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INFRARED EXCESS AND MASS-LOSS RATE OF THE EXTREME Of STAR HD 108

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Infrared observations of the extreme Of star HD 108 show an IR excess already at 2.3 microns. This infrared excess has been interpreted as due to a thermal ff + bf emission from an expanding ionized gas surrounding HD 108.

Between 5 and 10 microns the IR excess shows a distribution law of the type $S_\nu \propto \nu^{1.0\pm0.4}$, indicating that the 10 μ radiation originates from a region where the stellar wind is still undergoing acceleration. From the observed 10 μ ff + bf flux, and adopting a wind-velocity law of the type $v(r) = v_\infty(0.01 + 0.99(1 - R^*/r)^\beta)$ with $\beta = 1$, we derive a mass-loss rate for HD 108 of $\dot{\mathfrak{M}} \simeq 2 \times 10^{-5}\, v_\infty(\mathfrak{M}_\odot\ \mathrm{y}^{-1})$ with v_∞ in 10^3 km s^{-1}. This value, very similar to the mass-loss rate obtained for WR stars, indicates that radiation pressure only is insufficient to drive the wind in HD 108.

Key words: Of star—infrared photometry—stellar wind—mass-loss rate

I. Introduction

The star HD 108 (O7 If) has been known as an extreme Of star in which the presence of P Cygni emission profiles in the Balmer lines indicates a high mass-loss rate through a high-velocity stellar wind (Hutchings 1979). The near-IR spectrum of HD 108, obtained by Vreux and Andrillat (1979), shows the He I λ10830 line strongly in emission. This emission line, characteristic of the WR stars, suggests a very dense envelope surrounding the Of star.

Recently, ultraviolet spectra of HD 108, obtained by Hutchings and von Rudloff (1980) and Conti and Garmany (1980) with the IUE satellite, seem to indicate a low mass-loss rate several orders of magnitude lower than obtained from the optical observations, and anomalous for Of extreme stars. Therefore, a new determination of the mass-loss rate of HD 108 appears important in order to solve this problem and to understand the disagreement between the optical and ultraviolet determinations on $\dot{\mathfrak{M}}$.

In this paper we present accurate IR observations, up to 10 microns, of HD 108 obtained at the 2.3-m Wyoming Infrared Telescope. The infrared energy distribution derived from our IR photometry is analyzed and a few characteristics of the expanding envelope are given.

From the observed infrared excess at 10 microns, and applying a nonconstant velocity model of the ionized expanding envelope, as described by Persi et al. (1980), a value of the $\dot{\mathfrak{M}}/v_\infty$ for HD 108 is obtained. The consequences of our estimated value of the mass-loss rate in relation to the wind-driven theory are discussed and in particular the possible presence of a collapsed object in HD 108 (Hutchings 1975; Bekenstein 1976) is also considered in light of the recent X-ray observations made with the Einstein Observatory (Hutchings 1981).

II. Observations

The broad-band infrared photometry from 2.3 to 10 microns of HD 108 was obtained with the Wyoming multifilter Ge bolometer at the 2.3-m telescope of the Wyoming Infrared Observatory on two nights in September 1980.

The data were acquired using 5 arc sec beams separated by 14 arc sec. α Tauri and β Pegasi were used as standard stars during the observations. The infrared magnitudes of the standard stars and the absolute calibration of the Wyoming photometric system are reported by Gehrz, Hackwell, and Jones (1974).

Table I gives the infrared magnitudes of HD 108 corrected for air mass, and the relative 1 σ statistical errors.

The observations show that no significant infrared variability is seen with a time scale of about one day.

III. IR Excess and Mass-Loss Rate

To derive the energy distribution of HD 108, we corrected the magnitudes for the interstellar reddening law of Sneden et al. (1978) and for the color excess $E_{B-V} = 0.5$ obtained from uv spectra by Hutchings and von Rudloff (1980).

The infrared spectral points relative to the observations of 1980 September 25, and the B and V photometry of the Goy (1980) catalog are reported in Figure 1 (filled triangles). These points have been compared with the stellar continuum represented by the Kurucz (1979) model atmosphere for $T_{\mathrm{eff}} = 35{,}000$ K and $\log g = 3.5$. We obtain the IR-excess spectrum (open triangles in Fig. 1) from the difference between the observed fluxes and the stellar continuum.

TABLE I

INFRARED PHOTOMETRY OF HD 108

Date	UT	2.3μ	3.6μ	4.9μ	10μ
1980 Sept. 24	9:57	6.66 ± 0.08	6.33 ± 0.10	6.04 ± 0.09	—
1980 Sept. 25	8:34	6.60 ± 0.03	6.25 ± 0.02	5.98 ± 0.14	5.55 ± 0.21

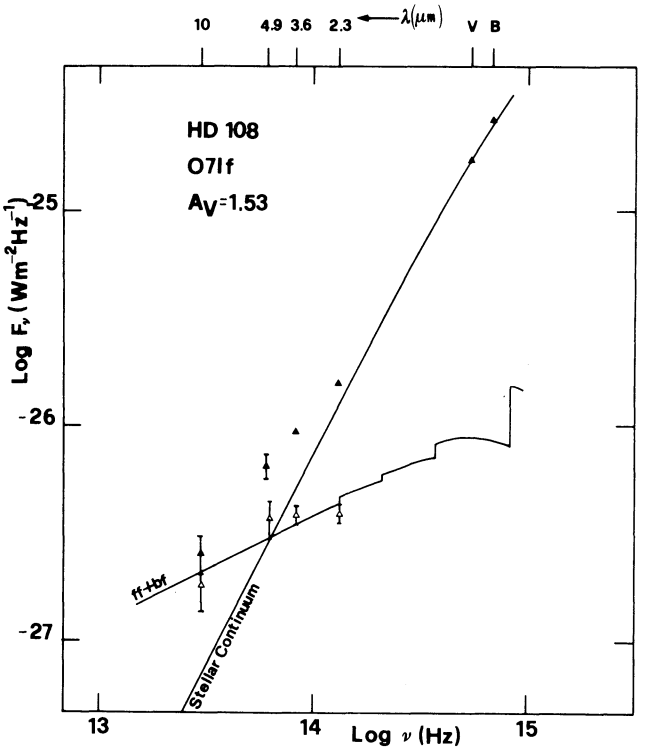


FIG. 1—Infrared energy distribution of HD 108. Infrared observations (▲); infrared excess (Δ). *BV* photometry is taken from Goy (1980). The Kurucz (1979) model atmosphere (= stellar continuum) and the ff+bf emission are indicated by continuous lines.

The infrared excess has been fitted by an isothermal ff+bf emission spectrum from an optically thick circumstellar envelope with an electron density law $n_e \propto r^{-2}$ and an electron temperature $T_e = 30{,}000$ K ($S_\nu \propto \nu^{0.65}$). Within the statistical errors the agreement is quite good (see Fig. 1), even if the slope between 5 μ and 10 μ could be steeper than 0.65 ($\alpha \simeq 1.0 \pm 0.4$), indicating that the 5 μ–10 μ radiation originates from a region where the stellar wind is still undergoing acceleration.

The mass-loss rate of HD 108 has been determined using the measured IR excess at 10 microns, $S_{10\,\mu}^{ff/bf} = 0.185 \pm 0.050$ (Jy), and the relations between the 10 μ ff+bf flux and the ratio $\dot{M}/v_\infty$ developed by Persi, Ferrari-Toniolo, and Grasdalen (1980) for an ff+bf model including a wind-velocity law of the type $v(r) = v_\infty(0.01 + 0.99(1-R^*/r)^\beta)$. If for HD 108 we adopt $R^* = 20\ R_\odot$, $T_e = 30{,}000$ K, $D = 3.5$ kpc, and $\beta = 1$, we obtain $\dot{M} \simeq 2\ 10^{-5}\ v_\infty$ ($\dot{M}_\odot$ y^{-1}) where v_∞ is expressed in 10^3 km s^{-1}. The distance here adopted has been obtained considering HD 108 to be a supergiant star with $M_v = -7.0$ (as measured from the Hγ line) and $E_{B-V} = 0.5$. A distance of ~ 1 kpc has also been suggested by Hutchings (1975) on the basis of the equivalent width of the Ca II K interstellar absorption line observed in HD 108. This distance would imply that HD 108 is a low-mass object with $M_V = -3.2$ and a mass-loss rate of $\dot{M} \sim 2\ 10^{-6}\ v_\infty(\dot{M}_\odot$ y$^{-1})$. However, this latter hypothesis is not likely because HD 108 is a member of the association Cassiopeia OB5 (Humphreys 1978).

The main source of error in the determination of the ratio $\dot{M}/v_\infty$ is represented by the fact that the wind-velocity law for early-type stars is not known with accuracy. Considering the extreme values that the exponent could assume in the velocity law ($\beta = 0.5,4$) (Castor and Lamers 1979), the maximum error in our derived value of $\dot{M}/v_\infty$ is not greater than 50%.

IV. Discussion

A critical point in the determination of the mass-loss rate from infrared observations is the choice of the terminal velocity of the expanding envelope. We know that O-type stars have high outflow velocities of about 1000 to 3000 km s^{-1}. For our purpose we have estimated for HD 108, $v_\infty \simeq 2500$ km s^{-1} by means of an average $v_\infty, T_{\rm eff}$ relationship obtained by Panagia and Macchetto (1980) including multiple photon scattering in the processes of radiative acceleration of the stellar wind. In every case an inaccuracy by a factor of 2 in v_∞ does not modify our conclusions.

Using the previous value of the terminal velocity, we obtain for HD 108 $\dot{M} \simeq 5\ 10^{-5}\ \dot{M}_\odot$ y^{-1}. This value of the mass-loss rate results to be one of the highest values obtained for luminous O-type stars, and is comparable to the mean value of $\dot{M}$ derived for the WR stars ($\dot{M}$(WR) ~ 4.5 $10^{-5}\ \dot{M}_\odot$ y^{-1}) by Barlow, Smith, and Willis (1981).

From our estimated value of $\dot{M}$, and adopting $L^* \simeq 1.2\ 10^6\ L_\odot$ ($\dot{M}_{\rm Bol} = -10.5$) as the luminosity for HD 108, we can calculate the ratio between the momentum carried by the wind ($\dot{M}v_\infty$) and the radiative momentum emitted from the star (L^*/c). This ratio, which is frequently used as a measurement of the efficiency of the spectral lines in absorbing momentum, is for HD 108, $\epsilon = \dot{M}v_\infty/(L^*/c) \simeq 5$. This ratio is greater than 1, also considering HD 108 as a low-mass object. The value of $\epsilon > 1$, indicates that radiation pressure only is

insufficient to explain the high mass-loss rate and the wind velocity observed in HD 108. This result could be extended in general to the Of stars. In fact, recently, Persi et al. (1981), from accurate IR observations at 10 μ, found several Of stars to have a ratio $\epsilon > 1$. Besides, VLA radio continuum observations of Abbott et al. (1980), and Felli and Panagia (1980), suggest a high value for ϵ for the stars 9 Sagittarii (O4 V(f)) and (O8 I*b*(f)). It is interesting to note that the star 9 Sgr, like HD 108, shows a slight evidence of mass-loss rate in its uv spectrum, while Abbott et al. (1980) found a value of $\dot{\mathfrak{M}} = 2.5 \times 10^{-5}\ \mathfrak{M}_\odot\ \mathrm{y}^{-1}$.

The binary nature of HD 108 found by Hutchings (1975) (not confirmed by Vreux and Conti 1979), induced Bekenstein (1976) to speculate on the possible presence of a collapsed object in HD 108. We may estimate the expected X-ray luminosity in HD 108, for a neutron star accreting in a spherically symmetric wind, using the orbital parameters obtained by Hutchings (1975), our $\dot{\mathfrak{M}}$, and the relationships derived by Wyckramasinghe and Whelan (1975). For $\mathfrak{M}_p = 60\ \mathfrak{M}_\odot$, $\mathfrak{M}_x \leq 2.5\ \mathfrak{M}_\odot$, $P = 4\overset{d}{.}6$, $\dot{\mathfrak{M}} = 5 \times 10^{-5}\ \mathfrak{M}_\odot\ \mathrm{y}^{-1}$, and $v_\infty = 2500\ \mathrm{km\ s^{-1}}$, we obtain $L_x = 2 \times 10^{35}\ \mathrm{erg\ s^{-1}}$.

Recent X-ray observations of HD 108 made with the Imaging Proportional Counter of the Einstein Observatory (Hutchings 1981), give an X-ray luminosity of $L_x \simeq 9 \times 10^{32}\ \mathrm{erg\ s^{-1}}$. This excludes the presence of an accreting neutron star in HD 108 orbiting with a period of $4\overset{d}{.}6$ or shorter as suggested by Vreux and Conti (1979), but another mechanism must be invoked to explain the observed X-ray luminosity in HD 108.

In conclusion, it appears from our IR observations that a very dense ionized gas envelope surrounding HD 108 is still undergoing acceleration in the region where the 5–10 micron radiation is formed. the derived high mass-loss rate and the presence of the He I λ10830 line strongly in emission make HD 108 very similar to a WR star.

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