THERMAL INFRARED AND NONTHERMAL RADIO: REMARKABLE CORRELATION IN DISKS OF GALAXIES

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ABSTRACT

A tight, linear correlation is established between the far-infrared flux measured by *IRAS* and the nonthermal radio flux density (at 1.4 GHz) from disks of spiral galaxies. This correlation defines a ratio of infrared to radio fluxes that is characteristic of star formation activity. Galaxies with nuclear starbursts seem to follow the correlation. If the far-infrared is reradiated luminosity from young massive stars, then the supernova remnants alone account for less than 10% of the radio emission. Our results indicate a close coupling between dust heating and cosmic-ray generation and confinement in a wide range of conditions.

Subject headings: infrared: sources - galaxies: stellar content - radio sources: galaxies - stars: formation

I. INTRODUCTION

Far-infrared emission from galaxies should be an excellent indicator of star formation activity, since dust heating is dominated by young massive stars (Rieke and Lebofsky 1979; Wynn-Williams 1982). Nonthermal radio emission from normal disk galaxies has been variously interpreted to arise in the old disk population (Hummel 1981; van der Kruit, Allen, and Rots 1977), or with massive young stars (Klein 1982; Lequeux 1971). There is also evidence that it correlates with CO (Morris and Rickard 1982 and references therein; Rickard, Turner, and Palmer 1985). Using the *IRAS* survey (*IRAS Explanatory Supplement* 1985) we find a strong correlation, extending over three orders of magnitude, between the farinfrared and nonthermal radio luminosities in spiral disks and starburst nuclei.

Dickey and Salpeter (1984) and de Jong *et al.* (1985) find good correlations between radio (1.4 and 4.8 GHz) and 60 μ m *IRAS* fluxes for spirals. But because of limited resolution, the correlation cannot be uniquely ascribed to the disks of galaxies. In fact, active galactic nuclei have a roughly constant ratio between their 1.4 GHz and their 10 μ m emission (Rieke 1978). This has been used as evidence for a starburst in those nuclei (Condon *et al.* 1982; Rieke *et al.* 1980), but also against it (Ulvestad 1982). The results described here relate directly the properties of starburst nuclei (Harwit and Pacini 1975) to those of disks, with star formation providing the link.

II. THE VIRGO SAMPLE

Figure 1 shows the comparison between total emission in the far-infrared and the radio continuum for an optically complete sample of Virgo spirals $(B_T^0 \le 12.8)$ in a square

window about 0.07 sr centered on the Cluster (Helou 1986). S_{ν} (1.4 GHz) are taken from the survey by Kotanyi (1980) of Virgo galaxies at Westerbork, with a resolution of about 20". At 1.4 GHz, nonthermal processes should dominate the disk emission (e.g., Rowan-Robinson and Israel 1984). The farinfrared data come from the *IRAS Point Source Catalog* 1985; if the *Catalog* indicated extended emission from a galaxy, the spatially integrated flux was estimated directly from detector output for telescope scans crossing the galaxies. The measurements from 60 and 100 μ m bands are combined into an estimate, FIR, of the flux between 42.5 and 122.5 μ m, where

FIR = $1.26 \ 10^{-14} * [2.58 f_{\nu} (60 \ \mu \text{m}) + f_{\nu} (100 \ \mu \text{m})],$

 f_{ν} are the flux densities in Jy, and FIR is in W m⁻².

Those galaxies where only an extended radio component is detected (filled circles) define a very tight correlation, except for one point (shown bracketed) to the left in Figure 1. This is NGC 4688, with S_{ν} (1.4 GHz) = 68 mJy (Kotanyi 1980), but which Turner, Helou, and Terzian (1985) fail to detect at 2.4 GHz ($S_{u} < 5$ mJy). In view of this discrepancy, NGC 4688 is dropped from the sample henceforth. On the other hand, galaxies with log FIR ≥ -13 , but undetected by Kotanyi (1980) are not necessarily inconsistent with the correlation: The emission is probably resolved by the Westerbork beam (20"), and the point source upper limits at 1.4 GHz plotted in Figure 1 should be revised upward as discussed by Kotanyi. As evidence for this interpretation, we note that for at least six of these galaxies, Dressel and Condon (1978), using a 2'.7 beam, show detections at 2.4 GHz with more flux density than the upper limits at 1.4 GHz; this is most likely due to the



FIG. 1.—Comparison of far-infrared and 1.4 GHz fluxes for a blue magnitude-limited sample of Virgo spirals. Galaxies where only extended emission is detected at 1.4 GHz (*filled circles*) show a tight correlation. The upper limits in this plot are all consistent with the correlation, as explained in § II.

difference in beam size, for otherwise these galaxies would have abnormal radio spectra.

III. THE FIELD SAMPLE AND THE STARBURST GALAXIES

Extensions of the above correlation was sought for field galaxies, using the Hummel (1980) all-sky survey at 1.4 GHz of bright galaxies. All spirals in the radio all-sky survey where only an extended component was detected were selected, and their *IRAS* fluxes were obtained from the *Point Source Catalog*: the sample was then restricted to galaxies that were unresolved by *IRAS* and free of confusion, so the Point Source fluxes could be used. There were 28 galaxies thus selected, hereafter called the "field sample" for simplicity. Their observed fluxes are shown in Figure 2, together with the 10 Virgo spirals with only extended radio emission. Also shown in Figure 2 are M31, M33 (data from Rice *et al.* 1985), and Arp 220 = IC 4553 (Soifer *et al.* 1984).

For comparison, six galaxies with starburst nuclei were added to Figure 2. These galaxies were classified by Heckman *et al.* (1983) as having H II region-like spectra, had 1.4 GHz measurements by Hummel (1980), and were pointlike and unconfused in the *IRAS Catalog*. More than half of the emission from these galaxies remains unresolved by Hummel at $\sim 20''$, except for M82, where only 7% of the emission is unresolved.

IV. ANALYSIS

Figure 2 confirms the tight correlation between far-infrared and radio in spiral disks. The line in Figure 2 fits the combined Virgo and field samples, but with a slope fixed at one. We express the ratio of infrared to radio as:

$$q = \log \left\{ \left[\text{FIR} / (3.75 \times 10^{12} \text{ Hz}) \right] / S_{\nu} (1.4 \text{ GHz}) \right\}$$

where 3.75×10^{12} Hz is the frequency at 80 μ m. Table 1 shows the dispersion in q for various subsamples. The estimated uncertainties on FIR are about 15%, apart from possible contamination by Galactic cirrus, which our selection minimizes (*IRAS Explanatory Supplement* 1985). Hummel (1980) and Kotanyi (1980) estimate 10%-15% errors on S_{ν} (1.4 GHz): for five objects in common, the ratio S_{ν} (Hummel)/ S_{ν} (Kotanyi) has a mean of 1.05, and a dispersion of 11%. The expected minimum dispersion on q is therefore about 0.08; the observed dispersion (Table 1) is so small that measurement errors may contribute substantially to the scatter in q, especially in some of the subsamples.

The six galaxies dominated by a starburst nucleus also follow the same relation: the mean and dispersion on q for these six (Table 1) make them indistinguishable statistically from disk galaxies (a 1 σ fluctuation).

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FIG. 2.—Comparison of observed far-infrared and 1.4 GHz fluxes for galaxies with extended emission, and no compact nuclear component detected at 1.4 GHz, both in the Virgo Cluster (*circles*), and in the field (*triangles*). Nine other galaxies identified by name, whose selection is explained in § III, are also shown for comparison.

TABLE 1CORRELATION STATISTICS FOR VARIOUS SAMPLES: $q = \log \{[FIR/(3.75 \times 10^{12} \text{ Hz})]/S_{\nu} (1.4 \text{ GHz})\}$

Sample	Sample Size	Mean q	Dispersion in q
Total sample	38	2.14	0.14 (38%)
Virgo galaxies	10	2.15	0.06 (15%)
Field galaxies	28	2.14	0.16 (45%)
Low FIR luminosity	16	2.19	0.06 (15%)
High FIR luminosity	22	2.10	0.16 (45%)
Starburst galaxies	6	2.21	0.14 (38%)
M31	1	2.37	
M33	1	2.50	
Arp $220 = IC 4553^a$	1	2.62	•••

^a The 1.4 GHz measurement is from Mirabel 1982.

In order to compare infrared and radio luminosities, Figure 3 shows for each galaxy the fluxes that would have been observed from it if it were at the distance of the Virgo Cluster; the scaling to Virgo is done using the distances in Hummel (1980). A linear regression to the 38 disk galaxies in Figure 3 yields a slope of 1.1 (*solid line*), which is not significantly different from a fit with a line of slope unity (*broken line*).

V. DISCUSSION

Perhaps the most remarkable aspect of the correlation is that it holds over such a wide range of objects and conditions: from quiescent disks like M31, to the steady state activity in late-type spirals, to galaxies dominated by a nuclear starburst. To first order, then, the observed mean q characterizes star formation activity in general.

The objects in Figure 3 seem to divide into two groups: (a) low-luminosity [16 field and Virgo galaxies, M31, and M33: log(FIR) < -12.], characterized by a small dispersion on q; and (b) high-luminosity (22 field and Virgo galaxies, six starburst galaxies, and Arp 220), with a larger dispersion on q (see Table 1). While formally uncertain, the larger dispersion on q for high-luminosity objects is not surprising, since these objects are probably undergoing an unusual enhancement in their activity, resulting in larger variations in the flux ratio, if only because of a time delay between infrared and radio brightening.

If the radio emission comes entirely from supernova remnants (SNR), we can estimate a value for q. For simplicity, we assume that all of the far-infrared luminosity from a galaxy is derived from 10 M_{\odot} stars, a fraction γ of whose total luminosity (10⁴ L_{\odot} for 2×10^7 yr) is reradiated by dust into the FIR spectral window. We also assume all such B stars generate SNRs radiating at 1.4 GHz, each with a lifetime energy output of Λ Jy Mpc² yr. The steady state q would then be

$$q \approx 6.33 + \log \gamma - \log \Lambda$$
.

The SNR models by Bandiera, Pacini, and Salvati (1984) can be integrated to obtain Λ . The most luminous model, for a Crab-like plerion, yields 440 Jy Mpc² yr over 10⁴ yr. Ulvstad (1982) uses $\Lambda = 396$ Jy Mpc² yr. An observational

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FIG. 3.—Comparison of far-infrared and 1.4 GHz luminosities, expressed as the fluxes expected if all objects were at the distance of Virgo. The galaxies shown here are the same as in Fig. 2, with the same ones identified by the letters. R is the ratio of flux densities at 60 and 100 μ m. Circles, triangles, and crosses refer, respectively, to cold, intermediate, and warm color temperatures: the figure indicates no dependence of the ratio q on this color temperature. The punctuated line through S and S' is discussed in § V.

determination of the mean Λ for a typical mix of plerions and pure shell SNR in our Galaxy (Smirnov and Sakhibov 1984), gives $\Lambda = 158$ Jy Mpc² yr. This estimate is shown on Figure 3 as the circled letter S, for $\gamma = 1/3$, one star per year, at a distance D = 20 Mpc. S' is the same as S, except for D = 10Mpc.

The line through S (q = 3.65) is severely discrepant with the data. The two lines cannot be reconciled by decreasing γ , for that would push the least active galaxies in Virgo to star formation rates of one B star per year, and a total of ~ 100 M_{\odot} yr⁻¹ over the full stellar mass spectrum, which would deplete their interstellar gas contents in a few million years. The alternative is to increase Λ , but even the most generous estimates (Rieke *et al.* 1980) leave a discrepancy of a factor of 5. Clearly then, SNRs account for less than 10% of the 1.4 GHz emission from galaxies; this agrees well with Biermann's (1976) models, and with D'Odorico, Goss, and Dopita (1982) who identify only about 2% of the total 1.4 GHz flux density of M33 with individual SNRs.

The nonthermal emission from disks is therefore dominated by synchrotron radiation from cosmic rays. This makes the tight correlation even more surprising, implying that cosmicray generation, confinement, or both, are closely related to star formation (as reflected in FIR), and that magnetic structure is very similar among the spirals in this sample. If these cosmic rays are depleted mainly by synchrotron losses, each SN is required to supply a very small fraction of its available energy in the form of energetic electrons: about 2×10^{46} ergs per SN in a galaxy with S_{ν} (1.4 GHz) = 1 Jy, at 20 Mpc, at a few GeV per electron in a 1 μ G field.

To the extent that star formation in disks has a signature q which is reproduced by "starburst" nuclei, the ratio q itself cannot be used to argue against these nuclei being driven by star formation: Ulvestad's (1982) remark that active nuclei have too much radio for the SNR count (based on U, B, V, and K data) must now be viewed as a constraint on models of cosmic ray generation and confinement.

VI. SUMMARY

A comparison of far-infrared and radio continuum fluxes from the disks of spiral galaxies in the Virgo Cluster and in the field shows a tight correlation, which is evidently followed also by starburst nuclei. This result suggests that starburst nuclei are indeed powered by star formation activity, even though the supernova remnants alone cannot account for the observed 1.4 GHz fluxes. This nearly constant ratio of infrared to radio emission may be a general signature of massive star formation in extragalactic systems.

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