THE CORONA PLUS COOL WIND MODEL FOR Of STARS AND OB SUPERGIANTS

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ABSTRACT

The anomalously strong OVI and NV lines in O stars and the CIV and Si IV lines in B supergiants may be due to Auger ionization by x-rays from a thin coronal zone at the base of their cool stellar winds. This paper summarizes the results of several studies to determine constraints on the size and temperature of coronal zones from calculations of the effects of coronae on continuum and line spectra. The model that has resulted can be tested by observations from HEAO-B of the predicted 2 kev emergent fluxes. The model explains very well the persistence of the OVI and NV in the ultraviolet spectra of supergiants to class B0.5 and B2 respectively, and it predicts that CIV should be observable in the ultraviolet spectra at and beyond B5I.

INTRODUCTION

The high stages of ionization that are seen in the Copernicus spectra of the luminous O and B stars can be explained either by assuming that the winds are at an elevated temperature and that the ions are produced by electron collisions and photoionization by the ambient diffuse field or by assuming that the winds are subjected to a radiation field which is harder than what is expected from photospheric models.

Lamers and Morton found that the overall degree of ionization in the wind of ζ Pup, O4f, is about the same as one would expect in an optically thin plasma at a temperature of 2×10^5 K. So they postulated that the winds have elevated or "warm" temperatures throughout the extended region in which OVI must exist.

One serious objection to the "warm wind" models is that an extremely large rate of mechanical energy deposition is required to maintain the elevated temperatures, because such temperatures are near the peak of the radiative cooling curves of, for example, Cox and Tucker (1969). If we assume that the temperature is maintained by the deposition of acoustic or mechanical energy that emanates from the surface of the star, the

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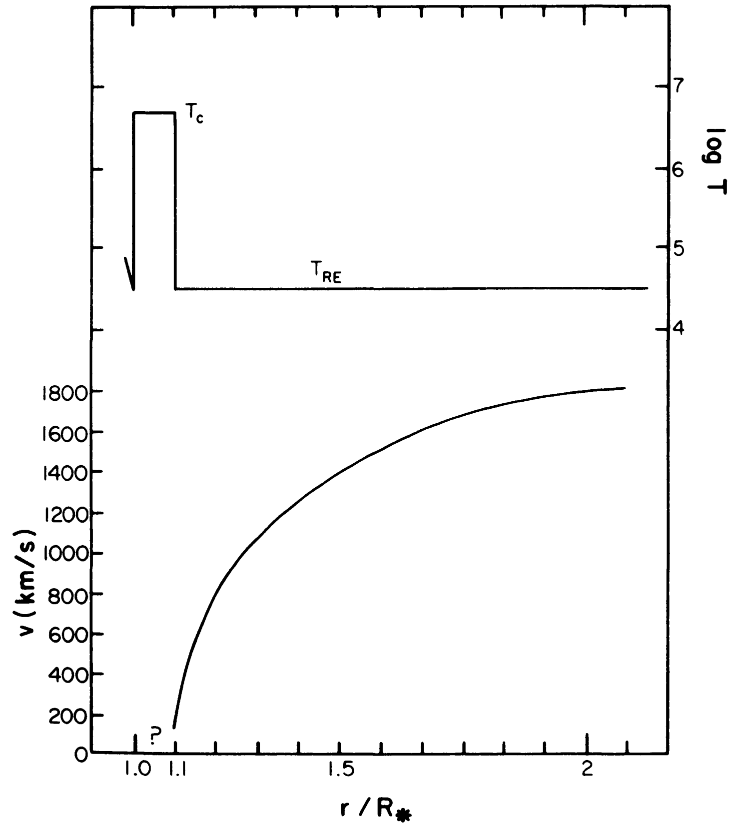
the mechanical luminosity of ζ Pup would be about 2 x 10^{38} ergs/sec or approximately 5 percent of the radiative luminosity of the star. Furthermore, it must be deposited over a spatially extended region of several radii.

The corona plus cool wind model is an alternate semi-empirical picture of the stellar winds of the O and B supergiants, which, as we shall see, can explain the anomalously high ionization stages and which requires a much smaller rate of mechanical deposition. In this model, we postulate that the mechanical energy is deposited only near the base of the stellar wind and it produces a thin coronal zone with a temperature near 5 x 10^6 K. Beyond the coronal zone, the winds are assumed to have the relatively cool temperatures of about 0.8 T_{eff} that would be appropriate for a gas in radiative equilibrium. Figure 1 shows the temperature distribution that has evolved from several studies that are reported below.



(Figure 1)

A two component temperature structure was first suggested for O and B supergiants by Hearn (1975). He proposed that the flows are driven to near escape speed by thermal pressure gradients in the coronal zone, and that the final acceleration to the high terminal velocities is due to radiation force on the line opacity in the cool wind. The transition from coronal to cool wind temperatures should occur, rather abruptly, where the mechanical deposition ceases, because the densities are so large ($\sim 10^{10} cm^{-3}$) that cooling by radiative recombination is very effective. Hearn deduced from a simplified analysis of the Hα P Cygni line in ζ Ori 09.5Ia that the coronal zone extends to 2 stellar radii.

Lee Hartmann, Gordon Olson, Roberto Stalio and I have investigated the observational consequences of hybrid corona-cool wind models in attempt to deduce whether the coronae exist. Although definitive proof of the existence of coronae has not resulted we have, in the process, developed a semi-empirical model which rather nicely explains the ionization anomalies, and which is useful for suggesting new observational tests.

In the next section is summarized the constraints that have been derived concerning the coronal structure in several papers which are already in print. In the last two sections the explanation of the high ionization stages for ζ Pup and for other O and B supergiants is presented.

CONSTRAINTS ON CORONAL STRUCTURE

The first models that were considered had the rather extended coronal regions that were suggested by Hearn (1975) on the basis of his Hα analysis.

Cassinelli and Hartmann (1977) calculated the effect of extended coronal zones on infrared continuum distributions. The infrared continuum can be used to probe the temperature and velocity structure at the base of the massive stellar winds of O and B stars because the opacity is rather high and optical depth unity occurs in these expanding layers. The free-free opacity varies as λ^2, and thus as one looks to longer wavelengths one "sees" an increasingly larger star. Because of their winds, the early type supergiants are expected to have infrared excesses. Cassinelli and Hartmann found that coronal zones should produce an additional excess or broad bump in the continuum between 20 μm and 100 μm, and some evidence for the bump should be seen between 10 and 20 μm. Barlow and Cohen (1977), however, found no significant extra rise in the continuum between 10 and 20 μm. Its absence can be explained in the context of the coronal plus cool wind model by assuming that the coronal zone is much thinner than originally postulated and that the temperature rise at the base of the flow is more abrupt.

Cassinelli, Olson and Stalio (1978) reinvestigated the evidence from Hα that there may be extended coronal zones, by calculating theoretical profiles using the Sobolev technique. It was found that models with extended coronal zones in which the outflow was raised to speeds of order

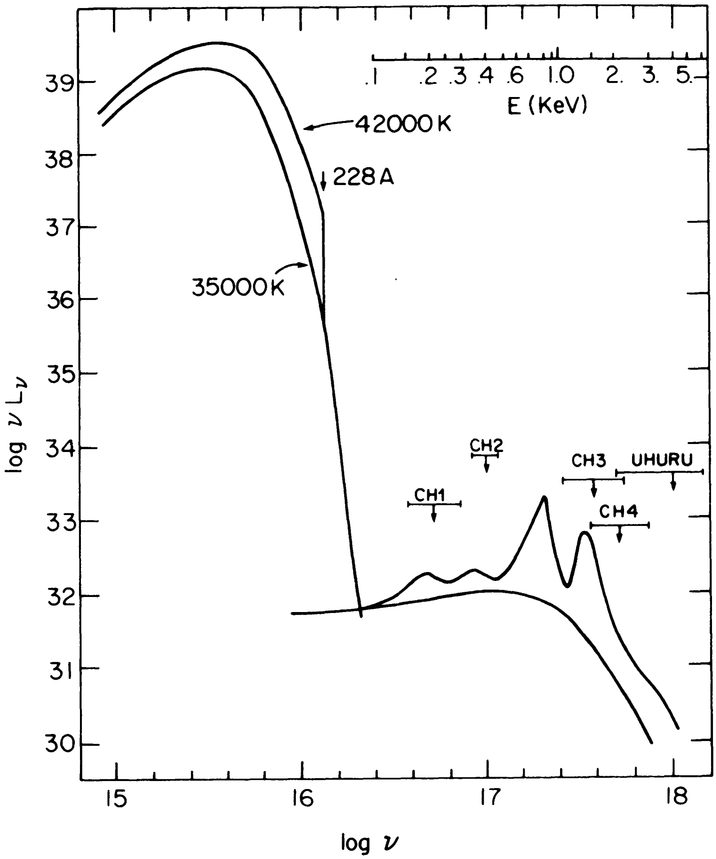
500 km/sec give rise to broad flat topped emission components of the P Cygni profiles. This is because the corona is a zone of null contribution to the profile and the extra emission that would have come from the denser lower wind layers is absent. Such broad flat topped Hα profiles are not seen in the spectra of O and B supergiants. It was concluded that the coronal zones must be very thin ($\sim 0.1\ R_*$) and that the flow velocity at the start of the cool wind zone is small, about 1/20 v_∞. This is a radical departure from the original Hearn model and it suggests that the coronae do not play the dominant role in driving the mass outflow, but may nevertheless, affect the ionization balance in the wind. Olson (1978) pursued the studies of line profiles and developed a method somewhat like that of Lamers and Morton (1976) for determining the ionization and velocity structure of winds from fits to ultraviolet line profiles. He derived the degree of ionization of several elements in the wind of ζ Pup and found that they compared favorably with the predictions of the corona plus cool wind model. The study showed that the fractional abundance of NV and OVI must be at least as large as 10^{-4} to account for the strong resonance lines in O and B supergiants. Olson found that a velocity distribution like that shown in Figure 1b gives rise to a good fit to the resonance lines in ζ Pup. Again, the initial velocity in the cool wind was found to be low ($\lesssim 0.1 v_\infty$).

The Hα and ultraviolet resonance lines have no contribution from the gas inside the coronal zone and hence the studies of these lines has led to no information concerning the velocity structure inside the zone. However, it is possible to derive some useful information concerning integrated properties of the corona, such as the coronal emission measure, $EM_c = \int N_e^2\, dvol$, and the average coronal temperature T_c by considering the production of the anomalous ionization stages in the winds. Cassinelli and Olson (1978) carried out such an analysis for ζ Pup.

EFFECTS OF CORONAL RADIATION ON THE WIND OF ζ PUP

ζ Pup is commonly chosen for the most detailed analyses because good observational constraints on the wind structure are available. The mass loss rate is known to be near $7 \times 10^{-6}\ M_\odot/yr$ from studies of Hα and ultraviolet line profiles and from infrared and radio continuum observations. (Lamers and Morton, 1976; Cassinelli, Olson and Stalio, 1977; Barlow and Cohen, 1977; Morton and Wright, 1978). The degree of ionization, of say OVI and NV, is know from the resonance line analyses of Lamers and Morton (1976) and Olson (1978).

The assumed radiative flux from the photosphere and corona of ζ Pup is shown in Figure 2. The star is assumed to have an effective temperature of 42000 K. There should be a drop in the emergent flux at the HeII, n=1, edge at 228Å, and in absence of the coronal zone there would be little flux shortward of the O^{+4} to O^{+5} ionization edge at 108Å. The energy emergent at the high energies is due to the corona, which is assumed to have a temperature of 5×10^6 K. The underlying coronal continuum is due to bremstrahlung and there is a large contribution from emission lines, which is shown as if smoothed into 5 to 10Å bands.

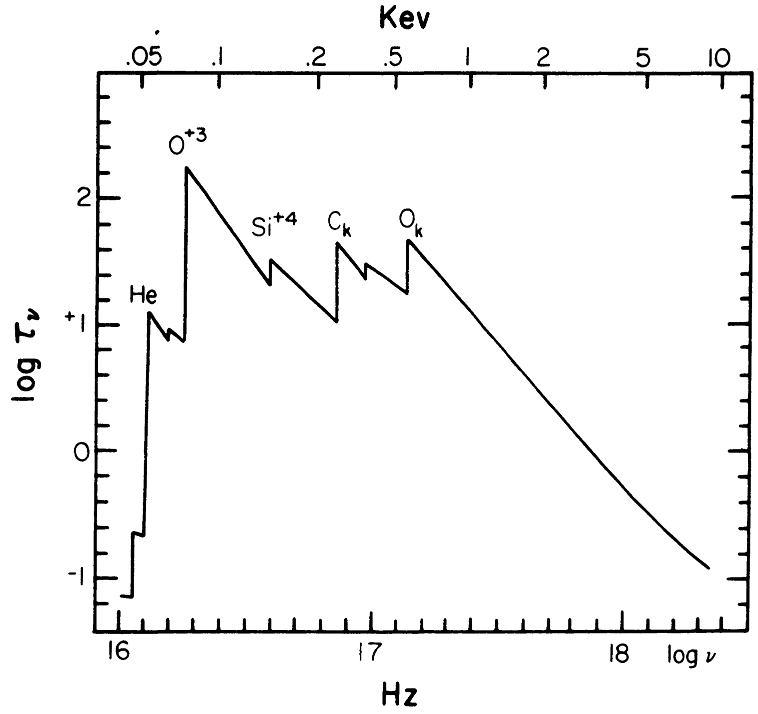


(Figure 2)

The knee in the coronal flux occurs near $h\nu/kT_c = 1$, thus, if the coronal temperature were increased, the knee would be shifted to higher energies. The coronal emission measure, EM_c, determines the magnitude of the coronal flux. The distribution shown of Figure 2 corresponds to $EM_c = 10^{56} cm^{-3}$. If the wind of ζ Pup were optically thin, that value for the emission measure would be sufficient to produce the required amount of OVI in the wind to explain the observed profile.

Also shown in the figure are x-ray upper limits for ζ Pup as were derived from four channels of the ANS detector and from Uhuru satellite observations. Thus, if the wind were thin the corona flux distribution would suffice to explain the ionization observations and to satisfy the x-ray constraints.

However, the winds of O and B supergiants and Of stars are not optically thin in the frequency range which contains many important ionization edges. Figure 3 shows the run of total optical depth versus frequency for a model of ζ Pup in which the wind is assumed to have an electron temperature of 35000 K. The optical depth is greater than 10 at the HeII n = 1 edge and it rises to even larger values as other opacity edges are



(Figure 3)

crossed. The last important opacity edges are due to K shell ionization of carbon, nitrogen and oxygen (two of which are noted as C_k and O_k in the figure). Beyond the oxygen K shell edge the opacity, and hence also the optical depth, decreases as $\nu^{-2.6}$, and not until the relatively high energy of 2 keV does the optical depth decrease to values less than unity. Therefore, only the harder x-rays penetrate far out into the wind where the high stages of ionization are known to exist.

Since the wind is thick for a broad range in frequencies it is necessary to account both for the attenuation of the coronal radiation field, and for the diffuse radiation that originates in the wind. The diffuse field plays an important but indirect role in explaining the anomalous ionization. It is important in determining the general ionization balance of the gas and in particular, determining the dominant stages of ionization because several important ionization edges occur at frequencies for which the wind is very thick. To a fairly good first approximation, in the cool wind model, one can assume that the diffuse radiation field is equal to $B_\nu(T_e)$ at these frequencies.

What is of particular interest to us is the production of the high stages of ionization by absorption of x-rays with energies beyond 1 keV. For C, N and O, an absorption of an x-ray K shell ionization essentially always leads to the net ejection of two electrons instead of one because of the Auger effect (Weisheit, 1974).

The process of determining the abundance of an interesting high stage of ionization can be carried out in two steps. The fractional abundance of the dominant stages of ionization can be determined as if there were no coronal radiation, because only a small fraction of a percent of the dominant stages are ionized to high stages by the Auger process. The second step is to determine the abundance of the "high stage," which is two ion states above. This can be determined rather easily as follows.

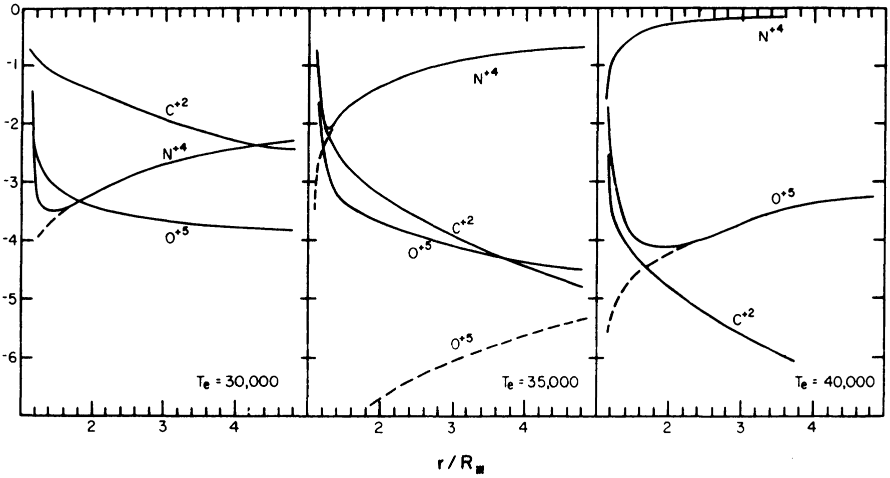
The coronal x-rays will be attenuated by the K shell opacities of C, N and O, and these opacities are nearly independent of the number of electrons in the outer shells of the ion that is absorbing the photon (Daltabuit and Cox, 1972). So one needs to know the column density of the nuclei of C, N and O, which depends on the mass loss rate and velocity law in the wind, but *not* on the assumed temperature of the wind. Letting $\theta_\nu(r)$ be the attenuation optical depth measured outward from the corona at r, then $\theta_\nu = \theta_o(\nu_o/\nu)^{2.6}$, where $\theta_o(r)$ is the value at the K shell edge of oxygen at ν_o (0.6 keV). The ratio of the number of high ions of an element El^{+p+2} to the number in the parent stage El^{+p} is given by

$$\frac{N(El^{p+2})}{N(El^{p})} = \frac{1}{N_e \alpha} \int_{\nu_{El}}^{\infty} \frac{4\pi}{h\nu} a_\nu W F_\nu^{c} e^{-\theta_\nu} d\nu \quad , \qquad (1)$$

where a_ν is the K shell absorption cross section $\approx a_o(\nu_o/\nu)^{2.6}$, $g W F_\nu^{c} e^{-\theta_\nu}$ is the spatially diluted and attenuated coronal flux, $N_e(r)$ is the electron density and $\alpha(T_e)$ is the recombination coefficient from El^{p+2} to El^{p+1}. Expressing the results in terms of the fractional abundance, $g(El^p) = N(El^p)/N_{El}$ and noting that the coronal flux distribution has the general shape of a bremmstrahlung spectrum, $C\, EM_c \exp(-h\nu/kT_c)$ we get

$$\frac{g(El^{p+2})}{g(El^{p})} \alpha(T_e) = \frac{4\pi}{h} \frac{a_o C W EM_c}{N_e(r)} \int_{\nu_{El}}^{\infty} \frac{\exp[-(h\nu/kT_c) - \theta_\nu]}{\nu^{3.6}} d\nu \quad . \qquad (2)$$

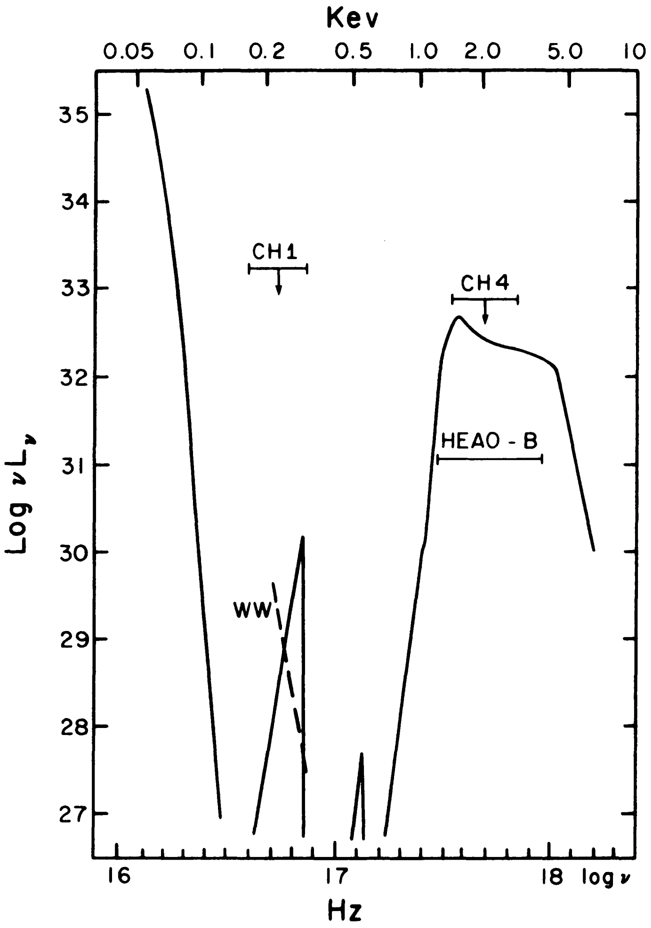
This equation nicely separates the quantities which depend on the wind temperature $g(El^p)$ and $\alpha(T_e)$ from quantities which depend only on the local radius, r, and the coronal parameters EM_c and T_c. Thus, we see immediately that the abundance of the "anomalously high stage" of ionization is directly proportional to EM_c and to the abundance of the parent stage. The dependence on coronal temperature is slightly more complicated, but we see that as T_c increases a greater fraction of the flux lies at the higher energies which can penetrate far into the wind. Because of the $\theta_\nu(r)$ term it is possible for the abundance of a high ion state to decrease in the outward direction, in contrast to the thin case in which the ionization increases in the outward direction.



(Figure 4)

Figure 4 shows the calculated spatial structure of the ionization for several ionization stages observed in the wind of ζ Pup. Note that the O^{+5} abundance decreases, because of optical depth effects for some cases. Results are shown for three assumed wind temperatures. The dashed line labeled O^{+5} shown in the second and third panel of the figure, are results for the case in which there is no coronal radiation, i.e., EM$_c$ = 0. Thus, the diffuse radiation field can produce a significant amount of O^{+5} if the wind is at temperatures larger than about 40,000 K. Castor has investigated in much greater detail the effect of the diffuse field in producing the anomalous ionization that is seen in O and B supergiants, and the model has been referred to as a "tepid wind" model to distinguish it from the Lamers "warm wind" models. The warm, tepid, and corona plus cool wind models are discussed in a review paper by Cassinelli, Castor and Lamers (1978).

Figure 5 shows the most important result of the calculations; the x-ray flux that is predicted to penetrate through the wind and hence is potentially observable. There is negligible flux transmitted between 0.1 to 1 keV because the wind is so thick at these frequencies, and hence soft x-ray detectors are not likely to find evidence of hot coronae. The soft x-ray flux expected for a warm wind model is indicated by the WW in the figure. The flux expected from the coronal plus cool wind model for ζ Pup is fairly large at 2 keV, and is just below the existing ANS upper limit. The predicted flux is above the estimated detection limit for HEAO-B which is scheduled for launch in late 1978. We can easily see that the crucial test of the corona plus cool wind model will be provided by the HEAO-B observations.



(Figure 5) Emergent x-ray flux from ζ Pup

THE ANOMALOUS IONIZATION IN B SUPERGIANTS

There are other predictions of the corona plus cool wind model that can be tested with existing satellite data. The most interesting concerns the persistence of the anomalous ionization stages into the B supergiant spectral range.

The Auger process produces enhanced abundance of ions which are two stages above the dominant stages of ionization. Thus, if oxygen is primarily in the ionization stage OIV in the stellar wind then we should expect to find a greatly enhanced OVI abundance. As we look at stars of later spectral types, we should expect that OVI will weaken and disappear at the spectral range for which the dominant stage of ionization is shifting from OIV to OIII. A similar situation should hold for NV as produced from NIII, and CIV as produced from CII.

The first step in the analysis is to estimate the ranges in effective temperature for which CII, NIII and OIV are expected to be very abundant. I have carried out some simplified calculation for this purpose, and assumed that Ne = 10^{10}cm^{-3} and used a dilution factor appropriate for two stellar radii. The electron temperature in the cool wind is determined by the effective temperature of the star, $T_e \approx 0.8\ T_{eff}$. From calculations of relative abundances versus effective temperature two useful temperature ranges can be derived: 1) The range in T_{eff} over which the ion has an abundance of at least 10 percent and is, therefore, a likely candidate for being a parent of an anomalously high ion stage; 2) The range in T_{eff} over which the ion has an abundance of at least 10^{-4} and is, therefore, likely to be seen even in absence of the Auger process.

Table 1 summarizes the results. Listed are resonance lines from relatively high stages of ionization whose appearance in the spectrum may indicate the presence of x-rays. The two ranges of effective temperatures discussed above are shown, as is the parent ion and the K shell ionization edge of that ion. For simplicity, it is assumed in this analysis that the Auger ionization of Silicon, Sulpher and Phosphorus will also lead primarily to enhancement of ions two stages higher. This is not entirely correct and better calculations are in progress.

Note from Table 1 that NV and OVI are to be expected, via the Auger process, in the spectra of supergiants with affective temperature as low as 20000 and 30000 respectively. (More detailed calculations lower these estimates even further) In absence of the x-ray ionization OVI should not be seen in the cool winds of any stars and NV should only be seen in the very hottest. (See also, Lamers and Snow, 1978).

COMPARISION WITH OBSERVATIONS

Table 2 again lists the lines from high ion stages and indicates whether or not the line is present in the spectra of 10 supergiants, with a wide range in effective temperature. A plus sign indicates that the line is seen, an exclamation mark (+!) indicates that the line is "anomalous", i.e., not expected to be produced by the photospheric radiation field or by collisions or diffuse radiation in a cool stellar wind. Finally, the range in effective temperatures above which the line could be produced by the Auger mechanism in the corona plus cool wind model is indicated by the series of asterisks (***).

- OVI is seen in the spectra of stars of spectral type as late as B0.5. Morton discussed earlier in this meeting that the line is not present at B1 and later.

- NV is present in the Copernicus spectra in the catalogue of Snow and Morton (1976) in stars as late as B1. To help me fill in the blank at B2 in the original catalogue, Walter Upson at Princeton and Blair Savage at Wisconsin have kindly allowed me to look at Copernicus spectra of θ Ara, and NV is definitely present. It disappears at B3, as we would expect from the Auger model.

Table 1

ULTRAVIOLET RESONANCE LINES LIKELY TO BE ENHANCED BY AUGER IONIZATION

LINE	(Å)	f	Abundance N_{El}/N_H	T_{eff} range normally expected (10^3 °K)	T_{eff} range ion expected via Auger process (10^3 °K)	Parent ion	K-shell edge (kev)
C IV	1548.2 50.8	0.194 0.097	3.7×10^{-4}	25 - 65	9 - 20	C^{+1}	.296
N V	1238.8 1242.8	0.152 0.076	1.1×10^{-4}	$T_{eff} > 39$	20 - 37	N^{+2}	.432
O VI	1031.9 1037.6	0.130 0.065	6.8×10^{-4}	$T_{eff} > 54$	30 - 50	O^{+3}	.595
Si IV	1393.8 1402.8	0.528 0.262	3.5×10^{-5}	20 - 45	8 - 16	Si^{+1}	1.88
P V	1118.0 1280.0	0.495 0.245	2.7×10^{-7}	33 - 70	14 - 29	P^{+2}	2.24
S IV	1062.7 1073.0	0.038 0.037	1.6×10^{-5}	19 - 50	8 - 19	S^{+1}	2.54
S VI	933.4 944.5	0.426 0.210	1.6×10^{-5}	$T_{eff} > 37$	25 - 44	S^{+3}	2.58

Table 2

RESONANCE LINES SEEN FROM HIGH STAGES OF IONIZATION IN OB SUPERGIANTS

STAR		T_{eff}	M 10^{-6} $M_\odot$/yr	S IV λ1065	Si IV λ1400	C IV λ1550	P V λ1120	N V λ1240	O VI λ1035	S VI λ940
ζ Pup	O4f	42000	7.0	+	+	+	+	+	+!	+
α Cam ζ Ori	O9.5 Ia	30000	2.5	+	+	+	+	+!	+!	
ε Ori	B0 Ia	24800 28800	4.3	+	+	+		+!	+!	
κ Ori	B0.5 Ia	26400	2.5	+	+			+!	+! ***	***
ρ Leo	B1 Iab	21000	1.0		+			+!	-	
θ Ara	B2 Ib	18000						+! ***	-	
o^2 CMa	B3 Ia	15500	2.0	-	+!	+!	***	-	-	
η CMa	B5 Ia	13300	.4	-	(+!)	(-) ***		-	-	
β Ori	B8 Ia	11600	1.0	- ***	+! ***					

\+ indicates that the line shows mass loss effects; P Cygni profile or displaced absorption.

\- indicates that the line shows no mass loss effects.

blank indicates no information.

( ) indicates an uncertainty.

+! indicates that this line is not expected in a cool radiative equilibrium wind, yet is seen.

*** above which is the region where Auger enhancement is expected.

- CIV is not easily detected on the Copernicus scans because the spectrometers are not sensitive at 1550Å. However, some useful data is available from the Skylab survey of Parsons et al (1977). The line is fairly strong at B3 but is much weaker or absent at B5. IUE data is now becoming available, and I think the line should be seen in the spectra of B5 stars and later, especially since Si IV is seen at B8I.

- Sulpher seems to disagree with the predictions but this may be due to the large K shell ionization energy (see Table 1) or due to our oversimplified analysis of the Auger process.

The predictions of the corona plus cool wind model agree very well with the observed persistence of OVI, NV and Si IV, and there is hint of agreement with CIV. However, this agreement of predictions and theory cannot be considered sufficient proof of the validity of the model because Lamers and Snow (1978) have shown that the persistence of OVI to B0.5 and Si IV to B8 could also be explained by assuming the temperature of the warm winds are lower (∿ 80000 K) for stars showing no OVI.

CONCLUSIONS

Several lines of evidence based on IR continuum, x-ray upper limits and profiles of Hα and ultraviolet resonance lines, indicate that if there are coronal zones at the base of the winds of luminous early-type stars, they must be very thin ($\lesssim 0.1\ R_*$). There is interesting positive evidence for the existence of the coronae in that the model explains, in a very natural way, the persistence of the anomalous ionization into the B spectral class. The span of effective temperatures over which the high ion states exists is explained by the Auger ionization process whereby two electrons are removed from the dominant stage of ionization, and thus the anomalously high ions cease to appear at temperatures at which the parent ion ceases to be the dominant stage. Conclusive proof for the existence of hot coronal zones in O and B supergiants will have to await the observations from the HEAO-B satellite.

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DISCUSSION FOLLOWING CASSINELLI

Hearn: How well does your model fit the IR observations?

Cassinelli: At one time we had a temperature maximum that extended to 2 stellar radii. This provided an IR "bump" which is not observed. Now, however, our coronal model is sufficiently thin in extent that there is no conflict with the IR data.

Hearn: Can you account for a wind in τ Sco in your model?

Cassinelli: I haven't considered this star.

Hearn: What about variability?

Cassinelli: One could imagine fluctuations in this high temperature corona of order of hours. This would drastically affect the ionization in the outer regions, and so could produce the kinds of variability observed in ultraviolet spectra by York et al. [Ap. J. 213, 261 (1977)].

Morton: Do C III and O VI resonance lines have same terminal velocity in supergiants?

Cassinelli: Yes, at least for the stars with large mass loss rates.