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FAR-INFRARED OBSERVATIONS OF IRC +10216

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ABSTRACT

Broad-band photometric observations of IRC +10216 in five wavelength intervals from 50 to 1000 μ are reported. The observed radiation is interpreted as thermal emission from dust in the extended molecular cloud heated by the compact 2–20 μ source as the core of the cloud. The shape of the 50–1000 μ spectrum suggests that the emissivity of the dust particles varies approximately as λ^{-1} over this spectral interval. The mass of dust inferred from the far-infrared emission is comparable with the mass of heavy molecules in the cloud.

Subject headings: infrared: sources — infrared: spectra — interstellar: matter — interstellar: molecules

I. INTRODUCTION

The bright infrared source IRC +10216 has been extensively studied at near-infrared and radio wavelengths. It was first noted as an unusual source by Becklin *et al.* (1969) who measured it at wavelengths between 1.25 μ and 20 μ. They also obtained an optical identification of the infrared source with a small nonstellar object visible in the red and near-infrared and suggested that the source was a late-type star surrounded by an opaque envelope. Subsequent observations by Lockwood (1970), Miller (1970), and Herbig and Zappala (1970) showed that the central object was a carbon star and suggested that the circumstellar envelope was due to mass loss from the star. Herbig and Zappala derived an approximate distance to the object of 300 pc, on the assumption that the central object was a bright carbon star. Later, lunar occultation measurements from 2 μ to 20 μ by Toombs *et al.* (1972) provided information on the temperature and size of the circumstellar envelope. Their observations are most simply interpreted as showing a cool envelope with a characteristic size of 2″ surrounding a hot, optically thick region 0″.4 in diameter. They found the average color temperature for the emission from the 0″.4 diameter region to be ~650 K and from the 2″ region to be ~375 K.

In addition to the infrared observations, radio astronomers have observed a considerable number of molecular species in IRC +10216, suggesting the presence of a shell of outflowing gas. The composition of the molecular gas is consistent with that expected in a carbon-rich environment (Morris *et al.* 1975). Of particular interest are the CO observations (Wilson, Schwartz, and Epstein 1973) indicating that the region of CO emission is about 2′.3 in diameter, and the recent studies by Morris (1975*a*), Morris *et al.* (1975), and Kuiper *et al.* (1976) showing that the molecular observations are fitted by a uniformly expanding cloud model in which the density decreases outward as r^{-2}.

We report here observations of IRC +10216 at five wavelengths between 53 μ and 1 mm. Together with the 34 μ measurement of Low, Rieke, and Armstrong (1973) and many earlier measurements at wavelengths between 1 and 20 μ these data provide a complete picture of the infrared spectrum of IRC +10216.

II. OBSERVATIONS

The results of the observations are summarized in Table 1. All measurements were made using standard dual beam chopping techniques. Column (1) gives the effective wavelength of the measurement, column (2) gives the beam diameter at half-intensity, and column (3) gives the separation between beams. Column (4) gives the measured flux, and columns (5) and (6) give the statistical and total errors, respectively. The statistical errors represent the quality of the detections. With the exception of the 175 μ measurement the signal-to-noise was about 5 to 1 or better. The total error includes the effects of uncertainties in the atmospheric extinction, the shape of the spectrum, and the absolute calibration.

The 53, 100, and 175 μ observations were made on the 91 cm telescope of the NASA G. P. Kuiper Airborne Infrared Observatory in 1975 March. The photometer and radiometer have been described by Harvey, Hoffmann, and Campbell (1975). The filter passbands used in the observations were 43–68 μ, 80–140 μ, and 140–250 μ. The calibration source was Saturn which was assumed to have an effective temperature for disk plus rings of 94 K (Armstrong, Harper, and Low 1972).

The 350 μ observations were made on the University of California, San Diego–University of Minnesota 1.5 m infrared telescope on Mount Lemmon in 1974

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TABLE 1

FAR-INFRARED FLUX MEASUREMENTS OF IRC +10216

Wavelength (microns) (1)	Beam Size (arc minutes) (2)	Beam Separation (arc minutes) (3)	Measured Flux (Jy) (4)	Statistical Error (Jy) (5)	Total Error (Jy) (6)
53	1.4	2	5040	370	1800
100	1.4	2	2460	380	900
175	1.4	2	880	510	600
350	1.6	4.1	107	19	27
1000	1.0	4.0	4.0	0.4	1.0

December. The system used has been described by Hudson, Lindsey, and Soifer (1974). The calibration source was Saturn, whose effective temperature for the disk plus rings was taken to be 100 ± 7 K (Hudson, Lindsey, and Soifer 1974). The 350 μ flux density was calculated assuming a far-infrared spectrum proportional to ν^3. If the spectrum were assumed to be Rayleigh-Jeans, the calculated flux would be decreased from 107 to 92 Jy.

The 1 mm observations were made at the prime focus of the 5 m Hale telescope in 1974 December–1975 January. The photometer and calibration procedures will be described by Gezari (1976) and by Elias *et al.* (1976). The calibration source was Uranus, whose effective disk temperature was measured to be 102 ± 8 K. The spectrum of IRC +10216 was assumed to be proportional to ν^3. If the spectrum were assumed to be Rayleigh-Jeans, the calculated flux density would be increased from 4.0 to 4.5 Jy.

At the time of the reported measurements, IRC +10216, which has a period of 600 days, was near maximum luminosity as determined from 1–20 μ data. Figure 1 shows the far-infrared measurements together with representative near-infrared measurements taken at similar phase. The point at 34 μ is the near-minimum observation of Low, Rieke, and Armstrong (1973) adjusted upward by 70 percent to convert it to a value appropriate for maximum luminosity. The point at 18 μ was taken in 1974 December by Forrest.

III. DISCUSSION

Within the framework of the near-infrared and radio molecular observations of IRC +10216 described in the Introduction, the most natural model for the far-infrared ($\lambda > 50\,\mu$) emission is that it is produced by a cloud of dust mixed with the expanding molecular gas and heated by the near-infrared radiation from the central few-arcsec–sized source. In this model the dust is assumed to be optically thin and to have the r^{-2} density fall-off that is indicated from observations of the molecular gas. Thus IRC +10216 is unusual among far-infrared sources in that the spectrum and the spatial distribution of the emitting dust and the location of the heating source are fairly well known. Comparison of models for this object with the present data may permit some useful constraints to be imposed on the properties of the far-infrared–emitting grains.

A possible additional source of far-infrared radiation, especially at 1 mm, is molecular line emission from the envelope. Estimates of the contribution made by emission from known species (Morris *et al.* 1975; Morris 1975*a*; Wilson, Schwartz, and Epstein 1973) give a value of the order of 5–10 percent of the total observed broad-band 1 mm flux. Thus even at 1 mm a considerable number of abundant, undetected molecular species would be needed to make molecular line emission the dominant source of the observed flux.

a) *Emissivity of Dust Grains*

For a cloud which is optically thin to the 2–20 μ heating radiation and which is made up of dust grains with an emissivity proportional to λ^{-n} for $\lambda > 20\,\mu$, the temperature of the grains at a distance r from the heating source is proportional to $r^{-2/(4+n)}$. Models with dust emissivities proportional to λ^{-1} and λ^{-2} have been fitted to the data. The temperature of the dust was taken to be 375 K at a radial distance 1″ from the heat source (Toombs *et al.* 1972), and the flux was computed for a spherical cloud of diameter 1′.5. This is comparable with the aperture sizes used for all the observations except at 1 mm where the predicted flux has been reduced by 25 percent to account for the smaller aperture used.

The predictions of the two models are shown in Figure 1. The λ^{-1} emissivity law gives a clearly better fit to the data than does the λ^{-2} law. This suggests that the grains probably cannot be small, pure graphite or silicon carbide particles with radii less than $\sim 1\,\mu$, for which the extrapolations by Gilman (1974) and Leung (1975) predict a λ^{-2} variation of the emissivity. The λ^{-1} slope of the emissivity could result if the particles are much larger than ordinarily assumed for interstellar dust, or if mantles or impurities enhance the long wavelength emissivity. The conclusion that the λ^{-1} emissivity law gives a better fit to the data than the λ^{-2} emissivity law is insensitive to modest changes in the assumed density and temperature structure of the cloud.

b) *Mass of Dust*

The total mass of the dust in the cloud can be estimated if the emissivity per unit mass of the grains is known. Although this number is uncertain, the recent calculations by Leung (1975) and by Aannestad (1975) indicate that for several types of grains the effective cross section per unit mass at 100 μ lies in the range 10–100 $cm^2\ gm^{-1}$. Adopting 50 $cm^2\ gm^{-1}$ as a typical value with an uncertainty of an order of magnitude in either direction, it is found that the mass of dust in the circumstellar envelope of IRC +10216 is 10^{-4}–10^{-2} $M_{\odot}$. This range of masses is quite comparable with recent estimates of the mass of heavy molecules, exclusive of H_2, in the shell of IRC +10216 (Morris 1975*b*; Kuiper *et al.* 1976). Therefore, to within the uncertainties of the estimates, IRC +10216 seems to be ejecting similar quantities of dust and heavy molecules. If, as Morris (1975*a*) argues, the mass loss has been at a roughly constant rate over the last $\sim 5 \times 10^3$ yr the mass loss rate in dust is 10^{-8}–10^{-6} $M_{\odot}\ yr^{-1}$, comparable with independent estimates of the mass loss rate in dust in the 2″ shell that emits at 10 μ and 20 μ (Forrest 1974).

The equipment used for the 1 mm observations was developed largely by W. E. Westbrook, who died in 1975 June after these observations were made. We thank Drs. E. E. Becklin, G. Knapp, T. Kuiper, and M. Morris for useful discussions; Dr. W. Forrest for assisting with the 350 μ observations and for making the 18 μ observation; and the staff and crew of NASA Kuiper AIRO for their excellent cooperation during the airborne work. This work was supported by NASA grants NGC 03-002-390 (Steward Observatory), and NGL 05-002-207 (Caltech). M. Werner is an Alfred P. Sloan Foundation Fellow. Infrared Astronomy research at the University of California at San Diego is supported by the NSF and NASA.

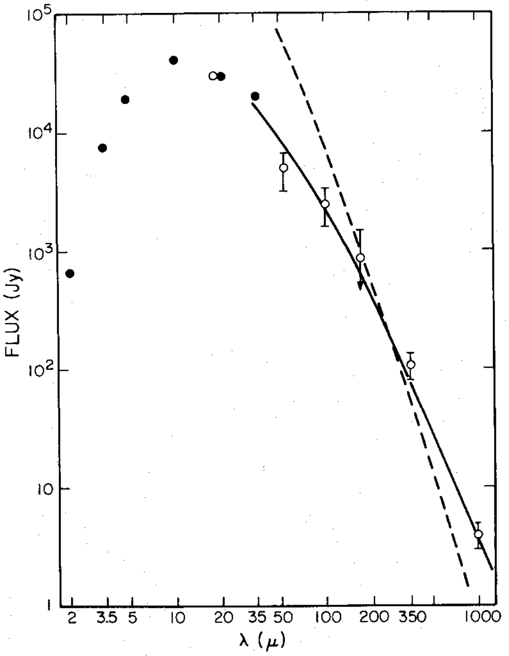

FIG. 1.—Infrared spectrum of IRC +10216. The present far-infrared measurements are shown as open circles; previous near-infrared measurements are shown as filled circles. The solid and dashed curves show the predicted far-infrared spectrum if the grain emissivity varies as λ^{-1} and λ^{-2}, respectively. The predicted spectra have been fitted by eye to the observed points.

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