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THE SUBMILLIMETER SPECTRAL BREAK IN SEYFERT GALAXIES

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ABSTRACT

We have observed four Seyfert 1 galaxies at 155 μm and three at 370 μm. Two of the galaxies were detected at 155 μm, but none was detected at 370 μm. The 155 μm data and the strong upper limits at 370 μm show that the infrared continua decrease sharply beyond 100–155 μm. These observations depict a clear spectral difference between radio-loud and radio-quiet active galactic nuclei. The limits on the 100–370 μm spectral slope are consistent either with synchrotron self-absorption of a nonthermal source or with thermal dust emission similar to that arising from the disks of normal galaxies. The 155 μm flux from NGC 4151 is spatially extended through a radius of at least 48″, arguing for substantial dust emission at $\lambda > 80$ μm and an even shorter cutoff wavelength for nonthermal emission from the active nucleus. The spectral breaks implied by our data suggest that the nuclear nonthermal sources must be smaller than ~10 light hours.

Subject headings: galaxies: Seyfert — galaxies: nuclei — galaxies: individual (NGC 4151, NGC 4253) — infrared: sources

I. INTRODUCTION

In spite of the great differences in their radio to optical flux ratio, radio-loud and radio-quiet active galactic nuclei (AGNs) have very similar continua at most other wavelengths (e.g., Elvis 1987; O'Brien, Gondhalekar, and Wilson 1988). In the infrared, from 1–100 μm, no observational distinction between the two types has been found (Neugebauer *et al.* 1987; Ward *et al.* 1987; Carleton *et al.* 1987), yet at 1 mm the difference is apparent (Ennis, Neugebauer, and Werner 1982). These results imply that the radio-quiet AGNs must have a sharp spectral break in the decade between 0.1 and 1 mm with a power-law slope change of at least 1.0.

Although many active galaxies show a decrease in flux density from 25 or 60 μm to 100 μm (Edelson and Malkan 1986; Edelson, Malkan, and Rieke 1987), the physical meaning of these declines has been debated. The presence of a dust emission component would produce a decline in the far-infrared spectrum whenever the temperature distribution of the dust produces more emission at 60 μm than at 100 μm. Carleton *et al.* (1987) concluded that most AGNs contain at least small quantities of dust associated with the emission-line regions. Another source of dust emission may be extranuclear star-forming regions (Ward *et al.* 1987) included in the necessarily large observing beams. In either case, dust warmer than ~40 K (Edelson *et al.* 1987) could contribute to the observed declines, and thus the evidence for a submillimeter break in the nuclear spectra has not been entirely convincing.

Determining the true location of the spectral break is important because it carries information about the emitting region. There are a number of reasons for believing that at least part of the infrared flux is nonthermal and closely linked to the central power source. These reasons include the tight correlation between infrared and X-ray or ultraviolet fluxes (Stein and Weedman 1976; Rieke 1978; Carleton *et al.* 1987), the flat, nearly power-law shape of many AGN continua (e.g., Neugebauer *et al.* 1976; Malkan and Filippenko 1983), the good match to extrapolated X-ray spectra (Elvis *et al.* 1986), variability (e.g., Lebofsky and Rieke 1980; McAlary *et al.* 1983, but see also Edelson and Malkan 1987), and weakness of stellar absorption lines in the near-infrared (Malkan and Filippenko 1983). If it becomes possible to determine the point at which the nonthermal component of the flux steepens, it will help determine the luminosity and nature of the nonthermal component. If one assumes that the turnover is due to self-absorption, one can also estimate the size of the emitting region.

This paper reports a search for the spectral break at wavelengths longer than 100 μm. In order to emphasize the nonthermal component, we have observed mostly objects that have flat or nearly flat infrared energy distributions. However, even in these objects, there is likely to be considerable thermal dust emission, as is common in AGNs (Rieke and Lebofsky 1981; Rieke 1985). In fact, of the objects observed, only NGC 5548, along with the comparison object 3C273, shows a pure power-law spectrum without any distinct infrared bumps indicative of dust emission.

Our criterion for detecting a spectral break is based on the nonthermal "infrared baseline" defined by Carleton *et al.* (1987) as a power law of slope $\alpha = -1$ ($f_\nu \propto \nu^\alpha$) normalized to the lowest measured νf_ν between 1 and 100 μm. They argue that the baseline represents a plausible measure of the nonthermal emission. In the following discussion, we will assume that the infrared baseline, or at least a large fraction of it, is nonthermal and that a decrease in the observed continuum level below the baseline implies a change in the character of the emission from the central source. Of galaxies previously claimed to show turnovers at wavelengths less than 100 μm (Edelson and Malkan 1986; Edelson *et al.* 1987), only Mrk 335 and 841 have fluxes that drop below the baseline established at shorter wavelengths.

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II. OBSERVATIONS

All of the observations were made with the University of Chicago far-infrared and submillimeter cameras (Harper *et al.* 1988). The detectors for these instruments consist of 32 silicon bolometers cooled with ^{3}He and arranged in a 6×6 square array (with the corner pixels missing). Each pixel was round, its diameter projected to 45″ on the sky, and the projected separation between adjacent pixels was 48″. The chopper throw was set to 96″ and aligned along one row of the array. This direction was east-west for the 370 μm observations and was cross-elevation for the 155 μm observations.

The 155 μm measurements were made on the Kuiper Airborne Observatory (KAO) during 1987. We observed NGC 4151, 4253, and 5548 in March and I Zw 1 in September. The bandpass filter had half-power points at 130 and 285 μm. We observed NGC 4151, 4253, and 5548 at 370 μm at the Infrared Telescope Facility (IRTF) in 1987 February. The 305–525 μm bandpass filter included both the 350 and 450 μm atmospheric "windows."

Maps of the galaxies and calibrators were made by observing at the nominal source position and at 4 positions offset 17″ at 45° angles to the array axes. The data on each object consist of six to 10 of these five-point maps. This approach reduces the effect of guiding and pointing errors at the cost of a slight reduction in the effective integration time compared to observations in which the source is kept centered on a single detector. The chopper throw was set to two pixel-spacings, giving simultaneous observations of both "positive" and "negative" beams with the array. This technique increases the effective integration time and reduces the effect of common-mode noise in the detectors. (Highly correlated "sky noise" was particularly prominent during the IRTF measurements.)

The photometric data have been corrected for atmospheric attenuation, which is principally due to water vapor. On the KAO, two water vapor radiometers continually monitor the zenith sky brightness. Although there are uncertainties about the calibration of these instruments during our flights, all of our measurements were conducted at a constant altitude of 41,000 feet, and both the radiometer signals and the far-infrared photometric data gathered indicate that the transmission did not vary significantly during the flights. For the IRTF measurements, we were able to measure the principal calibrator, IRC +10216, at nearly the same time and air mass as the galaxy observations. Comparisons of extinction curves of calibrators with curves derived from an atmospheric model (Traub and Stier 1976) indicate that the amount of precipitable water in the atmosphere during the observations of the AGNs was typically near 1 mm. Differential extinction corrections therefore amounted to less than 15%, and the uncertainties in these corrections are even smaller.

The effective wavelength and corresponding flux density of each measurement may depend on the intrinsic spectrum of the source observed and on the water vapor column density. In practice, the upper limits at 370 μm establish that throughout the observed wavelength ranges, the source spectra are similar enough to those of the calibrators so that the uncertainty in the amount of water vapor and in the source spectra result in less than 10% uncertainty in the flux densities at the quoted wavelengths.

The principal calibrators were M82 at 155 μm and IRC +10216 at 370 μm. For M82, we assumed a flux density at 155 μm of 830 Jy and a spectrum which can be approximated over this wavelength interval by a Planck function with a temperature of 53 K multiplied by an emissivity proportional to λ^{-2} (Telesco and Harper 1980, confirmed by more recent unpublished calibrations of M82 with respect to Mars). For IRC +10216, we assumed a temperature of 550 K, an emissivity of the form $\lambda^{-0.25}$, and a flux density of 32 Jy at 400 μm (Sopka *et al.* 1985). This was checked against measurements of both Mars and OMC-1 taken earlier in the night and confirmed to within 10% (exclusive of uncertainties due to possible changes in amount of water vapor over the longer time baseline).

III. RESULTS

The photometric results are shown in Table 1, where the quoted upper limits are 3 times the rms noise. For NGC 4151, we also detected emission at 155 μm in the two detectors adjacent to the one centered on the galaxy's nucleus. These two beams were oriented along the major axis of the galaxy, separated from the nucleus by 48″, and had a combined flux density of 5.4 ± 1.4 Jy. The other galaxies are more distant than NGC 4151, and a similar spatial extent would not have been detectable. Table 1 also shows flux densities at 60 and 100 μm from the *IRAS* satellite (Edelson *et al.* 1987).

Figure 1 shows the energy distributions of the four galaxies along with 3C 273 for comparison. All three upper limits at 370 μm lie well below power-law extrapolations of the infrared continuum. The limits in νf_ν also fall below the infrared baseline for all three galaxies observed at 370 μm and below the hard X-ray level for the two that have been measured above 2 keV. The 155 μm measurements are intermediate between the 100 μm flux densities and the 370 μm upper limits. In fact, the 155 μm flux densities fall about a factor of 2 below the infrared baseline, directly showing that the submillimeter turnover has begun by 155 μm.

NGC 4151 was the brightest of the galaxies observed and was consequently measured with the greatest precision. For this galaxy, the drop between 155 μm and 370 μm is more than a factor of 7 (in νf_ν), and the slope in f_ν between these two wavelengths is greater than 1.7. If this slope is extrapolated to longer wavelengths and the relatively flat radio spectrum is extrapolated to shorter wavelengths, the two power laws meet at a frequency above 40 GHz ($\lambda < 7.5$ mm).

IV. DISCUSSION

The presence of extended 155 μm emission in NGC 4151 suggests that the turnover of the nonthermal spectrum of the AGN may begin at an even shorter wavelength. The flux in the off-nuclear beams most probably arises from dust which is locally heated by starlight. Indeed, the detected surface brightness is lower than that seen in a sample of "normal" spiral galaxies in the Virgo cluster (Stark *et al.* 1988). For those galaxies, the average 155 μm flux density in a 45″ beam at the

TABLE 1

OBSERVED FLUX DENSITIES

Object	60 μm[a,b]	100 μm[a,b]	155 μm[b]	370 μm[b]
I Zw 1	2.1	2.4	1.9 ± 0.8	...
NGC 4151	6.7	8.6	4.8 ± 0.7	<1.1
NGC 4253 (≡ Mrk 766) ...	4.0	5.1	3.2 ± 0.6	<1.7
NGC 5548	1.11	1.80	<1.9	<0.9

[a] 60 and 100 μm data from Edelson, Malkan, and Rieke 1987.

[b] In janskys.

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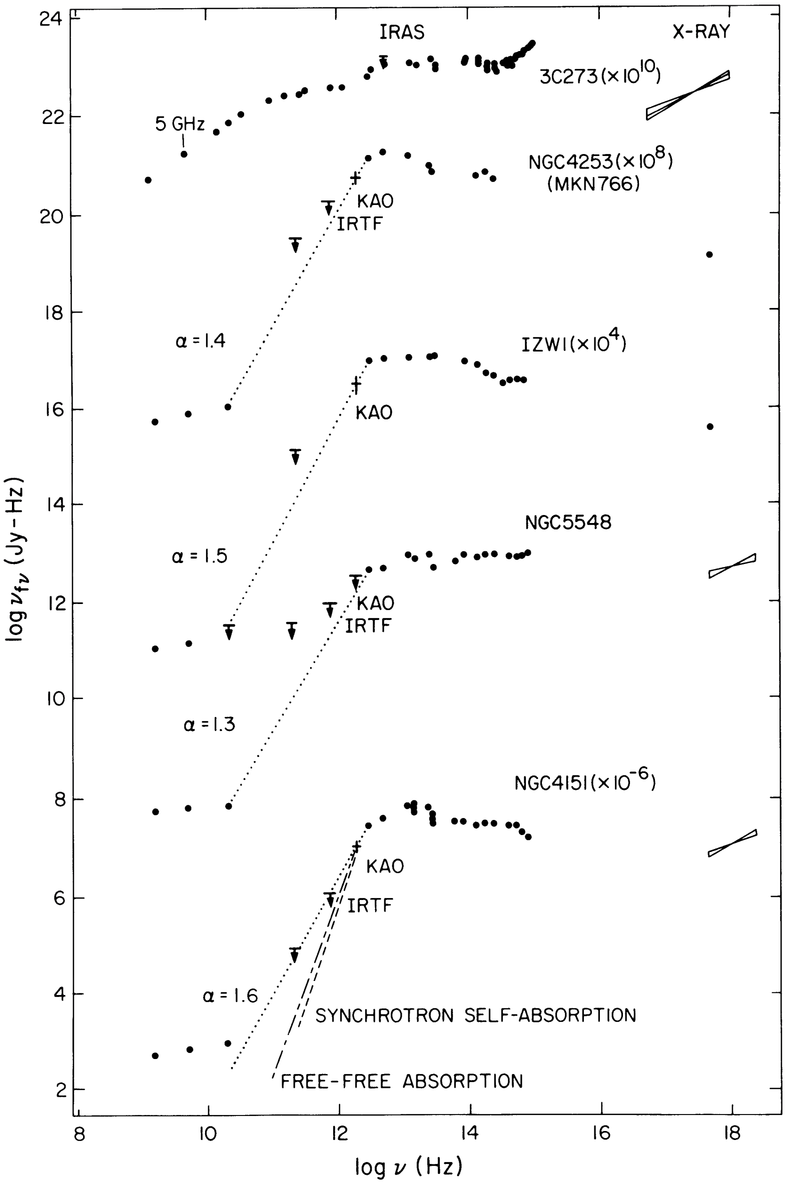

FIG. 1.—Energy distributions for four observed Seyfert galaxies and for the quasar 3C 273. The data have had a starlight contribution subtracted except for 3C 273, where it is negligible, and NGC 4253, where there is an unknown contribution at wavelengths around 1 μm. The dashed line shows a slope of $\alpha = 2.5$ ($f_\nu \propto \nu^\alpha$), representative of synchrotron self-absorption, while the line with alternating dashes shows a slope of 2.0, representative of free-free absorption. Emission by dust hot enough to be in the Rayleigh-Jeans limit would have a slope between 3.0 and 4.0, steeper than the self-absorption slope. Dotted lines show the minimum allowable spectral breaks, i.e., the shallowest power laws through the 100 μm points consistent with the longer wavelength data. *IRAS* data are from Edelson *et al.* (1987) and additional optical and infrared data are from Ward *et al.* (1987) and Edelson and Malkan (1986). The radio and submillimeter data for 3C 273 are from Owen *et al.* (1987) and Clegg *et al.* (1983). For other objects, the radio data are from Edelson (1987), and the 1.3 mm data are from Edelson *et al.* (1987). The X-ray data for NGC 4151 and NGC 5548 show 90% uncertainty ranges on the best fit 2–10 keV power laws (Mushotzky *et al.* 1980). For 3C 273 the X-ray data cover the 0.75–4.5 keV range (Petre *et al.* 1984), and the X-ray points for NGC 4253 and I Zw 1 are at 2 keV (Kriss, Canizares, and Ricker 1980).

nucleus is 16 Jy and at a radius of 48″ (4 kpc) is 9 Jy. The corresponding values for NGC 4151 are just 5 and 3 Jy, respectively. (The distance of NGC 4151 is about the same as that of Virgo.) NGC 4051, a galaxy with a weaker Seyfert nucleus, would show about the same 155 μm flux density as NGC 4151 if it were at the same distance (Smith *et al.* 1983). We might, therefore, suspect that the 155 μm measurement of the center of NGC 4151 includes a significant contribution by starlight-heated dust. On the other hand, the 100 μm flux for NGC 4151 is also smaller than the average of the Virgo galaxies by a factor at least as great. The lower flux from NGC 4151 may indicate that the AGN has removed dust from the central region of the galaxy (e.g., Begelman 1985), and some or all of the observed flux could come from the AGN rather than from dust in the galactic disk. If dust is present in the central beam, even local heating is likely to give a temperature high enough for the dust to emit significantly at 100 μm, and any dust $\lesssim 1$ kpc from the nucleus will be heated even more by the nucleus. If dust does indeed contribute to the 155 μm flux, it thus seems likely that the nonthermal spectrum of the AGN really turns over at 80 μm or less.

While possible dust emission may confuse the situation at shorter wavelengths, the 370 μm flux densities from all of the galaxies observed lie well below the infrared baseline. The nonthermal break must therefore occur at a considerably shorter wavelength, probably less than 100 μm. To clarify the situation further will require far-infrared observations at higher angular resolution or detailed studies of variability at a broad range of wavelengths, or both. Better measurements of luminous sources with extremely flat spectra, like NGC 5548, are especially desirable.

If there is a substantial synchrotron component in the 1–100 μm spectra of these galaxies, the most likely cause of the long-wavelength cutoff is synchrotron self-absorption. (An alternative explanation for a cutoff, free-free absorption, can probably be ruled out. The required emission measure would be of the order of 10^{14} cm^{-6} pc, but this value is far too large to be characteristic of the narrow line region and too small to be attributed to a single broad-line cloud.) Our upper limit on the wavelength of a spectral break then implies an upper limit on the size of the emitting region. If inverse Compton losses limit the source brightness temperature, and the synchrotron electrons are in equipartition with the magnetic field, the maximum brightness temperature will be 10^{12} K (Kellerman and Pauliny-Toth 1969). A cut off wavelength of 155 μm then implies a source size of the order of 10 light hours or $\sim 10^{15}$ cm or 70 M_8 Schwarzschild radii (Edelson and Malkan 1986). This size is similar to that of the inner regions of the hypothesized accretion disks in quasars. The observed radio fluxes from these objects must come from a much larger region.

V. CONCLUSIONS

The observed energy distributions of the nuclei of at least three Seyfert galaxies begin to decrease (in νf_ν) between 100 and 155 μm. These observations, together with those of Mrk 335 and 841 (Edelson and Malkan 1986), are the first to show long-wavelength infrared fluxes dropping below the infrared baseline and thus to show where the spectra of radio-loud and radio quiet-AGNs begin to differ. The nearest galaxy observed, NGC 4151, shows spatially extended emission at 155 μm but with a surface brightness lower than that of luminous "normal" spiral galaxies in the Virgo cluster. If the spatial distribution of the starlight-heated dust in NGC 4151 is like that of the Virgo galaxies, the active nucleus may make only a minor contribution to the far-infrared flux at $\lambda > 80$ μm. If there is a significant synchrotron component at shorter wavelengths, the observed cutoffs imply that the source sizes are comparable to those postulated for the inner regions of accretion disks.

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