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THE MASS LOSS RATE OF THE GALACTIC HYPERGIANT HD 152236 (ζ^1 SCORPII) FROM OPTICAL AND NEAR INFRARED OBSERVATIONS

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RESUMEN

Se presentan observaciones obtenidas a dispersión intermedia con un detector fotocontador en las regiones espectrales azul y roja de HD 152236, así como fotometría en el cercano infrarrojo (*J,H,K,L*). Se listan anchos equivalentes de las principales líneas y se calculan los excesos de flujo libre-libre en el infrarrojo. Se determinan tasas de pérdida de masa a partir de los excesos libre-libre a 2.2 y 3.5 μm y por medio de la intensidad de la emisión en Hα; se obtiene un valor de $\sim 9 \times 10^{-6}$-2×10^{-5} $M_\odot$ año^{-1} consistentemente con ambos métodos. La variabilidad espectral es discutida en relación con observaciones anteriores.

ABSTRACT

Intermediate dispersion spectra obtained with a photon-counting detector in the blue and red spectral regions of HD 152236, as well as near infrared photometry (*J,H,K,L*) are presented. Equivalent widths of the main lines are tabulated and infrared free-free fluxes derived. Mass loss rates are determined from the free-free excess at 2.2 and 3.5 μm and by means of the Hα emission strength; a consistent value of $\sim 9 \times 10^{-6}$ - 2×10^{-5} $M_\odot$ yr^{-1} is obtained with both methods. Spectral variability is discussed in connection with previous observations.

Key words: **STARS-EARLY TYPE – STARS-MASS LOSS – STARS-EMISSION LINES – STARS–IR EXCESS**

I. INTRODUCTION

HD 152236 (ζ^1 Scorpii) is a B1.5 Ia$^+$ star and is a member of the Sco OBI association. According to de Jager (1981) this star is the earliest galactic hypergiant known. The optical spectrum is notable for the sharpness of the hydrogen lines, the extreme P Cygni profiles of the Hα, Hβ and He I λ5876 lines and the pronounced velocity gradient of the Balmer lines (cf. Hutchings 1968). Constant monitoring of extreme objects like ζ^1 Sco is important since they present the opportunity to acquire a better insight into the evolutionary status of very massive objects moving from the blue to red supergiant region. According to Beals (1950) the first description of the spectrum of this star was given by Fleming (1912). Evidence of spectral variability is apparent since the first recorded observations. Cannon (1901) describes P Cygni type profiles of Hβ and Hγ. However, neither Code and Houck (1958) nor Hutchings (1968) confirm the emission component in Hγ. Nevertheless, Hutchings (1968) reports a shortward wing at Hγ, whereas Sterken and Wolf (1978) mention the presence of a discernible emission component in some of their coudé spectra. Later, Jaschek and Jaschek (1973) reported intensity variability of some CNO and He features from their photographic spectra. However, Walborn (1975) could not confirm this variability with photographic material. Photometrically the star has been analysed in the *V* band by Sterken (1977) who found a pseudo-period of 16.5 days and a semi amplitude of $0^m.05$. Analyses of the UV spectral region have been performed by Hutchings (1979), Wolf and Appenzeller (1979), and more recently by Burki *et al.* (1982). The star shows conspicuous P Cygni type profiles (as is the case of P Cygni itself) and narrow, blueshifted absorption features of resonance lines like Al III and Mg II. Both types of profile show intensity and velocity variations. Whereas the P Cygni absorption components show a tendency to increase in velocity with species of higher ionization energy (as expected from a spherical stationary accelerated outflow) the variability of the narrow blueshifted absorption features seems to correlate with the visual photometric variations. *UV* color variations are of the same order of magnitude as in the *V* band. Near infrared photometry was reported by Schild, Neugebauer, and Westphal (1971); their values are in very good agreement with photometry reported here (Table 2). This result tends to indicate that as for the *V* and *UV* regions, the color variations in the infrared (if any) are small. Two independent determinations of the mass loss rate exist for this object. They differ by a factor of ten (see section IV). New optical and near infrared observations have now been obtained that enable a redetermination of the controversial mass loss rate of this object. In addition, a list of equivalent widths for the best defined lines present in the optical range (surprisingly lacking up to now in the literature) is presented. The observations and results are described in section II. In section III previous observations are compared, whenever possible, to the new observations here presented. In section IV the near infrared photometry and the Hα emission strength are used to derive mass loss rates. Conclusions are finally given in section V.

II. OBSERVATIONS AND RESULTS

Intermediate dispersion spectra of the blue (4300-4900 Å) and red (5500-6800 Å) regions of HD 152236 were obtained with the Cassegrain image tube spectrograph on the South African Astronomical Observatory (SAAO) 1.9-m telescope. The detector is a solid state Reticon array which achieves photon counting in two 1D 1872 pixel arrays separated by 30 arcsec on the sky. In observing HD 152236 the sky aperture was situated 30 arcsec south and the length of the acquisition apertures was 6.0 arcsec. A 1200 lines mm^{-1} grating was used in first order (dispersion = 60 Å mm^{-1}) to examine the red spectral region from ∿ 5600 – 6800 Å, and the blue region was studied using the same grating in second order (dispersion = 30 Å mm^{-1}). The slit width was 100 μm, and the instrumental resolution, as determined by measuring the FWHM of arc lines, was ∿ 2.2 channels on the Reticon detector, corresponding to a resolution ∿ 1.0 Å in first order and ∿ 2.0 Å in second order. The exposure times were both 1200 seconds, and neutral density filters were employed to prevent the count rate from exceeding ∿ 2.0 counts $pixel^{-1}$ s^{-1}, above which the response of the image intensifier, image tube and Reticon detector combination departs significantly from a linear response. (At ∿ 3 counts $pixel^{-1}$ s^{-1} the coincidence losses are ∿7%). Both the red and blue spectra were divided by an exposure to a white light source in order to correct for the pixel to pixel variations of the detector ('flat field correction'). Wavelength calibration was effected using separate exposures to a Cu-Ar arc lamp and the neutral density filter response was corrected for. The spectral response of the instrumental combination at the two grating settings was calibrated by exposures to a standard star EG 158 = Feige 110 (Stone 1977) and the sky background was subtracted from the stellar spectrum. Table 1 lists the equivalent widths and heliocentric radial velocities of the main spectral lines observed in ζ^1 Sco; errors of both measurements are as discussed in López and Walsh (1983); typically ± 0.03 Å and ± 9 km s^{-1}, respecively.

Near infrared J(1.25 μm), H(1.65 μm), K(2.2 μm), and L(3.5 μm) photometry of HD 152236 was also obtained using the same telescope. The Mk I near-infrared photometer (Glass 1973; and SAAO Facilities Manual 1982) was used with focal plane chopping in a north-south direction with a throw of 70 arcsec.; the aperture size was 12 arcsec. The $JHKL$ magnitudes obtained are on the SAAO $JHKL$ photometric system, which is based on a revision of the standards of Glass (1974). Table 2 lists the observed magnitudes together with their standard deviations and filter characteristics.

TABLE 1

EQUIVALENT WIDTHS AND RADIAL VELOCITIES

Identification	λ (Å)	EW (Å)	V_{Hel} (km s^{-1})
Hγ	4340.468	– 0.90	108.36
O II	4349.426	– 0.49	30.43
He I	4387.928	– 0.66	48.94
He I	4471.507	– 0.82	67.01
Mg II	4481.228	– 0.31	31.59
Si III	4552.622	– 0.50	29.29
Si III	4567.872	– 0.58	15.84
Si III	4574.777	– 0.31	41.88
O III	4601.478	– 0.27	– 1.49
O III	4607.153	– 0.33	9.76
N III	4613.88	– 0.17	...
N III	4621.41	– 0.20	...
N III	4630.537	– 0.60	...
N III	4640	– 0.99	...
C III	4650	– 0.90	...
O II	4661.635	– 0.24	30.18
O II	4676.231	– 0.26	– 15.21
He I	4713.143	– 0.37	33.24
Hβ	4861.332	+ 0.46	9.04
...	...	– 0.70	129.85
He I	5876	+ 0.33	...
...	...	– 0.73	...
Hα	6562.8	+ 6.18	221.80
...	...	– 0.48	38.76
He I	6678	– 1.18	...

TABLE 2

NEAR INFRARED PHOTOMETRY

Filter	FWHM (μm)	λ_c (μm)	Observed magnitudes
J	0.2	1.25	3.53 ± 0.02
H	0.3	1.65	3.31 ± 0.02
K	0.4	2.20	3.13 ± 0.03
L	0.6	3.50	3.00 ± 0.02

III. THE OPTICAL SPECTRUM

The indications of spectral variability in this star make desirable a comparison of our material with that available in the literature. In order to compare our spectra with those shown by Jaschek and Jaschek (1973) we have reproduced in Figure 1*a* the same spectral region as that displayed in Figure 2 of their paper (i.e., ∿ λλ4550-4700). The spectrum shown in Figure 1*a* tends to resemble more the one taken by the Jascheks in 1968 on the basis of the relative intensities of the O II lines to neighbouring spectral features. Similarly, the relative intensity of Hγ to O II λ4349 is displayed in Figure 1*b* (∿ λλ4320-4370) in order to compare it with Figure 4 of Jaschek and Jaschek. Figures 2*a*, 2*b* and 2*c* show the three lines observed with extreme P Cygni characteristics, namely: Hα, Hβ and He I λ5876. Figure 2*a* also includes the He I λ6678 line which shows a weak but definite red emission. The Hα profile in Figure 2*a* is remarkably similar to the profiles of this line obtained by Rosendhal (1973) and Sterken and Wolf (1970). Although intensity and radial velocity variability have been shown to occur by these authors, apparently only minor variations (in comparison with other OB supergiants) of the emission-absorption profiles take place. The Hβ P Cygni profile (Figure 2*b*) shows a double absorption component, which is also reported by Hutchings (1968). The behaviour of this profile might contain important information on the structure of the stellar envelope and correlations of, for example, the variations of the narrow blue shifted absorption *UV* features (Burki *et al.* 1982) with the absorption components of Hβ should prove interesting. In the case of the He I λ5876 profile it is noted that the absorption component (in Figure 2*c*) is much stronger than in the spectra shown by Sterken and Wolf (1978). This line is sensitive to changes in surface gravity so variations in the local electron density could significantly alter the intensity of the absorption component.

IV. MASS LOSS RATES

The mass loss rates have been determined by means of the near-infrared photometry and the Hα emission strength. Barlow and Cohen (1977) used the IR photometry (*H* and *K*) of Schild *et al.* (1971) for ζ^1 Sco and, by adopting a distance of 1.54 kpc to the star and assuming

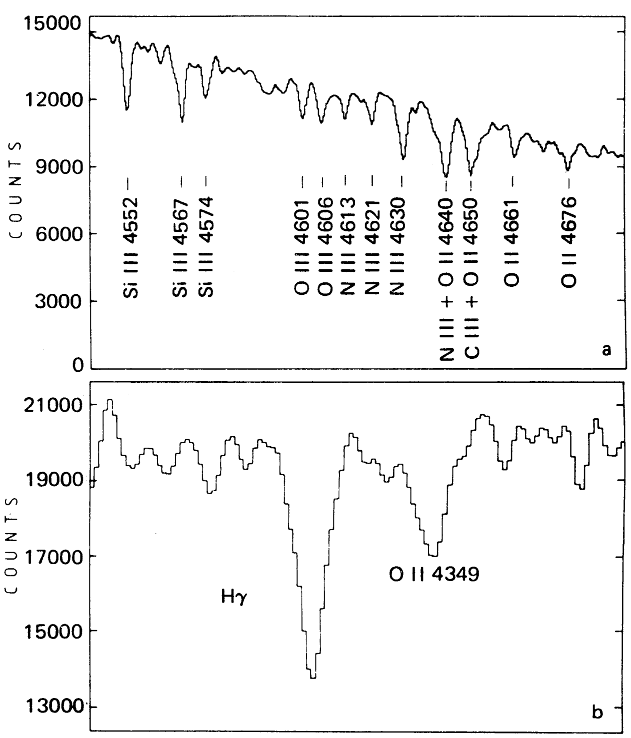

Fig. 1. Portions of the optical spectrum of ζ^1 Sco. Figure 1*a* shows the region ∿ λλ4550-4700, whereas Figure 1*b* the region of Hγ and O II λ4349. These spectra are very similar to those obtained in 1968 by the Jascheks (1973), see text.

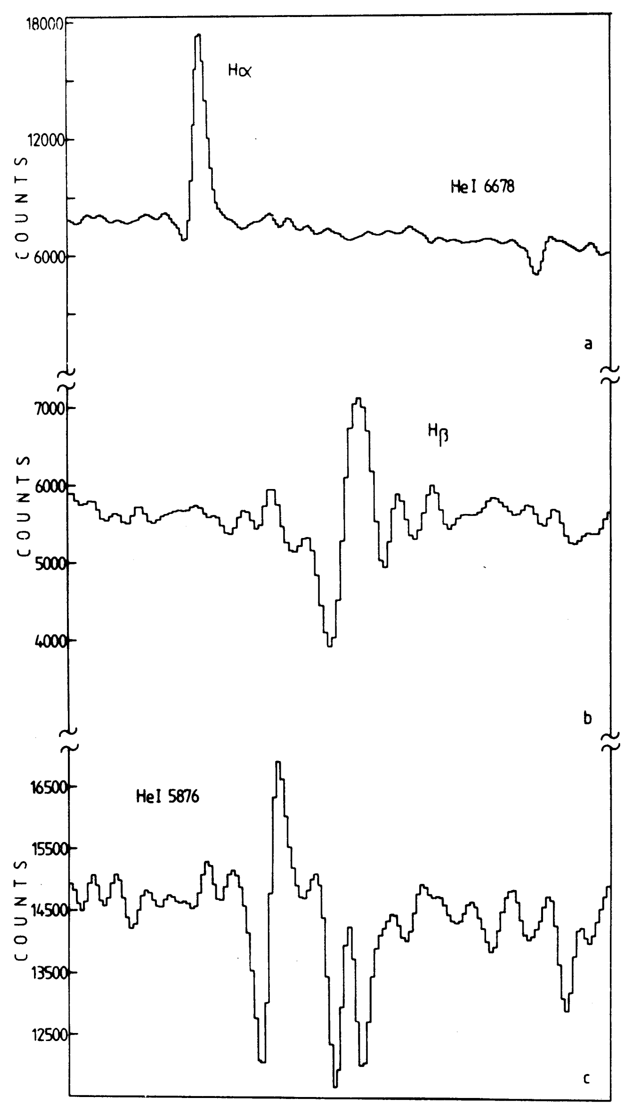

Fig. 2. The lines with extreme P Cygni type profiles in ζ^1 Sco. Figure 2*a* shows Hα and He I λ6678, whereas Figures 2*b* and 2*c* show Hβ and He I λ5876, respectively. Note that the vertical scales are significantly different.

the same (slow) velocity law as for P Cygni derived a mass loss rate, $\dot{M}$ of $\sim 1.4 \times 10^{-5}$ $M_\odot$ yr^{-1}. Later on, Sterken and Wolf (1978) combined their observations with the model of Hearn (1975) and a radiative velocity law to compute $\dot{M} \sim 1.8 \times 10^{-6}$ $M_\odot$ yr^{-1} from the Hα P Cygni profile. These results yield a factor of ten difference in the mass loss rate of ζ^1 Sco. Both methods are model dependent as well as sensitive to several physical and stellar parameters; therefore, in an attempt to resolve this factor of ten difference we have redetermined $\dot{M}$ adopting a standard set of parameters and assumptions. $\dot{M}$ from Hα has been computed with the model of Klein and Castor (1978) whereas in the case of the IR free-free flux two different spectral indices $\alpha = 0.75$ and $\alpha = 0.86$, (where $S_\nu \propto \nu^{\alpha}$) have been adopted. All relevant stellar parameters are listed in Table 3, along with their source reference.

TABLE 3

STELLAR PARAMETERS OF ζ^1 SCO

Parameter	Value	References[a]
Sp. type	B1.5 – B2 Ia$^+$	...
T_{eff}	17600 °K	(1)
$L_*/L_\odot$	1.1×10^6	...
$R/R_\odot$	114	(1)
$-M_V$	8.7	(1)
$-M_{bol}$	10.36	(1)
D	1.97 kpc	(2)
$M/M_\odot$	65	(3)
$(B-V)$	0.48	(2)
$(B-V)_0$	– 0.18	(4)
V_∞	500 km s^{-1}	(5)

a. References: (1) Underhill and Doazan 1981. (2) Humphreys 1978. (3) Burki *et al.* 1982. (4) Böhm-Vitense 1981. (5) Barlow and Cohen 1977.

a) *The Infrared Method*

Free-free thermal radiation in the extended envelopes of early-type stars produces an infrared "excess" which has been shown to be related to the mass loss rate of the star (Wright and Barlow 1975; Panagia and Felli 1975). A similar procedure to the one outlined by Barlow and Cohen (1977) has been applied to ζ^1 Sco to derive the mass loss rate of the star by using the *K* and *L* magnitudes listed in Table 2, and a distance of 1.97 kpc. In order to obtain the color excesses, relations (2) and (3) from Barlow and Cohen (1977) have been used to compute the intrinsic colors. A value of $(B-V)_0 = -0.18$ has been adopted; and a standard reddening law with R = 3.1 (Schild *et al.* 1971) has been assumed; the selective absorptions in the infrared have been scaled by means of the relations $A_K = 0.089\ A_V$ and $A_L = 0.046\ A_V$ that fit van de Hulst curve No. 15 (Johnson 1968). This procedure yields the predicted *K* and *L* magnitudes listed in Table 4. These predicted magnitudes as well as those observed are then corrected for interstellar extinction. The resulting magnitudes are then used to compute the fluxes. The differences obtained from comparing the predicted and observed flux are assumed to be due to thermal free-free radiation from the extended stellar envelope. To obtain the flux densities from the de-reddened magnitudes the calibration of Wilson *et al.* (1972) has been adopted. The free-free flux densities at *K* and *L* are also listed in Table 4. To estimate the mass loss rate of a star from this free-free "excess", one can make use of the formula derived by Panagia and Felli (1975) and Wright and Barlow (1975), namely:

$$\dot{M}/V_\infty = 0.095\mu\, S_\nu^{3/4}\, D^{3/2}/\gamma^{1/2} \times g^{1/2} Z\, \nu^{1/2}\ M_\odot\ yr^{-1}\ km\ s^{-1} \quad , \quad (1)$$

where $\dot{M}$ is in $M_\odot$ yr^{-1}, D is in kpc, S_ν in Jy, V_∞ is in km s^{-1}, ν is in Hz and g is the gaunt factor, Z is the rms ionic charge, γ the mean number of electrons per ion and μ is the mean molecular weight per ion. This equation is valid provided that the flux energy distribution follows an $S_\nu \propto \nu^{2/3}$ relation or, in other words, that the wind has reached its terminal velocity, (which occurs far away from the star, in the radio regime). In the near infrared the emitted flux comes from a zone where the wind is still being accelerated and, therefore, the wind's velocity law must be considered. Although some information on v(r) exists for the base of the wind in ζ^1 Sco (e.g., Hutchings 1979), the lack of observations at longer wavelengths than those here reported, together with the complex structure of the wind in this object (see discussion by Wolf and Appenzeller 1979) precludes any reliable determination of the velocity law for the entire extent of the envelope. An alternative way to proceed is to estimate from the infrared excess the flux density that one would expect to observe at λ6 cm assuming a certain spectral index. A similar method has been adopted by Barlow *et al.* (1981) in computing $\dot{M}$ of WR stars from near infrared photometry. This procedure allows one to use eq. (1) to calculate the mass loss rate for the expected S_ν at 6 cm from the infrared excesses at *K* and *L*. Two different spectral indices have been used to cover a reasonable range of options, namely: $\alpha = 0.75$ which corresponds to $\beta = 2.10$, where $n = R^{-\beta}$ describes the density distribution as a function of radius (i.e., $\beta = 2$ corresponds to constant velocity outflow); $\alpha = 0.86$ which describes a slightly steeper density distribution ($\beta \sim 2.25$). Values outside these limits seem unlikely for ζ^1 Sco. The extrapolated flux densities at λ6 cm for the two choices of α are listed in Table 4 together with the derived mass loss rates.

b) *The Hα Method*

The presence of Hα in emission in early type stars is

TABLE 4

MASS LOSS RATES

	K	*L*	Spectral Index
IR			
Predicted magnitudes	3.39	3.47	
$S_{\nu f\text{-}f}$ (Jy)	13.9	7.96	
$S_{\nu f\text{-}f}$ 6cm (Jy)	6.57×10^{-3}	5.42×10^{-3}	$\alpha = 0.75$
dM/dt ($M_\odot$ yr^{-1})	2.30×10^{-5}	1.99×10^{-5}	
$S_{\nu f\text{-}f}$ 6cm (Jy)	2.13×10^{-3}	1.86×10^{-3}	$\alpha = 0.86$
dM/dt ($M_\odot$ yr^{-1})	9.88×10^{-6}	8.93×10^{-6}	
Hα			
EW_{net} Hα(A)	+ 7.47		
L(Hα)/$L_\odot$	2.07×10^{2}		
dM/dt ($M_\odot$ yr^{-1})	1.15×10^{-5}		

regarded as indicative of the presence of an extended envelope. Furthermore, since this emission component is expected to yield information on the density and velocity of the inner parts of the envelope, then, there should be a correlation between its strength and the mass loss rate. Hearn (1975) developed a method to calculate this correlation for the Hα P Cygni profile of ζ Ori. This same method was applied by Sterken and Wolf (1978) to ζ^1 Sco. A similar model was investigated by Klein and Castor (1978) and mass loss rates for a number of OB stars have been determined using this model (e.g., Conti and Frost 1977; Ebbets 1982). This model assumes a spherically symmetric steady outflow where the velocity law is derived in terms of radiative acceleration only. The mass loss rate is obtained in terms of the stellar mass, effective temperature and the amount of energy emitted in the Hα line. In order to obtain the Hα luminosity, L(Hα), from the observed Hα profile one has to correct first the measured equivalent width for an assumed photospheric absorption line and multiply by the monochromatic continuum flux at Hα. The Non-LTE model of Mihalas (1972) for $T_{eff} = 17\,500$ and log g = 2.5 was used for this purpose. Figure 3 shows the observed and the theoretical Hα profiles. The net emission equivalent width is given by the dashed area in this figure. The relation involving the mass loss rate is given by the expression

$$\log L(H\alpha)/L_\odot = 2 \log |\dot{M}| - \log M/60\, M_\odot + c \quad , \quad (2)$$

where L(Hα)/$L_\odot$ and M/$M_\odot$ are the luminosity in Hα and the stellar mass, respectively, in solar units, and c is a constant which is mainly temperature dependent (for details see Klein and Castor 1978). The result of applying eq. (2) to ζ^1 Sco is listed in Table 4 together with the derived luminosity. Since this model adopts a steep (radiative) velocity law, the mass loss rate thus obtained might be expected to be overestimated. If the scaled rates of Lamers (1981) are considered to decrease the mass loss rate derived from equation (2) then a value of $\dot{M} \sim 6.2 \times 10^{-6}\ M_\odot\ yr^{-1}$ is obtained. The corresponding scaling factor was derived statistically (see Lamers 1981) and therefore is not necessarily the appropriate one in this particular case. It is interesting to note, however, that even when this large decreasing factor is introduced, the mass loss rate of ζ^1 Sco remains larger than the one derived by Sterken and Wolf (1978). It is also noted that the effect of adopting slightly different atmospheric parameters to compute the net equivalent width, would not alter the result significantly. The basic assumptions and physics employed in the models of Hearn (1975) and Klein and Castor (1978) are basically the same. Differences arise, however, in the treatment of the LTE departure coefficient, which directly affects the value of the electron density of the envelope, and therefore the mass loss rate.

Assuming that the star follows the same general trend as other OB stars in their relation of mass loss rate to stellar mass, luminosity and radius, then, the result of applying the empirical relations for the mass loss rate found by Lamers (1981) to ζ^1 Sco yield a $\dot{M} \sim 1.78 \times 10^{-5}\ M_\odot\ yr^{-1}$, in very good agreement with the results of Table 4.

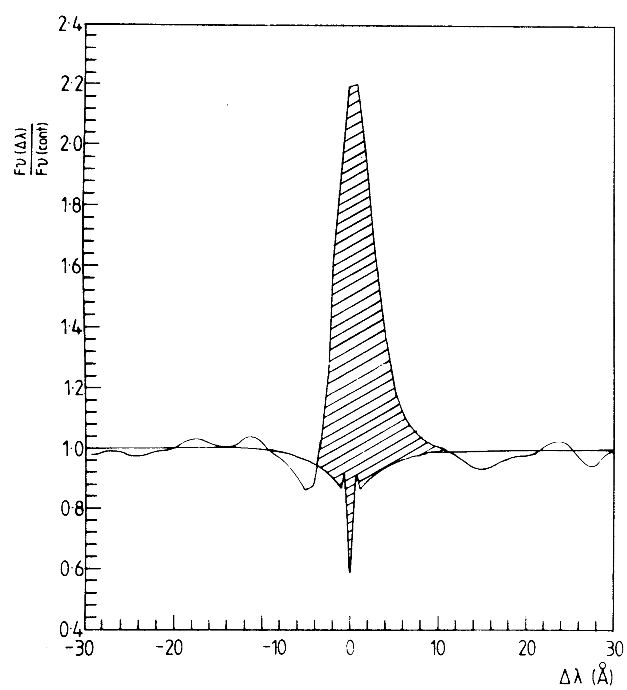

Fig. 3. The observed P Cygni type profile of Hα from Figure 1*a* is compared to the theoretical Non-LTE absorption profile with $T_{eff} = 17\,500$ K and log g = 2.5 (Mihalas 1972). The shaded area represents the net emission equivalent width component of the envelope.

V. CONCLUSIONS

Equivalent widths for several of the most important lines in the visible spectrum of ζ^1 Sco have been listed in order to facilitate future morphological comparisons. The spectrum seems in general not to have suffered drastic changes since the beginning of the century. The intensity variability of the elusive emission component in Hγ seems to be real. Since these changes are most probably due to density variations in the envelope, it is likely that intensity variations of CNO lines also take place. The evidence from the history of observations of this star suggests a rather complicated structure of the stellar wind. Nevertheless, a consistent result for the mass loss rate of 9×10^{-6} to 2×10^{-5} $M_{\odot}$ yr^{-1} has been obtained with the near infrared and Hα observations. Considering the characteristics of ζ^1 Sco. (e.g., high luminosity and large radius) it is thought that this value of $\dot{M}$ ($\sim 10^{-5}$ $M_{\odot}$ yr^{-1}) is quite representative for this star, even though the models employed assume a steady and uniform outflow. Radio observations at different wavelengths are highly desirable to determine accurately the spectral index of the envelope. Further simultaneous observations to monitor the *UV* absorption features and key optical lines such as Balmer and CNO lines should prove interesting. A better understanding of the physical processes involved in the mass loss mechanism and evolutionary stage of very luminous stars like ζ^1 Sco in particular and the OB supergiants in general, is still badly needed.

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