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THE 10-MICRON EMISSION PEAK OF COMET BENNETT 1969*i*

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ABSTRACT

Photometric observations of Comet Bennett from 2 to 20 microns show a blackbody-like continuum at short wavelengths, and a sharp peak at 10 microns identified as due to silicate grains.

It has been proposed that silicates produce a 10-μ emission feature observed in the spectra of cool M stars (Gillett, Low, and Stein 1968; Woolf and Ney 1969; Gilman 1969). An apparently similar feature was observed in the spectrum of the Orion Nebula (Ney and Allen 1969; Stein and Gillett 1969), and the identification has been made more probable by the discovery of stellar SiO absorption (Knacke *et al.* 1969). The typical reaction for forming a silicate would be

$$\mathrm{SiO} + \mathrm{Mg} + 2\mathrm{H_2O} \rightleftharpoons \mathrm{MgSiO_3} + 2\mathrm{H_2} \,.$$

The tentative identification of an interstellar silicate absorption by Knacke *et al.* was consistent with this other evidence.

When the silicate identification was proposed, it seemed that the laboratory demonstration of the spectra of small solid particles in emission would be difficult, so that astrophysical evidence for the identification would be desirable. Silicates have up until now been known only in the solar system, with certainty for the Earth, Moon, and meteorites and by presumption in other bodies. Two cases in which the matter is finely divided and the presumption has some basis are for the zodiacal cloud and for comets. The evidence for the zodiacal cloud comes from observation of burnout zones (Peterson 1967; MacQueen 1968), where the high temperature associated with those closest to the Sun would imply highly refractory materials. The evidence for silicate dust in comets comes from the observed orbital association of comets and shower meteors, and from the spectra of shower meteors showing lines of Na, Ca, Mg, Fe, Al, and Si, as well as traces of Cr, Mn, Ni, and Sr (McKinley 1961). Cometary solids must be extremely fragile because comets break up so easily. If any large fragments of outgassed comets strike the Earth as meteorites and survive, they must be among the most friable fragile objects. A possible class of such objects are the carbonaceous chondrites (DuFresne and Anders 1963). The analysis of these objects shows them to be mainly silicates (Wood 1963).

Attempts have been made at the University of Minnesota to observe infrared emission both from the zodiacal cloud and from comets. This Letter reports our first successful observations on 1970 April 4 of Comet Bennett 1969*i*. The observations were made with a multifilter photometer attached to the 30-inch telescope of the O'Brien Observatory. The diaphragm diameter was 26″. Observations were also made of the star μ Cep in which the 10-μ emission peak is very strong, and the Orion Nebula had been previously observed with this system. Three of the filters for this sytem, with mean wavelengths of 8.5, 10.6, and 12.0 μ, were each 1 μ wide and were chosen to delineate the peak in

* Raymond Maas was largely responsible for this observation of the comet. He died of a heart attack within 24 hours of making the observation. He was already aware of this result and its significance before his death.

stars, with the central filter being chosen to measure the highest emission of the peak while avoiding the terrestrial 9.6-μ ozone band.

Figure 1 shows the spectra of the comet, of μ Cep, and the Trapezium region of the Orion Nebula. The absolute calibration at all wavelengths comes from observations of the planet Mercury and the assumption that it emits like a blackbody, together with observations of α Lyr and some cooler stars. In Figure 1, observations of Mercury are shown reduced by a factor of 100 to bring them on scale. The 620° K blackbody fitted through the points assumes an emissivity of 1 and the angular diameter of the planet on April 4.

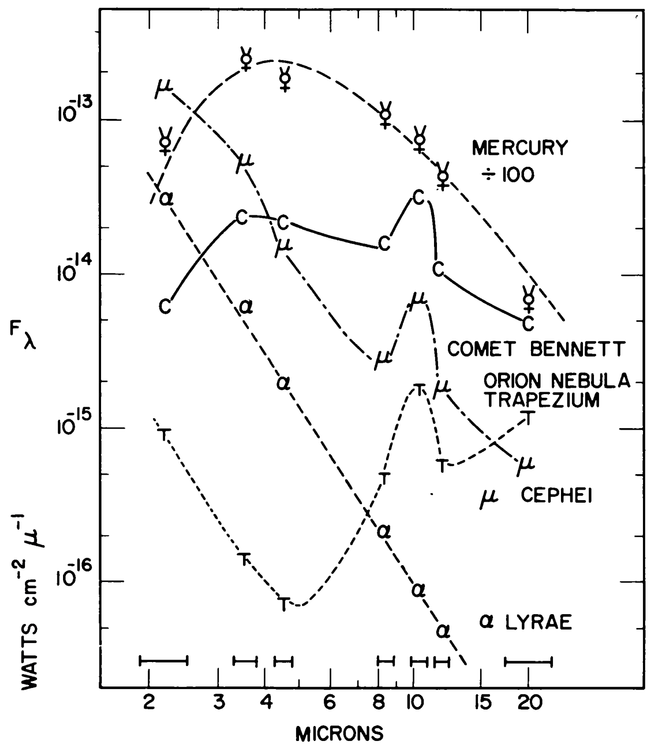

FIG. 1.—Comet Bennett spectrum compared with the spectra of two objects showing a 10-μ emission peak, μ Cep and the Trapezium region of the Orion Nebula. Two objects without this peak, observed with the same instrument, are also shown. The 620° K blackbody curve drawn through the measures of Mercury is appropriate for the angular diameter of the planet, fraction of the disk illuminated, and emissivity of 1. The widths of the filter bandpasses are shown above the wavelength scale.

Figure 2 shows that the cometary emission from 2 to 5 μ may be moderately well described by the shape of the 620° K blackbody. The comet's distance from the Sun was 0.64 a.u., and the black-sphere temperature at this distance is 350° K. Micron-sized particles would come into equilibrium with the radiation field in a fraction of a second. Becklin and Westphal (1966) have commented that the near-infrared color temperature also exceeded the black-sphere temperature for Comet Ikeya Seki up to approaches to the Sun where the color temperature exceeded 1000° K and the black-sphere temperature was 700° K.

The nuclear emission of the comet appeared to be slightly extended when traced with the 26″ diameter beam. The emission was about 4×10^4 times weaker than that expected from a 15″ diameter body of 620° K. Thus the comet was optically thin, although the individual emitting particles could be either optically thick or optically thin. The spectral distribution from 2 to 5 μ would be consistent with particles being optically thick. If so, however, the 10-μ peak could not be produced by the same particles because it rises far above the blackbody curve through the short-wavelength data. We shall therefore interpret the spectrum as being produced by two types of particles, one responsible for the 2- to 5-μ emission, and the other causing most of the 8- to 20-μ emission.

If the material responsible for the short-wavelength emission is similar in Comet Bennett and Comet Ikeya-Seki, then this must be a refractory material. Also, if the raising of the particle temperature above the black-sphere temperature is in part due to the fact that the particle size is less than the wavelength, the material must have a very high opacity for a grain to be optically thick. Possible materials fulfilling these conditions are iron (Becklin and Westphal 1966) and carbon.

The discovery of the 10-μ peak in the comet fulfilled the expectations of the silicate hypothesis and adds some weight to it. In all three objects of Figure 1 the 20-μ emission is also elevated, consistent with a second emission peak of silicates that is unfortunately partly hidden in the 15-μ terrestrial CO_2 absorption.

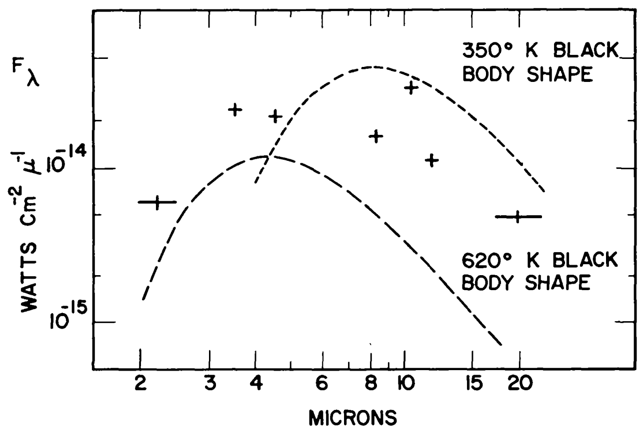

FIG. 2.—Observational points for Comet Bennett compared with the spectral shapes of a 620° K blackbody, and a 350° K blackbody appropriate to the black-sphere temperature of the comet's distance from the Sun.

If the silicate and blackbody particles had the same temperature, then the relative heights of the blackbody curves for the two types of particles would indicate the total projected areas of each of the materials. If the particles had the same sizes, then this ratio would also be the ratio of volumes and, for similar densities, the ratio of masses. Unfortunately, the silicate particles are optically thin, so that one knows only that the appropriate blackbody curve is above the 10-μ peak. With the assumptions above, we conclude that the mass of the silicate particles is several times greater than that of the blackbody particles. In the carbonaceous chondrites, the mass of the silicates exceeds 75 percent of the total, while the carbon abundance is sometimes as high as several percent. Within the great uncertainties bridged by the assumption above, this type of material could produce the observed spectrum.

From Figure 1, regardless of the identification of the material responsible for the 10-μ peak, it seems that the same material has been ejected from M giants, has survived in interstellar space, and has been incorporated in comets. DuFresne and Anders have commented that the material of the carbonaceous chondrites has an extremely varied history, with some material showing evidence of being produced in an oxidizing environment while others required a reducing environment. The theoretical study by Gilman shows that such different materials can be condensed from the atmospheres of cool stars merely by changing the abundance ratio of oxygen to carbon.

Studies of R CrB (Stein *et al.* 1969), R Lep (Woolf and Ney 1969) and RY Sgr (Lee and Feast 1969) suggest that carbon is ejected into space. The evidence from red giants like μ Cep suggests that silicates are ejected into space, while the observations reported here for Comet Bennett suggest that the mixture of these materials is present.

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REFERENCES

Becklin, E. E., and Westphal, J. A. 1966, *Ap. J.*, **145**, 445.
DuFresne, E. E., and Anders, E. 1963, *The Moon, Meteorites, and Comets*, ed. B. M. Middlehurst and G. P. Kuiper (Chicago: University of Chicago Press), pp. 496 ff.
Gillett, F. C., Low, F. J., and Stein, W. A. 1968, *Ap. J.*, **154**, 677.
Gilman, R. C. 1969, *Ap. J.* (*Letters*), **155**, L185.
Knacke, R. F., Gaustad, J. E., Gillett, F. C., and Stein, W. A. 1969, *Ap. J.* (*Letters*), **155**, L189.
Lee, T. A., and Feast, M. W. 1969, *Ap. J.* (*Letters*), **157**, L173.
McKinley, D. W. R. 1961, *Meteor Science and Engineering* (New York: McGraw-Hill Book Co.), pp. 141 ff.
MacQueen, R. M. 1968, *Ap. J.*, **154**, 1059.
Ney, E. P., and Allen, D. A. 1969, *Ap. J.* (*Letters*), **155**, L193.
Peterson, A. W. 1967, *Ap. J.* (*Letters*), **148**, L37.
Stein, W. A., Gillett, F. C., Gaustad, J. E., and Knacke, R. F. 1969, *Ap. J.* (*Letters*), **155**, L3.
Stein, W. A., and Gillett, F. C. 1969, *Ap. J.* (*Letters*), **155**, L197.
Wood, J. A. 1963, *The Moon, Meteorites, and Comets*, ed. B. M. Middlehurst and G. P. Kuiper (Chicago: University of Chicago Press), pp. 337 ff.
Woolf, N. J., and Ney, E. P. 1969, *Ap. J.* (*Letters*), **155**, L181.