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FAR-INFRARED LUMINOSITIES OF MARKARIAN STARBURST GALAXIES

L. K. DEUTSCH AND S. P. WILLNER
Harvard-Smithsonian Center for Astrophysics
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ABSTRACT

Total far-infrared luminosities have been calculated from measured *IRAS* fluxes for a sample of optically selected galaxies and for a comparison sample of spiral galaxies. The starburst galaxies are notably more luminous in the far-infrared and have higher dust color temperatures than the comparison galaxies. The far-infrared light dominates the total luminosity of the starburst galaxies, and a significant amount of dust must be present. The far-infrared emission correlates well with total blue luminosity, nuclear blue luminosity, and nuclear Hα luminosity. The dust that produces the far-infrared light is probably heated predominantly by B rather than by O stars.

Subject headings: galaxies: stellar content — infrared: sources — stars: formation

I. INTRODUCTION

A number of nearby galaxies, such as M82 and NGC 253, show evidence of bursts of massive star formation in their nuclei (Rieke and Lebofsky 1979; Rieke *et al.* 1980; Jones and Rodríguez-Espinosa 1984). These starburst galactic nuclei were discovered primarily through infrared observations. They are characterized by their observed mid- and far-infrared excesses, attributed to the reradiation by dust of ultraviolet radiation from hot, young stars and by several emission features in the infrared spectrum (Gillett *et al.* 1975; Russell, Soifer, and Merrill 1977; Willner *et al.* 1977). These infrared features do not appear in the spectra of galaxies other than those with giant H II region nuclei, i.e., starburst nuclei (Roche and Aitken 1985 and references therein).

Another potential set of starburst galaxies has been identified on the basis of optical observations (Weedman *et al.* 1981; Balzano 1983). Most of them are selected from the Markarian lists of unusually blue galaxies (Markarian, Lipovetskii, and Stepanian 1979*a*, *b*, and references therein), and we therefore refer to them as "Markarian starburst galaxies." Many of these galaxies show an ultraviolet excess, which seems to indicate a relatively low dust content. Even though these galaxies are more distant than the starbursts identified from infrared observations, their reddening is evidently less, and the Markarian starbursts provide an excellent opportunity to study both the optical and infrared properties of galaxies that have undergone recent bursts of star formation.

A substantial amount of data exists in the literature on the optical and near-infrared properties of Markarian starburst galaxies (Rieke 1985). However, until recently no far-infrared observations had been obtained for these galaxies. Newly acquired data from the *Infrared Astronomical Satellite* (*IRAS*) provide the first far-infrared observations of a large sample of Markarian starburst galaxies. As in the case of infrared-selected starburst galaxies, the existence of significant amounts of dust in the Markarian starburst galaxies would be indicated by luminosities dominated by the far-infrared radiation.

This *Letter* presents far-infrared luminosity functions for a large sample of Markarian starburst galaxies and for a comparison sample of normal spiral galaxies. The starburst galaxies are found to be significantly more luminous, and their ratios of blue to far-infrared luminosities indicate that dust absorbs most of the light emitted by young stars and reemits it in the infrared. Correlations between the far-infrared luminosities of the starburst galaxies and their blue light and Hα luminosities are examined to determine some of the properties of the bursts. Deutsch and Willner (1986, hereafter Paper II) give the luminosities of individual galaxies along with more details of the calculations.

II. THE SAMPLES

The Balzano (1983) sample of optically selected starburst galactic nuclei consists of 99 galaxies chosen from the Markarian surveys of galaxies and three galaxies from the Keel and Weedman (1978) list of bright galactic nuclei. All of the galaxies in the sample have nuclei that are stellar or semistellar in appearance and exhibit narrow emission-line spectra. The emission line widths and line ratios of the starburst nuclei are similar to those of galactic H II regions (Balzano 1983) and distinguish them from Seyfert and other active galactic nuclei (Baldwin, Phillips, and Terlevich 1981).

The models that best fit *UBV* colors of Markarian starburst nuclei consist of red star systems with recent bursts of star formation (Huchra 1977*a*). Balzano (1983) found the measured Hα emission to be consistent with the presence of young, hot stars and concluded that photoionization by stellar ultraviolet radiation is the likely ionization mechanism. The median reddening derived from the Hα/Hβ ratio is $A(\mathrm{H}\beta) = 2.1$ mag.

In order to compare the far-infrared luminosities of the Markarian galaxies with those of "normal" galaxies, *IRAS* observations of a sample of 60 Virgo spirals have also been studied. The comparison sample consists of all spiral galaxies in the Virgo Cluster or its southern extension listed in the *Revised Shapley-Ames Catalog* (Sandage and Tammann 1981). This sample was chosen because it has been the subject of previous infrared studies and because it consists of galaxies at a known distance. Comparison with a sample of field spirals would not change our results; Devereux, Becklin, and Scoville (1986) have shown that spirals in the Virgo sample have essentially the same far-infrared luminosities as field spirals. Scoville *et al.* (1983) measured galaxies in the Virgo comparison sample at 10 μm and found a continuous distribution of 10 μm luminosities over more than a decade of flux. They interpreted this distribution as evidence of some degree of star formation activity in all of the detected galaxies.

III. LUMINOSITIES

Far-infrared flux densities were taken from the *IRAS Point Source Catalog* (1985). A tape copy of the catalog was searched for position coincidences with galaxies in the Balzano (1983) and comparison samples. The Balzano sample yielded 81 associations, and the comparison sample yielded 56. Far-infrared (10 μm to ∞) fluxes were calculated from the *IRAS* flux densities; the calculation included flux from an assumed Rayleigh-Jeans energy distribution beyond 100 μm, but the actual observations could not detect any luminosity beyond 120 μm. Few galaxies were detected in all four *IRAS* bands, but bands with upper limits do not substantially affect the derived fluxes. Infrared cirrus (Low *et al.* 1984) was found to be unimportant for these samples. Six galaxies in the Balzano sample and four in the comparison sample could not be uniquely identified as the *IRAS* source, and for these the calculated fluxes were considered upper limits. Galaxies surveyed by *IRAS* but not detected were also assigned upper limits based on the *IRAS Explanatory Supplement* (1985).

Previous far-infrared observations, made with a 50″ beam, exist for two galaxies in the starburst sample and four in the comparison sample (Rickard and Harvey 1984). The *IRAS* flux densities exceed those in the small beam by factors of 1.3–5, and considerable emission must originate at distances greater than 2.5–5 kpc from the galactic nuclei.

Distances for the starburst galaxies were calculated from the redshifts, taking into account galactic rotation and infall into the Virgo cluster (Aaronson *et al.* 1982). Distances ranged from 10 to 270 Mpc with a median of 60 Mpc. The comparison galaxies were all assumed to be at a Virgo cluster distance of 18.7 Mpc, consistent with the flow model and an assumed Hubble constant of 75 km s^{-1} Mpc^{-1}.

The distances were combined with the far-infrared fluxes to give total far-infrared luminosities L(FIR) or upper limits for all of the galaxies in both samples. For the starburst sample, luminosities were also calculated for nuclear blue light ($L^*_{\rm nuc}$) and nuclear Hα emission [L(Hα)] based on Balzano's observations with 4″ diameter or 3″ by 8″ rectangular beams and for total blue light ($L^*_{\rm tot}$) based on Zwicky magnitudes (Zwicky *et al.* 1961–1968). The blue magnitudes were converted to fluxes by calculating νF_ν. Figure 1 shows the far-infrared luminosities of the starburst galaxies as functions of their total blue luminosities and of their Hα luminosities. Tabulated results for individual galaxies and additional plots are given in Paper II.

Far-infrared luminosity functions were determined for the Balzano and comparison galaxy samples with the maximum likelihood approach of Avni *et al.* (1980). This nonparametric method incorporates both measured luminosities and upper limits to calculate the probability distribution function. The

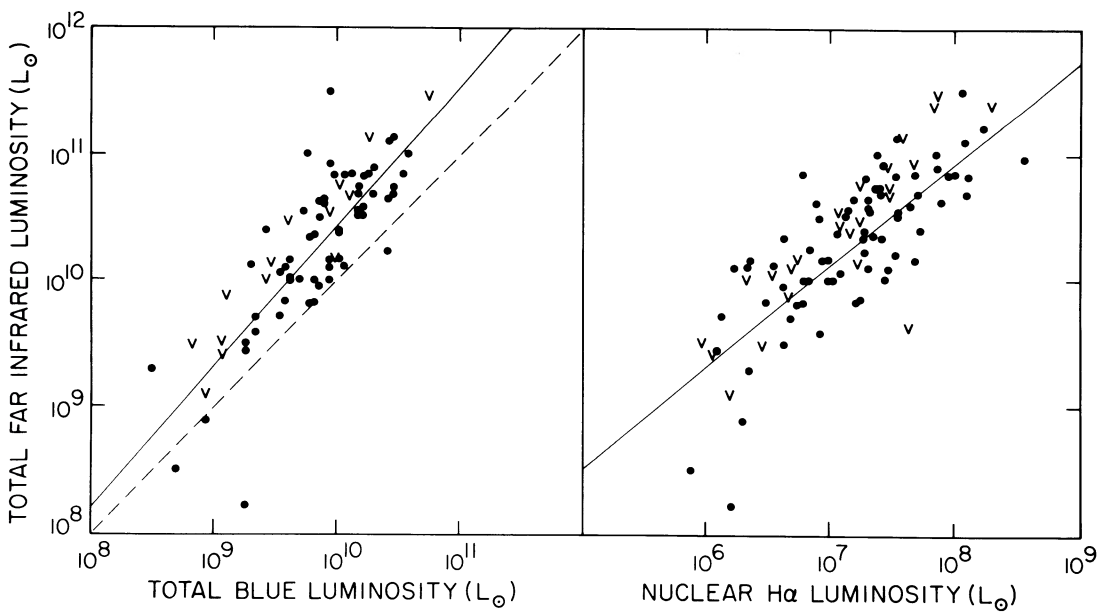

FIG. 1.—Far-infrared luminosities for the starburst sample as functions of blue light and of Hα luminosities. The blue luminositites were derived from Zwicky magnitudes and represent an estimate of the light from the entire galaxy. The Hα luminosities were derived from small beam measurements and represent only the emission near the nucleus. Carets indicate galaxies with upper limits on their far-infrared luminosity. The solid lines indicate the best-fit linear relations. The dashed line indicates equal blue and far-infrared luminosities. The left panel of the figure omits six galaxies that have upper limits on both coordinates; the omitted points are consistenent with the data plotted.

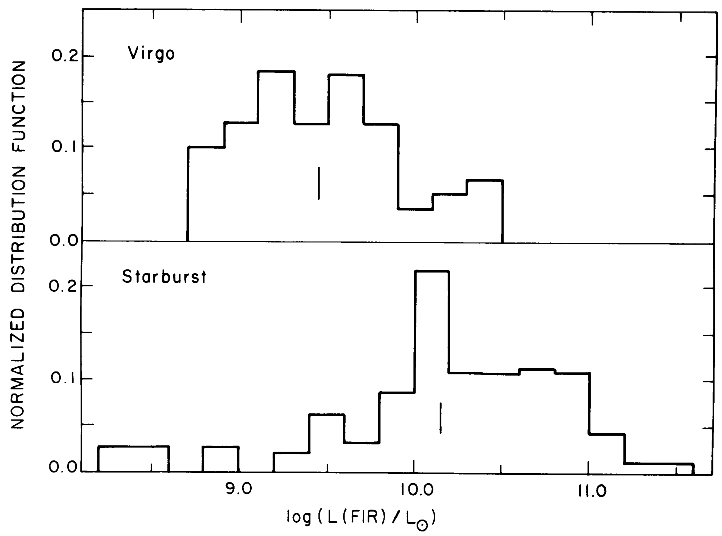

FIG. 2.—Histograms of the normalized far-infrared luminosity functions for the two galaxy samples. The vertical lines indicate the median luminosity of each sample. The upper histogram is for the Virgo spiral galaxies, and the lower is for the Balzano sample of starburst galaxies.

treatment of galaxies with luminosity upper limits assumes that these galaxies are drawn from the same population as the detected galaxies, i.e., that there is no separate population of "infrared-faint" galaxies. However, the fraction of galaxies with upper limits is small enough that their treatment does not significantly affect our conclusions. The derived luminosity functions are shown in Figure 2.

IV. DISCUSSION

Figure 1 shows that all but four of the starburst galaxies are more luminous in the far-infrared than in the blue. (The exceptions are Mrk 13, 190, 430, and 743.) The median ratio of far-infrared to total blue luminosity is 2.45 for the sample, and the far-infrared luminosity dominates the total galaxy brightness. This provides strong evidence for a significant dust content in the starburst galaxies. Since the galaxies in the Balzano sample were partially chosen on the basis of their unusually blue colors, the indicated dust content suggests that we view these galaxies along a line of sight with fortuitously low extinction. It is likely that other lines of sight are considerably dustier, and the space density derived from the optical data (Balzano 1983) could be severely underestimated. Weedman (1985) has found that the underestimate is about a factor of 2.

The luminosity functions in Figure 2 show that the starburst galaxies are notably more luminous than the comparison galaxies. Most of the starburst galaxies have greater luminosities than all but the few brightest Virgo spirals. The median luminosities for the two samples differ by a factor of 5, with the median log $L(\mathrm{FIR})/L_\odot = 10.16$ $(+0.18, -0.06)$ for the starbursts compared to 9.45 $(+0.09, -0.18)$ for the Virgo spirals; the latter value agrees with the one found by Devereux, Becklin, and Scoville (1986). The difference between the starbursts and the Virgo spirals cannot be attributed to an infrared deficiency in the Virgo spirals, because field spirals have essentially the same luminosities (Devereux, Becklin, and Scoville 1986). Part of the difference might be attributed to the starburst galaxies being more massive, as their median blue luminosity derived from Zwicky magnitudes is a factor of 2 greater than for the Virgo spirals. However, the blue light measurements probably exaggerate the difference between the samples, because the starburst itself causes the Markarian galaxies to be brighter in blue light than normal for their mass. Furthermore, even if the luminosity of each Virgo galaxy were doubled, the luminosity functions in Figure 2 would still differ substantially. The high far-infrared luminosities of the starburst galaxies are consistent with the presence of a hot, young star population as indicated by the existing optical data (Huchra 1977*b*; Balzano 1983). Two of the most luminous Markarian starburst galaxies (Mrk 617 and 201) are among the "super starburst galaxies" defined by Joseph and Wright (1985). However, most of the Markarian starbursts are less luminous than the super starbursts, which have a median log $L(\mathrm{FIR})/L_\odot = 11.50$ (for $H_0 = 75$ km s^{-1} Mpc^{-1}).

The Markarian starburst and Virgo galaxy samples differ in far-infrared color temperature as well as total luminosity. Of the 81 *IRAS* detections for the Balzano sample, the flux measured in the 60 μm *IRAS* band is the dominant contributor to the total flux for all but eight galaxies; seven of these have larger contributions in the 100 μm band, and one (Mrk 711) is dominated by the flux in the 25 μm band. The 100 μm flux is the second largest contributor for most of the sample. For the Virgo spirals, on the other hand, the flux in the 100 μm band is the dominant contributor to the total flux for all but five galaxies; three have larger contributions from the 60 μm band, and two are dominated by flux in the 12 μm band. The 60 μm flux is the second largest contributor to the total flux for the majority of the sample. Though both galaxy samples show evidence of star formation activity, the higher luminosities and hotter color temperatures imply a more luminous young star population in the starburst sample galaxies than in the comparison galaxy sample.

Figure 1 shows that there is a good correlation between the far-infrared luminosities of the starburst galaxies and their

TABLE 1

STARBURST LUMINOSITY CORRELATION COEFFICIENTS[a]

Parameter	L(FIR)	L(Hα)	L^*_{tot}
L(Hα)	0.77 ± 0.06	...	...
L^*_{tot}	0.84 ± 0.06	0.68 ± 0.08	...
L^*_{nuc}	0.83 ± 0.06	0.82 ± 0.05	0.85 ± 0.06

[a]Uncertainties represent 90% confidence limits.

TABLE 2

STARBURST LUMINOSITY SLOPES[a]

Parameter	L(FIR)	L(Hα)	L^*_{tot}
L(Hα)	$0.81^{+0.21}_{-0.22}$	...	...
L^*_{tot}	$1.12^{+0.26}_{-0.28}$	$0.84^{+0.16}_{-0.15}$	...
L^*_{nuc}	$0.93^{+0.19}_{-0.12}$	$0.92^{+0.15}_{-0.10}$	$0.75^{+0.14}_{-0.12}$

[a]Best-fit slope and uncertainty of luminosity in top row as a function of luminosity in left column. Uncertainties represent 94% confidence limits.

blue and Hα luminosities. These correlations among the luminosities have been quantified with a nonparametric maximum likelihood technique that incorporates both detections and upper limits (Schmitt 1985). The derived correlation coefficients among all four available luminosities are shown in Table 1 along with their uncertainties, and Table 2 gives the slopes and uncertainties for the best-fit regression lines.

The most striking aspect of the luminosity-luminosity comparisons is that all of the quantities are well correlated with one another. The correlations involving the far-infrared luminosities are not likely to be strongly affected by Malmquist bias since nearly all the galaxies in the sample were detected by *IRAS*. Furthermore, the flux-flux comparisons exhibit significant though somewhat weaker correlations.

Table 1 shows that the far-infrared luminosities are marginally better correlated with blue light than with the Hα emission. This result is rather surprising, because internal reddening should affect the blue light measurements more than the Hα and produce an effect opposite to the one seen. Both total blue light and blue light from the nucleus alone show the better correlation, so simple differences in spatial distribution are unlikely to be responsible. A possible explanation is that different stellar populations are responsible for heating the dust that produces the far-infrared radiation and for ionizing the gas that produces the Hα emission. Most of the ionizing photons should be contributed by the very hottest stars, which are present in small numbers, while most of the luminosity to heat dust should be provided by the much larger number of slightly cooler stars. We therefore infer qualitatively that most of the dust heating probably comes from B and perhaps A stars rather than from O stars.

All but one of the slopes given in Table 2 are consistent with the various luminosities being linearly proportional, but the total blue luminosity does not increase as fast as nuclear blue luminosity. This shallower slope is not surprising, because the most luminous galaxies tend to be the most distant, and the distant galaxies have a greater portion of their total light included within the small beam measurements. Another anomaly is that the three slopes relating nuclear Hα luminosity, total blue luminosity, and nuclear blue luminosity are not mutually consistent. The reason for the inconsistency is unclear, because we do not know how the Hα emission is distributed over the galaxy. If all luminosities were truly linearly proportional to each other and Hα were distributed in the same way as the blue light, we would expect the slope of L(Hα) versus L^*_{tot} to be about 1.33 rather than the value of 0.84 observed. In the other extreme spatial distribution, where Hα comes from a point source at the nucleus, the slope would be 1.0. Thus for either spatial distribution, it appears that Hα luminosity does not increase as fast as blue luminosity, and more luminous starbursts have lower proportions of the hottest stars. If all starbursts were identical at birth, stellar evolution would produce the opposite effect, as the youngest starbursts would be the most luminous and would also contain a greater proportion of hot stars. A greater average metallicity in higher luminosity starbursts might produce the observed effect, as the greater metal abundance in stellar atmospheres and possibly higher dust abundance could reduce the Lyman continuum emission relative to blue light. It is possible that the initial mass function could be affected as well. However, better data, especially information on the spatial distribution of Hα, are needed to confirm the suggested change in stellar population with luminosity.

V. CONCLUSIONS

1. The Markarian starburst galaxies are notably more luminous in the far-infrared than "normal" spiral galaxies, even though these normal spirals also show indications of star formation activity. In addition, the Markarian starburst galaxies have higher dust color temperatures. This indicates that the Markarian starburst galaxies contain many more hot, young stars than the comparison galaxies.

2. The far-infrared luminositites are the largest contributors to the total light from the Markarian starburst galaxies. Despite the unusually blue optical colors of these galaxies, the predominance of the far-infrared light provides strong evidence for the presence of a large dust content. If the observed blue colors can be interpreted as the result of a fortuitously dust-free line of sight, then the space density of these galaxies derived from the optical data has been significantly underestimated.

3. The far-infrared, Hα, and central and total blue luminosities of the Markarian starburst galaxies are well correlated with one another. To first order, the starburst properties seem independent of the total starburst luminosity. There is, however, some indication that the least luminous starbursts may originate with a greater proportion of the hottest stars.

4. The far-infrared luminosities are probably better correlated with the blue light than with the Hα luminosities, implying that the dust producing the far-infrared light is heated predominately by B rather than O stars.

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L. K. DEUTSCH and S. P. WILLNER: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138