THE ASTROPHYSICAL JOURNAL, 280:521–527, 1984 May 15

THE SPATIAL EXTENT OF THE 3.3 MICRON EMISSION FEATURE IN THE SEYFERT GALAXY NGC 7469[1]

ROC M. CUTRI, RICHARD J. RUDY[2], AND G. H. RIEKE
Steward Observatory, University of Arizona

ALAN T. TOKUNAGA
Institute for Astronomy, University of Hawaii

AND

S. P. WILLNER
Harvard-Smithsonian Center for Astrophysics
Received 1983 April 28; accepted 1983 November 23

ABSTRACT

Multiaperture observations of the type 1 Seyfert galaxy NGC 7469 have been made to examine the spatial extent of the source of the 3.3 μm emission feature and the 1–4 μm continuum. The near-infrared continuum is dominated by a source, possibly thermal in origin, less than 2″ (480 pc) in diameter. Nearly 80% of the 4.7×10^7 $L_\odot$ in the 3.3 μm feature, however, is found to arise in a region between 240 and 730 pc from the central source; this implies the presence of dust in this region with a temperature of $\geq$300 K. Neither the distant central continuum source nor the radiation from the broad and narrow emission-line clouds is capable of heating grains with normal emissivities outside the nucleus to such high temperatures. Dust heating must therefore occur in situ and is most likely due to radiation from young, hot stars in circumnuclear H II regions. Similarities between the strengths of the unidentified infrared emission features and the shapes of the nonstellar infrared continua in NGC 7469 and M82 suggest that the regions around the nucleus of NGC 7469 may support star formation complexes as large as those in M82. We propose several observations, including 10 μm multiaperture measurements, far-infrared observations, and off-nucleus optical spectroscopy, to test this hypothesis.

Subject headings: galaxies: individual — galaxies: Seyfert — infrared: sources — interstellar: matter

I. INTRODUCTION

The unidentified emission feature at 3.3 μm has now been found in five active extragalactic sources: NGC 4151 (Cutri and Rudy 1980), NGC 5506 and IC 4329A (Moorwood and Salinari 1981), NGC 7469 (Rudy *et al.* 1982), and NGC 3227 (Cutri, Rieke, and Lebofsky 1983); its detection in these galaxies provides direct evidence for the presence of dust. These observations are significant because thermal emission from dust grains is an attractive explanation for the infrared excesses which are nearly a universal characteristic of Seyfert galaxies (Rieke 1978). In addition, dust can strongly affect the observed optical and ultraviolet emission-line strengths and profiles (see, e.g., Netzer and Davidson 1978). If the 3.3 μm feature is to be utilized as an indicator of dust in the emission-line forming regions of these galaxies, and if we are to understand better how dust affects the spectra from these regions, we must have some knowledge of the actual location and distribution of the dust relative to the central engine. To this end, we have investigated the spatial extent of the 3.3 μm emission in the Seyfert 1 galaxy NGC 7469.

The identification of the 3.3 μm feature in NGC 7469 (Rudy *et al.* 1982) has been confirmed by the detection of the 11.3 μm emission feature, which is seen in nearly all galactic sources which display 3.3 μm emission, by Aitken, Roche, and Phillips (1981). Rudy *et al.* reported that preliminary mapping attempts suggested that the nonstellar 3.4 μm continuum flux was extended. Their measurements of the 3 μm spectrum with a 6″ aperture, however, provided no specific information on the true extent of the dust.

In this work, we report additional observations of the 3.3 μm feature and the infrared continuum in NGC 7469 using multiaperture techniques. While as much as 10^7 $L_\odot$ in 3.3 μm line emission may arise from within the nucleus, the data indicate that the 3.3 μm emission-line region is extended, with a significant fraction of the luminosity of the line originating at distances greater than 240 pc from the nucleus. Possible mechanisms for heating the dust associated with the extended emission are discussed together with observational tests which can be used to verify the more promising of these mechanisms.

II. OBSERVATIONS

Two multiaperture techniques were employed to investigate the nature of the 3.3 μm emission in NGC 7469. First, multiaperture photometry was performed with the 3 m NASA Infrared Telescope Facility on the nights of 1981 September 13 and 14 and 1982 September 10 (UT). The detector was an InSb photodiode cooled to solid nitrogen temperature used in conjunction with the IRTF circular variable filter-wheel (CVF), which has a spectral resolution of 2%. A 50″ chopper spacing was used for these measurements. At the IRTF in 1981, observations were made through apertures ranging from 1″.95 to 9″.8. At each aperture setting, continuum measurements were taken with broad-band filters centered at 1.25, 1.65, 2.2 and 3.45 μm. The flux density in the 3.3 μm feature was sampled with one of two narrow filters. On 1981 September 3

[1] Part of this work used the Multiple Mirror Telescope Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

[2] Visiting Astronomer at the Infrared Telescope Facility which is operated by the University of Hawaii under contract from the National Aeronautics and Space Administration.

we used the CVF set at 3.32 μm, while a broader (5%) discrete narrow-band filter centered at 3.29 μm was used on the following night. In 1982 September, a complete CVF scan was made through the feature using only the 5″85 aperture.

Secondly, multiaperture spectrophotometry was done with the Multiple Mirror Telescope. The spectrophotometric measurements were made on 1982 October 3, 4, and 5 (UT) using the MMT infrared spectrophotometer which employs a liquid helium cooled InSb photodiode and a 1% resolution CVF. These measurements were taken using a 17″ chopper spacing. Complete scans through the feature were performed with the MMT CVF, using apertures of 5″2 and 8″7 in diameter. The absolute levels of the MMT scans were independently verified with 3.25 and 3.5 μm flux densities measured at the University of Arizona 1.55 m telescope. Broad-band magnitudes measured with the 1.55 m telescope on 1980 October 4, 7, and 12 and 1980 December 3 are also included in this work.

Each of the IRTF and MMT measurements was reduced against observations of the standard star ρ Peg made using identical aperture and filter settings. This technique automatically corrects for scattered light intrinsic to the telescopes and detector systems. In Table 1A are listed the ratios of the flux densities at the center of the 3.3 μm feature to those at 3.45 μm. Because the 3 μm continuum of NGC 7469 is relatively flat in F_λ, the 3.45 μm flux is a reasonable measure of the continuum level for the feature. For comparison, the ratio of the 3.32 μm and 3.45 μm flux densities for I Zw 1, which has a flat 3 μm spectrum much like NGC 7469 but with no 3.3 μm feature, is 1.01 ± 0.03 (R. Rudy and A. Tokunaga, unpublished data). The ratio of

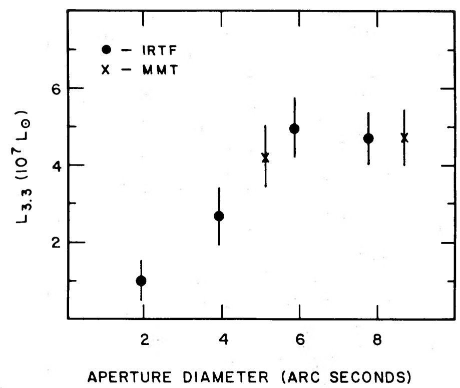

FIG. 1.—The 3.3 μm emission feature luminosities in NGC 7469 as a function of aperture diameter. The 3″9 and 5″85 data represent averages of several measurements, as listed in Table 1.

the CVF to the broad band flux density is, therefore, an efficient way to sample the feature.

In order to discuss the energy balance in the 3.3 μm feature, the luminosity in the feature has been estimated by taking the difference between the 3.32 μm and 3.45 μm flux densities. Luminosities were calculated by assuming the FWZI of the feature is 0.1 μm and constant, and the Hubble constant is 100 km s^{-1} Mpc^{-1} giving a distance of 50.2 Mpc to the galaxy. These luminosities are listed in Table 1B and are plotted in Figure 1 as a function of aperture diameter. When compared with the feature luminosities determined from spectrophotometric scans, the luminosities calculated using the above method underestimate the true luminosities by

TABLE 1

FLUX RATIOS AND LUMINOSITIES

A. $F_{3.32}/F_{3.45}$

Aperture (arc sec)	Date: 1980 Oct[a]	1981 Sep 13[a]	1981 Sep 14[a]	1981 Sep 14[b]	1982 Sep[a]	1982 Oct[a]
1.95.........	...	1.102 ± 0.053	...	...	...	...
3.90.........	...	1.178 ± 0.060	1.063 ± 0.026	1.277 ± 0.113	...	...
5.20.........	...	...	...	...	...	1.319 ± 0.058
5.85.........	1.293 ± 0.050	1.198 ± 0.098	1.182 ± 0.056	1.420 ± 0.134	1.377 ± 0.120	...
7.80.........	...	1.361 ± 0.067	1.141 ± 0.028	1.371 ± 0.073	...	...
8.70.........	...	...	...	...	...	1.327 ± 0.051
9.75.........	...	...	≤ 1.141	≤ 1.371	...	...

B. LINE LUMINOSITIES (10^7 $L_\odot$)

Aperture (arc sec)	Date: 1980 Oct	1981 Sep 13	1981 Sep 14	1981 Sep 14[b]	1982 Sep	1982 Oct
1.95.........	...	1.01 ± 0.52	...	...	...	...
3.90.........	...	2.09 ± 0.70	...	3.25 ± 1.36	...	...
5.20.........	...	...	...	...	...	4.24 ± 0.77
5.85.........	4.36 ± 0.74	2.43 ± 1.20[c]	...	5.16 ± 1.68	5.42 ± 1.73	...
7.80.........	...	4.56 ± 0.85	...	4.69 ± 0.92	...	...
8.70.........	...	...	...	...	...	4.71 ± 0.74
9.75.........	...	...	...	≤ 4.69	...	...

[a] Values of $\Delta\lambda/\lambda$ (3.32 μm): for 1980 Oct, 0.07; for 1981 Sep 13, 0.07; for 1981 Sep 14, 0.17; for 1982 Sep, 0.07; for 1982 Oct, 0.03.

[b] These data represent the measurements of 1981 Sep 14 which have been corrected for effective wavelength and bandpass differences.

[c] Line and continuum flux densities low, possibly due to guiding error.

about 5%. In Table 2 the broad-band magnitudes obtained in the course of this work and from Rudy *et al.* (1982) are summarized.

A comparison between the two data sets from 1981 listed in Table 1 shows a slight discrepancy in the flux density ratios. The variance in the sets of narrow-band fluxes results from the different central wavelengths and widths of the filters used on the two nights. The 3.32 μm CVF more closely matches line center in the observer's frame and consequently samples the peak line flux density more accurately than the 3.29 μm narrow band filter. Because the 3.32 μm CVF is also narrower than the 3.29 μm filter, the flux densities measured with the CVF detect the feature at higher contrast to the continuum level. Though the line luminosities derived for the September 14 data are too low, the relative levels in the respective apertures should be accurate. In order to correct the 3.29 μm line-to-continuum ratios to the effective wavelength and bandpass of the CVF data, the convolution of the transmission profiles of the two filters, which were taken to be approximately triangular, with the observed 3.3 μm feature profile (Rudy *et al.* 1982) was performed. This procedure yields a correction factor of 1.20 for the narrow-band data relative to the CVF data. Because the convolution was performed with data taken with a 5″85 aperture, the correction factor is only approximate for the narrow-band measurements made with other apertures. A column listing the corrected narrow-band ratios is included in the first part of Table 1, and these corrected ratios have been used to calculate the line luminosities listed in the second part.

Both of the individual flux densities measured in the 3.32 μm CVF and the 3.45 μm broad-band in 5″85 aperture from the night of 1981 September 13 are low in comparison with the observations in other apertures and at different epochs. As the observing conditions were photometric, we suspect that the nucleus of the galaxy may not have been accurately centered since those two measurements were taken sequentially, just before returning to the standard star. Therefore, because of the anamolously low levels of the individual measurements, we have discounted the 5″85 measurements of 1981 September 13 in the analysis that follows.

TABLE 2

BROAD-BAND MAGNITUDES OF NGC 7469

A. IRTF

Aperture (arc sec)	Filter	Date: 1980 Oct	1981 Sep	1982 Sep
1.95	*J*	...	12.19	...
	H	...	11.16	...
	K	...	10.23	...
	3.45	...	8.74	...
3.90	*J*	...	11.64	...
	H	...	10.66	...
	K	...	9.92	...
	3.45	...	8.55	...
5.85	*J*	11.30	11.33	11.29
	H	10.35	10.36	10.28
	K	9.66	9.70	9.57
	3.45	8.28	8.50 ± 0.05	8.32
7.80	*J*	...	11.19	...
	H	...	10.20	...
	K	...	9.57	...
	3.45	...	8.47	...
9.75	*J*	...	11.11	...
	H	...	10.12	...
	K	...	9.50	...
	3.45	...	...	...

B. MMT

Aperture (arc sec)	Filter	Date: 1980 Oct	1980 Dec	1982 Oct
5.20	*J*	...	...	11.32
	H	...	...	10.33 ± 0.06
	K	...	...	9.65 ± 0.05
	3.50	...	...	8.33

C. 1.55 METER

Aperture (arc sec)	Filter	Date: 1980 Oct	1980 Dec	1982 Oct
8.70	*J*	11.28	11.36	...
	H	10.38	10.35	...
	K	9.60	9.64	...
	3.50	8.27	8.35	...

NOTE.—All uncertainties are ≤0.04 mag unless otherwise listed.

III. DISCUSSION

It is clear from the entries in Tables 1 and 2 and from Figure 1 that a significant amount of both the continuum and the 3.3 μm line emission in NGC 7469 arises from extended regions. A point source should have exhibited nearly the same flux in all apertures since the data have been corrected for scattered light. Some fraction of the extended emission is, of course, due to the galactic stellar component.

The colors of the extended continuum emission, that is, the light from an angular region between 4″ and 10″ in diameter, are $J-H = 1.00 \pm 0.16$ and $H-K = 0.41 \pm 0.21$; these colors are marginally redder than the colors of the stellar population in a standard eiliptical galaxy, K-corrected for the small redshift of NGC 7469 ($z = 0.0167$) which are: $J-H = 0.74$, $H-K = 0.28$, and $K-L = 0.20$ (M. Lebofsky 1983, private communication). In smaller annuli, the $K-L$ colors are consistent with these normal stellar colors, within the measurement uncertainties. The spectral energy distribution of the annular region can most easily be attributed to a small amount of reddening acting on normal stellar emission. A minimum of 0.3 mag of reddening in $E(B-V)$ in the stellar light will produce the observed annular colors, using the interstellar extinction curve given by Rieke and Lebofsky (1983). Such a value is consistent with the amounts of reddening found in the nucleus of NGC 7469 by Lacy *et al.* (1982) and Malkan (1983), deduced from both the hydrogen and forbidden emission-line strengths.

An upper limit to the level of the reddened starlight can be found by assuming that all of the extended emission at 1.25 μm is from the galaxy. The 1.25 μm *annular* flux increases roughly as the first power of the aperture diameter. Extrapolating this trend back to 1″95 indicates that 35% of the total J flux in the 1″95 aperture is stellar. Using the 1″95 stellar flux as a reference point, and applying the apparent power-law dependence upon aperture, the stellar light in the 3″9, 5″85, 7″8, and 9″75 beams is then found to make up at most 61%, 70%, 74%, and 76% of the total light at 1.25 μm, respectively. The colors of the infrared galactic emission were reddened according to the extinction curve of Rieke and Lebofsky (1983) as follows:

$$J-H = (J-H)_0 + 0.107A_v ,$$
$$H-K = (H-K)_0 + 0.063A_v ,$$
$$K-L = (K-L)_0 + 0.054A_v ,$$

where the subscripted colors refer to the standard elliptical galaxy quoted above. Our lower limit to the reddening in the annular regions implies 0.93 mag of visual extinction. Normalizing the reddened stellar continua as described above, and subtracting them from the multiaperture observations of 1981 September gives the nonstellar flux in each subsequent aperture, shown in Figure 2.

Within the observational errors, there is no significant extended nonstellar continuum emission. Increasing the reddening to $E(B-V) = 0.4$–0.5 mag completely eliminates the suggestion of increasing flux with aperture in the H and K filter. Most importantly, the 3.45 μm emission is consistent with that from a point source, implying that the level of the 3.45 μm extended continuum emission is less than $\sim 8\%$ of the total light in the 7″8 aperture.

Because the aperture data provide evidence for a 3 μm point source, and since $\sim 10^7$ $L_\odot$ of 3.3 μm feature emission may arise within a 1″95 aperture, it is likely that there is thermal emission in NGC 7469 which is associated with the nucleus itself. The spatial extent of the 3.3 μm emission, however, implies that there is hot dust at a distance of at least 730 pc from the nucleus. In galactic sources that emit the 3.3 μm feature, the equilibrium grain temperatures are about 300 K or hotter (e.g., Sellgren 1981). It is difficult to see how the grains in NGC 7469 that are far from the nucleus could be heated to such high temperatures.

If the dust grains in NGC 7469 have a reasonably normal emissivity law, those far from the nucleus cannot be heated by radiation from the central source. The equilibrium temperature for grains 730 pc from a central heating source with a $F_\nu \propto \nu^{-1.2}$ spectrum and a luminosity of $\sim 7 \times 10$ $L_\odot$, such as that in NGC 7469 (Elvius, Lind, and Lindgren 1979), can be found by equating the radiative heating and cooling rates of the grains. The energy balance equation for a single grain is written as follows:

$$\pi a^2 \int_0^\infty F_\nu{}^h Q_\nu{}^{\rm abs} d\nu = 4\pi a^2 \int_0^\infty B_\nu(T_{\rm eq}) Q_\nu{}^{\rm em} d\nu ,$$

where a is the grain radius, $F_\nu{}^h$ is the heating flux incident upon the grain, $B_\nu(T_{\rm eq})$ is the Planck function for the equilibrium temperature of the grain, and $Q_\nu{}^{\rm abs}$ and $Q_\nu{}^{\rm em}$ are the absorption and emission cross sections of the grain relative to the geometrical cross section, respectively. We have adopted the Q-values of Rudy and Puetter (1982), which decline as λ^{-1} for silicates and λ^{-2} for graphite at $\lambda > a$, and which are both equal to unity for $\lambda < a$. The absorption efficiencies of both silicate and graphite grains may decline below ~ 100 Å, making heating less effective, but this spectral region contributes little to the total energy balance. Dwek *et al.* (1980) have performed a similar calculation for grains around hot stars. Their treatment produces somewhat different results than ours because of the different heating continua considered; the power-law source in NGC 7469 provides heating over a much larger spectral range than the blackbody emission from hot stars.

Silicate dust particles 0.1 μm in radius would have an equilibrium temperature of about 65 K 730 pc from the nuclear heating source in NGC 7469, in contrast with the ≥ 300 K temperatures typically found for the dust associated with the 3.3 μm feature in galactic sources. Silicate grains at a temperature of 300 K would have to be within ~ 16 pc of the nucleus, and graphite grains might attain 300 K temperatures out to ~ 120 pc since they cool much less efficiently. In either case, though, the nuclear continuum cannot directly heat the grains in the region of the extended 3.3 μm emission.

If the grains which emit at 3.3 μm have an extreme emissivity law, heating by the central source may be possible. A grain that emitted only at 3.3 μm, for example, would reach whatever equilibrium temperature is necessary to emit at that wavelength all of the energy its absorbs. Such a hypothesis requires that the grains which emit the 3.3, 7.7, 8.6, and 11.3 μm features be physically distinct, because otherwise only the longest wavelength feature would be seen. These features are always observed together, except in the single case of IC 418 (Aitken 1981). Such an extreme emissivity law, therefore, with continuum emissivity much less than one-twentieth of the peak value in the feature, seems unlikely. Sellgren, Werner, and Dinerstein (1983) have proposed that the grains which produce the 3.3 μm feature observed in three reflection nebulae have quite abnormal emissivities. The grains in these nebulae apparently have temperatures much higher than can be attained through equilibrium with the stellar radiation field. These authors suggest that either grains with extremely low ratios of infrared to ultraviolet emissivity or quite small thermally fluctuating grains may account for the inordinately high temperatures. If similar materials responsible for the emission from the reflection nebulae are sufficiently abundant and widely distributed around the nucleus of NGC 7469, they may aid in explaining the inordinately high dust temperatures. In a total volume of some 10^8 pc^3, however, relatively normal grain emissivities would be expected to dominate. In this case, the central source alone is incapable of directly heating the dust from which the extended 3.3 μm emission arises. Consequently, we consider possibilities for in situ heating of the dust in a

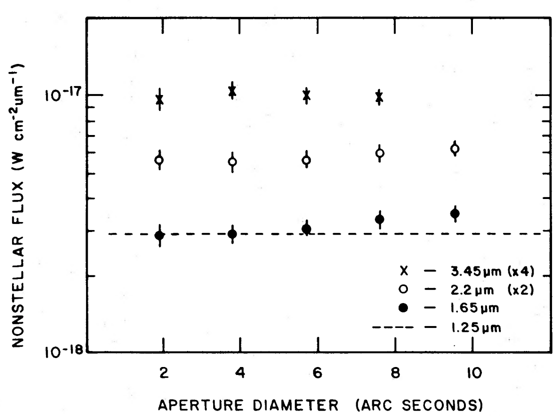

FIG. 2.—The nonstellar flux density in NGC 7469 plotted vs. aperture diameter. These data were derived from the observations of 1981 September 13 and 14 (UT) by subtracting an appropriately normalized stellar continuum, reddened by 0.3 mag in $E(B-V)$ (see text). The dashed line represents the level of the 1.25 μm emission which was assumed to arise from a point source.

region around the nucleus corresponding to the extent of the narrow emission-line forming clouds. The extent of this region, interestingly, is similar to the extent of the extended six centimeter radiation (Ulvestad, Wilson, and Sramek 1981).

An alternate source of energy which will contribute to dust heating is the line radiation from the broad and narrow emission-line clouds. Adding the total intensity of the major emission lines (Lacy *et al.* 1982) to the ultraviolet-optical continuum raises the heating flux by only $\sim 4\%$. This does not significantly alter the equilibrium temperatures attained by grains at large distances from the nucleus and the broad-line clouds. If the grains are mixed in with the emitting gas in the narrow-line region, however, the line radiation may provide additional heating. Krishna Swamy and O'Dell (1967) examined the heating of dust in H II regions by trapped Lyman-alpha photons, and Rudy and Puetter (1982) considered heating of dust in the broad-line regions of active galactic nuclei by Lyman-alpha and the Balmer lines; these authors concluded that this mechanism could be important. Two conditions must be met to heat grains successfully in this way. First, large optical depths in Lyman-alpha are necessary to trap photons and raise the energy density within the nebula, thus amplifying the available heating flux. Second, a sufficient number of ionizing photons must still reach the cloud face from the nucleus in order to produce enough heating within the cloud.

With densities on the order of $N_e = 5 \times 10^3$ cm^{-3} for the narrow-line region of NGC 7469 (Ulrich 1972), even clouds with diameters of a small fraction of a parsec will be optically thick to Lyman-alpha. The solid angle subtended by a cloud as seen from the central source will dictate whether or not enough ionizing photons can be intercepted. Since the distance separating the clouds and the central source is specified by our observations, the cloud size is the critical factor. Simple Strömgren depth calculations for a cloud of hydrogen with a density of 5×10^3 cm^{-3} 730 pc from the ultraviolet continuum source in NGC 7469 show that the depth of the fully ionized region is less than 10^{-3} pc. The Lyman-alpha heating flux within a spherical cloud of this size can be estimated by considering the equilibrium condition that the flux of Lyman-alpha photons leaving the surface of the cloud is equal to the number of recombinations occurring within the volume of the cloud. At the center, the flux of Lyman-alpha photons through a given area is the same as that through the same area on the surface of the cloud. The heating rate per unit surface area for a grain at the center of such a cloud is given by

$$\Gamma_h \approx \frac{N_e^2 \alpha_B h\nu_{\mathrm{Ly}\alpha}(4/3)\pi R^3 Q_\nu^{\mathrm{abs}}}{4\pi R^2}\,,$$
$$= 76.5 R(\mathrm{pc})\ \mathrm{ergs\ cm^{-2}\ s^{-1}}\,,$$

where N_e is the electron density, α_B is the recombination coefficient for $T_e = 10^4$ K, Q_ν^{abs} is the grain absorption cross section relative to the geometrical cross section (~ 0.7 at 1216 Å), and R is the radius of the cloud. Balancing the heating rate to the cooling rate for thermal radiation for a silicate grain gives an equilibrium temperature of

$$T_{\mathrm{eq}} = 132[R(\mathrm{pc})]^{1/5}\ \mathrm{K}$$

and

$$T_{\mathrm{eq}} = 325[R(\mathrm{pc})]^{1/6}\ \mathrm{K}$$

for a graphite grain. Thus, for the small sizes derived from the Strömgren depth calculations, dust could be heated to at most ~ 30 K or ~ 100 K within such clouds, for silicate and graphite grains, respectively. Due to the large distances we observe which separate the central source and the limits of the extended 3.3 μm emission, any narrow-line cloud would necessarily be too small to sustain an energy density of Lyman-alpha photons large enough to heat grains to the high temperatures associated with the 3.3 μm emission. Consequently, it is unlikely that the heating of dust by line radiation plays a significant role in the extended regions of the nucleus of NGC 7469.

Perhaps the most simple explanation for the extended 3.3 μm emission is that it arises from hot dust in circumnuclear H II regions. H II regions in our Galaxy are frequently the source of 3.3 μm emission (see, e.g., Soifer, Russell, and Merrill 1976) and such emission in other galaxies is well established. Both NGC 253 (Wynn-Williams *et al.* 1979, and references therein) and M82 (Gillett *et al.* 1975; Willner *et al.* 1977) show extensive complexes of H II regions and large ($3 \times 10^{10}\ L_\odot$) infrared luminosities (Telesco and Harper 1980). NGC 7469 could support similar regions with the remaining emission originating in the nucleus. Additional evidence for such a model comes from T. Heckman and B. Balick (1982, private communication) who have observed discrete condensations approximately 5″–12″ from the nucleus in their Hα photography of NGC 7469. No detail can be discerned within $\sim 4''$ of the nucleus due to the brightness of the narrow emission-line region. The distribution of the condensations, however, suggests that they probably extend farther down into that region.

The annular regions around the nucleus of NGC 7469 can be compared with the large H II complexes in the nuclei of galaxies such as M82 and NGC 253. The 3–10 μm spectrum of M82 (Willner *et al.* 1977) is like that of NGC 7469 (Rudy *et al.* 1982; Aitken Roche, and Phillips 1981) in that the continuum level is roughly constant in F_λ; both galaxies show the 3.3, 7.7, and 11.3 μm emission features as well as [Ne II] emission; and the 3.3 μm features have similar strengths relative to the near-infrared luminosities (M82: $L_{3.3}/L_{\mathrm{IR}} = 1.5 \times 10^{-3}$; NGC 7469: $L_{3.3}/L_{\mathrm{IR}} = 1 \times 10^{-3}$). The ratio of the flux in the 3.3 μm feature to the continuum flux in the annular region of NGC 7469 is ~ 3.8. In M82 the ratio is ~ 3.5 for the nonstellar emission within 15″ of the nucleus (Willner *et al.* 1977). If the H II region model is correct, then the similarities between the 3.3 μm features in the two galaxies imply that star formation must be occurring around the nucleus of this Seyfert galaxy on a scale as prolific as in M82.

One difference between the spectra of the two galaxies is that M82 displays a deep 9.7 μm silicate absorption feature, while little if any absorption is present in NGC 7469. The limits set for silicate optical depth in NGC 7469 by Rieke and Lebofsky (1979) and confirmed by Aitken, Roche, and Phillips (1981) are consistent with $0.1 < \tau_{\mathrm{si}} < 0.3$ derived from our estimates of the extinction in the extended regions. The apparent absence of any absorption simply implies that there is little absorbing material along our line of sight. Continuum emission at 10 μm from the inner nucleus may dilute a silicate feature produced by dust in the extended regions, if the cold silicates do not also obscure the nucleus. If we assume that the intrinsic 11.25 μm line to continuum flux ratios are comparable in M82 and the extranuclear regions of NGC 7469, as seems to be the case for the 3.3 μm feature, then the similarity of their strengths in the spectra of both galaxies further suggests that there is little dilution from the nucleus to the 10 μm emission in NGC 7469. This indicates that at longer wavelengths the continuum emission of the extranuclear dust may begin to dominate the spectrum, which is what would be expected from the rising infrared spectral distribution of an H II region (Thronson and Harper 1979).

Several tests can be proposed to verify the H II region model. As suggested above, the bulk of the 10 μm emission in NGC 7469 may be extranuclear, while less than 10% of the 2–3 μm continuum is from nonstellar emission in the extended regions. Multiaperture photometry, as we have done, or actual mapping of the nuclear regions should indicate whether the 10 μm emission is extended. Cool dust associated with the extranuclear H II regions should provide considerable emission at far infrared wavelengths. Scaling the limits for the 3 μm nonstellar flux for NGC 7469 with the ratios of the 40–100 μm fluxes to the 3 μm nonstellar flux in M82 (Telesco and Harper 1980; Willner *et al.* 1977) gives estimates of the far-infrared flux densities of 1.5×10^{-18}, 1.2×10^{-18}, 8.1×10^{-19}, and 1.2×10^{-19} W cm^{-2} μm^{-1} at 41, 58, 78, and 141 μm, respectively. Detection of such flux densities, though not conclusive evidence for the presence of large H II complexes, would support this hypothesis, and should easily be within the range of detectors on *IRAS*. This test should be accomplished as soon as the *IRAS* data are released. Molecular cloud material in the circumnuclear regions might also be expected to display CO emission. As discussed by Rudy *et al.* (1982), however, current upper limits to the CO flux from NGC 7469 are not adequate to detect the flux levels expected based upon the scaled M82 flux levels.

Finally, if the extended 3.3 μm feature emission arises within an H II region–like environment, the accompanying optical emission-line spectrum from these regions should have characteristics which distinguish it from the spectrum of a power-law ionized medium. Obviously, line width is a distinguishing factor, but the nuclear emission lines in NGC 7469 have both broad and narrow components, the narrow components presumably arising from the classical Seyfert narrow line region. In fact, Whittle (1982) has found the ratio of the strengths of [O III] $\lambda\lambda$5007, 4959 to the narrow component of Hβ to be $\sim$6, which is quite low for Seyfert 1 galaxies in general. This would imply some corruption of the narrow emission-line radiation by H II regions in which the ratio is at most $\sim$8 (Baldwin, Phillips, and Terlevich 1981). To investigate further the nature of the narrow emission lines, a program to perform high signal-to-noise ratio multiaperture spectroscopy of the galaxy is underway. By subtracting out the contribution of the inner nucleus, the remaining emission should display an ionization state characteristic of H II regions.

IV. CONCLUSIONS

Our observations of the near-infrared continuum and the 3.3 μm feature in NGC 7469 show that the continuum is dominated by the emission from an unresolved source no larger than 2″ (= 480 pc) in diameter, centered on the nucleus, and extended stellar radiation reddened by 0.3 mag in $E(B-V)$. However, of the total luminosity of 4.7×10^7 $L_\odot$ in the 3.3 μm feature, 3.7×10^7 $L_\odot$ arises from an annular region between 2″ and 8″ in diameter around the nucleus. This implies the presence of 300 K dust out to nearly 1 kpc, a region coincident with the narrow emission-line region of the Seyfert nucleus.

The central source in NGC 7469 is incapable of heating dust to the necessary high temperatures at those large distances. Consequently, there is likely to be some mechanism for heating the grains in situ. Line radiation from the broad-line emitting clouds is insignificant, and the narrow-line emitting clouds cannot intercept enough ionizing radiation from the central source to heat the dust via trapped Lyman-alpha photons.

The most plausible means of providing heating in the outer reaches of the nucleus is to have the dust associated with circumnuclear H II regions. This notion is supported by the similarities in the near-infrared spectra of NGC 7469 and M82, a galaxy which has large star formation complexes, and by Hα photographs of condensations within the central 12″ of NGC 7469. If H II regions are present, much of the 10 μm continuum flux may also arise from the same extended region that produces the 3.3 μm emission, the result of the rising spectrum of the H II complexes.

We propose several tests to verify the nature of the extended emission in NGC 7469. These include: 10 μm multiaperture measurements, far-infrared observations, and off-nucleus optical spectroscopy. We hope that such measurements, and work such as this paper presents, will become available for other active galaxies. Such data can begin to reveal whether the phenomenon of large-scale star formation in active galactic nuclei is a rare or common occurrence.

The authors would like to express their sincere gratitude to Drs. T. Heckman, and B. Balick, for making their data available to us before publication, and to Drs. M. Rieke, R. Puetter, K. M. Merrill, R. Williams, and K. Sellgren for their invaluable discussion and suggestions along the course of this work. We would also like to thank Ms. E. V. Cutri for her generous help in preparing the figures for this work. A. T. T. wishes to acknowledge the support of NASA contract NASW-3159.

REFERENCES

Aitken, D. 1981, in *IAU Symposium 96, Infrared Astronomy*, ed. C. G. Wynn-Williams and D. P. Cruikshank (Dordrecht: Reidel), p. 207.
Aitken, D., Roche, D., and Phillips, M. 1981, *M.N.R.A.S.*, **197**, 101P.
Baldwin, J., Phillips, M., and Terlevich, R. 1981, *Pub. A.S.P.*, **93**, 5.
Cutri, R., Rieke, G., and Lebofsky, M. 1983, in preparation.
Cutri, R., and Rudy, R. 1981, *Ap. J. (Letters)*, **243**, L141.
Dwek, E., Sellgren, K., Soifer, B. T., and Werner, M. 1980, *Ap. J.*, **238**, 140.
Elvius, A., Lind, J., and Lindgren, L. 1979, in *Proceedings of the First Year of IUE*, ed. A. J. Willis (London: University College London), p. 119.
Frogel, J., Persson, S., Aarson, M., and Mathews, K. 1978, *Ap. J.*, **220**, 75.
Gillett, F., Kleinmann, D., Wright, E., and Capps, R. 1975, *Ap. J. (Letters)*, **198**, L65.
Krishna Swamy, K., and O'Dell, C. 1967, *Ap. J.*, **147**, 529.
Lacy, J., *et al.* 1982, *Ap. J.*, **226**, 550.
Malkan, M. 1983, *Ap. J. (Letters)*, **264**, L1.
Moorwood, A., and Salinari, P. 1981, *Astr. Ap.*, **100**, L16.
Netzer, H., and Davidson, K. 1978, *M.N.R.A.S.*, **187**, 871.
Rieke, G. 1978, *Ap. J.*, **226**, 550.
Rieke, G., and Lebofsky, M. 1979, *Ap. J.*, **229**, 111.
———. 1983, preprint.
Rudy, R., Jones, B., LeVan, P., Smith, H. E., Willner, S., and Tokunaga, A. 1982, *Ap. J.*, **257**, 570.
Rudy, R., and Puetter, R. 1982, *Ap. J.*, **263**, 43.
Sellgren, K. 1981, *Ap. J.*, **245**, 138.

Sellgren, K., Werner, M., and Dinerstein, H. 1983, *Ap. J.* (*Letters*), **271**, L13.
Soifer, B. T., Russell, R., and Merrill, K. M. 1976, *Ap. J.*, **210**, 334.
Telesco, C., and Harper, D. 1980, *Ap. J.*, **235**, 392.
Thronson, H., and Harper, D. 1979, *Ap. J.*, **230**, 133.
Ulrich, M. 1972, *Ap. J. Letters*), **171**, L37.
Ulvestad, J., Wilson, A., and Sramek, R. 1981, *Ap. J.*, **247**, 419.
Whittle, M. 1982, Ph.D. thesis, University of Cambridge.
Willner, S., *et al.* 1977, *Ap. J.* (*Letters*), **217**, L121.
Wynn-Williams, C., *et al.* 1979, *M.N.R.A.S.*, **189**, 163.

ROC M. CUTRI, GEORGE H. RIEKE, and RICHARD J. RUDY: Steward Observatory, University of Arizona, Tucson, AZ 85721

ALAN T. TOKUNAGA: Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822

STEVEN P. WILLNER: Smithsonian Astrophysical Observatory, Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138