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THE COMPACTNESS OF FAR-INFRARED BRIGHT GALAXIES

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ABSTRACT

The linear size distribution of 218 galaxies in the *IRAS* infrared bright galaxy sample is studied by examining new measurements of the 1.49 Hz radio continuum emitting regions. Only spatially extended radio emitters are considered so as to exclude known AGNs and suspected nuclear "monster" sources. We find that the radio surface brightness varies over a wide range at a given luminosity, but its median scales approximately as luminosity to the power of 6/5. Consequently, the median effective radio size of galaxies in a given luminosity range actually *decreases* with increasing luminosity, especially among galaxies with $L_{\rm FIR} > 10^{11}\ L_\odot$. The close correlation between FIR and radio fluxes of these star-forming galaxies then leads to a picture contrary to earlier theoretical predictions that the sizes of FIR emitting regions should increase with luminosity. We propose that such a steep increase of surface brightness in luminous galaxies is a direct result of a high interstellar medium density and an enhanced radiation density of the heating photons driven by more active star formation.

Subject headings: galaxies: fundamental parameters — infrared: galaxies: — radio continuum: galaxies

1. INTRODUCTION

Star formation activity in a galaxy is often gauged using the far-infrared (FIR) luminosity ($L_{\rm FIR}$). *IRAS* observations of galaxies revealed a wide spread of FIR luminosities (from less than $10^8\ L_\odot$ to more than $2 \times 10^{12}\ L_\odot$; cf. Soifer, Houck, & Neugebauer 1987), suggesting a large variation in the extent to which stars are being formed. By attributing the FIR emission to a "disk", a "Seyfert nuclei", and a "starburst" component, Rowan-Robinson (1987) predicted that in all three cases the linear sizes of the emitting region should scale with $\frac{1}{2}$ power of $L_{\rm FIR}$. However, recent studies of objects in the *IRAS* Bright Galaxy Sample (Soifer et al. 1986, 1987, 1989; hereafter BGS) revealed that many of the highly luminous galaxies may be better characterized as having "nuclear starbursts" (Carico et al. 1990; Condon et al. 1991b). This may be taken as anecdotal evidence that the sizes of the bulk FIR emitting regions do not grow with luminosity as one would expect based on the simplified models. However, the full extent of the size scale and surface brightness variations among these galaxies have not been quantitatively examined.

Except for a few cases, FIR images of galaxies with adequate resolution are difficult to obtain at present. Thus to study infrared surface brightness, it is necessary to investigate other possible size measures for regions that generate the bulk radiative energy. In contrast to the rather large scatter in optical–FIR correlations, a galaxy's radio continuum emission has a remarkably tight correlation with its $L_{\rm FIR}$ (Helou, Soifer, & Rowan-Robinson 1985; Condon, Anderson, & Helou 1991a). In nearby galaxies where FIR sizes have been measured directly, the radio size (at 1.49 GHz) is known to match or be somewhat larger than the size scale in FIR (Bicay & Helou 1990). Hence, it is reasonable to expect radio continuum maps of galaxies to provide a reliable upper limit indicator for the sizes of the FIR regions.

Previous analyses of extragalactic sources have found no clear correlation between linear size and radio luminosity (e.g., Coleman & Condon 1985). However, the samples used in those studies were highly inhomogeneous, many with strong radio sources such as quasars, AGNs, and radio galaxies included along with normal galactic disks. Thus one might expect the interpretation of results to be greatly complicated due to the mixing of radio sources with diverse intrinsic properties. Even for a relatively homogeneous sample such as the BGS, several factors need to be checked before one could accept the radio-measured sizes as the measure of the FIR sizes of galaxies. One of the concerns is that the radio synthesis maps have the proper resolution so as to avoid being either undersampled or over-resolved. Another is to be able to distinguish and exclude in the measurements nuclear point sources that are often identified as AGNs. In an effort to explore the scale size and surface brightness variations among galaxies, and to characterize better the FIR emission parameters, we have analyzed the newly acquired radio continuum maps of the *IRAS* BGS sample. In this *Letter*, we present evidence of a general increase in compactness among these galaxies with increasing FIR (or bolometric) luminosity.

2. THE SAMPLE GALAXIES

The revised BGS sample (hereafter "the sample") consists of 330 northern galaxies with $f_\nu(60\ \mu{\rm m}) \geq 5.24$ Jy and Galactic latitude $|b| > 30°$. Since all objects in the sample are required to have an optical counterpart on the Palomar Sky Survey Plate, this can be considered a well-defined, flux-limited galaxy sample. In fact, all but one of the sources were identified with optical galaxies by Soifer et al. (1987, 1989) and the systemic velocities of all galaxies in the sample were either obtained from the literature, or determined in more recent surveys. After correcting for the Virgocentric motions of the Local Group, a distance was adopted for each galaxy by assuming a Hubble constant of 75 km s^{-1} Mpc^{-1}. The bolometric luminosities of BGS galaxies were evaluated based on the 60 and 100 μm fluxes measured by *IRAS*, using the usual definition of $L_{\rm FIR}$ (e.g., Helou et al. 1988).

An atlas of the 1.49 GHz radio maps based on VLA observations of all BGS galaxies has been compiled (Condon et al. 1990). Radio fluxes of these galaxies correlate well with the

IRAS fluxes in much the same way as was found earlier in a smaller sample (Helou et al. 1985). Condon et al. (1991a, b) have also obtained VLA maps at 8.44 GHz for a subsample of BGS galaxies which were unresolved at 1.49 GHz. Combined, these maps range in angular resolution from 0″.25 to 60″, depending on the source's apparent size.

It is important to note that the highest resolution used in the Condon et al. 1.49 GHz atlas is often the one that is just sufficient to *resolve* the emission. As a galaxy may be mapped with several different resolutions of the VLA, integrated fluxes were measured for each map separately. For galaxies considered "resolved", a pair of angular sizes were given in the catalog, corresponding to the major and minor axes of a two-dimensional Gaussian fit. In cases where a nuclear "monster" radio source is present, it was taken as a point source and excluded when evaluating the flux of extended emission. If the extended emission was too weak or highly irregular (e.g., Arp 229/NGC 3690), no size information was given in the atlas. Hence, for the remaining ~260 galaxies (or 79% of the BGS), one can be reasonably confident that the galaxy is actually resolved, at least in its longest dimension (see Condon et al. 1990 for further details of the radio observations).

3. BASIC ASSUMPTIONS AND ADDITIONAL SELECTION

Regardless of the mechanisms that produce the now well-known correlation between galactic FIR and radio continuum fluxes, the fact that $L_{\rm FIR}$ is approximately proportional to $L_{1.49\,\rm GHz}$ over four orders of magnitude strongly suggests that the radio and FIR emissions of the disk spatially coincide with each other as well. A comparison of radio and FIR maps of 25 nearby late-type galaxies (Bicay & Helou 1990) provided clear evidence in support of this assumption. The extent of the disk's radio emission is always similar to, and perhaps somewhat larger than the size measured in FIR emission. Helou & Bicay (1992) predict that the two sizes should match more closely in disks of more active and denser ISM. This appears to be true in nearby starburst galaxies such as M82 and NGC 253 (Bicay & Helou 1990; Carilli et al. 1992).

A potential uncertainty in using the sizes of the radio emission as an upper limit of the FIR sizes is due to possible AGN's or nuclear "monster" sources that are intrinsically different from the disk component (Condon et al. 1982; Heckman et al. 1983). Some nuclei in the BGS exhibit Seyfert or LINER signatures and have unresolved, steep-spectrum radio cores. If the source flux is comparable to or brighter than that of the extended emission, the radio size measurements could be misleading. To guard against this possible "contamination", we exclude from the sample 35 galaxies with known AGNs based on the extensive catalog of Véron-Cetty & Véron (1991). Furthermore, we checked the maps of all remaining objects to verify that the latter are *bona fide* extended emission sources. Since the characteristic size scale of "monsters" rarely exceeds 0.1 kpc, this provides confidence that the size scale measurements are truly representative of the star forming disks.

In the analysis, we assume that for BGS galaxies (i) the major axis $a_{\rm maj}$ of the extended radio emission at 1.49 GHz represents the largest extent of the FIR disk. To be conservative, we only adopt $a_{\rm maj}$ measurements that are at least $\frac{2}{3}$ of the VLA beamwidth used, and consider smaller size estimates from that map unreliable. (ii) in cases where the Condon atlas provides several measurements with different resolution for a single source, we select the angular size and flux data that correspond to *the largest beam with which the galaxy is still resolved*. This is because at higher resolution, the interferometric radio map may resolve out the extended emission, thus underestimating the total radio flux of the galaxy. (iii) in choosing the "lowest possible resolution map", we make sure that at the adopted resolution, the integrated radio flux differs no more than 40% from the total radio flux of the source.

4. VARIATION OF GALAXY SIZE WITH LUMINOSITY

Figure 1 is a plot of the FIR luminosity $L_{\rm FIR}$ versus effective radio size $A^{\rm eff}$ (defined as $A^{\rm eff} = \pi a_{\rm maj}^2 d^2/4$, where d is the distance of the galaxy) for all 218 BGS galaxies which meet the selection criteria in § 3. The tilted lines in Figure 1 are for constant FIR surface brightness defined as $L_{\rm FIR}/A^{\rm eff}$. Evidently, the effective radio size varies widely in each of the five distance bins. Yet, among all galaxies with $L_{\rm FIR} > 10^{9.5}\ L_\odot$, there is a clear trend of decreasing mean $\langle A^{\rm eff}\rangle$ with increasing distance d (indicated by different symbols). This suggests that the more luminous galaxies are *not* just spatially more extended star forming disks. Instead, their star-forming regions appear to be more compact in size, indicative of significantly different physical conditions from the fainter galaxies. As for the low luminosity galaxies, we note that almost all are within the distance range of 3 to 17 Mpc, including some irregulars and dwarfs in the Local Group.

A more explicit illustration of the size scale variation with luminosity is provided by radio surface brightness histograms in Figure 2. In this plot, the 218 BGS galaxies are grouped into six radio luminosity bins, one for each panel. The short-dashed

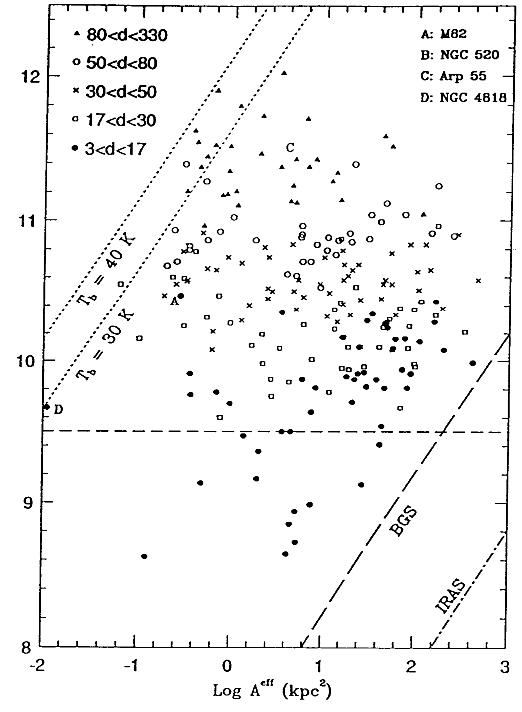

FIG. 1.—FIR luminosities of the BGS galaxies in five distance groups, plotted against effective area $A^{\rm eff}$ as defined in the text. Both axes are in logarithmic scale. Different symbols represent the distance bins, as shown in the upper left (d is in units of Mpc). Dot-dashed line in the lower right shows the *IRAS* detection limit, while the long-dashed line is the equivalent surface brightness level of the BGS threshold flux within the *IRAS* (60 μm) beam. The two dotted lines in the upper left mark the surface brightness of blackbody surfaces at temperatures T_b = 30 and 40 K. Data points representing several well-known galaxies are marked. The horizontal dashed line shows the luminosity below which local dwarf galaxies dominate.

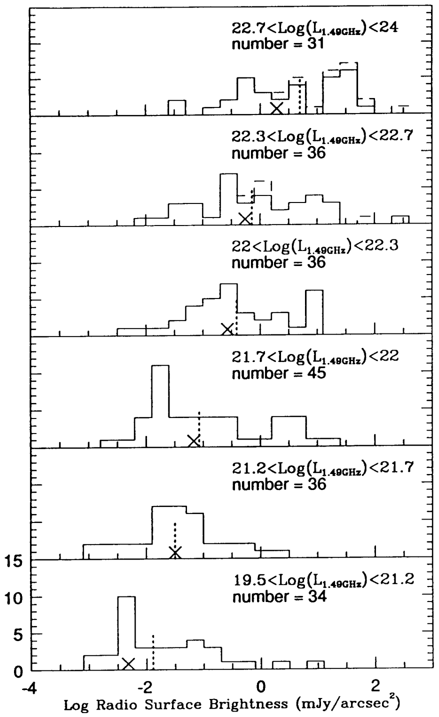

FIG. 2.—Histograms of effective radio surface brightness of the BGS galaxies in *six luminosity bins*. The bins are selected such that each has roughly the same number of galaxies. Labels at the upper right corner of each panel show the luminosity range and number of galaxies within the bin. The horizontal axis is in logarithmic scale. Short-dashed vertical line in each panel marks the median surface brightness in the luminosity bin. Crosses show where the median surface brightness would be *if* the sizes of galaxies are *independent* of luminosity, and remain the same as that of the second panel from bottom. Dashed lines in the top two panels indicate the addition of galaxies where only upper limits of their radio sizes are available.

line in each panel marks the median radio surface brightness $\langle L_{1.49\ \mathrm{GHz}}/A^{\mathrm{eff}}\rangle$ within the luminosity bin. Crosses indicate the expected median radio surface brightness in the hypothetical case where the median A^{eff} in all bins are the same (normalized to the second plane from the bottom). As mentioned above, our selection criteria are rather conservative, since sources smaller than $\frac{2}{3}$ of the radio beam are considered unresolved. The increase of surface brightness with luminosity is even steeper if these sources are included, using their measured sizes as upper limits of a_{maj}. We indicate the location of these "unresolved" sources by the dashed-line histogram in the two top panels of Figure 2.

Figure 2 shows that the *median radio surface brightness* (*SB*) *increases at least as fast as, or perhaps faster than the increasing luminosity* (*L*). In fact, a numerical fit to the data with a power-law relationship $\langle SB\rangle \sim \langle L\rangle^n$ for all galaxies in the top five panels yielded $n = 1.21 \pm 0.08$. This surface brightness variation with luminosity is statistically robust, in the sense that it is insensitive to the bins and averaging estimators (median, mean, or weighted mean). Furthermore, the changes are more dramatic among the higher luminosity ($L_{\mathrm{FIR}} \gtrsim 10^{11}\ L_\odot$) galaxies in the sample.

Since the correlation between FIR and radio continuum emission holds even at the highest luminosities of the BGS sample, the above results also point to smaller FIR emitting regions in galaxies of higher luminosities. Hence Figure 2 again implies that more active star-forming galaxies are not simply scaled-up versions of the "ordinary" disks, but both more intense and more concentrated. We note that a tentative suggestion of such an effect was made by Carico et al. (1990) in an independent work based on a smaller sample of galaxies.

5. DISCUSSION

5.1. *Biases and Uncertainties*

Before attempting to explain the above results, we need to consider the sample biases and possible sources of error. First, there is an implicit selection effect due to the absolute instrumental sensitivity limit of the *IRAS* sky survey which translates into a lower limit on surface brightness, or alternatively, *an upper limit* on the effective size,

$$A^{\mathrm{eff}}_{\mathrm{max}} \simeq 1.6 \times 10^4 \left(\frac{L_{\mathrm{FIR}}}{10^{10}\ L_\odot}\right) \mathrm{kpc}^2 ,$$

shown by the dot-dashed line in the lower right corner of Figure 1. This only affects nearby galaxies with apparent sizes exceeding the *IRAS* beam. For more distant objects, the above limit far exceeds a galaxy's angular size and thus is irrelevant. It is then replaced by a lower limit on the surface brightness of galaxies unresolved by *IRAS*, which corresponds to the BGS threshold flux density at 60 micron (5.24 Jy) being spread over the *IRAS* beam. This limit (*long-dashed line in Fig. 1*) scales exactly like the first one, except that it is about 25 times higher. Even this more stringent limit is far greater than $\langle A^{\mathrm{eff}}\rangle$ derived for galaxies with $L_{\mathrm{FIR}} \gtrsim 10^{9.5}\ L_\odot$. Thus, to the extent that BGS is a truly flux-limited sample, our results are essentially unaffected by the cutoff at the FIR flux threshold. Secondly, obtaining spatially resolved measurements from radio maps does not bias against larger objects of higher luminosity. To the contrary, we could only have missed objects which are small in A^{eff}, since sources that are considered unresolved at the VLA were rejected.

Some of the FIR bright galaxies are known to be interacting pairs too close together to be separated in *IRAS* measurements. Given the much higher resolution of the VLA maps, the radio size could in some cases be measuring only part of the FIR source. Fortunately, this problem is partially alleviated by the fact that sources with highly irregular radio morphology often have no size measurements reported in the Condon atlas. In order to test whether source confusion could remain as a problem, we eliminated about 20 sources in the sample that are suspected to be pairs (either interacting or merely geometric, cf. Bushouse, Lamb, & Werner 1988), and repeated the analysis. The results were almost identical.

We therefore conclude that selection biases associated with the definition of BGS and with the radio size measurements could not have induced the observed trend of increasing surface brightness with luminosity.

5.2. *Unlikely Scenarios*

We can rule out the possibility that it is merely the *apparent*—as opposed to physical—size of the galaxy that becomes smaller with increasing luminosity, caused for instance by anisotropic emission. The simplest argument against significant anisotropy is the excellent correlation between radio and infrared over the whole range of luminosity. Both radiations would have to be beamed in precisely the same way, an extremely unlikely situation given the intrinsic difference between the radiative processes at the two wavelengths, and the low optical depths in emission.

Another unlikely situation is that radio and infrared galaxy sizes diverge substantially as luminosity increases, or as a transient phenomenon during certain phases of a starburst. Large departures from the FIR-radio correlation appear to be quite rare: the BGS galaxies were analyzed by Condon et al. (1991a), and they have as tight a correlation as any other galaxy sample. In addition, they show no trend either in dispersion or in mean ratio with luminosity. Out of ~300 objects, only one galaxy shows an unusual FIR-to-radio ratio. These observations suggest that, since both radio and infrared disks are essentially powered by star formation, it is highly unlikely that they will be substantially different even in the extreme cases.

5.3. *Implications for Starbursts*

Our analysis indicates that the more luminous galaxies produce most of their infrared and radio power within similar, or even smaller volumes than their less luminous counterparts. This result confirms and extends the suggestion by Carico et al. (1990) that, based on near-infrared colors of a luminous subset of BGS galaxies, most of the FIR power appears to originate from the nuclear region of these galaxies. Our result disagrees sharply with the model expectation that the surface areas of star-forming regions should be proportional to the FIR luminosity (e.g., Rowan-Robinson 1987). Highly luminous systems that can be described as versions of ordinary galaxies scaled up in size either occur very rarely, or are extremely short-lived compared to more compact objects at similar luminosity. The data cannot, however, rule out more extended faint disks surrounding the bright active regions.

This picture is also in clear contrast to the situation in the visible (at least for the high surface brightness galaxies), where a well-defined magnitude-diameter relation exists (Freeman 1987). The latter dictates that the size of a system increases with luminosity in such a way that the central surface brightness is virtually constant. These differences, along with the large scatter of infrared-to-visible light ratios in galaxies, may point to the episodic or strongly fluctuating character of the infrared luminosity and the star formation activity compared to the more stable emission tied to the older stars.

The $\langle SB \rangle \sim \langle L \rangle^{6/5}$ relation based on the radio data must reflect an increase in the mean interstellar density or in the mean intensity of the heating photon flux. Independent evidence for the same trend is provided by the clear increase of FIR color temperatures of galaxies with increasing luminosity (Soifer et al. 1989). The most likely situation is that both increase with luminosity. This trend in physical parameters along the star-formation rate sequence should be figured into the interpretation of measurements, such as Hα or CO data, which are sensitive to density, temperature, or optical depth. We shall defer a detailed analysis of the correlation between surface brightness, dust temperatures and optical depths to a subsequent publication.

A preliminary comparison can be made here between our results and the CO observations which show a steep increase of FIR emissivity (per unit molecular mass) with H_2 surface mass density (Scoville & Soifer 1991; Okumura et al. 1991). The latter results have been interpreted as an enhancement of energy generation rate, i.e., star-formation efficiency, driven by higher mean interstellar densities. It should be noted that the results derived from CO data are not very sensitive to the uncertainties in the CO luminosity to H_2 mass ratio in these galaxies (e.g., Radford, Solomon, & Downes 1991).

Despite the elevated luminosities and densities of the more luminous galaxies, the optical depth of the FIR emission is still well below unity for $\lambda \lesssim 100$ μm. This can be seen in Figure 1, where we draw two dotted lines indicating the surface brightness for blackbody sources at 30 and 40 K. The position of these lines is only indicative for two main reasons: the uncertainty over which infrared wavelength to associate with the 1.4 GHz sizes, and the range of temperatures of the emitting dust. Since the 60-to-100 μm color temperatures of the more luminous BGS galaxies exceed 30 K (Soifer et al. 1989), the optical depths in emission must be even lower than suggested by Figure 1. However, because of the uncertainties mentioned above, we cannot decide in a model-independent way to what extent these low effective optical depths reflect small area filling factors as opposed to low column densities.

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