EXTENDED 20 MICRON EMISSION FROM THE CENTER OF NGC 1068

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ABSTRACT

We report multiaperture photometry of the Seyfert galaxy NGC 1068 which demonstrates that significant 20 μm emission originates at positions located more than 3″, or 260 pc, from the nucleus. These observations strongly support arguments that most of the infrared flux is thermal emission from dust. It is argued that the dust giving rise to this extended emission cannot be heated solely by a compact nuclear object. We speculate that there is a powerful energy-generation mechanism, possibly an enormous burst of star formation, operating on a scale much larger than that identified with the visible nucleus.

Subject headings: galaxies: nuclei — galaxies: Seyfert — infrared: spectra

I. INTRODUCTION

Extended infrared emission at wavelengths longer than 5 μm has been detected from the central regions of nearly a dozen galaxies (see, e.g., Kleinmann and Low 1970; Rieke 1976; Becklin et al. 1980). The emission from these galaxies originates in regions with scale sizes in the range 100 to more than 1000 pc (Rieke 1976; Telesco 1978). NGC 1068, by far the most luminous of these galaxies, with LIR = 3 X 1011 L⊙ at 18 Mpc (Telesco and Harper 1980; Sandage and Tammann 1975), is unique among this sample in being the only Seyfert galaxy.

The spectrum of NGC 1068 between 5 and 500 μm has been most simply interpreted as a superposition of two thermal spectra originating in different dust components of approximately equal luminosity (Jones et al. 1977; Telesco and Harper 1980). One component is associated with the 1″ diameter 10 μm source (Becklin et al. 1973) located at the nucleus (1″ = 88 pc); it is probable that this source dominates the emission out to approximately 40 μm. Telesco, Harper, and Loewenstein (1976) have shown that the radiation at wavelengths longer than 40 μm should originate in a region much larger than the 1″ nuclear source, based upon a fit of thermal spectra to the longer-wavelength spectrum.

Until recently no observations had been made which bore directly on the existence of infrared emission more extended than the 1″ nuclear source. Such information is needed to test the validity of the assumption that the infrared radiation from NGC 1068 is thermal emission, and it provides a basis for an understanding of the generation of the very large infrared power in the center of this and other galaxies. In this Letter we report multiaperture photometry of NGC 1068 which demonstrates that significant 20 μm emission originates at positions located more than 3″ (260 pc) from the nucleus, and we consider the implications of these observations.

II. OBSERVATIONS

The search for extended emission from the central region of NGC 1068 was made by using the same bolometer detector system at the f/35 foci of three different telescopes on Mauna Kea: the 0.6 and 2.2 m telescopes of the University of Hawaii and the 3 m telescope of the Infrared Telescope Facility. The projected diameters of the fixed 2.5 mm focal plane diaphragm at these telescopes were 25″, 7″, and 5″, respectively. For this technique the ratio of the beam size to the diffraction limit is the same for all three systems, yielding similarly shaped beam profiles. The separation between the signal and reference positions was 10″ for the smaller beams and 25″ for the largest beam, and was in the north-south direction. The width of the filter passband was 10 μm centered at 20 μm.

The observational procedure consisted of alternating measurements of the flux from NGC 1068 with that of the star α Ceti. We chose α Ceti as a comparison because its 20 μm flux density is comparable to that from NGC 1068 and because it is only 6° away from the galaxy. Because of the different shapes of the spectra of the two objects, the finite width of the filter passband, and the presence of many atmospheric water lines in the passband, changes in the ratio of the 20 μm fluxes from α Ceti and NGC 1068 will occur with changing air mass and changes in atmospheric water vapor column density. Calculations using data for the atmosphere above Mauna Kea (Morrison et al. 1973) show the change in the flux ratio to be < 2% for the range of air mass from 1.0 to 2.0. Similarly, a change of < 5% in the ratio occurs when the amount of water vapor increases by a factor of 3; monitoring of the 20 μm signal strengths indicated that the actual changes in the water vapor were much less than threefold. Finally, the 20 μm observations reported here were...
TABLE 1

<table>
<thead>
<tr>
<th>UT Date</th>
<th>Telescope</th>
<th>Beam (2.5 mm)</th>
<th>Nightly Mean</th>
<th>Grand Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 9</td>
<td>IRTF 3 m</td>
<td>5&quot;</td>
<td>0.75 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>Nov 10</td>
<td>IRTF 3 m</td>
<td>5&quot;</td>
<td>0.83 ± 0.03</td>
<td>0.83 ± 0.02</td>
</tr>
<tr>
<td>Dec 12</td>
<td>UH 2.2 m</td>
<td>7&quot;</td>
<td>0.82 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>Mar 15</td>
<td>UH 2.2 m</td>
<td>7&quot;</td>
<td>0.88 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>Jan 26</td>
<td>UH 0.6 m</td>
<td>25&quot;</td>
<td>1.05 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>Oct 26</td>
<td>UH 0.6 m</td>
<td>25&quot;</td>
<td>1.01 ± 0.06</td>
<td>1.07 ± 0.04</td>
</tr>
<tr>
<td>Oct 27</td>
<td>UH 0.6 m</td>
<td>25&quot;</td>
<td>1.08 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>Oct 28</td>
<td>UH 0.6 m</td>
<td>25&quot;</td>
<td>1.16 ± 0.08</td>
<td></td>
</tr>
</tbody>
</table>

* 1978.

made on each telescope on many nights, and the 20 μm signal strengths indicate similar average water vapor conditions at each telescope. Thus we expect no systematic effect in the average flux ratio greater than 2% due to the difference in shape of the two energy distributions.

Data were obtained on eight separate nights. The results of our observations are presented in Table 1 as the ratio of the total flux within the passband for NGC 1068 to that for α Ceti. Since there is not a statistically significant difference between the mean values of this ratio for the two smallest apertures, we have averaged together the corresponding nightly mean values. (For convenience, we refer to this data as being associated with a 6" aperture.) All uncertainties are the statistical standard deviations of the mean (σm), and all mean values have been obtained by weighting individual observations by σm⁻². Comparison of the grand mean values of the ratio demonstrates that (22 ± 5)% of the 20 μm flux observed within the 25" aperture originates in the annulus defined by the 6" and 25" diameter apertures. The emission within the annulus was not mapped in detail. A check was made, however, to see if there was substantial emission from the two 6 cm radio peaks found away from the nucleus by A. S. Wilson (1979, private communication) with the VLA. These peaks are 7.4 north and 7.5 southeast of the nucleus. No 20 μm emission was detected for the points above a 3 σ level of 0.4 Jy in a 5" diaphragm, so it can be concluded that these radio peaks are not specifically associated with the extended 20 μm emission.

The star β Peg was used as the absolute flux standard, assuming [20 μm] = -2.7. The derived values of the 20 μm flux density for NGC 1068 within the 6" aperture and in the 6"–25" annulus are (68 ± 8) Jy and (19 ± 6) Jy, respectively. The uncertainties include those presented in Table 1 as well as uncertainties associated with the use of α Ceti as a local standard based upon the flux from β Peg. These results are plotted in Figure 1 with the infrared spectrum of NGC 1068; the flux within the 6" aperture is plotted as an open circle and that within the annulus as an open square. The value of the flux within the small aperture is in excellent agreement with previous measurements obtained with comparably sized apertures and is almost certainly associated with the 1" diameter component measured by Becklin et al. (1973).

III. DISCUSSION

It has been argued that the infrared emission from NGC 1068 at wavelengths longer than 5 μm is thermal emission from dust grains (Becklin et al. 1973; Hildebrand et al. 1977; Lebofsky, Rieke, and Kemp 1978). Our detection of extended 20 μm emission implies that some of this dust is located at a distance of at least 3", or 260 pc, from the nucleus. This information allows us to examine critically models for NGC 1068 in which the grains at a distance of >260 pc from the nucleus are heated entirely by a centrally located object. The temperature T_d attained by a dust grain located at a distance r = 260 pc from a source of luminosity L_{\text{r}}(≈ 3 \times 10^{11} L_{\odot}) is given approximately by the relation

$$T_d = \left( \frac{L_r}{16\pi r^2 \sigma_{\text{r}}} \frac{Q_d}{Q_e} \right)^{1/4} = 29\left( \frac{Q_d}{Q_e} \right)^{1/4},$$

where Q_d and Q_e are Planck-averaged absorption and emission efficiencies. If the wavelength dependence of the grain emission efficiency is approximated by a power law Q(λ) = λ^−α, then Q_d/Q_e = (T_d/T_e)^α, where T_e is the temperature characterizing the energy distribution of the heating source. The dominant wavelength of the radiation heating the dust is probably ~20 μm, corresponding to the peak emission of the central nucleus of the galaxy as seen from the Earth; the energy distribution of the nuclear source can be approximated by that of a 250 K (= T_e) blackbody. Equation (1) then implies that the grains would attain a temperature T_d = 44 K for an emissivity law with a typical interstellar value of n = 1. This temperature is too low to be reconciled with the lower limit of 73 K for the color temperature as determined by fitting an emissivity-weighted (n = 1) Planck curve to the extended 20 μm flux density and the highest allowable value of the 60 μm flux density.

We note, however, that grains at a distance of 260 pc can attain a temperature consistent with the observed spectrum if the emissivity law varies more steeply than λ^−α. Although such a wavelength dependence cannot be ruled out, it is steeper than observed for Galactic far-infrared sources such as Sgr A (Gatley et al. 1977) or IRC +10216 (Campbell et al. 1976). It would also be possible for grains to be hotter than 44 K if the heating is dominated by radiation of much shorter wavelength.
than 20 \mu m \text{ (corresponding to higher values of } T_\text{e}), \text{ such as ultraviolet power-law or stellar emission seen from the nucleus (see, e.g., Neugebauer et al. 1980). However, since the observed shorter-wavelength flux is much less than that at infrared wavelengths, this assumption requires a very special configuration of obscuring matter around the nucleus; the extinction in the plane of the galactic disk, where much of the dust probably lies, would have to be significantly less than that in a direction out of the disk, toward the Sun.}

We therefore conclude that it is unlikely that the extended emission we see at 20 \mu m is heated solely by a central compact luminous object. Examination of the more sophisticated radiation transfer models by Jones et al. (1977) implies the same conclusion; such models for centrally heated dust clouds to explain the infrared emission from NGC 1068 predict radii of less than 2'' at 30 \mu m. It therefore seems probable that the dust emitting the extended 20 \mu m emission is heated at least partly by a collection of sources which are distributed throughout the emitting region, at r > 260 pc. We note that this analysis and conclusion are similar to those of Telesco (1978) for NGC 5128 (Cen A), an active galaxy exhibiting strong middle- and far-infrared emission extended over several kiloparsecs.

The most luminous sources of 20 \mu m radiation in our Galaxy are H II region/molecular cloud complexes, and it is useful to compare the infrared spectrum of NGC 1068 to the spectra of several of these Galactic sources. In Figure 1 the solid lines represent the energy distributions (Thronson and Harper 1979) of the two complexes DR 21 and W51 IRS-2, their spectra normalized at 20 \mu m to the flux density of the extended component in NGC 1068. It is evident that the relative values of the extended 20 \mu m and longer wavelength flux densities for NGC 1068 are comparable to those observed for the Galactic sources. Thus it is plausible that the 1.5 \times 10^{11} L_\odot emitted at \lambda > 40 \mu m comes from the same region of NGC 1068 that the 20 \mu m emission does, and that all of this power originates in H II region/molecular cloud complexes situated between 260 and 1100 pc from the nucleus. The existence of such complexes in the central regions of NGC 1068 is supported by the detection of strong microwave CO emission (Rickard et al. 1977) and 2.1 \mu m H\alpha emission (Thompson, Lebofsky, and Rieke 1978). Furthermore, NGC 1068 displays an unusually bright and sharply delineated central disk \textasciitilde 25'' in diameter which appears to include the inner spiral arms (see, e.g., Sandage 1961); Keel and Weedman (1978) point out that NGC 1068 has the brightest such disk encountered in their sample of 450 galaxies with bright nuclei.

Walker (1968) has shown that most of the bright emission-line flux from the nucleus of NGC 1068 is confined to a region less than 2'' in radius. In the bright central region of the galaxy, between 2'' and 10'' radius, the emission lines are generally narrower and more like those of H II regions, although some broad-line emission is seen even out to 6'' from the nucleus, particularly in the northeast direction (Balick and Heckman 1979). Because of the large velocities of the broad-line clouds, we consider the possibility
that they generate 20 $\mu$m radiation through shock-induced heating as they impinge on material in the plane of the galaxy. Pelat and Allion (1980) estimate the total kinetic energy in the emitting clouds to be $<10^{46}$ ergs and the velocities to be $<10^7$ km s$^{-1}$. For dynamical scale sizes $>500$ pc, the maximum luminosity that can be generated by this process is then $2 \times 10^4 L_\odot$; even if we allow for large uncertainties in the various parameters, shock-induced production of the extended 20 $\mu$m emission appears to be insignificant.

IV. CONCLUSIONS AND SPECULATIONS

The detection of extended 20 $\mu$m radiation from NGC 1068 strongly supports the arguments (e.g., Lebofsky, Rieke, and Kemp 1978) that most, if not all, of its 10–1000 $\mu$m flux is thermal emission extended on a scale of $>500$ pc. Furthermore, it implies that the dust that gives rise to this emission is heated by a number of local sources of power, rather than by a single compact nuclear source, and that a plausible cause of this heating is enormous bursts of star formation.

The most important implication of this result is that the bright nucleus and strong emission lines that give NGC 1068 its Seyfert character result from a power source that is not identical with the immediate source of power for the extremely strong far-infrared emission that distinguishes NGC 1068 from most other spiral galaxies. Since the infrared luminosity of NGC 1068 is comparable to that of other Seyfert galaxies (Rieke 1978), this result may pertain to the nuclei of other active galaxies as well. If so, it suggests the possibility that the intense nonthermal activity characteristic of the compact nuclei of Seyfert galaxies can induce a process such as star formation over a 500 pc surrounding region, or that the formation of a compact, bright nucleus is a by-product of energetic activity over a much more extended region in the center of the galaxy.

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