THE WINDS AND CORONAE OF EARLY-TYPE STARS

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ABSTRACT

The properties of the winds of hot stars as derived from radio, ultraviolet and X-ray observations is presented. Special focus is given to observations that test line driven wind theory. In this theory the wind properties are determined by the stellar effective temperature and surface gravity, but not parameters that specify the mechanical or wave fluxes from the star. Alternate explanations of the X-ray emission from the early-type stars are discussed. Evidence is given for the presence of coronal zones at the base of the stellar winds.

Conclusive evidence for winds from early-type stars was provided in the early days of ultraviolet astronomy by observations of OB supergiants by Morton (1967). Figure 1 shows a tracing of one of the early spectra of the supergiant ζ Ori(O9.5Ia). The lines of C IV and Si IV show profile with emission longward of line center and absorption extending far shortward of line center. Such profiles are called "P Cygni" profiles after the star P Cyg which shows prominent lines with this shape in the visible part of the spectrum. The lines observed in the ultraviolet have shown that luminous hot stars have fast massive winds. The velocities are typically in the range 1000 to 3000 km/sec or approximately 3 times the escape speed (Abbott 1978). The mass loss rates are greater than 10^{-6} solar masses per year. The wind temperature, T_w, appears to be comparable to the stellar effective temperature (30 to 50×10^3 K) as estimated from the low ion stages such as Si^{+3} that are observed to have P Cygni lines. These properties are very different from those associated with the solar wind ($v \sim 300$-700 km/sec, $\dot{M} \sim 10^{-14}\ M_\odot/yr$, $T_p \sim 10^6$K).

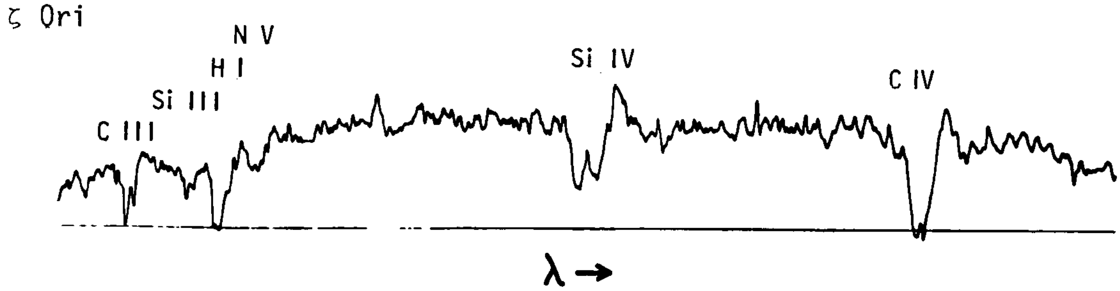

Fig. 1 - Shows Morton's (1967) early observation of the ultraviolet spectrum of ζ Ori O9.5Ia. Wavelengths increase to the right from 1140 to 1630 Å. Shown are the P Cygni profiles of C IV and Si IV and shortward displaced absorption lines of C III, N V, and Si III.

Three topics will be discussed in this review: 1) The basic methods that have been developed to derive the properties of winds; 2) The physical mechanisms for driving the fast massive winds; and 3) A summary of current research problems.

Stellar Wind Properties Derived from Observations

The most important diagnostic of the structure of the winds are the P Cygni profiles. The formation of a P Cygni profile for a strong resonance line that has a rest wavelength, λ_o, is illustrated in figure 2. Let us assume the velocity v(r) increases monotonically in the outward direction and reaches a terminal speed v_∞. In such a flow any parcel of gas sees light emitted from any other parcel or light from the star as redshifted. A photon emitted radially from the star at a wavelength slightly shortward of line center ($\lambda < \lambda_o$) may, in traversing the wind, become scattered in a "resonance shell" at a radius where the wind has the speed $v(r) = c(\lambda_0-\lambda)/\lambda_0$. If the line opacity is very large, the intercepted photon may be scattered many times in the resonant shell. The radiation transfer is well described by the Sobolev escape probability theory (Sobolev 1960, Castor 1970, Mihalas 1978). After the many scatterings, the photon may escape in a direction, θ, relative to the radial direction. The wavelength as seen by a distant observer will be redshifted to λ' from its original wavelength λ by an amount determined by the angleθ: $\lambda'=\lambda+(1-v/c \cos\theta)$. Thus the photon labelled 2' that was scattered from the back side of the envelope is seen at a wavelength larger than λ_o, and photon 1', last scattered from the front side will be seen shortward of λ_o. If we assume that the ion which is doing the scattering is very abundant in the wind, all of the photospheric photons shortward of line center from λ_o to $\lambda_o(1-v_\infty/c)$, will be scattered out of the direct line of sight to the observer and will be redistributed over the band $\lambda_o(1 \pm v_\infty/c)$. The net effect is a depletion of photons shortward of line center and an excess longward of line center, thus forming a P Cygni profile. We can see from this that it is very easy to determine the terminal velocity from the star of the lines showing a sharp shortward edge. Weak lines are also useful because from their shapes it is possible to derive information about the spatial distribution of the ion in the wind. If we assume the ion/proton abundance varies as r^β, the resulting P Cygni lines have the shapes shown in figure 3 for various values of β. For example, for $\beta = 2$ the ions are concentrated far from the star and the line shows a sharp displaced absorption near $\Delta\lambda=\lambda v_\infty/c$. The dashed lines in Figure 3 show saturated profiles; for these strong lines the information about the spatial distribution of the ion is lost.

A useful way to derive the rate of mass loss by stellar winds is to measure the long wavelength continua of hot stars. At infrared and radio wavelengths the dominant opacity is free-free absorption. This increases as λ^2, so if one observes the star at sufficiently long wavelength the radius at which optical depth equals unity can occur in the wind itself. This "effective photosphere" can grow larger as one looks at even longer wavelengths. This increasing area of the photosphere as a function of λ gives rise to an infrared and radio excess illustrated figure 4. At radio wavelengths the monochromatic photosphere may be

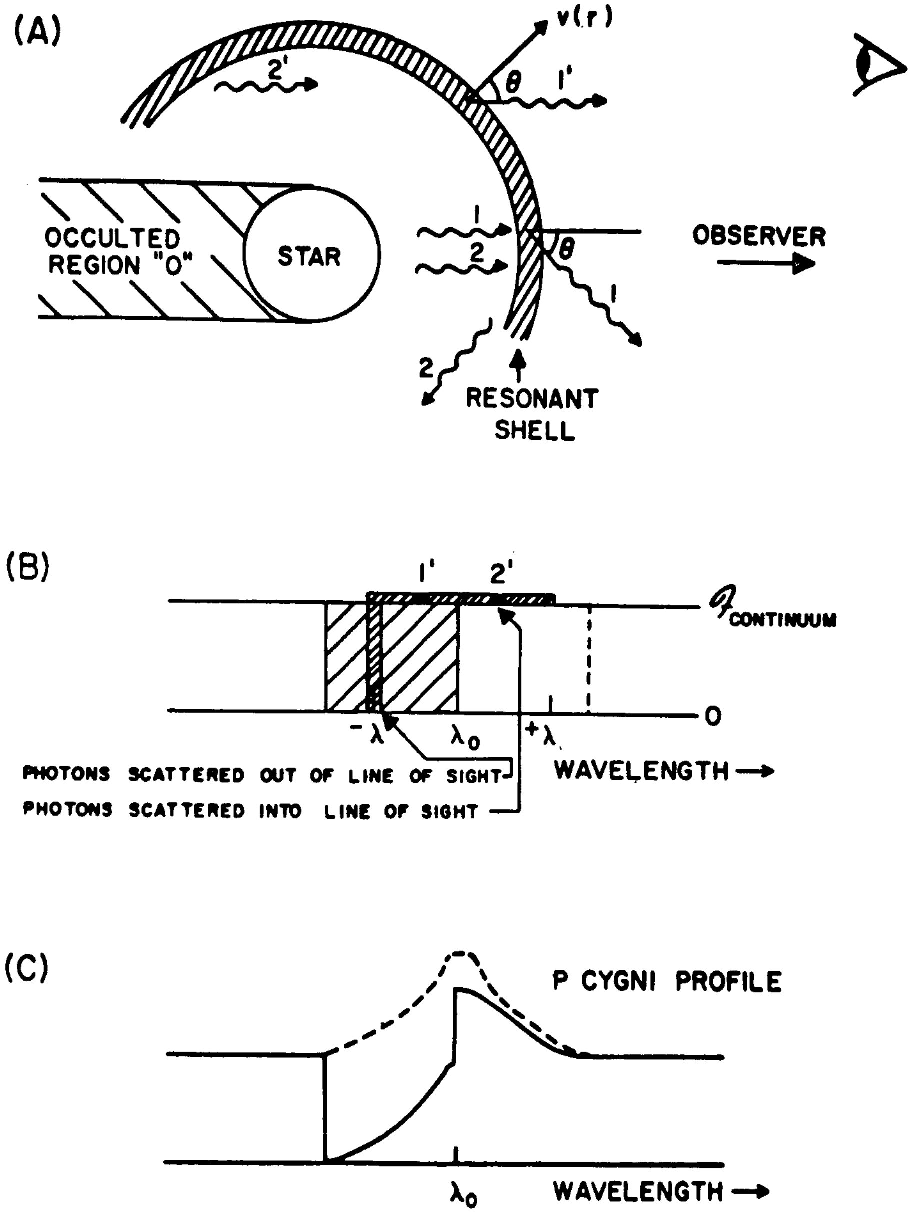

Fig. 2 - Illustrates the formation of a P Cygni profile of a resonance line. Panel A shows the scattering of two photons 1 and 2 out of the line of sight. In a spherically symmetric system, two other photons 1' and 2' will be scattered into the line of sight. As shown in Panel B these will be redshifted because of the expansion of the resonant shell. So scattered photons are redistributed over a region -λ to +λ. This produces the P Cygni profile shown in Panel C. The dashed line shows the distribution of re-emitted photons. The region labelled O corresponds to photons not seen by the observer because of the occultation by the star.

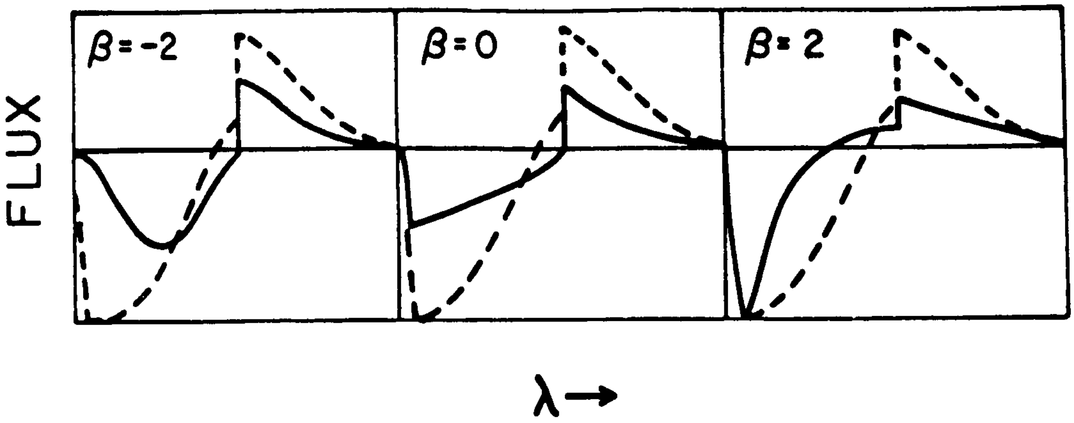

Fig. 3 - The dependence of P Cygni profiles on the ionization abundance of a line producing ion in the wind. The ion abundance is assumed to vary with radius as $g_i \propto r^\beta$. The results for three different values of β are shown. A) If an ion decreases in abundance with radius the absorption is at maximum depth for small velocity displacement. C) If an ion increases in abundance with r, the line may show little emission but a strong displaced absorption. The dashed lines show the results for a saturated line. Note these are all identical independent of β. (Adopted from Olson 1978).

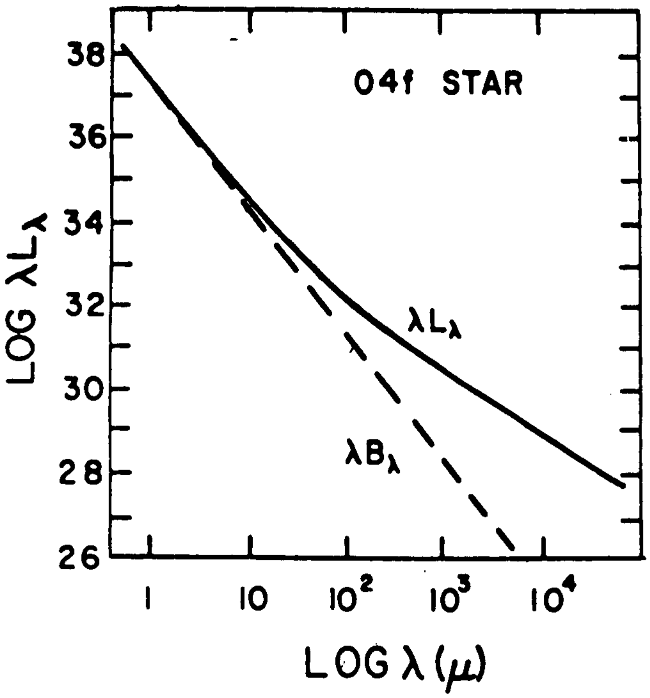

Fig. 4 - The effects of a massive wind on the free-free flux from an O4 star. In absence of the wind, the flux from the O4 star would resemble the Planck distribution B_λ. The flux in the radio region (6 cm) yields a good measure of the mass loss rate. The infrared 1 to 100 μ is sensitive to the density structure near the base of the wind. The data for the O4f star is from Cassinelli and Hartmann (1977).

at tens of stellar radii where the flow has reached terminal speed, and therefore ρ is decreasing as r^{-2}. Thus the optical depth to the photosphere ($\tau_\lambda \simeq 1$) is determined only by the mass loss rate $\dot{M}$, and we find for the energy distribution λL_λ = const $\lambda^{-5/3}(\dot{M}/v_\infty)^{4/3}$ (Cassinelli and Hartmann 1977). Infrared and radio observations have become one of the most important methods for deriving basic properties of stellar winds (Barlow and Cohen 1977; Abbott et al. 1980, 1981; Leitherer et al. 1982). With the Very Large Array (VLA) radio telescope in New Mexico it is even possible to marginally resolve the radio monochromatic photosphere. Resolved observations of the massive wind of P Cyg are discussed by White and Becker (1982) and they derive interesting results about the temperature and geometry of the flow.

The results for the mass loss rates in the HR diagram are shown in Figure 1 in MacGregor's paper present earlier. For the stars at the luminous hot end of the HR diagram, the mass loss rates are $>10^{-6}$ $M_\odot$/yr and can even approach 10^{-4} $M_\odot$/yr for Wolf Rayet and O3 f^+ and O4 f^+ stars.

Wind Dynamics

What can drive such fast massive winds? Lucy and Solomon (1970), and Castor, Abbott, and Klein (1976) argued that a Parker coronal wind mechanism could not be responsible. This is because speeds of 2000 km/sec would require a coronal temperature of $6\text{x}10^7$ K. This is incompatible with the low ionization stages such as C^{+3} and Si^{+3} which indicate cool wind temperature.

The early-type stars are very luminous, and it is reasonable to think that radiation pressure gradients play an important role in the mass loss. Line driven wind theory has become well developed over the past dozen years by Lucy and Solomon (1970), Castor, Abbott, and Klein (1975) (referred to as CAK), and Abbott (1980, 1982). The dominant question since 1970 has been Can the radiation alone from quiescent luminous stars be the cause of the fast massive winds? By "quiescent star" I mean a star with no source for mechanical energy deposition such as acoustic or magneto-acoustic waves. Early-type stars have negligible convection zones, but there may be other sources of mechanical energy associated with their fast rotation or possible magnetic fields or stellar pulsations. The question asks, however, whether the radiation field alone, in isolation from all these other effects, can drive the winds. It is a straightforward but difficult question.

The basic idea for line driven winds is as follows. Radiative acceleration of the gas is proportional to the product of the wind opacity, κ, and the flux F_λ. Opacity is very large at the wavelengths of the resonance lines, but the flux tends to be negligible at line wavelengths because of the line absorption deeper in the atmosphere. However if a parcel of gas is moving outward, the opacity is doppler shifted, and the parcel can be pushed by the large radiation flux that is present on the shortward side of the line. The flux and hence the outward acceleration varies as r^{-2} and thus the radiation effectively leads to a decrease in the gravitational field. In the presence of the radiation field the Parker momentum equation becomes;

$$\frac{1}{v}\frac{dv}{dr} = \frac{\frac{2a^2}{r} - \frac{GM}{r^2}(1-\Gamma)}{v^2 - a^2} \qquad (1)$$

where a is the sound speed and Γ is the ratio of the outward acceleration due to radiation to the inward acceleration of gravity. Note, firstly that because of the presence of Γ in Eq. 1, the effective gravity is greatly reduced and transonic flow can occur at relatively low sound speeds as appears to be required by the presence of low ion stages.

For there to be an outward increase of v in the subsonic region (where the denominator is negative), it is necessary that Γ be less than unity. However beyond the sonic point Γ is allowed to be greater than unity and this can lead to a very large velocity gradient. This is sometimes known as the "after burner" effect.

Lucy and Solomon (1970) showed that C IV λ1550 alone could drive a mass loss rate of $\dot{M}>10^{-9}$ $M_\odot$/yr to speeds v_∞>1000 km/sec. Thus the line formation process discussed in section 1 is directly associated with the acceleration of the flow.

To get the observed large mass loss rates of $\dot{M}>10^{-6}$ $M_\odot$ yr^{-1}, it is presumably necessary to account for thousands of lines. CAK developed a convenient way to do this. The total acceleration is a sum over all lines of the products of line opacity, κ_ℓ, and the flux in the line. The flux, in turn, depends on the line radiation transfer through the wind, and this can be treated using escape probability methods. Consider the resonance shell refered to in Figure 2. The flux at λ in the line is the stellar flux F^*_λ, times a penetration probability, $(1-e^{-\tau})/\tau$.

The optical depth, τ, through the shell is $\tau = \kappa_\ell \, \rho \, \Delta r \simeq \kappa_\ell \, \rho \, v_D (dv/dr)^{-1}$, which can be normalized to the optical depth for unit opacity as $\tau = \kappa_\ell \, t$. The acceleration on a strong line (i.e., $\tau \gg 1$) becomes;

$$\kappa_\ell F_\lambda = F^*_\lambda (\rho \, v_D)^{-1} \, dv/dr$$

From which we see that the opacity cancels out and the acceleration is proportional to dv/dr (or to 1/t). If we ignore weak lines, the total acceleration is proportional to the number of strong lines, N, times dv/dr. Using extensive line lists CAK and Abbott (1982) find that N can be fitted as $N = N_0 t^\gamma$. Therefore the total line acceleration is proportional to $(dv/dr)^\alpha$ with $\alpha = \gamma - 1$. The problem of line driven winds is complicated by two problems. 1) A very extensive line list is required. Abbott (1980) found that 20 chemical elements have potentially optically thick lines and must be included in the driving force. 2) the acceleration from line opacity varies as $(dv/dr)^\alpha$ with $0 < \alpha < 1$. The wind momentum equation for dv/dr is therefore non-linear and so is quite unlike the solar wind equation of Parker. It is interesting that Abbott (1982) finds that for stars with a wide range in effective temperatures $5000 < T_{eff} <$ 50,000K, the acceleration is $K(dv/dr)^{0.56}$ with approximately same force constant K and index α. This results in part because as T_{eff} changes the ions doing the driving changes, but they tend to have their strongest lines at wavelengths in the general region of the maximum of the Planck function.

The main predictions of the line driven theory are (Abbott 1982)

$$v_\infty = \left(\frac{\alpha}{1-\alpha}\right)^{.5} \times v_{esc} = 1.5\ v_{esc},$$

which is to be compared with the empirical result $v = 3\ v_{esc}$, and

$$\dot{M} = \text{const}\ (L/L_\odot)^{1.98},$$

versus the empirical result $\dot{M} \propto (L/L_\odot)^{1.77}$.

The difference from 1.5 to 3 v_{esc} for v_∞ can be explained if multiple scattering is accounted for, as shown by Friend and Castor (1983). Thus we see that the line driven wind theory does an amazingly good job in explaining the observations of early-type stars. One must conclude that the dominant mechanism in the acceleration of the winds of early-type stars has been identified.

The only stellar parameters accounted for so far are T_{eff}, and g. No mention has been made of wave energy and momentum or magnetic field phenomena that we associate with the solar wind. It sounds too good to be true. Maybe it is. There are several major problems that may not be explainable using the CAK theory and these problems are at the focus of current research. - 1) Wolf-Rayet stars present a serious problem because they appear to have an extremely large mass loss rate. If we equate the photon momentum per second from the star L/c to the momentum flow rate by the wind $\dot{M}\ v_\infty$, we derive an estimate of the maximum mass loss rate that can be driven by radiation; $\dot{M}_{Max} = L/v_\infty c$. Wolf-Rayet stars exceed this limit by a factor of 10 to 30 (Barlow 1982; Cassinelli 1982; and Abbott 1982). Several explanations are being considered. Firstly, within the context of line driven wind theory, it has been argued that the limit can be exceeded by a factor of 3 to 10 if multiple scattering is accounted for. The photons from the stars are not destroyed in being scattered in the wind but merely have been sent off in different directions, allowing further scattering and momentum deposition to occur. The problem can also be alleviated somewhat, if Wolf-Rayet stars are hotter and therefore have a higher luminosity than assumed in the deriving $\dot{M} > 10\ L/v_\infty c$. Panagia and Felli (1982) argue that the effective temperature may be 50% higher then usually assumed.

An alternate solution is that the winds of Wolf-Rayet stars are not driven by radiation pressure but by magnetic acceleration mechanisms (Cassinelli 1982). If the fields on Wolf-Rayet stars are $>10^4$ gauss the winds could be driven by Alfven waves as suggested for the solar wind by Belcher (1971), Jacques (1978) and for red supergiants by Hartmann and MacGregor (1980). As early-type stars are rapid rotators it is also plausible that Wolf-Rayet winds could be driven by the "fast magnetic rotator mechanism" of Belcher and MacGregor (1976) as applied to pre-main-sequence stars by Hartmann and MacGregor (1982).

2) A second major current topic of research concerns observational evidence for heating of the winds. Ionization stages higher than could be expected from the CAK line driven wind theory are seen in the UV spectra of O and B stars. Figure 5 shows the broad P Cygni lines in ζ Pup O4f and wind displaced lines in the main-sequence star τ Sco at the resonance lines of N V λ1239 and O VI λ1032. Lamers and Morton (1976) suggested that these indicate that the winds are heated to temperatures high enough to collisionally produce O VI ($\sim 2\times10^5$K). Cassinelli, Castor, and Lamers (1978) commented on several problems with this "warm wind" explanation. For example, to account for O VI over the entire wind of ζ Pup a mechanical luminosity of ~10% the radiative luminosity would be required to balance the very efficient cooling that occurs at $T = 2\times10^5$K.

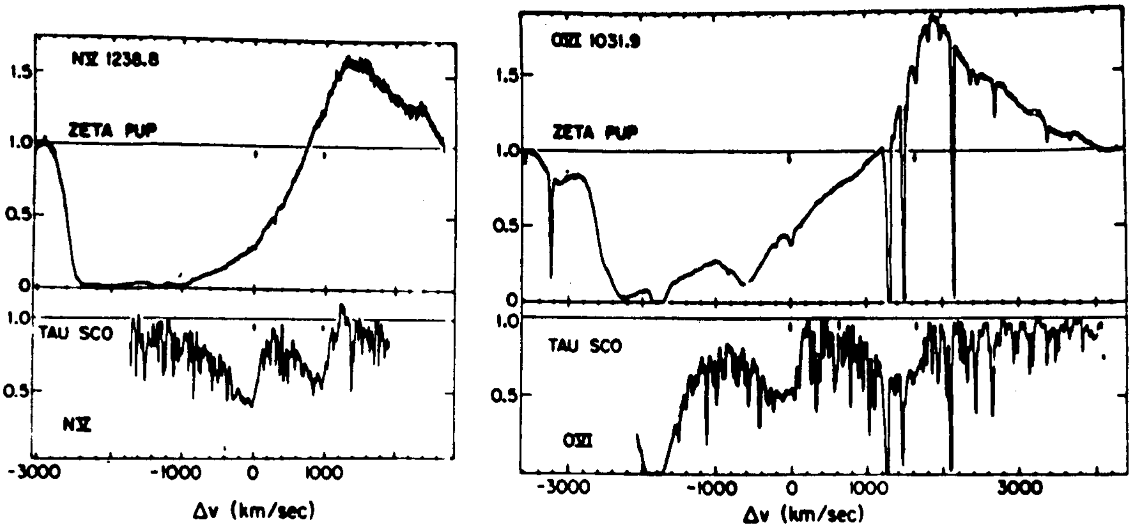

Fig. 5 - The spectra of ζ Pup O4f and τ Sco BOV in the region of the resonance doublets of O VI and N V. The horizontal axes give the velocity (km s^{-1}) in the frame of the star. The arrows indicate the laboratory wavelength of the lines. In the O VI spectral region, the strong line at -1900 km s^{-1} is Ly β. The sharp lines in the spectrum of ζ Pup are interstellar lines. Adapted from Lamers (1975).

Cassinelli and Olson (1979) suggested that the high ion stages could be produced as a result of X-rays emitted from a coronal region at the base of the wind. The Auger effect leads to the removal of two electrons upon K shell ionization of carbon, nitrogen or oxygen. Thus since O^{+3} is the dominant ion stage in the cool wind of an O star, K shell ionization can lead to a trace amounts of O^{+5} and thereby explain the observed O VI line. This model predicted that Of and OB supergiants would be X-ray sources with luminosities of $\sim 10^{32}$ ergs/sec. The first observations made with the Einstein satellite (1979) confirmed that essentially all O stars are X-ray sources (Harnden et al. 1979, Seward et al. 1979). The X-ray luminosities for various stars on the HR diagram are shown in Figure 6. The region over which the Auger enhanced lines of the O VI, N V, C IV, and Si IV are seen are also shown. For the early-type stars the X-ray luminosity is proportional the total luminosity of the star. ($L_X/L \simeq 10^{-7}$, Long and White, 1980; Vaiana et al., 1980; Cassinelli et al., 1981; and Seward and Chlebowski, 1982).

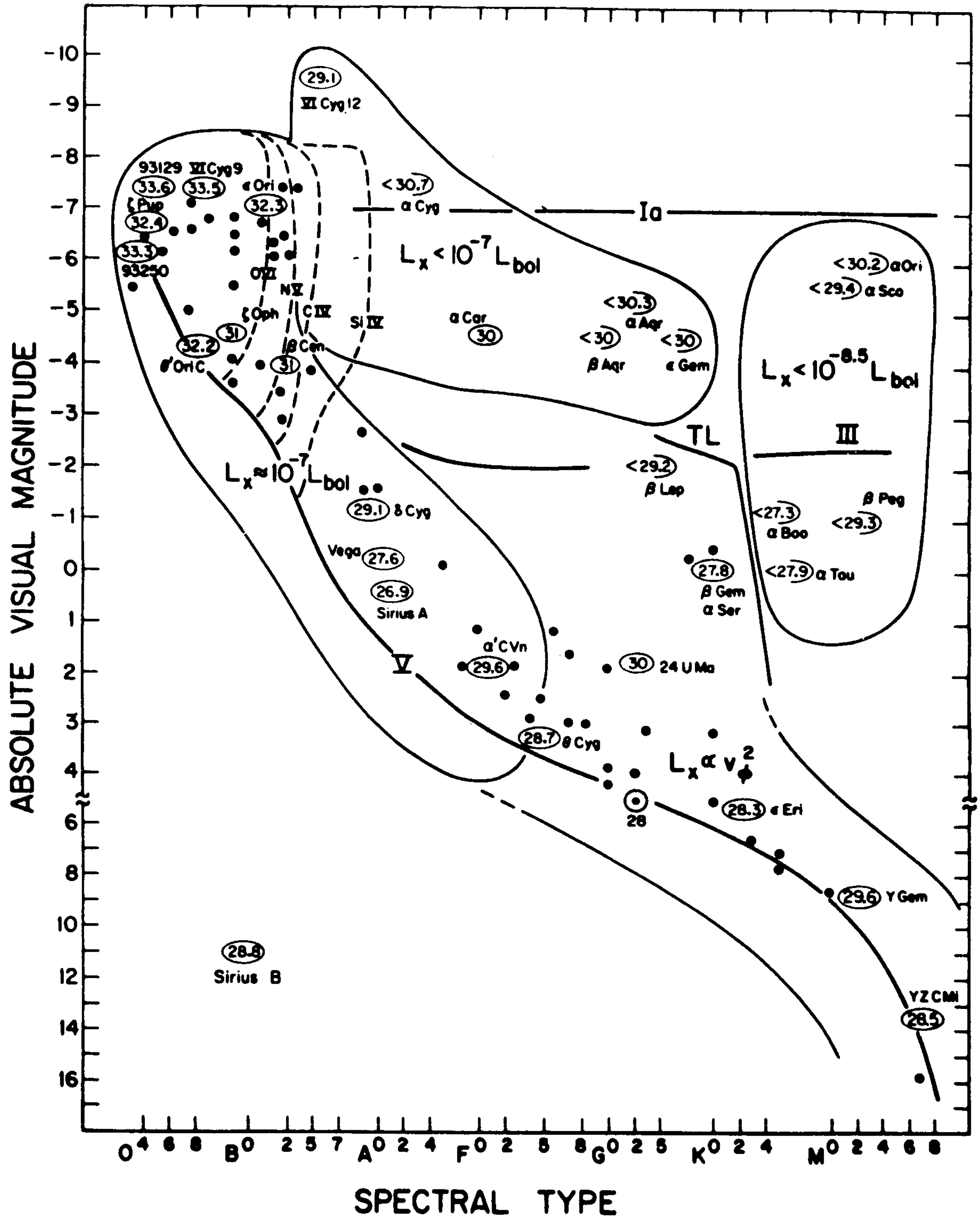

Fig. 6 - X-ray emission in the HR diagram. The solid dots indicate stars detected as X-rays sources by the *Einstein* satellite. For several stars the logarithm of the X-ray luminosity is shown in the ovals. Upper limits are also shown for a few supergiants and late-type giants. The extent of the presence of broad lines of the "superionization" ions in the UV spectra at O VI, N V, C IV, and Si IV are indicated by the dashed lines for the early-type stars. For early-type stars L_X is proportional to the stellar luminosity, as indicated, while for late-type stars the X-ray luminosity is proportional to rotation speed squared as might be expected from coronal emission that depends on a dynamo mechanism. This figure is from the review by Cassinelli and MacGregor (1983).

Does the detection of X-rays mean that the base corona plus cool wind picture is correct? If so, it implies that there is mechanical heating occurring at the base of the wind; and there is a flux of mechanical energy emergent from the stellar interior; and the mass loss is not fully explained by line driven wind theory. Figure 7a shows the X-ray energy distribution predicted from the slab corona plus cool wind model of Cassinelli and Olson (1979) compared with the observations of ε Ori B0.5Ia made from the Einstein satellite using the solid state spectrometer (SSS), (Cassinelli and Swank 1983). The empirical model predicted that there should be a sharp decrease in the flux at 0.6 keV because of attenation in the cool wind by the K shell edge opacity of oxygen. The observations show clearly that the edge is not there. The X-rays must be formed further out in the wind. The need for a base corona is no longer evident.

A recent explanation for the X-ray energy distribution gives fresh support for the radiatively initiated wind idea. Lucy and White (1981) and Lucy (1982b) have proposed that the X-rays arise in shocks embedded in the wind. Shocks should form, they argue, because line driven winds are unstable. Consider two neighboring gas elements at the same height in the atmosphere. If one is given a slight outward velocity increment relative to the other, it will have its line opacity doppler displaced into a frequency band with more flux (i.e. less blocking by the line opacity deeper in the atmosphere). Therefore the velocity increment will grow. This and the related instabilities of line driven winds has been analyzed by Nelson and Hearn (1978), MacGregor, Hartmann, and Raymond (1979), Carlberg (1980), and Kahn (1981). Lucy and White (1980) proposed that the instabilities grow to form blobs that are radiatively driven through the ambient gas and have X-rays formed in a bow shock at the front face of the blob. The X-rays are still formed relatively close to the base of the wind in this model and still predict a significant edge at 0.6 keV as is seen in Figure 7b. Lucy (1982b) has proposed a different limiting form for the flow instability. He suggests a periodic shock model, in which the shock is accelerated by radiation in the wavelength band corresponding to the increment in velocity that occurs from one shock to the next. (See Fig. 8).

The predictions of Lucy (1982b) are analyzed for ε Ori by Cassinelli and Swank (1983) (Figure 7c). To explain the X-rays some very strong shocks are needed with shock velocities >500 km/sec to provide $T \simeq 3 \times 10^6$K. One strong shock is needed every 21 hours. The wind flushing time, however, is only ~3 hours and large variations in the X-ray flux might be expected. The X-rays of ε Ori are not variable, however, (Cassinelli et al. 1983). Therefore the strong shock is not spherically symmetric about the star but must be broken into at least 25 or so "shreds" distributed through the flow. Lucy (1982a) offers further empirical support for his periodic shock model by arguing that the observed P Cygni profiles with their broad dark absorption imply the flow velocity is a non-monotonic function of radius.

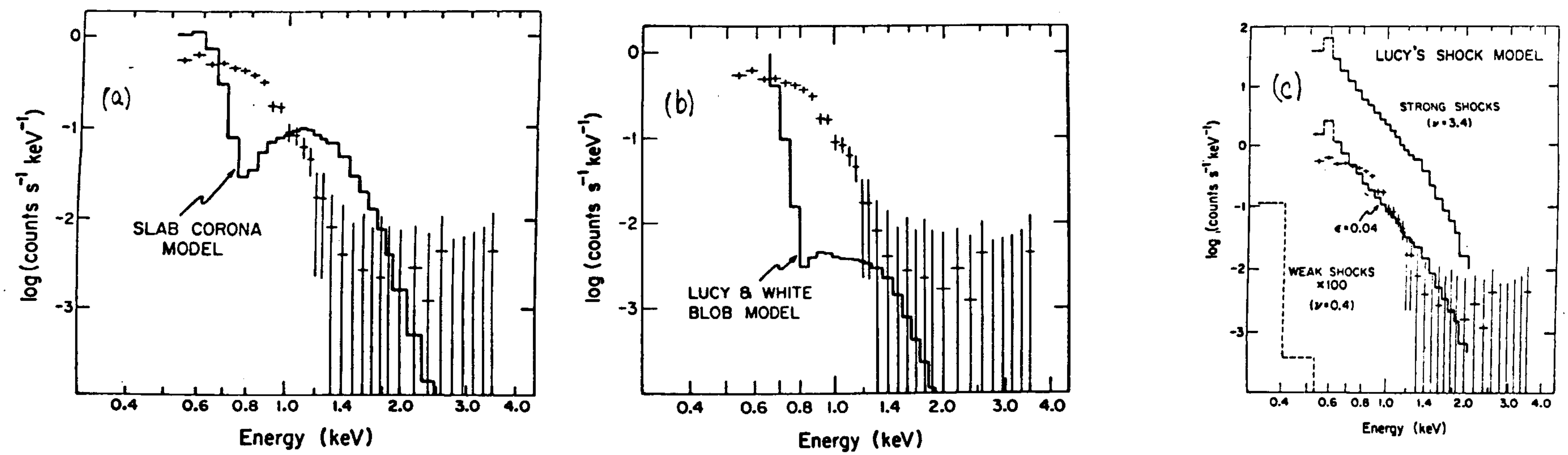

Fig. 7 - Shows the Solid State Spectrometer (SSS) spectrum of ε Ori (B0Ia) compared with predictions of 3 models. A) The heavy line shows the SSS spectrum predicted by a model in which the X-rays originate at the base of the wind in a thin slab corona. The absorption edge clearly seen at 0.6 keV is caused by K shell ionization of oxygen in the cool wind. The lack of this absorption in the observed spectrum suggests that much of the soft X-ray emission comes from sources well above most of the wind opacity. B) Shows the spectrum predicted from the radiatively driven blob model of Lucy and White(1980) for ζ Pup in which X-rays are expected to be formed near the base of the wind. C) Shows the spectrum of ε Ori predicted by Lucy's (1982b) periodic shock model. The shocks are parameterized by the quantity, ν,. Results for 2 values of ν are shown. The preferred value in the theory is ν = 0.4, but is seen to yield a spectrum that is far below (even after multiplying by 100) the observed distribution. The model with ν = 3.4 gives rise to a spectrum that is sufficiently hard but predicts more X-rays than are needed to fit the observation. If a fraction, ε = 0.04 of the X-rays are assumed to come from these strong shocks a reasonably good fit is achieved as is shown.

With the modification of radiation driven wind theory to include radiatively driven instabilities, it does appear that the answer to our original question is: Yes, a quiescient luminous star can push off a fast massive wind, and can explain the presence of "coronal" phenomena such as X-ray and anomalously high ionization lines. The debate is going on, nonetheless. Cassinelli and Swank (1983) point out that there is evidence for gas at ~15x10^{6}K in OB supergiants and O main-sequence stars. The stars show X-ray lines of Si XIII and S XV at ~2 keV. These may be difficult to explain with radiation driven wind models, but are easily explainable if the stars have magnetic loops analogous to magnetic structures in the solar corona. The Wolf-Rayet problem discussed earlier is also not yet resolved in that it is not yet clear whether an alternate wind driving mechanism is required. It is surprising, nevertheless, that so straightforward a model as the radiation driven wind model has withstood so many tests. Solar wind physicists are certainly encouraged to use their expertise to develop other diagnostics of the structure of the fast massive winds of early-type stars.

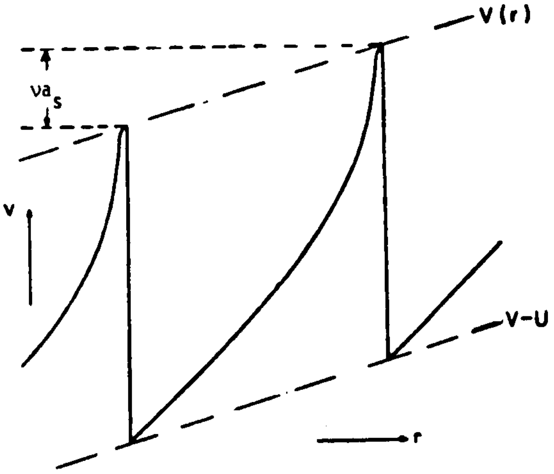

Fig. 8 - The phenemenological description of the hypersonic motions adopted by Lucy (1982b). The functions V(r) and U(r) denote the shock's velocity in the star's frame and their propagation speed, respectively, at radial distance r. The quantity ν is the basic parameter of the model and is defined such that νa_s is the velocity interval within which matter in a shock's wake is irradiated by unattenuated photospheric continuum. (adopted from Lucy 1982b).

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