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N87-24356

NUCLEAR INFRARED EMISSION AND THE COLORS OF IRAS GALAXIES

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ABSTRACT. J, H, K, L', and N observations of galaxies detected at 12 μm by IRAS are combined with IRAS flux densities to investigate the relationship between the infrared sizes and colors of galaxian infrared sources. It is found that typical IRAS galaxies have 10 μm radii of 0.5-2.0 kpc, while active galaxies and galaxies with higher 25-60 μm color temperatures are smaller. One unusual object, 23060+0505, is at high redshift and has an infrared luminosity of 1.5 x 10^{12} $L_{\odot}$. Its 1-100 μm energy distribution resembles that of a Seyfert 1 galaxy, but it shows very little sign of broad-line emission in the visible. Its properties suggest that it may be a prototype for a class of highly obscured active galaxy.

1. INTRODUCTION

As part of an IRAS follow-up program, the group at the University of Hawaii has been systematically obtaining redshifts, CCD imagery, and infrared photometry of a sample of IRAS point sources identified with galaxies. This paper presents some preliminary results from this large data base. In particular, a number of detections at N (10.1 μm) allow us to investigate the 10 μm size of many galaxies for comparison with other properties.

Three samples are considered. Galaxies in the first sample are drawn mainly from the preliminary P04 and P06 IRAS lists and constitute what we believe to be a "representative" sample of IRAS galaxies. Those in the second sample are from lists P11 and P16 and have "hot" ($S_{25\mu m}/S_{60\mu m}$ > 0.3) far-infrared energy distributions (some of these sources are from de Grijp et al. 1985). The third sample comprises those X-ray-selected active galactic nuclei (AGN) in the sample of McAlary et al. (1983) that have both published ground-based small-aperture N observations and IRAS detections at 12 μm.

2. OBSERVATIONS

Details of the observations will be reported elsewhere. The redshifts were obtained at the University of Hawaii 2.2 m telescope on Mauna Kea using a grism spectrograph or the Faint Object Spectrograph. The spectrographs and the Galileo/Institute for Astronomy 500 x 500 TI CCD were mounted at the Cassegrain focus, giving resolutions from 8 to 16 Å.

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[1]Visiting Astronomer, Infrared Telescope Facility, which is operated by the University of Hawaii, under contract with the National Aeronautics and Space Administration.

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J, H, K, L', and N photometry was obtained at the NASA Infrared Telescope Facility (IRTF) on Mauna Kea. Often the identification of the IRAS source was made or confirmed by the presence of strong infrared emission detected at the IRTF. These data were combined with flux densities either from the IRAS Point Source Catalog (IRAS Explanatory Supplement), or for fainter sources, from coadded IRAS scans processed at IPAC.

3. 10 μm SOURCE SIZE

The sizes of the 10 μm sources in these galaxies are characterized by a "compactness" parameter. This is the ratio of the small-beam, ground-based 10 μm flux density to that measured by IRAS at 12 μm and color corrected to 10 μm. The color correction is obtained simply by extrapolating the 25/12 μm flux density ratio down to 10 μm. Since this procedure could have systematic biases for individual sources, two standard corrections, a factor of 0.71 for the steeper "representative" IRAS galaxy sample and 0.76 for the "AGN" and "hot" IRAS galaxies, were adopted. These are based on the averages of the individual galaxy corrections within each group.

Figure 1 shows the compactness as a function of distance (H_0 = 75 km s^{-1} Mpc^{-1} assumed throughout). Also plotted is a simple-minded model in which the surface brightness of the infrared emission drops off exponentially with radius, with a characteristic scale length of r_0. A comparison with the observations can be made by synthesizing the compactness parameter for a series of characteristic sizes over the range of distances observed here.

It is evident that there is a separation between the "representative" IRAS galaxies and the AGN, with those IRAS galaxies having "hotter" far-infrared energy distributions falling among the AGN. The characteristic size of the "representative" IRAS galaxies is between r_0 = 0.5 and 2 kpc, while the AGN and "hot" IRAS galaxies are generally <0.5 kpc. The smaller size of these sources can be understood as a greater domination of the 10 μm emission by a point nuclear source, as would be expected in the presence of an active nucleus. This interpretation is confirmed for the "hot" objects by visible spectra that show line ratios characteristic of nuclear activity (see also de Grijp et al. 1985).

3.1. Source Compactness and Color

We can also investigate the effect of size on the J, H, K, and L colors of galaxies. The galaxies are divided into two groups--those smaller than and those larger than 0.5 kpc. The J-L color characterizes the shape of the near-infrared continuum, and the 25/60 μm flux density ratio, the far-infrared. Figure 2 shows that the smaller sources have larger values of J-L (proportionately more energy output at L) and, as would be expected from Figure 1, larger 25/60 μm flux density ratios (i.e., they are hotter). The probability of these correlations arising by chance are 0.025 and <<0.001, respectively. It is thus very likely that there is an additional mid-IR (3-30 μm) continuum component in the galaxies with smaller characteristic infrared size, and this component is associated with the nuclear emission in these objects.

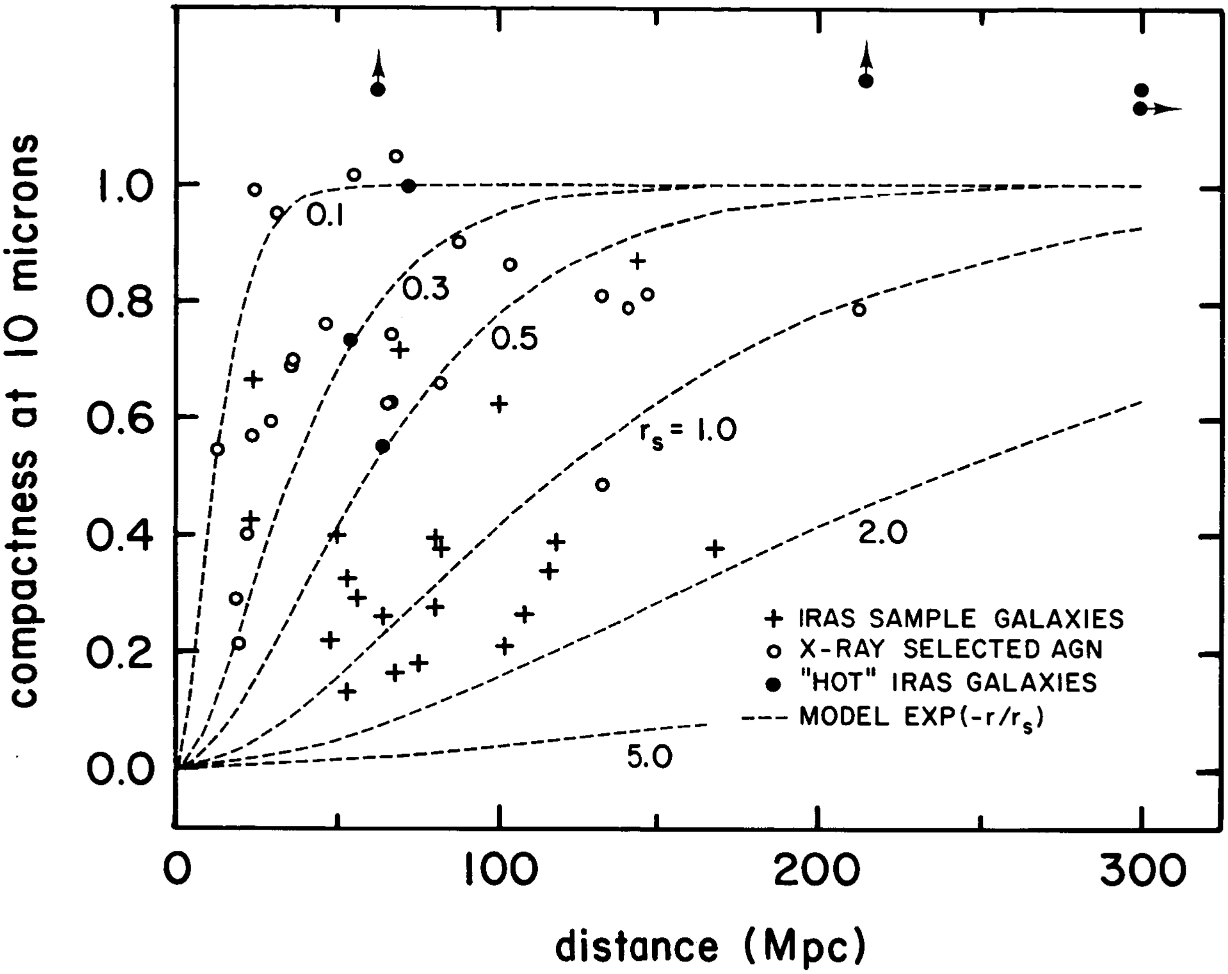

Figure 1. The 10 μm "compactness" (see text) of IRAS sources plotted against their distance in megaparsecs. The dashed lines represent a model in which the surface brightness drops as $\exp(-r/r_o)$ for a series of characteristic radii r_o in kpc. Data for the main sample of "representative" and "hot" IRAS galaxies were obtained at the IRTF with a 5.5" aperture. Data on the X-ray-selected AGN are taken from McAlary et al. (1983), with apertures ranging from 5" to 9".

4. IRAS 23060+0505P16: A HIGHLY OBSCURED 1.5 x 10^{12} $L_\odot$ AGN?

A particularly interesting source, discovered to have distinctive properties among the "hot" IRAS galaxy sample, is 23060+0505. At a redshift of z = 0.174, its luminosity is 1.5 x 10^{12} L_o, and its J-L' color is the largest (5.12) of all the galaxies in this study. This gives it one of the steepest near-infrared continua known (index α = 2.8, where $S_\nu \propto \nu^{-\alpha}$). Although its energy distribution most resembles that of a Seyfert 1 galaxy, its visible spectrum shows only weak evidence for the large broad permitted line flux expected from such objects. It does, however, show a large O III λ5007/Hβ line ratio characteristic of active galaxies, and it has a steep Balmer decrement. The radio luminosity from unpublished VLA "A" array observations is log P = 22.5 W Hz^{-1} $ster^{-1}$ at 6 cm, a value typical of Seyfert galaxies or radio quiet

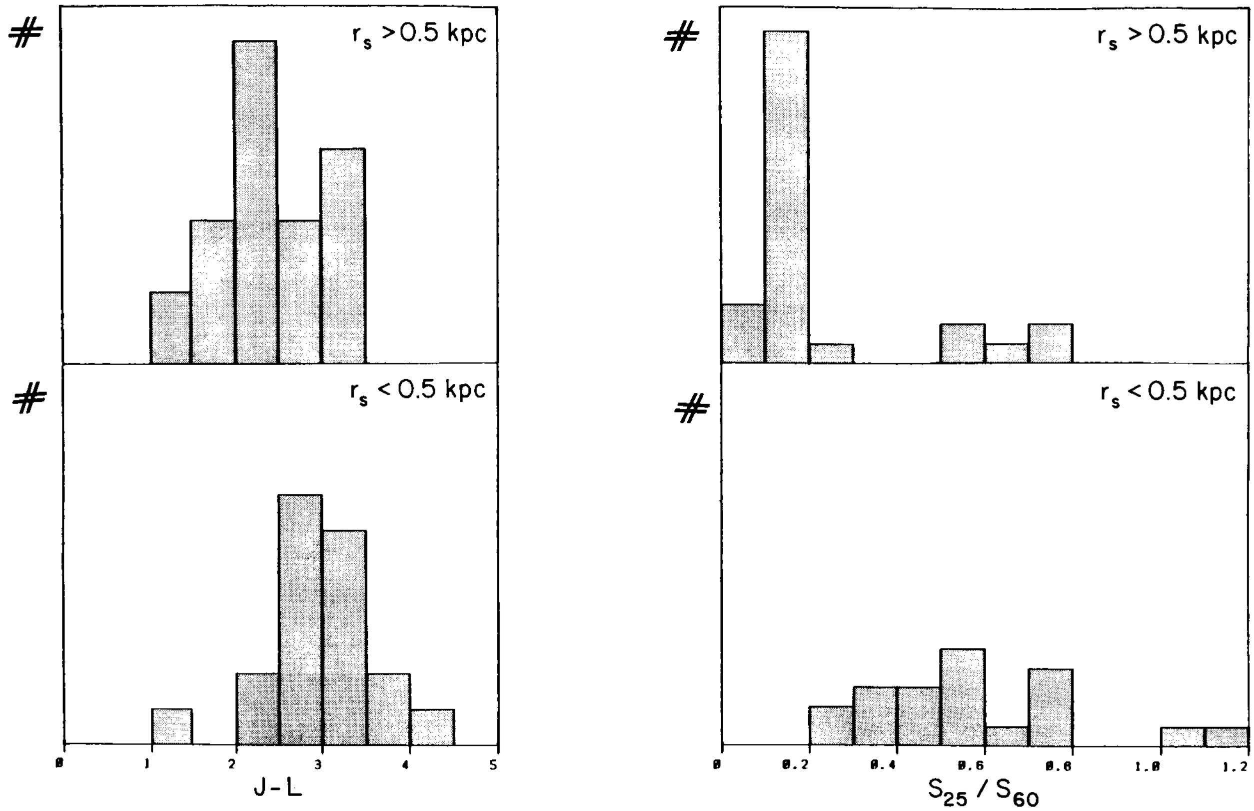

Figure 2. The distributions in J-L and 25-60 μm flux density ratio ($S_{25\mu m}/S_{60\mu m}$) for sources with characteristic 10 μm radii r_o >0.5 kpc and <0.5 kpc (sources for which there are only L' rather than L measurements have been corrected).

QSOs (Ulvestad and Wilson 1984).[2] Important clues to the nature of this object can be found in a comparison between its 1-100 μm energy distribution and those of different classes of extragalactic object (Figure 3).

4.1. The Energy Distribution

Figure 3a shows the energy distribution of 23060+0505 compared with the range observed for typical starburst and interacting galaxies (Joseph et al. 1984; Balzano 1983), and Figure 3b gives a comparison to Seyfert 2 galaxies (Rieke 1978). Both classes of galaxy are dominated at J, H, and K by the photospheric emission from late-type stars, which causes a characteristic inflexion in the energy distribution between 2 and 3 μm. This feature is not seen in 23060+0505, and it is evident that any stellar photospheric contribution to the near-infrared emission from this object is negligible compared to that observed in star-forming or Seyfert 2 galaxies and that the energy source is probably different.

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[2]The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

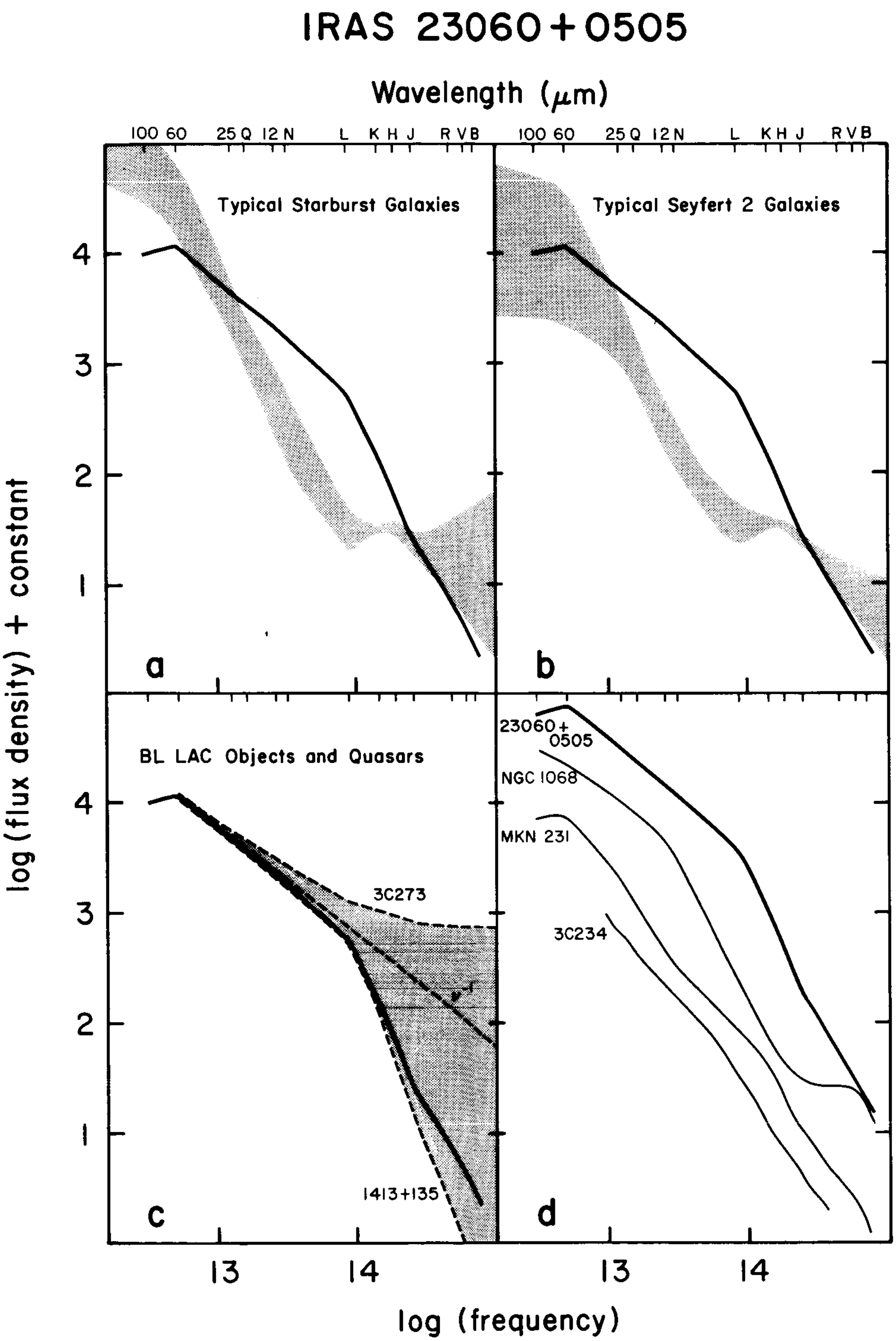

Figure 3. A comparison between the 1-100 μm energy distributions of IRAS 23060+0505 and those of other representative objects. Hatching denotes the range of values encountered for (a) starburst and interacting galaxies; (b) Seyfert 2 galaxies; and (c) Seyfert 1 galaxies, quasars, and BL Lac objects. Figure 3(d) shows 23060+0505 compared to the well-known active galaxies 3C234, NGC 1068, and Mkn 231.

A comparison to Seyfert 1 galaxies, QSOs, and BL Lac objects (Neugebauer et al. 1979; Impey et al. 1982) is made in Figure 3c. It is striking that the energy distribution bears a marked resemblance to that of the BL Lac object with the steepest energy distribution, 1413+135 (Beichman et al. 1981). However, the weakness of its radio emission is inconsistent with 23060+0505 being a BL Lac object. The result of the comparison between 1-100 μm energy distributions is that 23060+0505 most resembles a Seyfert 1 active galaxy.

4.2. Interpretation

Infrared evidence points to 23060+0505 containing a hidden AGN. Higher-quality spectra obtained with the Faint Object Spectrograph reveal only weak evidence for a broad wing to the Hα line, not the strong broad permitted lines characteristic of Seyfert 1 galaxies. This may be interpreted as being due to dust obscuration. An image obtained through the Faint Object Spectrograph shows a very compact morphology dominated by an unresolved nucleus.

An estimate of the reddening toward the region of line formation may be obtained from the Hα/Hβ line ratio, assuming an intrinsic case-B ratio of 2.8 (Osterbrock 1974). The observed ratio of >10 yields a visible reddening in excess of 4 magnitudes, indicating that the absence of strong broad lines, and probably the steepness of the visible to 4 μm continuum, is due to dust obscuration. Here a comparison to other broad-line AGN where large extinctions have been measured through observations of infrared recombination lines is enlightening (Figure 3d). The broad-line radio galaxy 3C 234 shows a strong Paschen-α line consistent with large reddening (Carleton et al. 1984), and it has a steep infrared continuum similar to 23060+0505 (Elvis et al. 1984). The highly luminous reddened broad-line AGN Markarian 231 (Rieke 1978; Lacy et al. 1982) most resembles 23060+0505 with its steep continuum and reddened hydrogen recombination lines.

The fact that this object was discovered in a survey of a relatively small number of candidates (≈20) argues that it may be a prototype of a significant, previously undetected, population of highly obscured AGN with luminosities approaching those of quasars. The selection effects against even slightly reddened AGN in optical and UV surveys are well documented (see Keel 1980 and Lawrence and Elvis 1982 for example), and it has been shown that there exists a significant population of active galaxies, mainly Seyfert 2, missed by other surveys but detected in the infrared by IRAS (de Grijp et al. 1985). It is possible that some of these galaxies, classified as Seyfert 2 on the basis of optical spectroscopy, are similar to IRAS 23060+0505 and contain hidden Seyfert 1 nuclei. It has been demonstrated here that near-infrared colors are a very useful and efficient way to identify such objects.

5. ACKNOWLEDGMENTS

This work was undertaken in collaboration with Gareth Wynn-Williams, Eric Becklin, and Jim Heasley. The author thanks Gerald Cecil for help with some of the observations reported here, John MacKenty for the use of computer programs, and Walter Rice for help with IPAC reductions. This research is supported by NSF grant AST 84-18197.

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