THE WARM WIND MODEL

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ABSTRACT

The analysis of the UV spectra of τ Sco (B0 V) and ζ Pup (O4 f) resulted in the empirical warm wind model. In this model the presence of O^{5+} and N^{4+} ions in the envelopes of early type stars is explained by collisional ionization in a 'warm' envelope of $T \simeq 2\ 10^5$ K.

I INTRODUCTION

The ultraviolet spectrum of a number of early type stars was observed by the Copernicus satellite. The spectra contain P Cygni profiles of the resonance lines of high ionization stages of abundant elements. One of the startling discoveries was the presence of wide O VI resonance lines in the spectrum of the standard B0 mainsequence star τ Sco (Rogerson and Lamers, 1975) which suggested an expanding envelope hotter than the stars' effective temperature of $3\ 10^4$ K. These lines were later found in the spectra of supergiants of types O to B1 (Snow and Morton, 1976). Lamers and Snow (1978) have shown that an anomalously high degree of ionization is found in the envelopes of all O stars and B type supergiants up to B8. Lamers et al. (1978) found evidence for an anomalously high Fe III/Fe II ratio in the envelope of α Cyg (A2 Ia).

In order to understand the proces of mass loss and the anomalously high degree of ionization in the envelopes, two stars were selected for a detailed study: ζ Pup (O4 f) by Lamers and Morton (1976) and τ Sco (B0 V) by Lamers and Rogerson (1978). The first star has a high mass loss rate of $7\ 10^{-6}\ M_\odot$/yr and strong P Cygni profiles whereas the second one has a small mass loss rate of $7\ 10^{-9}\ M_\odot$/yr and extended violet absorption wings. The profiles of the resonance lines of O VI, N V, Si IV and C IV in the spectrum of τ Sco are shown in Figure 1. The ultraviolet lines which show P Cygni profiles or extended violet wings are listed in Table 1. The extend of the violet absorption, V_{edge}, is also indicated.

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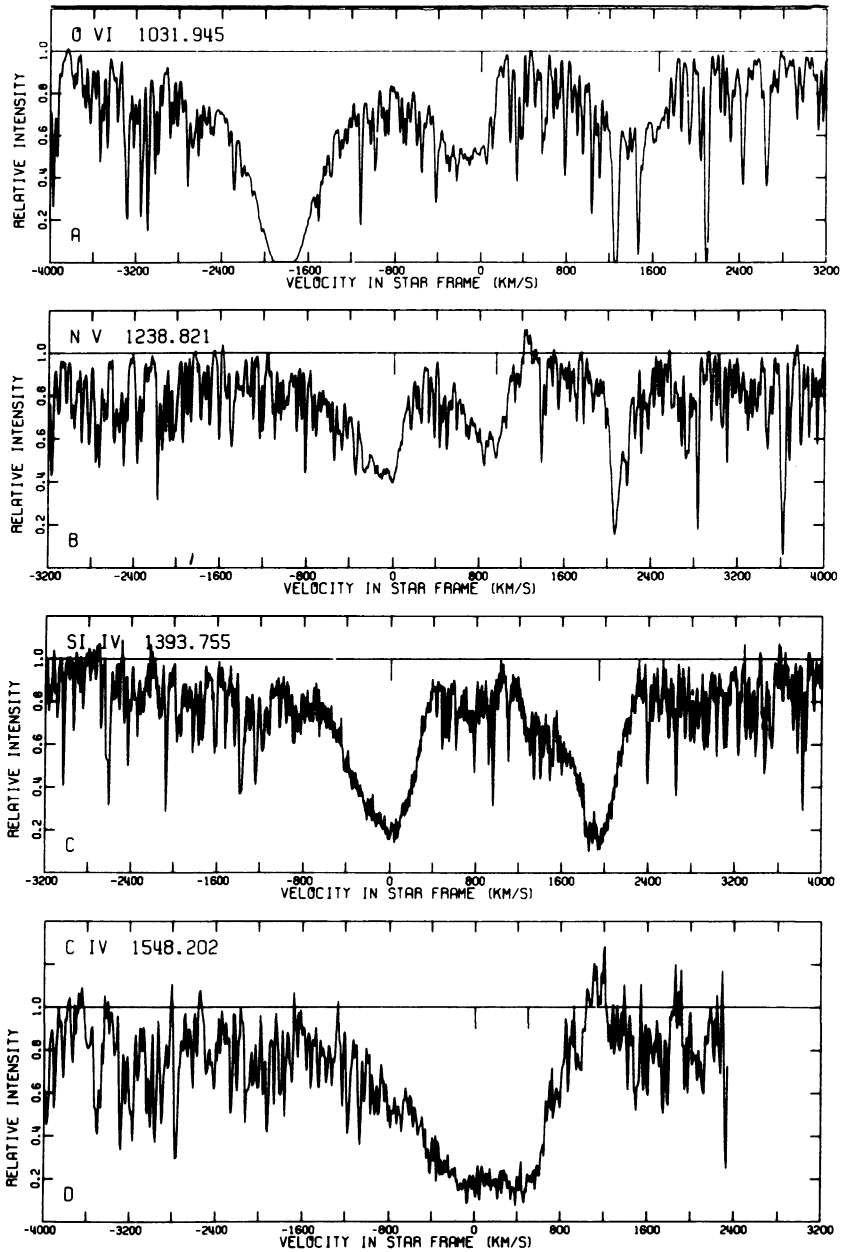


Figure 1. Parts of the tracing of the spectrum of τ Sco near the resonance doublets of O VI, N V, Si IV and C IV. The wavelength of the strongest component is written. The abscissa shows the velocity in the frame of the star. The laboratory wavelength of both components is indicated by vertical marks. The adopted continuum was determined from an inspection of a wavelength region of about 50 to 100 Å wide. The continuum and the zero level near the C IV lines is uncertain.

TABLE 1. ULTRAVIOLET ENVELOPE LINES IN THE SPECTRA OF ζ PUP and τ SCO

ION	LINES	EXC. POT	ζ PUP		τ SCO	
	λ (Å)	(eV)	profile	V_{edge} (km/s)	profile	V_{edge} (km/s)
C III	977	0	p^+	-2660	a	-2000?
	1176	6.50	p^+	-2660		
C IV	1548+1550	0	p^+	-2660	p^+	-2000
N III	990+ 992	0	a	-2660	a	-2000?
N IV	995+1719	16.20	p	-2000		
N V	1238+1243	0	p^+	-2660	a	-1400
O IV	1338+1343	22.40	a	- 800		
O V	1371	19.69	a	- 800		
O VI	1032+1038	0	p^+	-2660	a	-1000
Si IV	1394+1403	0	p^+	-2660	a	-1600
P V	1118+1128	0	p	-2660	a	- 700
S IV	1063+1073	0	p	-2660		
S VI	933+ 944	0	p^+	-2660		

p = P Cygni profile
p^+ = strong P Cygni profile, deeper than 50 per cent
a = extended absorption wing.

Since the warm wind model was derived from the observations of the UV lines in τ Sco and ζ Pup, we will briefly review the analysis of these two stars.

II THE IONIZATION BALANCE IN THE ENVELOPES OF ζ PUP AND τ SCO

The profiles were compared with theoretical profiles for a spherically symmetric expanding envelope, using the Sobolev approximation. By fitting the observed profiles to the predicted ones the radial optical depth could be derived:

$$\tau_{rad}(v) = \frac{\pi e^2}{mc} f \lambda n_i(r)(dr/dv) \qquad (1)$$

where $n_i(r)$ is the ion density and dr/dv is the inverse velocity gradient. At any velocity v the velocity gradient is the same (but unknown) for all ions. Consequently we compared at any velocity the ratios of the densities of all observed ions with the following results:

ζ Pup

i. The ratios between the different ions does not change with velocity. This implies that the ionization balance in the envelope of ζ Pup is constant from $v = 0.25\ v_\infty$ to $v = 0.9\ v_\infty$, i.e. from about 1.5 R_* to about 10 R_*.
ii. The degree of ionization in ζ Pup is higher than can be explained by radiative ionization by photospheric radiation, even if ζ Pup has an effective temperature of $5\ 10^4$ K. Especially the amount of O VI is orders of magnitudes larger than predicted.
iii. The ionization balance of all ions fits reasonably well (i.e. within a factor 3) with the predictions for collisional ionization in an optically thin plasma of $T_e = 2\ 10^5$ K throughout the envelope.

Recently, Olson (1978) has reanalyzed the UV lines in the spectrum of ζ Pup and noted that several of the lines studied by Lamers and Morton are optically thick, especially the O VI lines. These lines can also be fitted by adopting an ionization balance which changes with distance in a way predicted by the thin coronal model.

τ Sco

i. The violet lines of the O VI lines extend to -1000 km/s, the N V lines to -1400 km/s, the Si IV lines to -1600 km/s and the C IV lines to about -2000 km/s. This suggests that the degree of ionization decreases with increasing velocity in the envelope.
ii. The degree of ionization can be explained by collisional ionization in an optically thin envelope of $T_e \underset{\sim}{\sim} 2\ 10^5$ K at $v \underset{\sim}{\sim} 250$ km/s and $T_e \lesssim 1\ 10^5$ K at $v \gtrsim 1400$ km/s.
iii. If the high degree of ionization were due to radiative ionization from a large UV or X-ray flux one would expect the degree of ionization to *increase* with velocity since the flux decreases less rapidly with distance ($F \propto r^{-2}$) than the electron density ($n_e \propto v^{-1}r^{-2}$). The observations point to *decreasing* degree of ionization.

Lamers and Rogerson also noticed that the absorption of the O VI and N V lines extend at the long wavelength side to about +250 km/s (Fig. 1). These red absorption wings resemble Gaussian profiles with a Doppler velocity of 100 km/s. The presence of these absorptions show that O VI and N V ions are already present in the low layers of the envelope where the velocity is still small ($v \simeq 0$ km/s) and that these layers are very 'turbulent'. One should remember that τ Sco is a slow rotator ($v \sin i \lesssim 5$ km/s) and that the photospheric lines have a typical full width at half maximum of 23 km/s.

III THE WARM WIND MODEL

The warm wind model, proposed by Rogerson and Lamers (1975) is based on the analysis of the τ Sco. It is an empirical model and as such it fits the observations of τ Sco perfectly but it lacks a solid theoretical basis. This is in contrast to the radiation driven wind model which is theoretically solid but cannot explain the presence of O VI ions.

In the warm wind model the photosphere has some type of mechanical energy which is propagated upwards and dissipates above the photosphere. Due to this dissipation there is a chromosphere in which the temperature increases outward. In the layers where $T \simeq 2\ 10^5$ K about 10 per cent of the O and N ions are ionized to O^{5+} and N^{4+}. These ions have their resonance transitions at 1030 and 1240 A where the stellar flux reaches its maximum. As there are no strong *photospheric* absorptions of O VI and N IV the ions in the chromosphere absorb continuum radiation. The radiation pressure due to the O VI and N V lines alone gives a force which exceeds the gravitational force by a factor four. Consequently, the chromosphere will be accelerated outwards to a large velocity. As the envelope expands the temperature decreases outwards by radiative cooling. As a result of this the relative concentration of O VI and N V decreases, but the relative concentration of C III, C IV, N III and Si IV increases. These latter ions, whose resonance transitions are also in the ultraviolet produce a large radiation pressure as the flow velocity is large enough to shift those transitions outside the wavelength range of their photospheric counterparts. Consequently the acceleration continues up to large distances and large velocities of $v \gtrsim 2000$ km/s.

This scenario explains the presence of O VI and N V at small velocities. The large 'turbulent' motions observed in their resonance lines represent the motions in the dissipation layer. The asymmetric wings found in the high resolution profiles of the photospheric lines by Smith and Karp (1978) may indicate convection whose flux can provide the energy required for the heating of the chromosphere.

In this model the origin of the stellar wind is the radiation pressure by the UV resonance transitions. The mass loss is triggered by the heating as it produces the right type of ions which do not have strong photospheric lines. The warm wind model has a strong similarity to the imperfect flow model of Cannon and Thomas (1977) which also has a warm trans-sonic region heated by shocks. But in the imperfect flow model the origin of the mass loss is due to the presence of non thermal energy in the star which leaks out and produces a mass flux.

The warm wind model applied to ζ Pup has to be modified in two aspects. Firstly, the O VI and N V lines are not the dominant contributors to the radiation pressure of ζ Pup. In this star, which has a mass loss rate 10^3 times as large as τ Sco, the radiation pressure is provided by a large number of resonance lines in the Lyman continuum between 230 and 912 A (Lamers and Morton, 1976; Castor et al. 1976). Secondly, the presence of O VI up to the terminal velocity indicates the envelope is warm, $T \simeq 2\ 10^5$ K, up to large distances. Since radiative cooling is very efficient at this temperature an additional heating process throughout the flow is required to keep its temperature high. So the warm wind model does not fit the observations of ζ Pup as accurate as τ Sco.

IV COMPARISON WITH THE OBSERVATIONS

The anomalous degree of ionization is explained in the warm wind model by collisional ionization at $T \simeq 2.10^5$ K. Klein and Castor (1978) have pointed out that the observed Hα/He II 4686 ratio in O stars favors a cool wind, rather than a warm wind (see also III,b). However the dominant contribution to profiles of these lines comes from the region of small velocities $v \lesssim 0.3\ v_\infty$ where the temperature of ζ Pup is undetermined. Moreover, at these layers the profiles are sensitive to the velocity law, since $\rho \propto v^{-1}$, and the velocity law adopted by Klein and Castor is much steeper than the UV observations indicate.

The infrared excess of ζ Pup at 2.2 μm can be explained by the warm wind model, but this depends critically on the velocity law at $v < 0.25\ v_\infty$ for which there is no observational information.

The ¼ keV X-ray upperlimit for ζ Pup, measured by Mewe et al. (1975) is in agreement with the warm wind model. The warm wind is optically thick at ¼ keV. For an optically thick wind the emergent luminosity may be estimated from the Eddington-Barbier relation to be

$$L_\nu = 4\pi\ R_\nu^2\ (2/3)\ \pi\ S_\nu\ (2/3)$$

where R_ν is the radius at which the monochromatic optical depth, τ_ν, is 2/3, and S_ν is the source function at that radius. The source function is the ratio of the total emission to the total absorption. At ¼ keV the emission in a gas at $T_e \simeq 2\times10^5$ K is primarily due to recombination of helium and hydrogen. The opacity is bound-free absorption by metals, e.g. Si^{+4}, O^{+3}, Mg^{+3} and of He^+. The source function therefore tends to decrease with radius in proportion to N_e. The effective radius is at about 10 stellar radii. When these effects are taken into account, the predicted X-ray flux is well below the ANS upperlimit for ζ Pup. It should be noted that even though the warm wind may be rather optically thick at some frequencies, the calculated ionization balance is not inconsistent if the collisional ionization rates are larger than the radiative ionization rates.

REFERENCES

Cannon, C.J., Thomas, R.N.: 1977, Astrophys. J. 210, p. 910.

Castor, J.I., Abbott, D.C., Klein, R.I.: 1976, in *Physique des Mouvements dans les Atmosphères Stellaires*, ed. R. Cayrel and M. Steinberg, CNRS, Paris, p. 453.

Klein, R.I., Castor, J.I.: 1978, Astrophys. J.

Lamers, H.J.G.L.M., Morton, D.C.: 1976, Astrophys. J. Suppl. 32, p. 715.

Lamers, H.J.G.L.M., Rogerson, J.B.: 1978, Astron. Astrophys. 66, p. 417.

Lamers, H.J.G.L.M., Snow, T.P.: 1978, Astrophys. J. 219, p. 504.

Lamers, H.J.G.L.M., Stalio, R., Kondo, Y.: 1978, Astrophys. J. 223, p. 207.

Mewe, R., Heise, J., Gronenschild, E.H.B.M., Brinkman, A.C., Schrijver, J., den Boggende, A.J.F.: 1975, Astrophys. J. (Letters), 202, L67.

Olson, G.: 1978, Astrophys. J. (in press).

Rogerson, J.B., Lamers. H.J.G.L.M.: 1975, Nature, 256, p. 19.

Smith, M.A., Karp, A.H.: 1978, Astrophys. J. 219, p. 522.

Snow, T.P., Morton, D.C.: 1976, Astrophys. J. Suppl., 32, p. 429.

DISCUSSION FOLLOWING LAMERS

Hearn: Could you say something about the optical line observations and IR? Do they agree with your model?

Lamers: There may be troubles with the helium lines. Our model does not specify the temperature or velocity inside the region of about one-fourth the terminal velocity. The He I lines are probably formed here, and this would mean that this region is cool. However, this might not agree with the O VI lines. For the IR flux observed by Barlow and Cohen, we are not in difficulty. There are too many free parameters since the velocity law is not specified. One can't make a conclusive argument as yet.

Hearn: How about variability?

Lamers: One does observe photospheric motions in the spectrum of τ Sco [Smith and Karp, Ap. J. 219, 522 (1978)]. Presumably these will propagate outwards in some manner. Nobody has looked for variability in τ Sco.

Abbott: Would you care to put an uncertainty on your mass loss rate for τ Sco?

Lamers: The rate is $7.0 \pm 1.6 \times 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$.

Underhill: I have heard it said that your ζ Pup model has a high temperature out to 10 stellar radii. How do you get this result? Why can't you have this hot region which produces the O VI close to the star with a very rapid velocity rise?

Lamers: The ionization balance is more-or-less constant in the region from $0.25\ v_\infty$ to v_∞. The distance argument comes from the huge emission components to the P Cygni profiles. The more extensive the emission the more extended the envelope contribution.

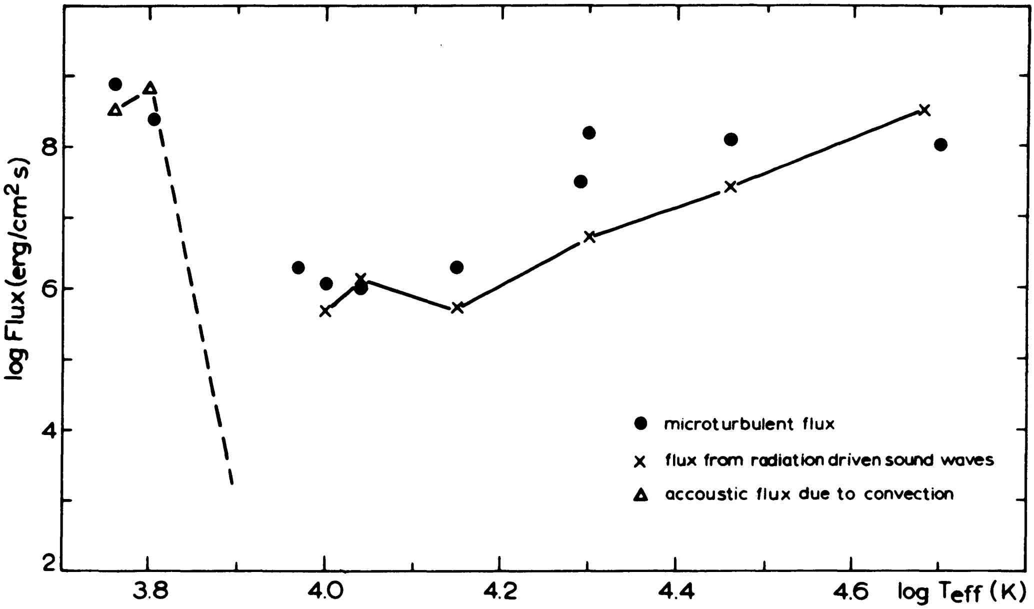
Underhill: This assumes that the same type of emission mechanism operates for all ions.

Lamers: Yes, we are assuming a scattering process for the emission. This assumption is justified for the UV resonance lines [e.g., Castor and Lamers, An atlas of theoretical P Cygni profiles, Ap. J. Suppl. (1979) in press]. We also assumed one velocity law for all ions.

Sreenivasan: What is the source of the turbulence in these stars? In τ Sco, for example? Does it have an appreciable rotation (V sin i)?

Lamers: No, the projected rotational velocity is smaller than 5 km/s. Smith and Karp [Ap. J. 219, 522 (1978)] proposed a He II convection zone.

de Loore and I have tried to find an explanation for the observed motions in the atmospheres of supergiants (Lamers and de Loore, 1976, in Physique des Mouvements dans les Atmosphères Stellaires, eds. Cayrel and Steinberg, CNRS, Paris). We compared the observed kinetic fluxes in 10 supergiants of types O5 to G2 with predicted fluxes.



The dots show the "observed fluxes" derived from the microturbulent velocities and assuming that these motions are in fact sound-waves. The triangles are the predicted fluxes of acoustic waves, generated by convection in the models by de Loore [Astroph. Space Sci. 6, 60 (1970)]. The crosses are the predicted fluxes of radiation-driven sound waves, predicted by Hearn [Astron. Astrophys. 23, 97 (1973)]. We conclude that: 1) Although the microturbulent velocity in early type supergiants does not change very much with spectral type, the associated flux shows a minimum around type A. This suggests that microturbulence in stars earlier than A is created by a different mechanism than in stars later than A. 2) The similarity of the observed and predicted variation of flux with T_{eff} suggests that the microturbulence in O and B stars is created by interaction of matter with radiation, and in supergiants of types F, G and possibly later by convection.