THE SIZE OF NGC 4151 AT 11.2 μm

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ABSTRACT

The size of the emission region of NGC 4151 at 11.2 μm has been measured to be $0.16'' \pm 0.04''$ (1σ). This size is in agreement with that expected from thermal emission from dust grains heated by a central luminosity source, but is inconsistent with nonthermal emission.

INTRODUCTION

The Seyfert galaxy NGC 4151 is the archetypical Seyfert 1 galaxy. It is one of the nearest and brightest of the Seyfert galaxies; $V \sim 11.85$ mag, $z = 0.003$ (Veron-Cetty and Veron 1989). Its infrared emission, which peaks at $\sim 100\,\mu$m, has a luminosity of $\sim 10^{10}\ L_0$ (Wade *et al.* 1987), dominating its output except in the x-ray/gamma-ray region (Perotti *et al.* 1981). The source, and even the emission mechanism, of the infrared emission in NGC 4151 is uncertain, but clearly determining the mechanism is a first crucial step in understanding the overall energetic of Seyfert 1 nuclei.

Arguments for the infrared emission from NGC 4151 being either thermal or nonthermal are given, e.g., in Rieke and Lebofsky (1975, 1981); Lebofsky and Rieke (1980); Edelson and Malkan (1986); Carleton *et al.* (1987), and Edelson, Malkan, and Rieke (1987). Currently, the most generally accepted view is that the infrared emission is predominantly thermal emission from dust grains heated by a central (nonthermal) luminosity source, but no unambiguous evidence for this interpretation has been obtained so far. The near-infrared source has been observed to vary on a timescale as short as two months (Penston *et al.* 1974; Lebofsky and Rieke 1980) and is polarized (Kemp *et al.* 1977). Both of these observations have been attributed to nonthermal emission, but both can very convincingly be explained by thermal reradiation from grains (Rieke and Lebofsky 1981). Edelson *et al.* (1988) have used a nondetection at 438 μm to argue that at least half the infrared emission is thermal; see, however, de Kool and Begelman (1989) for purely nonthermal models.

One potentially direct observation which could decide the nature of the emission mechanism is a measurement of the size of the infrared emitting region. If the continuum is nonthermal synchrotron emission, the size would, as discussed below, be small, $< 0.000\,001''$, and unresolvable. On the other hand, if the emission comes from heated grains, the size should be $> 0.1''$. In this paper we present observations of the size of the emission region of NGC 4151 near 10 μm which strongly favor the interpretation that the infrared emission comes from centrally heated dust grains.

OBSERVATIONS

All the observations were made at the $f/70$ Cassegrain focus of the 200 in. Hale telescope. The observational technique was designed to make size measurements of sources which are faint at 10 μm but relatively bright at 2.2 μm; the method is described in detail by Matthews *et al.* (1987). Briefly, two detecting systems, one an InSb photovoltaic detector with a 2.2 μm filter and the other a Ge:Ga bolometer with a 11.2 μm ($\Delta\lambda/\lambda = 0.1$) filter, were arranged in the focal plane to be at the same declination and separated by about 20″ in right ascension. Each detector viewed the sky through a slit 0.5″ wide in declination and about 5″ long in right ascension; the slits were accurately aligned to be collinear. The telescope was alternately scanned $\sim 8''$ north and south at a rate of $0.5''\ \mathrm{s}^{-1}$ with the object at the center of the scan. At the same time, the image was switched between the two slits at 50 Hz by means of the secondary mirror chopping perpendicular to the telescope motion. Similar scans over sources which are bright at both 2.2 and 11.2 μm showed the effects of image and telescope motion were closely the same for both wavelengths. Approximately every 5 min, after 20–40 crossings of NGC 4151, the telescope was moved to a nearby comparison star BS 4069 to serve as a calibrator. The observations were always limited to airmasses less than 1.5 and the airmass of the calibrator star was larger than, and always within 0.04, that of NGC 44151.

Observations were made on four nights: 10 and 11 March 1987 and 21 February and 20 May 1989. The number of crossings of the slit by NGC 4151 on each night were 192, 192, 740, and 320, respectively. The visual seeing disk diameter on each night was between 1″ and 1.5″, implying the 2.2 μm seeing was better than 1.1″ and the 11.2 μm seeing was better than 0.8″. On the nights in March 1987, a 10.1 μm broadband filter was used instead of the 11.2 μm narrowband filter; the effects of this change are discussed below.

ANALYSIS

Figure 1 shows the profiles from twenty typical crossings over NGC 4151 at 2.2 and 11.2 μm; it is seen that the profile of a single crossing of the image over the slit is invisible in the noise at 11.2 μm. In the reduction of the observations, a profile obtained from the 2.2 μm scans across the calibrator star was used to centroid the individual 2.2 μm peaks of both the calibrator star and NGC 4151. The resultant location of the 2.2 μm signal, which was well defined for each crossing of the slit, was then used to accurately register, for subsequent coaddition, each 11.2 μm scan. This accurate registration is necessary to remove image wander and irregularities in the telescope motion which would otherwise be larger than the desired precision of better than 0.05″. The results of the coaddition of one night's data at 11.2 μm, some 160 north-going and 160 south-going segments, are shown in Fig. 2. The width of the observed profiles of NGC 4151 [full width at half maximum (FWHM) $\sim 1''$] represents a convolution of the intrinsic width of the source in NGC 4151 with the slit width (0.5″), the seeing width ($< 0.8''$ at 11.2 μm), and the diffraction width (0.5″ at 11.2 μm). In the reduction, the data were binned into 100 ms time bins, each corresponding to 0.05″.

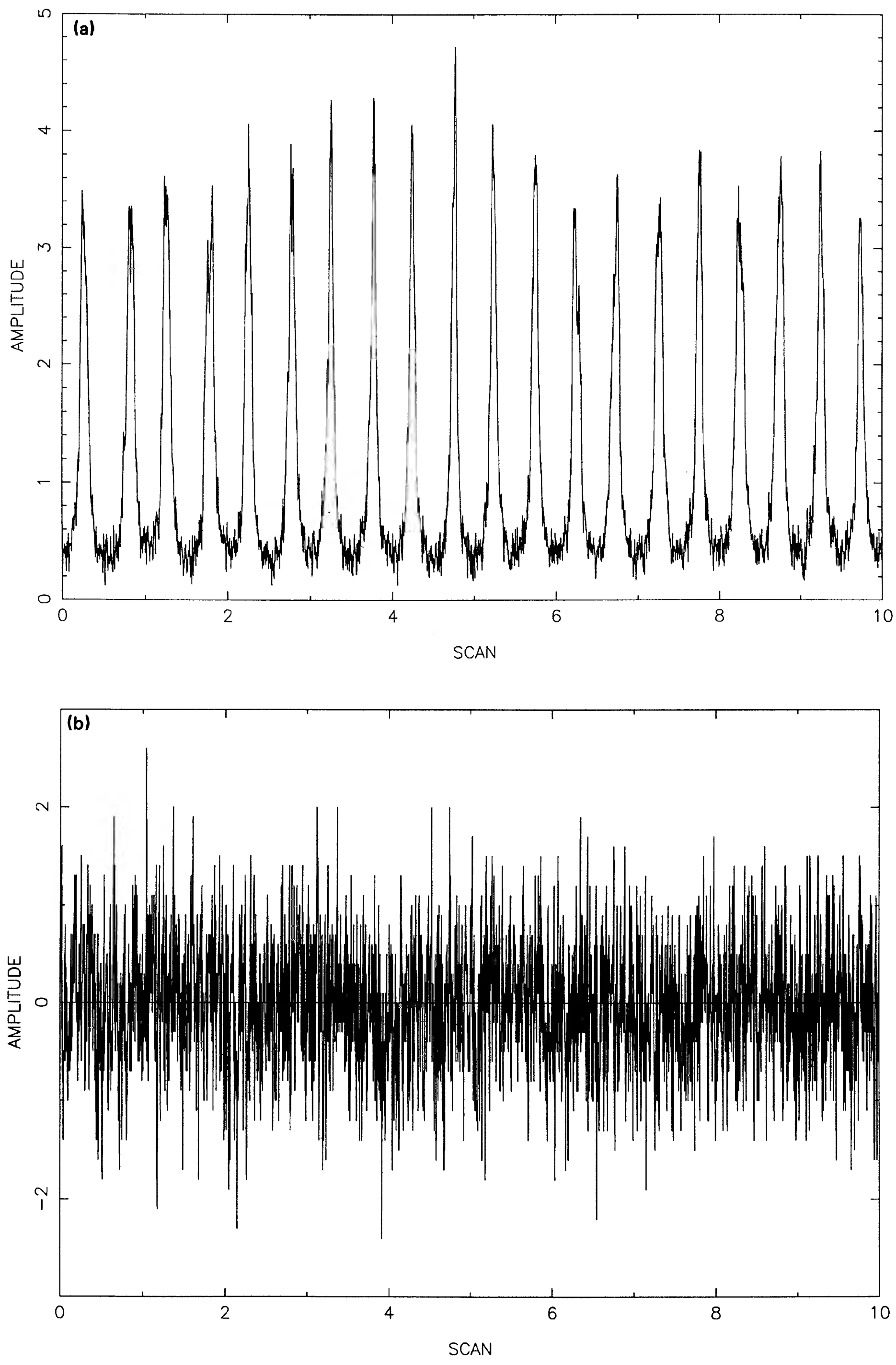

FIG. 1. Ten nearly simultaneous scans of the image of NGC 4151 over the slit filtered at 2.2 μm (top) and over the slit filtered at 11.2 μm (bottom) are shown. Each scan consists of a north-going segment centered on the object followed by a south-going segment. The near simultaneous coverage in two filters is accomplished by means of the $f/70$ secondary. See the text and Matthews *et al.* (1987). Some of the 2.2 μm peaks are broken up into the individual speckles.

The profiles of the coadded scans of NGC 4151 at 11.2 μm for each night were analyzed by comparing them with the profiles, appropriately modified, of coadded scans from the calibrator star. In the analysis, the differences between the size of the NGC 4151 profile and those of the calibrator star were determined. The rapid interleaving of the measurements of the two objects means that the systematic causes have the same effect on both profiles and that a width difference can be interpreted as being due to an underlying intrinsic width in NGC 4151. The profile of the 11.2 μm scans of the calibrator was derived from the observations using the same algorithms as were used to derive the coadded profiles of NGC 4151. Although NGC 4151 is embedded in a galaxy, the nuclear component dominates the signal within a 0.5″ slit and the width of the 2.2 μm peak of the object was the same as that of the calibrator star. Since the scan profiles were potentially different on each night and between the north- and south-going scans, north-going and south-going scans on each night were analyzed separately. The seeing on each of the nights was steady enough that it was considered

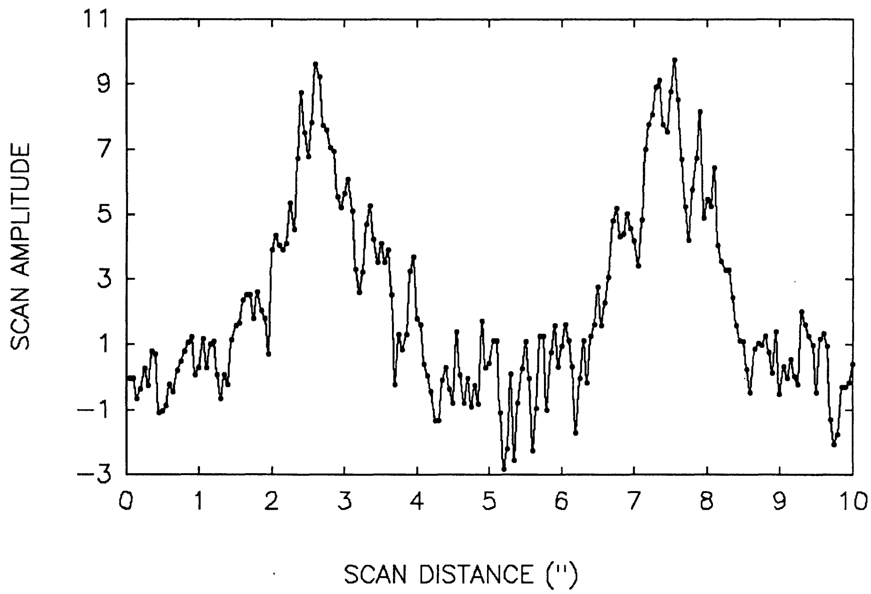

FIG. 2. The coadditions of 160 north-going scans (left) and 160 south-going scans (right) are shown. The individual scan profiles were registered for the coaddition by using the 2.2 μm scans. The corresponding profiles for the calibrator star at 11.2 μm showed negligible noise.

unnecessary to split the night's data further, but the observations of 21 February 1989 were arbitrary split into two equal portions.

The precision of the observations does not allow sophisticated modeling of NGC 4151. Therefore, the intrinsic nuclear source, which was convolved with the observed profiles from the calibrator star, was modeled simply as a set of circular Gaussian profiles whose FWHMs were set to values from 0.0" to 1.0". The calibrator star was assumed to be a point source. The probability that each assumed Gaussian profile represented the observations was evaluated by finding the chi-square sum for the fit between the nightly observations at 11.2 μm of NGC 4151 and the modified calibrator profile. The value of the baseline was adjusted to obtain the minimum value of the root-mean-square difference between the NGC 4151 and calibrator profiles.

The calibrator profiles used in the analysis of the observations of March 1987 required a modification because of the broad bandwidth (8.0–13.1 μm) used in the observations and because the spectral shape of NGC 4151 differs strongly from that of the calibrator star in this wavelength region. If f_ν is the flux density, f_ν (NGC 4151) $\alpha \nu^{-1}$ while f_ν (calibrator) $\alpha \nu^2$ and thus the effective wavelength of the calibrator star is 9.8 μm vs 10.6 μm for NGC 4151. The diffraction width for NGC 4151 is correspondingly larger than that for the calibrator star and would potentially introduce an incorrect artifact into the analysis. This effect was taken into account by deconvolving the stellar diffraction, corresponding to 9.8 μm, from the observed 10 μm profile for the calibrator star and then convolving a broader diffraction pattern, appropriate to 10.6 μm, with the remaining profile before the convolution with model Gaussian profiles was applied. The magnitude of this effect was approximately a 0.07" increase in the FWHM of the calibrator star. The widths of the filters used in the 11.2 μm observations were $\Delta\lambda/\lambda = 0.1$ so that no correction of the kind just described was necessary for the remaining observations.

Figure 3 shows the sum of the chi-square values for the fit between the observed coadded 11.2 μm profile of NGC 4151 and the convolution of the coadded calibrator profiles and Gaussian profiles as a function of the FWHM of the Gaussian profiles. The fit was limited to scans of length 2.3" on each side of the peak, i.e., to 92 points. The observations of all four nights (one divided into two portions) are included so the sum for each assumed Gaussian width contains the chi-square of 920 individual points. The curve exhibits a clear minimum at a FWHM of 0.16" $\pm$ 0.03" (1σ), where the uncertainty has been calculated assuming a normal distribution of noise (Press *et al.* 1987). The noise was established from the 11.2 μm data in both the individual scan profiles and in the coadded profiles; these two measures were consistent. Note that if the average noise were increased by 8% the reduced chi-square would approach unity and the uncertainty would be increased to $\pm$ 0.04".

The signal-to-noise ratios of the profiles found in one direction on an individual night were not large enough to make statistically meaningful separate size determinations. Nonetheless, the average value of the best fits of the ten separate portions is 0.16" $\pm$ 0.05" showing that the resultant is not due to a single large value. The data were also divided into two groups in a number of combinations to see if statistically significant size determinations would result indicating some systematic effects. The largest difference results between the north-going (0.22" $\pm$ 0.04") and the south-going scans (0.11 $\pm$ 0.04"). As a check whether or not the decreased signal-to-noise ratio observed in the 2.2 μm peaks of NGC 4151 caused a widening of the 11.2 μm peak, random noise corresponding to that observed in NGC 4151 was added to the observed 2.2 μm peaks of the calibrator star. No widening in the 11.2 μm peak that resulted from the coaddition was seen.

An additional result of the analysis is that the 11.2 μm profile of NGC 4151 had, within a statistical standard deviation of 0.04", the same location relative to the 2.2 μm profile as did the 11.2 μm peak to the 2.2 μm peak of BS 4069; i.e., the 11.2 μm peak is centrally located in NGC 4151.

DISCUSSION

We take 0.16" $\pm$ 0.04" as the measurement of the size of the emitting region of NGC 4151 at 11.2 μm. This size im-

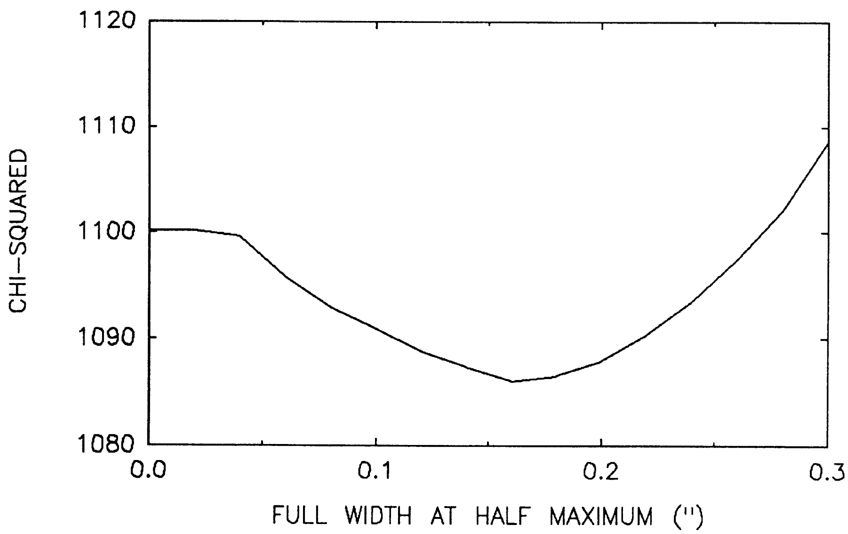

FIG. 3. The sum of the chi-square values for the fit between the observed coadded data for NGC 4151 and the convolution of Gaussian profiles with the observed calibrator profile is shown. The data 2.3" on each side of the maximum are included in each fit and ten sets of observations are included in the sum so that there are 920 contributions to each sum. The abscissa is the FWHM of the Gaussian that is convolved with the observed coadded calibrator profile.

mediately rules out a nonthermal origin for the emission and implies the emission is thermal radiation from heated grains.

If the emission is optically thick nonthermal synchrotron emission, the brightness temperature must exceed $m_e c^2/k = \sim 10^{10}$ K where m_e is the mass of the electron, c the velocity of light, and k the Boltzmann constant. At 11.2 μm the observed flux density is 1.72 Jy, implying the size of the emitting region must be less than a microarcsecond (FWHM). An alternate way of gauging the magnitude of the discrepancy is to note that if the emitting region has a FWHM of 0.16", the brightness temperature of NGC 4151 at 11.2 μm is 139 K.

If the emission is thermal, θ, the angular radial distance to grain at a temperature T_g, depends on Q_a, the grain absorption in the ultraviolet, Q_e, the grain emissivity in the infrared, and F, the total flux emitted by NGC 4151:

$$\theta = 0.5\left(\frac{(1+z)^2}{T_g^2}\right)\left[\left(\frac{\langle Q_a\rangle}{\langle Q_e\rangle}\right)\left(\frac{F}{\sigma}\right)\right]^{1/2},$$

where z is the redshift of NGC 4151, σ is the Stefan–Boltzmann constant and $\langle\ \rangle$ indicates an average over the blackbody function at the appropriate temperature. We assume the ratio $\langle Q_a\rangle/\langle Q_e\rangle$ to be as given by Draine and Lee (1984) for silicate and graphite particles of 0.1 μm radius. The color temperatures obtained from the ratios of narrowband photometry in the 8–12 μm region vary from 218 to 315 K. If the emissivity in the infrared varies as the inverse wavelength, the grain temperatures giving the observed ratios range from 185 to 262 K. Thus it is not unreasonable to assume the grain temperature of a typical grain to be as low as 200 K. The total infrared flux can be taken from Wade *et al.* (1987) to be 17.3×10^{-13} W m^{-2}. With these assumptions the diameter of the emitting region is predicted to lie between 0.15" for silicate grains and 0.32" for graphite grains. If the grain temperature is as high as 250 K these sizes become 0.09" and 0.18".

The measurements thus provide direct evidence that the 11.2 μm emission from NGC 4151 is thermal reradiation from heated dust grains. The coincidence of the 11.2 μm peak with the peak at 2.2 μm strongly argues that the Seyfert nucleus is heating the grains emitting at 11 μm. If the Hubble constant is taken as 75 km s^{-1} Mpc^{-1}, the radius to the dust grains is ~5 pc, located well outside the region of the active nucleus which is powering the emission whose size, from variability measures, is <0.05 pc (Rieke and Lebofsky, 1981 and references therin). On the other hand, this size is roughly the size of the narrow line region in NGC 4151, entirely consistent with current prejudices.

It is possible that the Seyfert nucleus is also heating the grains that produce the far-infrared emission. Engargiolia *et al.* (1988) have found a size for the far-infrared source of >48" at 155 μm. If the peak wavelength of emission from dust grains scales inversely with the temperature, and the linear size of a centrally heated source varies as $r \sim T^{-5/2}$, the size of the source at 155 μm would be ~700 times the source size at 11 μm. This is consistent with the observed size. On the other hand, the possibility that the far-infrared emission is a result of local heating by young stars, as suggested by Cutri *et al.* (1984) for NGC 7469, cannot be ruled out. It should also be noted that the observation also rules out warmer star cluster models with size much greater than 10 pc.

This observation puts NGC 4151, and by association other Seyfert 1 galaxies, among pure galactic nuclei whose far-infrared radiation is dominated by thermal emission. For example, Sanders *et al.* (1989) have concluded that the far-infrared emission from the majority of quasars, i.e., all but the flat spectrum radio-loud quasars, is dominated by thermal emission. It is not possible to tell whether the geometry proposed by Sanders *et al.* is also present in the Seyfert galaxies.

SUMMARY AND CONCLUSIONS

The diameter of the region emitting 11.2 μm radiation in the Seyfert 1 galaxy NGC 4151 has been measured to be 0.16" ± 0.04". This size is significantly bigger than that predicted from nonthermal models, but is in good general agreement with thermal models where grains of dust are heated by a central luminosity source.

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