Title
Multiwavelength Energy Distributions and Bolometric Luminosities of the 12 Micron Galaxy Sample

Journal
The Astrophysical Journal, 453(2)

ISSN
0004-637X

Authors
Spinoglio, Luigi
Malkan, Matthew A
Rush, Brian
et al.

Publication Date
1995-11-01

DOI
10.1086/176425

Peer reviewed

Multiwavelength Energy Distributions and Bolometric Luminosities of the 12–Micron Galaxy Sample[1,2]

Luigi Spinoglio
Istituto di Fisica dello Spazio Interplanetario, CNR
CP 27 00044 Frascati, Italy
Electronic Mail: luigi@orion.ifsi.fra.cnr.it

Matthew A. Malkan, Brian Rush
Department of Physics and Astronomy, University of California at Los Angeles
Los Angeles, CA 90024–1562
Electronic Mail: malkan@bonnie.astro.ucla.edu; rush@bonnie.astro.ucla.edu

Luis Carrasco[3], Elsa Recillas–Cruz[3]
Instituto Nacional de Astrofísica, Optica y Electrónica,
Apartado Postal 51, Puebla, Pue., México, CP 72000
Electronic Mail: carrasco@tonali.inaoep.mx; elsare@tonali.inaoep.mx

ABSTRACT

Aperture photometry from our own observations and the literature is presented for the 12 μm Galaxies in the near infrared J, H and K bands and, in some cases, in the L band. These data are corrected to "total" near–infrared magnitudes, (with a typical uncertainty of 0.3 magnitudes) for a direct comparison with our IRAS fluxes which apply to the entire galaxy. The corrected data are used to derive integrated total NIR and FIR luminosities. We then combine these with blue photometry and an estimate of the flux contribution from cold dust at wavelengths longward of 100 μm to derive the first *bolometric* luminosities for a large sample of galaxies.

The presence of nonstellar radiation at 2—3 μm correlates very well with nonstellar IRAS colors. This enables us to identify a universal Seyfert nuclear continuum from near– to far–infrared wavelengths. Thus there is a sequence of infrared colors which runs from a pure "normal galaxy" to a pure Seyfert/quasar nucleus. Seyfert 2 galaxies fall close to this same sequence, although only a few extreme narrow–line Seyferts have quasar–like colors, and these show strong evidence of harboring an obscured Broad Line Region. A corollary is that the host galaxies of Seyfert nuclei have normal near– to

[1]This paper has been accepted for publication in the 1995 November 10 issue of ApJ.

[2]The three data tables mentioned in this paper (which do not appear in this preprint) can be accessed via anonymous ftp at eggneb.astro.ucla.edu in the /pub/rush directory. These ASCII files are named Spinoglio95-Table{1,2,3}.dat. These data tables will also be included in the AAS CD–ROM Series "Astrophysics on Disc", Volume V, 1995.

[3]On sabbatical leave from UNAM, México

far–infrared spectra on average. Starburst galaxies lie significantly off the sequence, having a relative excess of 60 μm emission probably due to stochastically–heated dust grains. We use these correlations to identify several combinations of infrared colors which discriminate between Seyfert 1 and 2 galaxies, LINERs, and ultraluminous starbursts. In the infrared, Seyfert 2 galaxies are much more like Seyfert 1's than they are like starbursts, presumably because both kinds of Seyferts are heated by a single central source, rather than a distributed region of star formation.

Moreover, combining the [25—2.2 μm] color the [60—12 μm] color, it appears that Seyfert 1 galaxies are segregated from Seyfert 2s and starburst galaxies in a well-defined region characterized by the hottest colors, corresponding to the flattest spectral slopes. Virtually no Seyfert 2 galaxy is present in such a region. To reconcile this with the "Unified Scheme" for Seyfert 1s and 2s would therefore require that the higher frequency radiation from the nuclei of Seyfert 2s to be absorbed by intervening dust and re–emitted at lower frequencies.

We find that bolometric luminosity is most closely proportional to 12 μm luminosity. The 60 and 25 μm luminosities rise faster than linearly with bolometric luminosity, while the optical flux rises less than linearly with bolometric luminosity. This result is a confirmation of the observation that more luminous disk galaxies have relatively more dust–enshrouded stars. Increases in the dust content shifts luminosity from the optical to 25—60 μm, while leaving a "pivot point" in the mid–IR essentially unchanged. Thus 12 μm selection is the closest available approximation to selection by a limiting bolometric–flux, which is approximately 14 times νL_ν at 12 μm for non–Seyfert galaxies. It follows that future deep surveys in the mid–infrared, at wavelengths of 8 to 12 μm, will simultaneously provide complete samples to different bolometric flux levels of normal and active galaxies, which will not suffer the strong selection effects present both in the optical–UV and far–infrared.

Subject headings: Galaxies: Nuclei — Galaxies: Active — Galaxies: Photometry — Galaxies: Seyfert — Galaxies: Starburst — Infrared: Galaxies

1. INTRODUCTION

In Spinoglio & Malkan (1989—SM hereafter), we showed that the 12 μm flux is approximately a constant fraction of the bolometric flux in active galactic nuclei (AGNs) of all types (e.g., Quasar/Seyfert 1, Seyfert 2, Blazar). We therefore used the IRAS sky survey to select an all–sky ($|b| \geq 25°$) sample of galaxies to a limiting 12 μm flux, thereby providing an unbiased sample of AGNs. Recently, we used the *IRAS Faint Source Survey* data (Moshir et al. 1991) to extend this work to a fainter 12 μm flux limit, of 0.22 Janskys. Our resulting extended sample includes 893 galaxies, 120 of which are known to have Seyfert 1 or 2 nuclei (Rush, Malkan, & Spinoglio 1993—RMS hereafter). Note that the constant ratio of 12 μm to bolometric flux was shown to apply to measurements dominated by the active *nucleus*. The IRAS 12 μm selection is highly effective at discovering Seyfert galaxies because their hot nuclei usually dominate their total 12 μm fluxes. (This was verified by comparison with small–beam 10.5 μm measurements in Edelson, Malkan, & Rieke 1987—EMR hereafter). Until the present paper, however, multiwavelength determinations of the bolometric flux for a significant sample of *normal* (non–Seyfert) galaxies as a whole were not available.

The mid–to–far–infrared emission by which we selected these galaxies arises from dust grains which absorb short–wavelength energy and thermally re–radiate it. In a more intense radiation field, the grains will have higher equilibrium temperatures, and will tend to emit more at shorter infrared wavelengths. For many of the 12 μm selected galaxies, which are to some extent selected to have "hot" IRAS colors, much of the IRAS emission, especially at 12 and 25 μm is ultimately powered by luminous young stars, which are still embedded in the dust clouds out of which they recently formed. And of course in the case of AGNs, there is an additional source of mid–infrared flux powered by the nonstellar nucleus. Thus the IRAS fluxes, especially at 12 and 25 μm provide a measure of what is *unusual* about these galaxies. To better understand these galaxies, we also need quantitative information about their more *normal* attributes. In particular, it is very helpful to have good measures of the *underlying* stellar population which are relatively independent of the presence of: a) recent bursts of star formation; and b) internal absorption by dust. It is well known that these requirements are best met by observations in the near–infrared wavelengths. The light of normal galaxies in the standard photometric bands J[1.2 μm], H[1.6 μm], and usually K[2.2 μm] is dominated by red giants in the quiescent (old) stellar population, which is most closely tied to the total mass of the galaxy (Recillas–Cruz et al. 1990, 1991). Thus the intrinsic JHK colors of most galaxies are confined to a relatively narrow range (Frogel et al. 1978). Since the extinction in the near–infrared is much lower than that in the visual, only a small fraction of galaxies are dusty enough so that their near–IR colors are detectably altered by reddening. In some galaxies with exceptionally strong starbursts, or an AGN, a measurable "excess" above this stellar photospheric emission is detectable at 2.2 μm, and more easily at 3.5 μm. We detect both effects in the observations presented below.

This paper presents the results of an extended observing campaign in which we obtained accurate near–infrared aperture photometry for the 12 μm Galaxies (§ 2.). We then use these to derive colors and total near–infrared luminosities, for comparison with their IRAS and other properties (§ 3. and 4.). We compute the bolometric luminosities for a large sample of normal and Seyfert galaxies (§ 5.) and present and discuss their normalized spectral energy distributions (§ 6.). Finally, we give our conclusions (§ 7.).

2. OBSERVATIONS

We have collected J, H, K, and in some cases L, photometry on 321 galaxies during eleven photometric observing runs. Most of the data for northern galaxies were obtained with the 2.1 m reflector at the San Pedro Martir Observatory (hereinafter SPM; Baja California, México), and for the southern galaxies with the 1.0 m reflector at the European Southern Observatory (ESO), both equipped with standard InSb photometers. Some of the seyfert galaxies observed at SPM, had been included in a sample for variability studies of AGN's by Carrasco & Cruz–Gonzalez (1995). Additional photometry for a few galaxies was also collected in May 1981 on the Mount Wilson 60– and 100–inch telescopes and during March–April 1984. Eight to ten standard stars were observed on each night, with the scatter about the derived photometric zero points, after correction for airmass, being typically 0.01 to 0.02 magnitudes. The galaxies were observed with variable integration times that yielded maximum internal errors of

0.008 magnitudes. Although, the uncertainties in our galaxy photometry are usually dominated by the accuracy with which the signal could be "peaked–up" on the strip chart, this procedure was repeatable. Hence we feel confident that the typical errors obtained for the set of standard stars are representative of the ones expected for the galaxy sample. Standard stellar magnitudes, on the Caltech and ESO systems, were taken from Elias et al. (1982) and from Bouchet, Schmider, & Manfroid (1991), respectively.

In Table 1[4,5] we present the results, in flux densities (mJy), using the absolute calibrations of the SPM (Carrasco et al. 1991) and the ESO (Bersanelli, Bouchet, & Falomo 1991) photometric systems. The first column gives the galaxy name; the second gives its equatorial coordinates from the IRAS Faint Source Catalog (B1950.0); the third through sixth columns give the J, H, K and L flux densities (where available); the seventh column lists the diameter of the aperture used; the eighth one the telescope and observing date and the ninth the object class.

In our analysis below, we have included published J, H, K and L photometry from a large number of papers, all of which are summarized in the recently updated "Catalog of Infrared Observations" (Gezari et al. 1993). This adds 399 observations of 215 objects, bringing our database to a total sample of 483 galaxies for which we have complete J, H and K photometry. Fortunately, this includes virtually complete data for the Seyfert galaxies, which were the primary motivation for constructing the 12 μm Sample.

Some of the galaxies were also measured with similar apertures by previous investigators (e.g. Rudy, Levan & Rodriguez–Espinosa 1982; Balzano & Weedman 1981). The typical agreement in magnitudes is 0.07 mag rms, and the agreement on infrared colors is even better (1σ=0.04 mag), since several systematic sources of error cancel out.

[4]The three tables referenced herein do not appear in print in this paper, but in the AAS CD–ROM Series "Astrophysics on Disc", Volume V, 1995.

[5]During the infrared observing runs for this project, 14 galaxies were measured which were not included in the *final* 12 μm Sample (for various reasons; see discussion in RMS). The data for these objects are given in Table 2, which is constructed in the same manner as Table 1.

3. APERTURE CORRECTIONS: CALCULATION OF $H_{-0.5}$ AND TOTAL MAGNITUDES

RMS made a special effort to estimate the *total* far–infrared fluxes (representing the full spatial extent) for each of the 12 μm galaxies. This extra work, not undertaken in most other studies, was required so that valid flux comparisons could be made between distant and nearby galaxies. Calculations of quantities such as luminosity functions require that our measurement of a given galaxy's flux should not depend on whether or not it happens to be resolved by the IRAS beams. Our reported IRAS fluxes thus give good measures of the far–infrared light of the entire galaxy. In this paper we compare these with ground–based photometry of the total light from the underlying stellar population, as measured in the near–infrared. Unfortunately there are virtually no direct measurements of the total near–IR fluxes of nearby galaxies. Instrumental limitations and sky noise dictate that the J, H and K band measurements were made through circular apertures (6—30 arcseconds) much smaller than the effective IRAS beams. To allow a direct comparison of the near– and far–infrared fluxes we applied aperture corrections to transform the former into total magnitudes.

The procedure was straightforward for each of the 274 galaxies which has a value of A_{eff} listed in the Third Reference Catalog of Galaxies (De Vaucouleurs et al. 1991—RC3 hereafter) This "effective" aperture, which includes one–half the total flux from the galaxy–is available for (∼53%) of our sample galaxies with NIR photometry. We used the RC3 growth curves, (given in their Table 11), to extrapolate from the largest aperture used to the total flux. By comparing the growth curves in RC3 with the observed fluxes in different apertures, we obtained the best result when we adopted the growth curve for the NIR fluxes a curve corresponding to 3 morphological types earlier than the type listed in RC3. Evidently the near–infrared continuum for a galaxy of given morphological type in our sample is slightly more concentrated than the standard RC3 aperture growth curves would predict. For galaxies with A_{eff} but no RC3 morphological type, we assumed an early–type spiral, and in fact the differences in the growth curves over the range considered are subtle. The *total* corrections ranged from 1 to 3 magnitudes. If they would have exceeded 4 magnitudes, we consider the uncertainty too great to use this procedure, and we thus used the following method.

For about 391 (∼81%) galaxies of our sample (including all of those for which the RC3 gives an A_{eff}), the RC3 also gives a corrected isophotal diameter, D_0, defined at an isophote of 25.0 blue magnitudes per square arcsec. For these galaxies, we correct the observed H magnitudes to a standard aperture, $\log(A/D_0) = -0.5$, as is often done to obtain a characteristic measure of most of a galaxy's luminosity. These are the galaxy magnitudes used, for example, in the near–infrared Tully–Fisher method (Aaronson, Huchra, & Mould 1979—AHM hereafter). We have fitted a straight line to the average NIR magnitude growth–curve of AHM for early–type spirals: $\Delta m = m_{obs} - m_{-0.5} = -1.02 - 2.03 \times \log(A/D_0)$ for Sa's. For a typical value of $\log(A/D_0) = -0.90$, the (negative) correction to the observed magnitude was on average 0.81 mag. To correct these to "total" values, we examined the correlation between the −0.5 magnitudes and the total magnitudes derived for the 274 A_{eff} galaxies discussed above. We found that the total magnitudes were on average 0.9 mag. brighter, with an rms scatter of 0.35 mags. We therefore subtracted 0.9 mag from the −0.5 magnitudes. The resulting total magnitudes are not more accurate than 0.35 mag. (1 σ).

Several dozen galaxies have multi–aperture photometry which allows us to intercompare our estimates of total infrared magnitudes[6]. The total magnitude estimated from the smaller aperture is not on average different from that estimated using the larger observed aperture, and the random scatter among 30 pairs of measurements is ± 0.25 magnitudes (1 σ). This scatter is partly a measure of the consistency of our various sets of multiaperture photometry, and partly a measure of the adequacy of our assumption that the RC3 growth curves apply to the near–infrared fluxes of these galaxies. About the same scatter was found in comparisons of 60 −0.5 magnitudes calculated with the AHM D(0) technique.

For the Seyfert 2 galaxies, we derived total magnitudes by using the same extrapolation as for normal galaxies, but only when measured fluxes were available in large enough apertures that the nuclear component of the galaxy were no longer affecting the shape of the growth curve as compared to a normal galaxy. We tested this method by comparing growth curves for several Seyfert 2s (for which data were available spanning a wide range of apertures) to the growth curves from RC3 and found that they were fitting well outside the nuclear region, which is typically 10—20 arcseconds.

We did not follow this procedure for the Seyfert 1 galaxies, since their near–IR light is much more strongly centrally concentrated than any of the normal galaxy growth curves. Instead we used the galaxy/nucleus decompositions presented by Danese et al. (1992) and Kotilainen et al. (1992), and summed up the two components to measure the near–IR luminosity. For the 13 Seyfert 1 galaxies in common with the study of Danese et al., we added their estimated "galaxy" and "nucleus" fluxes to obtain the total flux at 1.2, 1.6, and 2.2 μm. In particular, for Mkn 975, Mkn 9, Mkn 704, Mkn 509, Mkn 530 and MCG+1–57–16 (2237+07), we have taken the nuclear and galactic magnitudes as given by them, while for Mkn 335, I Zw 1, Mkn 618, Mkn 79, Mkn 766, NGC 5548 and Mkn 817, we have taken the nuclear magnitudes and the K galactic magnitude that they give and assumed their average $(J-K)_G = 1.13$ and $(H-K)_G = 0.45$ to derive galactic J and H magnitudes.

We have 16 Seyfert 1 galaxies in common with the study of hard X–ray selected galaxies of Kotilainen et al. (1992). Two of these are also in the list of Danese et al. (1992) (NGC 5548 and Mkn 509), and we adopted their estimates. For the 14 remaining galaxies we have used the J and K absolute magnitudes of Kotilainen & Ward (1994) for both galaxy and nucleus, and converted into flux densities at earth using their quoted redshifts, H_0 and calibration (Wilson et al. 1972). For the H band fluxes, we adopted the values of non–stellar fluxes given by Kotilainen et al. (1992) for the nuclear component, while for the galactic component, we used the colors in an annulus around the nucleus (from their Table 2) to scale the galactic colors[7].

The computed total fluxes in the J, H and K wavebands are listed in Table 3, together with the [J–H], [H–K] and [K–L] colors in the smallest aperture available and the derived near–infrared, far–infrared and bolometric luminosities. We assumed

[6]Each observing aperture for a given galaxy, when extrapolated with the RC3 or AHM growth curves, gives an independent estimate of its total magnitude which, in the absence of errors, should agree with each other.

[7]Using $(J-H)_G = (J-K)_G/(J-K)_A \times (J-H)_A$, where subscript G is for "galaxy" and subscript A for "annulus"

$H_o = 75\ km\ s^{-1} Mpc^{-1}$. The K correction (generally very small) and the corrections of the observed redshift are described in RMS. The near–infrared luminosity is derived from direct integration assuming power–law interpolations between 1.2, 1.6, and 2.2 μm. Similarly, the far–infrared luminosity is derived by trapezoid–rule integrations of the IRAS fluxes.

In most of these 12 μm galaxies the tabulated bolometric (0.4—300 μm) luminosity has been computed by combining the total blue magnitude $B_{0(T)}$, taken from the RC3, the corrected JHK photometry and the IRAS fluxes. To account for the mid–infrared and submillimeter contributions, we used the L band flux[8] and we extrapolated the 60 μm and 100 μm IRAS fluxes with grey body emission[9], respectively. For most galaxies the calculated bolometric luminosity is 98% or more of the total luminosity we would have measured from *complete* multiwavelength coverage (since, the UV flux drops rapidly beyond the Ca II HK break, as shown, for example, in Malkan & Oke's (1983) "STDGAL" spectral energy distribution). However for the Seyfert galaxies, both UV and X–rays can significantly contribute to their bolometric luminosities. Therefore we have included a crude power–law interpolation between the B band (4400Å), the 1330Å band as measured by the IUE SWP (Edelson et al. 1995) and the soft X–ray band at 1 KeV as measured by the ROSAT All Sky Survey (Rush et al. 1996a; details of these data will be presented in Rush, Malkan, & Spinoglio 1996b). For most of the Seyfert 2s, UV and X–ray detections were not available. Fortunately, we have verified that in those which the UV and X–ray emission *is detected*, it adds only about 3% percent to the 0.4—300 μm luminosity. This justifies our decision to ignore the UV and X–ray wavebands in the calculation of all Seyfert 2, LINER and starburst bolometric luminosities.

4. ANALYSIS: CORRELATIONS OF COLORS

4.1. Near Infrared Colors

Figure 1*a* shows the [J–H] vs. [H–K] two–color diagram for all available measurements (483) of the 12 μm Sample of Galaxies. In all of the diagrams filled squares represent Seyfert 1 galaxies, open squares Seyfert 2 galaxies, asterisks high IR–luminosity non–Seyfert galaxies which we refer as to "starburst galaxies" (see the discussion in RMS), open circles "LINERs" (Low Ionization Nuclear Emission Region galaxies; Heckman 1980) and diagonal crosses represent "normal" (i.e., all other) galaxies. In this and following diagrams, when a near–IR color is plotted (i.e., and combination of J, H, K or L magnitudes), the data—referred to simply as "nuclear"—refer to the smallest aperture available, since this is usually the one with the best L magnitude coverage (due to the lower sky noise). The smaller aperture accentuates the difference between galaxies with and without active nuclei. In the near–infrared color/color diagrams, vectors show the effects of 1 and 5 magnitudes of visual extinction. This is for an external screen obeying a standard interstellar reddening law (Rieke & Lebofsky 1985). In reality the dust and starlight are probably intermixed, resulting in higher reddening being inferred at longer wavelengths.

The region of "normal galaxy colors" is indicated in Figure 1*a* with a circle whose radius is equal to 2σ, centered on the average colors of <J–H> = 0.77 ± 0.008 and <H–K> = 0.34 ± 0.007 (uncertainties represent the standard deviation of the mean; the 1σ scatter in individual data points are 0.12 and 0.15, respectively; in fact an ellipse would be somewhat more appropriate due to the positive correlation between these two colors). These values are redder than the average colors of normal galaxies measured by Frogel et al. (1978) and Recillas–Cruz et al. (1990, 1991), of <J–H> = 0.72 and <H–K> = 0.22. Although the effect is subtle and the scatter is large, the inconsistency is that there is about 12% excess K flux in our sample compared to the others. These "2.2 μm excesses" may be attributable to thermal emission from extremely hot dust, presumably in actively star–forming regions (since our galaxies have higher SFRs than other "normals" on average; as, for example, Joseph et al. (1984) found K–excesses in starburst galaxies), as well as a possible contribution from red supergiants. Nonetheless, within our sample, most (90%) of the non–Seyferts lie within the "normal" circled region. A small number of the non–Seyferts are substantially redder in [H–K] *and* [J–H], and appear to lie along the reddening vector shown in the lower right corner. Thus these galaxies could have intrinsically "normal" colors, with the addition of large line–of–sight extinctions (of typically 3—5 magnitudes in

[8] If the L band flux was not measured, we estimated it from the correlation of [K–L] with [H–K] color, as discussed in Appendix A..

[9] We refer to Appendix B. for the details of this computation.

A_V). Only about 10 of the non–Seyferts fall significantly to the right of the normal–galaxy region, indicating that very few normal galaxies have strong 2.2 μm excesses (again, probably due to hot dust or red supergiants), and about half of these have high infrared luminosities. One galaxy only, NGC 3353 (= Mkn 35), has a [J–H] color which is much bluer than the average (see Figure 1*a*) . This is one of the bluer members of the class of compact dwarf galaxies already known to have abnormally blue colors in the NIR (Thuan 1983).

The Seyfert nuclei cannot be distinguished from the non–Seyferts in [J–H], but they tend to be much redder in [H–K]. As is well known, this is because the red giant spectra in normal galaxies have rising flux densities from 1.2 to 1.6 μm, and then falling fluxes from 1.6 to 2.2 μm. The Seyfert nuclear continuum has a flux density which rises monotonically from 1.2 to 1.6 to 2.2 to 3 μm, and therefore stands out better at longer wavelengths. Most ($\sim$ 73%) of the Seyfert 1's and nearly half of both the Seyfert 2s ($\sim$ 41%) and the starburst galaxies ($\sim$ 44%) lie outside the 2σ circle defined by the normal galaxies and have significantly non–stellar [J–K] colors in small apertures. In agreement with Cruz–Gonzalez (1984), the Seyfert 1s lie somewhere along the track which shows a mixture of normal starlight plus varying proportions of "quasar light". The redder Seyfert 1 nuclei in this and other color diagrams are very similar to the 9 brightest PG quasars (Edelson 1986), whose average infrared colors (<J–H> = 0.85 $\pm$ 0.14 <H–K> = 0.98 $\pm$ 0.31 <K–L> = 1.59 $\pm$ 0.18; Neugebauer et al. 1987) are indicated by the cross. These are in turn very similar to the average zero–redshift quasar colors from Hyland & Allen (1982) of: <J–H> = 0.95 <H–K> = 1.15. As expected the published estimates of pure normal galaxy colors and pure quasar colors are very consistent with the two extremes of the IR color sequence in Figure 1*a*.

The nuclear component we identified in Seyfert 1's—pure "quasar light" has a flux at 60 μm only slightly higher than at 25 μm. We believe that the nuclei most if not all Seyfert 1s and quasars have a peak in their flux density at a wavelength of 30—50 μm. In other words, pure quasar light has a peak energy output, in $\nu \times f_\nu$, at wavelengths of 15—20 μm. In the less luminous Seyfert 1s the observed flux at 60 μm has a substantial contribution from the host galaxy. Since the active nucleus produces very little 100 μm emission, observations at that wavelength instead measure the host galaxy.

An even more sensitive measure of excess infrared flux over that expected from red giant photospheres is found in the [H–K] vs [K–L] diagram of Figure 1*b*, although fewer measurements are available (123), especially for non–Seyferts (only 36 normal galaxies). The average colors for normal galaxies (given with 1σ individual scatter) are: <H–K> = 0.34 ± 0.12 (as mentioned above), and <K–L> = 0.75 ± 0.64, the latter having the much larger scatter. Only one normal galaxy (NGC 5253) (see Figure 1*b*), lies close to the region defined by the PG quasars. The average colors of the 39 Seyfert 1's are <H–K> = 0.84 ± 0.33 and <K–L> = 1.31 ± 0.49; for the 24 Seyfert 2's they are <H–K> = 0.61 ± 0.37 and <K–L> = 01.05 ± 0.59; for the 8 starburst galaxies they are <H–K> = 0.58$\pm$0.13 and <K–L> = 1.09 ± 0.30; for the 17 LINERs they are <H–K> = 0.32 ± 0.11 and <K–L> = 0.38 ± 0.30.

4.2. Combined Near Infrared and IRAS Colors

The IRAS and near–infrared wavebands can be combined to separate the different galaxy classes. The ratio between the 25 μm flux and the K band flux (hereafter referred to as the [25–K] color) plotted against the [60–25] color has already been shown to discriminate well between Seyfert 1s and Seyfert 2s (EM, EMR). We show this in Figure 2*a* for our sample. The [25–K] color alone is evidently one of the best discriminators of Seyfert 1 and Seyfert 2 galaxies. As noted by EM and EMR, the Seyfert 2 mid–infrared slopes are systematically steeper by about 0.5 than the Seyfert 1s and quasars. Interestingly, the two luminous "Seyfert 1" galaxies with the most unusual colors (steep 2—25 μm slope but flat 25—60 μm slope) are both powerful radiogalaxies: 3C 234 and 3C 445. It is also evident in Figure 2*a* that the starburst galaxies tend to have steeper 2—25 μm slopes than normal galaxies.

Similar useful results are obtained with the [25–K] vs. [H–K] two–color diagram (Figure 2b). Here Seyfert galaxies are well separated from LINERs and that the high–luminosity non–Seyferts are also well separated from LINERs, although they overlap with the Seyferts having the smallest [H–K] colors. Again the starburst galaxies are redder in H–K than normal galaxies, and show some overlap with the Seyfert 2s but not the Seyfert 1s.

One of the sharpest separations in all of these diagrams is between the colors of “LINERs” and those of the ultraluminous IRAS galaxies (our “starbursts”). In virtually all cases, the LINERs lie within the range of colors defined by “normal” galaxies, concentrated to the weakest far–IR fluxes. In contrast many of the starbursts have significant excesses in the mid–infrared (in fact, from 2.2 up to 25 μm). This is strong prima facia evidence against the notion that LINERs harbor *any* unusual current star formation. If a recent burst of star formation were to explain the characteristic LINER emission line spectra, it would at have to be very different from those studied previously. The energy from this activity would at the least have to be hidden at mid–IR wavelengths. There is no evidence for abnormal emission at *any* infrared wavelength in the LINERs in our sample. The extreme colors of the starbursts could be understood if the 3.5 μm, 25 μm, and 60 μm emission in those objects is affected by emission of small stochastically–heated dust grains, as found in the Orion Complex by Bally, Langer, & Liu (1991) and Wall et al. (1995).

The combination of IRAS and near–infrared colors also defines a clear sequence from normal galaxies and active ones. The [60–25] color versus the [H–L] is shown in Figure 3. In the upper left of this diagram, normal galaxies and LINERs define a locus of low nuclear activity. A few Seyferts and the high–luminosity non–Seyferts also lie in this region. However, the Seyfert galaxies (both types) also extend to the lower right part of the diagram, where no normal galaxy is located, defining a region of high nuclear activity. Thus the steep far–IR slopes of normal galaxies and high–luminosity non–Seyferts correspond to the bluer near–infrared spectra, while the flatter far–IR active galaxies have redder near–IR slopes. As we will discuss in a future paper (Rush et al. 1996b), this infrared trend to more dominant Seyfert activity is mirrored in several optical observables which shift systematically as the galaxy is found closer to the lower right corner of the figure. The least squares line between all data points also fits the Seyfert galaxies alone with similar regression coefficients (R= 0.67 for all galaxies, R= 0.64 for all Seyferts). This line, fitting all the data points, happens to connect the average colors of normal galaxies (at the upper left corner of the figure) exactly to the average color of the 9 brightest PG quasars selected by Edelson (1986). The high luminosity non–Seyferts, as can be seen from their average colors, are significantly off the best fitting line, having an excess in the 60 μm emission. It follows that the infrared energy distributions of these ultraluminous IRAS galaxies, which do not harbour a “classical” Seyfert nucleus, cannot be explained by the combination of a quasar plus a galactic component which fits the Seyfert galaxies.

It is not surprising that the only Seyferts classified as “Type 2” in the lower right portion of the diagram (near the realm of “pure quasar light”) are the most extreme members of this class: Mkn 348 and 463, NGC 1068 and 5506, FSC 00521–70 and Tololo 109. In fact spectropolarimetry, infrared and/or X–ray spectroscopy has indicated that most of these AGNs harbor an obscured Seyfert 1 nucleus. This is consistent with our conclusion from Figure 3 that these are best described as reddened Seyfert 1 galaxies.

The fact that most Seyfert 1s are located in the lower right part of the diagram while most Seyfert 2s are displaced in the upper left corner, where only a few Seyfert 1s are found (as well as most Messier galaxies classified as Seyfert 1s or 2s by Vèron–Cetty & Vèron (1991)—see RMS), shows that the energy distributions of the two Seyfert classes are different: the Seyfert 1s are steeper in the near–infrared and flatter in the IRAS wavebands, while the Seyfert 2s behave in the opposite way. The mid–infrared wavelengths, from 3.6 to 12 μm, are depressed for the “Type 2” galaxies and enhanced for the “Type 1” galaxies. It can very well be that the hot nuclear continuum of Seyfert 1s is either non–existent in Seyfert 2s (if the latter have physically different nuclei compared to Seyfert 1s), or it is blocked by circumnuclear material, as hypothesized in a popular version of the unified model. The mid–infrared flux of the Seyfert 2s would therefore be due partly to the galactic component, plus—in some cases such as NGC 1068—a starburst component which steepens both the [H–L] and [60–25] colors. These results are in agreement with those of Maiolino et al. (1995), who find that the nuclear 10 μm luminosity of Broad Line Seyfert galaxies, i.e. “Type 1” galaxies, is systematically larger than that of those Seyferts without a BLR, i.e. “Type 2” galaxies; and that the host galaxies of Seyfert 2 nuclei tend to have a higher star formation rate than the host galaxies of Seyfert 1s (this is discussed in more depth in Appendix C.).

The effect of adding a strong starburst component is to increase the H–L color without much altering the 60/25 μm flux ratio (i.e., corresponding to a horizontal translation to the right in Figure 3). The classical Seyfert galaxies which show this effect most strongly

(Mkn 231, Mkn 273, NGC 1068, and NGC 7469) are already known to contain unusually powerful starbursts. On the other hand, Arp 220 has too small (blue) an H–L color to be consistent with a Seyfert 1 ("buried quasar") as the principal energy source.

Figure 4*a* shows an even clearer separation between the Seyfert sequence and the starbursts. The former tend to have "hot" 12—60 μm colors, while the latter have steep 12—60 μm slopes. This is because the starburst enhances both the 25 and 60 μm continuum, while the Seyfert nucleus enhances the 25, 12 and 3.5 μm emission. Also in this diagram the two objects Arp 220 and Mkn 273 have high 60 μm emission relative to Seyfert galaxies and quasars.

In principle, a good physical definition of a "starburst" would be: a region where current rate of star formation substantially exceeds the rate averaged over its past history. However, translating this into direct quantitative observational terms has proven difficult. We have therefore simplistically and arbitrarily designated all galaxies with infrared luminosities above $1.5 \times 10^{11} L_\odot$ as "starbursts". We find that these galaxies have colors which differ systematically from those of the "normal" galaxies. Nonetheless, the "starbursts" appear to be simply the extreme tail of the distribution of normal galaxies. The starbursts have the largest relative proportions of young stars and warm dust, but there is no clear dividing line and no qualitative distinction.

Figure 4*b* shows the [H–K] color plotted versus bolometric luminosity. At the highest bolometric luminosities, there is a clear separation between the Seyferts and the high–luminosity non–Seyferts. In this diagram, like the two previous ones, Arp 220 appears as an extreme starburst galaxy, while the high-luminosity objects with dominant nuclear activity have much redder [H–K], like the PG quasars, which have [H–K] = 0.98 (see Figure 4*a*) .

The basic hypothesis of the "Unified Scheme" for Seyfert 1 and 2 nuclei is that these are intrinsically the same physical objects, except that the former are seen face–on, while the latter are viewed closer to edge–on. On this hypothesis, therefore, a sample of Seyfert 1's should not differ from a sample of Seyfert 2's in any emission which is *isotropic*, such as low–frequency radio or [OII] 3727 line emission. Figure 5 shows the [25–K] versus [60–12] color–color diagram which includes Seyfert galaxies and high luminosity non–Seyferts. This diagram, as already shown in EMR for the CfA Seyfert galaxies, segregates Seyfert 1s in the lower left part of the diagram. Only 5 out of 52 Seyfert 2s lie in this region, three of which are close to the edge, while 30 out of 48 Seyfert 1s are inside this region. One version of the Unified Scheme could explain this, if those objects with an edge–on torus, the Seyfert 2s, have steeper infrared energy distributions. This would make both [60–12] and [25–K] redder, because the high frequency radiation is absorbed by the optically thick torus and re–emitted at lower frequencies (Pier & Krolik 1993). Their best–fit model to the small–aperture photometry for NGC 1068 is also shown in this diagram, as are the average colors for normal galaxies in our sample and the colors of various mixtures of the two (see figure). According to this scheme, our whole–galaxy colors for NGC 1068 appear to have roughly a 30—40% contribution from the galaxy at 12 μm.

5. ESTIMATING BOLOMETRIC LUMINOSITIES

5.1. Multiwavelength Properties and Twelve–Micron Selection

As discussed above (and well known since the early days of IRAS), normal galaxies display an enormous range of properties when viewed over a wide spectral range (from optical to IRAS wavelengths). Classical optically–selected galaxies emit only a modest fraction of their bolometric luminosity in the thermal infrared (e.g., log(L_{FIR}/L_B ∼–0.3 — –0.4 for Shapley–Ames galaxies—De Jong et al. 1984). In contrast, IRAS discovered some galaxies which are very faint optically, and emit most of their large luminosities through re–radiation by dust grains. Thus a rule similar to that noted by SM for Seyfert nuclei may well apply to disk galaxies: they define a sequence of increasing dust content. As the proportion of dust increases (or intercepts an increasing fraction of the primary stellar radiation), the galaxy becomes fainter in the optical and brighter in the infrared. Or even for a fixed dust content, if a larger proportion of stars (probably younger ones) are embedded in warm dust, a growing fraction of the galaxy's bolometric output will be transferred particularly to the 25 μm and 60 μm bands. Since the old stellar population in the IR–Luminous galaxies is not unusually luminous, these galaxies are not extremely massive. Instead their high luminosities are probably the result of a temporary increase in the current star formation rate which results in an unusually low mass/light ratio. This could well be a phase that many normal galaxies pass through, with a relatively low duty cycle. It has already been noted that this duty cycle could coincide with the fraction of the lifetime spent by a normal galaxy in close encounters with other galaxies.

As SM found for Seyfert nuclei, it is also plausible that some intermediate waveband is relatively unaffected by these processes. In other words, for a wide range of normal galaxies of the same bolometric luminosity, there could be a crossover wavelength in the energy distributions where a relatively constant proportion of the luminosity is emitted. Our new data suggest that this occurs and, as is the case for Seyfert nuclei, the crossover wavelength is in the mid–IR near 12 μm, the wavelength at which our sample was defined.

We note that 12 μm selection is biased in favor of objects which emit strongly at 12 μm, just as every flux–limited sample is biased at the selection wavelength—*by definition*. The particular strength of 12 μm selection is that it is biased in favor of a homogeneous group of galaxies, for which the 12 μm flux is linearly proportional to the bolometric flux. In other words, our sample will preferentially include objects which are stronger at mid–IR wavelengths, but these same objects also have higher bolometric luminosities and *should* be preferentially included in any sample complete to a given bolometric flux. The tight correlation between 12 μm flux and bolometric flux for our different classes of galaxies (SM; this work—§ 5.2.) is an empirical relationship that holds true *regardless* of the particular mechanisms (e.g., hot non-thermal nuclear continuum, thermal emission from dust heated by starbursts) which elevate the 12 μm flux. Thus, although the spectral energy distributions of a wide variety of galaxies show a wide range of shapes (from the bluest objects which are strong in the optical/near–IR and weak in the far–IR, to objects which show the opposite characteristics), they converge best near 12 μm(see Figure 1 in SM). Thus, the mid–IR is the "pivot" point where the fraction of the bolometric luminosity emitted is roughly constant.

Within our sample, this is not only the case for Seyfert galaxies, late–type spirals, and bolometrically luminous galaxies, but also for galaxies in general, including early–type spirals and E/S0 galaxies. Even though the average fraction of the bolometric flux emitted at 12 μm is lower for E/S0 galaxies as a general class (one the order of a percent—Knapp et al. 1989; Mazzei & De Zotti 1994; Mazzei, De Zotti, & Xu 1994) than for other galaxies, the unusual E/S0 galaxies *in our sample* have the same relation between $L_{12\mu m}$ and L_{bol} as the entire sample ($<L_{12\mu m}/L_{bol}> \sim 7\%$ and $L_{12\mu m} \propto L_{bol}^{1.08}$—see § 5.2. and § 6.), so that those objects which *do* get into our sample still have their bolometric flux well represented by the flux at 12 μm. The more subtle difference between the E/S0s and other galaxies in our sample is exemplified in Figure 6, where we plot the [B–H] vs. [K–12 μm] colors for our sample. The X's represent the average values for all galaxies and for the E/S0 galaxies (with dotted circles representing 1σ individual scatter). The E/S0 galaxies are roughly evenly distributed over most of the range in which we see spirals, *except* for the lower right part of the graph. The average values of $\log(F_{12\mu m}/F_{2.2\mu m})$ and [B–H] are 0.75 and 3.85 for our E/S0 galaxies, as compared to 1.12 and 3.53 for our entire sample, reflecting the different dust content and, to a lesser extent, the stellar populations of these types of galaxies. Thus, the fact that our E/S0s still obey the same relation between 12 μm and total luminosity as do the other galaxies in our sample, while being much stronger in the near–IR and optical, simply points to the fact that the E/S0s represent the extreme end of far–IR–weak and optical/near–IR–bright galaxies mentioned above.

5.2. Individual Versus Bolometric Luminosities

Figures 7*a*—*d* show the correlation of 12, 25, 60 and 100 μm luminosities with bolometric luminosity for the non–Seyferts. Deviations from linearity are present for 25 μm, 60 μm and to a lesser extent for 100 μm, but not for 12 μm. Since the "warm excess" luminosity emerges at *both* 25 and 60 μm, the galaxies of higher luminosity do not appear to have unusual [25–60] colors. This is not an artifact of the redshift since it is present for 60 and 25 but *not* 12 μm.

For completeness, we also present the same correlations for Seyfert galaxies in Figures 8*a*—*d*. However, we are fully aware that, since the bolometric luminosities computed here refer to the whole galaxy, the correct fit for the Seyfert galaxies will have to await for total *nuclear* luminosities, from which starlight had been removed. This will be done in Rush et al. (1996b) by using optical photometric and spectroscopic data, and it is beyond the scope of the present paper. As can be seen from Figures 8*a*, for all Seyferts together the coefficient of the correlation of 12 μm luminosity versus bolometric luminosity is 1.09 (with regression R = 0.95, for 47 objects). For Seyfert 1s only, this is close to unity (1.03 with R = 0.97 for 19 objects), while for Seyfert 2s it is higher (1.16, with R = 0.93 for 28 objects). At higher wavelength luminosities increase slightly faster with the bolometric luminosity (see the figures for the slopes and regression coefficients).

The near infrared luminosity, obtained by integrating the total J, H and K magnitudes, as described in § 3., is also a good measure of the bolometric luminosity for normal galaxies (see Figure 9*a*). However it is clear from the figure that it does not hold for the high luminosity non–Seyferts, which show a relative lack of near infrared emission. For all Seyfert galaxies together, the near infrared luminosity increases almost linearly with bolometric luminosity (see Figure 9*b*). While Seyfert 1s have a linear correlation, Seyfert 2s have a significantly flatter slope (0.84 with R = 0.94 for 29 objects), indicating that the low bolometric luminosity objects have a near infrared excess, due to a greater contribution from starlight.

The blue luminosity, for normal galaxies, rises slower than linearly with the bolometric luminosity (see Figure 10*a*); again the high luminosity non–Seyfert galaxies deviate the most from linearity. For Seyfert galaxies (Figure 10*b*) the blue luminosity—bolometric luminosity relation is even flatter, indicating that a strong bias is always present in optical surveys.

6. NORMALIZED SPECTRAL ENERGY DISTRIBUTIONS

For most of the galaxies of our sample, we have computed the spectral energy distributions (SEDs) normalized to the total fluxes in the frequency range $12.5 < \log \nu[\mathrm{Hz}] < 15.0$. Specifically, we have considered all galaxies in the 12um sample for which were available fluxes (or magnitudes) in the following wavebands: B, J, H, K, L, 12, 25, 60, 100. We integrated by connecting each waveband with a local power–law slope, to derive a total 4000Å—300 μm flux which is essentially the bolometric flux. In each non–Seyfert 1 galaxy the fluxes in each waveband were then normalized by its total flux. Energy distributions of the Seyfert 1 galaxies were normalized by including the 1330Å and soft X–ray wavebands. The 1330Å flux is the average of all archived IUE SWP spectra for each Seyfert 1, from Edelson et al. (1995) and the X–ray flux is from the Rosat All Sky Survey results in Rush et al. (1996b). These soft X–ray fluxes were extrapolated out to 30 keV assuming a -1 energy index. For an additional comparison the average normalized SEDs (also including the UV and X–ray wavebands) of the 6 brightest PG quasars, for which IUE spectra were available, has also been computed (Edelson 1986).

We have used IUE observations from Edelson et al. (1995) to test our assumption that the shorter wavelength power can be safely neglected in all the galaxies aside from the Seyfert 1s. In the 17 Seyfert 2s observed by both IUE and ROSAT, the UV+X–ray spectrum contributes from 5 to less than 1% of the total (bolometric) flux. In two high–luminosity IR starburst galaxies detected by IUE, their UV flux is 1—2.5% of their bolometric flux. In the one 12 Micron Sample LINER detected by IUE—NGC 1052—the UV flux is 5% of the total. Neglecting these contributions therefore has added negligible error to our bolometric flux estimates.

Figure 11 shows the average normalized energy distributions of normal galaxies (mean of 288) Seyfert 1s (mean of 19), Seyfert 2s (mean of 29), high–luminosity non–Seyferts (mean of 19), and LINERs (mean of 15). In these plots the vertical (flux) scale is *linear* so that the integrals correspond to the usual total power. This is a useful way to visualize which wavebands make the principal contributions to the bolometric luminosity. For comparison, the average energy distribution of the 6 PG quasars is also given. The normalization for these quasars has been computed from optical through infrared data from the literature and by assuming a ratio of UV+X–ray to total flux of 0.08, which is derived from the average of the 5 Seyfert 1s,[10] for which we have a measure of the bolometric luminosity, and that were lying close to the PG quasars in the [60–25] versus [H–L] diagram (Figure 3). In Figure 12 we show the individual SEDs for all galaxies where we have calculated bolometric luminosities (except for the normal galaxies, which are too numerous to plot individually).

In Figure 12*a* we show the median and first and third quartiles of the 288 normal galaxy spectra. The scatter in the SEDs of normal galaxies is smallest in the 8–12 μm region. Stating this another way, all normal galaxies emit about 7±1% of their bolometric

[10] Namely: IZw1, Mkn9, Mkn704, Mkn1040 and N5548.

flux at 12 μm (as measured by $\lambda F\lambda$). This means that a galaxy sample complete to a given 12 μm flux limit is also nearly complete to a given bolometric flux limit (of ~14 times the 12 μm flux limit).

In Figure 12*b*, we show the normalized SEDs of the 22 Seyfert 1 galaxies: all objects have similar behavior, with flatter energy distributions than any other category. In the near– to mid–IR ($13 < \log\nu[\mathrm{Hz}] < 14$) they are relatively brighter than any other galaxy type of our sample galaxies. Only the average spectrum of the bright PG quasar is similar to the Seyfert 1s, and even brighter at $13 < \log\nu[\mathrm{Hz}] < 14$.

In Figure 12*c*, we show Seyfert 2s, the SEDs of which differ from those of Seyfert 1s in two main ways: (1) slightly more 60—100 μm flux, as is expected from dustier objects which reprocess more of the lower–wavelength radiation into the far–IR; and (2) higher relative fluxes at J and H, i.e. the Seyfert 1s have a greater average 2.2—3.5 μm excess from a strong AGN, as also indicated in the color–color diagrams in Figure 1 above.

In Figure 12*d*, the high–luminosity non–Seyferts are shown, the shape being similar for all objects. They carry the same fraction of flux at 25 μm compared to Seyfert 1s, however they drop down by almost one magnitude at 12 μm having the same fractional flux as the normal galaxies; they show the weakest optical emission of any class. This is because so much of their bolometric flux emerges in the far–infrared, and their optical continua are heavily reddened. These are both caused by large quantities of dust intermixed with large numbers of luminous stars. Note that their SEDs intersect those of normal galaxies around 12 μm: both types emit about 7% of their bolometric luminosity in that waveband. To consider an extreme example of such high–luminosity galaxies, we compared these objects to the ultra–luminous IRAS galaxy F10214+4724, which also has a spectrum that peaks in the infrared. This object's IRAS fluxes densities (Rowan–Robinson et al. 1991) increase steeply at least up to 100 μm ($\log(F_{\nu 100\mu m}/F_{\nu 60\mu m}) \sim 0.48$), corresponding to a rest wavelength of ~30 μm (with $z \sim 2.29$—Brown & vanden Bout 1991), indicating that the emission is dominated by stellar processes similar to that from the much closer high–luminosity galaxies in our sample.

In Figure 12*e* the LINERs are shown. Again, the SEDs are very similar, most of the energy coming from the standard population of red giants characteristic of early–type galaxies. Small to negligible energy is produced by reradiation from cool dust grains. There is no evidence at any infrared wavelength of any flux that could be associated with a nonstellar nucleus. The LINERs have the lowest emission at infrared frequencies and the highest in the visual. In other words, they have the most "normal" infrared properties of any galaxy subgroup. Their spectra also show a wavelength of minimum scatter–around 6 to 8 μm. The energy they emit at 12 μm—νL_ν—is a constant 5% of their bolometric luminosity for all 12 of our LINERs.

7. SUMMARY AND CONCLUSIONS

We have calculated bolometric luminosities and normalized spectral energy distributions for galaxies in the the 12 μm Galaxy Sample, finding this sample to be approximately complete in normal galaxies down to a well–defined *bolometric* flux limit of $\nu F_\nu^{lim}/0.07 = 1.1 \cdot 10^{-10}$erg s^{-1} cm^{-2}, given our 12 μm flux limit of 0.22 Jy. Future deeper surveys conducted at wavelengths of 8 to 12 μm will *simultaneously* provide samples of normal and active galaxies which will be complete to well–defined bolometric flux limits. The normal galaxy sample will be about 5 times larger, but will be about 2 times less deep. The depth of the Seyfert galaxy sample at low luminosities will be limited by how well the nucleus can be spatially separated from the host galaxy. We will use small–beam mid–infrared photometry to make this separation for the 12um Seyferts in an upcoming paper (Rush et al. 1996b). The future surveys at these mid–infrared wavelengths will not be biased in favour or against particular types of galaxies (e.g. blue quasars, starbursts, etc.) because the mid–infrared emission for any class of objects is that most closely proportional to the bolometric luminosity (whereas the far–infrared/optical luminosities rise faster/slower than linearly with bolometric luminosity).

The near– to far–infrared energy distributions, as shown by the [H–L] and the [60–25] colors, define a clear sequence of increasing nuclear activity from normal galaxies, having blue [H–L] color and cold [60–25] color, to those Seyfert galaxies which have similar properties of quasars, with red [H–L] color and hot [60–25] color. Those Seyfert galaxies having a strong galactic component—relative to the nuclear component—have intermediate colors. However, the high luminosity non–Seyferts (we include Arp 220 in this class) lie significantly off the "nuclear activity" sequence, indicating that their relative energy distribution cannot be explained by the mixture of galaxy plus quasar light, but—most probably—only by the occurrence of violent bursts of star formation which simultaneously flattens [60–25] and steepens [H–L]. Combining near– and far–infrared photometry is therefore a powerful diagnostic for identifying the emission mechanisms (quasars and/or star formation) which are ultimately responsible for the emitted light of galaxies.

We also find that Seyfert 1s and Seyfert 2s are separated on infrared color–color diagrams. This can be reconciled with "Unified Schemes" in which Seyfert 1s are seen face–on, Seyfert 2s are seen edge-on, and thus have much of their higher frequency radiation absorbed by an intervening torus, resulting in redder colors.

We thank the IRAS (Infrared Astronomical Satellite) Team and the staff at IPAC (Infrared Processing and Analysis Center, Pasadena, CA), noting that without the success of the IRAS mission, this work could not even have been conceived. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We also thank the ESO (European Southern Observatory, Chile) and San Pedro Martir Observatory (Baja California, Mexico) staff for assisting us during the various campaigns. We are grateful to K. Matthews and G. Neugebauer for support of the infrared photometer at Mount Wilson, and C. Beichman and D. Dickinson for assistance with the observations. We are also grateful to Marion Schmitz who gave us the electronic version of the Catalog of Infrared Observations promptly upon its completion, thus saving us from making a thorough and endless literature search. We thank Jill Knapp for providing us with electronic copies of the data tables from Knapp et al. (1989). This work was supported by NASA grants NAG 5–1358 and NAG 5–1719 and DGAPA/UNAM grant PAPIID:IN103992.

A. ESTIMATED [3.5 μm] MAGNITUDES FOR COMPUTATION OF BOLOMETRIC FLUXES

The dramatic increase of sky noise with wavelength makes it extremely difficult to obtain large–beam photometry for $\lambda > 3\mu m$. Nonetheless, for many of the brightest 12 μm Galaxies, and for most of the Seyferts, we measured fluxes at L [3.5 μm] or L' [3.75 μm], which were presented in Table 1. For most non–Seyfert galaxies, however, we lack L photometry. To obtain the bolometric luminosities in § 3. above, we *assigned* these galaxies an L magnitude based on the correlation between [H–K] and [K–L] shown in Figure 2. The regression line we show for non-Seyferts is:

$$[K - L] = ([H - K] - 0.13)/0.33$$

This relation shows a scatter of ± 0.3 magnitudes, which is only a minor contributor to the final uncertainties of our bolometric luminosities.

B. ESTIMATED SUB–MILLIMETER FLUXES FOR COMPUTATION OF BOLOMETRIC FLUXES

Although our "L_{IRAS}" integrations were stopped at 100 μm, it is known that substantial thermal flux emerges from cooler dust at longer wavelengths. Since the flux density often peaks at wavelengths longer than 100 μm, the IRAS 60 and 100 μm fluxes alone, if fitted with a single–temperature component, tend to under–estimated the total sub–mm flux. Longer wavelength data are needed to determine the necessary correction. The relatively few measurements in the far–infrared at $\lambda > 100\ \mu m$ are sufficient to demonstrate that not all galaxies show the same spectral shapes beyond 100 μm. To compare these results, we have reduced all of this long–wavelength data to one measure of the far–IR spectral turnover: the color temperature of a greybody, for an assumed dust emissivity $\propto \lambda^{-1}$, which would pass through the 100 μm flux measured by IRAS.

As shown in Figure 13, the far–IR/sub–mm color temperature is correlated with the 60—100 μm slope. The data are from Rickard & Harvey (1984), Telesco & Harper (1980), Thronson et al. (1990), Stark et al. (1989), Joy et al. (1986), Hunter et al. (1989), and Smith 1982. Not surprisingly, galaxies which appear hotter in the IRAS bands also appear hotter in the far–IR/sub–mm, although the inferred dust temperatures for the longer wavelengths are systematically lower than the 60—100 μm color temperature, because of the increasing contribution of colder dust at longer wavelengths. We have used the correlation shown in the figure, $T_{color} = 11.4 \cdot (\alpha_{60-100} + 4.67)$K to estimate color temperatures for each galaxy in our sample. We then added the integrated flux of a $\epsilon \propto \lambda^{-1}$ greybody for $\lambda > 100\mu m$ to our IRAS fluxes in deriving the Bolometric Luminosities of Table 3. The assumed emissivity law is probably conservative. If emissivity in fact drops like λ^{-2}, even *less* than 20% of the Bolometric Luminosity typically emerges at $\lambda > 100\mu m$.

C. COMPARISON WITH OTHER STUDIES

After submitting the original version of the present paper, we received preprints discussing the mid–infrared emission from Seyfert nuclei (Maiolino et al. 1995; Giuricin, Mardirossian & Mezzetti 1995). In this section we show our results to be consistent with theirs, as we discuss further some differences between the observed properties of Seyfert 1s and 2s. As mentioned above in § 4.2., the main conclusions of Maiolino et al. are, first, that the nuclear 10 μm luminosity of Broad Line Seyfert galaxies is systematically larger than that of those Seyferts without a BLR; and, second, that the host galaxies of Seyfert 2s nuclei have higher star formation rates than the hosts of Seyfert 1s. From the average energy distributions, normalized to the total luminosities, that we computed in § 6. (see Figure 11), we find that the average ratio of 12 μm to total luminosity average is 0.075±.039 for the normal galaxies, 0.130±.052 for the Seyfert 1s, 0.097±.04 for the Seyfert 2s, 0.077±.027 for the Starbursts (and for comparison 0.039±.023 for the LINERs). Although the scatter around the mean is quite large, the trend is for a decreasing fraction of the *total* luminosity to emerge at 12 μm going from Seyfert 1s through Seyfert 2s to normal galaxies and starburst galaxies, and ending with LINERs. If we assume that the average galactic component of the 12 μm emission in Seyfert galaxies is equal for both types to the total emission present in normal galaxies, it follows that the nuclear 12 μm component of the Seyfert 1s is brighter than that of the Seyfert 2s. This is essentially the first conclusion of Maiolino et al.

We can check their second conclusion by using the normalized 60 μm luminosity to infer the star formation rate. For our sample, the average ratio of 60 μm to total luminosity is 0.38 for "starbursts", 0.20 for normal galaxies, 0.19 for Seyfert 2s, 0.15 for Seyfert 1s, and 0.11 for LINERs. Although the scatter is again large (the standard deviations of the above ratios range from 0.085 to 0.090) the trend indicates a decrease in the fractional 60 μm emission from starburst galaxies, through normal, Seyfert 2s, then Seyfert 1s and LINERs. This behavior can also be seen from the [60—12] color for the whole 12 μm galaxy sample (i.e., the $\log(F_{60\mu m}/F_{12\mu m})$, as plotted, for example, in Figure 4*a*). The more a galaxy is dominated by star formation processes the redder is its [60—12] color. In fact, the [60—12] color decreases from starburst galaxies (1.31±0.21 for 38 galaxies), through normal galaxies (1.05±0.22 for 705 objects), LINERs (1.00±0.25 for 30 objects), Seyfert 2s (0.98±0.37 for 65 objects), to Seyfert 1s (0.70±0.38 for 55 objects). We expect that much of the scatter in this relation will be explained with further observations, as is already the case for several exceptions to this trend among the Seyferts: several Seyfert 2s with the lowest [60—12] values (<0.9; NGC 1068, MKN 348, and MKN 463, i.e. the best observed ones) are known to have an obscured BLR, while three Seyfert 1s with high values of [60—12] (>1.2; NGC 1365, NGC 7469, and MKN 231) are already known to have significant starburst components.

Giuricin et al. (1995) used a compilation of ground-based, small aperture photometric observations at 10 μm for 117 Seyfert galaxies. They find that the 10 μm luminosity distribution of Seyfert 1s extends to greater values than that of Seyfert 2s. This is not surprising. In fact, in the 12 μm galaxy sample (SM, RMS), the 12 μm and 60 μm luminosity functions of Seyfert 1s extend to higher luminosities than those of Seyfert 2s. This effect is also observed in Maiolino et al., who reported a 2σ difference between the 10 μm luminosities of broad-line and narrow-line Seyfert galaxies. Giuricin et al. also find that Seyfert 1s and Seyfert 2s differ significantly in their IRAS 12—25 μm color, Seyfert 2s being redder than Seyfert 1s.

We agree with Maiolino et al. that the above results can be reconciled with the unified models for Seyfert galaxies if the 10 μm nuclear emission is moderately anisotropic. This might imply that the physical size of the 10 μm source has to be no larger than the hypothesized obscuring torus and that this has to be moderately optically thick in the mid-infrared. We also agree with their suggestion that some Seyfert host galaxies have enhanced levels of star formation. In particular, this probably helped some of the Seyfert 2's get into the 12 μm sample.

REFERENCES

Aaronson, M., Huchra, J., & Mould, J. 1979, ApJ 229, 1 (AHM)

Bally, J., Langer, W.D., & Liu, W. 1991, ApJ 383, 645

Balzano, V.A. & Weedman, D.W. 1981, ApJ 243, 756

Bersanelli, M., Bouchet, P., & Falomo, R. 1991, A&A 252, 854

Bouchet, P., Schmider, F., & Manfroid, J. 1991, A&AS 91, 409

Brown, R.L. & vanden Bout, P.A. 1991, AJ 102, 1956

Carrasco, L. & Cruz–Gonzalez, I. 1995, in preparation

Carrasco, L., Recillas–Cruz, E., Garcia–Barreto, A., Cruz–Gonzalez, I., Serrano, A.P.G. 1991, PASP 103, 987.

Cruz–Gonzalez, I. 1984, Ph.D. Thesis, Harvard University

Danese, L., Zitelli, V., Granato, G.L., Wade, R., De Zotti, G., & Mandolesi, N. 1992, ApJ 399, 38

De Jong, T., Clegg, P.E., Soifer, B.T., Rowan–Robinson, M., Habing, H.J., Houck, J.R., Aumann, H.H., & Raimond, E. 1984, ApJL 278, L67

De Vaucouleurs, G., De Vaucouleurs, A., Corwin, H.G., Jr., Buta, R.J., Paturel, G., & Foque,P. 1991 *Third Reference Catalog of Bright Galaxies* (New York: Springer–Verlag) (RC3)

Edelson, R.A. 1986, ApJL 309, L69

Edelson, R.A., Malkan, M.A., & Rieke, G.H. 1987, ApJ 321, 233 (EMR)

Edelson, R.A. et al. 1995, preprint

Elias, J.H., Frogel, J.A., Matthews, K., & Neugebauer, G. 1982, AJ 87, 1029

Frogel, J.A., Persson, S.E., Aaronson, M., & Matthews, K. 1978, ApJ 220, 75

Gezari, D.Y., Schmitz, M., Pitts, P.S. & Mead, J.M. 1993, *Catalog of Infrared Observations*, NASA Reference Publication 1294, June 1993.

Giuricin, G., Mardirossian, F., & Mezzetti, M. 1995, ApJ in press. (preprint SISSA Ref. 5/95/A)

Heckman, T.M. 1980, A&A 87, 152

Hunter, D.A., Thronson, H.A., Casey, S., & Harper, D.A. 1989, ApJ 341, 697

Hyland, A.R. & Allen, D.A. 1982, MNRAS 199, 943

Joseph, R.D., Meikle, W.P.S., Robertson, N.A., & Wright, G.S. 1984, MNRAS 209, 111

Joy, M., Lester, D.F., Harvey, P.M., & Frueh, M. 1986, ApJ 307, 110

Knapp, G.R., Guhathakurta, P., Kim, D.-W., & Jura, M. 1989, ApJS 70, 329

Kotilainen, J.K., Ward, M.J., Boisson, C., DePoy, D.L., & Smith, M.G. 1992, MNRAS 256, 149

Kotilainen, J.K., & Ward, M.J. 1994, MNRAS 266, 953

Malkan, M.A. & Oke, J.B. 1983, ApJ 265, 92

Maiolino, R., Ruiz, M., Rieke, G.H., & Keller, L.D. 1995, ApJ in press

Mazzei, P. & De Zotti, G. 1994, ApJ 426, 97

Mazzei, P., De Zotti, G., & Xu, C. 1994, ApJ 422, 81

Moshir, M., et al. 1991, Explanatory Supplement to the IRAS Faint Source Survey, Version 2. (Pasadena: JPL)

Neugebauer, G., Green, R.F., Matthews, K., Scmidt, M., Soifer, B.T., & Bennett, J. 1978, ApJS 63, 615

Pier, E.A. & Krolik, J.H. 1993, ApJ 418, 673

Recillas–Cruz, E., Carrasco, L., Serrano, A., Cruz–Gonzalez, I. 1990, A&A 229, 64

Recillas–Cruz, E., Carrasco, L., Serrano, A., Cruz–Gonzalez, I. 1991, A&A 249, 312

Rickard, L.J. & Harvey, P.M. 1984, AJ 89, 1520

Rieke, G.H. & Lebofsky M.J. 1985, ApJ 288, 618

Rowan–Robinson, M. et al. 1991, Nature 351, 719

Rudy, R.J., Levan, P.D., & Rodriguez–Espinosa, J.M. 1982, AJ 87, 598

Rush, B., Malkan, M.A. & Spinoglio, L. 1993, ApJS 89, 1 (RMS)

Rush, B., Malkan, M.A., Fink, H.H., & Voges, W. 1996a, in preparation.

Rush, B., Malkan, M.A. & Spinoglio, L. 1996b, in preparation

Smith, J. 1982, ApJ 261, 463

Spinoglio, L., & Malkan, M.A. 1989, ApJ 342, 83 (SM)

Stark, A.A., Davidson, J.A., Harper, D.A., Pernic, R., Loewenstein, R., Platt, S., Engargiola, G., & Casey, S. 1989, ApJ 337, 650

Telesco, C.M. & Harper, D.A. 1980, ApJ 235, 392

Thronson, H.A., Hunter, D.A., Casey, S., & Harper, D.A. 1990, ApJ 355, 94

Thuan, T.X. 1983, ApJ 268, 667

Vèron–Cetty, M. P., & Vèron, P. 1991, A Catalogue of Quasars and Active Nuclei, 5th edition. ESO Scientific Report No. 10 — October 1991 (Munich: European Southern Observatory)

Wall, W.F., et al. 1995, submitted to ApJS

Wilson, W.J., Schwartz, P.R., Neugebauer, G., Harvey, P.M., & Becklin, E.E. 1972, ApJ 177, 523

FIGURE LEGENDS

Figure 1 — *a*: [J–H] vs. [H–K] color–color diagram. The normal galaxy colors are indicated by the large circle whose radius is 2σ. Also indicated is the mean value of the 9 brightest PG quasars (see text). The extinction of 1 and 5 optical mag. is also given. *b*: [H–K] vs. [K–L] color–color diagram. In this and all following figures, the filled squares represent Seyfert 1s, open squares Seyfert 2s, asterisks high–luminosity non–Seyferts, open circles LINERs and diagonal crosses normal galaxies.

Figure 2 — *a*: [25–K] vs. [60–25] color–color diagram. The [25–K] color gives a clear separation of Seyfert 1s from Seyfert 2s (see the text). *b*: [25–K] vs. [H–K] color–color diagram.

Figure 3 — [60–25] vs. [H–L] color–color diagram. The line represent the least squares fit of all data points. Seyfert 1s and 2s are labelled with their names. The average colors with 1 σ errors are indicated for normal galaxies, high luminosity non–Seyferts, LINERs and the brightest PG quasars (see text).

Figure 4 — *a*: [60–12] vs. [H–K] color–color diagram. *b*: [H–K] color vs. bolometric luminosity.

Figure 5 — [25–K] vs. [60–12] color–color diagram. The broken lines at [60–12]=1. and [25–K]=1.35 define a region where almost only Seyfert 1 galaxies are present. The cross represents the 1 σ scatter for the normal galaxies. The point in the upper left refers to the best fit model of an optically thick torus seen edge–on for the nuclear colors of NGC1068 (Pier & Krolik 1993). The dotted line shows a mixture of those nuclear colors plus our average galactic colors (the numbers give the fraction of galactic to nuclear flux at 12 μm). For comparison we also show our large aperture data of the same galaxy.

Figure 6 — [B–H] vs. [K–12 μm] color–color diagram. Elipses representing the 1–σ scatter in each color are centered on the average value for the E/S0 galaxies and for all galaxies.

Figure 7 — Monochromatic luminosities vs. bolometric luminosity for normal galaxies and high luminosity non–Seyferts. Also shown are the points representing LINERs. The lines represent the least squares fit to all but the LINERs points. *a,b,c,d*: 12, 25, 60, and 100 μm luminosity vs. bolometric luminosity.

Figure 8 — Monochromatic luminosities vs. bolometric luminosity for *Seyferts*. The lines represent the least squares fit to all data points, except the one relative to Arp 220 (which isn't likely a Seyfert—see text), whose position is labeled. *a,b,c,d*: 12, 25, 60, and 100 μm luminosity vs. bolometric luminosity.

Figure 9 — Near–infrared luminosity vs. bolometric luminosity for *a*) normals and high–luminosity non–Seyferts, and *b*) Seyferts. The solid lines represent the least squares fit to all data points. The dashed and dotted lines in *b* are the fits to the Seyfert 1s and 2s, respectively.

Figure 10 — Total blue luminosity vs. bolometric luminosity for *a*) normals and high–luminosity non–Seyferts and LINERs, and *b*) Seyferts. The lines represent the least squares fit to all data points.

Figure 11 — Average spectral energy distribution normalized to bolometric flux of all classes of galaxies. Also included is the average PG quasar spectrum (see text).

Figure 12 — Spectral energy distribution, normalized to bolometric flux, of individual galaxies in the 12 μm Sample. *a,b,c,d,e*: normal galaxies, Seyfert 1s, Seyfert 2s, high–luminosity non–Seyferts, and LINERs, respectively. For the normal galaxies, we plot only the logarithmic spectral energy distribution of the median and first and third quartiles points at each observed frequency.

Figure 13 — Least squares fit of the spectral index $\alpha_{60-100\mu m}$ as a function of the color temperature, assuming grey body emission with dust emissivity law $\epsilon \propto \lambda^{-1}$.