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SPECTROPHOTOMETRIC OBSERVATIONS OF MU CEPHEI AND THE MOON FROM 4 TO 8 MICRONS

R. W. RUSSELL, B. T. SOIFER, AND W. J. FORREST
Department of Physics, University of California, San Diego
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ABSTRACT

We have obtained the first 4–8 μ spectrophotometric observations ($\Delta\lambda/\lambda \sim 0.01$) of μ Cep and the Moon, using the NASA Airborne Infrared Observatory. The lunar spectrum shows nongray behavior from 6.5 to 8 μ. The spectrum of μ Cep, an M2 Ia star with circumstellar emission, shows no evidence for circumstellar excess emission from 4 to 8 μ; we conclude that silicates provide the only infrared-active component of the circumstellar material.

Subject headings: circumstellar shells — Moon — spectra, infrared

I. INTRODUCTION

Infrared observations have established the existence of a broad 10-μ emission feature in many highly evolved late-type (oxygen-rich) stars. This has been interpreted as positive evidence for associated circumstellar matter, and in particular, evidence for the existence of silicate mineral grains surrounding these stars (Woolf and Ney 1969). The star μ Cep, an M2 Ia supergiant, was one of the stars used to identify the silicates observationally. Spectrophotometry ($\Delta\lambda/\lambda \sim 0.01$) of μ Cep in the atmospheric windows from 3 to 14 μ clearly established the existence of the 10-μ emission feature while showing the stellar continuum for $\lambda < 5$ μ (Gillett, Low, and Stein 1968).

Direct observations of the μ Cep spectrum from 5 to 8 μ, not observable with ground-based telescopes due to very strong H_2O atmospheric absorption, are important to define the stellar continuum, and to establish properly the strength and extent of the 10-μ emission feature. These observations can be used to search for other infrared-active circumstellar materials to test current theories of grain formation in stellar atmospheres (Gilman 1969; Salpeter 1974). We report here spectrophotometric observations from 4 to 8 μ, obtained on a flight of the recently commissioned NASA flying 36-inch (91 cm) infrared telescope (the Airborne Infrared Observatory).

II. EQUIPMENT

The observations were obtained with a cooled filter-wheel spectrometer designed by F. C. Gillett (see Gillett and Forrest 1973 for details) and built at UCSD specifically for airborne observations. The circular variable filter wheel covered the wavelength range 4.1–8.1 μ (mostly inaccessible from ground-based telescopes) with a resolution $\Delta\lambda/\lambda \approx 0.011$. In addition to the narrow-band observations, the spectrometer had broad-band filters ($\Delta\lambda/\lambda \sim 1/10$–$\frac{1}{2}$) covering the wavelengths 2–8 μ to allow for photometric observations of sources, for calibration, and for intercomparison with ground-based photometry.

The spectrometer was mounted at the bent Cassegrain focus of the telescope using a beam-splitter photometer, and used the chopping secondary mirror available on the AIRO. This allowed continuous viewing of the focal plane for guiding and for infrared observations. The signal was processed with the usual phase-sensitive amplifier, sampled through an analog-to-digital converter, recorded and displayed by the on-board computer system to give real-time signal-to-noise ratios for a given measurement.

III. THE OBSERVATIONS

The observations of μ Cep were obtained on an AIRO flight on the night of 1974 September 5/6. The aircraft altitude for most of the flight was 41,000 feet (12.5 km), and the precipitable water vapor above the aircraft (monitored in flight) was 7 ± 1 μm.

Since these are the first observations of stellar objects in this wavelength range, the spectral calibration of the observations is most important. Photometry and spectrophotometry of α Lyr, β Peg, and the Moon were used to calibrate the observations. The primary standard was α Lyr, which was taken to be a blackbody with a temperature of 10,000 K. Broad-band observations from 2 to 8 μ and narrow-band observations from 4.5 to 6.5 μ of α Lyr served to calibrate the observations of β Peg. The narrow-band observations of α Lyr were necessary to calibrate the β Peg spectrum in this wavelength range, where there is a slight depression (at ~5 μ) in the β Peg spectrum, probably due to molecular opacity of CO (Solomon and Stein 1966). Broad-band observations at 6.5 μ ($\Delta\lambda \approx 3$ μ) and 8.4 μ ($\Delta\lambda \sim 0.8$ μ) verified that β Peg behaves as a hot blackbody for $\lambda \gtrsim 5.5$ μ.

The calibrated spectrum of β Peg was used in turn to deduce the lunar spectrum. This spectrum, taken with a 17″ diameter aperture at the approximate Selenographic coordinates 6° S, 67° W, is shown in Figure 1. The shape from 4.5 to 6.5 μ and at 8 μ fits a 355 K blackbody fairly well, but the depression from 6.5 to 8.0 μ shows that this particular position is not a gray body in this wavelength range. Murcray, Murcray, and

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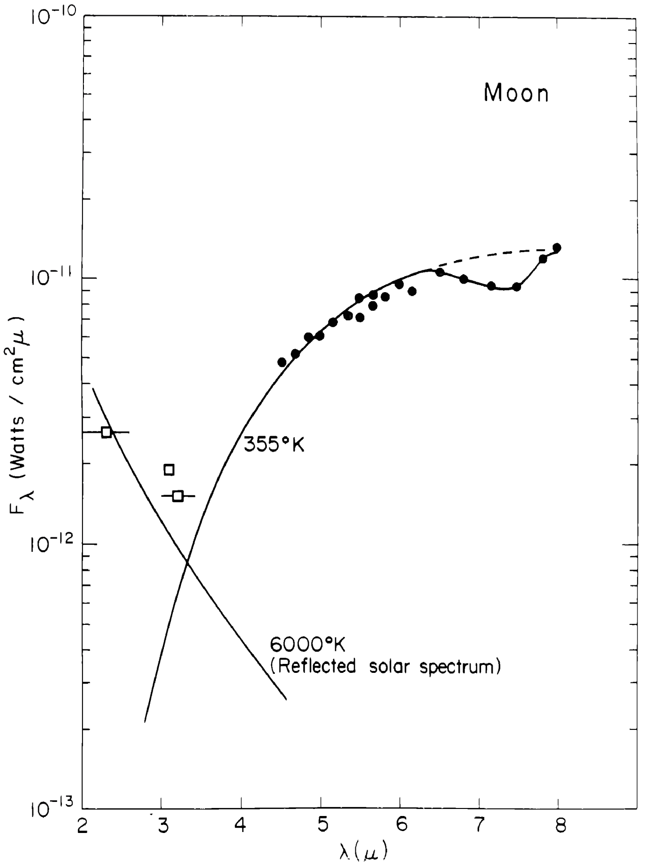

FIG. 1.—The lunar spectrum, obtained on the AIRO. Broad-band data (*open squares*) and narrow-band data (*closed circles*) were calibrated using α Lyr and β Peg as standards. The filter bandpasses are shown when larger than plotted points. The scatter in the narrow-band data reflects the noise in the calibration of the standards β Peg and α Lyr, not noise in the lunar spectrum. The system solid angle is 5.5×10^{-9} sr, so that the 355 K curve corresponds to emissivity = 1. The reflected solar curve corresponds to an albedo of 0.08.

Williams (1970) have previously found this nongray behavior in the lunar spectrum. We attribute this wavelength dependence of the lunar emissivity to the chemical/physical composition of the surface layer which was observed. Possible materials with spectral features in this region are carbonate minerals and silica glasses (Hunt, Wisherd, and Bonham 1950). The question of the source of the 7-μ lunar depression should be investigated further in light of the present knowledge of the composition of the surface layers of the Moon.

Finally, the lunar spectrum, smoothed from Figure 1, was used to calibrate the 4.5–8 μ spectrum of μ Cep (Fig. 2). (The seemingly circuitous route to the calibration of the Cep spectrum was necessary because the data on β Peg were less complete than those for the Moon or μ Cep.) We have included in Figure 2 infrared observations of μ Cep from 2 to 14 μ, including ground-based broad-band and narrow-band observations of Forrest, Gillett, and Stein (1974), as well as broad-band and narrow-band AIRO observations, and our previously unpublished narrow-band observations at 2 and 3 μ.

The broad-band observations from the AIRO and ground-based observations show excellent agreement. The 8.4-μ broad-band magnitudes, obtained with identical filters, agree to 0.03 mag between airborne and ground-based observations.

IV. DISCUSSION

The main features of the 4–8 μ spectrum of μ Cep are the slight depression at $\sim$5 μ, and the blackbody nature of the spectrum from 5.5 μ to 8 μ. The 5-μ depression is attributed to CO absorption in the stellar atmosphere (Solomon and Stein 1966).

The 5.5–8 μ flux appears to be long-wavelength emission from a blackbody at a higher flux level than that deduced from the $\lambda < 5$ μ observations. This could be due, for instance, to decreased stellar opacity in this wavelength region—allowing us to see to a higher temperature level ($T \sim 4200$ K) than is observed shortward of 5 μ ($T \sim 3500$ K). An alternate explanation of this flux would have excess emission from circumstellar dust combining with the stellar continuum to mimic closely a hot blackbody. This is unlikely, both because of the temperature requirements on such particles ($T > 1000$ K) and the peculiar optical properties such grains would require (virtually no emission for $\lambda < 5$ μ and featureless spectra from 5 to 8 μ).

If the entire 5–8 μ flux were attributed to stellar emission, there would be several consequences. First, the strength of the 10-μ emission feature, which we derive by subtracting a hot blackbody fitted to the short-wavelength data, is slightly reduced, while the emission profile rises more sharply from 8 to 9 μ compared with the result using the technique of Forrest *et al.* (1974). This new profile is also shown in Figure 2. The lack of evidence for any other infrared-active circumstellar material in the 5–8 μ spectrum of μ Cep confirms the assumption that "silicates" are the only grain material observed in this star. This is consistent with theories of grain formation in the atmospheres of oxygen-rich red giants, which predicts that silicates will be the dominant grains formed in these stars (since all C will be in the form of CO—see Gilman 1969; Salpeter 1974 for descriptions of the theory).

Finally, there is no evidence (to 20% of the continuum) for molecular opacity due to SiO, which would peak at 7.8 μ (Gillett, Stein, and Solomon 1970).

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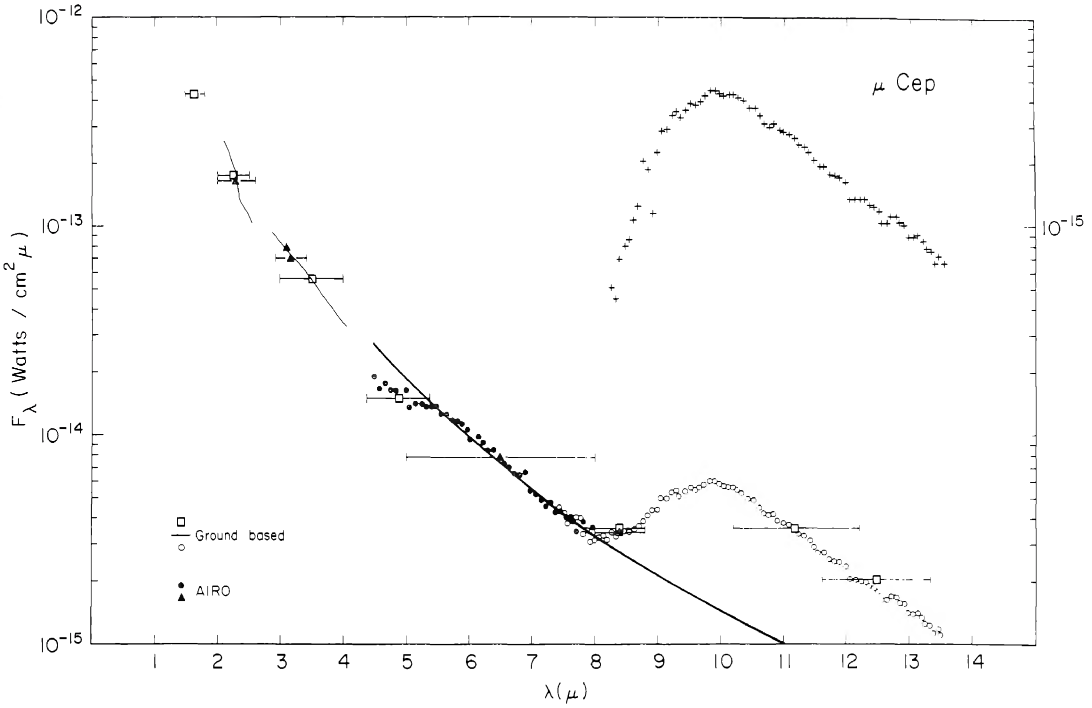

FIG. 2.—The spectrum of μ Cep from 2 to 14 μ. The ground-based data are broad-band observations (*open squares*), and narrow-band observations from 8–13 μ (*open circles*, Forrest *et al.* 1974), and narrow-band observations from 2 to 4 μ (*thin lines*, previously unpublished observations of Soifer and Russell). The AIRO data are broad-band (*filled triangles*), and narrow-band (*filled circles*) observations. Filter bandpasses are shown where they are larger than the plotted points. The errors are about 5% of the flux for the AIRO data, and $\lesssim 3\%$ for the ground-based data. The heavy line is the fit of a 4200 K blackbody to the narrow-band data between 5.5 and 8 μ. The 8–13 μ excess spectrum (*pluses*) is the difference between the observed flux and the 4200 K fit to the data. The scale factor on the right side of the figure refers to the 8–13 μ excess flux.

REFERENCES

Forrest, W. J., Gillett, F. C., and Stein, W. A. 1975, *Ap. J.*, **195**, 423.
Gillett, F. C., and Forrest, W. J. 1973, *Ap. J.*, **179**, 483.
Gillett, F. C., Low, F. J., and Stein, W. A. 1968, *Ap. J.*, **154**, 677.
Gillett, F. C., Stein, W. A., and Solomon, P. M. 1970, *Ap. J.* (*Letters*), **160**, L173.
Gilman, R. C. 1969, *Ap. J.* (*Letters*), **155**, L185.
Hunt, J. M., Wisherd, M. P., and Bonham, L. C. 1950, *Anal. Chem.*, **22**, 1478.
Murcray, F. H., Murcray, D. G., and Williams, W. J. 1970, *J. Geophys. Res.*, **75**, 2662.
Salpeter, E. E. 1974, *Ap. J.*, **193**, 579.
Solomon, P. M., and Stein, W. A. 1966, *Ap. J.*, **144**, 825.
Woolf, N. J., and Ney, E. P. 1969, *Ap. J.* (*Letters*), **155**, L181.

W. J. FORREST: Center for Radiophysics and Space Research, 220 Space Sciences Blvd., Cornell University, Ithaca, NY 14850

R. W. RUSSELL and B. T. SOIFER: Department of Physics, University of California, San Diego, Mail Code C-011, La Jolla, CA 92037