THE ASTRONOMICAL JOURNAL VOLUME 94, NUMBER 2 AUGUST 1987

THE SIZE OF Mrk 231 AT 10 μm

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Received 1 April 1987; revised 7 May 1987

ABSTRACT

A technique is described for obtaining high-sensitivity measurements with high spatial resolution at 10 μm. An application of the method to Mrk 231 confirms the point-like nature of the nucleus at 10 μm.

INTRODUCTION

Mrk 231 is unique in several respects. Spectroscopically, the nucleus has been classified both as that of a Seyfert 1 galaxy (see, for example, Boksenberg *et al.* 1977) and as a broad-absorption-line quasar (Rudy, Foltz, and Stocke 1985). The galaxy has for some time been recognized as being extremely luminous in the infrared (Young, Knacke, and Joyce 1972; Rieke and Low 1972); it is the most luminous object in the local universe as measured in the *IRAS* survey (Sanders *et al.* 1987). The underlying galaxy is extremely luminous and is possibly undergoing massive starbursts (Cutri, Rieke, and Lebofsky 1984). Sanders *et al.* (1987) have tentatively identified the nucleus of Mrk 231 as an object in that stage in the evolution from ultraluminous galaxy to quasar when the bare quasar is just visible through the obscuring matter from which it formed.

It is clearly of interest to spatially resolve the nucleus of Mrk 231. Although Mrk 231 is very luminous, it is too faint at 10 μm, the longest wavelength generally accessible from, for example, Palomar Observatory, to enable 10 μm speckle measurements to be made of it. Even scans with narrow slits at 10 μm do not have sufficient signal-to-noise ratios to assess its size.

The object shares with many other extragalactic objects the property of having a relatively bright component at 2 μm, although it is faint at 10 μm. In this paper, we describe a technique that allows us to utilize this property in order to make measurements that show that at 10 μm the nucleus of Mrk 231 is unresolved with the 5 m telescope.

OBSERVATIONS—TECHNIQUE

The present observations were all made at the 5 m Hale telescope at Palomar Observatory. The telescope is equipped with an *f*/70 chopping secondary that allows the image of two places in the sky to be compared. The amplitude of the chopping spacing and its direction in the sky can be easily varied and accurately controlled. The 10% to 90% transit time of the chopper for chopping amplitudes $<20''$ is 1.2 ms. Critical for the application described here is the fact that the image path of the chopping is very straight and extremely stable. The telescope is also equipped with a Ge:Ga bolometer for observations at 10 μm and an InSb photovoltaic detector for observations from 1.2 to 4.8 μm. The two detectors are arranged so they simultaneously view the sky with a separation of $\sim 18''$.

For the observations described in this paper, narrow slits were placed over both detectors and the slits were lined up in the focal plane parallel to each other and the direction of the chopping displacement. The telescope was now scanned back and forth over the source in a direction perpendicular to the direction of the chopping at a rate fast with respect to long-term seeing fluctuations, but slow with respect to the chopping frequency. The net effect of the combined telescope motion and chopping was to produce, essentially simultaneously, scan profiles at two wavelengths whose widths are a convolution of the intrinsic width of the source, the seeing diameter, and the width of the slit. It should be noted that with the above orientation of the slits, any departure of the chopping motion from a perfect square wave would produce a minimum effect on the width of the two scan profiles.

When the telescope is scanned in this manner over a source like Mrk 231, the amplitude of the scan profile at one wavelength, here 2.2 μm, sufficiently exceeds the noise so it can be used to align the profiles of the second, noisier channel, here that at 10 μm. This procedure serves to synchronize accurately the scans at 10 μm so they can be coadded to increase the signal-to-noise ratio in that channel without significantly broadening the profile. The efficacy of this technique is demonstrated in Fig. 1, which shows single scans of Mrk 231 at 2.2 and 10 μm, as well as the results of coaddition of 40 scans whose relative positions along the scan direction were adjusted by means of the clearly visible 2.2 μm profile. A comparison of individual simultaneous scans at each wavelength over a bright source (Fig. 2) indicates that, in fact, large-scale fluctuations due to seeing are mimicked at the two wavelengths.

OBSERVATIONS—Mrk 231

In this paper we report the results of measurements made with $0\farcs5 \times 5''$ slits of the nucleus of Mrk 231 on 21 and 26 December 1985. The chopper had an amplitude of 18″ and a chopping frequency of 50 Hz. On the first night, the visual-seeing image was $\sim 1\farcs5$ in diameter, and a total of 96 alternating east-going and west-going scans were made over the source. On the second night, the visual seeing was $<1''$ in diameter and a total of 80 alternating north- and south-going scans were made. On both nights, the scans over Mrk 231 were made at a rate of $0\farcs5\ \mathrm{s}^{-1}$ and were interspersed with a comparable number of scans over a nearby bright star.

The position of the peak at 2.2 μm on each scan was located by cross correlating each individual 2.2 μm profile with a mean 2.2 μm profile. The displacements of the individual 10 μm scans were then adjusted to correspond to a common position of the 2.2 μm profiles, after which the 10 μm signals were coadded. In the subsequent analysis, all the scans were combined in order to obtain the best overall signal-to-noise ratios from the observations, but the scans were also separated into subsets of various combinations in order to assess systematic effects.

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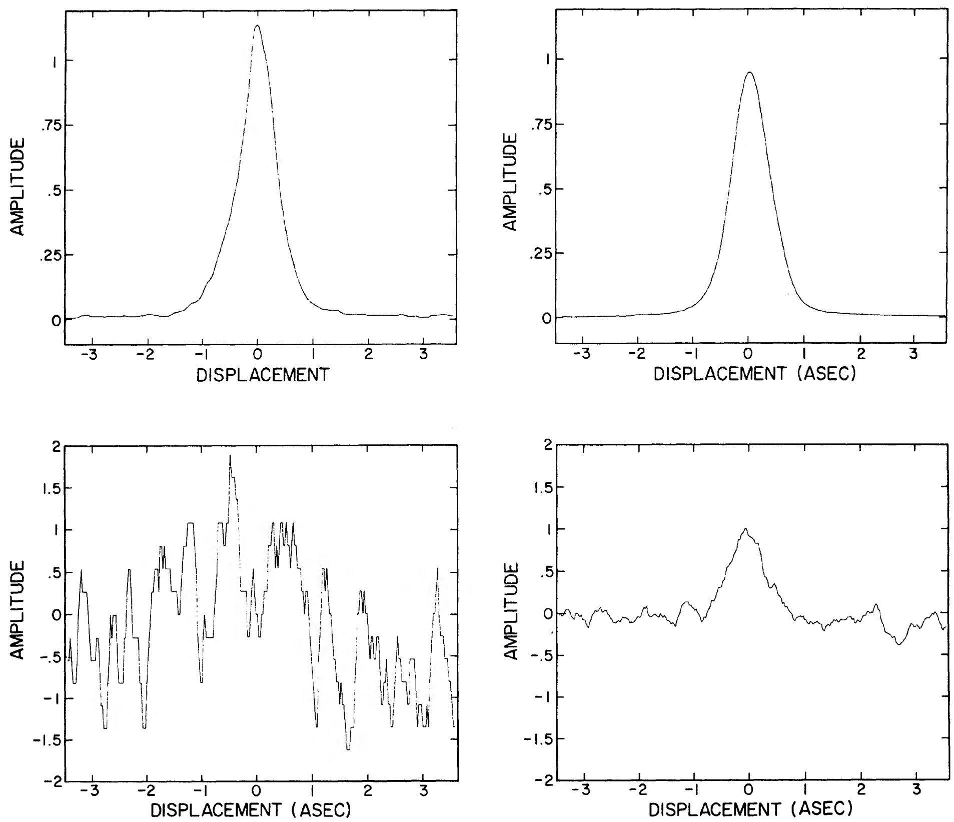

FIG. 1. The left-hand panels show a single north-going scan of Mrk 231 at 2.2 μm (top) and at 10 μm (bottom). The right-hand panels show the coaddition of 40 north-going and 40 south-going scans at 2.2 μm (top) and at 10 μm (bottom). The 2.2 μm profiles were used to align the 10 μm scans.

ANALYSIS

The profiles were analyzed by assuming they represented an intrinsic circularly symmetric Gaussian brightness distribution convolved with the slit width and seeing profile. The latter was chosen to be the summed 10 μm profile formed in the same manner as that of Mrk 231 from the contemporaneous set of scans over the bright star. The width of the Gaussian profile was determined by fitting the data in a least-squared sense and varying the width of the assumed Gaussian distribution. It should be emphasized that this method cannot reconstruct the shape of the source; only parameters of a preselected brightness distribution can be determined.

The widths of the Gaussian for the best fit to each of the summed profiles were formally 0″ for each of the east-, west-, and north-going scans; the individual south-going scans indicated a formal width of 0″.2. The summed profiles indicated a best fit for a formal width of 0″ for both the east–west and north–south scans. The limits to the extent of the Gaussian profiles were determined from the width when the sum of the squares of the differences between the reconstructed profile and that observed was twice the minimum value. For both the north- and south-going scans, this limit corresponded to a full width for half the enclosed luminosity of 0″.5. It is seen in Fig. 3 that subjectively the fit is significantly degraded at this limit. For the east-going scans, made under poorer seeing conditions, the corresponding limit is 0″.7, while for the west-going scans it is 1″.3. The dispersion in the full widths at half-maximum calculated from the subsets of the observations is less than 0.2″.

DISCUSSION

The observations indicate that the size of the nuclear component of Mrk 231 is consistent with an unresolved source at 10 μm with a limit to the full width at half-maximum of <400 pc (0″.5). (Mrk 231 is at a distance of 164 Mpc for a Hubble constant of $H_0 = 75$ km s^{-1} Mpc^{-1}.) The far-infrared measurements indicate the bolometric luminosity of Mrk 231 is $3.4\times10^{12}\ L_\odot$ and the color temperature observed between 12 and 25 μm is 165 K. A grey grain only 26 pc from a single luminosity source of $3.4\times10^{12}\ L_\odot$ would be heated to 165 K, while a similar grain at a distance of 200 pc would reach a temperature of 59 K. In contrast, if the emissivity beyond 0.5 μm were to vary inversely as the wavelength, then the physical temperature indicated by the 12 and 25 μm measurements would be 138 K, while a grain at 200 pc would reach a temperature of 156 K. A stronger dependence of emissivity with wavelength becomes clearly incompatible with the observations. Thus the present observations are consistent with a model of grains being heated by a central luminosity source with subsequent reradiation from the grains, but constrain the variation of the emissivity with wavelength. If a more stringent limit to the 10 μm size of Mrk 231 is obtained, a more sophisticated model for the thermal emission will clearly be required.

The limit also puts severe constraints on the luminosity density of any starburst activity in the core of Mrk 231. Rieke *et al.* (1980), in a classic description of the starburst galaxy M82, found that a luminosity of $3\times10^{10}\ L_\odot$ was emitted from an area 450 pc$\times$150 pc. If the depth of the volume is taken as 300 pc, the luminosity density of this

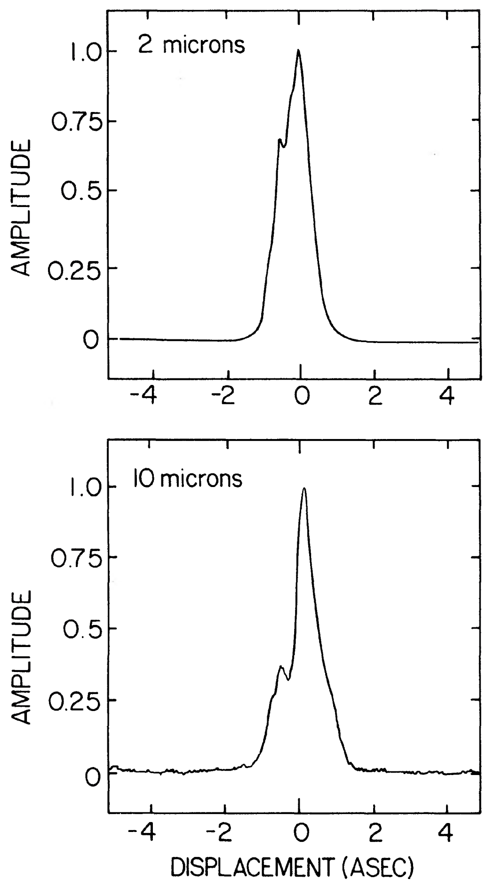

FIG. 2. Simultaneous slit scans of a bright star at 2.2 μm (top) and 10 μm (bottom) are shown. The similar effects of seeing at the two wavelengths are shown by the dips on the leading side of the profiles.

archetypical starburst galaxy is 1500 $L_\odot$ pc^{-3}. If the matter in Mrk 231 were to have the same luminosity density as M82, a spherical volume enclosing the luminosity of Mrk 231 would have a diameter of $\sim$1500 pc, well in excess of that observed. Alternatively, a luminosity density in excess of 65 times that in M82 would be required in Mrk 231 to fit these observations.

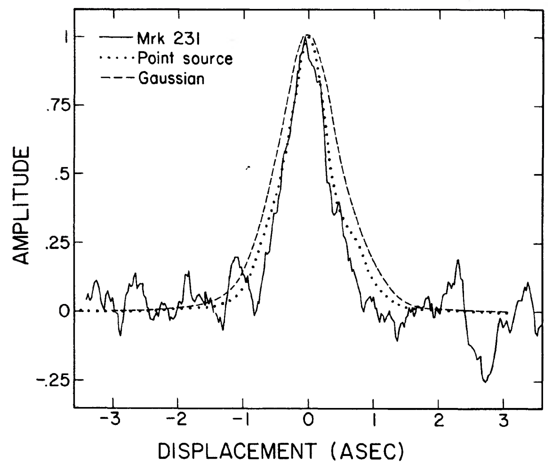

FIG. 3. The coadded profiles of 40 north-going scans and 40 south-going scans of Mrk 231 are shown by the solid line. The profile of a nearby point-like source is shown by the dotted line. The convolution of this point source with a Gaussian of 0".5 full width at half-maximum is shown by the dashed lines. This is taken to be the limiting size of the intrinsic source in Mrk 231 and corresponds to a doubling of the χ^2 sum in the fit. All the profiles have been normalized to the same peak amplitude for ease of comparison.

CONCLUSION

We have demonstrated a new technique at the Palomar 5 m telescope of using the signal from a source at a wavelength where it is strong to assist in determining its size at another wavelength where its strength is too weak to determine its size by other means. The observations of the size of the nucleus of Mrk 231 at 10 μm are consistent with a picture of a single luminosity source, perhaps obscured by dust. The variation with wavelength of the emissivity of the grains is constrained to be less than (wavelength) $-$ 1. The measurements are inconsistent with Mrk 231 being a starburst galaxy with a luminosity density similar to that of M82.

The night of 26 December 1985 was assigned to S. E. Persson and he generously permitted us to make the north–south slit scans. We thank him, and also the staff of the Palomar Observatory, for their help in obtaining the observations. Infrared astronomy at Caltech is supported by a grant from the National Science Foundation.

REFERENCES

Boksenberg, A., Carswell, R. F., Allen, D. A., Fosbury, R. A., Penston, M. V., and Sargent, W. L. W. (1977). Mon. Not. R. Astron. Soc. **178**, 451.
Cutri, R. M., Rieke, G. H., and Lebofsky, M. J. (1984). Astrophys. J. **287**, 566.
Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., and Tokunaga, A. T. (1980). Astrophys. J. **238**, 24.
Rieke, G. H., and Low, F. J. (1972). Astrophys. J. Lett. **176**, L95.
Rudy, R. J., Foltz, C. B., and Stocke, J. T. (1985). Astrophys. J. **288**, 531.
Sanders, D., Soifer, B. T., Elias, J., Madore, B. F., Matthews, K., Neugebauer, G., and Scoville, N. (1987). Astrophys. J. (submitted).
Young, E. T., Knacke, R. F., and Joyce, R. R. (1972). Nature **238**, 263.