MASS LOSS FROM HOT STARS

THEORY OF WINDS FROM HOT STARS

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1. INTRODUCTION.

Mass loss from hot stars was first established by Morton (1967). He observed 3 OB supergiants, δ, ε and ζ Orionis, with an ultraviolet spectrograph sent up with a rocket. In the wavelength range of 1200 A to 2000 A he observed 6 resonance lines of highly ionized atoms such as C III, C IV, N V and Si IV. These resonance lines showed a P Cygni type line profile with an absorption component displaced to the blue corresponding to a velocity away from the stars of 1400 km s^{-1}. Since the escape velocity from these stars is about 800 km s^{-1} these observations indicated the loss of mass from the stars. With rather simple assumptions he deduced a mass loss from the stars of 1 to 3 10^{-6} $M_{\odot}$ yr^{-1}. In spite of many more refined satellite observations and interpretations, the accepted value for mass loss from these stars has not changed by more than a factor of 2 or 3.

The basic mechanism for the mass loss from hot stars was explained by Lucy and Solomon (1970). When the photospheric radiation of the star is scattered isotropically by the resonance lines the momentum of the radiation is transferred to the gas. The resulting force can be considerable. With one unsaturated resonance line of an ion of carbon or nitrogen situated at the peak of the Planck function of an OB supergiant, the resulting radiative force outwards is typically 300 to 1000 times the force inwards due to gravity. But brute force is not sufficient to drive a supersonic continuous mass loss from a star as Marlborough and Roy (1970) showed. By modifying the basic equations of the Parker solution of the solar wind with an extra force outward in the equation of motion, they showed that if the extra force outward (be it a radiative force or some other force) is always greater than the inward force due to gravity the stationary subsonic supersonic solution with its critical point disappears and the flow remains subsonic. This is contrary to the observations of mass loss from hot stars since the stellar wind is highly supersonic. The reason for the flow remaining subsonic is that the extra force outward compresses the gas, thereby decelerating it instead of accelerating it. This is a good example of the contrariness of nature,

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the harder you push it the slower it goes.

There were two solutions proposed to overcome this problem. Hearn (1975) suggested on the basis of the interpretation of Balmer α line profiles that a corona of limited geometrical extent might exist at the base of the stellar wind of hot stars. Since the coronal temperature would be high, the ions responsible for accelerating the wind would not be present and the radiative force in the coronal region would be negligible apart from the force resulting from electron scattering. The ions that are present in the corona have their resonance lines at such short wavelengths that the star is not emitting there. Beyond the corona the temperature falls to photospheric temperatures and the ions of C III, C IV, N V etc. are present to yield the radiative forces necessary to sweep the stellar wind away to infinity with high velocity. In this model the initial acceleration of the stellar wind to supersonic velocities is done by a thermal mechanism, the Parker mechanism. The critical point exists in the corona and the mass loss is determined by the mechanical heating of the corona and not directly by the radiative forces.

There is no observational evidence of the existence of a small corona, either in the X-ray or infrared. Hearn (in preparation) has constructed fully self consistent theoretical models of a corona plus cool wind for an OB supergiant, but none of the models calculated has a mass loss greater than $3\ 10^{-11}\ M_\odot\ yr^{-1}$. Further work by Morse and Hearn (in preparation) leads to the conclusion that small corona models for stellar wind in OB supergiants do not exist for mass loss rates greater than $10^{-10}\ M_\odot\ yr^{-1}$. It would appear from the existing observational and theoretical studies that small coronae do not exist in the winds of OB supergiants and that if they exist at all it can only be in some late B main sequence stars where the mass loss is less than $10^{-10}\ M_\odot\ yr^{-1}$.

The second solution to the problem posed by Marlborough and Roy (1970) was proposed by Castor, Abbott and Klein (1975). They pointed out that the resonance lines are strong lines which saturate rapidly. This reduces the radiative force to less than that due to gravity. They developed a self-consistent theory in which the velocity gradient in the subsonic region is sufficiently small to give saturation of the resonance lines. In the supersonic region the velocity gradients and radiative forces are high. The theory gives a very rapidly accelerating stellar wind. The critical point lies just above the photosphere. In the Castor, Abbott and Klein theory the mass loss rate and the velocity distribution are determined together self-consistently and uniquely by the radiative forces alone.

In a review of this length it is not possible to discuss all the interesting developments in the theory of winds from hot stars which have taken place in the last few years, and the choice reflects personal taste and interest. I will discuss three developments:

a) Significant improvements in the Castor, Abbott and Klein theory which have substantially improved the agreement of the theory with the observations.
b) The problem of Wolf Rayet stars.

c) The theoretical problems raised by recent observations of Be stars.

This leaves unfortunately no room to discuss other interesting developments such as radiative driven instabilities in the winds of hot stars, the explanations of X-ray from OB supergiants or the problem of the narrow absorption components.

2. DEVELOPMENTS IN THE CASTOR, ABBOTT AND KLEIN THEORY.

The Castor, Abbott and Klein theory made a number of assumptions and simplifications.

a) The star is treated as a point source, so that all radiation streams radially.
b) A representative list of 900 lines of C III was used. It was assumed that the lines from all ions and elements would behave in a similar way.
c) The Sobolev approximation for the radiative transfer was used. This approximation is used if the thermal broadening velocity of the ions is negligible compared with the range of velocity occurring in the stellar wind. This gives a great simplification in the radiation transfer changing it from the solution of an integral equation over all space to a purely local solution. The result of the Sobolev approximation for strong resonance lines is that the radiative force is proportional to the velocity gradient $\frac{dv}{dr}$.
d) Optically thin lines give a radiative force which is independent of the velocity gradient $\frac{dv}{dr}$, and proportional to the number density of absorbing ions. Castor, Abbott and Klein assumed that the radiative force resulting from the mixture of optically thick and optically thin lines is proportional to $(\frac{dv}{dr})^{\alpha}$. From the representative line list of C III they found the radiative force was fitted by a coefficient α of 0.7.
e) They assume that continuous opacity in the wind is negligible, but of course important in the star. This is called the core-halo approximation.
f) Any modification of the stellar photosphere by the presence of the wind is ignored.
g) Mutiple line transfer is neglected. The momentum of a photon is only used once.

This theory gives simple results. The velocity distribution is

$$v^2 = v_o^2 + (v_\infty - v_o)^2 \left(1 - \frac{r_o}{r}\right) \quad (1)$$

where v is the velocity at distance r from the star's centre, v_o and v_∞ are the velocities at the stellar radius r_o and at infinity respectively. Since v_o is very small compared with v_∞ this is usually written

$$v = v_\infty \left(1 - \frac{r_o}{r}\right)^{\frac{1}{2}} \quad (2)$$

In the interpretation of observations this velocity distribution is usually parameterized by setting the power of the function of distance equal to β. The Castor, Abbott and Klein theory therefore gives β equal to 0.5. The ratio of the final wind velocity v_∞ to the escape velocity v_{esc} from the surface of the star is a function only of the radiative force fitting parameter α

$$\frac{v_\infty^2}{v_{esc}^2} = \frac{\alpha}{1-\alpha} \qquad (3)$$

For the value of α used in the original theory, 0.7, v_∞ equals 1.5 v_{esc}. The mass loss rate $\dot{M}$ is also uniquely specified by the radiative forces

$$\dot{M} \propto L \left(\frac{\Gamma}{1-\Gamma}\right) \qquad (4)$$

where L is the total luminosity of the star and Γ is the ratio of the force due to electron scattering and that due to gravity. Γ is a function of the luminosity and also of the evolved state of the star, but Equation (4) gives an approximate relation that the mass loss is proportional to the luminosity to the power 1.5. The precise power depends on the details of the assumptions made.

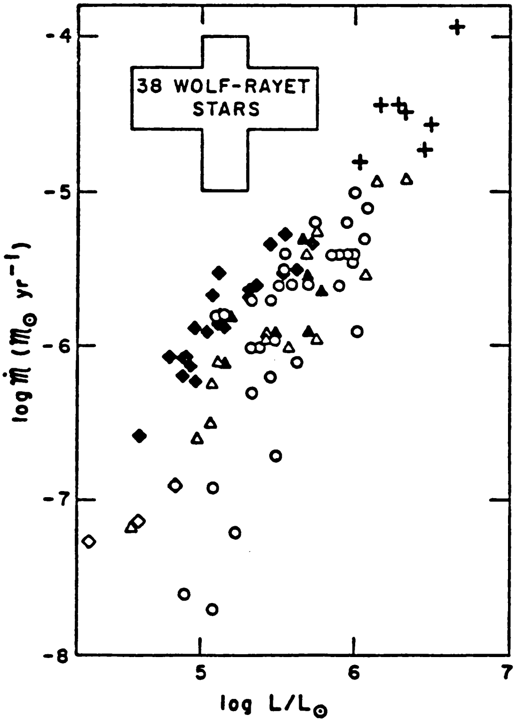

Figure 1. The mass loss rates and luminosities of O type and Wolf Rayet stars. (From P.S. Conti, 1982)

Figure 1 shows the observed mass loss rate plotted logarithmically against the luminosity. Whether the spread in the points is intrinsic or experimental is uncertain. There are uncertainties in the derivation of the mass loss, particularly in the ionization balance needed to convert a mass loss rate of ions to a total mass loss rate, and in the bolometric correction needed to deduce the total luminosity. A least squares fit gives a mass loss rate proportional to $L^{1.6}$. The cross shows the region in which the Wolf Rayet stars come according to Willis (1982). It is clear from these results that the Wolf Rayet stars do not fit the relationship derived from the other stars. This discrepancy is discussed in the next section of this review.

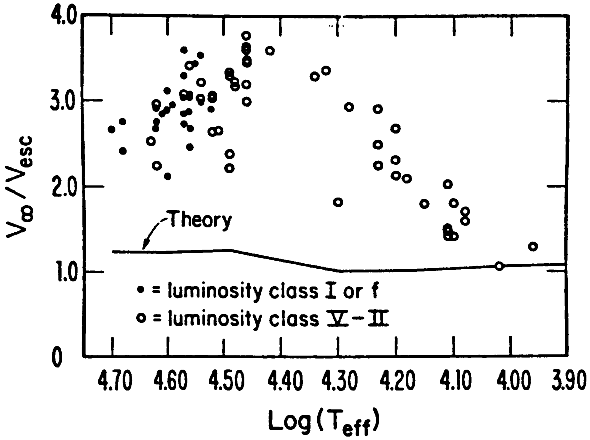

Figure 2. The ratio v_∞/v_{esc} is plotted against effective temperature. The solid line is the constant of proportionality predicted by the Castor, Abbott and Klein theory. (From D.C. Abbott 1982)

Figure 2 shows the ratio v_∞/v_{esc} derived for a number of stars (Abbott 1982). According to the theory this ratio should be almost constant, whereas the observations show a significant decrease towards the hotter and cooler ends of the range. In terms of the original Castor, Abbott and Klein theory there is no explanation for this variation. A very illustrative method of plotting these results has been done by Garmany and Conti (1984) and this is shown in figure 3. Stars with a v_∞/v_{esc} ratio greater than 3.0 are plotted with an open circle and stars with a v_∞/v_{esc} ratio less than 3.0 are plotted with a filled circle. This diagram shows clearly that as stars evolve from the main sequence the final velocity v_∞ of the stellar wind increases. Since the mass loss also increases with evolution this is a surprising result.

The approximation that the star is treated as a point source has been removed by Pauldrach, Puls and Kudritzki (1986) and by Friend and Abbott (1986). The results of Pauldrach et al. (1986) are shown in Table 1.

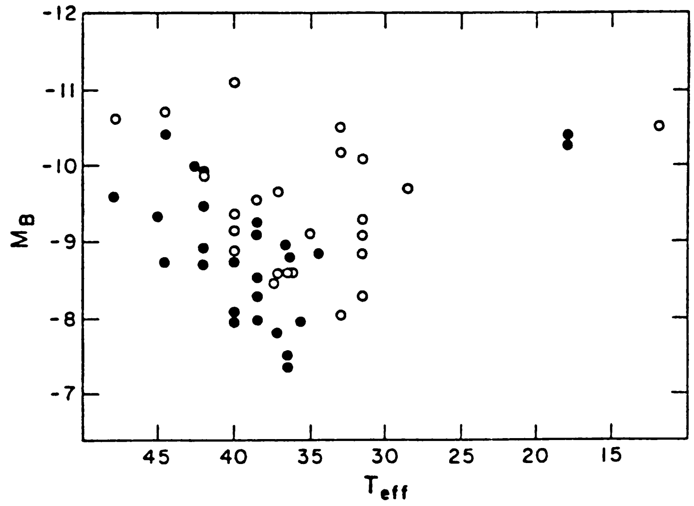

Figure 3. An H-R diagram with bolometric magnitude plotted against effective temperature. Stars with a v_∞/v_{esc} ratio greater than 3.0 are plotted with an open circle and stars with a ratio less than 3.0 are shown with a fitted circle. (From Garmany and Conti 1985)

Table 1 Stellar wind solutions for an 05 V star

	$\dot{M}$ (10^{-6} $M_\odot$ yr^{-1})	v_∞ (km s^{-1})
radial streaming	6.7	1559
finite core	3.52	5123
Abbott's line list		1270
Abbott's line list + finite core	6.76	2915

(From Pauldrach et al. 1986)

Pauldrach et al. (1986) calculated first the Castor, Abbott and Klein solution following the original paper for a 05 V star of 13.8 solar radii, log g 3.94 and an effective temperature of 49290 K. When the star is assumed to be a point source the radiation streams radially. If the star has a finite size, so that the radiation streams in a finite cone, the mass loss is halved and the final wind velocity is increased by more than a factor 3. This final velocity is now much higher than the observed final velocity of about 3000 km s^{-1}. The reason for these results is that near the star the radiative forces are used less effectively because they are not directed completely radially. Since the critical point is near the star this gives a lower mass loss. This lower mass loss is then accelerated to higher final velocities in the outer regions of the wind.

Abbott (1982) included a realistic line list in the theory instead of the representative C III lines used in the original paper. He included the ions from the 1st to 6th stages of ionization for the elements from hydrogen to zinc. More than 200 000 lines were involved in the calculation. The inclusion of Abbott's line list with radial streaming reduces the final velocity to a value that is far lower than the observed velocity. But the combination of the finite size of the star with the Abbott line list gives results for the mass loss and final velocity that are in very good agreement with the observations.

Pauldrach et al. (1986) have applied the modified theory to a range of stars including 3 OV stars, 2 evolved 0 stars and 2 B supergiants. A summary of their results is shown in Table 2.

Table 2. Comparison of calculated and observed stellar winds

		$\dot{M}$ (10^{-6} $M_\odot$ yr^{-1})		v_∞ (km s^{-1})		
star	spectral type	obs	calc	obs	calc	β
P Cyg	B1 Ia	20 -30	29	400	395	0.98
ε Ori	B0 Ia	3.1	3.3	2010	1950	0.72
ζ Ori A	09.5 I	2.3	1.9	2290	2274	0.72
9 Sgr	04(f)V	4.0	4.0	3440	3480	0.81
HD48099	06.5 V	0.63	0.64	3500	3540	0.81
HD42088	06.5 V	0.13	0.20	2600	2600	0.79
λ Cep	06 e f	4.0	5.1	2500	2500	0.79

$$v = v_\infty \left(1 - \frac{r_o}{r}\right)^{\beta}$$

(From Pauldrach et al. 1986)

The stars chosen for Table 2 all have not too uncertain stellar parameters, but during the fitting procedure these parameters have been adjusted within the allowed limits of error to give the best agreement with the observations. The agreement between the theory and observations is very good. Even for the highly evolved supergiant P Cygni is the calculated mass loss and final velocity in good agreement with the observations. However in this case the predicted velocity distribution is far from the observed velocity distribution. β equal to 1 in the parameterization of the velocity distribution gives a very rapid rise in the velocity, reaching 200 km s^{-1} at 2 stellar radii. This is contrary to the results obtained by Waters and Wesselius

(1986) from the IRAS infrared observations. They concluded that the velocity rises almost linearly from 30 km s^{-1} near the photosphere to 100 km s^{-1} at 5 stellar radii. Why this discrepancy should exist is not clear.

In a second paper Kudritzki, Pauldrach and Puls (1986) have studied the effect of reducing the metal abundance on the stellar wind models.

The stars in the two Magellanic clouds have significantly lower metallicities than the stars in our own galaxy. Since the metal ions are mainly responsible for driving the wind, differences are to be expected. Kudritzki et al. (1986) have calculated stellar wind solutions using the finite cone approximation and the Abbott line list for an 05 V star with an effective temperature of 45000 K, log g 4.0 and a radius of 12 solar radii. The solutions have been calculated for normal abundances, and for metal abundances reduced to 0.28 and 0.1 of the normal abundances. These models represent a star in our galaxy, the larger Magellanic cloud and the smaller Magellanic cloud respectively. The results are shown in Table 3.

Table 3. Stellar wind models of an 05 V star with Galactic and Magellanic cloud metallicities

	Z	$\dot{M}$ (10^{-6} $M_\odot$ yr^{-1})	v_∞ (km s^{-1})
Z_{gal}	Z_o	2.12	3350
Z_{lmc}	0.28 Z_o	1.35	2900
Z_{smc}	0.10 Z_o	0.72	2435

(From Kudritzki et al. 1986)

Garmany and Conti (1985) studied a sample of normal OB stars with well defined spectral types. They concluded that O stars of luminosity class III and V in the larger Magellanic cloud have a final wind velocity about 600 km s^{-1} slower than comparable stars in our galaxy, and stars in the smaller Magellanic cloud 1000 km s^{-1} slower. Further they concluded that the mass loss was about the same for comparable stars in the three systems.

Pauldrach et al. (1986) conclude that the smaller final velocity measured in stars in the Magellanic clouds can be reproduced by the calculations. The comparison of the mass loss rates is more complicated since, as they point out, if evolved objects of lower mass in the smaller Magellanic cloud are compared with more massive but less evolved stars in the galaxy because of a selection effect, then very similar mass loss rates can be obtained.

3. THE THEORY OF MASS LOSS FROM WOLF RAYET STARS.

Figure 1 shows that with the accepted parameters for Wolf Rayet stars, the mass loss is far higher than for comparable OB stars and that the Castor, Abbott and Klein theory cannot explain the observed mass loss rates. In fact the problem is more severe than this. If every photon emitted by the star is used once to drive the mass loss then from the momentum balance one obtains a theoretical maximum mass loss from the star given by L/cv_∞ where L is the total luminosity of the star, c is the velocity of light and v_∞ is the final velocity of the stellar wind. For Wolf Rayet stars the observed mass loss is far higher than this maximum. Barlow, Smith and Willis (1981) derived mass loss rates for WN 5, 6 and 7 and WC 5 stars which are 10 to 20 times this limit, and up to 50 times the maximum for WC 7 and 8 stars. Willis (1982) quotes even more extreme examples of mass loss 100 times greater than the theoretical maximum mass loss. For comparison, stars such as ζ Puppis have a mass loss equal to about half the theoretical maximum.

Panagia and Macchetto (1982) proposed that photons could be used more than once and estimated that the maximum mass loss could be increased by a factor of 10. More recently Abbott and Lucy (1985) have performed multiple scattering Monte Carlo calculations for ζ Puppis with a prescribed velocity distribution. They find that many scatterings occur within the same hemisphere as opposed to the scattering from one hemisphere to the other as envisaged by Panagia and Macchetto (1982). From their calculation the increase in mass loss through multiple scattering is only a factor 3. This would appear to be insufficient to solve the Wolf Rayet mass loss problem.

Cherapashchuk, Eaton and Khaliullin (1984) have taken photometric measurements from 2460A to 3.5μ of V444 Cygni. This is an eclipsing binary with a 4.2 day period composed of a WN5 star with an 06 star. From the observations they deduced the density and velocity structure of the WN5 star and concluded that the effective temperature of the star is 90000 K. The radius of the star, defined by the electron scattering optical depth being 2/3, is 2.9 solar radii. The velocity of the stellar wind at the stellar surface is supersonic, 400 km s^{-1}. The temperature in the wind drops gradually to 20000 or 30000 K at 3 stellar radii. The mass loss rate is 1.2 to 1.8 10^{-5} $M_\odot$ yr^{-1}.

Pauldrach, Puls, Hummer and Kudritzki (1985) have applied the Castor, Abbott and Klein theory with the Abbott line list and a finite star size to the result of Cherapashchuk et al. (1984) and obtain good agreement between the theory and the observation. The results of the comparison are shown in Table 4 and figure 4.

Table 4. Stellar parameters of the WN5 star

	PPHK	CEK
T_{eff}	91317 K	80-100 000 K
L/L_o	5.29 10^5	3.1 - 7.6 10^5
R_*/R_o	2.70	2.90
$\dot{M}$	1.39 10^{-5} M_o yr^{-1}	1.2 - 1.4 10^{-5} M_o yr^{-1}
V_∞	1950 km s^{-1}	2000-2500 km s^{-1}
Γ_e	0.7	

(From Pauldrach, Puls, Hummer and Kudritzki 1985)

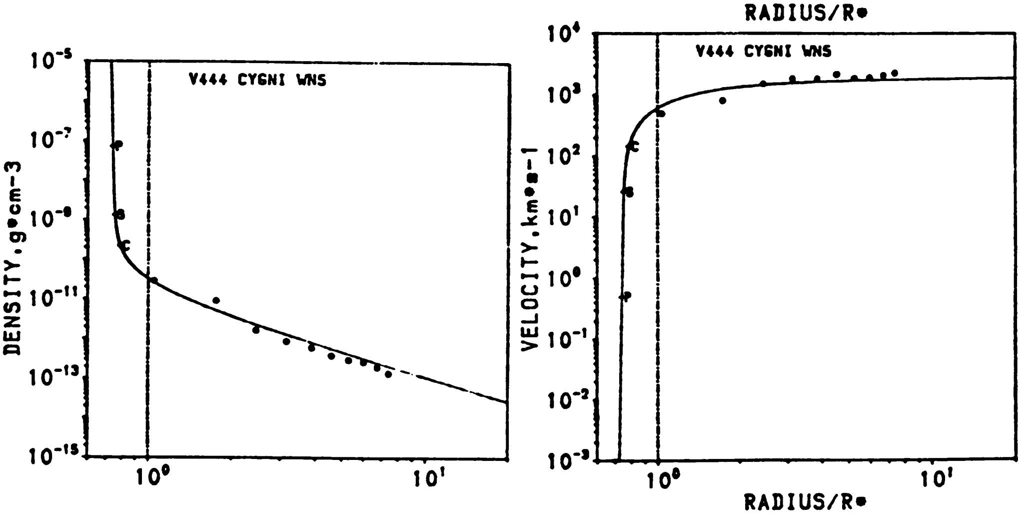

Figure 4. The density and velocity is plotted against the distance in stellar radii for the WN5 component of V444 Cygni. The dots are the results of Cherapashchuk, Eaton and Khaliullin (1984) and the lines from Pauldrach, Puls, Hummer and Kudritzki (1985)

Figure 4 shows the density and velocity plotted against the distance in stellar radii: the dots are the results of Cherapashchuk, Eaton and Khaliullin (1984) and the lines are the best fit obtained by Pauldrach, Puls, Hummer and Kudritzki (1985). The points labelled C, S and P are the critical point, the sonic point and the location of optical depth 10 measured in the electron opacity.

If the interpretation of the photometric observations by Cherapashchuk et al. (1984) is correct and Wolf Rayet stars have a much higher effective temperature than had been previously thought, then it appears that their mass loss can be explained by the Castor, Abbott and Klein theory. This conclusion has in fact been contested by a poster paper at this meeting by Schmutz, Hamman and Wessolowski. On the basis of comoving frame calculations of the helium lines they dispute that the effective temperature can be higher then 60000 K.

Cassinelli and v.d. Hucht (1986) have argued that evolutionary calculations of Wolf Rayet stars show large abundances of carbon and oxygen. If these abundances are included in the mass loss determination from the radio observations instead of the pure ionized helium wind used by other authors, then Cassinelli and v.d. Hucht conclude that the mass loss is 2 or 3 times greater still and the mass loss still exceeds the theoretical maximum by a factor of 20 to 60 for WC 7 to 9 stars. They use only the theoretical L-M relation and believe that still some other mechanism is necessary.

4. MASS LOSS FROM Be STARS.

There have been a number of developments in the mass loss from Be stars recently. These seem to show that at least for a part of the mass loss from Be stars some other mechanism is necessary. Although this is a review of the theory of mass loss from hot stars, this part of the review is a discussion of the work which shows that further theory is necessary.

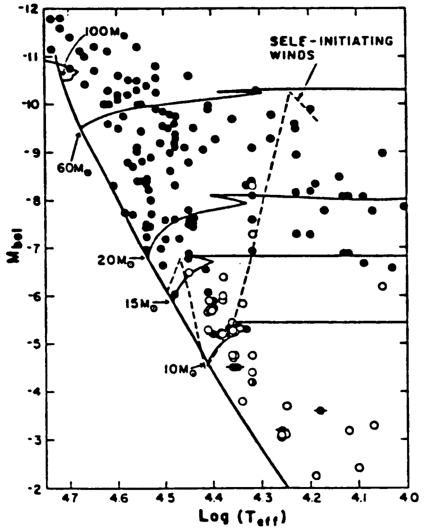

Figure 5. An H-R diagram with the bolometric magnitude plotted against the effective temperature. Stars with a mass loss detected in the ultraviolet profiles are plotted by a filled circle. Stars for which no mass has been found are plotted as an open circle. If the mass loss from the star is probable, then the star is plotted with a half filled circle. Be stars are plotted with a line through the circle. The dotted line is the limit for self-initiating radiative driven wind (From Abbott 1984)

In the earlier discussions on the Castor, Abbott and Klein, one of the objections raised against the theory was that the radiative driven wind is not self-starting. In answer to this criticism, Abbott (1984) calculated the radiative forces for stars in hydrostatic equilibrium. If the radiative force in the outer layers of the star is greater than the force due to gravity, then Abbott argues that for these stars the radiative driven wind is self-starting.

Figure 5 shows in an H-R diagram the limit of self-initiating winds. In this diagram the bolometric magnitude is plotted against the effective temperature. The stars for which mass loss has been detected in the ultraviolet profiles are plotted as filled circles. Stars with no evidence of mass loss are plotted as open circles, and for stars with a probable mass loss the circle is half filled. The Be stars are represented by a line through the circle. Figure 5 shows that in the main sequence and stars just evolved off the main sequence the only stars having a detected mass loss that lie below the limit of self-initiating radiative driven winds are Be stars. This suggests that some other mechanism is at work in Be stars.

Infrared observations of Be stars made with IRAS have been interpreted by Waters (1986) (See the review by Lamers in this conference proceedings). Waters finds that the observed infrared excess of 4 Be stars, α Eri, ϕ Per, δ Cen and χ Oph can be explained by a disc extending round the equator of the star. The infrared observations show that the density of gas in this disc decreases as $r^{-2.4}$, and extends to 6 or 8 stellar radii. This density dependence means that the velocity of the wind in the disc is increasing very slowly with distance. By assuming a velocity for the wind in the disc near the surface of the star, Waters concludes that the mass loss is 50 to 100 times greater than that deduced from the ultraviolet P Cygni lines profiles, which is presumably measuring the mass loss from the polar regions of the Be star. The mass loss which is deduced from the infrared observations scales directly with the velocity that is assumed at the base of the disc. This interpretation of Waters (1986) also implies a different mechanism for mass loss from Be stars. Radiative driven winds of the Castor, Abbott and Klein type do not have very slow accelerations and the observed mass loss rate may be very much higher than can be explained by that theory.

Non-radial pulsations have been observed in Be stars. Absorption lines in these stars are found to have asymmetric features which cross the absorption profile steadily in about 5 hours. These features have been interpreted by Vogt and Penrod (1983) and Baade (1984) as non-radial pulsations in the Be stars. Figure 6 shows the distortions in the line profile and the pattern of non-radial pulsation deduced by Vogt and Penrod for ζ Oph O.9 Ve. The contours are drawn every 5 km s^{-1}. The darkest shaded region represents material that is moving away from the observer, while the lightest regions represent material moving towards the observer. The non-radial pulsation shown here is an $l = 8$, $m = 8$ mode.

The disc model deduced by Waters (1986) for the Be stars is reminiscent of the old Struve model. But one sees from the work of Vogt and Penrod (1983) and Baade (1984) that it is not that the equator of the star is rotating so rapidly that it is near break up that is important, but that the non-radial pulsations are confined to the region round the equator of the star. What the physical connection is between the non-radial pulsation and the mass loss is not clear.

What is also very interesting is that there is some evidence that Be episodes in ζ Oph coincide with changes in the mode of the non-radial pulsation. Further there appears to be a systematic difference between normal B stars and Be stars. Normal B stars appear to pulsate with 1 or 2 short period high ℓ modes whereas Be stars appear to pulsate in a long period ℓ equals 2 mode plus a short period high ℓ mode.

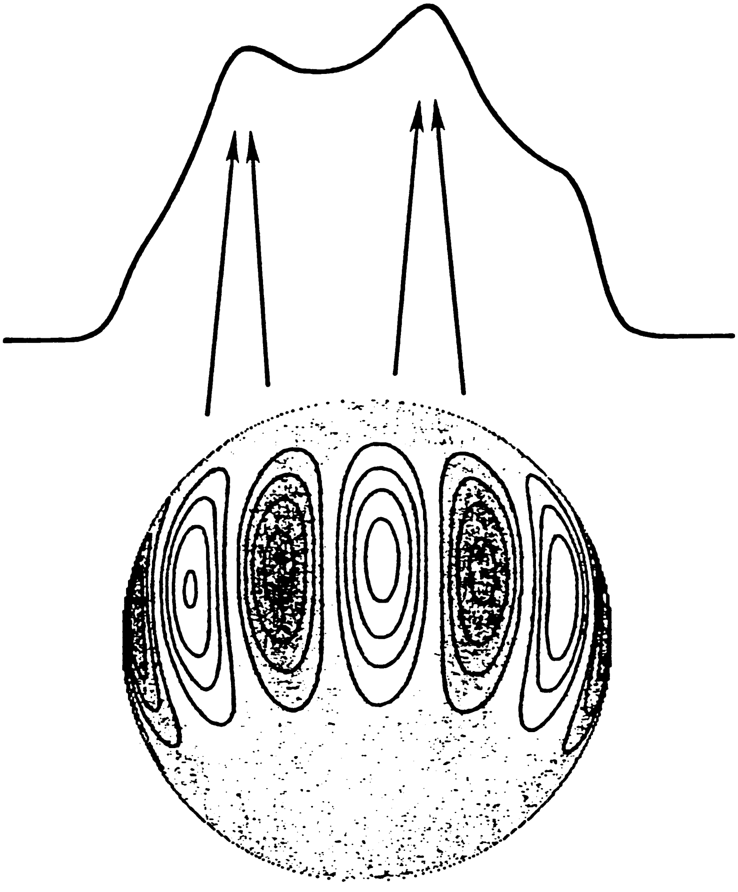

Figure 6. The formation of distortions in the line profiles of a rapidly rotating star undergoing non-radial pulsations. The contours of the non-radial pulsation are drawn every 5 km s^{-1}. The darkest region represents material moving away from the observer, the lightest region represents material moving towards the observer. (From Vogt and Penrod 1983)

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