

## IRAS OBSERVATIONS OF SEYFERT GALAXIES

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## ABSTRACT

*IRAS* measurements at 25, 60, and 100  $\mu\text{m}$  have been used to analyze the infrared properties of Seyfert galaxies from the Markarian and NGC catalogs. One hundred sixteen of 186 Seyfert galaxies were detected. About 50% of all Seyfert galaxies in the sample have 60  $\mu\text{m}$  luminosities in excess of  $\sim 10^{10} L_{\odot}$ , and the mean 60  $\mu\text{m}$  luminosity increases with the optical  $B$  absolute magnitude. The luminosity functions of the Seyfert 1 and Seyfert 2 galaxies appear quite similar. It is possible, however, to statistically separate the two types of galaxies in color-color plots. The 100 to 60  $\mu\text{m}$  energy distributions flatten systematically with increasing 60  $\mu\text{m}$  luminosity. The infrared measurements provide a measure of the bolometric luminosity of the Seyfert galaxies but do not discriminate between the physical processes involved.

*Subject headings:* galaxies: Seyfert — infrared: general

## I. INTRODUCTION

The mid- and far-infrared properties of Seyfert galaxies are intriguing for several reasons but have been measured for only a few galaxies. The *IRAS* survey of the sky at 12, 25, 60, and 100  $\mu\text{m}$  (Neugebauer *et al.* 1984*a*) has for the first time provided a means of making a statistical survey of a significant number of Seyfert galaxies at these infrared wavelengths.

In this *Letter* we present highlights of an initial statistical survey of the infrared properties of Seyfert galaxies and contrast these properties on the basis of *IRAS*-produced luminosity and spectral information.

## II. THE SAMPLE

All Markarian and NGC galaxies classified as either Seyfert 1 or Seyfert 2 in the compendium of Veron-Cetty and Veron (1984, hereafter VCV) were selected as the prime sample of Seyfert galaxies. Since one of the main goals was to compare the properties of different classes of Seyfert galaxies, the few objects from the sample whose type designation by Huchra (1984) differed from that of VCV were excluded. The sample chosen in this way, which consisted of 104 Seyfert 1 and 84 Seyfert 2 galaxies, had similar selection criteria to the sample used by Meurs (1982) to compute the radio luminosity function of Seyfert galaxies but is enlarged to include later installations of the Markarian catalog. Galaxies from the 3% of sky not covered by the *IRAS* survey (see *Explanatory Supplement to the IRAS Catalog 1985*, hereafter *Supplement*) were excluded from consideration. In order to provide a comparison, the Markarian and NGC galaxies detected by *IRAS* and designated by VCV as having nuclear emission-line spectra characteristic of H II regions were also selected as a separate subset of emission-line galaxies.

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Associations with *IRAS* sources were defined purely on the basis of position and included all *IRAS* sources in the *IRAS Point Source Catalog* (Joint *IRAS* Science Working Group 1985) within a radius of 90'' of each Seyfert galaxy in VCV (see *Supplement*). When no source was detected in the *Point Source Catalog*, limiting flux densities were obtained from the *IRAS* Working Survey Data Base described in the *Supplement*. The chance of a spurious association is about 1 part in 800 at  $|b| > 45^{\circ}$  and increases toward the Galactic plane. *IRAS* sources were associated with 50 of the 104 Seyfert 1 galaxies in VCV and 66 of the 84 Seyfert 2 galaxies.

A discussion of the *IRAS* observations and uncertainties is given in the *Supplement*. For the purpose of the statistical study, flux densities of good and medium quality in the *IRAS Point Source Catalog* (1985), as defined in the *Supplement*, are included in the sample of detected sources. Objects with good quality flux densities comprise more than 90% of the sample. No color correction was applied to the quoted catalog flux densities since such a correction is less than 3% at 60 and 100  $\mu\text{m}$  and less than 10% at 25  $\mu\text{m}$  for the observed colors of the Seyfert galaxies.

## III. RESULTS

Figure 1 is a plot of  $\alpha(100, 60)$ , the 100 to 60  $\mu\text{m}$  spectral index, plotted against  $\alpha(60, 25)$ , the 60 to 25  $\mu\text{m}$  spectral index. The spectral index  $\alpha$  is defined by  $f_{\nu} \propto \nu^{\alpha}$ , where  $f_{\nu}$  is the flux density, and  $\nu$  is the frequency. In those cases where only a limit has been measured for one of the flux densities involved in defining the spectral index, no index has been plotted. From the figure it can be seen that there is a segregation of points in the color-color plot. Although the lower right of the diagram appears to be populated by all three classes of galaxies, the upper portion is predominantly filled with Seyfert 1 galaxies. The median spectral indexes for the sources detected at at least one of 25, 60, or 100  $\mu\text{m}$  and divided according to galaxy type are given in Table 1.

The fraction of Seyfert galaxies observed as a function of the 60  $\mu\text{m}$  luminosity was calculated taking into account not

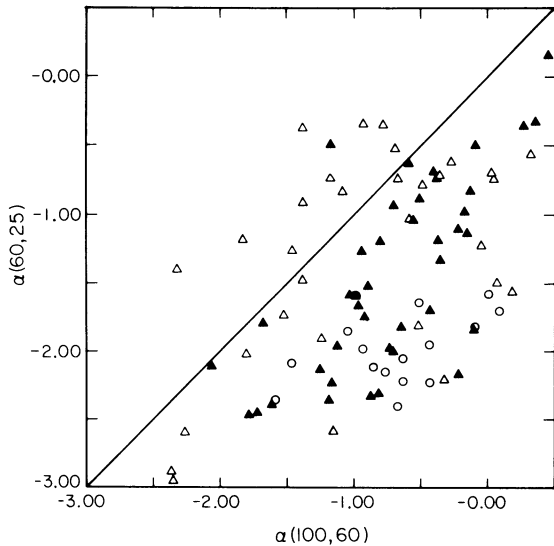


FIG. 1.—A mid- to far-infrared color-color plot for galaxies with strong nuclear emission lines. The spectral indexes are defined in the text. In all figures, Seyfert 1 galaxies are denoted by open triangles, Seyfert 2 galaxies are denoted by filled triangles, and galaxies with H II region nuclear regions by circles.

TABLE 1

SPECTRAL INDICES FOR SELECTED GALAXIES OF VARIOUS TYPES

TYPE	$\alpha(100, 60)$		$\alpha(60, 25)$	
	Median	Spread <sup>a</sup>	Median	Spread <sup>a</sup>
Seyfert 1.....	-1.1	1.7	-1.0	1.6
Seyfert 2.....	-0.8	0.7	-1.2	1.1
H II.....	-0.6	0.8	-1.8	0.5

<sup>a</sup>Spread calculated from  $2 \times |\text{median} - 33.3 \text{ percentile}|$ .

only the detected sources but also the detectability of all sources in the sample. The  $60 \mu\text{m}$  luminosity of each source was estimated as the product  $\nu L_\nu$ , where  $L_\nu$  is the luminosity density of the source.<sup>3</sup> The luminosity fraction was found by dividing the number of sources of measured luminosity  $\nu L_\nu$ , and with flux density  $f_\nu$ , above an adopted completeness limit in each luminosity bin by the number of sources in the VCV sample that could have been detected above the completeness limit if they had the luminosity of that bin (see, e.g., Meurs 1982). Although the *IRAS* survey is complete to  $f_\nu = 0.5 \text{ Jy}$  at  $60 \mu\text{m}$ ,  $0.7 \text{ Jy}$  was chosen as a conservative limit. The resultant distribution in Figure 2 shows that there is no significant difference between the  $60 \mu\text{m}$  fractional luminosity function of Seyfert 1 and Seyfert 2 galaxies. The higher detection rate of Seyfert 2 galaxies is due simply to the fact that the mean distance of the Seyfert 2 galaxies is half that of the Seyfert 1 galaxies in the sample. About half the sample of Seyfert galaxies have luminosities at  $60 \mu\text{m}$  in excess of  $\sim 10^{10.1} L_\odot$  or  $\sim 10^{36.7} \text{ W}$ . A comparison of the  $60 \mu\text{m}$  fractional luminosity function with that at the optical *B* waveband shows that the two curves have a displacement consistent with

<sup>3</sup>Throughout this *Letter*, the Hubble constant will be taken as  $H = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

a simple proportionality between the infrared and optical luminosities.

Figure 3 shows that when the 100 to  $60 \mu\text{m}$  spectral index is plotted against the  $60 \mu\text{m}$  luminosity, higher luminosity objects tend to have flatter energy distributions. The different effective diaphragm sizes at  $60 \mu\text{m}$  ( $\sim 1.5 \times 4.8$ ) and at  $100 \mu\text{m}$  ( $\sim 3' \times 5'$ ) could create an obvious selection effect. For extended sources this would result in an underestimate of the  $60 \mu\text{m}$  flux density relative to that at  $100 \mu\text{m}$  up to a factor of 2 or  $\sim 1.4$  in  $\alpha(100, 60)$ . This would only affect energy distributions of sources close enough to be significantly resolved. If the typical size of a galactic disk is 20 kpc, a  $3'$  diaphragm corresponds to recessional velocities  $\leq 1700 \text{ km s}^{-1}$ . Since the correlation is still present after removal of the dozen points due to the Seyfert galaxies closer than this, this effect is probably not important.

#### IV. DISCUSSION

The infrared observations of Seyfert galaxies have given a measure of the bolometric luminosities of these galaxies. Large numbers of these galaxies (more than 60% of Seyfert 2 galaxies) have their maximum energy output in the mid- and far-infrared, implying that this emission must play a crucial role in the overall energetics.

In a simplified picture based on previous observations, the infrared emission from Seyfert galaxies is conjectured to be a mixture of three components:

1. A cold ( $\sim 30 \text{ K}$ ) disk component having spectral indexes similar to those in spiral galaxies with nonactive nuclei.
2. A nonthermal nuclear component which extrapolates into the optical and X-rays with an approximate power-law index.
3. A mid-infrared nuclear component which peaks between 20 and  $50 \mu\text{m}$  (see, e.g., Jones *et al.* 1977).

The observations in Figure 1 and Table 1 show that between 60 and  $100 \mu\text{m}$ , Seyfert galaxies have energy distributions which are flatter than those characteristic of nonactive galaxies (e.g., de Jong *et al.* 1984) or infrared selected galaxies (e.g., Soifer *et al.* 1984). For both these latter groups typical spectral indexes are  $\alpha \approx -1.7$ , while more recent samples of infrared selected galaxies have  $\alpha \approx -1.5$ . The flat energy distributions of Seyferts would be a natural consequence of a relatively larger contribution to the infrared emission from the nuclear components of these active galaxies. The observed colors of this optically defined sample are also consistent with recent spectroscopic observations of objects identified with flat-spectrum *IRAS* sources. Using a color selection criterion of  $-1.5 < \alpha(60, 25) < -0.25$ , de Grijp *et al.* (1985) achieved a 70% success rate in detecting hitherto unknown Seyfert galaxies.

The fact that almost all Markarian Seyfert nuclei are located in spiral galaxies might well explain the correlation between luminosity and spectral index in Figure 3. At the larger distances at which the more luminous objects tend to be located, the disk component would be relatively fainter and the composite spectrum would be flatter.

The statistical difference between the spectral indexes in Seyfert 1 and Seyfert 2 galaxies can also be explained by

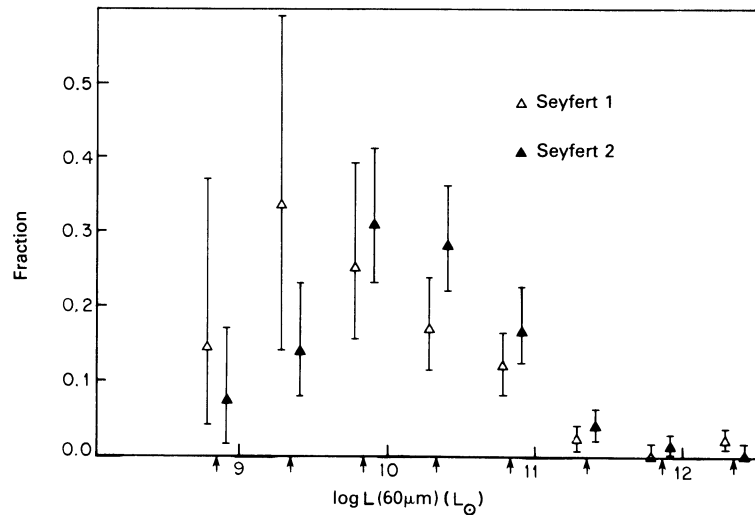


FIG. 2.—The fraction of Seyfert galaxies as a function of their  $60 \mu\text{m}$  luminosity. This was derived by dividing the number of detected galaxies in a given luminosity bin by the number of objects in the sample that could have been detected in that luminosity bin. Although for ease of plotting each pair of points is plotted side by side, the relevant luminosity for both points in the pair is the mean indicated by the arrows.

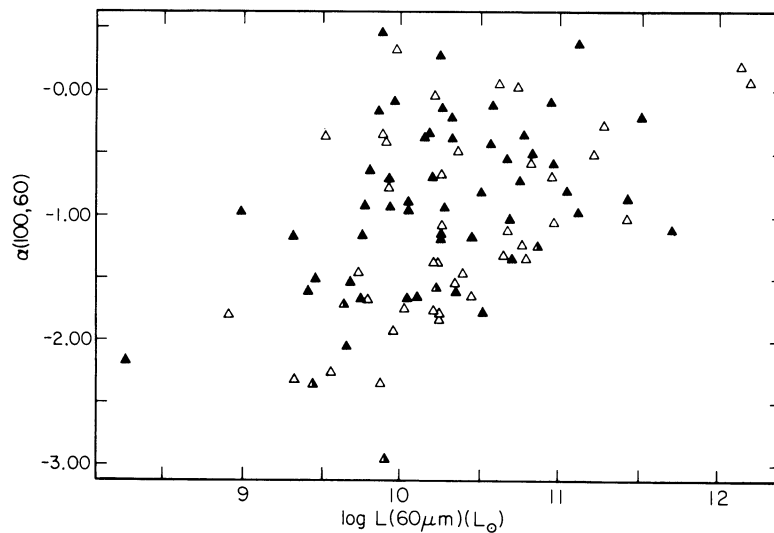


FIG. 3.—A plot of the 100 to  $60 \mu\text{m}$  spectral indices vs. the  $60 \mu\text{m}$  luminosities for Seyfert galaxies

different relative contributions of nonthermal and thermal nuclear components. Malkan (1984) has shown that Seyfert 1 galaxies have a very narrow spread in near-infrared to X-ray luminosity ratios corresponding to a continuum following a power law between  $3.3 \mu\text{m}$  and 2 keV with an index of  $-1.18 \pm 0.07$ . The agreement between this slope and that observed in the mid- and far-infrared can be taken to imply that either the power law extends into the mid- to-infrared or that a cutoff in the presumed nonthermal power law component is balanced by increased emission from other components of infrared emission.

The mean colors of the Seyfert 1 galaxies also agree with those of the handful of objects (not in the above samples) with strong flat-spectrum radio cores and known mid- and far-infrared colors. Examples of such sources are NGC 1275, 3C

120 (*IRAS Point Source Catalog* 1985) and 3C 273, 3C 345, and 0537–441 (Neugebauer *et al.* 1984b).

The separation between the Seyfert 1 and Seyfert 2 galaxies in Figure 1 can be accentuated by displaying the spectral curvature at  $60 \mu\text{m}$  rather than the indexes themselves. In Figure 4 histograms of the curvature, defined as  $\alpha(60, 25) - \alpha(100, 60)$  are shown for the three classes of emission-line galaxies in the samples. It is seen that the Seyfert 2 galaxies show greater curvatures than do Seyfert 1 galaxies, approaching those of the H II galaxies. The curvature is in the sense that there is excess emission at  $60 \mu\text{m}$  relative to a continuum with a fixed power law between 25 and  $100 \mu\text{m}$ .

A clue in understanding the implications of the preferred  $60 \mu\text{m}$  curvature comes from the measurement of the archetypical Seyfert 2 galaxy, NGC 1068. The location of this galaxy in

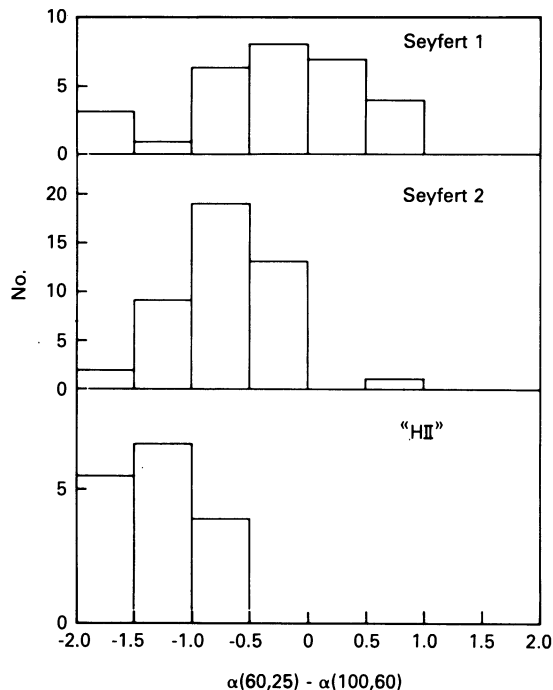


FIG. 4.—Histograms of the 60  $\mu\text{m}$  curvature are shown for the three classes of emission-line galaxies studied.

Figure 1 is given by  $\alpha(100,60) = -0.49$  and  $\alpha(60,25) = -0.87$ , an undistinguished position. For this object, Jones *et al.* (1977) have concluded that the mid- and far-infrared emission is almost certainly thermal in origin. Indeed, for this galaxy much of the far-infrared flux comes from star-forming regions outside the nucleus. Given the quite ordinary location of NGC 1068 in Figure 1, it seems reasonable to postulate the

widespread existence of similar components in many Seyfert 2 galaxies.

It should be noted, however, that if the infrared emission from Seyfert 1 and Seyfert 2 emission do have fundamentally different origins it seems strange that they just happen to produce similar luminosities and spectral distributions in the *IRAS* bands. The relatively flat 60 to 100  $\mu\text{m}$  energy distribution and pronounced 60  $\mu\text{m}$  curvature in the H II galaxies indicate that these starburst galaxies contain thermal components similar to those in the Seyfert 2 galaxies but that the temperature of the dust is slightly lower.

The purpose of this *Letter* has been to summarize the main general characteristics of Seyfert galaxies in the mid- and far-infrared. Although by themselves the *IRAS* observations place no unambiguous constraints on the radiation mechanisms involved, the observations are consistent with current prejudices. A more detailed analysis will consider the overall spectrum of individual galaxies from the radio through the infrared to the optical and X-ray as well as the relationship of the infrared emission to the detailed properties of the nuclear emission lines. Also, analysis of pointed observations made with *IRAS* of several hundred active galaxies with various well-defined types should in the future allow the infrared properties of radio galaxies and quasars to be compared with those of the Seyfert galaxies.

We thank our *IRAS* associates on the science team, on the technical staff, and in project management for their valuable support and assistance. We particularly thank Judy Bennett for her valuable assistance. T. Heckman and H. Marshall made useful comments on an early draft of the manuscript. The work described here was supported in part through the Jet Propulsion Laboratory under contract with NASA.

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