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SPECTROPHOTOMETRY OF OH 26.5+0.6 FROM 2 TO 40 MICRONS

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ABSTRACT

Airborne and ground-based observations show that OH 26.5+0.6 has strong 10 μm and weak 18 μm silicate absorptions superposed on an overall energy distribution much like a blackbody. The flux level, color temperature, and depth of the 10 μm absorption have varied during 2 years of observations. A model of the source as a late-type variable star that has ejected an optically thick dust shell is suggested; the mass-loss rate implied is greater than $\sim 10^{-5}\, M_\odot$ year^{-1}. The fact that significant flux from the source is observed between 4 and 7 μm is evidence that oxygen-rich dust has significant opacity in that wavelength range.

Subject headings: infrared: sources — stars: circumstellar shells — stars: late-type — stars: mass loss

I. INTRODUCTION

The source OH 26.5+0.6 was first discovered by Andersson *et al.* (1974) to be a bright 1612 MHz OH maser source and was classified by them as a type II OH source. Quite independently, OH 26.5+0.6 was found to be a bright 10 μm infrared source, designated as CRL 2205 (Walker and Price 1975). Workers at the University of Arizona (Low *et al.* 1976) obtained an accurate position and listed the source as UOA 19, and it was one of the sources studied by Evans and Beckwith (1977). This paper reports infrared spectrophotometric observations from 2 to 40 μm of this interesting infrared/OH maser source, obtained over a 2 year period. The source is variable on time scales of months in both flux density and spectral shape.

II. OBSERVATIONS

The observations reported here were obtained between 1974 May 3 and 1976 June 25; a variety of telescopes and spectrometer systems have been used. The observing log is given in Table 1 and lists the observer, wavelength range, and telescope employed. The 2–4 μm, 4–8 μm, and 8–13 μm observations were all obtained with filter wheel spectrophotometers of basically the same design (Gillett and Forrest 1973), while the 16–40 μm observations were obtained with a cooled grating spectrophotometer (Forrest, Houck, and Reed 1976). All the observations were obtained with resolution $\Delta\lambda/\lambda \approx 0.01$–$0.02$ except for the 25–40 μm observations, for which $\Delta\lambda/\lambda \approx 0.08$. The telescopes used were the UCSD–University of Minnesota 1.5 m infrared telescope on Mount Lemmon, the 1.3 and 2.1 m telescopes at Kitt Peak National Observatory, and the 90 cm telescope of the Kuiper Airborne Observatory flying at an altitude of 12.5 km (41,000 feet).

The 2–40 μm spectrum of OH 26.5+0.6 obtained between 1976 May 21 and 1976 June 25 is shown in

TABLE 1
OBSERVING LOG

Date (UT)	Wavelength Range (μm)	Telescope	Aperture (arcsec)	Observer
1974 May 3............	8–13	Mount Lemmon 1.5 m	22	K. M. M.
1974 May 21............	8–13	Mount Lemmon 1.5 m	22	B. T. S., R. W. R.
1974 October 2..........	8–13	KPNO 2.1 m	7	F. C. G.
1975 March 24..........	2–4	Mount Lemmon 1.5 m	17	B. T. S., R. W. R.
1975 April 28...........	2–4	Mount Lemmon 1.5 m	17	B. T. S., R. W. R.
1975 May 1............	8–13	KPNO 1.3 m	11	F. C. G.
1975 May 27............	8–13	KPNO 2.1 m	10	J. L. P., B. T. S.
1976 May 6............	2–4	Mount Lemmon 1.5 m	17	B. T. S., R. C. P.
1976 May 21............	16–40	KAO 90 cm	30	J. R. H., W. J. F., J. F. McC.
1976 May 28............	4–8	KAO 90 cm	30	B. T. S., R. W. R., S. P. W.
1976 June 20, 24.........	2–4	Mount Lemmon 1.5 m	17	K. M. M., R. W. R.
1976 June 25............	8–13	Mount Lemmon 1.5 m	17	K. M. M., R. W. R.

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Figure 1. The broad-band 8.4 μm photometry obtained on 1976 May 28 from the KAO and on 1976 June 25 from Mount Lemmon indicate that the flux at this wavelength agreed to 0.01 mag, so no normalization corrections were applied to the plotted data.

The spectrum shows several distinct features superposed on a smooth continuum that, from 2 to 4 μm, approximates a blackbody at a temperature of about 375 K, as shown in Figure 2. The most significant deviations from a smooth continuum are a deep absorption feature at 10 μm and a weaker feature near 18 μm; such features are characteristic of silicate materials. In position and shape, the 18 μm feature is similar to the emission feature seen in the Trapezium by Forrest and Soifer (1976) and Forrest, Houck, and Reed (1976). The 18 μm absorption in OH 26.5+0.6 was first detected by Simon and Dyck (1975).

There are also some very weak features that appear to be absorptions near 2.4 and 3.1 μm, although the location of the continuum is uncertain. The upper portion of Figure 2 most clearly illustrates the presence of these features. The wavelengths of the features suggest identification as gaseous CO and H_2O absorption, respectively, in a stellar photosphere (Merrill and Stein 1976). The feature near 3 μm is unlikely to be the 3.1 μm ice band absorption, because, within the dense region of the circumstellar envelope, the grain temperature is almost certainly higher than 100 K, at which temperature ice will rapidly sublime. Interstellar grains apparently cannot produce appreciable ice absorption outside the protection of dense molecular clouds (Merrill, Russell, and Soifer 1976), which are not present here.

If the 2.4 and 3.1 μm depressions are photospheric absorptions, the flux removed by these bands is a lower limit on the "unabsorbed" photospheric flux at these wavelengths. This lower limit at 2.5 μm, combined with a 3 σ upper limit (obtained 1976 May 13) of 1.7×10^{-19} W cm^{-2} μm^{-1} on the 1.65 μm flux, places a lower limit on the reddening between 1.65 and 2.5 μm of about 5.8 mag. To derive this limit, it was assumed that the temperature of the photosphere is 2000 K and that there is no photospheric absorption at 1.65 μm. A [1.65 μm] − [2.5 μm] color excess of 5.8 mag corresponds to a visual extinction of about 70 mag; a similar result is obtained from the 3.1 μm feature.

The spectra of OH 26.5+0.6 show that the source is variable both in amplitude and spectral shape. The lower spectrum in Figure 1 was obtained in late April and early May of 1975. The upper spectrum was obtained in 1976 May when the source was in a relatively bright phase; the 8 μm flux was about a factor of 2 higher than in 1975 April–May. During this period the 2–4 μm flux increased more than did the 8 μm flux, and the 2–4 μm color temperature increased from about 350 to 375 K. Also, when the flux and temperature were lower, the depth of the 10 μm silicate feature was greater by roughly 0.4 optical depths. This behavior is consistent with a model consisting of a variable star surrounded by an optically thick dust shell, as discussed below.

The observations that cover the longest time interval and best show the variability are those of the 8–13 μm spectrum. Figure 3 shows the 8–13 μm spectra obtained over 2 years. The decreasing depth of the 10 μm absorption with increasing flux is readily seen in these spectra.[1]

III. DISCUSSION

The major characteristics of OH 26.5+0.6 are the presence of a type II OH/IR source, an overall energy distribution within a factor of 3 of being like that of a blackbody, and a deep silicate absorption. These characteristics suggest a model of this object as a central star surrounded by a localized cloud of gas and dust that is optically thick at visual wavelengths and is reradiating the stellar luminosity at infrared wavelengths. The type II OH classification and luminosity variability suggest that we are observing a star in the late stages of stellar evolution that is undergoing large mass loss. That OH 26.5+0.6 is in a late stage of evolution is consistent with the absence of nearby H II regions, large molecular clouds, or young stellar objects.

a) The 10 and 18 μm Absorption Features

The 10 and 18 μm absorption bands, which are identified with the stretching and bending modes, respectively, of silicate minerals, provide useful information concerning the environment within the opaque circumstellar envelope. These absorptions are produced in a cloud of material that is colder than that producing the underlying emission. The fact that the depth of the 10 μm absorption decreases as the infrared luminosity increases is evidence that the absorbing dust is local to the energy source. It is our interpretation that the varying luminosity of the central source within the cloud modulates the dust temperature, causing the apparent change in the 10 μm absorption depth.

The 18 μm absorption is much weaker than that at 10 μm (Fig. 1), even though the absorptivities of the two features are comparable (Forrest, Houck, and Reed 1976). The weakness of the 18 μm feature probably indicates that the dust that is absorbing at 10 μm is warm enough to radiate significantly at 18 μm (Kwan and Scoville 1976). The formulation of Jones and Merrill (1976) suggests that the relative apparent depths of the features are consistent with the presence

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[1] Observations obtained 1977 April 21 from Mount Lemmon give the following narrow-band flux densities: 8.00 μm, 6.0×10^{-15}; 10.0 μm, 7.1×10^{-16}; 12.5 μm, 2.6×10^{-15} W cm^{-2} μm^{-1}. Observations obtained 1977 June 22 from the KAO have a better signal-to-noise ratio than those presented in Fig. 1 and give the following flux densities: 16.0 μm, 1.45×10^{-15}; 18.5 μm, 1.10×10^{-15}; 21.0 μm, 1.05×10^{-15}; 30 μm, 5.3×10^{-16}; 38 μm, 2.6×10^{-16} W cm^{-2} μm^{-1}. These flux densities are the brightest yet observed for this object and indicate that the period, if any, is longer than 3 years. The spectral shape is similar to that shown in Fig. 2, but the 9.5 and 18.5 μm absorptions are the shallowest yet seen. The change in absorption depth is in qualitative agreement with the model suggested in § III.

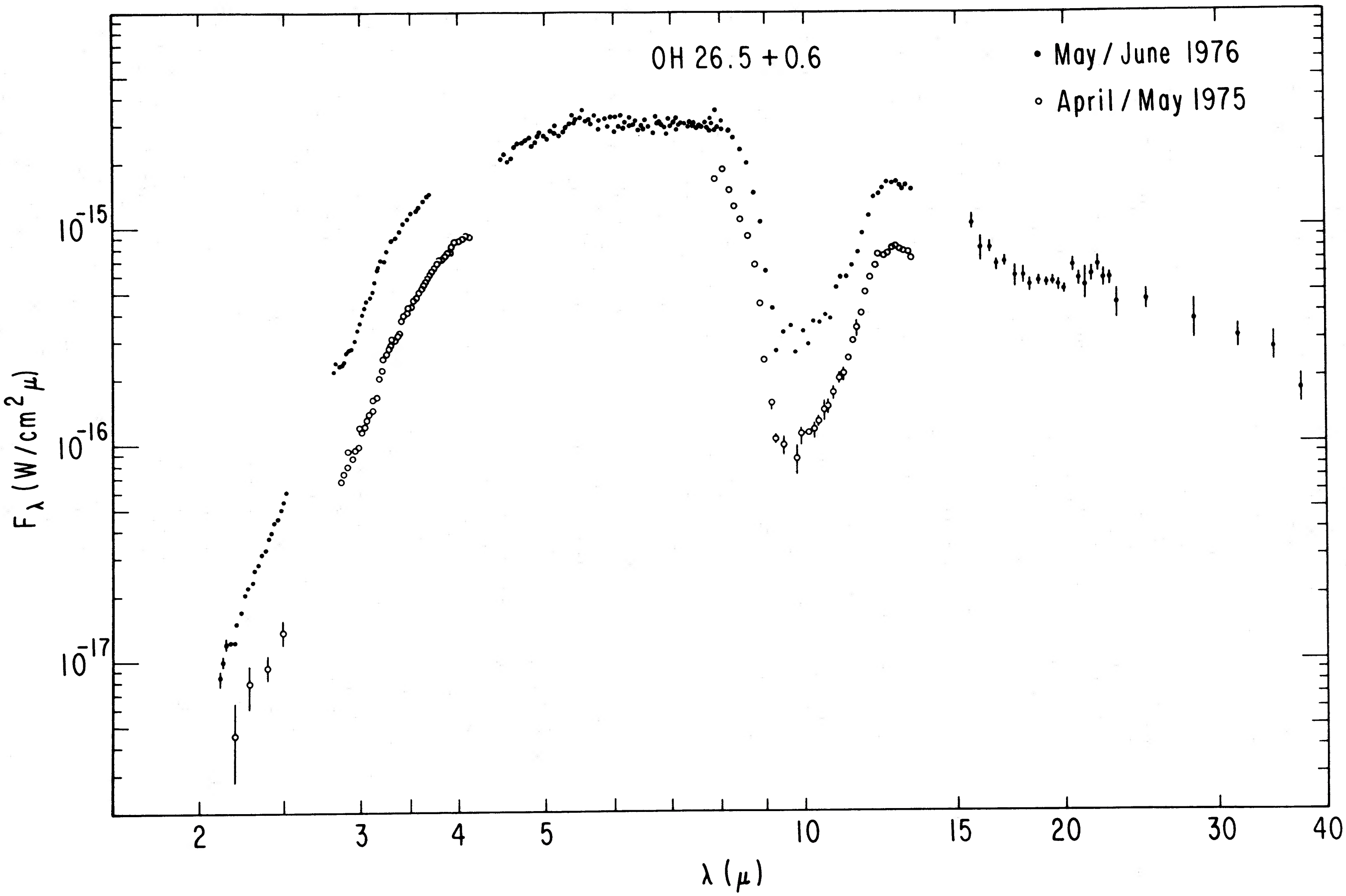

FIG. 1.—Two to 40 μm spectra of OH 26.5+0.6. Error bars are shown for points whose statistical uncertainties exceed 5%.

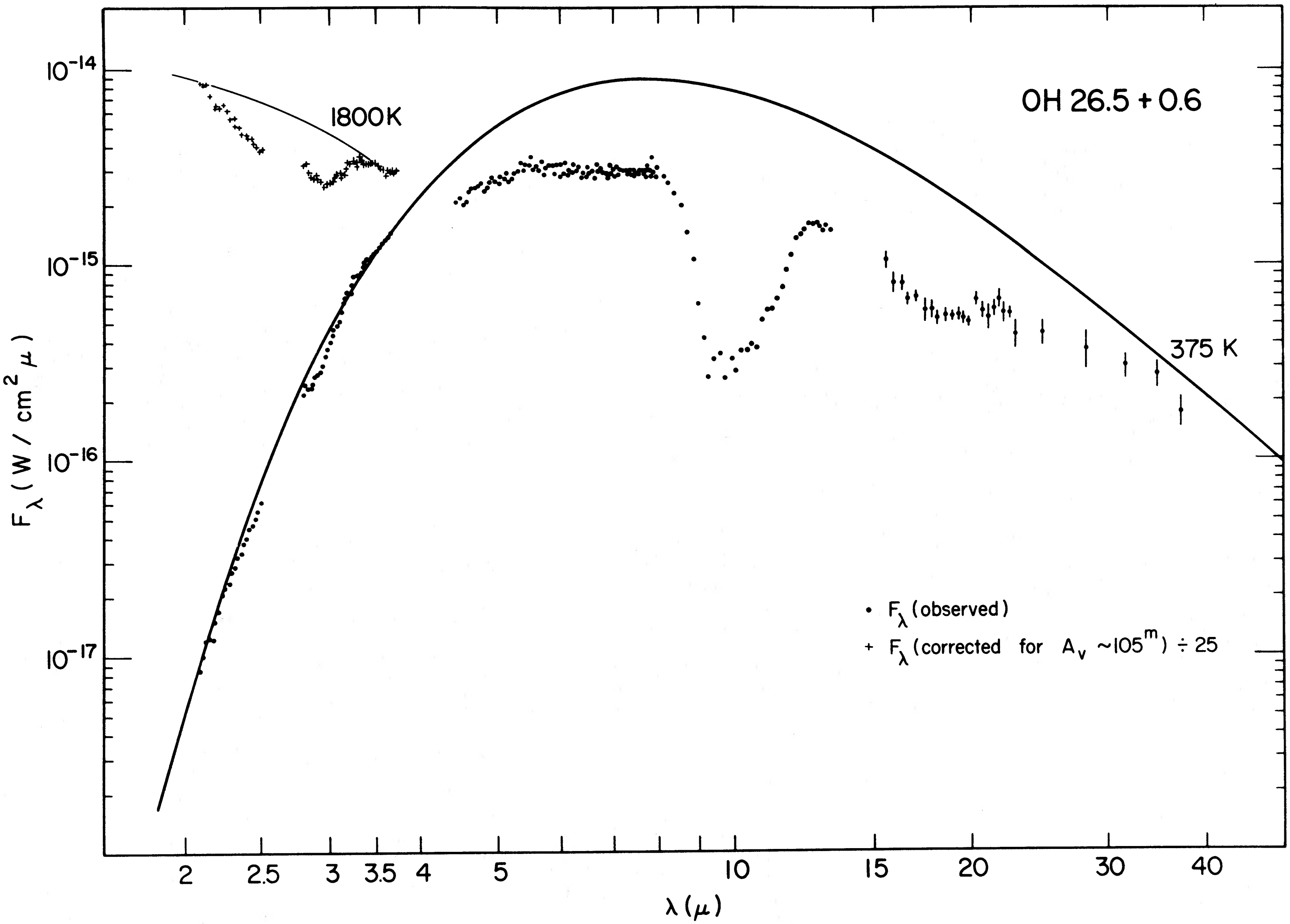

FIG. 2.—Spectrum of OH 26.5+0.6 obtained in 1976 May–June. The solid line represents a 375 K blackbody fit to the 2–4 μm data only. The pluses in the upper portion of the figure are the 2–4 μm data, corrected for an amount of reddening corresponding to A_V = 105 mag. The thin line represents a blackbody fit through the corrected 2.0 and 4.0 μm points. This portion of the figure is meant only to illustrate the 2.4 and 3.1 μm features; the amount of reddening was chosen arbitrarily.

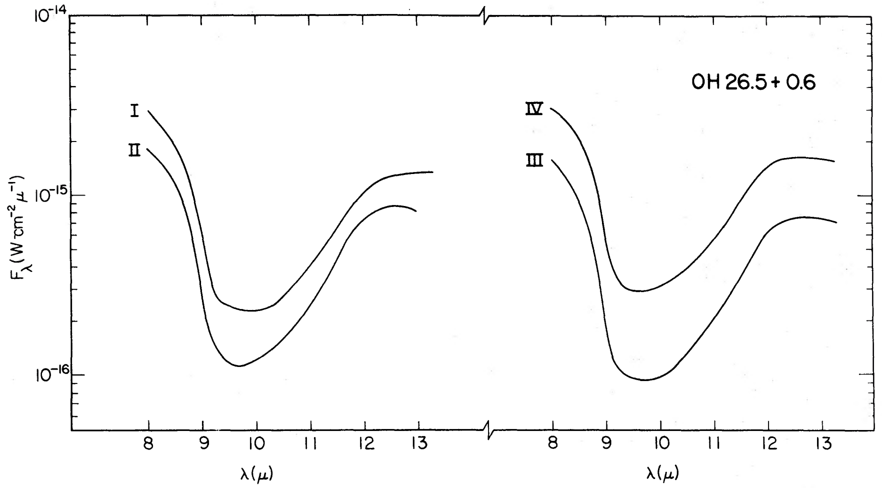

FIG. 3.—Eight to 13 μm spectra obtained at four different times. The larger apparent depth of the absorption when the source is fainter is seen. The dates of the spectra are I: 1974 May 3 and 21, II: 1974 October 2, III: 1975 May 1 and 27, and IV: 1976 June 25.

in the circumstellar envelope of substantial optical depth due to dust at $T \geqslant 160$ K (the Wien-law temperature for an energy distribution having a maximum at 18 μm) and comparatively smaller optical depth due to colder dust.

Because the dust producing the 10 μm absorption is apparently warm enough to emit at 18 μm, it is physically unrealistic to describe the emergent spectrum from the circumstellar dust envelope as an "underlying continuum" suffering absorption from relatively cold dust. Although such a description may be useful in a qualitative or even semiquantitative sense, a complete radiative-transfer calculation (Jones and Merrill 1976; Kwan and Scoville 1976; Finn and Simon 1977) is needed. Detailed knowledge of the wavelength-dependent dust emissivity is a prerequisite for such a calculation. The spectra presented here will restrict the range of possible solutions.

Preliminary models, based on the formulation of Jones and Merrill (1976), for dust shells with 10 μm optical depths greater than 6 surrounding M-type stars produce reasonable agreement with the observed spectrum (Jones, private communication). The relative 10 and 18 μm absorption depths, the variation of apparent 10 μm optical depth with luminosity, and the weak absorption features near 2.4 and 3.1 μm can be reproduced. The agreement of the model with the observations indicates that the picture of an optically thick dust envelope surrounding a cool variable star is reasonable.

b) *Optical Depth in the Shell*

The amount of extinction A_λ through the shell at short wavelengths can be estimated from the ratio of the observed flux density F_λ to that expected from the central star alone; that is,

$$A_\lambda \geq 2.5 \log [\Omega_* B_\lambda(T_*)/F_\lambda]\,, \tag{1}$$

where Ω_* is the solid angle subtended by the star and B_λ is the Planck function. T_* is the central star temperature, which is taken to be 2000 K; the result is insensitive to the temperature assumed. Equation (1) gives only a lower limit on A_λ, because circumstellar dust may contribute to the emission. The solid angle subtended by the central star may be estimated from the requirement that energy be conserved in the radiation-transfer process, so

$$\Omega_* \frac{\sigma}{\pi} T_*^4 = \int_0^\infty F_\lambda d\lambda\,. \tag{2}$$

It is found that at least 7 mag of extinction are required at 2.2 μm, indicating a visual extinction $A_V \geq 80$ mag. If $A_V \geq 80$ mag, the 10 μm optical depth through the shell is $\tau_{10\,\mu\text{m}} \geq 6$ if the dust materials are similar to those in the line of sight to VI Cyg No. 12 (Gillett *et al.* 1975). The model calculations of Jones and Merrill (1976) indicate that an optical depth $\tau_{10\,\mu\text{m}} > 6$ would indeed be required to fit the observed spectrum of this source.

The very large optical depth inferred here indicates that most of the extinction must be local to the source, in agreement with the previous discussion of the 10 and 18 μm absorption features. The extinction appears to be large enough to be consistent with the identification of the 2.4 and 3.1 μm absorption features as photospheric features of a late-type star. Finally, the large optical depth implies that the mass-loss rate from this star must be quite large, as discussed below.

c) *The Mass Loss from* OH *26.5+0.6*

The strong radiation pressure exerted on the dust grains surrounding a very luminous star will accelerate the grains and associated gas and result in mass loss from the circumstellar envelope (Gehrz and Woolf 1971; Gilman 1972; Salpeter 1974). The rate at which mass is lost can be estimated from the outflow velocity and the observed infrared spectrum. For type II OH sources, the velocity of outflow is probably one-half the separation of the two emission peaks (Elitzur, Goldreich, and Scoville 1976, and references therein); that this velocity is found to be constant with time (Wilson and Barrett 1972) indicates a steady-state mass loss.

One estimate of the mass-loss rate comes from the requirement that linear momentum be conserved in the radiation-transfer process (Forrest 1974; Salpeter 1974). The observed spectrum indicates that stellar radiation is absorbed by the dust grains and reradiated; this process produces a radial acceleration of the circumstellar shell. In order to conserve momentum in the shell, mass must be entering the shell at a rate $\dot{M}$, given by (Salpeter 1974):

$$\dot{M} \approx (\tau_s/Vc)\mathscr{L}_* , \tag{3}$$

where V is the observed final velocity, c the speed of light, $\mathscr{L}_*$ the stellar luminosity, and τ_s the effective radiation-pressure optical depth through the shell. This is part (2) of equation (11) of Salpeter (1974), with a factor of 2 correction (Salpeter, private communication) and with gravitational force ignored in comparison with the force from radiation pressure. A reasonable estimate is that $0.4\tau_{2.2\,\mu\mathrm{m}} \lesssim \tau_s < \tau_{2.2\,\mu\mathrm{m}}$, because the optical depth at 2.2 μm is greater than that at any longer wavelength, except for wavelengths within the 9.7 μm silicate band. For an observed outflow velocity $V \approx 13$ km s^{-1} (Andersson *et al.* 1974), a lower limit $\tau_{2.2\,\mu\mathrm{m}} \gtrsim 7$, and a luminosity $\mathscr{L}_* \approx 10^4\,\mathscr{L}_\odot$ typical of Mira variables (Smak 1966; Lee 1970; Evans and Beckwith 1977), the mass-loss rate $\dot{M} \gtrsim 4.5 \times 10^{-5}\,M_\odot$ year^{-1}.

A second estimate of the mass-loss rate arises from the requirement that $\tau_{10\,\mu\mathrm{m}} \geq 6$ in silicate dust through the circumstellar cloud. For radiation-pressure–driven mass loss, with all the dust condensing at a distance $R_0/r_* > 1$, the approximate mass-loss rate will be given by part (1) of equation (11) of Salpeter (1974):

$$\dot{M} = 2\pi(\tau_\lambda/f\kappa_\lambda)R_0 V , \tag{4}$$

where κ_λ is the mass opacity coefficient of the dust and f is the fraction of mass in dust. Equation (4) expresses the column density in terms of the optical depth and mass opacity at a particular wavelength, rather than in terms of wavelength-averaged quantities as in Salpeter (1974). For silicate dust, $f \leq 1/300$ for cosmic abundances, $\kappa_{9.7\,\mu\mathrm{m}} \approx 3 \times 10^3$ cm^2 g^{-1} (Gillett and Forrest 1973), and $\tau_{9.7\,\mu\mathrm{m}} \gtrsim 6$. Theory (Jones and Merrill 1976) and observation (Zappala *et al.* 1974) indicate that $R_0/r_* \gtrsim 3$ for stars of this type, which for $r_* = 6.5 \times 10^{13}$ cm—corresponding to $\mathscr{L}_* = 10^4\,\mathscr{L}_\odot$ and $T_* = 2000$ K—gives an estimated mass-loss rate of $\dot{M} \geq 1.5 \times 10^{-5}\,M_\odot$ year^{-1}. Within the uncertainties, this is in agreement with the previous estimate of mass loss; both estimates indicate a mass-loss rate for this star more than an order of magnitude larger than Gehrz and Woolf (1971) found for typical M-type Mira variables with thinner circumstellar shells.

The mass-loss rates found here are in good agreement with the models for type II OH/IR stars discussed by Goldreich and Scoville (1976) and Elitzur *et al.* In these models the size of the OH maser source is $R \approx 3 \times 10^{16}$ cm, so the time scale for this phase of stellar evolution is at least $R/V \approx 10^3$ years. During this phase, OH 26.5+0.6 has ejected a total of at least $\sim 2 \times 10^{-2}\,M_\odot$ in gas and dust into the interstellar medium; this mass estimate depends primarily on the model of mass loss for the source and the luminosity estimate, rather than on the details of the observations.

d) *The Nature of the Dust*

If OH 26.5+0.6 is a star in the process of shedding mass, then the circumstellar dust is manufactured in the shell of ejected material. The presence of silicates and OH indicates that the material is oxygen rich; presumably this material is typical of oxygen-rich material ejected into the interstellar medium. Terrestrial silicates have very little opacity shortward of 7 μm; this fact makes it difficult to fit silicates into the framework of interstellar dust, because some additional source of opacity is needed to provide the known opacity of interstellar dust for $\lambda < 7\,\mu$m. The spectrum of OH 26.5+0.6 shows substantial emission at $\lambda < 7\,\mu$m and indeed is within a factor of 3 of a blackbody curve from 4 to 7 μm. If the emission at these wavelengths were from the photosphere, the central star would be radiating more energy than is observed. Most of the emission must therefore come from the dust; this shows that the oxygen-rich material produced in OH 26.5+0.6 has significant opacity at these wavelengths.

e) *Summary*

It appears that OH 26.5+0.6 is a late-type variable star which is losing mass. The extreme thickness of the dust shell implies that the rate of mass loss is greater than $\sim 10^{-5}\,M_\odot$ year^{-1}; this rate is one of the largest known for such stars.

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