THE THEORY OF WINDS IN EARLY TYPE STARS

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I assume that the purpose of this review of the theory of winds from early type stars is to summarize the way in which the mass loss rate of a star may be included in a calculation of stellar evolution. Let me summarize my conclusions. It is not possible. One can only use estimates of mass loss rates obtained from the observations. Even these give a large uncertainty. The observed mass loss rates for different stars of the same spectral type vary. Further the mass loss rates obtained by different methods for the same star differ. An extreme example of this is 9 Sgr. The mass loss rate derived from the radio observations is forty times greater than that derived from the U.V. and optical measurements (Abbott et al. 1980).

The last discussion of the theory of winds from early type stars took place in the I.A.U. symposium No. 83 on mass loss and evolution of O-type stars held at Vancouver Island in 1978. (Conti and De Loore 1979.) At that time only the U.V. observations from Copernicus and I.U.E. were available, and one afternoon was devoted to a panel discussion of four different interpretations and theories of what causes the mass loss from O-type stars and what the physical structure of the wind might be (Conti and De Loore 1979, session 4).

The four panel speakers were Castor, on the radiatively driven wind theory of Castor, Abbott and Klein (1975); Lamers, on the warm wind model of Lamers and Rogerson (1978); Cassinelli, on the small corona and cool wind model of Cassinelli et al. (1978) and Thomas, on the imperfect wind tunnel model of Cannon and Thomas (1977).

It appeared from these discussions that observations with Einstein would resolve the arguments about the nature of the winds from hot stars. Einstein did measure X-rays from OB stars (Harnden et al. 1979), but it has not resolved the discussion. As so often happens, more observations have raised more problems than they have settled.

In what follows the impact of the Einstein observations on the four theories discussed in I.A.U. symposium No. 83 is described, together with some other ideas on mass loss from early type stars.

C. Chiosi and R. Stalio (eds.), Effects of Mass Loss on Stellar Evolution, 125–130.

The theory of Castor, Abbott and Klein (1975) describes a model wherein the mass loss is driven by the radiative forces associated with the resonance lines of ions such as C III. That these forces would be very important in the winds from early type stars was suggested by Lucy and Solomon (1970). Castor, Abbott and Klein assumed a stellar atmosphere that is in radiative equilibrium and their theory gives a mass loss rate that is a function of the luminosity of the star and the ionization balance of wind (which determines how many absorption lines are contributing to the force outward). The Castor, Abbott and Klein theory is a modification of the Parker solar wind equations (Parker 1958) with an extra force in the equation of motion due to the radiative forces. They assume that these forces are proportional to the velocity gradient, a result that comes from the Sobolev approximation. (See also the review of this model by Cassinelli 1979.) The Castor, Abbott and Klein theory is a delicate balance between the radiative forces, the velocity gradient and gravity, for Marlborough and Roy (1970) showed that if the radiative forces outwards exceeded the gravity force inward the flow through the critical point from subsonic to supersonic velocities disappears and the result is a subsonic decelerating wind. This is contrary to the observations which show supersonic winds. This balance makes the Castor, Abbott and Klein model very difficult to set up in the first place. A further problem is that the flow is unstable against the radiative driven instabilities suggested by Nelson and Hearn (1978), Martens (1979) and Mac Gregor et al. (1979). These instabilities will break up the flow destroying the balance between the forces and the result will be either to heat a corona or to set up the system of radiative driven blobs suggested by Lucy and White (1980) or both.

Everyone agrees that the radiative forces are responsible for the acceleration of the winds from early type stars to their large final velocities, typically 1000 to 3000 km s^{-1}. The point at issue is whether these forces also determine the mass loss rate. It has been argued that since all the momentum of the wind comes from the radiative forces, then the radiative forces must determine the magnitude of the mass flux. That this does not have to be true can be seen from an analogy. Consider a tank full of water sitting well above the ground in a very strong wind. If the tap at the bottom of the tank is turned on water will stream out and it will be blown to one side by the wind. The horizontal momentum gained by the water comes entirely from the wind, but the flow of water in the horizontal direction is completely determined by the tap. I would maintain that in a star the tap is the flux of mechanical energy coming out through the photosphere. Thomas would maintain that the tap is the dynamical motion below the photosphere.

The Castor, Abbott and Klein theory started with a model in radiative equilibrium. Castor (1979) was able to modify the theory to explain the observation of O VI from winds of hot stars, but it does not seem possible to explain the X-rays observed by Einstein.

The warm wind coronal model was proposed by Lamers and Rogerson (1978) to explain the presence of O VI in the Copernicus spectrum of τ Sco. The observation of O VI by Rogerson and Lamers (1975) was the first indication of the presence of mechanical heating in the atmospheres of early type stars. Their model has an extended warm corona with a temperature in the region of 3 10^5 K. It was never proposed as a model for predicting mass loss rates.

Their model cannot explain the X-rays observed from OB supergiants, but it may turn out to be right for main sequence stars such as τ Sco for which it was first proposed. X-rays have been measured from τ Sco using the solid state spectrometer on Einstein (White 1980). The spectral distribution gives a temperature in the range of 5 to 7 10^6 K. A single temperature does not fit the observations. One must conclude that a corona of such a high temperature must be confined in coronal loops by a magnetic field. In that case the warm wind model of Lamers and Rogerson (1978) remains a possibility for the open regions responsible for the mass loss.

The coronal model for early type stars was proposed by Hearn (1975). He concluded from Hα profile measurements that a corona could extend from the star out to 2 stellar radii. This analysis was refined by Cassinelli et al. (1978) who concluded that the corona could not be more than 0.1 stellar radii thick. Cassinelli and Olson (1979) showed that the O VI lines could be explained by Auger ionization of O IV in the cool wind above the corona by X-rays coming from a small corona.

The early observations of X-rays from early type stars seemed to confirm this model. But measurements of the X-rays give a spectral distribution that is much softer than was predicted by Cassinelli and Olson (1979) and one must conclude that the observed X-ray spectrum cannot be explained by the small corona model (Long and White 1980, Olson and Castor 1980, Cassinelli et al. 1980), though the presence of a small corona is not ruled out by the observations.

A small corona just above the star cannot explain the observed X-ray spectrum because for X-rays with an energy below 1.5 keV the optical depth of the wind round a star like ζ Puppis is about 30 and they are all absorbed. The observations show a peak in the X-ray intensity round 0.8 keV. (Long and White 1980.) Lucy and White (1980) have suggested a two component model for the winds. Radiatively driven blobs move through an ambient gas. The resulting shock heating is responsible for the emission of X-rays. Because the emission takes place throughout the wind it can explain the soft X-ray observations.

In their discussion of mass loss from stars, Cannon and Thomas (1977) have argued that mass loss is determined by the dynamics below the photosphere and that until this is understood one cannot predict the mass loss rates for stars. This also implies that mass loss rates cannot be represented as a function of the parameters of classical model atmosphere calculations (T_{eff}, g). The discussion by Thomas (1979) in the meeting at Vancouver is easier to understand than the Cannon and Thomas article.

There are two sets of observations which provide good evidence in support of this suggestion. Conti and Garmany (1980) have determined the mass loss rates for 25 O and Of stars from IUE observations and they find that when the mass loss rate is plotted against the bolometric magnitude, there is a significant scatter of the results. This means that stars of the same bolometric magnitude can have mass loss rates that differ by factors up to 100. (See also the review by Conti in these proceedings.) Conti and Garmany conclude that the mass loss cannot be understood in terms of radiative forces alone and that other physical effects must contribute.

Lamers et al. (1980) have found that the mass loss rates deduced from UV and visual observations for Of stars are four times greater than O stars of the same luminosity. The difference is smaller because Lamers et al. do not include main sequence stars. However Lamers (see these proceedings) has produced results which show that for O type stars of all luminosity classes the mass loss rate can be represented as proportional to $\frac{T_{eff}^4}{g^{\frac{1}{2}}}$.

Doazan, Stalio and Thomas (see these proceedings) have assembled measurements of Hα emission for a Be star for the last hundred years. The Hα emission is very variable over the years and it is usually assumed that it is a measure of the mass loss. If this interpretation is true then it means that the mass loss varies by a large factor with time, and it cannot be represented in terms of the classical stellar parameters.

There is one theory of mass loss that was not discussed on Vancouver Island, that is the fluctuation theory of mass loss by Andriesse (1979, 1980a, 1980b, see also these proceedings). Andriesse argues that a star has two characteristic time scales. The first is the dynamical time scale, the time for free fall in the gravitational field of the star and this time scale is very short. The second is the Kelvin-Helmholtz time scale, the time for which gravitational energy will maintain the radiation of the star if the nuclear energy source is cut off. This time scale is long. Andriesse argues that the ratio of the two time scales is a measure of how far out of equilibrium the star is and that this is a measure of the mass loss rate. What is not clear in this theory is the physical connection between the lack of equilibrium and mass loss. However the theory does appear to give good predictions for a very wide range of stars, not only for early type stars. More recently Andriesse (1980c) has shown that the predictions of his fluctuation theory are consistent with the observed differences in mass loss rates between O and Of stars.

Finally some comments on coronae and mass loss in hot stars. Hearn and Vardavas (1980) have developed a new numerical method for calculating stellar coronal models. The equations of motion, continuity and energy balance are solved iteratively with boundary conditions specified in the photosphere of the star and at infinity, and the method ensures that the velocity distribution passes through the critical point. The coronae are heated by a saw tooth wave for which the dissipation is calculated from weak shock wave theory. At present neither radiative forces nor wave pressure is included in the calculations. A number of coronal models have been calculated for a star like ζ Orionis 09.5 Ib. For a flux of mechanical energy of 10^3 and 10^4 erg cm^{-2} s^{-1} imposed in the photosphere, the calculation gives an extended, conduction dominated corona of the solar type. The temperature in the outer regions is proportional to $r^{-2/7}$. A flux of mechanical energy of 10^5 erg cm^{-2} s^{-1} gives a corona with a rather steeper temperature distribution. The radiative and wind losses in the outer regions are becoming significant and the second derivative of the temperature must increase to balance these losses. A flux of mechanical energy of 10^6 erg cm^{-2} s^{-1} gives a completely different result. The corona is only 0.03 stellar radii thick, having collapsed because the radiative losses in the outer regions are so great that they can no longer be maintained at coronal temperatures. Further while the other extended coronae had modest mass loss rates, this small corona is hydrostatic. This small corona is the sort of corona deduced by Cassinelli et al. (1978). It has already been mentioned that such a small corona does not explain the soft X-ray emission, but that its existence is not ruled out by the observation, and perhaps this model gives the key to what defines the mass loss from early type stars.

In the model calculated there are no radiative forces. The model corona is hydrostatic because, although there is a valid critical point in the corona, the velocity distribution calculated through it does not extend to infinity. The reason for this is that the radiative equilibrium region beyond the small corona, does not supply enough energy to the flow to ensure that it can reach infinity. If the radiative forces from the resonance lines were included in this region, they would provide enough momentum to ensure that the flow reached infinity. Under these circumstances it seems likely that the radiative forces are necessary for mass loss to occur and the magnitude of the final flow velocity would be determined by them. But that the mass loss rate will be determined by the critical point in the corona and this will depend on the mechanical flux being supplied to heat the corona. To increase the mass loss rate one must increase the mechanical flux.

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