THE ASTROPHYSICAL JOURNAL, 399:573–575, 1992 November 10

A SURFACE BRIGHTNESS CORRELATION BETWEEN CARBON MONOXIDE AND NONTHERMAL RADIO CONTINUUM EMISSION IN THE GALAXY

R. J. ALLEN
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
Received 1992 March 18; accepted 1992 May 7

ABSTRACT

The relation between the projected face-on velocity-integrated CO (1–0) brightness I_{CO} and the 20 cm nonthermal radio continuum brightness T_{20} is examined as a function of radius in the Galactic disk. Averaged in 1 kpc annuli, the ratio I_{CO}/T_{20} is nearly constant with a mean value of 1.51 ± 0.34 km s^{-1} from 2 to 10 kpc. This value is very close to that reported recently for the disks of eight normal spiral galaxies (Adler, Allen, & Lo), where $\langle I_{CO}/T_{20} \rangle = 1.3 \pm 0.6$ km s^{-1} in spite of the fact that the values of surface brightness in CO and radio continuum in the sample vary by more than a factor of 100.

The manner in which I_{CO} and T_{20} are derived for the Galaxy is different in several significant respects from the more direct observational determinations possible in nearby galaxies. The fact that the Galaxy also follows this correlation further strengthens the generality of the result.

Subject headings: ISM: molecules — radio continuum: interstellar

1. INTRODUCTION

The fact that nearby normal disk galaxies with strong CO (1–0) emission are also bright in nonthermal radio continuum emission was first noticed by Rickard, Turner, & Palmer (1977). With the instrumentation available at that time, CO emission had been detected coming from the central few arcminutes in six disk galaxies out of a total observed sample of 15. These six CO–bright galaxies also had bright radio continuum disks, with average 20 cm surface brightness $\langle T_{20} \rangle$ in excess of about 1.5 K, whereas the remaining nine galaxies which were not (yet) detected in CO had (with one exception) radio disks which were generally fainter than this value. Rickard et al. suggested that a "rough correlation" may be expected since bright CO emission had already been linked to the active formation of massive stars, and the accompanying increase in numbers of supernovae would lead to increased cosmic-ray density and hence to brighter nonthermal radio continuum. This theme was subsequently pursued by Israel & Rowan-Robinson (1984) who, for a sample of 28 galaxies with types in the Sb–Sc range, found a statistical correlation between the CO (1–0) line strength observed at the center of a galaxy with a 1′ beam and the mean radio continuum surface brightness. In addition, they showed that the correlation persisted on a point-to-point basis for seven galaxies in that sample which were large enough to have I_{CO} measured at several positions. They interpreted this correlation in terms of the efficiency of OB star formation in galaxy disks.

A more detailed study of the relation between CO (1–0) emission and the nonthermal radio continuum has been carried out recently by Adler, Allen, & Lo (1990, 1991). These authors examined the ring-averaged radial distributions of I_{CO} and T_{20} on length scales of 1–3 kpc for a sample of eight nearby galaxies. They showed that the ratio I_{CO}/T_{20} not only remains nearly constant over the disk of each galaxy (with a slight but clearly significant increase in the 4–6 kpc range of radius in several galaxies), but that this ratio is also numerically very similar from one galaxy to another. Whereas the individual values of I_{CO} and T_{20} vary by more than a factor of 100, the ratio I_{CO}/T_{20} remains in the range of 0.6–2.4 with a mean of 1.3 ± 0.6. If we could view the Galaxy face-on from a great distance as we have done for the other eight galaxies in the sample of Adler et al., would we also see the same I_{CO}–T_{20} correlation? This paper answer that question, in the affirmative, and, therefore, provides additional constraints on the "massive-star-formation ⇒ supernovae ⇒ cosmic rays" scenario.

2. DATA ON I_{CO} AND T_{20} FOR THE GALAXY

2.1. CO (1–0) *Data*

Two major surveys of the CO (1–0) distribution have been made over a wide range in Galactic longitude and latitude: the "Massachusetts–Stony Brook Survey" (Sanders et al. 1986; Clemens, Sanders, & Scoville 1988), and the "Columbia Survey" (Cohen, Dame, & Thaddeus 1986; Bronfman et al. 1988). Of these two, the "Columbia Survey" satisfies the present need better since it includes data from virtually identical radio telescopes in both the northern and southern hemispheres and, therefore, permits the construction of an axisymmetric Galactic model of the CO (1–0) emission for the average of both the first and the fourth galactic quadrants. Such a model is also available for the nonthermal radio continuum as will be discussed later. Of course, the observations which Bronfman et al. analyze consist of CO profiles at an enormous number of sky positions, each profile representing the integrated intensity along the line of sight. The "deprojection" into a distribution of *volume emissivity* involves fitting the parameters of a model CO distribution to the observed profiles, assuming a standard Galactic rotation curve with $V_c = 250$ km s^{-1} and solar distance $R_\odot = 10$ kpc. The axisymmetric model adopted by Bronfman et al. assumes that the CO emissivity can be represented in the form

$$\epsilon(R, z) = \epsilon_0(R) \exp\{-\ln 2 \times [z - z_0(R)]^2/[z_{1/2}(R)]^2\}, \quad (1)$$

where $\epsilon(R, z)$ is the volume emissivity of CO (1–0) in K km s^{-1} kpc^{-1} and $z_{1/2}(R)$ is the half-width at half-maximum of the CO disk (about 75 pc). These parameters are tabulated by Bronfman et al. as a function of Galactic radius (their Table 3 and their Fig. 9) at intervals of 0.5 kpc from 2.25 to 9.75 kpc; it is

TABLE 1

RADIAL DEPENDENCE OF THE MEAN SURFACE BRIGHTNESS IN CO AND IN NONTHERMAL RADIO CONTINUUM EMISSION FOR THE GALAXY, AVERAGED IN 1 kpc ANNULAR RINGS

R (kpc) (1)	I_{CO} (K km s^{-1})[a] (2)	T_{20} (K)[b] (3)	I_{CO}/T_{20} (km s^{-1}) (4)
0.50..........	...	1.10 ± 0.15	
1.50..........	...	0.61 ± 0.08	
2.50..........	0.40 ± 0.09	0.34 ± 0.05	1.19 ± 0.31
3.50..........	0.76 ± 0.06	0.50 ± 0.07	1.50 ± 0.24
4.50..........	1.33 ± 0.09	0.90 ± 0.12	1.47 ± 0.22
5.50..........	1.60 ± 0.08	0.78 ± 0.11	2.05 ± 0.30
6.50..........	1.24 ± 0.06	0.72 ± 0.10	1.71 ± 0.25
7.50..........	1.16 ± 0.08	0.66 ± 0.09	1.77 ± 0.28
8.50..........	0.68 ± 0.08	0.50 ± 0.07	1.36 ± 0.25
9.50..........	0.38 ± 0.23	0.39 ± 0.05	0.99 ± 0.62

[a] Computed from data in Bronfman et al. 1988.

[b] 408 MHz data from Beuermann et al. 1985 courtesy E. Berkhuijsen, converted to 20 cm using a spectral index of 2.85 ± 0.10 from Reich & Reich 1988.

their "combined fit" values which are of interest here. From these parameters it is easy to determine the "face-on" surface brightness I_{CO}:

$$I_{CO} = \sqrt{\pi/\ln 2} \times \epsilon_0(R) z_{1/2}(R) . \quad (2)$$

This is calculated in Table 1; the data have been averaged into 1 kpc annuli for comparison with the radio continuum results and the sample of Adler et al. The uncertainties listed in column (2) have been calculated from the errors in $\epsilon_0(R)$ and $z_{1/2}(R)$ given by Bronfman et al., taking account of the averaging in radius done here. Their model fits do not provide results outside the solar circle $R_\odot$ where the determination of distance is much more uncertain and requires a number of additional assumptions.

As an indication of the accuracy of the CO data, it is interesting to compare the northern hemisphere results of Bronfman et al. with those of Sanders et al. For instance, at a radius of 5 kpc, the maximum volume emissivities in the plane near $Z = 0$ are about 14 and 23 K km s^{-1} kpc^{-1}, respectively, which is cetainly a significant difference. But the FWHMs of the Galaxy CO disk derived by the two groups are about 150 and 90 pc, leading to virtually identical "face-on" values of I_{CO} of 2.10 and 2.07 K km s^{-1}. This similarity of the averaged and integrated I_{CO} results of the two surveys extends over the range of northern hemisphere Galactic radius common to both. As described above, we use the all-sky averaged results of Bronfman et al. in order to obtain a radial distribution of I_{CO} which is representative of the Galaxy as a whole.

2.2. *Radio Continuum Data*

The history of radio continuum surveys of the Galaxy is much older than that of the CO surveys, but the earlier observations were generally taken at frequencies of 200 MHz or lower (see, for example, the summary in Haslam et al. 1981)[1]. An all-sky survey of the Galaxy at 20 cm (1490 MHz) is not yet available in the literature, but there are surveys at 408 MHz, and the spectral index of the Galactic background is known well enough to permit a sufficiently accurate extrapolation to 20 cm. The 408 MHz all-sky survey by Haslam et al. (1981 and references therein) has been used to constrain an axisymmetric model of the Galaxy by Beuerman, Kanbach, & Berkhuijsen (1985) in order to derive the radial dependence of volume emissivity and face-on surface brightness. The main results of present interest are in Figure 6 of Beuermann et al. which gives the volume emissivities $\epsilon_n(R)$ and $\epsilon_b(R)$ of the thin (n) and thick (b) disks as a function of radius. These authors also define an "equivalent width" $Z_{eq,b}(R)$ of the thick disk in their model as follows:

$$Z_{eq,b}(R) = 3.6 \times \exp [(R - 10)/10] , \quad (3)$$

for R and Z in kpc. The thin disk "equivalent width" is fixed at $0.1Z_{eq,b}(R)$. The face-on surface brightness is then computed from

$$T_{408}(R) = Z_{eq,b}(R)[\epsilon_b(R) + 0.1\epsilon_n(R)] . \quad (4)$$

The spectral index of the Galactic background has also been the subject of much observational work in the past. A summary of previous, generally lower frequency work is given by Reich & Reich (1988), who also provide new results between 408 and 1420 MHz based on their own 20 cm survey of the northern sky. These authors provide the parameters for a circularly symmetric model of the spectral index distribution for the Galaxy which is relevant for the 408–1420 MHz range of frequencies. Near the Galactic plane the nonthermal emission for $R \leq 7$ kpc has a brightness temperature spectral index of -3.10; if we added to this the small contribution by thermal emission at $Z = 0$ ($\sim 15\%$ at 408 MHz), this value flattens slightly to -2.85. The value -2.85 is also relevant for $R > 7$ kpc; the contribution of thermal emission there is thought to be negligible. How the spectral index varies with Z in the Galaxy is still controversial. Many authors of earlier work concluded that it became steeper, based on an observed steepening of the emission with increasing Galactic latitude, but this is disputed by Reich & Reich (1988) who suggest that local foreground features have caused confusion at the lower frequencies of the earlier surveys. Fortunately, none of this is very important for our purposes here; since the main contribution to the total *face-on* continuum surface brightness will come from the regions with $Z < 1.5$ kpc, we may safely take a spectral index of -2.85 to apply to the entire disk of the Galaxy. In order to estimate the uncertainty in the final result the spectral index is taken to be -2.85 ± 0.10; this approximately represents the range of values which can be determined from the data in the paper by Reich & Reich, at least within the solar circle. The face-on surface brightness of the Galaxy at 20 cm wavelength is then determined from

$$T_{20}(R) = T_{408}(R)[1490/408]^{-2.85 \pm 0.10} . \quad (5)$$

This quantity is listed in column (3) of Table 1.

In order to rank the radio continuum surface brightness of the Galaxy among the others in the sample by Adler et al. we first need an estimate of the scale length of the Galaxy optical disk. Van der Kruit (1986) has calculated a value of 5.5 ± 1.0 kpc (for $R_\odot = 8.5$ kpc) based on a direct survey of the sky brightness at low resolution by the *Pioneer 10* spacecraft after it passed beyond the asteroid belt. Van der Kruit (1990) has also recently discussed this and other methods of arriving at a scale length and suggested a "best" value of 5.0 ± 0.5 kpc (still for $R_\odot = 8.5$ kpc). This becomes 5.9 ± 0.6 kpc for the value of $R_\odot = 10$ kpc which is used here. At this distance from the center of the Galaxy, the 20 cm surface brightness T_1 is 0.75 K.

3. DISCUSSION

The ratio I_{CO}/T_{20} for the Galaxy is calculated in column (4) of Table 1 and plotted as a function of Galactic radius in

[1] A notable exception is the first 480 MHz map of the northern Milky Way by Reber (1948).

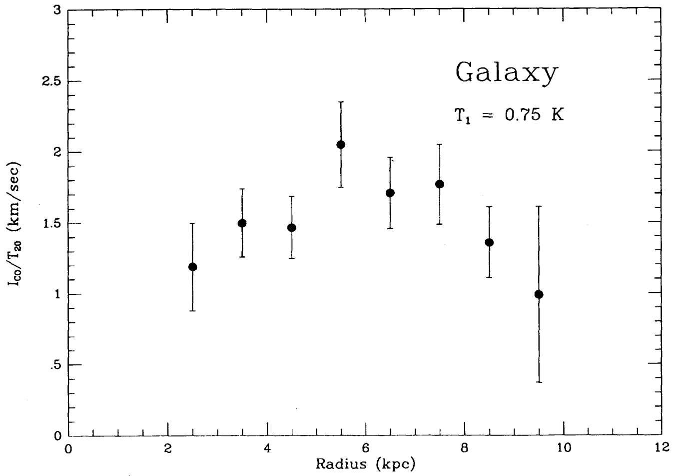

FIG. 1.—Ratio of the velocity-integrated CO surface brightness I_{CO} to the 20 cm radio continuum brightness temperature T_{20}, vs. galactocentric radius for the Galaxy, averaged in 1 kpc annular rings. T_1 is a characteristic surface brightness for the Galactic disk at 20 cm; see text for details. This figure has been constructed assuming $V_c = 250$ km s^{-1} and $R_\odot = 10$ kpc.

Figure 1. The ratio shows no significant variation with R; the mean value of I_{CO}/T_{20} over the range of radius from 2 to 10 kpc is 1.51 km s^{-1}, with a standard deviation of 0.34 km s^{-1} and a mean deviation of 0.13 km s^{-1}. This value is very close to that reported recently for the disks of eight normal spiral galaxies (Adler et al. 1991), where $\langle I_{CO}/T_{20} \rangle = 1.3$ km s^{-1} with a standard deviation of 0.6 km s^{-1} and a mean deviation of 0.23 km s^{-1}. The 20 cm continuum surface brightness of the Galaxy at one scale length is 0.75 K (see § 2), which puts it near the faint end of the sample following IC 342 (with $T_1 = 2.3$ K) and M81 (0.9 K), but before M101 (0.6 K) and M31 (0.2 K). The Galaxy is, therefore, not unusual in this respect. The fact that the numerical value of I_{CO}/T_{20} for the Galaxy is essentially the same as that of the eight galaxies in the sample by Adler et al. is remarkable when one considers the great differences in the methods used to arrive at the individual values of I_{CO} and T_{20}.

The constancy of this ratio across the whole sample, including the Galaxy, is even more remarkable when one considers that the typical FWHM in Z for the CO layer in the Galaxy is ≈ 150 pc, whereas the nonthermal emission is coming from a disk which is about 20 times thicker. It is not unreasonable to assume that a similar disparity exists in the spatial distribution of CO and radio continuum emission in the rest of the galaxies in the sample.

What are the possible explanations for this correspondence between the CO and the radio continuum surface brightnesses? Chance occurrence is unlikely, although never strictly impossible. A simple richness effect, i.e., that "bigger galaxies have more of everything" is a common source of correlation in discussions of global properties of galaxies;[2] however, the correlation presented here is between *surface brightnesses* (albeit on a 1–2 kpc scale length), and it is difficult to appeal to a straightforward richness explanation. As a counterexample, the total H I content of galaxies in atomic hydrogen is correlated with their total optical luminosities, but the distribution of H I surface brightness in galaxy disks almost nowhere follows that of the optical light. The global M_{HI}–$L_\odot$ correlation appears to be dominated by the richness effect. Locally, the optical surface brightness drops faster with radius than the surface brightness in H I on the 1 kpc length scale, and the connection of H I to the star formation process is thought to occur only indirectly through the formation of molecular clouds. This is clearly not the case with the CO brightness and the nonthermal radio continuum brightness, and it appears that we shall have to look for a closer physical connection between these quantities.

Adler et al. (1991) have suggested that the CO–nonthermal radio brightness correlation is a consequence of the fact that the low-energy cosmic-ray protons are the dominant source of heating of the low-density interstellar medium (ISM) (the part to which we are most sensitive on the 1–2 kpc length scale), and the accompanying energetic electrons produce the synchrotron emission. This explanation has the virtue of simplicity but, if true, has at least two interesting consequences not emphasized by Adler et al.: First, it means that the changes in CO brightness are largely an effect of changing excitation and have little to do with the column density of molecular hydrogen; this proposal has been made before, by others and for other reasons, and has elicited strong counterarguments. Second, it is easy to show from equations (1) and (2) of Adler et al. that the magnetic field energy density in the ISM is inversely related to the cosmic-ray density, $B^2 \sim (1/n_{cr})^p$, where p is in the range 0.1–0.7; this result is of considerable interest for the dynamics of cosmic rays. Both of these conclusions are dependent on several simplifying assumptions made by Adler et al. which deserve to be discussed in greater detail than is possible here.

I am grateful to my colleagues at the Kapteyn Astronomical Institute in Groningen for their hospitality during the summer of 1991 when this work was initiated and to E. Berkhuijsen of the MPI in Bonn for details of the data in Beuermann et al. The Space Telescope Science Institute is operated by AURA for NASA under contract NAS5-26555.

[2] See, for example, the discussion on the correlation of the global CO flux with the radio continuum flux density of the whole galaxy in Adler et al. (1991).

REFERENCES

Adler, D. S., Allen, R. J., & Lo, K. Y. 1990, in The Interstellar Medium in External Galaxies: Summaries of Contributed Papers, ed. D. J. Hollenbach & H. A. Thronson, Jr. (NASA Conf. Pub. 3084), 130
———. 1991, ApJ, 382, 475
Beuermann, K., Kanbach, G., & Berkhuijsen, E. 1985, A&A, 153, 17
Bronfman, L., Cohen, R. S., Alvarez, H., May, J., & Thaddeus, P. 1988, ApJ, 324, 248
Clemens, D. P., Sanders, D. B., & Scoville, N. Z. 1988, ApJ, 327, 139
Cohen, R. S., Dame, T. M., & Thaddeus, P. 1986, ApJS, 60, 695
Haslam, C. G. T., Salter, C. J., Stoffel, H., & Wilson, W. E. 1981, A&AS, 47, 1
Israel, F. P., & Rowan-Robinson, M. 1984, ApJ, 283, 81
Reber, G. 1948, Proc. IRE, 36, 1215
Reich, P., & Reich, W. 1988, A&A, 196, 211
Rickard, L. J, Turner, B. E., & Palmer, P. 1977, ApJ, 218, L51
Sanders, D. B., Clemens, D. P., Scoville, N. Z., & Solomon, P. M. 1986, ApJS, 60, 1
van der Kruit, P. C. 1986, A&A, 157, 230
———. 1990, in The Milky Way as a Galaxy, ed. G. Gilmore, I. R. King, & P. C. van der Kruit (Mill Valley: University Science Books), 336