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# THE RELATIONSHIP BETWEEN THE CARBON MONOXIDE INTENSITY AND THE RADIO CONTINUUM EMISSION IN SPIRAL GALAXIES

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## ABSTRACT

The relationship between the velocity-integrated CO emission and the nonthermal radio continuum brightness in the disks of normal spiral galaxies is examined on a variety of length scales. On a global scale, the total CO intensity correlates strongly with the total radio continuum flux density for a sample of 31 galaxies. On scales of $\gtrsim 2$ kpc in the disk of individual galaxies, we find that the ratio $I_{CO}/T_{20}$ remains fairly constant over the entire disk as well as from galaxy to galaxy. For the eight spirals in our sample, the disk-averaged values of $I_{CO}/T_{20}$ range from 0.6–2.4, with the average over all eight galaxies being $\langle I_{CO}/T_{20} \rangle = 1.3 \pm 0.6$. However, studies of giant molecular cloud complexes in the arms of nearby galaxies indicate that the relationship ceases to be constant on smaller ($\lesssim 1$–2 kpc) scales, with the CO dominating the ratio.

We conclude that what these various length scales actually trace are differences in the primary heating mechanism of the gas in the beam. The observed relationship between CO and nonthermal radio continuum emission can be explained by assuming that molecular gas in galactic disks is heated primarily by cosmic rays. We use the observed relationship to show that the brightness of synchrotron emission is proportional to $n_{cr}^{0.4-0.9}$ in galactic disks.

Finally, we conclude that while in a general sense star formation is undoubtedly the primary source of energy that causes the relationship to exist, the details of the specific mechanism(s) at work are complicated by the very different scale heights and (small-scale) spatial distributions of the CO and nonthermal radio continuum emission.

*Subject headings:* galaxies: interstellar matter — interstellar: molecules — radio sources: galaxies

## 1. INTRODUCTION

Early detections of carbon monoxide in nearby spiral galaxies showed that many of these systems appeared bright in CO (Rickard et al. 1975; Combes et al. 1977, 1978; Morris & Lo 1978). However, this trend did not extend to all large spirals; for example, M101 (Solomon et al. 1983) and M81 (Combes et al. 1977) proved to be relatively faint in CO emission. To the extent that the CO emission can be considered as a reliable tracer of total molecular ($H_2$) gas mass, it thus became apparent that the amount of molecular gas in a galaxy was not strictly a function of galaxy size.

It was noted by Rickard, Turner, & Palmer (1977) that galaxies which show strong CO emission also tend to be bright in the nonthermal radio continuum. While the relationship was apparent on a global scale, a lack of high-resolution CO surveys of galactic disks precluded an investigation of the effect on local scales. Over the past decade the resolution and mapping capabilities of millimeter-wave telescopes have steadily approached those of centimeter-wave radio telescopes used for the continuum observations. In particular, work in the early to mid-1980s at the Five College Radio Observatory 14 m telescope (Young & Scoville 1982; Scoville & Young 1983; Scoville et al. 1985, and others) and at the National Radio Astronomy Observatory 11 (now 12) m telescope (Rickard & Palmer 1981; Solomon et al. 1983, and others) made it possible to begin investigating the relationship on scales of the order of a few kpc.

In this paper, we study the relationship between the integrated CO intensity and centimeter-wave radio continuum brightness temperature on three different scales. First, we look at the global values integrated over the entire galaxy; both CO and radio continuum data were available in the literature (CO—Verter 1985; radio continuum—Condon 1987). In § 2, we confirm that a global relationship exists between the integrated CO intensity and the radio continuum flux density for the galaxies in the survey. This is consistent with the results of Israel & Rowan-Robinson (1984), who found a similar relationship for the inner regions of several spirals. Next, we utilized mapping observations of galaxy disks to determine if the relationship holds on smaller scales (typically 1–3 kpc). We have selected only those galaxies for which the available CO and radio continuum data provide reliable estimates of the average radial surface brightnesses on length scales of 1–3 kpc or smaller. Only a few galaxies fit this criterion. These data show a striking result—*the ratio of the surface brightness of* CO *emission* ($I_{CO}$) *to radio continuum surface brightness* ($T_{20}$) *remains fairly constant over the disk of each galaxy.* In addition, *there is very little variation in this ratio from galaxy to galaxy.* The constancy of this ratio is all the more surprising when one considers that the surface brightness in the disks (and from galaxy to galaxy) varies by over two orders of magnitude. These results are consistent with a less well-sampled (major axis only) survey of a larger sample of spiral galaxies (Devereux & Young 1990).

Finally, we investigate the relationship on smaller scales ($\leq 1$ kpc) to determine if the measured ratio continues to hold. We find that in the spiral arms of M51, where a high-resolution, fully sampled CO map (Adler et al. 1991) is compared to radio continuum observations of the thermal and nonthermal radio emission (Tilanus et al. 1988), the relationship between CO and radio continuum ceases to hold on small size scales.

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Previous evaluations of this phenomenon have attributed the relationship between CO intensity and nonthermal radio continuum emission solely to the star-formation process (Israel & Rowan-Robinson 1984; Devereux & Young 1990) as follows: when a molecular cloud collapses, massive young stars form; these stars then account for the thermal radio emission (through the ionization of the surrounding cloud). Once the massive stars have evolved to the supernova stage, it is generally held that the ejected relativistic electrons interact over time with galactic magnetic fields, giving rise to the nonthermal radio emission (Israel & Rowan-Robinson 1984). The nonthermal emission dominates the galaxy radio image at centimeter wavelengths on length scales of a few kpc; the thermal emission is a small fraction ($\leq 20\%$) of the total flux density at 20 cm and is concentrated in discrete H II complexes. The result of this scenario of star-forming events, if true, will be to produce a correlation between the nonthermal radio continuum emission and the CO brightness which holds on all scales. We discuss possible problems with this scenario in the discussion section.

The observations are discussed in § 2, with the different length scales being discussed separately. In § 3 we discuss the nature of the relationship, including a discussion of the contribution of the star-formation process to the observed relationship between the CO and nonthermal radio continuum emission. In this section we also derive the dependence of the synchrotron intensity on the density of relativistic cosmic rays electrons. Our results are summarized in § 4.

## 2. THE RELATIONSHIP BETWEEN CARBON MONOXIDE AND RADIO CONTINUUM

### 2.1. *Global Scale*

The first step in the study of the relationship between integrated CO intensity and radio continuum emission was to determine it on global scales. Israel & Rowan-Robinson (1984) showed that there was a good correlation between the two quantities when considering the inner regions of spiral galaxies (after first subtracting the contribution of the nuclear source from the radio continuum emission). The addition of several surveys since that time allows us to use more complete data to determine CO intensities and radio continuum fluxes integrated over the entire disk. Verter (1985) fit exponential radial profiles to published data and calculated integrated CO intensities assuming a maximum radius of CO emission. Radio continuum flux densities at 1.49 GHz are taken from the survey of Condon (1987). Figure 1 shows the relationship between the integrated CO intensity and total radio continuum flux density for the galaxies that are common to both surveys. Open circles represent galaxies for which the total radio continuum flux density is not recovered by the interferometer; these values are estimated from single-dish measurements (Condon 1987). It can be seen that there is indeed a good correlation between the integrated CO emission and the radio continuum emission.

This result is not unexpected since the total molecular emission of spiral galaxies has been shown to correlate with several other global parameters of galaxies. Verter (1988) has shown that the total molecular emission depends strongly on galactic scale with less of a dependence on galactic morphology. The total CO emission in Verter's (1988) sample correlates well with the total H I, H$\alpha$, and far-infrared emission as well as the blue luminosity. Wielebinski (1988) showed that a strong linear correlation between CO luminosity and magnetic field strength

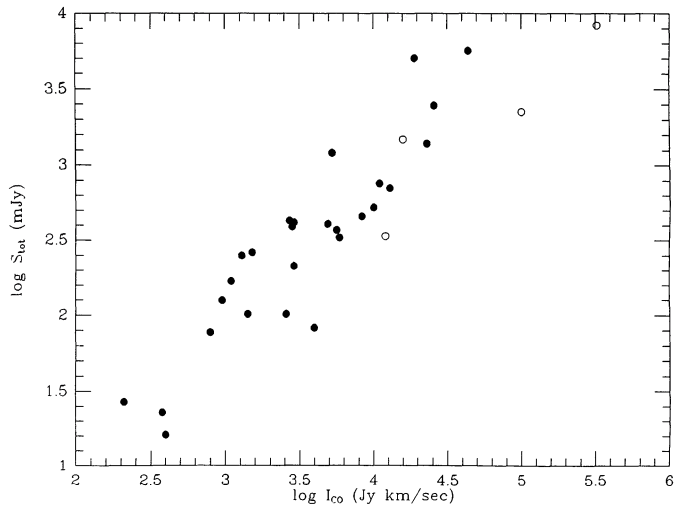


FIG. 1.—Total radio continuum flux density vs. total CO flux density for a sample of 31 spiral galaxies. The integrated CO intensities are taken from Verter (1985); the radio continuum flux densities from Condon (1987). Open circles represent galaxies for which the VLA did not recover all of the flux density; single-dish measurements were used to estimate the total flux (Condon 1987).

exists for 10 spiral galaxies. Also, the nonthermal radio continuum emission has been shown to correlate well with the far-infrared luminosity (de Jong et al. 1985; Wunderlich, Klein, & Wielebinski 1987). It thus comes as no surprise to see the strong correlation between the integrated CO intensity and total radio continuum emission over several orders of magnitude. However, it should be noted that at least some fraction (if not all) of the global correlations will simply be related to a "richness" effect; namely, larger galaxies have more of everything. This effect obscures the physics and frustrates attempts to determine the underlying cause of the correlations. In order to make progress it is essential to determine whether the correlation exists as we look at galactic disks in even greater detail, and if it does not, establish at what *length scale* it ceases to hold.

### 2.2. *In the Disks of Individual Galaxies*

We limit this part of the survey to galaxies which are "well studied" in the CO (1–0) line, i.e., for which full mapping or at least radial distributions are available. Table 1 lists the eight galaxies of this sample along with the reference to the CO and the radio continuum data.

We approach this topic by analyzing azimuthally averaged values of both the CO intensity and radio continuum brightness temperature as a function of galactocentric radius. For these well-studied systems, we could then determine if there were any systematic trends in the ratio from the bright central regions to the faint outer regions. The published data were often in a form which made this averaging straightforward.

For the smaller (angular size) galaxies, the radio continuum maps of Condon (1987) were used. The maps were corrected for inclination, azimuthally averaged, and converted to 20 cm brightness temperature using the conversion factors quoted by Condon (1987). For the more extended sources which had less reliable data (i.e., less flux density recovered by the interferometer), other radio continuum maps from the literature were used. For surveys done at different frequencies, the published spectral index was used to convert to 1.49 GHz flux

TABLE 1

GALAXY PARAMETERS

| Galaxy | D (Mpc) | $i$ | 1′ on Major Axis (kpc) | Radio Reference ($\nu_{\mathrm{GHz}}$) | CO Reference | Radio Beam (kpc) | CO Beam (kpc) | $T_{20}(r/r_o = 1)$ (K) | $\langle I_{\mathrm{CO}}/T_{20} \rangle$ (km s$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| M51 .............. | 9.6 | 20° | 2.8 | C87 (1.49) | SY83 | 54″ 2.5 | 50″ 2.3 | 5.8 | 1.06 ± 0.14 |
| NGC 6946 ....... | 10.1 | 30 | 2.9 | C87 (1.49) | YS82 | 48 2.3 | 50 2.4 | 4.8 | 0.96 ± 0.22 |
| IC 342 ............ | 4.5 | 25 | 1.3 | GB88 (4.75) | YS82 | 147 3.2 | 50 1.1 | 2.3 | 1.37 ± 0.30 |
| M83 .............. | 8.9 | 26 | 2.6 | C87 (1.49) | L87 | 54 2.3 | 50 2.2 | 7.7 | 1.09 ± 0.40 |
| | | | | | C78 | | 64 2.8 | | 0.85 ± 0.13 |
| M81 .............. | 3.3 | 59 | 1.0 | B85 (4.75) | B88 | 147 2.5 | 60 1.0 | 0.9 | 0.64 ± 0.26 |
| M101 ............. | 7.2 | 22 | 2.1 | I75 (1.41) | S83 | 66 2.3 | 60 2.1 | 0.6 | 1.64 ± 0.73 |
| NGC 253 ......... | 3.4 | 78 | 1.0 | K83 (10.70) | S85 | 71 1.2 | 50 0.8 | 8.9 | 2.39 ± 1.03 |
| M31 .............. | 0.7 | 78 | 0.2 | B82 (2.70) | D91 | 264 0.9 | 522 1.8 | 0.2 | 0.79 ± 0.23 |
| | | | | | S85a | | 102 0.3 | | 2.15 ± 0.91 |

REFERENCES.—C87: Condon 1987; GB88: Gräve & Beck 1988; B85: Beck et al. 1985; I75: Israel et al. 1975; K83: Klein et al. 1983; B82: Beck 1982; SY83: Scoville & Young 1983; YS82: Young & Scoville 1982; L87: Lord 1987; C78: Combes et al. 1978; B88: Baudry et al. 1988; S83: Solomon et al. 1983; S85: Scoville et al. 1985; D91: Dame et al. 1991; S85a: Stark 1985.

densities. These flux densities were then converted to brightness temperatures in the usual way and azimuthally averaged. Details of the reductions from the individual galaxies are presented below.

In general, the CO surveys are not as well sampled as the radio continuum maps. In most instances, the data consists of four or more radial cuts through the center of the galaxy. After correcting for the inclination of the disk, the data is binned and azimuthally averaged in the same manner as the radio continuum data. In some of the CO surveys from the literature, the radial distribution is fit by an exponential; these fits are used as described below.

The ratio of the integrated CO intensity to 20 cm radio continuum brightness temperature ($I_{\mathrm{CO}}/T_{20}$) is then calculated for the different radii in the disk. Since the CO sampling in general is more coarse than in the radio continuum maps, the sampling of $I_{\mathrm{CO}}/T_{20}$ is set by the spacing of the CO data. Table 1 contains information on each galaxy concerning the angular size of the beam, the linear size of the beam projected on the major axis (using the quoted distance in the respective literature), the 20 cm radio continuum brightness temperature at one scale length, and the average ratio of $I_{\mathrm{CO}}/T_{20}$ over the entire disk. Figure 2 presents the azimuthally averaged radial profiles of $I_{\mathrm{CO}}/T_{20}$ for eight of the galaxies discussed in this section.

### 2.2.1. *M51*

The radio continuum data were taken from Condon (1987) and converted to brightness temperature using the scaling $T_b/S_\nu = 0.19$ K (mJy per beam)$^{-1}$. The CO intensities are taken from Scoville & Young (1983). They found that the CO intensity falls off exponentially from the center. A fit to the data (using $I_{\mathrm{CO}} = I_o e^{-R/R_o}$) gives values of $I_o = 23.6$ K km s$^{-1}$ and $R_o = 3.9$ kpc. This fit was used to determine the integrated CO intensity at a given radius. The continuum map has an rms noise of roughly 0.1 mJy per beam; the published noise in the CO maps is $\pm 0.5$ K km s$^{-1}$. A value for $I_{\mathrm{CO}}/T_{20}$ was calculated every 30″ along the disk.

Figure 2 shows that $I_{\mathrm{CO}}$ *remains quite constant* over the entire galaxy up to a radius of about 12 kpc. The error bars are bigger at larger radii due to the lower levels of both CO and radio continuum emission in the outer regions. The constancy of the CO to radio continuum ratio over the disk of the galaxy is quite remarkable in view of the fact that it persists even though the radio continuum and CO intensity drop by over an order of magnitude in the region surveyed.

The small "bump" in the $I_{\mathrm{CO}}/T_{20}$ distribution at about 4 kpc could be due to the high concentration of CO in the inner arms; the CO distribution is clumpier and is more peaked than the radio continuum emission (Adler et al. 1991; Tilanus et al. 1988). The outer CO arms are fainter and at a lower contrast than the inner arms (Adler et al. 1991) which explains the lack of a bump in the outer regions of the $I_{\mathrm{CO}}/T_{20}$ distribution. These small-scale discrepancies from the constant ratio could indicate that the constancy of the ratio is beginning to break down on smaller size scales. This will be discussed later in this section.

### 2.2.2. *NGC 6946*

The 20 cm data for this galaxy were also taken from the Condon (1987) survey. The integrated CO intensities were taken from Young & Scoville (1982); again, the data were fit with an exponential, with a fit of $I_o = 23.4$ K km s$^{-1}$ and $R_o = 4.5$ kpc. The fit was sampled every 30″ to obtain the $I_{\mathrm{CO}}$ values for the ratio. The noise levels are the same as quoted for M51.

Figure 2 shows the distribution of $I_{\mathrm{CO}}/T_{20}$ versus galactocentric radius; the results are consistent with those found for M51.

### 2.2.3. *IC 342*

The CO intensities for IC 342 were also taken from Young & Scoville (1982). They found an exponential fit with parameters $I_o = 12.7$ K km s$^{-1}$ and $R_o = 4.1$ kpc. Condon's (1987) map of IC 342 did not recover all of the flux density; Gräve & Beck (1988) provide flux densities ($\nu = 4.75$ GHz) as a function of galactocentric radius in the disk from a single-dish survey. The flux densities were scaled to 1.49 GHz and converted to brightness temperatures. Values were taken every 45″ for the calculation of the ratio.

The bump in the distribution of $I_{\mathrm{CO}}/T_{20}$ versus galactocentric radius appears larger than in either M51 or NGC 6946. Since the linear beam size is smaller (1.3 kpc as compared to 2.8 for the other two), this larger bump further confirms our suspicion that the $I_{\mathrm{CO}}/T_{20}$ relationship begins to break down on such scales.

### 2.2.4. *M83*

The radio continuum data was taken from Condon (1987). Combes et al. (1978) surveyed the CO emission in the inner

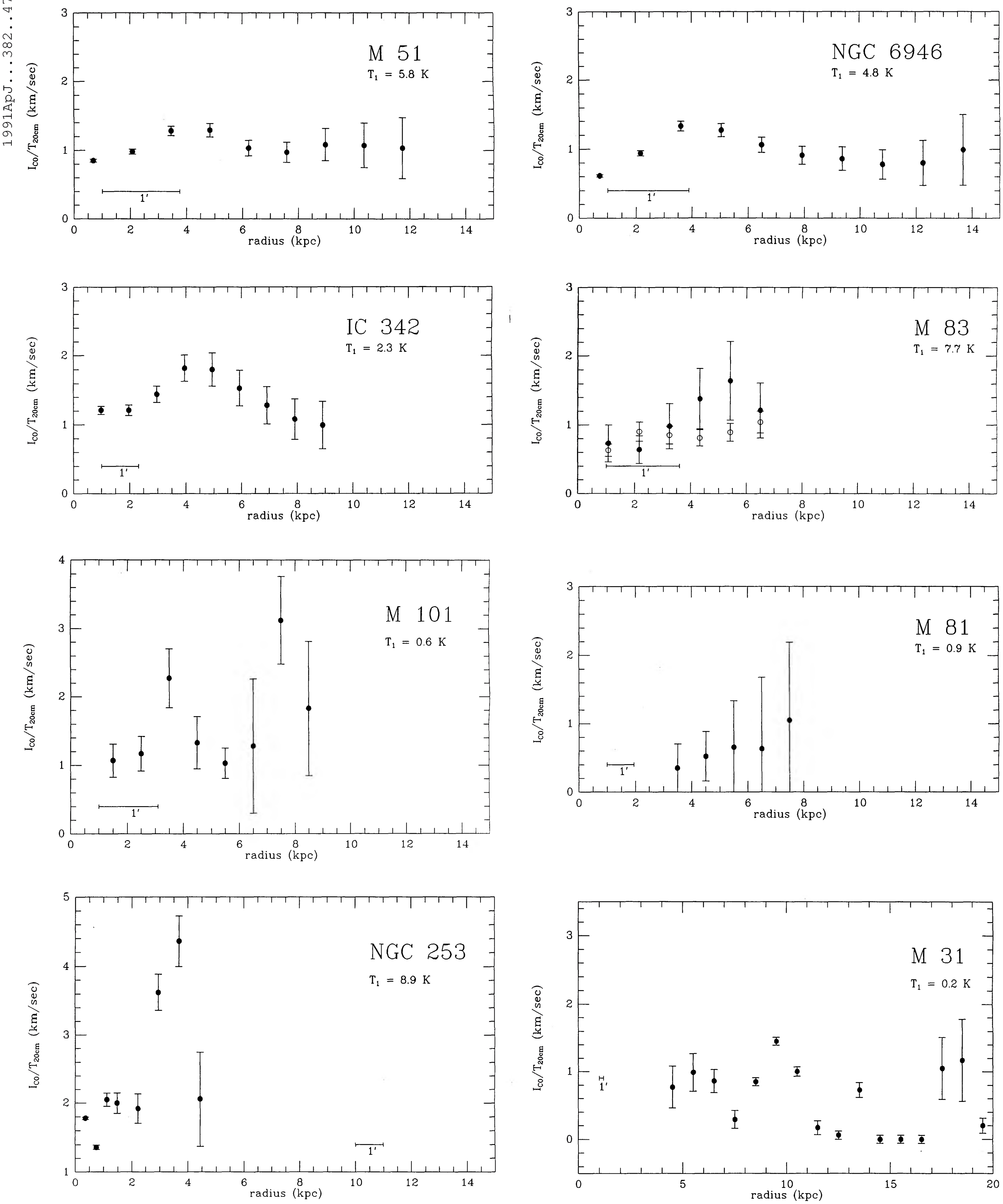


FIG. 2.—Ratio of integrated CO intensity to 20 cm radio continuum brightness temperature vs. galactocentric radius for the eight spirals in our sample. $T_1$ refers to the radio continuum brightness temperature at one scale length. The error bars correspond to the respective noise quoted in the literature. The plot for M83 includes data from L87 (*filled circles*) and C78 (*open circles*).

disk and determined a radial distribution of $I_{CO}$ out to a radius of 3′. Their fit was used to generate an $I_{CO}/T_{20}$ value every 25″; these points are represented by open circles in Figure 2. However, since the Combes et al. (1978) distribution was fit to only six data points, it is not a very reliable indicator of the radial distribution of $I_{CO}$. A more complete survey is provided by Lord (1987), who surveyed 21 positions throughout the disk. This data was converted to the disk of the galaxy and binned every 25″; it is displayed as filled circles in Figure 2.

#### 2.2.5. *M81*

The radio continuum distribution was taken from a survey of Beck, Klein, & Krause (1985) at 6.3 cm. Values were taken from their plot of brightness temperature versus galactocentric radius and converted to 20 cm using the published spectral index of $\alpha = 0.64$. The CO data was taken from a recent study of Baudry, Brouillet, & Combes (1988) which allowed detections to a much lower level than previously attainable. These values were corrected for the inclination of the galaxy and binned every 1 kpc. Figure 2 shows that despite the low amounts of both radio continuum and CO emission, the results are in agreement with the other galaxies in the survey. The CO observations did not go into the center of the galaxy, hence $I_{CO}/T_{20}$ values could only be computed outside of 3 kpc.

#### 2.2.6. *M101*

The distributions of both the CO and radio continuum emission were not easily obtained for this galaxy. The radio continuum brightness temperatures are taken from Israel, Goss, & Allen (1975). A 1.41 GHz map was used to generate brightness temperatures along the major axis; some interpolation was necessary to get values every kpc. The CO data was taken from a plot of $I_{CO}$ versus radius by Solomon et al. (1983); these values were also binned every kiloparsec. Figure 2 shows that despite the rough method used to obtain the ratios, the results are consistent with the other galaxies in our survey.

#### 2.2.7. *NGC 253*

Radio continuum data from Klein et al. (1983) at 10.7 GHz were available along the major axis only. The brightness temperatures were converted to 20 cm values using the published spectral index of $\alpha = 0.72$. The CO data was taken from the major axis data from Scoville et al. (1985). The azimuthal average thus used only the data from both sides of the center of the galaxy. The high ratios depart from the relationship found in the other galaxies. This result supports the previous findings that on small linear scales, the $I_{CO}/T_{20}$ relationship appears to no longer be constant.

#### 2.2.8. *M31*

The radio continuum emission was taken from a map at 11.1 cm by Beck (1982), which was already averaged in kiloparsec bins and corrected for the inclination of the galaxy. We converted to 20 cm using the quoted spectral index of $\alpha = 0.88$. The CO data is taken from a recent survey by Dame et al. (1991) who used the 1.2 m telescope of the Center for Astrophysics with a resolution of 8.′7, with a beam spacing of 4.′5. Figure 2 shows that the ratio in the inner 10 kpc is generally around 1, with the CO ring at 10 kpc (Dame et al. 1991) evident in the slightly higher $I_{CO}/T_{20}$ values at that point. Except for some radii with very little CO emission (giving an $I_{CO}/T_{20}$ value of zero) the ratio stays at approximately 1 up to 19 kpc. It is interesting to compare this to data taken with a smaller beam. Stark (1985) looked at several points along the major axis on each side of the center of the galaxy using the Bell Labs Telescope with a resolution of 1.′7. Using this data for $I_{CO}$, the values of $I_{CO}/T_{20}$ are much higher with a lot more scatter. The average $I_{CO}/T_{20}$ using the Stark (1985) data is $2.15 \pm 0.91$. This is probably due to the fact that the Stark (1985) data corresponds to a very different linear size scale (0.3 kpc) than any of the other CO surveys studied so far ($\geq 1$ kpc). It thus appears that what we are again seeing is a departure from the observed $I_{CO}/T_{20}$ relationship on small linear scales. Since the CO is highly concentrated to the arms (Stark 1985), it makes sense that the CO will dominate (and $I_{CO}/T_{20}$ will therefore increase) when looking at a spiral arm region. It thus appears that the breakdown of the constant ratio between the CO intensity and radio continuum brightness temperature occurs on size scales of roughly 1 kpc and is due to an increase in the CO intensities on these scales.

#### 2.2.9. *M82*

The galaxy M82 is a well-known starburst galaxy with a very high level of radio continuum emission in the nucleus. The data of Condon (1987) was used for the radio continuum maps. Young & Scoville (1984) give major axis values for the CO intensity; an average of the values on each side of the center were used. The CO data extends out to less than 3 kpc, so we do not include this galaxy in Figure 2. The high levels of radio continuum emission in the nucleus are evident in the fact that there are very low values of $I_{CO}/T_{20}$ ($\leq 0.2$) in the inner two kpc. As the radio continuum disk begins to fall off, the values of $I_{CO}/T_{20}$ begin to return to values similar to the other galaxies in the survey.

Inspection of Figure 2 shows that for most of the galaxies surveyed $I_{CO}/T_{20}$ *is roughly constant over the disk of each galaxy* up to a radius of 19 kpc, beyond which no reliable CO data exists. The high-inclination systems have a fair amount of scatter in the data, making it difficult to reach conclusions about these galaxies.

Not only is $I_{CO}/T_{20}$ roughly constant in a given system, but *it is also quite constant from galaxy to galaxy*. Table 1 shows that the average value of $I_{CO}/T_{20}$ ranges from 0.6 to 2.4 km s$^{-1}$ for all of the galaxies in the survey; the average value is $\langle I_{CO}/T_{20} \rangle = 1.3 \pm 0.6$. Excluding the high inclination systems gives a range of 0.6 to 1.6, with an average value of $\langle I_{CO}/T_{CO} \rangle = 1.1 \pm 0.3$. The constancy of this ratio is all the more remarkable when one considers that it holds for a range of almost two orders of magnitude in surface brightness.

These results are in agreement with a similar (but less detailed) study along the major axes of a larger number of galaxies. Devereux & Young (1990) studied the distribution of CO along the major axes of 65 spirals from the FCRAO Extragalactic CO survey (Young et al. 1991). They used the Condon (1987) maps for the radio continuum data. From their sample, they determine that there is no systematic increase or decrease in the ratio of the CO intensity to radio continuum emission as a function of radius in the majority (~90%) of systems. They do find five galaxies (including M82) where the ratio of CO intensity to radio continuum emission increases as a function of radius in the disk. They interpret this as meaning that the star formation efficiency decreases as a function of radius in these systems, but that the majority of the galaxies studied have star formation efficiencies that do not systematically increase or decrease with radius.

Our values are also in good agreement with those of Israel & Rowan-Robinson (1984), who find that $I_{CO}/\sigma_{21} = 0.15$–$0.45$ in the disks of their sample galaxies, where $\sigma_{21}$ is the mean radio surface brightness at 21 cm in units of mJy arcmin$^{-2}$. When these values are converted to $I_{\rm CO}/T_{20}$, their range of values is 0.79–2.38, in excellent agreement with the values found in our survey.

While our observational results agree with the work of these other surveys, our interpretation of the results is different. Israel & Rowan-Robinson (1984) explain the occasional lack of correlation in the disks to a lack of CO around H II regions (where the parent clouds have presumably been destroyed by star formation). However, they agree that the thermal fraction of the radio continuum emission is small and variable (5%–25%), so it cannot affect the correlation to any significant degree. In our results the deviations from a constant $I_{\rm CO}/T_{20}$ ratio on small scales are due to the different spatial structure of the CO when compared to the more uniform distribution of nonthermal radio continuum. Devereux & Young (1990) attribute the relationship solely to star formation, but they fail to take into account the lack of correlation on small spatial scales. We conclude that while star formation in a broad sense is undoubtedly the primary cause of the observed relationship, some other mechanism(s) must make a contribution in order to fully explain the various properties of the relationship (see the introduction and § 2.3).

### 2.3. *Smaller Scales*

The results of our survey seem to show that as galaxies are studied with smaller linear beam sizes ($\sim$1–2 kpc), the ratio of CO intensity to radio continuum brightness temperature departs from the constant value it has on larger length scales, with $I_{\rm CO}$ beginning to dominate the ratio. Interferometer maps of the CO emission in nearby spiral galaxies allow us to study the relationship on subkiloparsec scales. Since interferometer maps typically recover only 25%–50% of the total flux density, the "missing flux-density" must be restored before comparison to the radio continuum is made.

A recent high-resolution, fully sampled CO interferometer map of M51 of Adler et al. (1991) makes the comparison possible. They used a single-dish map to generate short-spacing tracks to fill in the "missing" interferometer spacings, the result of which is a fully sampled map of two 2′ fields in the central region of the galaxy with a synthesized beamwidth of 7″ × 11″ (corresponding to 350 × 550 pc at a distance of 9.6 Mpc). As in previous (interferometer-only) maps (Lo et al. 1987; Vogel, Kulkarni, & Scoville 1988; Lo et al. 1989; Rand & Kulkarni 1990), they found that the distribution of CO in the disk is highly clumpy and primarily confined to the arm regions. A map of the nonthermal radio continuum emission in M51 (Tilanus et al. 1988) shows a distribution which is much smoother and not as tightly confined to the arms as the molecular gas. Thus on scale sizes on the order of an arm width (1–1.5 kpc for M51, Adler et al. 1991) and smaller, the ratio of CO intensity to nonthermal radio continuum is larger than the constant value found from the intermediate size scales for the general disk emission (§ 2.2).

These results agree with the results from the current survey for galaxies with small linear beam sizes (i.e., NGC 253, IC 342, and M31 for the Stark 1985 data). It was also apparent from the $I_{\rm CO}/T_{20}$ plot for IC 342 that the bump at a radius of 4 kpc was larger than for NGC 6946 or M51; the linear beam size for IC 342 is $\sim$1 kpc, while it is almost 3 kpc for the other two. Clearly, some mechanism begins to dominate the gas heating processes when viewing galaxies on length scales of $\gtrsim$2 kpc to create the observed relationship between the CO and nonthermal radio continuum emission. It is only when we approach length scales on the order of spiral arm widths (1–2 kpc) that we begin to see the $I_{\rm CO}/T_{20}$ ratio increase in the regions of spiral arms. The importance of this length scale is discussed in the next section.

## 3. DISCUSSION

On a global scale, a relationship is seen to exist in spiral galaxies between the integrated CO intensity and the total nonthermal radio continuum flux density. The relationship continues on intermediate length scales of $\geq$2 kpc. Furthermore, the ratio stays fairly constant not only in the galactic disks (up to galactocentric radii of 20 kpc) but also from galaxy to galaxy. When investigating length scales on the order of less than 1–2 kpc through either high-resolution surveys of spiral arms in external galaxies or GMCs in the Galaxy, it becomes apparent that the relationship ceases to hold in the neighborhood of spiral arms, with CO generally dominating the ratio.

It is important to note at this point that sampling regions of CO emission in spiral galaxies on various length scales as we have done in this survey is actually equivalent to sampling regions which are dominated by different heating mechanisms. For the global scale as discussed in § 2.1, the CO emission will be dominated by the molecular gas in the interarm regions, which is heated primarily by cosmic rays and encompasses the majority of the disk area. The contribution by the arm regions, which are heated primarily by young stars, will get "smeared out" in these large beams. It is the heating mechanisms in the low-density, low-excitation temperature regions of the interarm regions (which have relatively few young stars) which will determine the properties of the observed emission in the beam. The azimuthal averaging performed in § 2.2 will have the same smearing effect, since at any given galactocentric radius, the majority of the (spatial) contribution to the bin will also be from the low-density interarm regions. Surveys using individual beams with linear scales on the order of several kpc (Israel & Rowan-Robinson 1984; Devereux & Young 1990) will show the same effect, albeit to a lesser level. It is not until surveys are performed with small linear beams that the contribution from high-density clumps with high surface brightness and nearby sources of excitation becomes more important.

In the Galaxy, it appears that molecular clouds and cloud complexes in the arms are warmer than the interarm gas (Solomon, Sanders, & Rivolo 1985). Assuming that clouds in external galaxies show the same trends, by surveying small length scales *in spiral arms*, the observed CO intensities will be dominated by emission from gas heated by nearby hot young stars. For the low molecular hydrogen densities ($\leq$few $\times 10^3$ cm$^{-3}$) it is expected that cosmic ray heating alone is sufficient to balance the gas cooling (Goldsmith & Langer 1978). However, for hotter and denser gas, as would be found in the spiral arms, it is expected that cosmic ray heating is no longer the dominant heating mechanism; other processes act here to raise the CO cloud temperatures above the values due to cosmic ray heating alone. Therefore, the CO emission will dominate over the nonthermal radio continuum emission and $I_{\rm CO}/T_{20}$ becomes large. When surveying the *interarm* region with a small linear beam the constancy of the observed ratio still holds, since there appear to be no significant clumps of CO emission (M51—Adler et al. 1991) and the low-levels of CO emission (Garcia-Burillo & Guelin 1991) and radio-continuum emission (Tilanus et al. 1988) are both fairly smooth. The beam in these regions will be sampling lower density and lower temperature regions than in the arms, and since there are few hot young stars in the interarm regions, cosmic ray heating will dominate, thereby leading to a constant $I_{CO}/T_{20}$ ratio. We therefore expect that as more high-resolution, fully sampled maps of the CO and nonthermal radio continuum emission become available, the $I_{CO}/T_{20}$ ratio will be seen to hold at a constant value ($\sim 1$–1.5) in the interarm regions, but to become larger and more variable in the arm regions.

At this point, it is useful to explore possible scenarios as to why the relationship between the CO and nonthermal radio continuum emission exists. It is always possible that what we are seeing is just a continuation of the "richness effect" mentioned in § 2.1, i.e., that larger galaxies simply have more of everything. While we cannot rule this out entirely, it appears to be unlikely. Since $I_{CO}/T_{20}$ holds for such a large range of surface brightness in both the individual disks and from galaxy to galaxy, it appears that the relationship cannot be attributed simply to a richness effect.

Another possibility is that both the nonthermal radio continuum emission and CO emission have a *common* origin. Star formation is the obvious process that woud likely give rise to each of these quantities. Hydrogen recombination lines (mostly H$\alpha$ and H$\beta$) are often used to trace sites of recent star formation. Kennicutt (1983) compares the total H$\alpha$ flux to the total galactic radio flux density for 83 galaxies and finds a good correlation. Verter (1988) finds a good correlation between CO luminosity and the H$\alpha$ emission for a sample of 20 galaxies. So on a global scale, it appears that there may be cause to consider recent star formation as the origin of both the CO and nonthermal radio continuum emission. Of course, global properties have the problem with the richness effect, so it would be useful to look at the correlations in the disks.

On intermediate size scales, the distribution of H$\alpha$ emission does not always follow that of the CO and nonthermal radio continuum emission. Recent high-resolution observations of M83 (Allen, Atherton, & Tilanus 1986) and M51 (Tilanus et al. 1988; Vogel et al. 1988; Rand & Kulkarni 1990; Adler et al. 1991) show that the H$\alpha$ emission is shifted downstream from the nonthermal radio continuum emission and the dust lanes. In M51, the molecular arm is aligned with the dust lane (Vogel et al. 1988; Rand & Kulkarni 1990), while in M83 the CO is shifted downsteam from the dust lane, aligned with the H$\alpha$ emission (Wiklind et al. 1990; Lord & Kenney 1991). The CO is very clumpy and appears to be highly restricted to the arms (Adler et al. 1991); the H$\alpha$ emission is restricted to the arms, with most clumps not corresponding to the molecular clumps (Allen et al. 1986; Tilanus et al. 1988; Wiklind et al. 1990; Lord & Kenney 1991); and the nonthermal radio continuum emission, while having a modest concentration to the arms, is generally quite smooth in its distribution. The $z$-scale heights are also quite different; for NGC 891, the CO is seen to be confined to a very thin disk (Sofue, Nakai, & Handa 1987), while the nonthermal radio continuum emission has a much larger $z$-extent (Allen, Baldwin, & Sancisi 1978). It therefore appears that on intermediate and larger length scales, the H$\alpha$ emission is not always a reliable tracer of either the CO or nonthermal radio continuum emission.

Also, a problem arises when trying to determine the source of the star formation activity in the disks of spirals of varying morphological types. It is generally held that star formation activity (as measured by H$\alpha$ luminosities) is higher for the late-type galaxies (Kennicutt & Kent 1983). One would then naturally assume that the late-type galaxies have a higher level of total gas mass (needed to feed the star formation activity) than the earlier types. However, in a recent paper by Young & Knezek (1989), it was shown that the total interstellar gas mass per unit disk area in early-type galaxies is not significantly less than for late-type galaxies.

We therefore conclude that while star formation in a broad sense is likely to be the dominant cause of the observed relationship between CO and nonthermal radio continuum emission, some other mechanism must make a significant contribution to account for the discrepancies listed above.

Another possible explanation for the observed ratio is that there is a *direct* relationship between the CO and nonthermal radio continuum emission, i.e., either bright CO causes bright nonthermal radio continuum, or bright nonthermal radio continuum emission causes bright CO. At this time, there is no known method to have CO emission give rise to nonthermal radio continuum emission. However, if there is a mechanism that causes bright nonthermal radio continuum emission because of an increase in cosmic ray electron density, we can heat the CO by using the accompanying cosmic ray protons.

By determining the dependence of $I_{CO}$ on the density of cosmic ray protons, we can use the observed $I_{CO}/T_{20}$ ratio to make some statement about the dependence of the synchrotron brightness at 20 cm (i.e., the equivalent Rayleigh-Jeans brightness temperature, $T_\nu$) on the cosmic ray density. For low molecular hydrogen densities ($\leq$ a few $\times\ 10^3\ \mathrm{cm}^{-3}$), and excitation temperatures on the order of 6–15 K, cosmic ray heating alone appears to be sufficient to balance gas cooling (Goldsmith & Langer 1978). By assuming that the molecular clouds in external galaxies behave the same as molecular clouds in the Galaxy, we can use the cooling curves of Goldsmith & Langer (1978) to determine the dependence of $I_{CO}$ on the density of cosmic ray protons.

By balancing the cosmic ray heating rate and computed cooling rate (Goldsmith & Langer 1978), we can determine the relationship between the kinetic temperature of the cloud ($T_k$) and the density of cosmic ray protons ($n_{crp}$). Goldsmith & Langer (1978) compute cooling curves for kinetic temperatures of 10, 20, and 40 K; for densities below a few $\times\ 10^3\ \mathrm{cm}^{-3}$, we get $T_k \propto n_{crp}^{0.4-0.9}$. If we assume we are dealing with optically thick CO emission with a constant filling factor from beam to beam, $T_A \propto T_k$. If we also assume the distribution of cloud sizes does not change as a function of position in the galaxy (on size scales of several kiloparsec) or from galaxy to galaxy, we can write $I_{CO} \propto T_k$, due to the presence of a size-line width relationship for molecular clouds. From the above expression for $T_k$, we can write $I_{CO} \propto n_{crp}^{0.4-0.9}$. By taking the density of cosmic ray electrons ($n_{cr}$) proportional to the density of cosmic ray protons, this can be written $I_{CO} \propto n_{cr}^{0.4-0.9}$. Then using our constant ratio of $I_{CO}/T_{20}$, we infer that the brightness of synchrotron emission goes as

$$T_\nu \propto n_{cr}^{0.4-0.9} . \tag{1}$$

At first sight, this result appears to contradict the well-known expression for the synchrotron volume emissivity:

$$\eta_\nu \propto n_{cr} B^{1.7} \nu^{-0.7} \tag{2}$$

from an ensemble of relativistic electrons with a density distribution of:

$$n(E) = n_{cr} E^{-2.4} . \tag{3}$$

For flux freezing in a perfectly compressible ISM, $B \propto n_{\rm cr}^{2/3}$, and

$$T_\nu \propto \int \eta_\nu \, dl \propto n_{\rm cr}^{2.1} \nu^{-2.7} \, . \tag{4}$$

However, there is a strong inverse coupling of $n_{\rm cr}$ with the magnetic field $B$ in the interstellar medium owing to streaming of cosmic rays along field lines away from high-density regions and the subsequent growth of magnetic instabilities (Parker 1965). It is expected that the result of this coupling will be to substantially reduce the density dependence of $T_\nu$, but up to now the theory has not been able to provide the value of the exponent in the equation $T_\nu \propto n_{\rm cr}^x$. Our results can be interpreted as providing an observationally determined value of $x = 0.4$–$0.9$ over a wide range of density and length scales in galactic disks.

## 4. CONCLUSIONS

The findings of this paper can be summarized as follows:

1. We have reconfirmed earlier results (Israel & Rowan-Robinson 1984) showing a good correlation between the integrated CO intensity and total radio continuum flux density on a global scale. We attribute the correlation on this scale at least partially to a "richness effect," namely that larger galaxies simply have more of everything.

2. We have also found that the ratio of velocity-integrated CO surface brightness to nonthermal radio continuum brightness temperature remains constant over the disks of individual galaxies up to galactocentric radii of 19 kpc. The ratio not only remains constant in the disks of individual galaxies, but also from galaxy to galaxy. This is quite remarkable when considering that the range of surface brightness over the sample is over two orders of magnitude. For the eight galaxies in our sample, the average ratio is $\langle I_{\rm CO}/T_{20} \rangle = 1.3 \pm 0.6$.

3. On small linear scales, we find that the observed ratio is no longer constant when looking at complexes of clouds in the spiral arms of external galaxies, with the CO emission dominating the ratio.

4. We attribute the existence (and lack) of this correlation to the inference that the bulk of the CO emission from galactic disks arises from molecular gas heated by cosmic rays. The presence of these cosmic rays provides a source for the nonthermal radio continuum emission, thus balancing the presence of molecular emission in the $I_{\rm CO}/T_{20}$ ratio. When looking at the spiral arms, cosmic rays are no longer the primary source of heating; other mechanisms, such as hot young stars, act to raise the gas temperature and therefore the brightness of the CO.

5. The $I_{\rm CO}/T_{20}$ relationship is used to show that the dependence of the brightness of synchrotron emission on the density of cosmic ray electrons is $T_\nu \propto n_{\rm cr}^{0.4-0.9}$, in rough agreement with theoretical expectations. This result depends on the assumption that the distribution of cloud sizes is roughly the same within a given galaxy (on size scales of several kpc) as well as from galaxy to galaxy.

6. While star formation in the general sense is most likely the primary cause of this relationship, some other mechanism(s) are needed to help explain the discrepant $z$-scale heights and differences in the small-scale distributions of the CO and nonthermal radio continuum emission.

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