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THE PERPLEXING SPECTRUM OF AFGL 2789 (V645 CYGNI)

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ABSTRACT

Visual spectra and photometry from 0.35 to 18 μm show that AFGL 2789 may be one of the most interesting of the infrared sources now identified with reflection nebulae. It has an Ae-type shell spectrum with strong emission lines of hydrogen, Fe II, Cr II, and Ti II, but the most remarkable feature is a broad absorption band near 5500 Å, presumably molecular, with three possible band heads. This absorption band was present on only one of two spectra taken one night apart. The two known molecules with wavelengths closest to the observed band heads are C_2 and H_2O^+, although there are problems with either of these as possible identifications.

Subject headings: infrared: sources — nebulae: reflection — stars: circumstellar shells — stars: individual

I. INTRODUCTION

The infrared object AFGL 2789 (V645 Cygni) is a member of a growing class of infrared sources now identified with distinctive visual reflection nebulae illuminated by obscured stars. Cohen (1977) discussed spectrophotometric, polarimetric, and radio continuum observations of AFGL 2789, and has modeled the object as a bipolar nebula. Our more recent spectroscopic and photometric observations show that AFGL 2789 may be one of the more interesting objects of its kind. The photographic spectra indicate a typical Ae-type shell spectrum with strong Ca II H and K lines, and P Cygni profiles at Hβ, Hγ, and the strongest Fe II lines. Yet the most intriguing and perplexing feature of these spectra is the appearance of a broad absorption band, presumably molecular, near 5500 Å, which was quite strong one night, but was not detectable the preceding night. The spectra, the optical and infrared photometry, and possible identifications of the absorption band at 5500 Å are discussed in this *Letter*.

II. OBSERVATIONS

Broad-band photometry of AFGL 2789 at wavelengths from 0.36 to 18 μm was obtained with a variety of systems. The *UBVR* observations were made with an RCA 31034 GaAs phototube on the Mark I "computer photometer" at the KPNO 84 inch (2.1 m) telescope on 1978 August 30 and 31 (UT). The optical photometry, summarized in Table 1 and shown in Figure 1, applies only to the NW filament of nebulosity (cf. the photograph in Cohen 1977) and excludes the more condensed nebulosity to the south and east which appears almost stellar (Cohen's position N0). In Figure 1 we show our optical photometry both for the filament which includes Cohen's positions N1 and N2 and for the filament plus his synthesized photometry for position N0.

The infrared broad-band photometry from 1.2 to 18 μm was obtained with the University of Minnesota bolometer system at the O'Brien Observatory 30 inch (0.8 m) telescope (26″ beam) and the UM-UCSD 60 inch (1.5 m) telescope (9″ beam) at Mount Lemmon and with the InSb photovoltaic and Ge:Hg photoconductive systems (18″ beam) at Mount Lemmon. The infrared-averaged photometry, summarized in Table 1 and shown in Figure 1, refers to the position of peak 3.6 μm flux without reference to specific optical features. No significant beam size effects were evident in the 9″–26″ range, and the individual observations agree to ~15%. The IR spectrophotometry with a resolving power of $\lambda/\Delta\lambda \sim 65$ was obtained at Mount Lemmon (18″ beam) with essentially the same systems used by Merrill and Stein (1976*a*, *b*). The spectra at 2.09–3.63 μm and 8.0–13.1 μm shown in Figure 1 were obtained on 1977 October 24 and 1976 November 30, respectively. The IR data in Table 1 and the 10 μm spectrum are in excellent agreement with those of Gosnell, Hudson, and Puetter (1979) obtained with the same instrument. The fluxes reported by Lebofsky *et al.* (1976) are in agreement at 3.6 and 10 μm but are significantly lower at 2.2 and 5 μm. The 4.6 μm datum of Joyce *et al.* (1977) is significantly higher.

As can be seen in Figure 1, in the infrared the overall energy distribution is broader than that of a blackbody and resembles a circumstellar dust envelope with a range of temperatures. Since the energy distribution has not yet "turned over" at 20 μm, the dust envelope

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1980ApJ...237L..17H

TABLE 1

Average Photometric Data for AFGL 2789

$\lambda_{\rm eff}$ ($\Delta\lambda$) (μm)	Magnitude	Note
U: 0.365	+15.74	1
B: 0.44	+15.16	1
V: 0.55	+14.06	1
R: 0.70	+12.91	1
1.2 (0.14)	+9.3	2
1.65 (0.30)	+7.1	2, 5, 6
2.28 (0.50)	+4.8	2, 3, 4, 5, 6
3.6 (1.2)	+2.6	2, 3, 4, 6
4.8 (1.0)	+1.2	3, 4, 6
8.5 (.85)	−0.4	3, 4, 6
10.5 (1.1)	−0.7	3, 6
11.2 (2.0)	−1.1	4
12.2 (1.1)	−1.5	3, 6
12.5 (1.2)	−1.5	4
18 (4.7)	−3.0	3, 6

Note.—Observing log for averaged data: (1) 1978 Aug 30/31 KPNO (GaAs phototube); (2) 1976 Sep 6 Mount Lemmon (InSb); (3) 1976 Nov 14 O'Brien (bolometer); (4) 1976 Nov 29 Mount Lemmon (photoconductor); (5) 1977 Oct 24 Mount Lemmon (InSb); (6) 1977 Nov 22 Mount Lemmon (bolometer).

contains considerable cold material. The 2–4 μm spectrum is featureless at this resolution with an apparent blackbody temperature of $\sim$1000 K. At higher resolution, Harvey and Lada (1980) report detection of weak Brackett series hydrogen emission lines. At 10 μm, AFGL 2789 closely resembles LkHα 101 (AFGL 585) and AFGL 989 (Merrill and Stein 1976*a*, *b*), which are also embedded sources. The broad 9.7 μm absorption band attributed to silicates dominates the otherwise featureless 10 μm spectrum. The energy received from AFGL 2789 between 1 and 21 μm is 6.3×10^{-16} W cm^{-2}, which, with a conservative correction for an assumed Rayleigh-Jeans distribution at longer wavelengths, gives a total energy of 7.5×10^{-16} W cm^{-2} radiated into a spherical shell.

The photographic spectra $\lambda\lambda$3500–6000 were obtained at 79 Å mm^{-1} with the "gold" spectrograph, scanning plateholder, and three-stage image tube on the KPNO 4 m telescope. The spectra were taken on 1978 September 8 and 9 (UT) with exposure times of 10 and 20 minutes on nitrogen-baked IIa-O plates. Both spectra correspond to Cohen's position N1 and are reproduced in Figure 2 (Pl. [L2]).

The absorption-line spectrum of AFGL 2789 can be classified A5e on the basis of the strong Ca II H and K lines, the higher Balmer lines (Hδ, Hϵ, Hζ, etc.), and the metallic lines. Cohen (1977) assigned a spectral type O7 to the underlying star primarily because of weak He I lines, the strength of Hα, and radio continuum emission from a surrounding nebulosity. Lines of He II such as $\lambda\lambda$4686, 4542, which should be present in an O star are absent from both his and our spectra. A possible feature in the noise to the blue of the Na I D lines in our first spectrum might be due to He I λ5876, but it is not present in the second spectrum. Other He I lines sharing the same lower state ($\lambda\lambda$4471, 4026, and 3819) are not present in our spectra. A hot star might be revealed by ultraviolet spectra, or as Cohen points out, indirectly by observation of an associated ionized nebula; however, the absence of nebular emission lines of [O III] and [O II] restricts the physical conditions in any photoionized region. The strongest emission lines are identified with H, Fe II, Cr II, and Ti II. The identification and relative strengths of the strongest emission and absorption features in our spectra agree well with the strongest lines listed by Herbig (1960) for the Ae-type star V380 Ori.

Eight absorption lines without P Cygni profiles give a mean heliocentric velocity of -297 ± 15 km s^{-1}, while 11 emission lines yield a heliocentric velocity of $+10 \pm 9$ km s^{-1} (-4 km s^{-1} LSR). Two Balmer lines (Hβ and Hγ) and the three strongest Fe II lines have P Cygni profiles for which the mean velocity difference between absorption and emission is 339 km s^{-1}. The A-type absorption spectrum is produced in an expanding shell, and there is no evidence in our spectra about the nature of the underlying star.

The most interesting feature of our observations is the absorption band near 5500 Å, which is very obvious on the September 9 spectrum, but not present at all on the spectrum from the previous night. The sudden appearance of this feature may cast some doubt upon its reality; however, nothing resembling this feature has been seen in previous spectra taken with this spectrograph, so it is unlikely to be due to an instrumental effect or to the residual spectral image of a brighter star. The short variability ($\sim$1 day) also suggests that this absorption band might have arisen in the Earth's atmosphere. However, the difficulty of identification with a common molecule (see § III) and the lack of previous reports in astronomical spectra make an atmospheric origin seem doubtful. It could be attributed to some freak atmospheric phenomenon, but the weather conditions on the night the spectrum was taken were normal. It was a clear night.

This broad absorption feature seems to be molecular in origin. Close examination of Figure 2 shows that the feature is composed of three distinct bands, and the band heads have rest wavelengths of approximately 5530 (5523), 5512 (5506), and 5495 (5488) Å, assuming the mean absorption (emission) line velocity.

III. DISCUSSION

The "molecular" bands in the broad absorption feature near 5500 Å do not correspond to any commonly recognized features in Ae-type stars or pre–main-sequence stars. If the three "band heads" are assumed to represent the *P*-, *Q*-, and *R*-branches of the same band, their separations imply a rotation constant $B \approx 28$–30 cm^{-1}. Such a large value would suggest a diatomic hydride or triatomic dihydride, but with so little information about the absorber, attempts at identification must be considered highly speculative. Alternatively, the "band heads" might be different bands in the same progression. One identification of each variety can be suggested, namely H_2O^+ and C_2, but neither is entirely satisfactory.

The apparent wavelengths agree approximately with

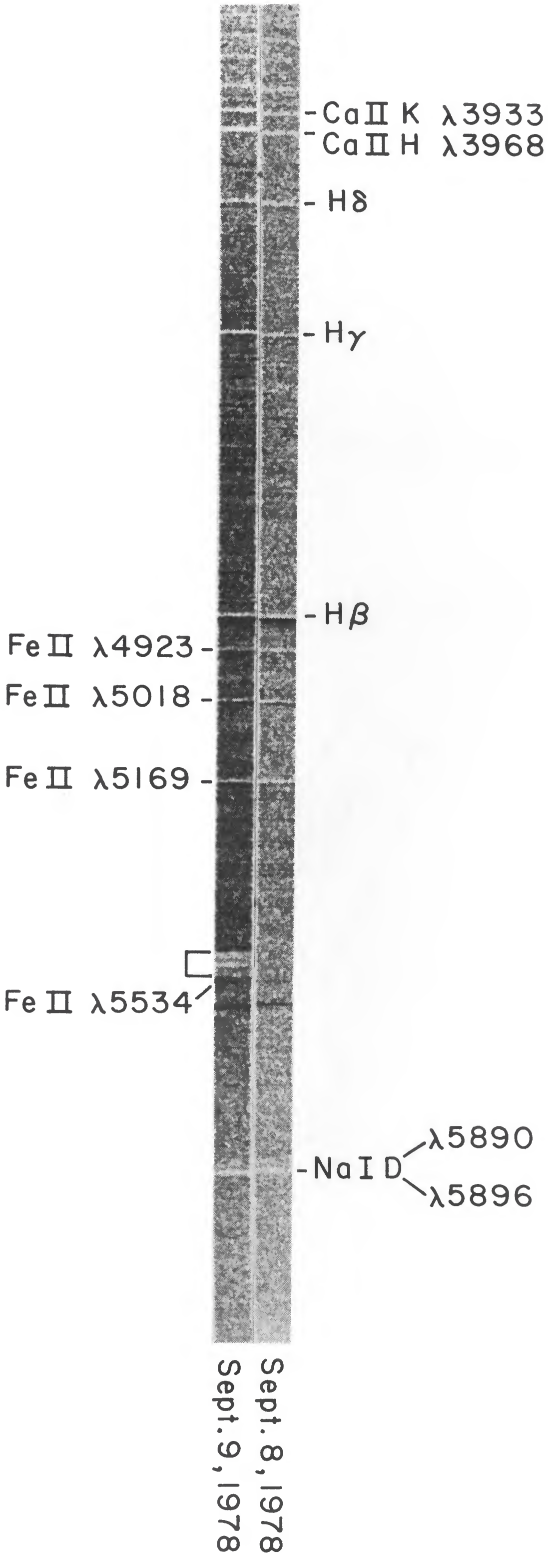

FIG. 2.—Two spectra of AFGL 2789 obtained on 1978 September 8 and 9 (UT). The strongest absorption and emission lines are identified, and the position of the molecular feature is marked with a bracket. The strong emission line to the red of λ5539 is due to [O I] λ5577, which is mostly night sky.

HUMPHREY *et al.* (*see* page L18)

bands in the $\Delta V = -1$ progression of the Swan system of C_2: 2–3, 5540.7 Å; 3–4, λ5501.9 Å; and 4–5, 5470.3 Å. Neither the 0–1 band (λ5635) nor the 1–0 band (λ4737) is discernible in the spectra, and the P Cygni profile of the line at 5169 Å argues against its identification with the 0–0 band rather than Fe II. The absence of *stronger* bands (4–3, 5–4, and 6–5, all near 4680 Å) expected from the same lower vibrational states adds further doubt to an identification with the $\Delta V = -1$ progression of the C_2 Swan system.

A slightly more plausible identification is the $^2A_1$–$^2B_1$ (0, 10, 0)–(0, 0, 0) band of H_2O^+, first observed astronomically in emission in Comet Kohoutek (Wehinger *et al.* 1974). The spin doublets of greatest line strength in this band are at 5478.55, 5481.22; 5510.76, 5512.44; and 5519.79, 5523.06 Å (Lew 1977). If this identification were correct, one would expect to see the (0, 11, 0)–(0, 0, 0) and (0, 9, 0)–(0, 0, 0) complexes near 5194 and 5800 Å, respectively. Neither of these features appears, and in spite of the suggestive wavelength coincidence for the (0, 10, 0)–(0, 0, 0) band, the identification with H_2O^+ must be considered uncertain.

The notion of transient H_2O^+ features is difficult to support anyway. Rapid photoionization (with threshold at 983 Å) of H_2O in a molecular shell should probably be accompanied by other changes in the spectrum. An alternative source of H_2O^+ is charge transfer

$$H^+ + H_2O \rightarrow H_2O^+ + H$$

(cf. Wyckoff and Wehinger 1976), and one could imagine a model of the source in which stellar-wind protons stream outward through an inhomogeneous medium containing an occasional molecular condensation. A column density of H_2O^+ of order 10^{16} cm^{-2} would be required to produce an absorption of the observed strength, given a band oscillator strength $f = 0.0028$ determined from the lifetime measurements of Erman and Brzozowski (1973). Because H_2O^+ is removed rapidly by reaction with H_2, its lifetime against destruction is about $\tau \approx 10^4/n(H_2)$ days, where $n(H_2)$ is the number of density of H_2 in cm^{-3}. The formation of an observable column density of H_2O^+ on a time scale of 1 day would require a large $n(H_2)$, which would in turn imply that the molecular ions must be short-lived.

The identification of the 5500 Å absorption band certainly presents a problem. Identification with either C_2 or H_2O^+ may seem unlikely; however, it is interesting

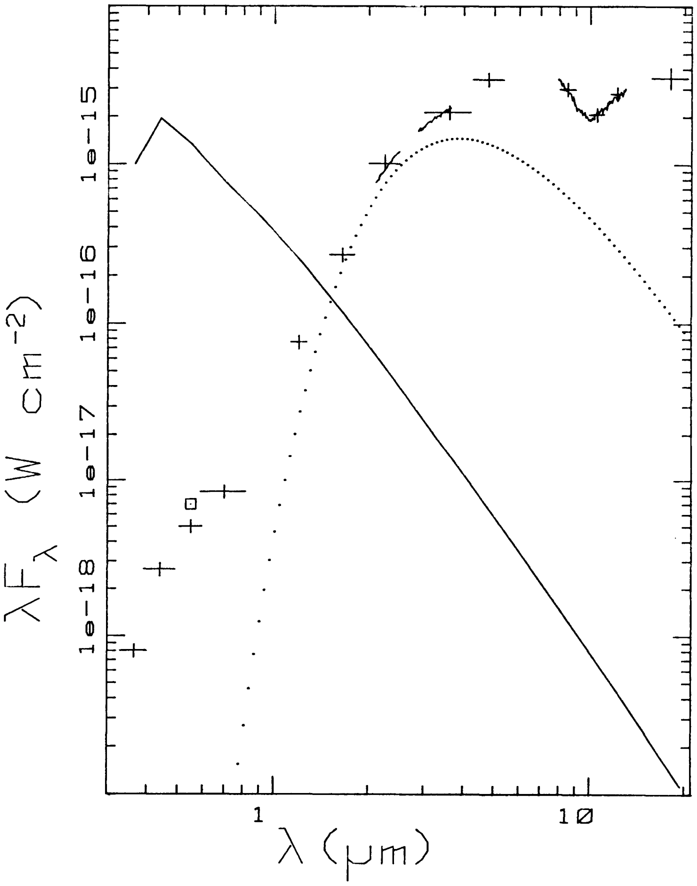

FIG. 1.—Observed energy distribution of AFGL 2789 is shown using the broad-band photometry from Table 1. 2.09–3.63 μm and 8.0–13.1 μm spectra are also displayed. The flux for an A0 star of 8th magnitude and a 950 K blackbody are shown for comparison. The combined visual magnitude using the present data for the NW filament and Cohen's (1977) estimate for position N0 is shown as a square.

to note the recent detection of variable H_2O maser emission toward AFGL 2789 by Sargent (1979). The association of a possible transient optical molecular feature with a variable radio frequency maser is very significant with potential impact upon the understanding of physical and chemical processes within circumstellar envelopes.

The observed variability of the absorption feature in about 1 day also places serious constraints on the geometry of any model for AFGL 2789. If the reflecting cloud is illuminated by the source at right angles to the line of sight then the light travel time across the nebula (the entrance aperture was 2″) requires that it be no more than 100 or 200 pc from the Sun. More likely the illuminating source is behind the reflection nebula along the line of sight or at a favorable angle to it.

Some comments can also be made concerning the visual extinction and distance to AFGL 2789. Since Cohen (1977) reports similar spectra and synthesized colors for three separate positions in the nebula, we have reason to assume that our spectra and colors apply to the entire reflection nebula. Even though the colors are likely to be too blue, we can derive some information about the visual extinction from the two-color diagram, $U - B$ versus $B - V$, which gives a color excess $E_{B-V} = 1.2$ mag ($A_V = 3.6$) for a main-sequence star. Herbig (1975) remarks that it is difficult to assess the accuracy of the extinction determined by this method, but in several similar cases it does yield the correct unreddened color of the illuminating star. For AFGL 2789 this method gives unreddened colors of $B - V = -0.09$ and $U - V = -0.29$, corresponding to a B8 V star. Following Gillett *et al.* (1975*a*), the 10 μm data are best fitted by a dust envelope of featureless emitting material viewed through a column of cold silicate dust with an absorption optical depth $\tau_{9.7} \approx 0.5$. This is to be compared with the interstellar extinction toward Cyg OB2 No. 12, which yields $\tau_{9.7} \approx 0.7$ (Gillett *et al.* 1975*b*), $E_{B-V} \approx 3.4$ mag, and $A_V \approx 10$ mag. This suggests that the extinction to the infrared source exceeds that to the optical nebula.

Inspection of the POSS prints reveals that AFGL 2789 is in a region of prominent dust lanes, one of which passes through its immediate vicinity: much of the extinction is probably due to this dust. Furthermore, in the direction of AFGL 2789 ($l = 94^\circ\!.6$, $b = -1^\circ\!.8$) the color excess is greater than 0.9 mag for distances between 1 and 2 kpc (FitzGerald 1968). Unless most of the reddening of AFGL 2789 is local to the source, the distance to this star is greater than 1 kpc. However, since the average reddening is already greater than 0.9 mag at 2 kpc, a distance as large as 6 kpc is difficult to reconcile with the observed reddening. At such a distance the line of sight would pass through the material of the Perseus arm at about 4 kpc as well as through material local to the source, and hence might reasonably be expected to produce a total reddening in excess of the 1.2 mag observed. Thus the kinematic distance of about 6 kpc determined for molecular clouds in the direction of AFGL 2789 (Harvey and Lada 1980) and estimated by Cohen on the basis of an assumed spectral type (O7) for the illuminating star may be an overestimate.

The radio measurements of V645 Cyg are also perplexing. A molecular cloud with a kinematic distance of 6 kpc is suggested by the detection of H_2O maser emission at -50 km s^{-1} (Sargent 1979) and thermal CO emission at -45 km s^{-1} (Harvey and Lada 1980). However, source confusion is not unlikely in this direction. Using the 46 m antenna of the Algonquin Radio Observatory ($\sim 2'.5$ beam) at 2.8 cm (10.6 GHz), Kwok (1979) detected a flux of 15 mJy (with a maximum scale error of 30%) at V645 Cyg with high signal-to-noise ratio on 1979 August 26 and 27. Comparison with the flux of $\sim 150 \pm 50$ mJy at 30 and 90 GHz reported by Cohen (1977) suggests that radio interferometry is necessary to establish the position, size, and spectrum of the radio continuum source.

The features in our optical spectra and the other observations discussed here are consistent with an obscured star with a shell spectrum of type A5e. The confirmation and identification of the perplexing absorption feature near 5500 Å is sufficiently important to warrant further spectroscopic observations. The short-term variability implies that frequent spectroscopic monitoring is needed.

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