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UNUSUAL INFRARED LINE PROFILES IN THE POST–ASYMPTOTIC GIANT BRANCH STAR HD 56126

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ABSTRACT

Brackett series lines with very broad inverted P Cygni and shell-like profiles have been detected toward the post–AGB star HD 56126. These profiles suggest that an active phase of mass loss has begun recently in this star. The star has had at least one previous episode of intense mass loss, attested to by its strong far-infrared emission. HD 56126 is also known for having a broad emission feature at 21 μm. The unidentified emission bands at 3.3 and 3.4 μm are also present in the spectrum of HD 56126, but the near-infrared spectrum provides little help in establishing the carrier of the 21 μm band.

Subject headings: infrared: sources — nebulae: planetary — stars: circumstellar shells — stars: evolution

I. INTRODUCTION

HD 56126 (=SAO 96709 = IRAS 07134+1005) is one of the four *IRAS* sources recently found to have the unidentified 21 μm emission feature (Kwok and Hrivnak 1989; Kwok, Volk, and Hrivnak 1989). All four sources display the spectra of F and G supergiants (Hrivnak, Kwok, and Volk 1989; Hrivnak and Kwok 1990). They show strong far-infrared excesses, but unlike most strong far-infrared sources, they are identified with bright optical stars. Approximately equal fluxes are detected from the photospheric and circumstellar components, giving them strikingly "double-peaked" energy distributions. Their far-infrared radiations presumably originate from dust shells that are well separated from the surfaces of the stars (Parthasarathy and Pottasch 1986). Circumstellar molecular emissions characteristic of asymptotic giant branch (AGB) stars have been detected (Woodsworth, Kwok, and Chan 1990) toward these objects. It has been suggested that the dust/molecular envelopes surrounding these objects are the result of mass loss (since ceased) on the AGB, and the stars themselves are in the process of evolving from the AGB to the planetary nebula stage (Volk and Kwok 1989).

The chemical compositions of these stars are interesting. Their optical spectra show evidence of strong carbon enrichment (Hrivnak and Kwok 1990), and thus the 21 μm emission feature is likely to be due to a carbon-based molecule. In an effort to find possible related features in the near-infrared, we have obtained moderate-resolution spectra of one of the four sources, HD 56126, in some of the near infrared atmospheric windows. In this *Letter*, we report the discovery of very broad inverse P Cygni profiles of hydrogen recombination lines, as well as the well-known 3 μm emission features in this source.

II. OBSERVATIONS

HD 56126 was observed on 1989 December 15–16 and 1990 February 10 (UT) at the United Kingdom 3.8 m infrared telescope on Mauna Kea, as part of the UKIRT Service observing program. The seven-channel cooled grating spectrometer (CGS2) at that facility was used in the H (1.65 μm), K (2.2 μm), and L (3.4 μm) wavelength bands with spectral resolutions of 0.0037, 0.0085, and 0.0076 μm, respectively. Spectra were sampled every one-third resolution element, except at the ends of each spectrum. All spectra were obtained in a 5″ aperture using chopper throws of $\sim 30''$ (EW). The spectra of HD 56126 were then calibrated by dividing by spectra of BS 2421, BS 2484, and BS 1543 and multiplying by blackbody functions assuming that the stellar continua are blackbodies at temperatures typical of their spectral types. Details are given in Table 1. Wavelength calibrations were derived from observations of an argon lamp. The resultant H and L band spectra of HD 56126 are shown in Figures 1 and 2. Condensed H, K, and L spectra are shown in Figure 3. The K band spectrum, which required correction for a Brγ line in the photosphere of the comparison star, contained no spectral features above its noise level.

III. RESULTS

Figure 1 shows the H band spectrum of HD 56126. At least 10 lines from the Brackett series are detected; these range from 10–4 at 1.74 μm to 19–4 at 1.52 μm. The 10–4 through 14–4 lines show inverse P Cygni profiles with the emission and absorption peaks separated by ~ 1000 km s^{-1}. Careful examination of these profiles suggests that weak redshifted emission is also present in most or all of these lines, as a slight elevation in the flux level is present just longward of the absorption. The wavelength calibration shows that the absorption lines all occur at LSR velocities close to zero (i.e., $V_{abs} < 200$ km s^{-1}); hence, it may be concluded that the emission components are highly blueshifted relative to the stellar velocity. For n–4, $n > 14$, both blue- and redshifted emission appear to be present at roughly equal strengths, with the absorption still present and at low velocity. It must be cautioned, however, that in the short-wavelength portion of the H window where these lines occur, the spectrometer does not completely

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TABLE 1

OBSERVING LOG FOR HD 56126

Date (UT)	Spectral Band	Observing Time (minutes)	Calibration Star: Name	Calibration Star: Assumed Magnitude	Calibration Star: Assumed Temperature (K)
1989 Dec 15..........	K	8	BS 2421	$K = 1.90$	10000
	L	10	BS 2421	$L = 1.90$	10000
1989 Dec 16..........	H	12	BS 2484	$H = 2.35$	6500
1990 Feb 10..........	L	13	BS 1543	$L = 2.05$	6300

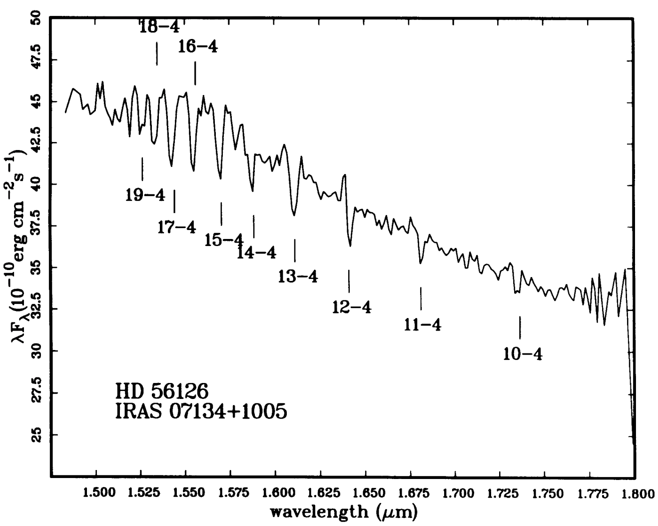

FIG. 1.—Spectrum of HD 56126 from 1.48 to 1.80 μm. The detected Brackett series lines are indicated.

separate the individual line profiles, and placement of the continuum is uncertain. Both the absorption and emission components of the Brackett lines appear to be strongest for principal quantum numbers near 16. This behavior is similar to that observed in the post–AGB star HR 4049 by Geballe *et al.* (1989*a*), although only line absorption was detected in HR 4049. In both stars, the Brγ (7–4, 2.166 μm) line is absent in the K band spectrum. No other features (such as H_2 line emission and CO and atomic absorption lines) are evident in the K band spectrum of HD 56126. After fitting a continuum through the spectrum, the emission and absorption fluxes were calculated. These are listed in Table 2. No values are given for transitions above 14–4 because the absorption and emission lines are not adequately resolved under the present spectral resolution of 700 km s^{-1}.

TABLE 2

OBSERVED INTEGRATED BRACKETT LINE FLUXES

Line	λ_0 (μm)	λ_{em} (μm)	Emission[a] (10^{-13} ergs cm^{-2} s^{-1})	λ_{ab} (μm)	Absorption[a] (10^{-13} ergs cm^{-2} s^{-1})
10–4......	1.737	1.730	1.40	1.735	−1.48
11–4......	1.681	1.677	1.72	1.682	−2.29
12–4......	1.641	1.639	2.00	1.642	−3.57
13–4......	1.611	1.605	3.32	1.611	−4.81
14–4......	1.588	1.581	3.56	1.588	−2.65

[a] Lower limits, due to blending at observed spectral resolution.

In the L band spectrum of HD 56126, shown in Figure 2, the well-known unidentified emission features at 3.3 μm and 3.4 μm can be seen. The 3.3 μm feature is likely due to the fundamental CH stretching vibration in polycyclic aromatic hydrocarbons (PAHs) and related molecules.

Figure 3 shows the near-IR spectra of HD 56126 plotted

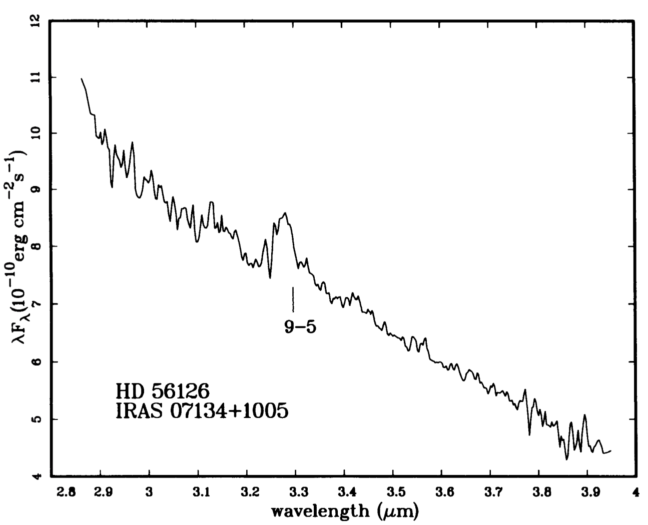

FIG. 2.—Spectrum of HD 56126 from 2.8 to 4.0 μm. The spectrum has been smoothed by the Hanning method. The expected position of the Pfund series 9–5 line is also indicated.

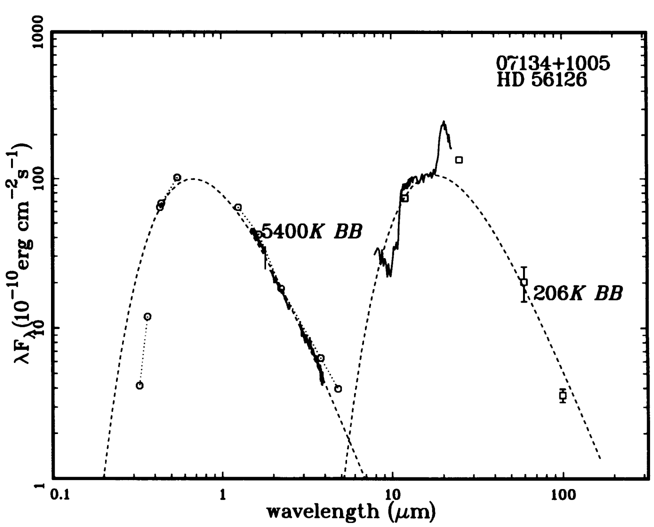

FIG. 3.—Energy distribution of HD 56126. The solid line between 7 and 23 μm is the *IRAS* Low Resolution Spectrum, the squares are *IRAS* broad-band photometry, and the circles are ground-based photometry from Hrivnak, Kwok, and Volk (1989). Included are our new H, K, and L band spectra.

together with the optical through far-infrared photometry of the object. The double-peaked structure of the overall energy distribution is prominent. The flux densities of the H, K, and L band continua are consistent with the continuum level of the reddened photosphere of the central star.

IV. DISCUSSION

a) Hydrogen Recombination Lines

The fact that the wavelengths of the H I absorption features in HD 56126 are approximately coincident with the rest wavelengths suggests that the absorption lines are photospheric in origin. In this case, the emission components probably originate from material ejected from the star. If we assume that the emission lines are circumstellar in origin, the emission measure can be estimated from the integrated line fluxes F_{mn} by the following formula:

$$F_{mn} = \frac{h\nu\alpha_{mn} \int n_e n_p dV}{4\pi D^2}, \tag{1}$$

where α_{mn} is the effective recombination coefficient for the m–n transition, D is the distance, and n_e and n_p are the electron and proton densities, respectively. Using the 10–4 transition as an example, the observed integrated line flux of 1.4×10^{-13} ergs cm^{-2} s^{-1} implies a value for the emission measure ($\int n_e n_p dV$) of at least 5.5×10^{58} (D kpc^{-1})^2 cm^{-3}. This value is a lower limit because the absorption and emission components are partially blended at the observed resolution. The value for α_{mn} is assumed to be 2.7×10^{-16} cm^3 s^{-1}, which is the case B value for a kinetic temperature of 10,000 K (Giles 1977).

The ionized region is unlikely to be created by photoionization by Lyman-continuum photons from the relatively cool central star (F5 I). One possibility is that the ionization is a result of a fast new wind impacting on the previous ejecta. The difficulty with this hypothesis is that redshifted emission is not observed in all lines (see below).

Another possibility is that the ionized region is located near the stellar surface, where the stellar disk could obscure the redshifted (backside) emission component, and the high density in the wind allows collisional ionization or photoionization from the $n = 2$ level of the hydrogen atom. Assuming that a wave is generated from the photosphere and gradually accelerated as the result of decreasing density, the small scale height of the atmosphere will allow the velocity to grow to hundreds of km s^{-1} and become supersonic. The difficulty with this hypothesis is that most of the emission is expected to occur at low velocity where the density is high, not at high velocity where the density is low.

Independent of the causes of the ionization, the broad hydrogen recombination line profiles observed in HD 56126 suggest that the star has recently initiated a very active phase of mass loss since the AGB mass loss. The AGB mass loss, which appears to have ceased ~100 yr ago, is responsible for the far-infrared flux (Hrivnak, Kwok, and Volk 1989). However, the origin of the inverted P Cygni and shell-like profiles and their variation with principal quantum number is not completely clear. As mentioned earlier, the line emission might occur in the deceleration zone of a fast wind, which is shock-ionized upon collision with the remnant AGB envelope, a mechanism which is now widely accepted as critical to the development of planetary nebulae (Kwok, Purton, and FitzGerald 1978). However, as the envelope in HD 56126 is quite distant from the central star, one would expect to find equally intense blue- and redshifted emissions; this is not seen for $10 \leq n \leq 14$. Previously, evidence for the existence of a fast wind in planetary nebulae has been based mostly on P Cygni profiles observed in the ultraviolet spectra of central stars of planetary nebulae (Perinotto 1983). If radiation pressure on resonance lines is the mechanism driving this fast wind, then it is not expected to be significant until the central temperature of the star reaches ~30,000 K (Kudritzki and Méndez 1989). Thus, what is being seen in HD 56126 is either an entirely separate phenomenon from the hot, fast wind that is believed to drive the expansion of an existing planetary nebula, or the fast wind that creates the nebula begins at much lower temperatures than previously believed. It is possible that this wind begins as a neutral flow, as observed in the proto–planetary nebula AFGL 618 (Gammie *et al.* 1989; Cernicharo *et al.* 1989), and is ionized upon collision with the remnant AGB wind.

A series of H band Brackett absorption lines has also been detected in HR 4049, a carbon-rich star of A7 I spectral type, which is probably also in the post–AGB stage of evolution (Geballe *et al.* 1989*a*). The Hα line of HR 4049 has been known to vary from a P Cygni to a shell-like profile on the time scale of a month. The transition appears to be associated with the photometric variability of the object: P Cygni profiles are found when the star is bright and blue and a shell profile when it is faint and red (Waters, Waelkens, and Trams 1990). High-resolution optical spectra of HD 56126 also show inverse P Cygni profiles in the Balmer line Hα (A. W. Woodsworth, private communication). The velocity of the Hα absorption component ($V_{LSR} = 65$ km s^{-1}) coincides with the stellar velocity ($V_{LSR} = 71$ km s^{-1}) implied by the radio CO observations, again suggesting that it is photospheric. The velocity shift of the Hα emission component (-28 km s^{-1}) is, however, much smaller than the velocities of the Brackett lines. It would be interesting to monitor the Hα profile and the integrated light of HD 56126 to search for variations similar to those for HR 4049. If the inverse P Cygni profiles do change into shell profiles with time, then the shock-ionization model would be more acceptable.

b) Dust Features

The 3.3 μm feature and the satellite feature at 3.4 μm are commonly seen in planetary nebulae, reflection nebulae, and H II regions. They also have been detected in HR 4049 (Geballe *et al.* 1989*a*). The rarely occurring 3.53 μm feature, which also was detected in HR 4049 (Geballe *et al.* 1989*a*), is not present in the spectrum of HD 56126. The 3.3 and 3.4 μm features are part of a family of features believed to be due to PAH and/or related molecules. In HR 4049, another member of the family, the 11.3 μm feature, is present in the *IRAS* LRS spectrum (de Muizon, Cox, and Lequeux 1989; Waters *et al.* 1989). There is no evidence of the 11.3 μm feature in the LRS spectrum of HD 56126. However, the lack of a detectable 11.3 μm feature is probably not significant in view of the weakness of the 3.3 μm feature in HD 56126. The origin of the 3.4 μm feature is unclear (Geballe *et al.* 1989*b*; Sellgren, Tokunaga, and Nakada 1990). It may be due to transitions between excited vibrational levels of the CH stretch (Barker, Allamandola, and Tielens 1987) or it may be a fundamental vibrational transition in a more complex bond (de Muizon *et al.* 1986).

As the 21 μm feature, which has been detected in HD 56126 and three other *IRAS* sources, is not seen in the many objects that have strong PAH emission, the present spectra of HD

56126 shed little light on the identity of this newly discovered feature. One possible anomaly of the 3.3 μm feature in HD 56126 is that its maximum, at $\sim$3.285 μm, appears to be at a slightly shorter wavelength than normal (e.g., see Geballe *et al.* 1985). However, there appears at present to be no link between the 21 μm feature and PAHs and related molecules.

V. CONCLUSION

Hydrogen recombination lines are detected in the infrared spectrum of HD 56126. These lines have inverse P Cygni and shell-like profiles, with emission Doppler shifts of $\sim$1000 km s^{-1}. The H I line profiles suggest that the star is undergoing a new phase of mass loss, approximately 100 yr after the end of the previous phase of mass loss which created the cold dusty shell detected by *IRAS*. Two different hypotheses to explain the observed line profiles have been discussed, but neither can be considered completely satisfactory. Also not clear is why the absorption (photospheric) and the emission (circumstellar) components are of roughly equal strength, and why the line strengths change with the hydrogen principal quantum number. The standard 3 μm PAH emission features have also been detected from HD 56126. No new spectral features were seen which might provide hints as to the origin of the 21 μm emission feature recently detected in this and a few other objects.

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