CO Observations of Nearby Galaxies and the Efficiency of Star Formation

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ABSTRACT. We have observed the CO distributions and total molecular content of 160 galaxies using the 14 meter millimeter telescope of the FCRAO (HPBW = 45"). For the luminous, relatively face-on Sc galaxies, the azimuthally averaged CO distributions are centrally peaked, while for the Sb and Sa galaxies the CO distributions often exhibit central CO holes up to 5 kpc across. None of the Sc galaxies have CO distributions which resemble that in the Milky Way.

The shapes of the azimuthally averaged CO distributions in the face-on Sc galaxies are similar to those observed in Hα, blue light, and radio continuum, and markedly different from the flat extended distributions of atomic gas. The relative constancy of the Hα/CO ratio as a function of radius in NGC 6946 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 contrast, the spiral arm structures in M51 appear to be regions of enhanced star formation efficiency; we find that the Hα/CO ratio (at 45" resolution) is a factor of 2 higher on the arms than between the arms in M51.

We find a general correlation between total CO and IR luminosities in galaxies, as noted previously (Rickard and Harvey 1984; Young et al. 1984; Sanders and Mirabel 1985; Young et al. 1986a). The scatter in this relation is highly correlated with dust temperature, in that there is a tight correlation between IR and CO luminosities within 3 distinct ranges of dust temperature. We find no strong correlation of IR luminosities with HI masses, and thereby conclude that the infrared emission is more directly tied to the molecular content of galaxies.

The ratio of IR/CO luminosities increases roughly as T^4, consistent with the IR emission of thermal origin at the characteristic temperature given by the dust temperature. If the IR/CO luminosity ratio is a measure of the emergent stellar luminosity per unit molecular mass, or the star formation efficiency (SFE), we find that this efficiency varies over two orders of magnitude from galaxy to galaxy. We suggest that galaxies which have high SFEs produce more stars per unit molecular mass, thereby increasing the average temperature of the dust in star forming regions. Irregular galaxies and galaxies previously identified as mergers have the highest observed star formation efficiencies. For the mergers, we find evidence that the IR/CO luminosity ratio increases with the merger age estimated by Joseph and Wright (1985).

Lastly, we find that isolated galaxies have a mean value of $L_{IR}/M(H_2)$ of 11 L_o/M_o, while the ratio for the interacting galaxies in our sample is 44 L_o/M_o. Clearly, the environment has a strong influence on the efficiency of star formation in galaxies.

Carol J. Lonsdale Persson (Editor)
Star Formation in Galaxies

1. INTRODUCTION

The evolution of a galaxy must depend in part on the distribution and abundance of molecular clouds within it, since stars form in molecular clouds. Furthermore, the evolution of a galaxy can be described in terms of the star formation history of the disk: 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, and the distribution of molecular clouds indicates the underlying potential for star 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 earliest detection of molecular clouds in external galaxies (Rickard et al. 1975), there have been a large number of investigations of CO in galaxies, including both detailed studies of nearby galaxies, and comparisons of the global properties of selected samples of galaxies. These observations have been used to determine (1) the shapes of the CO distributions in galaxies and the dependence of this shape on galaxy type, (2) the relationship between the molecular content and the star formation rate within galaxies and from galaxy to galaxy, and (3) the relationship between the molecular and atomic gas distributions and masses in galaxies. In this paper, I shall use both studies of individual galaxies as well as large samples of objects to address the question of the star formation efficiency in galaxies.

The data upon which this discussion is based consist of CO observations at 2.6 mm (115 GHz) of 160 galaxies made primarily by myself, J. Kenney, L. Tacconi, and S. Lord using the 14 meter millimeter telescope of the Five College Radio Astronomy Observatory (HPBW = 45", for references see Young 1986). Of these 160 galaxies, CO was detected in 2/3, and mapped along the major axis in more than half. While the galaxies we have surveyed do not constitute a complete sample, since they were chosen to span a wide range of luminosity, morphological type, and environment, most of the objects are brighter than 10 Jy at 100 μm.

Also, I shall not use the common terms "normal" galaxy or "starburst" galaxy. Rather, in order to characterize the present state of star formation in a galaxy, I shall refer to the star formation rate per unit molecular gas mass, or the star formation efficiency (SFE). In this context, "starburst" galaxies are ones with high SFEs, and "normal" galaxies are galaxies with low SFEs; whether, in fact, a low SFE turns out to be the norm for galaxies remains to be determined.

2. CO RADIAL DISTRIBUTIONS IN NEARBY SPIRAL GALAXIES

In this section, I shall describe the CO radial distributions in the galaxies more nearby than the Virgo cluster (45" corresponds to 4.4 kpc for D = 20 Mpc) and for which we have made more than 5 CO measurements along the major axis. Throughout this paper, I will assume that H_2 surface densities are directly proportional to integrated intensities of CO emission (cf. Young and Scoville 1982a; Dickman, Snell and Schloerb 1986), with a constant of proportionality given by $N(H_2)/I_{CO} = 4 \times 10^{20}\ \mathrm{cm}^{-2}/(\mathrm{K\ km\ s}^{-1})$.

2.1. Sc Galaxies

The CO radial distributions have been measured in 7 relatively face-on nearby Sc galaxies -- NGC 598 (M33) and NGC 2403 (Young 1986), NGC 5194 (M51) (Scoville and Young 1983), NGC 5236 (M83) (Combes et al. 1978; Lord, Strom and Young 1986, this conference), NGC 5457 (M101) (Solomon et al. 1983), NGC 6946 and IC 342 (Young and Scoville 1982a). Figure 1 shows the CO radial distributions corrected to the plane of the galaxy (i.e. corrected for inclination) for 6 of the galaxies listed above. In each galaxy, the azimuthally averaged distribution of CO integrated intensities peaks in the center and decreases with radius in the disk. Also shown in Figure 1 is the Milky Way CO distribution at 1 kpc resolution, indicating the central peak, absence of gas between 1 and 4 kpc, and molecular annulus between 4 and 8 kpc (cf. 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.

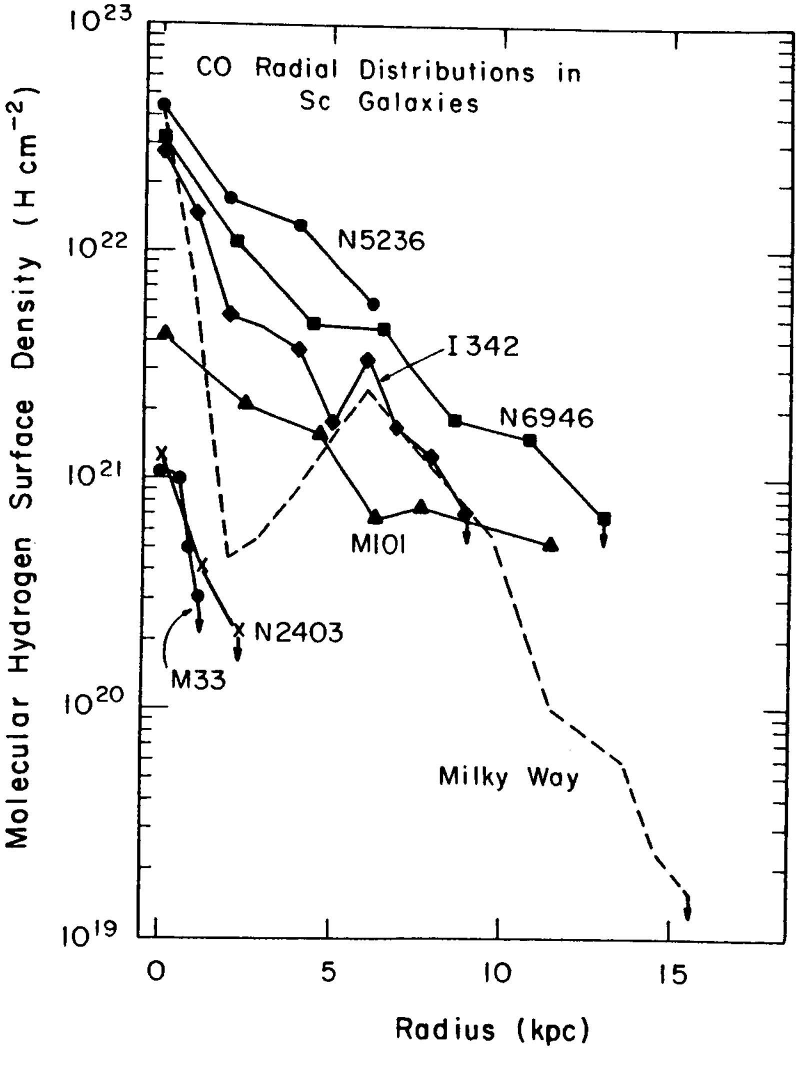

Figure 1. CO radial distributions corrected to the plane of the galaxy in 6 Sc/Scd galaxies (Young and Scoville 1982a; Solomon et al. 1983; Young 1986; Lord, Strom, and Young 1986) at 45" resolution. Also shown (dashed line) is the distribution found for the Milky Way (Sanders, Solomon, and Scoville 1984).

It is clear from Figure 1 that there is a wide range of molecular hydrogen surface densities found in Sc galaxies: the high luminosity galaxies M83 and NGC 6946 have the highest H_2 surface densities at all radii, while the low luminosity galaxies M33 and NGC 2403 have the lowest H_2 surface densities. In contrast, the atomic gas distributions in these same galaxies show little variation from one object to the next. This is illustrated in Figure 2, which compares the H_2 and HI radial distributions in high and low luminosity Scd galaxies (HI from Rogstad and Shostak 1972; CO from Young and Scoville 1982a and Young 1986). Although the low luminosity galaxies are small, so their HI disks have a small radial entent, the azimuthally averaged HI surface densities reach the same peak value of ~ 10^{21} cm^{-2} as the high luminosity galaxies, in addition to exhibiting central HI holes. Thus, the ratio of H_2/HI surface densities is highest in the centers of the Sc galaxies, and is lower in the disks. Furthermore, the inner disks of the high luminosity galaxies have higher molecular-to-atomic gas ratios than the low luminosity galaxies.

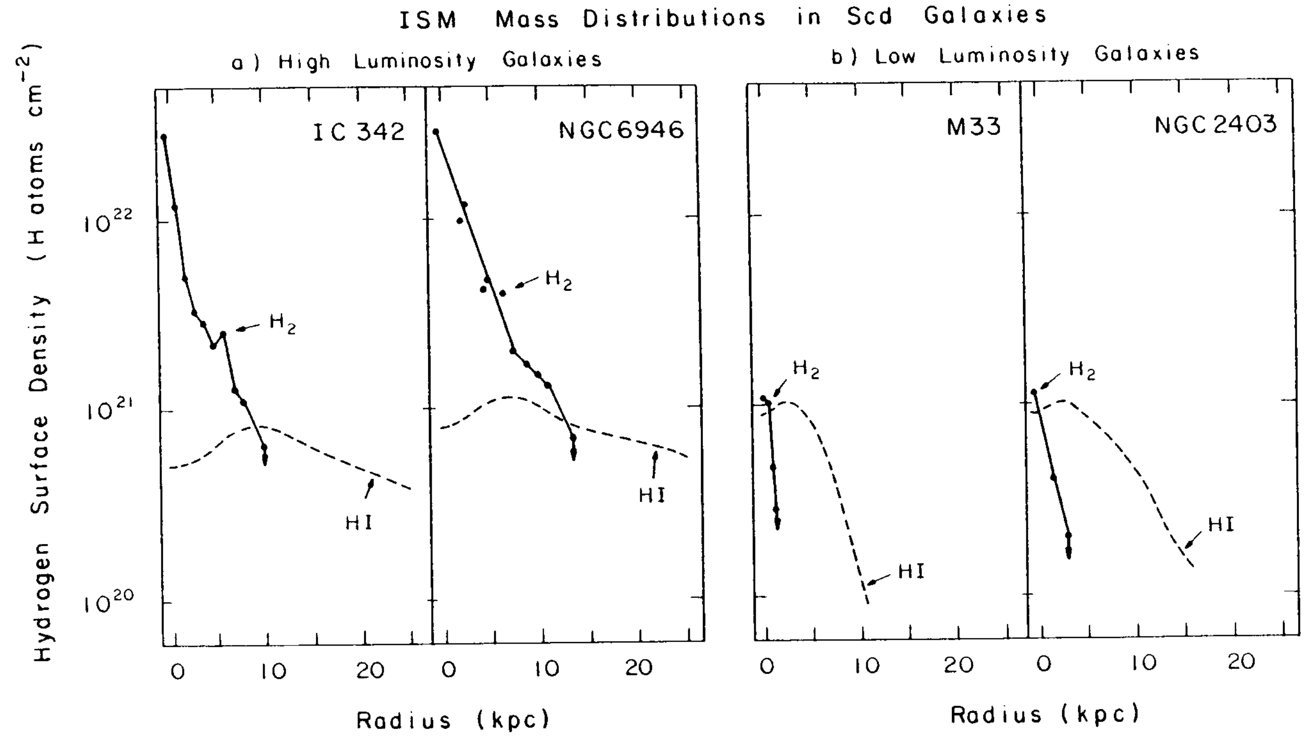

Figure 2. Comparison of the H_2 and HI radial distributions in high and low luminosity Scd galaxies (HI from Rogstad and Shostak 1972; CO from Young and Scoville 1982a and Young 1986).

2.2. Sa and Sb Galaxies

The CO morphologies of some of the early type spiral galaxies are distinctly different from those of the Sc galaxies. Of the 14 nearby Sa and Sb galaxies whose CO distributions have been measured, 5 have been observed to exhibit central CO depressions. These are NGC 224 (M31; Stark 1979), NGC 891 (^{12}CO by Solomon et al. 1983, ^{13}CO and ^{12}CO by Sanders and Young 1986), NGC 2841 and NGC 7331 (Young and Scoville 1982b), and NGC 4736 (Garman and Young 1986).

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 14 galaxies surveyed, or 40% of the early type spiral galaxies have central CO depressions. For NGC 2841 and NGC 7331, Young and Scoville (1982b) have pointed out that the central CO hole is coincident with the extent of the nuclear bulge, as determined from the separation of the blue light distribution into bulge and disk components (Boroson 1981). Obviously, higher resolution CO observations may reveal central CO depressions in more of the Sa and Sb galaxies.

Figure 3 shows a comparison of the H_2 and HI distributions in the Sb galaxies NGC 7331 and NGC 2841. As for the Sc galaxies in Figure 2, the HI distributions exhibit central holes (Bosma 1978), and the H_2 surface densities are greater than those of HI in the inner disk. The difference here is that for the Sb galaxies there are holes in both the atomic and molecular gas distributions, although the extents of the H_2 and HI holes differ.

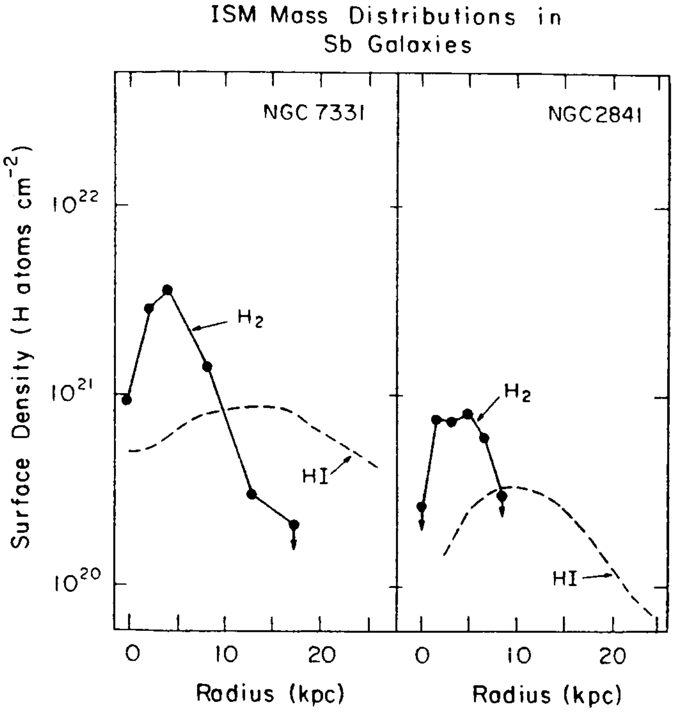

Figure 3. Comparison of the H_2 and HI radial distributions in two Sb galaxies, showing central holes in both CO and HI (HI from Bosma 1978; CO from Young and Scoville 1982b).

3. THE STAR FORMATION HISTORIES OF INDIVIDUAL GALAXIES

3.1. NGC 6946

The measurement of the CO distribution in a galaxy enables us to determine the star formation history of the galaxy through a comparison of tracers of star formation in the disk which are sensitive on different time scales. 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 1986a), CO (Rickard and Palmer 1981; Young and Scoville 1982a; Tacconi and Young 1986a), radio continuum (van der Kruit, Allen and Rots 1977; Klein et al. 1982), and blue light (Ables

1971; Elmegreen and Elmegreen 1984), as discussed in detail in Tacconi and Young (1986a). Figure 4 shows the azimuthally averaged radial distributions of H_2, HI, Hα, blue light and radio continuum emission for NGC 6946 (see also Tacconi and Young 1986b, this conference). It is remarkable that all of the radial distributions show similar behavior except that of the atomic gas. Furthermore, the same features in the various radial distributions are seen in most luminous Sc galaxies (see also Kenney and Young 1986b, this conference), and therefore the conclusions stated in this section apply more generally than simply to NGC 6946.

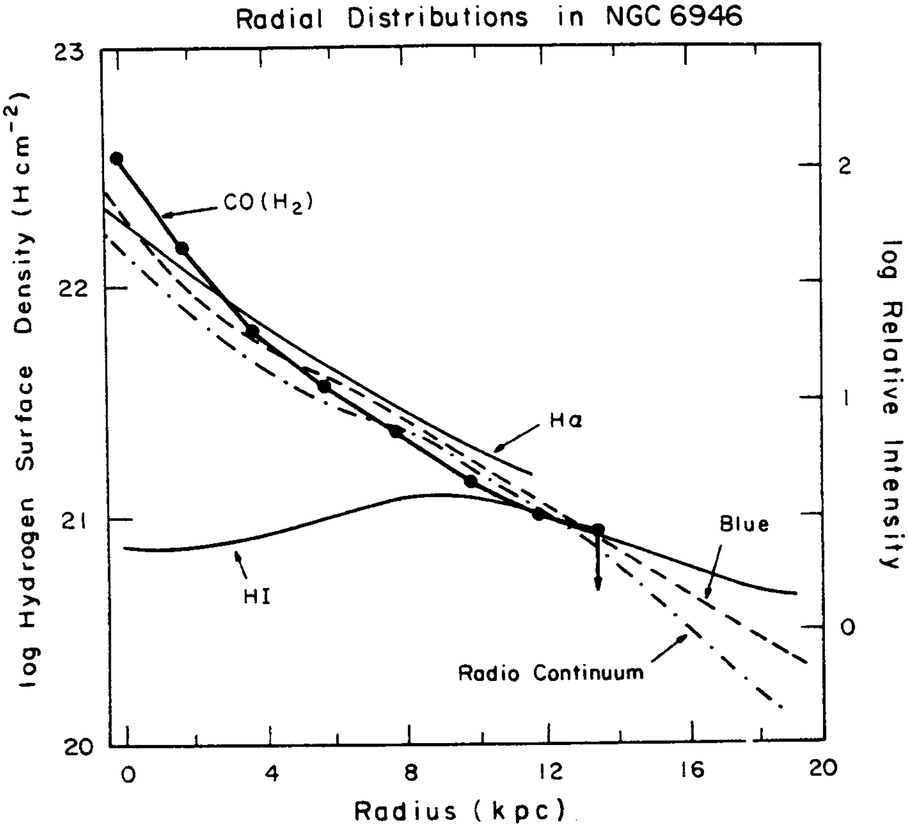

Figure 4. Comparison of the CO (H_2), HI, Hα, blue light, and radio continuum radial distributions in NGC 6946 (for references see text). All intensity scales are relative except that for the HI, which is plotted relative to H_2.

The fact that the CO, blue light, and Hα distributions in NGC 6946 all show similar radial behavior is significant in terms of 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), and the Hα flux indicates the massive star formation rate (SFR), the fact that the ratio of blue/CO surface densities is constant (Young and Scoville 1982a), and the ratio of Hα/CO surface densities is constant (DeGioia-Eastwood et al. 1984), indicates that the amount of star formation which occurs is proportional to the available supply of molecular gas. That is, the star formation efficiency is constant as a function of radius in NGC 6946.

From a comparison of the ISM surface density distributions in NGC 6946, it is apparent that the shapes of the atomic and molecular gas distributions are very different (see also §2.1). 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 (Tacconi and Young 1986a). 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.

3.2. M51

While the star formation efficiency is constant as a function of radius in the disk of NGC 6946 and other luminous Sc galaxies, there are azimuthal structures in the disks of galaxies which are known as spiral arms. If the star formation efficiency were constant at all locations in a disk, then the spiral patterns which are so apparent optically should also be apparent in the molecular gas. However, searches over the years in a wide range of Sc galaxies and with a variety of resolutions have indicated that molecular spiral patterns are not the dominant feature of the molecular gas distributions. Indeed, studies of M51 with the OVRO interferometer resolve out more than half of the emission (Lo et al. 1984), indicating that the arm/interarm contrast in CO is not as high as that in Hα.

To determine the star formation efficiency on and off the arms in M51, we have compared the Hα image of Kennicutt (1985) with our fully sampled CO map, both at 45" resolution (Lord and Young 1986). In Figure 5 (top), we plot the Hα and CO surface brightnesses as a function of spiral phase, where the dust lanes are specified to be at phases 90° and 270°. While the spiral pattern in

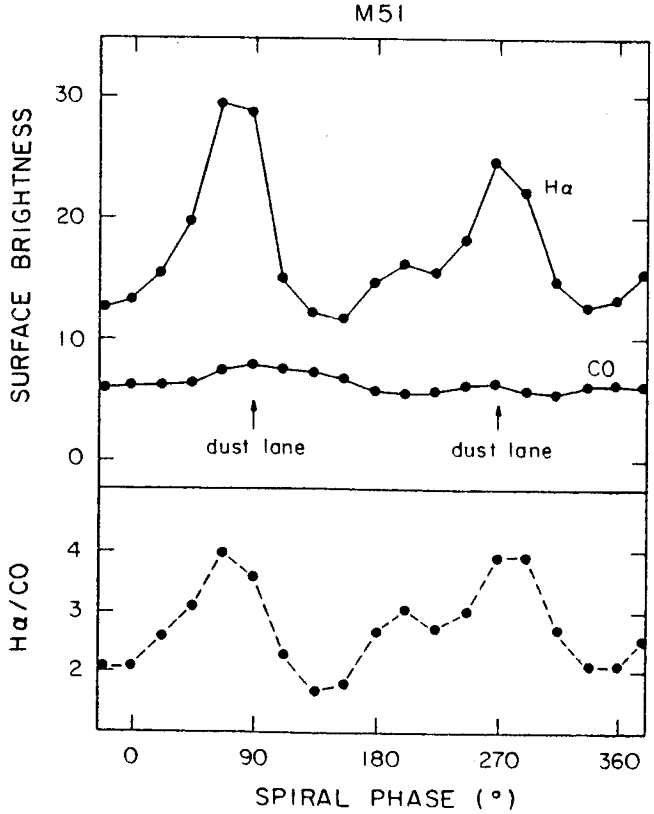

Figure 5. Hα and CO azimuthal distributions in M51 at 45" resolution (top) plotted as a function of spiral phase, with 90° and 270° chosen to be the locations of the arms (Hα from Kennicutt 1983; CO from Lord and Young 1986). Also shown (bottom) is the Hα/CO ratio as a function of spiral phase; the highest values of this quantity are found on the spiral arms in M51.

Hα is apparent, even at 45" resolution, that in CO is not. At the bottom of Figure 5, the ratio of Hα/CO surface brightnesses is shown to vary in azimuth, with the highest values on the arms. Thus, the star formation efficiency is higher on the arms than between the arms in M51. This result requires that star formation is not simply a local process, depending only on the mass of available gas, but that some mechanism has operated to produce more stars per unit molecular mass in the arms of M51.

4. THE STAR FORMATION EFFICIENCY FROM GALAXY TO GALAXY

4.1. Correlation of Total CO and IR Luminosities

With the success of the IRAS, the IR flux densities and color temperatures have now been measured for galaxies over the entire sky. These observations provide a 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 forming in molecular clouds (cf. Rieke et al. 1980; Telesco and Harper 1980). 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, enables us to deduce the star formation efficiency in galaxies.

Only a small number of CO-IR comparisons have been made in galaxies because of the limited amount of IR data previously available. From observations between 40 and 160 μm using the KAO, 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 general correlation between CO and 100 μm luminosities was found. Sanders and Mirabel (1985) compared the central 1' CO luminosities and 40 to 120 μm IR luminosities for a sample of 21 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. However, the above galaxy samples are too inhomogeneous to determine which parameters are primarily responsible for this scatter.

From a comparison of total CO and IR luminosities in 27 IR bright galaxies, Young et al. (1986a) found that the scatter in the L_{CO} - L_{IR} plot is highly correlated with dust temperature, in that there is a tight correlation between the IR and CO luminosities for galaxies in each of three distinct ranges of dust temperature.

Figure 6 shows the total IR and CO luminosities for 122 galaxies -- 27 from Young et al. (1984 and 1986a), 15 from Sanders et al. (1986), 23 in Virgo from Kenney and Young (1986), 13 galaxies of large angular size (Young and Scoville 1982a and 1982b; Scoville and Young 1983; Young, Tacconi and Scoville 1983; Scoville, Young and Lucy 1983; Solomon et al. 1983; Young and Scoville 1984; Scoville et al. 1985; Sanders and Young 1986), and 44 major axis CO maps observed during the past six months (Young et al. 1986b). The data shown in Figure 6 are coded by dust temperature, from which it is clear that there is a good correlation between IR luminosity and CO luminosity (or H_2 mass) within each dust temperature bin.

We have fitted the data in Figure 6, with a power law, and find that

$$L_{IR} \propto M(H_2)^{0.8\pm0.1} . \tag{1}$$

with an overall correlation coefficient of 0.90. For each dust temperature bin, the IR luminosity is roughly proportional to the first power of the H_2 mass. Also shown in Figure 6 is the position of the Milky Way (from Scoville, this conference), indicating a similarity to the galaxies with the coldest dust temperatures.

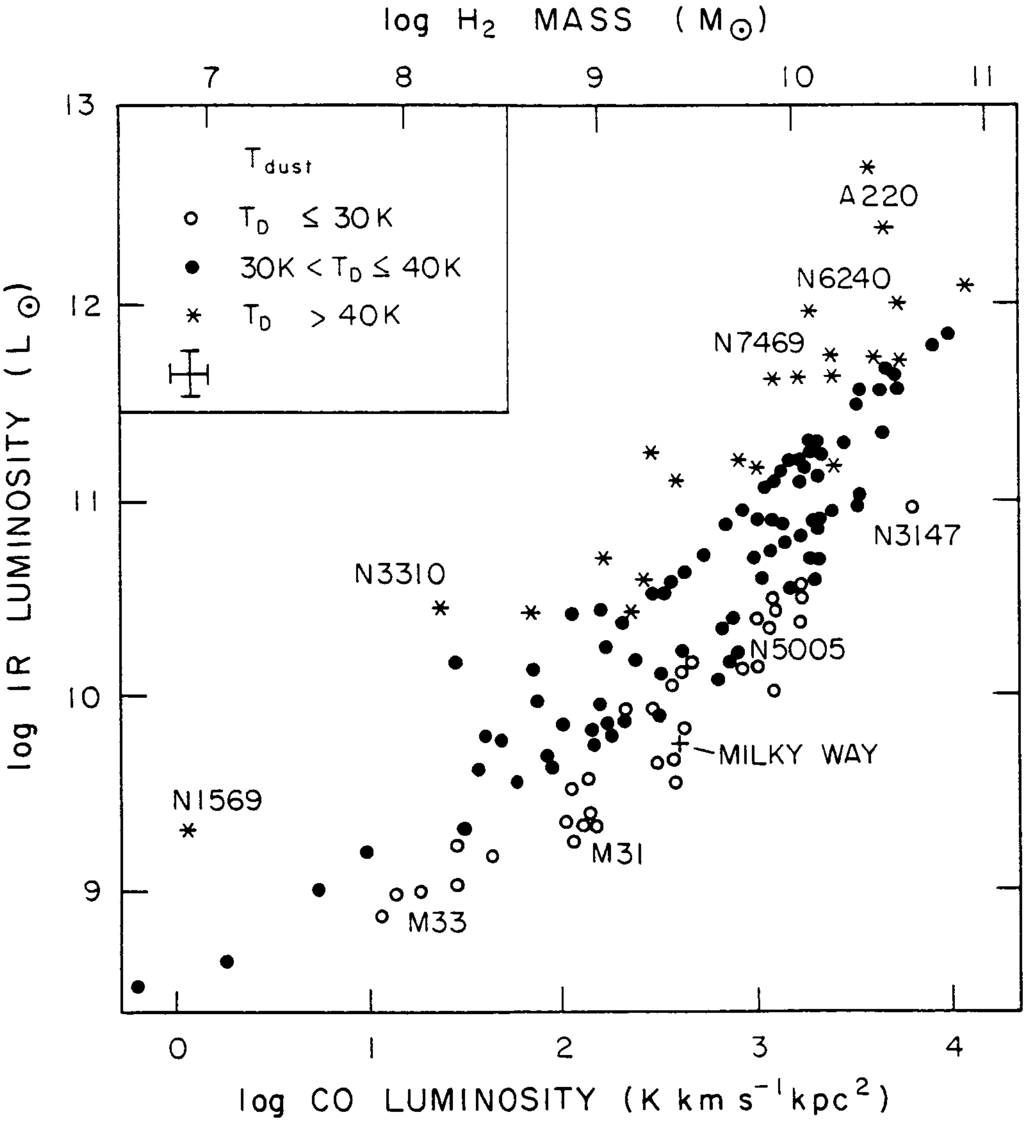

Figure 6. Comparison of the total IR and CO luminosities for 122 galaxies (27 from Young et al. 1984 and 1986a; 23 in Virgo from Kenney and Young 1986a; 15 from Sanders et al. 1986; 13 galaxies of large angular diameter -- for references see Young 1986; and 44 IR bright galaxies from Young et al. 1986b). The data plotted include total CO luminosities from both major axis maps and single CO observations. The IR luminosities are from the IRAS Point Source Catalogue (JISWG 1985) and from coadded survey data (Young 1986), following the method outlined by Lonsdale et al. (1985). Data points are coded by dust temperature as indicated in the upper left hand corner of the plot.

The data in Figure 6 can alternatively be illustrated as in Figure 7, 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, as noted by Young et al. (1986a). This result is further emphasized by the fact that we find no correlation of the IR luminosities with HI masses. For the galaxies with the coldest dust temperatures, the mean value of $L_{IR}/M(H_2)$ is 5 $L_\odot/M_\odot$, while for the galaxies with the highest dust temperatures the mean value is 56 $L_\odot/M_\odot$.

Young et al. (1986a) 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.

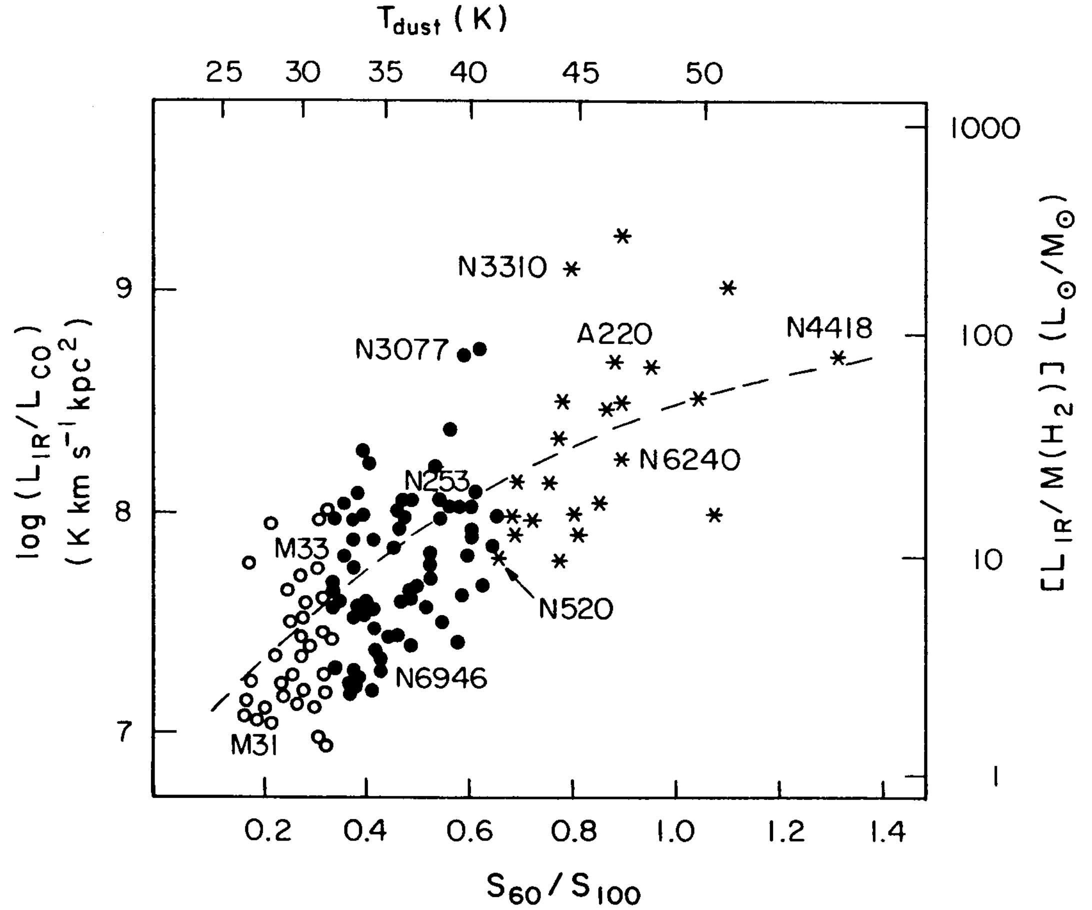

Figure 7. Ratio of IR/CO luminosities versus the ratio of 60/100 μm flux densities for the galaxies plotted in Figure 6. The dust temperatures indicated at the top of the figure were derived from the ratio of 60/100 μm flux densities, assuming a λ^{-1} emissivity law. The dashed line superposed on the 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. Young et al. 1986a). The different symbols represent the same three different dust temperature bins as in Figure 6.

Furthermore, the galaxies previously identified as mergers (cf. Joseph and Wright 1985) are among the galaxies with the highest SFEs. We suggest that efficient star formation is responsible for the high dust temperatures observed, through the formation of more stars per unit molecular mass. Thus, the interacting galaxies which are luminous in the IR and therefore have high rates of star formation (cf. 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 merger NGC 3310 and the irregular galaxy NGC 1569, the efficiency of using the molecular gas in these systems is high as well.

Finally, Young et al. (1986a and 1986b) 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. Figure 8 is a plot of the mass of warm dust versus the H_2 mass in 122 galaxies, indicating a good correlation over 4 orders of magnitude, such that

$$M(H_2) \propto M_D^{1.2 \pm 0.1} . \qquad (2)$$

However, the mean value of the molecular gas-to-warm dust ratio is 500, not ~ 100 as it is for the Milky Way (cf. Hildebrand 1983). The most likely explanation for this discrepancy is that IRAS is sensitive only to the warm dust in a galaxy. 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.

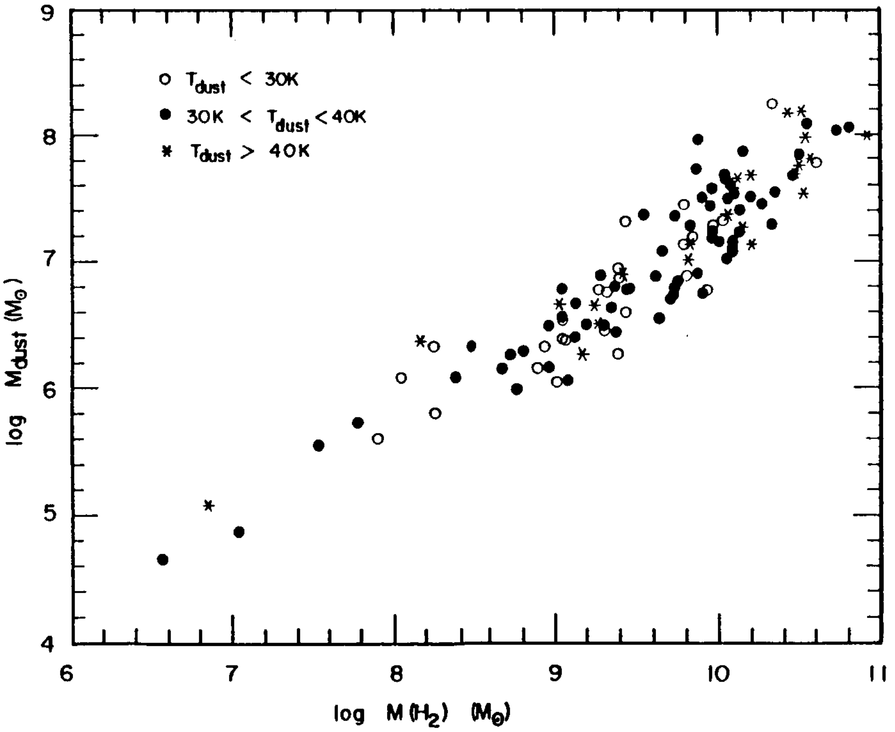

Figure 8. Comparison of the mass of dust, derived from the IRAS observations (cf. Hildebrand 1983), with the H_2 mass inferred from CO. The fit to all galaxies is given by $M(H_2) \propto M_D^{1.2 \pm 0.1}$ with a correlation coefficient of 0.91.

4.2. The Effect of Environment on the Efficiency of Star Formation

It is apparent from the above studies that galaxy mergers are among the galaxies with the highest values of $L_{IR}/M(H_2)$ (i.e. NGC 3310, NGC 6240, and Arp 220). Therefore, we have searched for CO in 30 objects specifically chosen to represent the extremes of environments: isolated galaxies, and merging or strongly interacting galaxies (Young et al. 1986b).

Isolated galaxies were taken from the Karachentseva Catalog of Isolated Galaxies (1973), with the additional requirement that they not be included in any groups (Sandage and Tammann 1975; Turner and Gott 1976; Geller and Huchra 1983). This selection procedure yielded 26 isolated galaxies brighter that 13th magnitude, of which 13 were observed in CO. Examples of galaxy mergers were selected from the paper of Joseph and Wright (1985); interacting galaxies were selected from the Arp Atlas of Pecuiar Galaxies (1966) to be pairs of galaxies in contact. This sample of galaxies includes 15 mergers and interacting galaxies. One striking difference between the galaxies in these samples is that the ratio of 60/100 μm flux densities for the isolated galaxies is 0.35 ±0.11, while that for the interacting galaxies is 0.83 ± 0.21.

The principal difference between these two galaxy samples is in the value of the IR luminosity per unit H_2 mass, or the star formation efficiency. Figure 9 shows a plot of the ratio $L_{IR}/M(H_2)$ as a function of the 60/100 μm flux density ratio, with the data points coded by environment: stars indicate mergers and interacting galaxies, while circles indicate the isolated galaxies.

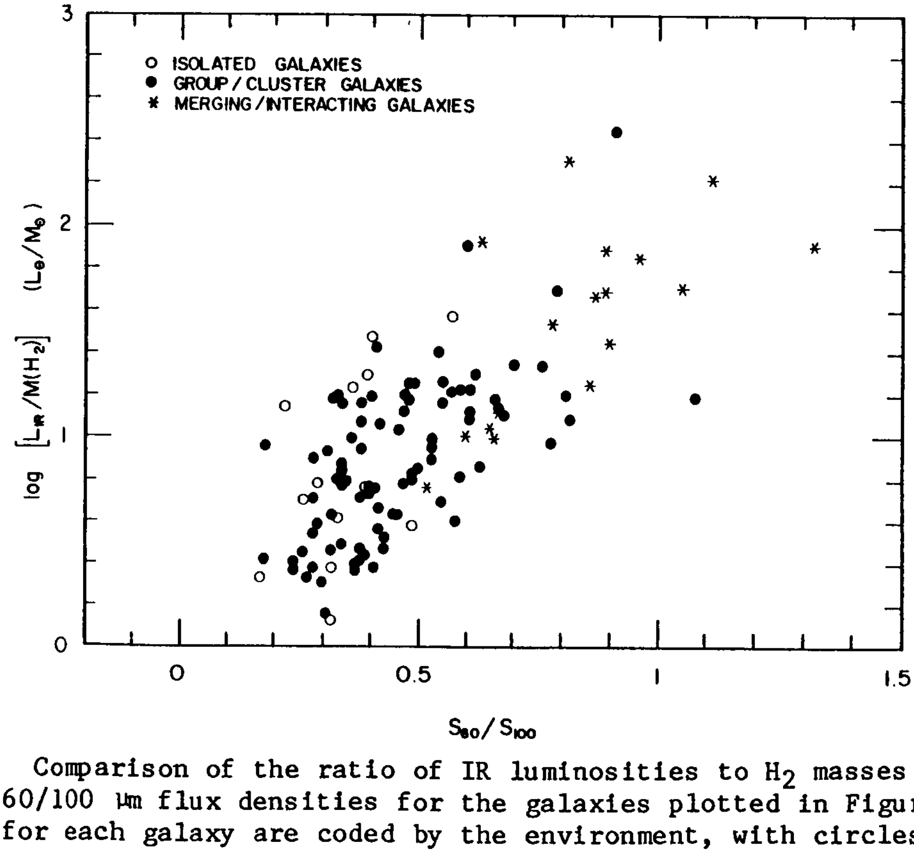

Figure 9. Comparison of the ratio of IR luminosities to H_2 masses with the ratio of 60/100 μm flux densities for the galaxies plotted in Figure 7. Here, the data for each galaxy are coded by the environment, with circles for isolated galaxies, and stars for interacting galaxies. Both the $L_{IR}/M(H_2)$ ratio and dust temperature are high in interacting galaxies and low in isolated galaxies.

We find clear separation between the two samples, in that the isolated galaxies have low values of $L_{IR}/M(H_2)$ and dust temperature, while the interacting galaxies have high values of both quantities; the mean value of $L_{IR}/M(H_2)$ is 11 L_o/M_o in the isolated galaxies and 44 L_o/M_o in the interacting galaxies.

However, within each sample we find a range of more than two orders of magnitude in both the IR luminosities and H_2 masses. The isolated galaxies were found to contain between $3x10^7$ and 10^{10} M_o of H_2, while the range for the interacting galaxies is between 10^8 and $3x10^{10}$ M_o of H_2. Similarly, the IR luminosities are between $4x10^8$ and 10^{11} L_o for the isolated galaxies and between $2x10^{10}$ and $2x10^{12}$ L_o for the interacting galaxies. The physical mechanism which causes star formation to be more efficient in interacting galaxies must operate over a wide range of masses and luminosities since even low luminosity galaxies with low star formation rates may have high star formation efficiencies.

4.3. Gas Depletion Timescales

Assuming that the observed IR and blue luminosities are produced primarily by O, B, and A stars, it is possible to estimate the inferred global rates of star formation in these galaxies. If the early type stars produce energy using the CNO cycle, and process 13% of their mass while on the main sequence, Scoville and Young (1983) have shown that the star formation rates are given by $M_{O,B,A} = 7.7x10^{-11} L_{tot}/L_o$, where L_{tot} is the sum of the IR and blue luminosities, and $M_{O,B,A}$ is in M_o yr^{-1}. Figure 10 is a plot of the total luminosities $(L_{IR} + L_B)$ and total ISM gas masses $(H_2 + HI)$ for the galaxies in our sample.

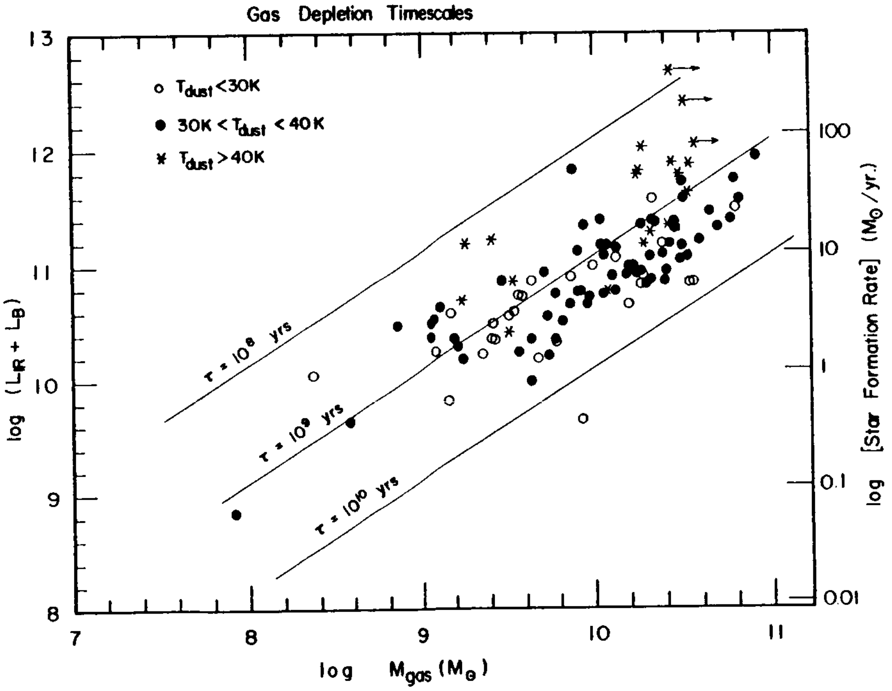

Figure 10. Comparison of the total luminosity $(L_{IR} + L_B)$ with the interstellar gas mass $(H_2 + HI)$ for the 114 galaxies in Figure 6 for which HI masses and blue luminosities were available. For galaxies with HI absorption profiles, only lower limits to the gas masses are plotted. The star formation rates were computed following Scoville and Young (1983), and the solid lines indicate the depletion times for the ISM gas masses.

The lines drawn in Figure 10 indicate 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 10, the timescales for gas depletion range from 10^8 years to 6×10^9 years. In the sample of 27 galaxies studied by Young et al. (1986a), the galaxies with the highest star formation efficiencies and highest dust temperatures have an average gas depletion timescale of 1×10^9 years, while those with lower efficiencies and dust temperatures have an average gas depletion timescale of 4×10^9 years. Obviously, if the episodes of intense star formation in merging and interacting galaxies are relatively short-lived compared to 10^8 years, then the gas depletion timescales for these objects could in fact be considerably longer.

5. THE VIRGO CLUSTER

In order to understand the effect of environment on star formation for nearby galaxies, we have observed the molecular content of a complete optically selected sample of spiral galaxies in the Virgo cluster (Kenney and Young 1985 and 1986a). The Virgo cluster environment appears to be altering the atomic gas content of some of the member galaxies (cf. Giovanelli and Haynes 1983), and the star formation rates of Sc galaxies in the cluster core seem to have been reduced (Kennicutt 1983). Thus, the Virgo cluster serves as an environment for investigating the histories of star formation and molecular cloud formation in galaxies.

From HI observations of large samples of galaxies, it has been demonstrated 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, from comparisons with isolated galaxies of the same type and optical diameter (cf. Haynes, Giovanelli, and Chincarini 1984). The presently favored explanation for the HI deficiency is stripping of the atomic gas as the galaxies move through the intracluster medium. Recent maps of the HI disks of Virgo spirals indicate that the HI radial extents have been reduced in the HI deficient galaxies (Giovanelli and Haynes 1983; van Gorkom and Kotanyi 1985; Warmels 1985), and that the stripping occurs primarily in the outer parts of the disk.

Kenney and Young (1986a and this conference) 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 atomic and not the molecular gas. Additionally, they find that the ratio of CO diameters to HI diameters decreases with distance from M87, providing further evidence for the conclusion that only HI is stripped from the galactic disks. Furthermore, Kenney and Young (1986b) have shown that the atomic gas is stripped even from the inner disks of the HI-deficient galaxies, where the CO appears normal. Since the CO has not responded to the atomic gas removal, then this implies a long lifetime for the molecular phase of the ISM, of order 10^9 years which is the cluster crossing time.

A question which remains 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 be for any of several reasons. First, it is possible that some of the Hα emission from 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 resulting star formation) has been truncated. This could explain the lower Hα fluxes for the Virgo galaxies. On the other hand, the molecular cloud size distribution in the Virgo spiral galaxies may have been altered as a result of the HI stripping. If the IMF depends on the molecular cloud size distribution, then the consequent Hα flux may have been reduced. More detailed Hα and far-IR observations of galaxies in the Virgo cluster are needed to address this question.

6. CONCLUSIONS

From observations of the CO content and distributions in galaxies, we have investigated questions related to star formation and its efficiency in galaxies and found the following.

1) The CO radial distributions show central peaks in the Sc galaxies and central CO holes in 40% of the Sb galaxies.

2) The azimuthally averaged distributions of CO, Hα and blue light are similar in the disks of luminous, relatively face-on, late-type spiral galaxies. In NGC 6946, we conclude that the star formation efficiency is constant as a function of radius.

3) The distribution of Hα emission in M51 at 45" resolution shows an enhancement of a factor of 2 on the spiral arms relative to the interarm regions, while that of CO shows at most a 25% enhancement on the arms. Thus, the efficiency of star formation on the arms of M51 appears to be higher by a factor of two relative to the interarm regions.

4) From CO maps of the disks of IR bright galaxies, we find that the CO emission is distributed throughout the disks, and not concentrated solely in the nucleus of the galaxy.

5) We find a general correlation between the total IR luminosity and total CO luminosity of a galaxy, in that galaxies with high CO luminosities (H_2 masses) have high IR luminosities. The scatter observed in the IR luminosity-H_2 mass comparison is highly correlated with dust temperature; for a given H_2 mass the IR emission observed is higher for galaxies with higher dust temperatures.

6) The ratio of $L_{IR}/M(H_2)$ 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 result that there is little correlation between the IR luminosities and HI masses in galaxies.

7) The dust masses are well correlated with the H_2 masses from galaxy to galaxy, even though we are only observing that fraction of the dust which is 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 10% - 20% of the dust <u>mass</u> in some galaxies with IRAS. However, IRAS is sensitive to the <u>majority</u> of the dust luminosity in these galaxies.

8) The implied rates of massive star formation required to produce the observed total luminosities range from 0.4 to 190 M_o yr^{-1}. If the galaxies are in a steady state, the available supplies of ISM (H_2 + HI) will therefore be depleted in 10^8 to 6 x 10^9 years.

9) The star formation efficiency, as measured by the ratio of IR luminosities to H_2 masses, is found to vary by two orders of magnitude from galaxy to galaxy. The galaxies with high values of $L_{IR}/M(H_2)$ are galaxies with high dust temperatures, independent of whether or not they have high values of the total luminosity. Thus, Arp 220 and NGC 1569 both have high dust temperatures and ratios of $L_{IR}/M(H_2)$, even though they have IR luminosities which differ by 4 orders of magnitude. We suggest that the high efficiency of star formation in these galaxies is probably responsible for the high dust temperature.

10) Those galaxies previously identified as mergers are among the galaxies with the highest star formation efficiencies and dust temperatures. Conversely, a sample of isolated galaxies we have studied is characterized by low star formation efficiencies and low dust temperatures. This indicates that the star formation efficiency from galaxy to galaxy does depend on global factors, and not only on the amount of molecular gas present.

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REFERENCES

Ables, H.D. 1971, Publ.U.S.Naval Obs., Series II, Vol. 20, Part 4.
Arp, H. 1966, Ap.J.Suppl., 14, 1.
Boroson, T. 1981, Ap.J.Suppl., 46, 177.
Bosma, A. 1978, Ph.D. thesis, University of Groningen.
Burton, W.B., and Gordon, M.A., Bania, T.M., and Lockman, F.J. 1975, Ap.J., 202, 30.
Combes, F. Encrenaz, P.J., Lucas, R., and Weliachew, L. 1978, Astron.Ap., 67, L13.
De Gioia-Eastwood, K., Grasdalen, G.L., Strom, S.E., and Strom, K.M. 1984, Ap.J., 278, 564.
Dickman, R.L., Snell, R., and Schloerb, F.P. 1986, Ap.J., in press (October).
Elmegreen, D.M., and Elmegreen, B.G. 1984, Ap.J.Suppl., 54, 127.
Garman, L., and Young J.S. 1986, Astron.Ap., 154, 8.
Geller, M.J. and Huchra, J.P. 1983, Ap.J.Suppl., 52, 61.
Giovanelli, R., and Haynes, M.P. 1983, A.J., 88, 881.
Haynes, M.P., Giovanelli, R., and Chincarini, G.L. 1984, Ann.Rev.Astr.Ap., 22, 445.
Hildebrand, R.H. 1983, Quart.J.R.A.S., 24, 267.

Joint IRAS Science Working Group. 1985, IRAS Point Source Catalogue (Washington, D.C.: US Government Printing Office).

Joseph, R.D., and Wright, G.S. 1985, M.N.R.A.S., 214, 87.

Karachentseva, V.E. 1973, Comm.Spec.Astrophys.Obs., 8.

Kenney, J. and Young, J.S. 1985, in ESO Workshop on the Virgo Cluster of Galaxies, ed. O.-G. Richter and B. Binggeli (Garching: ESO), p. 165.

----- 1986a, Ap.J.(Letters), 301, L13.

----- 1986b, this conference.

Kennicutt, R.C. Jr. 1983, A.J., 88, 483.

Klein, U., Beck, R., Buczilowski, U.R., and Wielibinski, R. 1982, Astron.Ap., 108, 176.

Lo, K.Y., et al. 1984, B.A.A.S, 16, 977.

Lonsdale, C.J., Helou, G., Good, J.C., and Rice, W.L. 1985, "Catalogued Galaxies and Quasars Observed in the IRAS Survey," JPL preprint.

Lonsdale, C.J., Persson, S.E., and Matthews, K. 1984, Ap.J., 287, 95.

Lord, S.D., Strom, S.E., and Young, J.S. 1986, this conference.

Lord, S.D., and Young, J.S. 1986, Ap.J., submitted.

Rickard, L.J., and Harvey, P.M. 1984, A.J., 89, 1520.

Rickard, L.J., and Palmer, P. 1981, Astron.Ap., 102, L13.

Rickard, L.J., Palmer, P., Morris, M., Zuckerman, B., and Turner, B. 1975, Ap.J.(Letters), 199, L75.

Rieke, G.H., Lebofsky, M.J., Thompson, R.I., Low, F.J., and Tokunaga, A.T. 1980, Ap.J., 238, 24.

Rogstad, D.H. and Shostak, G.S. 1972, Ap.J., 176, 315.

Rogstad, D.H., Shostak, G.S., and Rots, A.H. 1973, Astron.Ap., 22, 111.

Rydbeck, G., Hjalmarson, A., and Rydbeck, O.E.H. 1985, Astron.Ap., 144, 282.

Sandage, A. and Tammann, G.A. 1975, 1975, Ap.J., 196, 313.

Sanders, D.B., and Mirabel, I.F. 1985, Ap.J., 298, L31.

Sanders, D.B., Scoville, N.Z., Young J.S., Soifer, B.T., Schloerb, F.P., Rice, W.L., and Danielson, G.E. 1986, Ap.J.(Letters), 305, L45.

Sanders, D.B., Solomon, P.M., and Scoville, N.Z. 1984, Ap.J., 276, 182.

Sanders, D.B., and Young, J.S. 1986, Ap.J., submitted.

Scoville, N.Z., Soifer, B.T., Neugebauer, G., Young, J.S., Matthews, K., Yerka, J. 1985, Ap.J., 289, 129.

Scoville, N.Z., and Solomon, P.M. 1975, Ap.J.(Letters), 199, L105.

Scoville, N.Z. and Young, J.S. 1983, Ap.J., 265, 148.

Scoville, N.Z., Young, J.S., and Lucy, L.B. 1983, Ap.J., 270, 443.

Searle, L., Sargent, W.L.W. and Bagnuolo, W. 1973, Ap.J., 179, 427.

Solomon, P.M. 1982, in "Greenbank Workshop on Extragalactic Molecules," p. 41.

Solomon, P.M., Barrett, J. Sanders, D.B. and de Zafra, R. 1983, Ap.J.(Letters), 266, L103.

Stark, A.A. 1979, Ph.D. Thesis, Princeton University.

Tacconi, L.J., and Young, J.S. 1985, Ap.J., 290, 602.

----- 1986a, Ap.J., in press (September).

----- 1986b, this conference.

Telesco, C.M. and Harper, D.A. 1980, Ap.J., 235, 392.

Turner, E.L. and Gott, J.R. 1976, Ap.J.Suppl., 32, 409.

van der Kruit, P.C., Allen, R.J., and Rots, A.H. 1977, Astron.Ap., 55, 421.

van Gorkom, J., and Kotanyi, C. 1985, in ESO Workshop on the Virgo Cluster of Galaxies, ed. O.-G. Richter and B. Binggeli (Garching: ESO), p. 61.

Warmels, R.H. 1985, in ESO Workshop on the Virgo Cluster of Galaxies, ed. O.-G. Righter and B. Binggeli (Garching: ESO), p. 51.

Young, J.S. 1986, in preparation.

Young, J.S., Gallagher, J.S., and Hunter, D.A. 1984, Ap.J., 276, 476.

Young, J.S., Kenney, J., Lord, S. and Schloerb, F.P. 1984, Ap.J.(Letters), 287, L65.
Young, J.S. et al. 1986b, Ap.J., submitted.
Young, J.S., Schloerb, F.P., Kenney, J., and Lord, S.D. 1986, Ap.J., 304, 443.
Young, J.S. and Scoville, N.Z. 1982a, Ap.J., 258, 467.
----- 1982b, Ap.J. (Letters), 260, L41.
----- 1984, Ap.J., 287, 153.
Young, J.S., Tacconi, L., and Scoville, N.Z. 1983, Ap.J., 269, 136.

DISCUSSION

SOLOMON: The Hα emission in M51 only gives a measure of the ionized gas or star formation rate from photons which escape out of the HII region. Much of the star formation may be inside molecular clouds and the Hα may be trapped and heat the dust. Thus, only the far-infrared could give a true measure of the star forming activity.

YOUNG:
There are sources of far-infrared emission which are not directly linked to star formation, such as dust in planetary nebulae, or dust in HI clouds heated by the ambient stellar radation field and more closely linked to older, stellar populations. Thus, the far-infrared is not a better measure of star forming activity, but an alternative measure to the use of Hα. Unfortunately, the Hα emission has extinction uncertainties; there are problems with Hα if more HII regions are on the far side of clouds (which is, of course, unlikely), or if there are radial gradients in the extinction. At the present time, however, the Hα distributions in galaxies have much higher resolution than the infrared, and continue to be essential for comparisons with CO.

SOLOMON:
The separation of galaxy properties such as L_{IR}/L_{CO} according to the 100μm – 60μm color or dust temperature does not really tell us anything about the galaxy. As I mentioned in my talk, for molecular clouds within the galaxy, $L_{IR}/L_{CO} \alpha\ T^{5.5}$. This is exactly what is expected for thermal radiation. The fact that hotter galaxies (hotter dust) have higher L_{IR}/L_{CO} is just a consequence of the Planck law and the dust emissivity. The $T^{5.5}$ dependence overwhelms any possible difference in the infrared luminosity due to differences in the percentage of dust which is heated.

YOUNG:
Phil, I agree completely. In my recent *Ap.J.* paper, I pointed out that the dependence of L_{IR}/L_{CO} on T^4 in galaxies is precisely what is expected for thermal emission. However, if the IR emission is of thermal origin, then why do some galaxies have hotter dust? I have suggested that a higher efficiency of star formation, thus producing more stars per unit molecular mass, will heat the dust to a higher temperature in some galaxies.

BECKLIN:
In M51 what is the spiral arm enhancement in the far-infrared?

YOUNG:
The IRAS data do not have sufficient resolution to see arm structures in M51, since they are ~30" across. The 49" resolution 170μm map of Smith (1982) does not show spiral arms to the extent that the Hα (at 45" resolution) does. However, at 170μm, the cold dust should agree more with the CO, since IRAS measures only warm dust.

FORREST:

The Brackett α emission could be a good tracer of the star formation rate, being less affected by extinction.

YOUNG:

It would be interesting if the emission could be mapped over the optical disk.