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THE INFLUENCE OF HIGH-DENSITY ENVIRONMENT ON THE RADIO–FAR-INFRARED CORRELATION OF SPIRAL GALAXIES

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ABSTRACT

It is found that the far-infrared and radio luminosities of a sample of spirals in high-density environments from the Hickson Compact Group Catalogue 1982 (Hickson 1982) are highly correlated even though the radio radiation originates almost entirely in extranuclear regions for most of the spirals. A comparison of the above correlation with that for a sample of isolated spirals shows that, statistically, the total radio emission from the group spirals is lower by about a factor of 2 than the isolated spirals. These results can be interpreted on the basis of a model in which interactions among group galaxies produce inflow of gas toward the centers, resulting in enhanced star formation, which in turn produces enhancement of far-infrared and radio radiation from those regions. At the same time removal of gas and magnetic fields from the disk of the galaxies results in a decrease of total radio emission from those galaxies. It is interesting that, except for one Seyfert galaxy, the radio luminosities of all the group galaxies are less than about 10^{22} W Hz^{-1} at 20 cm, which suggests that the high-density environment is not conducive for the development of powerful radio sources at the present epoch.

Subject headings: galaxies: clustering — galaxies: interstellar matter — infrared: sources — radio sources: galaxies

1. INTRODUCTION

A number of recent investigations have shown that the radio luminosity and the far-infrared luminosity of spiral galaxies are very closely correlated (Dickey & Salpeter 1984; De Jong et al. 1985; Helou, Soifer, & Rowan-Robinson 1985; Hummel 1986; Wunderlich, Klein, & Wielebinski 1987; Hummel et al. 1988; Cox et al. 1988; Devereux & Eales 1989). It is generally believed that the main contribution to the far-infrared luminosity is from the dust in the disk of the spirals heated by a combination of ultraviolet radiation from the general interstellar radiation field and from star-forming regions in the disk system, and a possible nonthermal continuum from the nuclei of the galaxies (Rowan-Robinson & Crawford 1990). Of these three components the latter two appear to be the dominant contributors, the relative contributions being dependent on the existence of a nuclear component in the particular galaxy. This is found to be particularly true of Seyfert galaxies. The radio radiation is believed to be predominantly synchrotron radiation from cosmic-ray electrons radiating in the galactic magnetic field. As has been pointed out by a number of authors, the close correlation between radio and far-infrared luminosities suggests that the density of cosmic-ray electrons in the disk is directly related to the star-forming regions which contain the hot stars. The detailed comparison of the far-infrared and 20 cm continuum emission within a number of galaxies carried out by Bicay, Helou, & Condon (1989) and Bicay & Helou (1990) suggests that spiral galaxies are characterized by an infrared disk with a shorter scale length than that of the continuum disk, the latter as a consequence of smearing by cosmic-ray propagation. I shall return to this question later in this paper.

A variety of samples of spiral galaxies has been studied with the specific purpose of isolating the influence of interactions in triggering star formation and subsequent enhancement of far-infrared radiation, particularly from the central regions of the interacting systems. In an earlier paper (Hickson et al. 1989b) the far-infrared radiation from spirals in high-density–group environments was compared with that from similar but isolated spirals, and it was found that the far-infrared radiation from the groups was significantly enhanced compared to their isolated counterparts. The radio properties of these group spirals have been systematically studied as part of a larger study of group galaxies (Menon 1990), and in this paper I shall discuss the radio and far-infrared properties of group spirals and compare them with that of isolated spirals.

2. OBSERVATIONS

The high-density–group sample consisted of all 147 spirals in 71 groups from the Hickson (1982) catalog of compact groups. These groups, a subsample above declination −20° from the original 100 groups, had a minimum of four members with concordant redshifts (Hickson 1990; Hickson et al. 1988) and also satisfied the original Hickson criteria of surface brightness and isolation. The optical data are given in Hickson, Kindl, & Auman (1989a). The isolated spiral sample of 87 galaxies is a subsample of that used as a "control sample" by Hummel et al. (1987). I have left out the S0 galaxies from their control sample. The radio observations of the groups were carried out with the Very Large Array (VLA) of the National Radio Astronomy Observatory at 1.49 GHz and 4.885 GHz during the years 1985–1989 (Menon 1990). The total flux densities at 1.49 GHz were measured from the VLA C configuration maps, since the vast majority of galaxies had angular sizes less than 1′. Comparison of the flux densities determined from the B-array maps confirmed that the detected source sizes were significantly smaller than the C-array beamwidths of 15″–20″. Fifty-threee galaxies out of 147 were detected at 1.49 GHz, and the 3 σ upper limits for the nondetections were 1 mJy. The radio data for the isolated sample were taken from Condon (1989) and Hummel et al. (1987). The far-infrared flux densities for the groups were taken from the *IRAS* Point Source Catalog since practically all the spirals in this sample had optical sizes less than 1'.5 and hence PSC fluxes should contain most of the flux density (Hickson et al. 1989b). Twenty-three galaxies were found above the *IRAS* detection limit at both 100 μm and 60 μm, while four galaxies were detected either at 60 μm or 100 μm. The far-infrared flux densities for the isolated spirals were taken from either Soifer et al. (1989) or Rice et al. (1988).

3. ANALYSIS AND DISCUSSION

For the vast majority of the radio-loud group spirals, the radio radiation originates in central regions significantly smaller than the optical dimensions of the galaxies. The exceptions were four edge-on galaxies which had detectable disk emission superposed on a strong central component and one galaxy in which the radio radiation originates in a ring of giant H II regions coinciding with a spiral arm. The positions of the peak of the radio emission and the optical center coincided in most cases to within 3" (Menon 1990). The upper limits to the linear sizes of the central radio sources range from 0.5 to 4 kpc for a value of $H_0 = 100$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$. The flux densities of the isolated sample taken from Condon (1987) are the integrated values, and the flux densities of central components within 10" of the center were taken from Hummel et al. (1987).

Figure 1 shows the basic plot of the total far-infrared luminosity in units of $L_\odot$ against the total radio luminosity at 1.49 GHz for both high-density–group galaxies and the isolated galaxies. The far-infrared luminosity has been computed using the expression

$$L_{\rm ir} = 3.65 \times 10^5[2.58S_{60\,\mu{\rm m}}({\rm Jy}) + S_{100\,\mu{\rm m}}({\rm Jy})]D^2({\rm Mpc})L_\odot\ , \qquad (1)$$

and the radio luminosity using the expression

$$L_r = 1.131 \times 10^{17}S_{20}({\rm mJy})D^2({\rm Mpc})\ {\rm WHz}^{-1}\ . \qquad (2)$$

The values for q_0 and H_0 are the same as above. The well-known correlation between the far-infrared and radio luminosities is extended to higher far-infrared luminosities by the inclusion of the high-density–group sample. There are two and five known Seyfert galaxies in the group and isolated samples, respectively. They are marked in Figure 1. There are a number of very interesting implications suggested by the plot in Figure 1. As pointed out earlier, the spatial distribution of the radio radiation is, in general, significantly different for the galaxies in the two samples except for the Seyfert galaxies, in which the radio radiation is confined to small central sources. The overall strong correlation between the far-infrared and radio luminosities appears, therefore, to be independent of the spatial distribution of the two radiation components. However, when we look at the correlation in detail, there are some very significant differences, as discussed below.

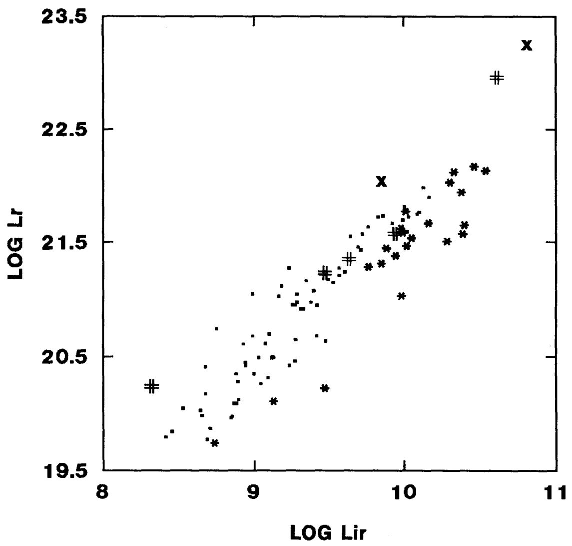

FIG. 1.—Correlation between the luminosities at 20 cm L_r and in the far-infrared $L_{\rm ir}$ for spiral galaxies in high-density groups (*stars*) and isolated galaxies (*filled squares*). The Seyfert galaxies in the two samples are presented by crosses and pound signs, respectively.

It was remarked earlier that the far-infrared radiation may have up to three different components with different sources of heat for the dust particles responsible for each component. There has been considerable discussion regarding the slope of the relation between far-infrared and radio radiation (Cox et al. 1988; Devereux & Eales 1989). Devereux & Eales (1989) have determined the slope for a sample of 237 spiral galaxies from the Revised Shapley-Ames Catalogue (Sandage & Tammann 1981) and obtain a mean slope of 1.28 for the far-infrared–radio correlation. Since their sample consisted of all morphological types of spirals and included the possibility of different components for the far-infrared radiation, there is no reason to expect all types of spirals to follow the same relation. As a matter of fact, Figure 1 suggests that (1) the Seyfert galaxies have on average higher radio luminosity than the rest of the two samples, and (2) the isolated and group spirals follow different slopes. Least-squares fits have been made for the data in Figure 1 for the three groups of galaxies: the Seyferts, the isolated galaxies, and the total sample including groups. The parameters of these fits are given in Table 1 for the relation

$$\log L_r = A + B \log L_{\rm ir}\ . \qquad (3)$$

The parameter values in Table 1 substantiate the reality of the departure of the slope from unity but at the same time indicate that the slope may be different for different samples. Fitt, Alexander, & Cox (1988) and Devereux & Eales (1989) have interpreted the departure-from-unity slope on the basis of a model in which a galaxy's far-infrared radiation consists of two components, one of which is from star-forming regions and the other is related to the interstellar radiation field. The second component is assumed to be a constant fraction f of the blue luminosity of the galaxy. They derive a value of 0.14 for f for their sample. This model implicitly assumes that the two components are uniformly distributed throughout all the galaxies. Bicay, Helou, & Condon (1989) and Bicay & Helou (1990) have shown that for typical spiral galaxies, there is a significant gradient from the center to the edge of the disk in the ratio of the flux densities at 60 μm and 20 cm, such that the ratio

TABLE 1

LEAST-SQUARES FIT PARAMETERS

Sample	Number	B	r^2
Seyfert	7	1.23 ± 0.15	0.93
Isolated	71	1.27 ± 0.06	0.88
Group	22	1.38 ± 0.11	0.87
Isolated (log $L_r > 21$)	34	0.91 ± 0.06	0.86
Group (log $L_r > 21$)	18	0.96 ± 0.19	0.62

decreases with increasing radius. These authors propose that in the spiral galaxies the infrared-disk scale length is shorter than the radio-continuum–disk scale, the latter being smeared as a result of cosmic-ray propagation. The very tight correlation between far-infrared and radio radiation is taken to imply a very tight coupling between the sources of infrared and radio radiation. Hence for normal spirals the model proposed by Devereux & Eales (1989) may be a good approximation.

In the case of the high-density–group spirals, it was emphasized earlier that even though most of the radio radiation originates in the central regions, there is still a tight correlation between far-infrared and radio radiation, suggesting that the far-infrared radiation also originates in the same regions. However, there is a very clear indication of the flattening of the correlation in Figure 1 at the high-luminosity end dominated by the group spirals. This is confirmed by the slopes for the regions above $L_r > 21$ for both samples given in Table 1. The morphological distributions of the two samples are almost identical and, therefore, unlikely to be a factor in explaining the above effect. A similar effect had been noticed earlier by Sopp & Alexander (1989). If we assume that the least-squares line defined by the isolated non-Seyfert spirals is applicable in general, then it is found that the group spirals have, on the average, a factor of 3 lower radio luminosity for their far-infrared luminosity. It was shown earlier (see Hickson et al. 1989) that the ratio of far-infrared to blue luminosity is significantly higher for the group spirals when compared to that of the isolated spirals. Figure 2 shows the cumulative distribution of the above ratio for the two samples in the present study. These curves were derived using the methods of survival analysis as discussed by Isobe, Feigelson, & Nelson (1986). The median values of the ratios for the two samples are given in Table 2. The normalization using the total blue luminosity may not be quite appropriate in view of the differences in the intensity distributions at various wavelengths which may be expected in star-forming galaxies. We do not as yet have detailed data to model these gradient variations, but, in view of the results of Bicay & Helou (1990) mentioned earlier, it would appear that the true differences between the two samples could be significantly higher than those shown in Figure 2.

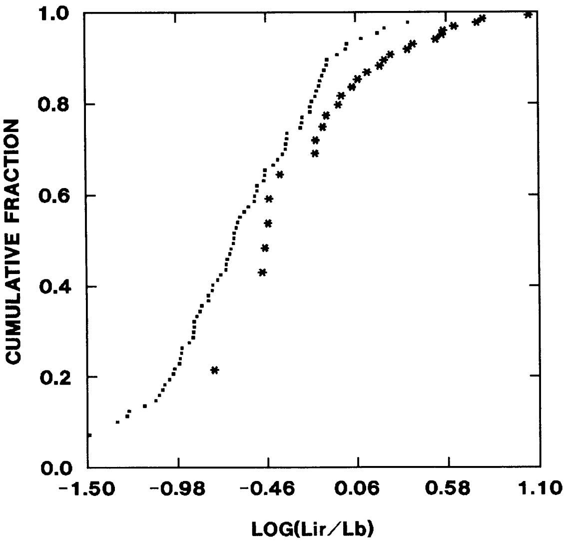

FIG. 2.—Cumulative distribution function of the ratio of far-infrared to blue luminosity for group spirals (*stars*) and isolated spirals (*filled squares*).

TABLE 2

MEDIAN VALUES OF LUMINOSITY RATIOS

Sample	L_{ir}/L_B	R_{Total}	R_{nucleus}
Group	0.34	2.7	2.7
Isolated	0.18	6.6	0.2

A similar analysis of the ratio R of the total radio to optical luminosity for the two samples has been carried out, and the median values of R are given in Table 2. The ratio R is defined by the relation

$$R = S \text{ dex } [(B^0_{\mathrm{TS}} - 12.5)0.4] , \qquad (4)$$

where S is the flux density in mJy and B^0_{TS} is the corrected blue luminosity. A detailed discussion of the radio properties of the samples will given elsewhere (Menon 1990). The important point to note here is that, statistically, the total radio-to-optical-luminosity ratio R of the group spirals is about a factor of 2.5 lower than that of the isolated spirals. However, it is more appropriate to compare the radio properties of the central regions of the isolated sample with those of the group sample. Hummel et al. (1987) have measured the 20 cm flux densities from the inner 10″ of their sample, and I have used these values to compute R_c for the central regions. In the case of the four edge-on galaxies with extended emission, I have used only the flux densities of the central sources. The median values of R_c obtained by survival analysis procedures given in Table 2 shows that the value for the group spirals is over 10 times that of the isolated spirals. Similar results for the central radio sources had been obtained earlier by Hummel (1980, 1981a, 1981b) and Hummel et al. (1990), but the situation regarding the R total had been ambiguous until now (see Gavazzi & Jaffe 1986). The present results clearly show that the group sample has a lower median R total than the isolated sample, while the central regions have a significantly higher median R value. The main results, so far, may be summarized by the statement that the high-density spirals have on the average twice the far-infrared luminosity but about 0.4 times the total radio luminosity when compared to isolated galaxies, while the central regions of group spirals are about 10 times more luminous than the central regions of isolated spirals.

We can compare the far-infrared–to–radio flux density ratio directly from the distribution of the quantity q defined by Helou et al. (1985) as follows

$$q = \log \{[\mathrm{FIR}/(3.75 \times 10^{12}) \text{ Hz}]/S_\nu(1.4 \text{ GHz})\} . \qquad (5)$$

Figure 3 is a plot of the quantity q as a function of radio luminosity for the spirals detected at both radio and far-infrared wavelengths for the two samples. It is seen that the ratio q is systematically higher for the group galaxies at all radio luminosities, and the mean values for the two samples are 2.68 and 2.37, respectively. Helou et al. (1985) obtained values of q in the range 2.14–2.62 for a variety of spirals ranging from normal spirals to ultraluminous, far-infrared galaxies. It is interesting that the mean value of q for the far-infrared–detected–group spirals is comparable to that of the ultraluminous galaxies such as Arp 220, and that the values for the Seyfert galaxies are in general lower than those for isolated galaxies. From a detailed study of the distribution on the 60 μm infrared and 20 cm radiation within a number of galaxies,

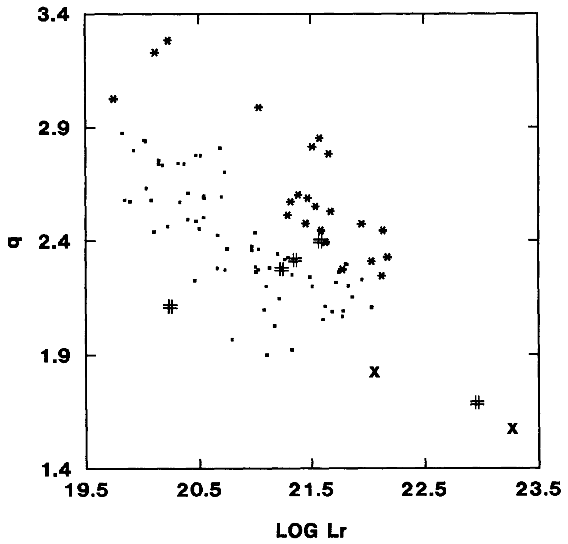

FIG. 3.—Plot of the ratio of far-infrared–to-radio flux densities q for the detected group spirals (*stars*) and isolated spirals (*filled squares*) against the luminosity L_r at 20 cm. Crosses and pound signs are Seyfert galaxies in the two samples, respectively.

Bicay & Helou (1990) have shown that the values of the 60 μm-to-20 cm ratio (Q_{60}) within central regions are often enhanced by a factor of 2–3 with respect to values in the outer disks, whereas the corresponding enhancement in radio surface brightness is greater by at least an order of magnitude. The behavior of the three ratios in Table 2 suggests that in the case of group spirals we have a more extreme case of the situation in normal spirals, as seen in the sample of Bicay & Helou (1990), combined with the property of lower total radio luminosity as compared with isolated spirals. A model consistent with all the above data should not only explain the strong correlation between far-infrared and radio radiation, but also the relative lower total radio luminosity of the group spirals. The decrease in the total radio luminosity may be attributed to either a decrease in radio radiation from the disks of the spirals or a delay in the full development of radio emission due to differences in the time scales of the processes involved. The stars responsible for the current ionization rate and the far-infrared luminosity are the most massive stars with lifetimes of the order of a few million years, while the nonthermal radio radiation is related to the larger number of stars with masses >8 $M_\odot$ producing supernova of Type II (Kennicutt 1984) over a longer period of time of the order of 30 million years. Since the luminosity $L_{\rm ir}$ is an average over the lifetime of the most massive stars and since L_r is proportional to the number of electrons produced over the residence time of the electrons and the lifetime of the supernova progenitors, it is possible for the radio luminosity to reach its maximum at a time later than the far-infrared maximum after a specific episode of interaction-induced star formation.

A number of theoretical scenarios regarding the effects of interactions among disk galaxies suggest that in addition to causing inflows toward the center and subsequent star formation, the interactions remove gas from the outer regions of the galaxies (see Noguchi & Ishibashi 1986; Olson & Kwan 1990). Observations by Williams & Rood (1987) suggest a deficit of neutral hydrogen in the group spirals, and the optical studies by Rubin (1988) show that that the rotation curves of many group spirals are highly distorted. It seems highly likely that the removal of gas from the outer regions will result in the decrease of the magnetic field from those regions and a consequent decrease in radio radiation from those regions. An additional possibility is that the radio synchrotron radiation in the outer regions could be suppressed because of the energy loss of the cosmic-ray electrons by inverse–Compton scattering off the far-infrared photons from the starburst in the central regions. In either case the present results concerning the far-infrared and radio properties of high-density groups may be considered strong support for such a scenario.

4. CONCLUSIONS

The purpose of the present paper is to compare the radio–far-infrared correlation of spiral galaxies in a high-density environment with that of isolated spirals. My results show that, even though the radio radiation in most of the group spirals originates in small, extranuclear regions, there is still a strong correlation with the far-infrared radiation from those galaxies. This suggests that both types of radiation originate predominantly in star-forming regions in the inner parts of the galaxies. However, it is found that the ratio of the far-infrared to radio luminosities for the group spirals is a factor of 3 higher than for isolated spirals. These observations are best interpreted by a model in which interactions among group galaxies lead to enhanced star formation in the central regions followed by removal of gas and the magnetic field from the major portions of the disk of the galaxies. The enhanced star formation in the central regions in turn produces enhanced radio emission from those regions, while the loss of gas and the magnetic field from the disk decreases the total emission from the disk.

In view of the short time scales mentioned earlier, it appears that for most of the group spirals we are probably witnessing a recent episode of interaction-induced star formation. If the groups are bound systems with crossing times of a few times 10^8 years, the radio and far-infrared luminosities from one epoch of interaction could substantially decrease before a subsequent interaction. If the above interpretation of the lower total radio luminosity is correct, then galaxies which have undergone many interactions are likely to contain only nuclear sources with minimal star-forming activity. It is worth pointing out that, except for one Seyfert galaxy, the radio luminosities of all the group spirals are less than about 10^{22} W Hz^{-1} and hence in the flat part of the local radio luminosity function for spirals (Condon 1989). As shown elsewhere (Menon 1990), this is true for the whole group sample, including E and S0 galaxies. Hence it appears that the environment of high-density groups is not conducive for the development of high-luminosity sources. It would be very interesting to compare in detail the optical, Hα, radio, and infrared morphologies of the group spirals to trace the effects of repeated interactions. Such a program is in progress.

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