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THE INFRARED-TO-RADIO RATIO WITHIN NGC 5236 (M83) AND NGC 6946

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ABSTRACT

A detailed comparison of the distribution of 60 μm infrared and 20 cm radio continuum emission within NGC 5236 (M83) and NGC 6946 is presented. Local maxima in the thermal infrared and nonthermal radio maps are found to be spatially coincident on scales $\leq 0.3h^{-1}$ kpc. Superposed on this broad correlation, we observe in the disks of both galaxies a slow decrease of the 60 μm-to-20 cm ratio (Q_{60}) with increasing radius. Values of Q_{60} within the central regions are enhanced by roughly a factor of 3 with respect to the outer disks, whereas the corresponding enhancement in radio surface brightness is at least a factor of 20. The 100 μm-to-20 cm ratio shows a similar but shallower gradient. To account for these observations, we propose that spiral galaxies are characterized by an infrared disk with a shorter scale length than that of the radio continuum disk, the latter being smeared as a result of cosmic-ray propagation.

Subject headings: galaxies: structure — infrared: sources — radio sources: galaxies

I. INTRODUCTION

A tight *global* correlation between thermal infrared and radio continuum emission from spiral galaxies has been firmly established. This correlation links 60 μm and 100 μm *IRAS* flux densities, singly and in combination, with radio fluxes at several wavelengths (Dickey and Salpeter 1984; de Jong *et al.* 1985; Helou, Soifer, and Rowan-Robinson 1985). The correlation is seen in a variety of galaxy samples: selections of UGC galaxies (Gavazzi, Cocito, and Vettolani 1986; Condon and Broderick 1988), in bright radio galaxies (Sanders and Mirabel 1985), in Sbc galaxies (Hummel 1986), and in a sample spanning a wide range of morphologies (Wunderlich, Klein, and Wielebinski 1987). More recently, Cox *et al.* (1988) have extended the correlation down to 151 MHz in sources from the Cambridge 6C survey. Below a few GHz, the radio emission is attributed almost entirely to nonthermal processes. The tight correlation between radio and far-infrared (FIR) luminosities extends over at least three orders of magnitude in spiral disks and in galaxies with starburst nuclei. The presence of this correlation in such diverse environments suggests a simple explanation for its physical basis, but such an explanation has been elusive.

In an effort to understand the physical processes underlying these results, we set out to determine whether the infrared-radio correlation is found *spatially* within a given galaxy by examining the 60 μm-to-20 cm ratio at various points within the disk. A similar search by Beck and Golla (1988) has found a close correlation between FIR and 11 cm radio emission within the disks of four nearby galaxies (see also Wainscoat, de Jong, and Wesselius 1987). Preliminary results presented here indicate that while local maxima in the infrared and radio emission of NGC 5236 and 6946 are spatially coincident on scales of $\leq 0.3h^{-1}$ kpc [where $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$ is the reduced Hubble constant], the 60 μm-to-20 cm ratio decreases slowly with increasing radius in the disks of these galaxies.

II. DATA AND ANALYSIS

We have performed a detailed comparison of 60 μm infrared and 20 cm radio continuum measurements within 61 "large" galaxies selected from Figure 6 of Condon (1987). The radio data consist of 1.49 GHz VLA maps obtained with the C/D and D arrays, with typical resolution of ≈0′.9 and a sensitivity of ≈0.1 mJy per beam. The missing flux at low spatial frequencies ("zero spacing") in these maps is estimated to be small. The infrared data consist of *IRAS* survey mode observations at 60 μm (Neugebauer *et al.* 1984). The raw time-ordered calibrated detector output, sampled every 0′.48 during the mission, was interpolated using cubic spline fits, and resampled every 0′.1.

For each galaxy, a 30′ × 30′ VLA map was convolved with a model beam equivalent to the appropriate *IRAS* 60 μm detector response function to yield a "smoothed" map. Slices through this two-dimensional map, corresponding to one-dimensional in-scan profiles, were then compared with actual *IRAS* data. A typical profile contained either multiple peaks of emission (corresponding to the nucleus and resolved disk features) or a single maximum associated with unresolved emission. The in-scan maxima in each pair of infrared and radio profiles yielded two useful parameters: (1) a local measure of spatial coincidence between the infrared and radio continuum emission; and (2) the mean value of the 60 μm-to-20 cm ratio at a given point within the galaxy, defined here as $Q_{60} = f_\nu(60\ \mu\text{m})/f_\nu(20\ \text{cm})$. Infrared and radio results for two galaxies are presented here; further results and analysis will appear in a forthcoming paper (Bicay and Helou 1989, hereafter Paper II).

III. RESULTS

In this *Letter*, the radial dependence of Q_{60} is presented for two galaxies: NGC 5236 (M83), a SBc(s)II galaxy with $B_T = 8.51$, $D_{25} \times d_{25} = 11'.2 \times 10'.2$, at a distance of $3.45h^{-1}$ Mpc; and NGC 6946, a Sc(s)II galaxy with $B_T = 9.68$, $D_{25} \times d_{25} =$

11$'$.0 × 9$'$.8, at a distance of $3.35h^{-1}$ Mpc. The synthesized beams in the VLA maps have half-maximum widths of 0$'$.9 (NGC 5236) and 0$'$.8 (NGC 6946). Each galaxy was reasonably well sampled at 60 μm during the *IRAS* survey. From the maxima of the IR-radio profiles, values of Q_{60} were derived at 42 points within NGC 5236 (from 29 independent detector scans) and at 56 points within NGC 6946 (from 37 detector scans).

The in-scan positions (rms uncertainty <0$'$.1) of the local maxima in any pair of radio and *IRAS* profiles for NGC 5236 and NGC 6946 were typically coincident to ≤0$'$.2, suggesting that the 60 μm and 20 cm emission is spatially correlated on scales of $\leq 0.3h^{-1}$ kpc (1 σ level). This value is similar to the scale at which the correlation is observed to break down in our Galaxy (Boulanger and Pérault 1988).

The radial dependence of Q_{60} is illustrated in Figure 1. Each data point is the result of computing the ratio of maxima in an independent pair of infrared and radio profiles. In the case of NGC 5236, these points were derived along a line with position angle (PA, measured east of north) of 118° ± 5°, perpendicular to the predominant in-scan direction in which the galaxy was surveyed by *IRAS*. The data for NGC 6946 were obtained

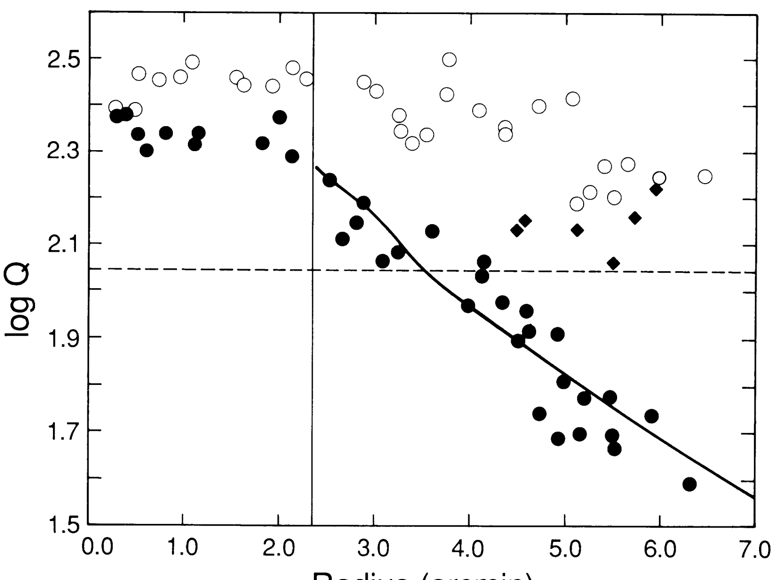

FIG. 1*a*

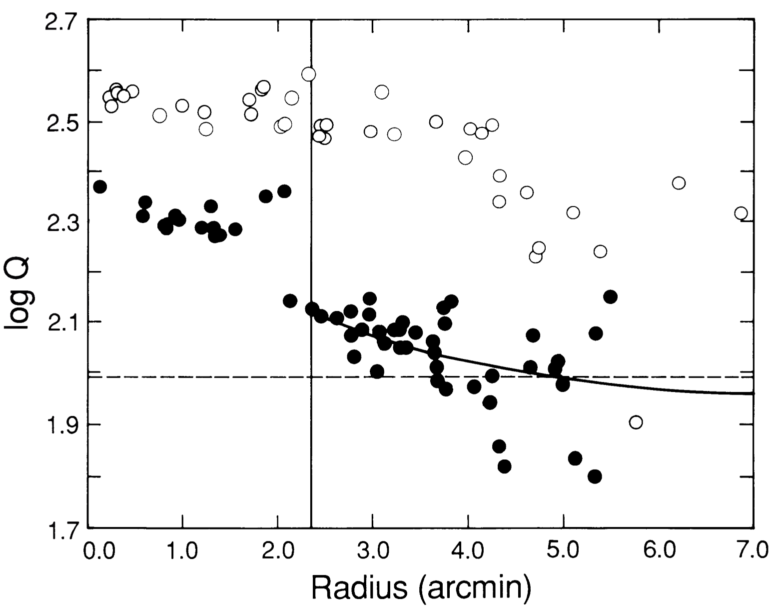

FIG. 1*b*

FIG. 1.—The ratios log Q_{60} (*solid circles*) and log Q_{100} (*open circles*) as a function of radius for (*a*) NGC 5236 and (*b*) NGC 6946. The vertical line at $R_0 \approx 2'.35$ corresponds to the semimajor diameter of a typical *IRAS* 60 μm or 100 μm detector; Q_{60} and Q_{100} out to this radius are dominated by emission from a point source at the galaxy center. Values of Q_{60} associated with identified supergiant H II regions are shown as filled diamonds. The solid curved lines are the result of the model described in the text. The horizontal dashed lines indicate the global Q_{60} (from integrated flux densities) for each galaxy.

from a wider range of scan angles, oriented along PA = 30° ± 12°. Inspection of the VLA maps reveals that (to first order) there are no major azimuthal asymmetries, and hence the results in Figure 1 are expected to be insensitive to scanning geometry. The effective resolution in Figure 1 is a complicated function of the detector's cross-scan diameter, the underlying distribution of Q_{60}, and the details of the scanning geometry (especially the cross-scan spacing of the sampled tracks). Within a radius $R_0 = 2'.35$ of the center (the half-width of the 60 μm cross-scan dimension), the plotted values of Q_{60} are dominated by the bright central source. Within the disk, the effective cross-scan resolution is estimated to be on the order of 1′ because of the steep drop in surface brightness. The scatter in Q_{60} measured at neighboring points within the disk indicates that the uncertainty in Q_{60} is $\sim 10\%$.

Figure 1 shows that Q_{60} (*filled circles*) is clearly enhanced in the central region of both galaxies relative to their outer disk. Q_{60} is about 225 near the nucleus of both systems, and drops to ~ 50 (NGC 5236) and to ~ 100 (NGC 6946) beyond radii of 4′ ($\sim 4h^{-1}$ kpc). By contrast, the enhancement in radio surface brightness over the same spatial extent is a factor of 20 or more. Beyond R_0, Q_{60} falls steadily with increasing radius in NGC 5236. The decrease is far less dramatic in NGC 6946, due in part to the greater dispersion. An analysis of the variance in slope suggests that at the 95% confidence level, the Q_{60} gradient in NGC 6946 is negative. Results from other spiral galaxies (to appear in Paper II) indicate that a slowly decreasing Q_{60} *within the disk* is a common feature. Apart from the radial gradient, the infrared-to-radio ratio is usually enhanced near prominent H II regions (Haslam and Osborne 1987; Fürst, Reich, and Sofue 1987). Maps of NGC 5236 reveal that the 60 μm data points to the upper right in Figure 1*a* (*filled diamonds*) may be a result of enhanced infrared emission from the supergiant H II regions designated 266 and 275 by Rumstay and Kaufman (1983). The dashed lines in Figure 1 denote the global value of the 60 μm–to–20 cm ratio, obtained from the integrated flux densities listed in Rice *et al.* (1988) and in Condon (1987).

We have also examined the 100 μm–to–20 cm ratio Q_{100} in the two galaxies (*open circles*) and found a similar radial gradient, but one which is shallower than that seen at 60 μm. It is clear that if the FIR–to–radio ratio (as defined by Helou, Soifer, and Rowan-Robinson 1985) rather than Q_{60} was studied within disks, it would display a similar radial trend, albeit with a reduced gradient.

IV. DISCUSSION

The above results, in conjunction with those in Paper II and in Beck and Golla (1988), reveal a common trend among spiral galaxies for the ratio of infrared-to-radio emission to be highest in the central regions, and to fall with increasing radius. The gradient in this ratio is much shallower than the gradient in radio surface brightness, so the behavior can be described in terms of an infrared disk with a scale length shorter than that of the radio disk. As a preliminary interpretation of these results, we propose that the propagation of cosmic rays leads to a radio disk that is broader than the infrared counterpart.

We have tried to model the behavior of the data based on two physical assumptions: (1) a tight coupling between the origins of the dust-heating radiation and the radio-emitting cosmic-ray electrons, and (2) a steady-state picture of star-formation activity *within the disk.* The coupling in (1) is strongly suggested by the remarkable constancy of the global infrared-to-radio ratio in galaxies displaying various levels of star formation activity. It implies that the infrared and radio disks reflect the same source distribution, smoothed by radiative transfer of UV photons in the first case, and by cosmic-ray transport in the other. The typical distance traveled by a UV photon before being converted into the infrared can be obtained from A_v/N_H, and is found to be ≤ 200 pc in the diffuse interstellar medium, and much less in star formation regions. By contrast, electrons of a few GeV will diffuse away from their sources with negligible energy loss, spreading the radio emission in a time t to a radius $r_d = 1$ kpc $[(t/10^7 \text{ yr})(v/c)(\lambda/1 \text{ pc})]^{1/2}$, where v/c is the cosine of the pitch angle, and λ is the mean free path of the cosmic-ray electrons. It is expected that λ is at least 1 pc (Wentzel 1974), so that in the course of 10^8 yr, r_d could easily reach several kpc (see also Cesarsky 1981). Based on these estimates, our model neglects the smoothing associated with the infrared emission, and therefore equates the infrared disk and the source distribution. Assumption (2) implies the same time dependence (over scales $\leq 10^8$ yr) for star formation throughout the disk (nucleus excluded), thus allowing us to use a single cosmic-ray smoothing function. Young H II regions are the obvious exception, as pointed out in § III above.

A first constraint on the model is provided by the VLA radio map, which results from a convolution of the true radio emission with the VLA beam. In both NGC 5236 and NGC 6946, the radio map clearly features a central unresolved (or nearly so) component in addition to a disk falling off exponentially to at least 4′ and then dropping more sharply. A second constraint on the model is provided by the data in Figure 1. We will model the behavior of Q_{60} in the disk only, and hence explicitly ignore the central point source. In modeling the behavior of Q_{60} in NGC 5236, the values associated with the identified supergiant H II regions will be excluded.

We describe the underlying source distribution as an exponential disk, equate it to the infrared disk, and smooth it with a cosmic-ray spreading function to obtain the radio disk. In requiring the resulting model disks (smeared to the instrumental resolution) to satisfy the observational constraints, we obtain the following results:

1. A Gaussian smoothing function yields excessively broad radio disks, indicating that the cosmic-ray spreading is not dominated by random-walk diffusion.
2. In the disk, an exponential smoothing function fits the data, suggesting that the critical process may be cosmic-ray escape from the disk, with the probability of escape proportional to distance traveled from the source, as in the leaky box model of cosmic-ray confinement (Cesarsky 1981).
3. Apart from a central point source, NGC 5236 and 6946 are well described by exponential infrared disks (scale lengths = 0′.9 and 1′.4, respectively), smoothed by an exponential spreading function (scale length = 0′.9 and 0′.6, respectively) to generate the observed radio disks. Note that the significant dispersion of Q_{60} in NGC 6946 makes the latter scalelengths less certain.
4. The unresolved central peaks display an enhancement in Q_{60} over and above the values found in the inner disk, leading us to speculate that the nuclear activity is very recent ($t \leq 10^6$ yr), or that cosmic rays escape more easily from this region instead of diffusing out into the disk. On the other hand, the enhancement of Q_{60} observed near H II regions is most probably due to the time lag between the availability of ionizing photons and the onset of wide-scale supernovae explosions in OB associations.

V. SUMMARY

The 60 μm–to–20 cm ratio Q_{60} within the nearby spiral galaxies NGC 5236 (M83) and NGC 6946 has been examined in detail. In both galaxies, the local maxima in infrared and radio continuum emission are found to be spatially coincident on scales $\leq 0.3h^{-1}$ kpc. There is a radial dependence in Q_{60}, with values in the central region enhanced by roughly a factor of 3 with respect to the corresponding outer disk. This radial gradient in the infrared-to-radio ratio is also seen in other sample galaxies selected from the "large" galaxy maps of Condon 1987 (results to appear in Paper II). While the 100 μm–to–20 cm ratio also decreases with increasing radius in NGC 5236 and NGC 6946, the contrast between the inner regions and the outer disk is less pronounced than at 60 μm. As a preliminary interpretation of these results, we suggest that spiral galaxies have infrared disks that are characterized by a shorter scale length than the radio continuum disk, the latter being smeared through the effects of cosmic-ray spreading.

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