A Relationship Between the Integrated CO Intensity and the Radio Continuum Emission in Spiral Galaxies

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In an effort to determine the role played by cosmic ray electrons and interstellar radiation fields on the collapse of molecular clouds, a survey was begun to investigate the relationship between the radio continuum brightness emission and the integrated CO intensity in spiral galaxies. The investigation was done on two scales; a global galaxy to galaxy comparison of integrated disk values, and a ring-averaged study over the disks of individual galaxies.

For the large-scale survey, radio continuum flux densities integrated over the full disk at 1.49 GHz were taken from Condon (1987) and the total CO fluxes were taken from Verter (1985). The galaxies with values included in the two catalogs are displayed in Figure 1. It can be seen that a good correlation exists between the integrated CO emission and radio continuum emission.

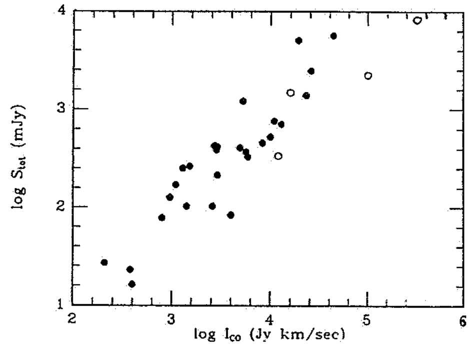

Figure 1. Total radio continuum flux versus total CO flux density for 31 spiral galaxies. Open circles denote galaxies which are missing radio continuum flux.

This is not an unexpected result since the total molecular emission of spiral galaxies has been shown to correlate with several other galactic features. Verter (1988) showed that the total molecular emission depends strongly on galactic scale, with less dependance on galactic morphology. The total CO emission in Verter's sample correlates well with the total HI, Hα, and far-infrared emission, as well as the blue luminosity. Wielebinski (1988) showed a strong linear correlation between CO luminosity and magnetic field strength for ten spiral galaxies. The non-thermal radio continuum of spirals has been shown to correlate well with the far-infrared luminosity (de Jong, *et al.* 1985). So it comes as no surprise to see the strong correlation between total radio continuum emission and integrated CO intensity as displayed in Figure 1. At least some fraction of these global correlations may be related to a "richness" effect: namely, larger galaxies have more of everything.

The next step was to determine if the relationship holds in the disks of individual galaxies. Since only a few spirals have been adequately observed in CO (see Verter 1985 for a list of galactic CO surveys), this part of the survey was limited to a few of the better studied systems. Table 1 lists the galaxies included in this part of the survey.

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Table I. Galaxy Parameters

Galaxy	D Mpc	i (°)	1' on m.a. kpc	radio ref (ν_{GHz})	CO ref	radio beam (")	radio beam (kpc)	CO beam (")	CO beam (kpc)	$T_{20}(r/r_o=1)$ K	$< I_{CO}/T_{20} >$ km/sec
M 51	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
M 83	8.9	26	2.6	C87 (1.49)	L87	54	2.3	50	2.2	7.7	1.74±0.62
					C78			64	2.8		0.85±0.13
M 81	3.3	59	1.0	B85 (4.75)	B88	147	2.5	60	1.0	0.9	0.64±0.26
M 101	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
M 31	0.7	78	0.2	B82 (2.70)	S85a	264	0.9	102	0.3	0.2	2.15±0.91

The radio continuum data was usually presented in the literature in azimuthally-averaged form, corrected for the inclination of the galaxy. The data taken from Condon's (1987) survey was analyzed using an AIPS ring-averaging routine. Data taken at other frequencies was converted to 1.49 GHz using the published spectral index. Flux densities were converted to brightness temperatures when necessary.

The CO maps were generally less complete than the radio continnum maps. The data usually consisted of four or more radial cuts in a given galaxy. In some instances, exponentials were fit to the data (M 51, IC 342, and NGC 6946); these fits were used in this survey. In most cases, the data were converted to the plane of the galaxy and averaged in galactocentric radial bins. The sampling of the CO maps determined the sampling intervals of the CO to radio continuum ratios in the individual galaxies.

The ratio of integrated CO intensity to 20 cm radio contiuum brightness temperature was calculated at each of the sampled radial points for the individual galaxies as shown in Figure 2. For the low-inclination galaxies, I_{CO}/T_{20} *is roughly constant over the disk* up to radii of 14 kpc. The highly inclined systems (NGC 253 and M 31) show a lot more scatter as well as higher I_{CO}/T_{20} values. In the case of M 31, the linear size of the CO beam (0.3 kpc) is much smaller than the other galaxies in the survey. We don't expect to see a CO - radio continuum correlation on this scale, because of the shift of the CO emission from other phases of the ISM seen in the spiral arm regions (Lo *et al.* 1988; Vogel *et al.* 1988). The radio continuum data for NGC 253 was presented only for the major axis, so the uncertainties with this galaxy may be due to a lack of completeness.

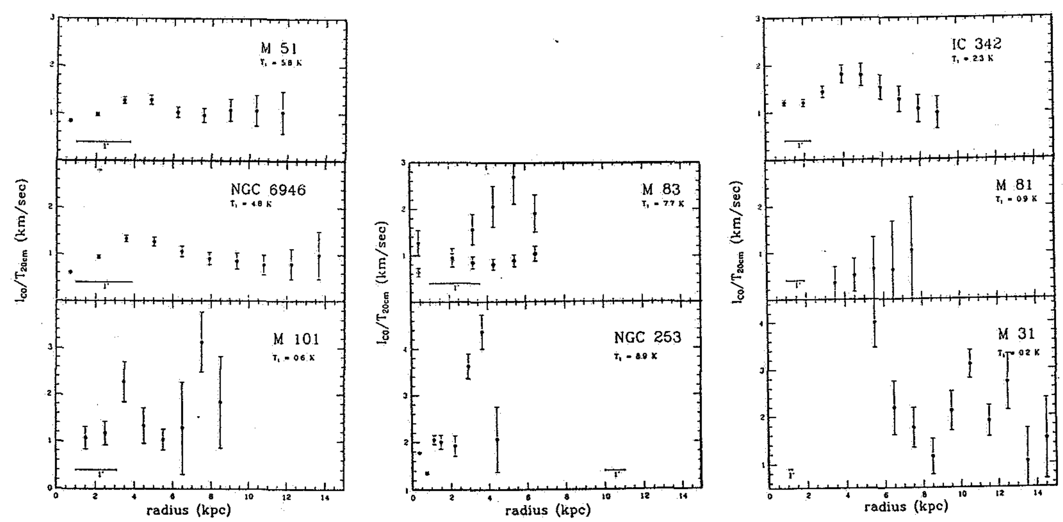

Figure 2. Ratio of integrated CO intensity to 20 cm radio continuum brightness temperature versus galactocentric radius. Error bars correspond to quoted values of the noise in the respective beams. The plot for M 83 includes CO data from L87 (filled circles) and C78 (open circles).

Not only is I_{CO}/T_{20} fairly constant in a given system, but *it also appears to be constant from galaxy to galaxy.* Table 1 lists the average value (and standard deviation) of I_{CO}/T_{20} for the individual galaxies. The average value of the eight galaxies is $I_{CO}/T_{20}=1.50\pm0.60$ km/sec; excluding the two high inclination systems gives a value of 1.35 ± 0.34 km/sec.

This constant value is remarkable when one considers that it holds for almost two orders of magnitude in surface brightness from galaxy to galaxy. Table 1 gives the surface brightness temperature for each galaxy at one scale length of the radio continuum emission. The range of surface brightnesses in the individual galaxies for which the ratio holds constant is also on the order of two magnitudes.

The standard models for the origin of the radio continuum emission relate it to the supernova rate, and therefore the rate of formation of massive stars. Similarly, models for the origin of CO emission relate it to the star formation rate through the formation of molecular clouds. Therefore, one possible explanation for the observed correlation is that these two apparently disparate quantities are both measures of the star formation rate. However, the correlation is all the more surprising when one considers the very different scale heights between the CO emission and radio continuum emission in spiral galaxies.

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