THE ASTROPHYSICAL JOURNAL, **278**:L71–L74, 1984 March 1

INFRARED GALAXIES IN THE *IRAS*[1] MINISURVEY

B. T. SOIFER, M. ROWAN-ROBINSON, J. R. HOUCK, T. DE JONG, G. NEUGEBAUER, H. H. AUMANN,
C. A. BEICHMAN, N. BOGGESS, P. E. CLEGG, J. P. EMERSON, F. C. GILLETT, H. J. HABING,
M. G. HAUSER, F. J. LOW, G. MILEY, AND E. YOUNG
Received 1983 September 16; accepted 1983 November 16

ABSTRACT

A total of 86 galaxies have been detected at 60 μm in the high galactic latitude portion of the *IRAS* minisurvey. The surface density of detected galaxies with flux densities greater than 0.5 Jy is 0.25 deg^{-2}. Virtually all the galaxies detected are spiral galaxies and have an infrared to blue luminosity ratio ranging from 50 to 0.5. For the infrared-selected sample, no obvious correlation exists between infrared excess and color temperature. The infrared flux from 10 to 100 μm contributes approximately 5% of the blue luminosity for galaxies in the magnitude range $14 < m_{\rm pg} < 18$ mag. The fraction of interacting galaxies is between one-eighth and one-fourth of the sample.

Subject headings: galaxies: photometry — infrared: general — infrared: sources

I. INTRODUCTION

Many galaxies have been observed to emit strongly at far-infrared wavelengths (for reviews and references, see, e.g., Rieke and Lebofsky 1979; Stein and Soifer 1983). This *Letter* describes the properties of a flux-limited sample of infrared-selected galaxies drawn from the *IRAS* minisurvey.

II. OBSERVATIONS

We report here an analysis of the galaxy content of the *IRAS* minisurvey (Neugebauer *et al.* 1984; Rowan-Robinson *et al.* 1984). A list was created of candidate galaxies that were bright at 60 μm (see below). In addition, the sources had to be hours-confirmed at least twice (Neugebauer *et al.*), have a galactic latitude $|b| > 20°$, have a declination greater than $-2\overset{\circ}{.}5$, and have a flux density F_ν increasing from 12 to 60 μm.

Sources which are twice hours-confirmed are highly reliable (Rowan-Robinson *et al.* 1984). The galactic latitude constraint was used to remove galactic sources while still leaving a reasonable area of sky to study. The constraint of flux density ratios eliminated stellar sources. The declination constraint was used to ensure overlap with the *Uppsala General Catalogue of Galaxies* (Nilson 1973, hereafter UGC), which is complete to roughly $m_{\rm pg} = 14.5$ mag or diameters greater than 1′ in this declination range. All visual magnitudes are tied to the magnitudes of the *Catalogue of Galaxies and Clusters of Galaxies* (Zwicky *et al.* 1961–1968).

The criterion for having a "bright" source at 60 μm was developed empirically as an efficient way of selecting galaxies. Unfortunately, the selection criteria introduce biases which result in an incomplete sample. Warm galaxies would have a greater flux at 12 or 25 μm than at 60 μm. To investigate this, we looked at those 17 sources satisfying the first three criteria listed above and having flux densities at 25 μm greater than at 60 μm. All these sources were identified either with cataloged stars or with stars on the Palomar Observatory Sky Survey. Thus, there is no evidence that such warm galaxies comprise a significant fraction of galaxies detectable by *IRAS*. Such galaxies do, however, exist (e.g., 3C 390.3, see Miley *et al.* 1984).

The above criteria also discriminate against very cold galaxies which would be found only through their 100 μm flux. The number of these is uncertain since the analysis of the 100 μm sources is incomplete because of the confusion by extended emission (see Low *et al.* 1984; Hauser *et al.* 1984). The *IRAS* 60 μm detectors are, however, a factor of 3 more sensitive in detecting flux density, so a search at 60 μm is an efficient way of detecting even cold galaxies with 60–100 μm color temperatures as low as 25 K.

Another potential source of incompleteness is that galaxies extended in the infrared have been missed by the point-source detection algorithm (Neugebauer *et al.* 1984). Several lines of evidence suggest that this problem is negligible. First, the detector apertures at 60 μm are $1\overset{\prime}{.}5 \times 4\overset{\prime}{.}5$; the point-source detection algorithm detects sources as large as the smaller dimension of the aperture. Second, of the detected galaxies that are identified with UGC galaxies (a total of 22), the largest has a major diameter in the blue of $2\overset{\prime}{.}6$, the next largest has a major axis of $1\overset{\prime}{.}7$, and all the rest are smaller. The UGC galaxies are the largest seen in the sample, so no evidence in the data suggests that optically large galaxies are missing unless, of course, the infrared sizes of galaxies are significantly greater than the sizes in the visual.

Significant flux may have been missed in the point-source detection process, especially at 12 and 25 μm, because the detector apertures in this case are $0\overset{\prime}{.}75 \times 4\overset{\prime}{.}2$, and significant numbers of the detected galaxies are visually larger than the smaller dimension. However, the raw scans of many of these galaxies show no obvious extended emission, even at 12 and

---

[1] The *Infrared Astronomical Satellite* was developed and is operated by the Netherlands Agency for Aerospace Programs (NIVR), the US National Aeronautics and Space Administration (NASA), and the UK Science and Engineering Research Council (SERC).

25 μm. Furthermore, only one galaxy was detected at 25 μm to have a size (1ʹ.5) between 1ʹ and 8ʹ.

III. RESULTS

Based on the described selection criteria, 182 sources were identified as possible galaxies. The fields of each of these were inspected on enlargements of the Palomar Schmidt Sky Survey O and E plates. A source was considered identified with a galaxy if an obvious galaxy was within 60ʺ of the *IRAS* source position. Of the 182 candidate sources, 86 were identified with galaxies, usually within 30ʺ of the *IRAS* position. Since the identification program did not reach astrometric accuracy, we do not quote the positional agreements. The properties of the high-latitude *IRAS* sources not identifiable as galaxies are discussed in the *Letters* by Houck *et al.* (1984) and Rowan-Robinson *et al.* (1984).

What fraction of the identifications could be random coincidences? Empirically, as discussed below, we identified galaxies to a limiting magnitude of $m_{\mathrm{pg}} \sim 18$ mag. From Tyson and Jarvis (1979) and references therein, there are approximately 50 galaxies per square degree that are brighter than $J = 18$ mag, so there is a probability of 0.06 of a random coincidence between an optical galaxy and the $2' \times 2'$ *IRAS* search box. Because our magnitudes are quite crude, we do not distinguish between m_{pg} and J, the photographic magnitude. Thus, roughly 10 of the reported identifications from the original 182 candidates could be spurious. In the discussion that follows, no attempt has been made to correct for random coincidences.

The *IRAS* sources identified with galaxies are listed in *IRAS Circular, No. 6* (1983). Of the 86 identifications, 38 were matched with previously cataloged galaxies, 22 of which are in the UGC. The other identifications came from the *Morphological Catalog of Galaxies* (Vorontsov-Velyaminov and Krasnogorskaja 1962; Vorontsov-Velyaminov and Arhipova 1963–1974) and the six volumes of the *Catalogue of Galaxies and Clusters of Galaxies* (Zwicky *et al.* 1961–1968). For the identifications with cataloged galaxies, the cataloged magnitude, m_{pg}, corrected to the face-on value using the precepts of de Vaucouleurs, de Vaucouleurs, and Corwin (1976), is reported. Because of the possibility that some of these are extremely dusty galaxies, this correction has a large uncertainty. For unidentified sources, the magnitude was estimated by establishing the face-on magnitude versus major axis diameter relationship for identifications in the UGC and then extrapolating this empirical relation. (The corrections to face-on values were small compared with the dispersion in the fit of size versus magnitude.) The estimated magnitudes of these uncataloged galaxies have uncertainties of at least 1 magnitude.

For the *IRAS* galaxies with $F_\nu(60) > 0.5$ Jy, a differential log N–log S relation has been determined. The best fit power law for these data has a slope of $\alpha = -1.4 \pm 0.1$, clearly consistent with the Euclidean case, $\alpha = -1.5$. Correcting for the incompleteness due to the absence of cold ($T_c < 26$ K) galaxies (see above) pushes the result closer to the Euclidean result. There were five galaxies with $F_\nu(60) < 0.5$ Jy; incompleteness has clearly set in at this point.

The 81 *IRAS* galaxies brighter than 0.5 Jy at 60 μm were found in a total area of 330 deg^2. This implies an integrated number density of 0.25 deg^{-2} for galaxies brighter than 0.5 Jy at 60 μm and brighter than $m_{\mathrm{pg}} \sim 18$ mag. Because of the relatively small number of galaxies included and the incompleteness effects described above, this number is uncertain by approximately 50%.

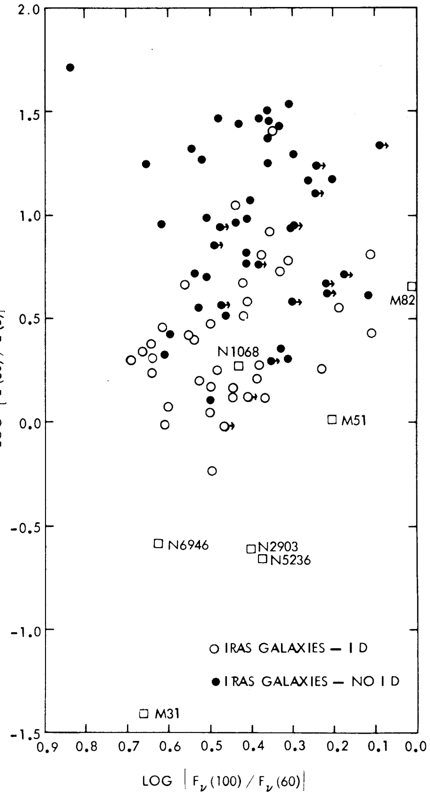

FIG. 1.—The ratio of flux per octave, i.e., νF_ν, at 80 μm to that in the blue is plotted vs. the ratio of flux density at 100 and 60 μm. The 80 μm flux density is defined as the average of the observed 60 and 100 μm flux densities. Where the 100 μm flux was only an upper limit, the 80 μm flux density was estimated by extrapolating the 60 μm flux density using an $\alpha = -1$ power law. For the galaxies identified in the figure (□), the infrared observations were taken from Smith (1982) for M51, Habing *et al.* (1984) for M31, and Telesco and Harper (1980) for the other galaxies. The blue magnitudes for these galaxies were taken from de Vaucouleurs, de Vaucouleurs, and Corwin (1976).

The ratio of the infrared to blue luminosities, $L(80)/L(B)$, for the *IRAS* galaxies is compared to their infrared colors in Figure 1. The luminosity at a particular frequency is defined as proportional to νF_ν at that frequency. The infrared-selected galaxies all have very large ratios compared with optically selected galaxies that are also plotted in Figure 1. The total range of $L(80)/L(B)$ for spiral galaxies extends over a factor of 1000. Galaxies previously known to be extremely active at infrared wavelengths do not show a particularly extreme infrared to blue luminosity ratio compared with the galaxies found in the *IRAS* survey. The well-known starburst galaxy M82 has $L(80)/L(B) \sim 4$ when considering the galaxy as a whole (Telesco and Harper 1980; de Vaucouleurs, de Vaucouleurs, and Corwin 1976), placing it near the upper, but by no means extreme, end of infrared-selected galaxies. The lower end of the range of $L(80)/L(B)$ is M31, which has a ratio of 0.04 (Habing *et al.* 1984). The Galaxy has a ratio

1984ApJ...278L..71S

$L(80)/L(B) \sim 1$ (Nishimura, Low, and Kurtz 1980; Gispert, Puget, and Serra 1982; de Vaucouleurs and Pence 1978).

The cutoff at large, 100 μm to 60 μm, flux ratios seen in Figure 1 is the result of our selection criteria. We estimate that 10% of the detectable galaxies have been missed because their color temperatures are too low (see § III above). At the low end of the flux ratio, the observed color temperature does seem to be reaching a limit of $F_\nu(100)/F_\nu(60) \sim 1.4$, corresponding to a maximum physical temperature of about 45–50 K for λ^{-1} emissivity grains. The observed far-infrared color temperature of M82 (Telesco and Harper 1980) does represent an extreme example of an infrared-selected galaxy.

De Jong *et al.* (1984) have found a rough correlation between infrared color and the infrared to blue luminosity ratio for the *IRAS* detected galaxies from the *Revised Shapely-Ames Catalog of Bright Galaxies* (Sandage and Tamman 1981). The infrared-selected galaxies do not show a tight correlation. In fact, the location of the infrared-selected galaxies in Figure 1 is almost exclusively in the region not populated by the Shapely-Ames galaxies in de Jong *et al.* (1984). The large spread in the infrared to blue luminosity ratios can be understood, in large part, as reflecting a wide range in the amount of dust within the galaxies sampled. For example, varying the dust optical depths in the blue in a galaxy from 0.1 to 0.5 will change the apparent infrared to blue luminosity ratio by a factor of 6. In addition, enhanced star formation activity could easily increase the infrared luminosity of very dusty galaxies much more.

Jura (1982) has predicted the appearance of spiral galaxies in the infrared using a simple model where starlight is thermalized in the disk of a galaxy and the dust is uniformly mixed with the stars. This model predicts temperatures near the lower limit found here, but not the warmer temperatures found in the majority of the *IRAS* galaxies. There are at least two causes for this discrepancy. The selection of 60 μm sources biases the sample toward warm galaxies, and Jura's simple models do not include the contribution to the infrared emission from recently formed stars still embedded in or associated with their parental clouds.

Figure 2*a* shows the histogram of the distribution of infrared to blue luminosity ratios. In Figure 2*b*, we show how the fraction of galaxies varies with the ratio L_{IR}/L_B. This fraction was derived by comparing the surface density of galaxies with a given L_{IR}/L_B to the surface density of all galaxies (Tyson and Jarvis 1979) at the limiting blue magnitude of the galaxies detectable by *IRAS* for that L_{IR}/L_B. Clearly, the *very active infrared galaxies are a small fraction of all galaxies*. A rough estimate of the total contribution of the observed infrared luminosity to the total luminosity of galaxies was made by summing the total flux from the *IRAS* galaxies and comparing this to the total blue flux from all galaxies down to the $B = 18$ mag limit. This led to $L_{\mathrm{IR}}/L_B \sim 0.05$. We conclude that the sum of the infrared luminosities is less than that of the blue luminosities in the magnitude range $14 < m_{\mathrm{pg}} < 18$ mag. Adding the contribution of the high-latitude unidentified sources that could be galaxies (Houck *et al.* 1984) increases the fraction by 10%. Note that this estimate refers only to the *measured IRAS* fluxes of galaxies and does *not* include flux at longer wavelengths from cold material.

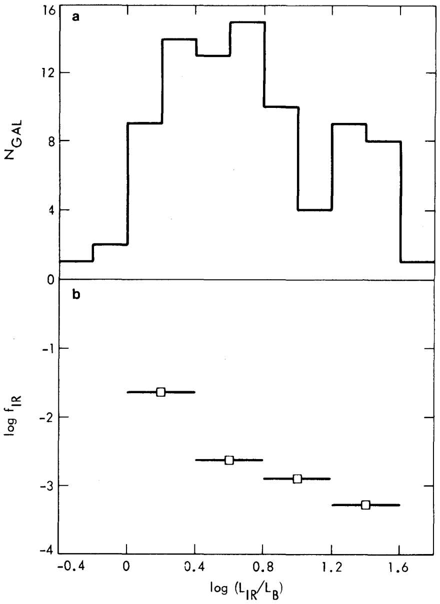

FIG. 2.—(*a*) The histogram of the number of galaxies in the infrared sample as a function of the infrared to blue luminosity ratio. (*b*) The fraction of galaxies plotted as a function of the infrared to blue luminosity ratio. The fraction was calculated as the ratio of the surface density of galaxies in the *IRAS* sample having a given infrared to blue luminosity ratio, to the total surface density of galaxies that would be detectable by *IRAS* at this infrared to blue luminosity ratio.

The galaxies in our sample that could be classified morphologically are spiral galaxies. This is not particularly surprising since few elliptical galaxies have been detected by *IRAS* (de Jong *et al.* 1984; Habing *et al.* 1984).

More interesting perhaps is the fraction of galaxies detected by *IRAS* that have neighbors. Of the 86 galaxies, 11 have neighboring galaxies within 2′, while another 8 have objects within 2′ which are possibly galaxies. Since the expected number of such events for randomly distributed galaxies brighter than $m_{\mathrm{pg}} = 18$ mag is roughly 4, this number of associated galaxies is marginally significant. It has become apparent that a galaxy's interactions with its neighbors and its environment can have a dominant effect on its evolution and can trigger outbursts of star formation (e.g., Larsen and Tinsley 1978). The evidence from our sample is perhaps suggestive that the interaction of a galaxy with its neighbors might be quite important in triggering the extreme outbursts of star formation.

It is a pleasure to thank all the people who have contributed to the success of the *IRAS* mission. The data used in this *Letter* were processed using the Science Data Analysis System at JPL, and we thank the many people who have contributed to the development and operation of this facility. We also thank C. Lonsdale and G. Helou for several useful discussions, and Joy Hodges for perseverance through the trying period of manuscript preparation.

REFERENCES

de Jong, T., Clegg, P. E., Soifer, B. T., Rowan-Robinson, M., Habing, H. J., Houck, J. R., Aumann, H. H., and Raimond, E. 1984, *Ap. J.* (*Letters*) **278**, L67.

de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G., Jr. 1976, *Second Reference Catalogue of Bright Galaxies* (Austin: University of Texas Press).

de Vaucouleurs, G., and Pence, W. D. 1978, *A.J.*, **83**, 1163.

Gispert, R., Puget, J. L., and Serra, G. 1982, *Astr. Ap.*, **106**, 293.

Habing, H., *et al.* 1984, *Ap. J.* (*Letters*), **278**, L59.

Hauser, M., *et al.* 1984, *Ap. J.* (*Letters*), **278**, L15.

Houck, J., *et al.* 1984, *Ap. J.* (*Letters*), **278**, L63.

IRAS Circ., No. 6. 1983 (to be published in *Astr. Ap.* and *Nature*).

Jura, M. 1982, *Ap. J.*, **238**, 499.

Larsen, R. B., and Tinsley, B. M. 1978, *Ap. J.*, **219**, 46.

Low, F. J. *et al.* 1984, *Ap. J.* (*Letters*), **278**, L19.

Miley, G., Neugebauer, G., Clegg, T., Harris, S., Rowan-Robinson, M., Soifer, B. T., and Young, E. 1984, *Ap. J.* (*Letters*), **278**, L79.

Neugebauer, G., *et al.* 1984, *Ap. J.* (*Letters*), **278**, L1.

Nilson, P. 1973, *Uppsala General Catalogue of Galaxies* (*Uppsala Astr. Obs. Ann.*, Vol. **6**) (UGC).

Nishimura, T., Low, F. J., and Kurtz, R. F. 1980, *Ap. J.* (*Letters*), **239**, L101.

Rieke, G. H., and Lebofsky, M. 1979, *Ann. Rev. Astr. Ap.*, **17**, 477.

Rowan-Robinson, M., *et al.* 1984, *Ap. J.* (*Letters*), **278**, L7.

Sandage, A., and Tamman, G. A. 1981, *A Revised Shapley-Ames Catalog of Bright Galaxies* (Washington, D.C.: Carnegie Institution of Washington), Publ. 635.

Smith, J. 1982, *Ap. J.*, **261**, 463.

Stein, W. A., and Soifer, B. T. 1983, *Ann. Rev. Astr. Ap.*, **21**, 177.

Telesco, C. A., and Harper, D. A. 1980, *Ap. J.*, **235**, 32.

Tyson, J. A., and Jarvis, J. F. 1979, *Ap. J.* (*Letters*), **230**, L153.

Vorontsov-Velyaminov, B. A., and Arhipova, V. P. 1963–1974, *Morphological Catalog of Galaxies*, Vols. **2–5** (Moscow: Moscow State University).

Vorontsov-Velyaminov, B. A., and Krasnogorskaja, A. A. 1962, *Morphological Catalog of Galaxies*, Vol. **1** (Moscow: Moscow State University).

Zwicky, F., and Herzog, E. 1963–1968, *Catalogue of Galaxies and Clusters of Galaxies*, Vol. **2** (1963), Vol. **3** (1966), and Vol. **4** (1968) (Pasadena: California Institute of Technology Press).

Zwicky, F., Herzog, E., and Wild, P. 1961, *Catalogue of Galaxies and Clusters of Galaxies*, Vol. **1** (Pasadena: California Institute of Technology Press).

Zwicky, F., Karpowicz, M., and Kowal, C. T. 1968, *Catalogue of Galaxies and Clusters of Galaxies*, Vol. **5** (Pasadena: California Institute of Technology Press).

Zwicky, F., and Kowal, C. T. 1968, *Catalogue of Galaxies and Clusters of Galaxies*, Vol. **6** (Pasadena: California Institute of Technology Press).