THE IRAS BRIGHT GALAXY SAMPLE. II. THE SAMPLE AND LUMINOSITY FUNCTION

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ABSTRACT

A complete sample of 324 extragalactic objects with 60 µm flux densities greater than 5.4 Jy has been selected from the IRAS catalogs. Only one of these objects can be classified morphologically as a Seyfert nucleus; the others are all galaxies. The median distance of the galaxies in the sample is ~30 Mpc, and the median luminosity $L_{\nu}(60 \mu m)$ is $\sim 2 \times 10^{10} L_\odot$. This infrared selected sample is much more “infrared active” than optically selected galaxy samples.

The range in far-infrared luminosities of the galaxies in the sample is $10^9 L_\odot$ to $2 \times 10^{12} L_\odot$. The far-infrared luminosities of the sample galaxies appear to be independent of the optical luminosities, suggesting a separate luminosity component. As previously found, a correlation exists between $60 \mu m$ flux density ratio and far-infrared luminosity. The mass of interstellar dust required to produce the far-infrared radiation corresponds to a mass of gas of $10^8$–$10^{10} M_\odot$ for normal gas to dust ratios. This is comparable to the mass of the interstellar medium in most galaxies.

The infrared luminous galaxies are found to be an important component of extragalactic objects, being the most numerous objects in the local universe at luminosities $L > 10^{11} L_\odot$, and producing a luminosity density of $\sim 1/2$ that of the observed starlight in normal galaxies. Approximately 60%–80% of the far-infrared luminosity of the local universe is likely attributed to recent or ongoing star formation. If the infrared active phase ($L_{\nu IR} > 10^{11} L_\odot$) is a nonrecurring event of duration less than $10^8$ yr in galaxy evolution, then more than ~10%, and perhaps all of the galaxies with blue luminosities greater than $10^{10} L_\odot$ must undergo such an event.

Subject headings: galaxies: general — infrared: general — infrared: sources — stars: formation

I. INTRODUCTION

The IRAS survey was the first infrared all-sky survey with sufficient sensitivity to detect a significant number of extragalactic sources. One result of the survey is the discovery that far-infrared emission dominates the total luminosity in a significant fraction of galaxies. Another, as discussed here, is the demonstration that the infrared luminous galaxies form a significant component of the local universe. To establish this, it is necessary to make a census of the galaxies that are infrared emitters, to determine the space densities of these galaxies, and to compare infrared bright galaxies with other known classes of extragalactic objects.

We have begun a study of the properties of the brightest infrared galaxies discovered in the IRAS survey with the goal of understanding the physical processes responsible for the infrared emission in galaxies. In this paper we describe a statistically complete sample of 324 objects selected for these studies, derive the far-infrared luminosity function of these galaxies, and compare the space densities of the IRAS bright galaxy sample with those of other major classes of extragalactic sources. A preliminary description of the results of the luminosity function for $L > 10^{10} L_\odot$ was reported by Soifer et al. (1986, hereafter Paper I), and a detailed description of the optical spectra and morphologies of the most luminous objects in this sample will be reported elsewhere (Sanders et al. 1987a).

II. THE IRAS BRIGHT GALAXY SAMPLE

The sample selected for study was designed to meet the following criteria: (1) it should be a complete sample of far-infrared-emitting extragalactic objects; (2) the size of the sample should be large enough to be able to make statistically significant statements regarding the space densities of infrared-emitting objects; (3) the objects in the sample should be accessible from northern hemisphere telescopes; and (4) the optical identifications should be made with as little ambiguity as possible. The final bright galaxy sample comprised all extragalactic objects observed by IRAS with 60 µm flux densities greater than 5.4 Jy, galactic latitude $|b| > 30^\circ$, and declination $\delta > -30^\circ$ for 0–12 hr, $\delta > -15^\circ$ for 12–14 hr, and $\delta > -20^\circ$ for 14–24 hr. The declination boundaries indicate areas where redshift information is complete. An extension of the bright galaxy survey to the rest of the sky covered by IRAS at $|b| > 30^\circ$ and away from the Magallenic Clouds is currently underway (Elias, private communication).

For an object to be included in the IRAS bright galaxy sample it is necessary for it either to be identified with a cataloged extragalactic object or to have a redshift indicating it to be extragalactic. Although no morphological criteria were set for inclusion in the sample other than that there be an optical counterpart on the Palomar Sky Survey (POSS), all but one of the objects ultimately selected for inclusion in the sample are clearly extended on the POSS. The one exception to this is an
object with a starlike Seyfert nucleus, IRAS 0518−25 (Sanders et al. 1987a).

The total area covered by the bright galaxy survey is about \(14,500 \text{ deg}^2\). Within the boundaries described above, small areas of the sky are not included because the \(2 \mu\text{m}\) and \(60 \mu\text{m}\) survey of the \(60 \mu\text{m}\) flux densities is taken (in decreasing order of priority) from the LGC, the SSSC, and the PSC. This order of selection ensures that the estimate of the largest total flux density for a given galaxy has been used. Twenty-nine galaxies in the bright galaxy sample have \(60 \mu\text{m}\) flux densities taken from the LGC; 53 \(60 \mu\text{m}\) flux densities were obtained from the SSSC. In the case of NGC 5195, because of its proximity to M51, the \(60 \mu\text{m}\) and \(100 \mu\text{m}\) flux densities were estimated from one-dimensional co-addition of the \(60 \mu\text{m}\) survey data by subtracting a contribution from M51 that was assumed to be symmetrically distributed about the position of M51. Because the galaxies in this sample are all comparatively bright, the uncertainties in the reported flux densities are all dominated by systematic and calibration uncertainties, and should be less than 15%.

The flux densities reported in Table 1 have been corrected for the large bandwidths of the \(60 \mu\text{m}\) and \(100 \mu\text{m}\) filters, assuming the intrinsic spectrum to be a Planck curve multiplied by an emissivity proportional to frequency. Typically the corrections are 30%–10% at \(60 \mu\text{m}\) and <2% at \(100 \mu\text{m}\). The uncertainty in the intrinsic spectrum of the source leads to an uncertainty in the correction term of roughly \(\pm 5\%\) (see the IRAS Explanatory Supplement 1985).

Distances established from primary distance indicators (Sandage and Tammann 1981) or the Tully-Fisher relation (Aaronson and Mould 1983) and modified for the distance adopted for the Virgo cluster (see below), have been adopted where available. For galaxies where neither of these are available, heliocentric radial velocities, from the literature (Palumbo, Tazzella-Nitta, and Vettolani, 1983; Huchra et al. 1983; Rood, private communication), were used in combination with a Hubble constant of 75 km s\(^{-1}\) Mpc\(^{-1}\).

For those galaxies where no radial velocity was found in the literature, observations of the optical spectrum were made using the double spectrograph (Oke and Gunn 1982) on the 5 m Hale telescope of the Palomar Observatory. For these observations, the resolution was 12 \(\AA\) at H\(\alpha\), and the uncertainty in the radial velocity is \(\pm 300 \text{ km s}^{-1}\). In all cases where a galaxy redshift was determined from observations obtained at Palomar, the galaxy had strong emission lines of H\(\alpha\), [N ii], [O iii], and H\(\beta\). The optical spectra of these galaxies are discussed in detail by Sanders et al. (1987b).

Where distances were determined from redshifts, the distance to each galaxy was derived using the Virgo-centric flow of Aaronson et al. (1982b). For all galaxies where distances were taken from the Fisher-Tully relation or the Virgo-centric flow model the distances were scaled assuming Virgo is at 17.6 Mpc and the infall velocity toward Virgo is 350 km s\(^{-1}\) (i.e., \(H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}\) at large distances). All galaxies within 6° of the center of the Virgo cluster were assumed to be members of
the cluster, and their distances are taken as 17.6 Mpc. In addition the galaxies within 20° of the center of Virgo, whose distances are not derived from another source, and whose radial velocity is within 400 km s⁻¹ of that of Virgo, are assumed to be cluster members. All distance and redshift information used for the bright galaxy sample is given in Table 1.

IV. COMPLETENESS OF THE TABLE

Because the completeness limit of the PSC at 60 μm is ~0.5 Jy (IRAS Explanatory Supplement 1985) the IRAS bright galaxy sample should be highly complete. The completeness of the PSC is well understood (Chester 1986; IRAS Explanatory Supplement 1985). The SSSC is estimated to be complete above 10 Jy at 60 μm, although this has not been investigated in detail (SSSC Introduction, 1986). Thus there could be some incompleteness in sources selected from the SSSC for inclusion in the bright galaxy sample. This is unlikely to be significant since the differential number counts with the flux density of the sources in the bright galaxy sample in Figure 1 shows an acceptable fit to an $N \propto f_{\nu}^{-3/2}$ distribution to the lowest flux bin. It therefore appears that the bright galaxy sample is, to a good approximation, a complete and unbiased sample of 60 μm extragalactic sources. Note that the objects in the bright galaxy sample have been selected on the basis of completeness of the PSC.
Thus the Virgo cluster presents a 10% contribution to the bright galaxy sample.

Histograms of the far-infrared and blue luminosities of the objects in the bright galaxy sample are plotted in Figure 3. The total far-infrared luminosity $L_{\text{FIR}}$ for the galaxy is calculated using the far-infrared flux $f_{\text{FIR}}$, which is derived by fitting the 60 $\mu$m and 100 $\mu$m flux densities to a single temperature Planck function multiplied by an emissivity $\epsilon_{\nu}$ (Cataloged Galaxies and Quasars Observed in the IRAS Survey, Appendix B, 1985). For luminosity calculations the deceleration constant $q_0$ was assumed to be zero. The blue luminosity is the quantity $L_{\nu} (0.43 \mu$m) and is derived from the Zwicky (blue) magnitudes given in Table 1. The blue flux $f_{\nu} = v$ (0.43 $\mu$m), has been estimated from the relation between $m_v$ and $r$ suggested by the Virgo cluster. Thus the Virgo cluster presents a 10% contribution to the bright galaxy sample.
The range of observed far-infrared luminosities extends from $\sim 10^8 L_\odot$ to greater than $10^{12} L_\odot$, with the mode of the distribution occurring at $\sim 2 \times 10^{10} L_\odot$. A similar distribution (adjusted to the same Hubble constant) was found by Lawrence et al. 1986. All the sources in the bright galaxy sample have far-infrared flux densities much greater than can be attributed directly to a stellar population, while none are known radio-loud objects where the infrared emission could be expected to be an extension of the radio nonthermal emission. Furthermore, many of the objects in the sample show spatial extent at 60 $\mu$m. Thus, we assume that the far-infrared peak in the energy distribution is due to thermal emission by dust. For far-infrared luminosities of $\sim 2 \times 10^{10} L_\odot$ and typical dust temperatures of $\sim 35$ K, the mass of dust required to produce the observed luminosity is $\sim 4 \times 10^4 M_\odot$, assuming optically thin dust emission and normal dust parameters (e.g., Draine and Lee 1984). This corresponds to a total gas mass of $\sim 10^9 M_\odot$, quite typical for the interstellar medium of large spiral galaxies.

As can be seen from Figure 3 the mean blue luminosity is significantly lower than the far-infrared luminosity, while the dispersion in the blue luminosities is about half that in the far-infrared luminosities. For the 312 galaxies with blue
IRAS BRIGHT Galaxies

The objects in the bright galaxy sample are, not surprisingly, "infrared active" as those in an optical magnitude limited sample detected in the IRAS survey. This is illustrated in Figure 4, where histograms of far-infrared to blue flux ratios are plotted for the bright galaxy sample and for the galaxies brighter than 14.5 mag in the UGC catalog (Nilson 1973; Rice, private communication) that have IRAS detections.

For the infrared-selected sample the values of \( \log (f_{\text{FIR}/f_b}) \) range from \(-0.9\) to \(2.1\), while for the range for the optically selected sample is \(-1.5\) to \(2.1\). The median value of \( \log (f_{\text{FIR}/f_b}) \) for the IRAS galaxies is \(\sim 0.4\), while for the optical sample the median value is \(\sim -0.2\). Note that the UGC galaxies without \( \text{IRAS} \) detections will have \( \log (f_{\text{FIR}/f_b}) = 0 \). Since only half of the UGC galaxies with \( m_b < 14.5 \) mag are detected by \( \text{IRAS} \), the median value of \( \log (f_{\text{FIR}/f_b}) \) for an optically selected sample with infrared measurements for all sources must be still smaller. From Figure 4 it is clear that the infrared flux-limited sample consists of galaxies with much greater average infrared luminosity than does the optically selected sample.

Figure 5a shows that \( f_{\text{FIR}/f_b} \), correlates with \( L_{\text{IR}} \), while there is no correlation between \( f_{\text{FIR}/f_b} \) and \( L_b \), as shown in Figure 5b. As seen in Figures 3 and 5b the blue luminosities of the galaxies in the bright galaxy sample have a dispersion of \( \sim 1 \) mag about a mean of \( \sim 10^{10} L_\odot \) that larger \( f_{\text{FIR}/f_b} \) ratios require larger \( L_{\text{IR}} \). The simplest explanation of these results is that the far-infrared and blue luminosity components are basically independent, and the correlation of \( f_{\text{FIR}/f_b} \) with \( L_{\text{IR}} \) is due to increasing infrared emission in the more luminous galaxies.

\( \sigma[\log (L_b)] = 0.43, \) while \( \sigma[\log (L_{\text{FIR}})] = 0.70 \) for all 324 galaxies in the sample.

\( \sigma[\log (L_{\text{FIR}})] = 0.70 \) for all 324 galaxies in the sample.

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TABLE 1—Continued

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ous galaxies, rather than due to extinction of the visible radiation.

The bright galaxy sample contains no galaxies with low far-infrared luminosities and with $f_{\text{IR}}/f_{\text{UV}}$ ratios greater than 10. This lack cannot be a selection effect. At $L_{\text{IR}} \approx 10^{10} L_\odot$ the bright galaxy sample includes galaxies to 30 Mpc, certainly a large enough volume to detect such galaxies, if they were common. Even at $L_{\text{IR}} \approx 10^{9} L_\odot$ galaxies would be detected to $\sim 10$ Mpc. Such galaxies might have very low visible surface brightness and hence not be visible on the POSS. Such galaxies would, if their sizes were similar to the optical size of dwarf irregular galaxies (Gallagher and Hunter 1984), be point sources at distances greater than 6 Mpc, so that they would be contained in the PSC for over 80% of the volume surveyed. Thus the identifications from this subset of the bright galaxy sample, where only one object is not accounted for (see above), preclude a significant contribution of dwarf galaxies. The lack of any visible, faint galaxy counterparts to extended sources also argues against such a class of galaxies being present in the SSSC. The work of Helou (1986a) has shown that a very small fraction of known dwarf galaxies have detectable 60 µm emission, and this is at a comparatively low level and usually associated with H II regions in these galaxies.

Seven galaxies in the bright galaxy sample are contained in the blue compact galaxy sample of Thuan and Martin (1981). The average absolute blue magnitude of these seven galaxies is $M_B = -19.9$ mag. The mean far-infrared luminosity of these galaxies is $1.8 \times 10^{10} L_\odot$, and their mean ratio of infrared to blue light is 2.5; all of these values are close to the median of the entire sample. Thus the infrared properties of the blue
In Figure 6a the 60 \mu m/100 \mu m flux density ratio, which is monotonic with color temperature, is plotted versus far-infrared luminosity. In Figure 6b the 60 \mu m/100 \mu m flux density ratio is plotted versus blue luminosity. There is a correlation between the color temperature and the far-infrared luminosity in the sense that higher luminosities correspond to higher 60 \mu m/100 \mu m color temperatures, while there is clearly no correlation between the far-infrared color temperature and the blue luminosity. Such a correlation has been found previously by Miley, Neugebauer, and Soifer (1985) and Rieke and Lebofsky (1986).

The absence of high-luminosity, cold galaxies from the bright galaxy sample is probably not a selection effect. Cold galaxies of a given far-infrared luminosity will have weaker 60 \mu m fluxes than do warm galaxies, so the volume within which they can be detected at 60 \mu m is smaller. This selection effect does not account for the change in color temperature with luminosity and does not appear to be accurate for the observed lack of cold galaxies at high luminosity. The volume searched for galaxies having the median 60 \mu m/100 \mu m color of those galaxies with L_{\text{IR}} \approx 10^{10} L_{\odot} is \approx \frac{1}{3} that of those galaxies with median color at L_{\text{IR}} \approx 10^{12} L_{\odot} at the same luminosity. Therefore the lack of detection of any such cold galaxies cannot be simply a color selection effect, but rather indicates a significant decrease in the space density of galaxies at high luminosities and cold color temperatures. Furthermore,
TABLE 1—Continued

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<td>UGC 12915/4</td>
<td>23 59 7.7</td>
<td>+23 12 58</td>
<td>5.8</td>
<td>14.1</td>
<td>4590</td>
<td>...</td>
<td>10.82</td>
<td>13.2</td>
</tr>
</tbody>
</table>

* Magnitude taken from Zwicky catalogs (Zwicky et al. 1961–1968). Note (1) indicates magnitude is blue magnitude, from Sanders et al. 1987a.

Fig. 1.—Differential number counts of sources plotted vs. flux density for sources in the bright galaxy sample. Each bin includes a range of 1.67 in flux density, while fractional error in each bin is $N^{-1/2}$, where $N$ is number of sources in bin. Line shown is best-fit of data to $N \propto f^{-0.5}$ power-law number count distribution, and is an acceptable fit to data.
Fig. 2.—Histogram of distances to galaxies in bright galaxy sample, determined as described in text. Lower envelope represents galaxies not associated with Virgo cluster, while histogram above this line includes Virgo cluster galaxies.

Fig. 3.—Histograms of luminosities of galaxies in bright galaxy sample. Blue luminosity (dotted line) is $nL_{0.43} \mu$m, while far-infrared luminosity (solid line) is the luminosity effectively from 40–400 $\mu$m (see text). In plot and in text luminosities are given in solar (bolometric) luminosities. Note much narrower distribution of blue compared to far-infrared luminosity.
FIG. 4.—Histograms of ratio of far-infrared flux to blue flux for two samples of galaxies detected in IRAS survey. Solid line is infrared limited bright galaxy sample, while dashed line is distribution for galaxies in UGC catalog with $m_r < 14.5$ detected in IRAS survey (Bothun, Lonsdale, and Rice 1987). Nondetections in UGC catalog have $\log f_{\text{IR}}/f_b < 0$. Histogram for UGC galaxies has been normalized to peak of bright galaxy sample, but contains ~10 times more galaxies. One object from UGC galaxies at $\log f_{\text{IR}}/f_b = -1.55$ fell below limits of plot.

VI. SPACE DENSITY OF IRAS GALAXIES

a) The 60 μm Luminosity Function

The space density of galaxies in terms of 60 μm luminosity, $\nu L_{\nu}(60 \mu m)$, and the uncertainty in the space density were derived using the expressions

$$\rho = \left( \frac{4\pi}{\Omega} \right) \left( \frac{1}{V_n} \right),$$

where $\rho$ is the space density, $\Omega$ is the solid angle, $V_n$ is the volume, and $\nu L_{\nu}(60 \mu m)$ is the 60 μm luminosity.

A search of the PSC at 100 μm with $b > 50^\circ$ showed no high-luminosity, cold objects that were not contained in the bright galaxy sample.

The apparent maximum 60 μm/100 μm flux density ratio in Figure 6a, independent of $L_{\text{EIR}}$, implies that the intensity of the radiation field heating the radiating material reaches an effective maximum. The increase of the lower bound of 60 μm/100 μm flux density ratio with increasing luminosity indicates that the minimum radiation field seen by the radiating material is increasing with luminosity.

Lines of constant mass of radiating dust (assuming optically thin dust emission) corresponding to total gas masses (assuming $M_g/M_d = 200$) of $10^8$, $10^9$, and $10^{10} M_\odot$ are shown in Figure 6a. They show that the amount of material responsible for the far-infrared radiation is roughly comparable to the amount of interstellar matter in normal galaxies, and generally increases with increasing luminosity. Nearly all the galaxies in the bright galaxy sample have masses of dust within this range, with a tendency for the higher luminosity sources to have more radiating material. This range of mass is quite comparable to the amount of mass expected in the interstellar medium of normal spiral galaxies (Sanders et al. 1986). Since cold galaxies need more material to produce a given luminosity, absence of galaxies with high luminosities and low color temperatures may reflect the absence of galaxies having enough interstellar matter to produce such high luminosities without having a generally warmer interstellar medium.

Another statement of this is that a luminosity of $10^{12} L_\odot$ is sufficient to heat the dust corresponding to more than $10^{10} M_\odot$ of gas and dust to temperatures significantly greater than those found in normal galaxies.

Figure 7 combines the previous two figures, showing the ratio $f_{\text{IR}}/f_b$ plotted versus $f_{\nu} (60 \mu m)/f_n (100 \mu m)$ for the bright galaxy sample. This plot shows the same general correlation shown previously by de Jong et al. (1984) and Soifer et al. (1984), where increasing ratio of infrared to blue light is correlated with increasing color temperature. At a given 60 μm/100 μm ratio, the spread in $f_{\text{IR}}/f_b$ is greater in the bright galaxy sample than in the optically selected sample of de Jong et al., while the lower envelope of the $f_{\text{IR}}/f_b$ versus $f_{\nu} (60 \mu m)/f_n (100 \mu m)$ relation is consistent with the results from the optically selected sample.
Fig. 5—(a) Plot of ratio of far-infrared to blue flux vs. far-infrared luminosity for bright galaxy sample. Increase in average ratio of far-infrared to blue flux is closely linearly proportional to far-infrared luminosity. (b) Plot of ratio of far-infrared to blue flux vs. blue luminosity for bright galaxy sample. There is no apparent correlation between these quantities.
FIG. 6.—(a) Plot of ratio of 60 µm/100 µm flux densities vs. far-infrared luminosity bright galaxy sample. Ordinate is also shown as grain temperature for grains having emissivity $\epsilon \propto v$. Lines of gas mass of $10^8$, $10^9$, and $10^{10} M_\odot$ are drawn, where $M_\text{gas}/M_\odot = 200$ has been assumed. Dust is assumed to radiate with temperature given by right hand temperature scale, and 100 µm dust opacity is taken from Draine and Lee (1984). (b) Plot of ratio of 60 µm/100 µm flux densities vs. blue luminosity for bright galaxy sample. No correlation is apparent between these quantities.
Fig. 7.—Plot of ratio of far-infrared to blue flux vs. 60 µm/100 µm flux density for bright galaxy sample. There is a tendency for higher values of $f_{\text{IR}}/f_b$ to be associated with higher 60 µm/100 µm ratios.

and

$$\sigma_p = \left(\frac{4\pi}{\Omega}\right)\left(\sum \frac{1}{V_m^2}\right)^{1/2},$$

where $\Omega$ is the solid angle of the survey, and $V_m$ is the maximum volume to which the object could have been detected in the survey, and the summation is over all galaxies in a given luminosity bin (Schmidt 1968).

The more sophisticated estimator of Felton (1976) reduces to the above expression for a uniform flux limit for the survey, as is the case here. Here $V_m$ was individually estimated for each galaxy in the sample. The $K$ correction, determined using a power-law slope (Sandage 1975) defined by the observed 60 µm and 100 µm flux densities, was taken into account in calculating $V_m$. Since all redshifts are comparatively small, this power law defines the spectrum near 60 µm better than the slope between 25 µm and 60 µm does.

The space densities as a function of luminosity are given in Table 2, along with the number of galaxies in each luminosity bin, the uncertainty in the space density, and the average $V/V_m$ for that bin along with its uncertainty. The quantities are given both including and excluding galaxies deemed to be associated with the Virgo cluster. The luminosity function that excludes

### Table 2

**Luminosity Function at 60 Microns**

<table>
<thead>
<tr>
<th>log $L^*$ $(L_\odot)$</th>
<th>All Galaxies</th>
<th>Galaxies: Virgo Excluded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N$ ($\rho$ (Mpc$^{-3}$ mag$^{-1}$))</td>
<td>$V/V_m$</td>
</tr>
<tr>
<td>8.2</td>
<td>4 $3.2 \pm 1.7 \times 10^{-2}$</td>
<td>0.50 ± 0.13</td>
</tr>
<tr>
<td>8.6</td>
<td>8 $1.6 \pm 0.6 \times 10^{-2}$</td>
<td>0.36 ± 0.09</td>
</tr>
<tr>
<td>9.0</td>
<td>11 $5.6 \pm 1.8 \times 10^{-3}$</td>
<td>0.45 ± 0.08</td>
</tr>
<tr>
<td>9.4</td>
<td>41 $4.4 \pm 0.7 \times 10^{-3}$</td>
<td>0.59 ± 0.05</td>
</tr>
<tr>
<td>9.8</td>
<td>62 $2.1 \pm 0.3 \times 10^{-3}$</td>
<td>0.44 ± 0.03</td>
</tr>
<tr>
<td>10.2</td>
<td>78 $6.6 \pm 0.8 \times 10^{-4}$</td>
<td>0.42 ± 0.03</td>
</tr>
<tr>
<td>10.6</td>
<td>53 $1.1 \pm 0.2 \times 10^{-4}$</td>
<td>0.45 ± 0.04</td>
</tr>
<tr>
<td>11.0</td>
<td>29 $1.5 \pm 0.3 \times 10^{-5}$</td>
<td>0.58 ± 0.05</td>
</tr>
<tr>
<td>11.4</td>
<td>25 $4.0 \pm 0.8 \times 10^{-6}$</td>
<td>0.47 ± 0.06</td>
</tr>
<tr>
<td>11.8</td>
<td>9 $3.1 \pm 1.1 \times 10^{-7}$</td>
<td>0.46 ± 0.09</td>
</tr>
<tr>
<td>12.2</td>
<td>4 $4.3 \pm 2.2 \times 10^{-8}$</td>
<td>0.29 ± 0.15</td>
</tr>
</tbody>
</table>

$*L(60 \mu m) = vL_{\odot}(60 \mu m)$. © American Astronomical Society • Provided by the NASA Astrophysics Data System
the Virgo cluster takes no account of the volume excluded from the sample; this volume is less than 8% of the total surveyed volume in all bins.

In Figure 8 the quantity $V/V_m$ as a function of 60 µm luminosity is plotted. Where appropriate, the $V/V_m$ data with the Virgo galaxies included and excluded are shown. There are no significant deviations from the value of 0.5 expected for a sample that homogeneously fills the volume, with the maximum deviation from the uniform case being for the bin log $[\nu L_5(60 \mu m)] = 10.2$ with $V/V_m$ of 0.43, a 2.5 $\sigma$ result. For the entire sample, $V/V_m = 0.47 \pm 0.02$, again not significantly different from 0.5. The effect of the Virgo cluster can also be seen in the points where these galaxies are included. In the bins at log $[\nu L_5(60 \mu m)] = 9.4, 9.8,$ and 10.2 the inclusion of the Virgo cluster galaxies makes $V/V_m$ differ significantly from 0.5.

Other 60 µm luminosity functions have been derived based on different samples taken from the IRAS data (e.g., Lawrence et al. 1986; Rieke and Lebofsky 1986; Smith et al. 1987). All of these 60 µm luminosity functions are compared with the luminosity function for the bright galaxy sample in Figure 9. All the luminosity functions have been converted to the units adopted here. In the case of the Lawrence et al. results, the only conversion necessary was for different Hubble constants. No attempt was made to account for differing value of $d_0$, since the largest redshifts in the bright galaxy sample are less than $z = 0.1$. For the Smith et al. results the only conversions necessary were for the Hubble constant and a different multiplier of $L_5(60 \mu m)$. For the Rieke and Lebofsky sample, the relation $L = 1.6 \times \nu L_5(60 \mu m)$ was adopted based on the distribution of flux ratios presented in their work. As can be seen from Figure 9, the agreement between the luminosity functions derived from different samples is excellent.

While the criteria used to define the bright galaxy sample were based on 60 µm flux density and optical identification, it is interesting to consider whether this sample differs from galaxy samples chosen based on infrared color criteria for studies of the spatial distribution of infrared galaxies (e.g., Yahil, Walker, and Rowan-Robinson 1986; Meiksin and Davis 1986). All of the objects in the bright galaxy sample meet the criteria for inclusion in both of these samples, while neither Yahil, Walker, and Rowan-Robinson nor the Meiksin and Davis samples include objects that would be excluded based on color criteria from the bright galaxy sample. Thus it appears that there are no substantial differences between these samples, and the bright galaxy sample can be used as a fiducial point for fainter, more distant samples of infrared selected galaxies.

Rieke and Lebofsky (1986) have shown that the Schechter (1976) type luminosity function falls below the observed luminosity function at high luminosity. This is also seen in Figure 9. Two power laws fitted to the observed 60 µm luminosity function are also shown in Figure 9. At low luminosities the best-fit power law gives a slope $p = -0.8$, while at high luminosities the best-fit slope is $p = -2.0$, again in good agreement with the best-fit power law slope of $-2.1$ estimated by Rieke and Lebofsky. The slope at low luminosity agrees well with the slope for this region of $-0.8$ derived by Lawrence et al. (1986), while at the high-luminosity end the slope is steeper than that

Fig. 8.—Mean $V/V_m$ for the galaxies in bright galaxy sample plotted vs. luminosity of appropriate bin. Crosses represent bins where Virgo cluster galaxies have been excluded, open circles represent all galaxies in those luminosity bins. Only with inclusion of Virgo galaxies are any statistically significant deviations from value of 0.5 expected for galaxies uniformly distributed in volume.
of $-1.7$ from Lawrence et al., consistent with the observed space densities in the sample of Lawrence et al. being higher at the highest luminosities. The luminosity of the break between the two power laws is $1.7 \times 10^{10} L_\odot$; this is the most frequent luminosity seen in this flux-limited sample.

Whether the 60 $\mu$m luminosity function can be extrapolated to higher luminosities is quite uncertain. Based on the luminosity function derived above, approximately three objects should have been discovered in the bright galaxy sample with luminosities placing them in the next greatest luminosity bin. Clearly the absence of any such examples has no statistical significance, while a handful of fainter, more luminous objects are already known to exist in the $IRAS$ survey (e.g., 3C 48 and Mrk 1014; Neugebauer, Soifer, and Miley 1985). Furthermore, two infrared “loud” objects have been found in the luminosity range $10^{13} L_\odot$ (Kleinmann and Keel 1987; Vader 1986). The existence of these objects suggests that an extrapolation of the observed luminosity function by an order of magnitude is not unrealistic. However, the extension of the far-infrared luminosity function to such luminosities must await a survey of sufficient numbers of $IRAS$ galaxies.

It is tempting to use the different luminosity functions to search for potential evolutionary effects. The largest range in distance is achieved by comparing the bright galaxy luminosity function with that of Lawrence et al. (1986), where the completeness limit was 0.85 Jy, and by selecting the highest possible luminosity bin for comparison. Figure 9 shows a suggestion of the luminosity function changing in the expected way if there were an increased density of high-luminosity infrared galaxies in the past. Formally, the increase in density of
galaxies in the range \( \log [\nu L_\nu(60 \, \mu m)] = 12.0-12.4 \) is a factor of \( \sim 3 \). This highly uncertain increase in space density with redshift is consistent with the analysis of the counts of 60 \( \mu m \) sources at the 50 mJy level by Hacking, Condon, and Houck (1987).

b) Comparison with Other Classes of Objects

One goal of the present study is to understand the significance of far-infrared emission in the local universe. This requires comparing the luminosities emitted at different wavelengths by very different classes of objects. In Figure 10, the bolometric luminosity functions of a variety of different classes of extragalactic objects are plotted. The far-infrared luminosity described above has been adopted as the bolometric luminosity for the IRAS bright galaxy sample. The total far-infrared luminosities calculated in this way are \( \sim 50\% \) greater than the 60 \( \mu m \) luminosities. This ignores an additional contribution of \( \sim 25\% \) to the total luminosity from the emission at shorter wavelengths.

Table 3 gives the far-infrared luminosity function. The calculations were done as for the 60 \( \mu m \) space densities; the only difference was the binning by total far-infrared luminosity,
rather than 60 μm luminosities. The data in Table 3 are used below to compare “bolometric luminosity functions” of different luminosity components in galaxies.

The bright galaxy sample is only strictly complete at 60 μm, and not in a bolometric sense over the entire far-infrared wavelength range. Thus there could be cold or warm objects that are extremely numerous but would not be included in the bright galaxy sample. The PSC was searched using 60 μm/100 μm and 25 μm/60 μm color criteria intended to determine if objects colder or warmer than those selected here might be numerous compared to the bright galaxy sample. While both cold and warm galaxies were found, based on the additional searches of the PSC such objects are likely to comprise less than 25% of the galaxies at a given far-infrared luminosity within a given volume. We conclude that the bright galaxy sample represents a legitimate sample of the local universe in the far-infrared.

For comparison, luminosity functions taken from the literature for “normal galaxies,” “starburst galaxies,” Seyfert galaxies, and quasars are included in Figure 10. The published luminosity functions are given in terms of $M_B$, i.e., absolute blue luminosity, so it was necessary to estimate a bolometric correction for each of the classes of objects. The steps taken to derive these bolometric corrections were described in Paper I, but the details are repeated in the Appendix for completeness.

It is important to remember, when comparing the different luminosity functions, that some galaxies can simultaneously be classified in more than one category of object, and are not necessarily evaluated at the same luminosity in each category. Figure 10 should thus be viewed as a comparison of the space density of sources of far-infrared luminosity with that of sources of luminosity that emerge predominantly at shorter wavelengths. For example, the starburst galaxies comprise a subset of the “normal” galaxies, and their luminosity is estimated in a similar way. The bolometric corrections described in the Appendix for these classes of galaxies do not include the far-infrared luminosity emitted by such galaxies (above that in the stellar photospheres). For the Seyferts and quasars, an estimate of the far-infrared luminosity has been included in the calculation of the luminosity, but this is only 10%–15% of the total luminosity of these objects.

One can immediately see from Figure 10 that the emission from infrared bright galaxies represents a significant component of the luminosity in the local universe. The infrared galaxies are more numerous by a factor of ~3 than Markarian starburst galaxies at $L_{\text{FIR}} \lesssim 10^{10} L_\odot$. In the range $10^{10} L_\odot-10^{11} L_\odot$, the densities of the two classes of objects are comparable. For luminosities above $2 \times 10^{11} L_\odot$ infrared luminous galaxies appear to be the dominant source of luminosity in the local universe, having virtually the same space densities as the Seyferts at the lower end of this range, and a significantly greater space density than quasars at the higher luminosities. A detailed discussion of the spectroscopic and morphological properties of the galaxies in this highest range of infrared luminosities of the bright galaxy sample is in preparation (Sanders et al. 1987a).

For luminosities below $2 \times 10^{11} L_\odot$, normal galaxies dominate the space densities in the local universe. From the far-infrared luminosity function the contribution to the luminosity density of the local universe can be estimated. The infrared galaxies with far-infrared luminosities greater than $10^{10} L_\odot$ produce $\sim 9 \times 10^{7} L_\odot$ Mpc$^{-3}$ in far-infrared emission, with $4 \times 10^{7} L_\odot$ Mpc$^{-3}$ being generated in galaxies with far-infrared luminosities greater than $10^{10} L_\odot$. By comparison, the normal galaxies produce a bolometric luminosity density of $\sim 4 \times 10^{7} L_\odot$ Mpc$^{-3}$, where the integrated blue luminosity density taken from Felton (1977) and Yahil, Sandage, and Tammann (1980), corrected to $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, has been corrected by the same bolometric correction as adopted for normal galaxies. Thus the far-infrared luminosity is ~25% of the stellar luminosity of galaxies. Felton and Yahil, Sandage, and Tammann estimate the luminosity density of normal galaxies by reducing the absolute scale factor for the local luminosity function to that determined from the number counts at faint magnitudes (see Appendix). There is no evidence that this same factor should be applied to the infrared luminosity function. Indeed, the agreement between the luminosity functions of the bright galaxy sample and that of Lawrence et al. (1986) suggests that the 60 μm luminosity function remains constant in normalization when the median galaxy distance changes from ~30 Mpc to ~100 Mpc. Perhaps the absence of elliptical and dwarf galaxies from the infrared selected samples contributes to the more uniform density.

At luminosities greater than $10^{10} L_\odot$ it is likely that star formation is the dominant form of energy generation in infrared bright galaxies (Becklin 1987), at least until the very highest luminosities. Several authors (Persson and Helou 1986; Helou 1986b; Rowan-Robinson and Crawford 1987; de Jong and Brink 1987) have suggested that a significant fraction of the far-infrared luminosity in less active galaxies is recycled stellar radiation not directly associated with star-formation regions. Thus, directly or indirectly, star formation accounts for between 60% and 80% of the far-infrared luminosity generated in the local universe.

The total space density of galaxies with far-infrared luminosities greater than $10^{11} L_\odot$ is $\sim 1.2 \times 10^{-3}$ Mpc$^{-3}$. Figure 5a shows that 85% of these galaxies have blue luminosities greater than $10^{12} L_\odot$. From Christensen (1975), the space density of normal galaxies with $L_B > 10^{10} L_\odot$ is $3.4 \times 10^{-3}$ Mpc$^{-3}$, or ~0.3% of the galaxies with $L_B > 10^{10} L_\odot$ have $L_{\text{FIR}} > 10^{11} L_\odot$. If the infrared bright phase has a lifetime $t_{IR}$ and the optical phase has a lifetime $t_{opt}$ then the fraction of galaxies that have undergone such an infrared active phase is $0.003 \times t_{IR}/t_{opt}$. If the overall normalization of the optical luminosity function is reduced by a factor of 2.3 (Felton 1977) while the far-infrared luminosity function remains constant, as suggested in Figure 9, then the fraction of galaxies undergoing this
phase become $0.007 \times t_b/t_{IR}$. As noted in Paper I, if $t_b \sim 10^{10}$ yr and the infrared bright phase is a nonrecurring starburst phase with $t_{IR} < 10^8$ yr (Rieke et al. 1980; Gerz, Sramek, and Weedman 1983), then a significant fraction, perhaps more than 50%, of galaxies with $L_\phi > 10^{10} L_\odot$ must have undergone such an infrared active period. If $t_b$ is as small as $10^9$ yr and $t_{IR}$ is $\sim 10^7$ yr, then almost 10% of such galaxies could undergo such a phase.

VII. SUMMARY

From a complete sample of the brightest galaxies detected at 60 $\mu$m in the IRAS all-sky survey, we have found the following:

1. Far-infrared emission is a significant luminosity component in the local universe, representing 25% of the luminosity emitted by stars in the same volume. Above $10^{11} L_\odot$ the infrared luminous galaxies are the dominant population of objects in the universe, being as numerous as the Seyfert galaxies, and more numerous than quasars at higher luminosities.

2. The infrared luminosity appears to be independent of the optical luminosity of galaxies. Most infrared bright galaxies appear to require much, if not all, of their interstellar matter to be contributing to the observed infrared luminosity.

3. Approximately 60%-80% of the far-infrared luminosity of the local universe can be attributed, directly or indirectly, to recent or ongoing star formation.

It is a pleasure to thank members of the IPAC staff for assistance in assembling IRAS data, our night assistants at Palomar, Juan Carasco and Skip Staples, for assistance in obtaining the optical spectra and optical photometry, and George Helou, Paul Schechter, and Jeremy Mould for illuminating conversations. This research was supported in part by NASA through the IRAS Extended Mission program, and in part by the NSF. G. E. D. is supported by NASA contract NAS5-25451. B. F. M. is supported in part by the Natural Sciences and Engineering Research Council of Canada and by the Canada Council through a Killam Fellowship. This is contribution No. 4427 of the Division of Geological and Planetary Sciences.

APPENDIX

CONVERSION OF LUMINOSITY FUNCTIONS TO BOLOMETRIC LUMINOSITIES

Nearly all of the luminosity functions derived for classes of extragalactic objects are given in units of $M_\odot$. Since the comparison of the far-infrared luminous galaxies with other classes of extragalactic objects requires measuring in comparable units of luminosity, and blue luminosity is not applicable to the infrared luminous galaxies, bolometric luminosity has been selected for comparison of the various luminosity functions.

Felton (1977) has discussed nine optical luminosity functions derived for nearby galaxies, and has concluded that all but one agree. The analytic form of this function formulated by Schechter (1976) is a good fit to these data, and is adopted here as the optical luminosity function of the normal galaxies. Felton has suggested that the local luminosity function for normal galaxies is too high by a factor of $\sim 2.3$ when comparing the number counts of galaxies at fainter magnitudes with those predicted from the local luminosity function. Since the IRAS bright galaxy luminosity function has been derived over roughly the same distances as the normal galaxy luminosity function, no adjustment has been made in the normalization of the normal galaxy luminosity function. An average $B - V$ color for the normal galaxies was taken as 0.8 mag, and a bolometric correction of 0.9 mag was adopted. This bolometric correction is consistent with the $V - K$ colors of typical galaxies (Aaronson 1977; Johnson 1966).

The non-Seyfert Markarian galaxies represent the most complete sample of optically selected starburst galaxies (Bohuski, Fairall, and Weedman 1978) and the luminosity function for these galaxies was taken from the work of Huchra (1977). A mean $B - V$ color of 0.5 mag and a bolometric correction of 1.2 mag are adopted for these galaxies (Huchra 1977; Balzano 1983). This correction includes contributions for the photospheres of late-type and hot stars in these galaxies.

The luminosity function for Seyfert galaxies, assumed to be characterized by the luminosity function for the Markarian Seyferts, was taken from Huchra (1977), while the luminosity function for the quasars was taken from Schmidt and Green (1983). The bolometric correction for both of these classes of objects was assumed to be the same and was estimated as $9 \times vL_(0.43 \mu m)$. This was derived by assuming a three-step power-law flux distribution, where the slope ($f_\nu \propto \nu$) was taken as $-1$ for $3 \times 10^{10} - 3 \times 10^{11} \text{ Hz}$, $-0.5$ for $3 \times 10^{11} - 3 \times 10^{12} \text{ Hz}$, and $-1.5$ for $3 \times 10^{12} - 3 \times 10^{13} \text{ Hz}$ (Malkan and Sargent 1982; Malkan 1983; Elvis et al. 1986; O'Dell, Scott, and Stein 1986). A comparison of this approximation with the integrated energy distributions of a variety of AGNs from 0.1 to 100 $\mu$m (Edelson and Malkan 1986) indicates that it represents the total bolometric luminosity of these objects to within 30%.

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