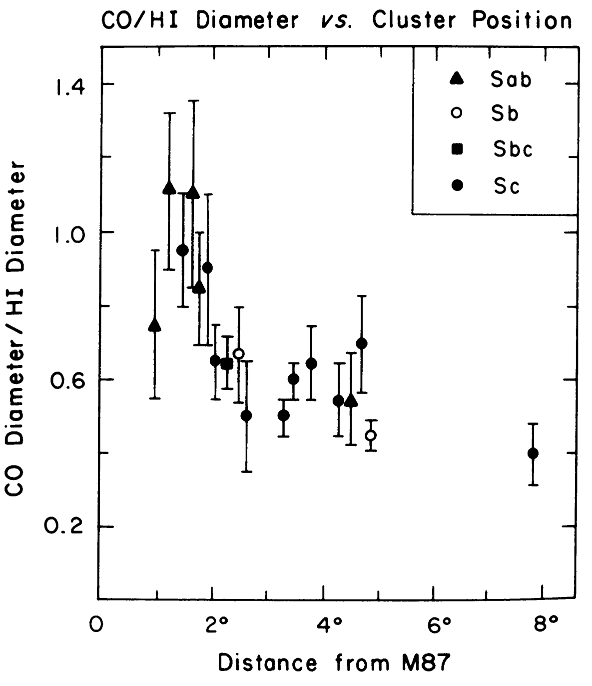

Figure 10. The ratio of CO/HI diameters for galaxies in the Virgo cluster versus angular distance from the cluster center (M87) (Kenney and Young 1986). Different symbols are plotted for different galaxy types, due to the presence of morphological segregation in the cluster. The galaxies with the largest ratios of CO/HI diameter are those with the smallest HI extents; while the HI appears to have been stripped, this does not appear to be the case for the CO.

Several additional questions at present remain unanswered regarding the star formation and molecular cloud formation histories of Virgo cluster spirals. First, is HI stripped in the inner disks where the CO is present ? If, in fact, the HI is stripped in the inner disks and the CO has not responded to the atomic gas removal, then this implies a long lifetime for the molecular phase of the ISM in the Virgo galaxies (Kenney and Young 1985, 1986; Stark et al. 1986). Estimates of the molecular phase lifetime, based on the assumption that the HI is stripped in the inner disk while the CO is normal, range from several times 10^8 years to 10^9 years.

A second question which is unanswered relates to the Hα emission from the Virgo galaxies. If the CO is not stripped, then why are the Hα properties of Virgo Sc galaxies different from those in the field (cf. Kennicutt 1983) ? This could reflect any of several possibilities. First, it is possible that some of the Hα emission from the field galaxies arises in the outer disk where it is difficult to detect CO. In the outer disks of the Virgo galaxies where the HI has been stripped, subsequent molecular cloud formation (and the consequent star formation) has been truncated. This could explain the lower Hα fluxes for the Virgo galaxies. Alternatively, it is possible that the molecular cloud size distribution in the Virgo spiral galaxies has been altered as a result of the HI stripping. If the IMF depends on the cloud size distribution, less Hα emission could result. Answers to both of these questions await more detailed observations of the Virgo galaxies at several wavelengths.

Another question which arises is whether the Virgo galaxies have unusual ratios of molecular to atomic gas mass compared with non-Virgo galaxies. At the present time, there is not an appropriate control sample with which to compare the Virgo galaxies; however, it is still interesting to compare the range of observed H_2/HI mass ratios for Virgo and non-Virgo galaxies to investigate any possible differences. Figure 11 shows the ratio of H_2 to HI masses [$M(H_2)/M(HI)$] as a function of

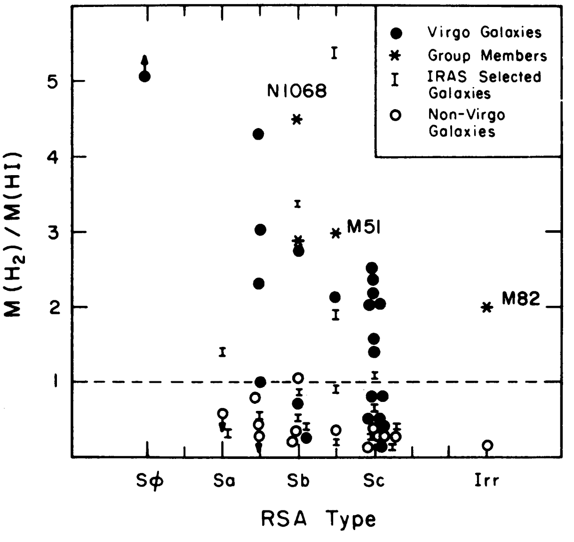

Figure 11. Ratio of H_2/HI masses for 56 galaxies in which CO maps have been made (see Table 1) and for which HI masses were available in the literature (see references in Young 1986). The dashed line indicates where the H_2 mass is equal to the HI mass, as is the case for 34 galaxies. The 22 galaxies with more mass in molecular than atomic clouds include HI deficient Virgo galaxies, galaxies in small groups, and several IRAS selected galaxies. Not all group members are labeled as such on this plot.

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galaxy type for 56 galaxies for which the total CO and HI masses are known (see references in Young 1986). Of these 56 galaxies, $M(H_2)/M(HI) > 1$ in 22, and $M(H_2)/M(HI) < 1$ in the remaining 34. Of the galaxies with more molecular then atomic gas, 13 are in Virgo (and nearly all are HI-deficient), 4 are in small groups (NGC 1068, NGC 3627, M51, and M82), and 5 are IRAS-selected galaxies. In contrast, the 34 galaxies with less overall molecular than atomic gas include 9 Virgo galaxies, most of which are HI-normal, and other so-called "normal" or non-interacting galaxies, along with some galaxies in groups. Figure 11 illustrates that there are probably several ways for a galaxy to attain a large value for the H_2/HI mass ratio. The HI can be removed as in Virgo, in which case the quantity of H_2 is not itself enhanced, or there can be unusual conversion of atomic to molecular gas, as may be the case for the galaxies interacting in small groups and for the Seyfert galaxy, NGC 1068. However, the more "normal" galaxies appear to have more atomic than molecular gas. It will certainly be interesting to see the results of a similar comparison when 500 galaxies have been observed in CO.

6. IRREGULAR GALAXIES

While irregular galaxies may not be remarkable for either their masses or their sizes, they exhibit abundant evidence for present day star formation (cf. Hunter 1982; Hunter, Gallagher, and Rautencranz 1982), and are of interest in their own right as well as in relation to the star formation process occurring in spiral galaxies. Several CO studies of irregular galaxies have been conducted (Elmegreen, Elmegreen, and Morris 1980; Young, Gallagher, and Hunter 1984; Tacconi and Young 1985). While the number of irregular galaxies in which CO has been detected is small, all of the published studies indicate the same general feature of the CO content of irregular galaxies -- they have very little CO relative to their optical and IR luminosities.

One irregular galaxy, NGC 1569, was included in the CO-IR comparison in Figures 7 and 8. It stands out in having the highest ratio of IR/CO luminosities of any of the galaxies in the sample of Young _et al._ (1986). This high IR luminosity relative to the supply of molecular gas is suggestive of a high efficiency of star formation, a conclusion which is further supported by a high Hα/CO ratio. This high efficiency of star formation in a small galaxy may be attributable to a galaxy-wide burst of star formation. In the stochastic star formation picture of Gerola, Seiden, and Schulman (1980), galaxy-wide star formation bursts are most likely to occur in the smaller galaxies. It is possible that when averaged over the lifetime of the galaxy, the mean star formation efficiency would be somewhat lower. While it is not possible to average the star formation efficiency over time for a single galaxy, observations of a sample of irregular galaxies (including active as well as inactive galaxies) are needed to determine the full range of star formation efficiencies and star formation histories in galaxies of this type.

7. CONCLUSIONS

Studies of the molecular content of galaxies are of crucial importance for understanding the evolution of galaxies, both through the formation of stars from molecular clouds, and in understanding the relationship between the molecular and atomic components of the ISM. As more and more galaxies are observed, and more statistics on CO in galaxies are obtained, our understanding of the star formation histories of galaxies can only increase.

While we may not be able to envision the most interesting questions which will be asked in 5 years, there are a number of questions which now lie at the heart of studies of the evolution of galaxies and the histories of star formation. Some of these are listed below, in the hope that within the next few years the answers will be learned.

1) Why are there CO peaks in the centers of late-type spiral galaxies which have central HI depressions ? Are bars present in the centers of all galaxies which are luminous in CO ? Do barred spiral galaxies exhibit high ratios of H_2/HI surface densities in the vicinity of the bar ?

2) Is the star formation efficiency higher in spiral arm regions of galaxies than in inner arm regions ? Is the molecular cloud formation efficiency higher in spiral arms than in inner arm regions ? Do flocculent galaxies have lower star formation efficiencies than grand design spiral galaxies ?

3) Do merging and interacting galaxies have high star formation efficiencies at every location, or is the SFE highest in the center ? Are most galaxies which have high values of the H_2/HI mass ratio found in disturbed environments or interacting systems ? Do all galaxies go through phases where the relative amounts of mass in atomic and molecular forms vary ?

4) Does the star formation efficiency in low luminosity galaxies show different behavior than that in high luminosity galaxies ? Does it correlate more strongly with the total ISM mass than with the mass of H_2 alone ? Does it depend on the metallicity ?

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T. Stark: I disagree so strenuously with so many of your conclusions that I hardly know where to begin.

J. Young: Well, please do.

T. Stark: First, IRAS 60 and 100 μm bands are sensitive to temperatures that are higher than the mean temperature of galactic molecular clouds, and the flux is therefore extremely sensitive to temperature increases due to a variety of possible causes. I see no reason to call this particular observable divided by the CO luminosity the "star formation efficiency." For example, if you apply this measure of the "star formation efficiency" to the inner 4 kpc of M31, you get an enormous value in a region where very little star formation actually occurs.

J. Young: In answer to this first question, I agree completely that there are a number of sources of IR emission in a galaxy. If the IR luminosity in different galaxies were dominated by random contributions from different dust components (dust in H_2 clouds in some cases, and dust in circumstellar shells or HI clouds in other cases, for example), then we would not expect to see any correlation between the IR and CO luminosities. The fact that such a correlation is present is evidence that the IR emission is from dust in molecular clouds. If the dust is heated by stars forming in the molecular clouds, then the luminosity of the dust measured by IRAS is a measure of the luminosity in young stars. With regard to M31, you are completely correct that the center of the galaxy would have a very high ratio of IR/CO luminosity, when very little star formation occurs there. I would argue that as a global measure for an entire galaxy, the IR/CO luminosity ratio is a measure of the star formation efficiency. I also stated in my talk that this IR emission is extremely sensitive to the temperature of the dust. It is this sensitivity which enables the use of IRAS data, which detects the emission from 40 to 120 μm, to infer the total IR luminosity. The reason for this is as follows: suppose that only 50% of the dust mass in a galaxy is heated to 30 K, and that the other 50% is at 15 K. Because of the T^5 dependence of the IR luminosity (assuming a λ^{-1} emissivity law), the warmer 50% of the dust will emit 97% of the total IR luminosity.

T. Stark: Secondly, in the Bell Laboratories observations of 47 Virgo galaxies, we find essentially no correlation between CO luminosity and blue light, either globally or in radial distribution. Most of the CO is more centrally condensed that the blue light.

J. Young: With regard to the CO and blue light distributions in individual galaxies, I am aware of only three Virgo galaxies for which the blue luminosity profiles have been measured. In NGC 4303, Jeff Kenney and I found that the CO and blue light distributions were similar (Kenney and Young 1985). I do not believe that your observations can address this issue, since you have only two radial observations along the major axis with which to compare the blue light distributions. And for the global CO and blue light comparison, I believe that your data do not extend over a large enough range of blue luminosity to see the correlation I have presented.

T. Stark: Third, no CO deficiency in Virgo galaxies does not imply long cloud lifetimes, it implies long molecular lifetimes. In other words, a given proton spends a long time in an H_2 molecule before being converted to HI, although that H_2 molecule may cycle between small and large clouds. I have other comments, but must yield the time to others.

J. Young: Lastly, I agree completely that the CO normalcy in Virgo spirals may indicate a long lifetime of the molecular phase -- this was first pointed out by Kenney and myself (1985, 1986) and more recently by you (Stark et al. 1986). However, the critical test has not yet been made. HI must be shown to be deficient in the same region where CO is detected to be normal in order to conclude that the molecular phase lifetimes are long.

F. Mirabel: Is there any indication that the Milky Way has a greater star formation rate than M31 ? And do you take into account self-absorption and absorption against the radio continuum in your estimation of the HI masses ?

J. Young: From the infrared luminosity alone, the Milky Way is ~ 5 times more luminous than M31, but it also has more CO. The resulting ratios of IR luminosity to H_2 mass, or the star formation efficiencies, are similar. The HI data I have used are taken from the literature, and only include the corrections which other authors have applied.

M. Peimbert: There is a metallicity gradient present in most spiral galaxies. In simple models of galactic chemical evolution, an increase of metallicity is expected when the gas mass fraction diminishes. Have you looked at the gas mass fraction as a function of distance to the center of NGC 6946 and to possible models of galactic chemical evolution ? (It seems to me from your NGC 6946 figure that M_{gas}/M_* is constant with radius; if this is the case it would be difficult to explain an abundance gradient with a simple model of galactic chemical evolution).

J. Young: In NGC 6946, McCall (1984) measures a very small change in the [O/H] ratio with radius. Between radii of ~ 3 and 11 kpc, the metallicity drops by only a factor of ~ 1.4. If the ratio of mass in gas to stars is constant in NGC 6946, this is consistent with the conclusion that the star formation efficiency is constant with radius and with the resultant small metallicity gradient.

M. Iye: You argued that cloud formation is a global process since the cloud formation rate is a decreasing function of r. Dr. Elmegreen argued yesterday that the star formation is not triggered by density waves. Do you agree with him ? What kind of global process do you have in mind as the cloud formation process ?

J. Young: Density wave triggering. I disagree with Bruce's conclusion that star formation is not triggered by density waves because I do not believe the data he presented justify such a conclusion. He presented a global comparison of Hα flux per unit area in a large number of galaxies. He then concluded, from the global similarities in the star formation rates per unit area in flocculent and grand design spirals, that there are no local effects of density waves on star formation. To look for these local effects, it will be necessary to study individual galaxies in detail rather than investigating the global properties of large samples of galaxies.

M. Kutner: I would like to inject a cautionary note on the use of I_{CO} as a mass tracer with a constant conversion factor.

1) I think that Rickard and Blitz draw the opposite conclusion from what you are quoting.

2) In the work that Leung and I have published, we find at least a linear temperature dependence in $N(H_2)/I(CO)$ and $N(H_2)/I(^{13}CO)$. Therefore, even if CO and ^{13}CO distributions agree, they may be tracing temperature, not just mass. This would be a natural explanation for the CO following the Hα, since gas with heat sources will be more luminous per unit mass.

J. Young: With regard to Rickard and Blitz, they measured a lower mean value for the ratios of $^{12}CO/^{13}CO$ integrated intensities in 4 galaxies. They did not make precisely the same measurements that Dave Sanders and I made (that is, they chose to sample completely in azimuth rather than determine the radial distribution), and the origin of the differences still needs to be resolved. As I have demonstrated (see equation 1), the CO luminosity is a tracer of H_2 mass and gas temperature. At the present time, however, there are no measures of the radial variation in the mean molecular gas temperature in external galaxies, and in the absence of such data, the best approximation is to assume a constant conversion factor. To get an indication of possible radial temperature gradients, I have used IRAS data to determine the dust temperature as a function of radius in a number of galaxies. The largest variation I have found is a decrease of a factor of 1.5 to 2 in the dust temperature over the entire disk of a galaxy. If the gas temperature variations are similar, it may be possible to explain a small part (factor of 2) of the CO radial distributions this way, but in NGC 6946 the CO surface brightness decreases by a factor of 30 over the detectable disk, and most of this is probably due to the molecular hydrogen surface density.