THE THEORY OF MASS LOSS FROM HOT STARS

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Although some evidence had been available earlier, it was the work of Morton (1967) that proved that the OB Supergiants are losing mass. He obtained spectra with a rocket borne spectrograph of the three stars in Orion's belt, δ, ε and ζ Orionis. These stars are all supergiants of spectral type O9.5 or B0. The spectra showed resonance lines of ions such as C III, C IV, Si IV, N V with P-Cygni type profiles. The deepest part of the absorption profile corresponded to a velocity away from the star of 1400 km s^{-1}, and the absorption profile extended out to wavelengths corresponding to velocities of 2000 km s^{-1} away from the star. Since these velocities are much greater than the escape velocities from the surface of these stars, it is clear that matter is escaping from them. With a number of simplifying assumptions Morton deduced that the rate of mass loss is about 10^{-6} $M_{\odot}$ yr^{-1}. This order of magnitude has remained unchanged by the many high quality observations made since that time.

On the basis of Morton's observations, Lucy and Solomon (1970) suggested that the mass loss could be explained by the radiative forces associated with the observed resonance lines. Radiation carries momentum, and if radiation coming from one direction is absorbed by a resonance line and then re-emitted isotropically, the result is that the absorbing matter experiences a force. Just one of the typical resonance lines absorbing the radiation from the photosphere of an OB supergiant contributes, if it is unsaturated, an outward force which is 300 to 1000 times the inward force due to gravity. Therefore it can explain the mass loss.

A radiation pressure explanation of mass loss from hot stars was attractive for several reasons. At the time there was no observational evidence of coronae round hot stars and further model atmosphere calculations show quite insignificant convection zones which are incapable of heating a corona in the way that they do for the Sun. If the high terminal velocity of the mass loss is explained by a simple Parker type stellar wind then a coronal temperature of at least 10^8 K is required and that is quite inconsistent with the observations of ions

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such as C III, C IV, etc.

An objection to this simple explanation was raised by Marlborough and Roy (1970) and later by other authors. They studied the effect of an outward radiative force on the equations which give the Parker solar wind solution with an acceleration of the atmosphere from subsonic velocities near the star to supersonic velocities at greater distances, and they found that if the outward radiative force is greater than the inward force due to gravity the subsonic-supersonic solution disappears. The result of a large radiative force is not an acceleration of the atmosphere, but a compression of the flow resulting in a deceleration. This result seems to be an excellent example of the sheer perversity of nature: the harder you push it, the slower it goes. But the conclusion is clear, it is not possible to accelerate a steady flow to supersonic velocities by large radiative forces. However Cassinelli and Castor (1973) showed that when the flow is supersonic, a large radiative force will cause a further rapid acceleration of the flow.

It seems to be universally agreed that the radiative forces associated with the resonance lines are responsible for accelerating the flow from supersonic velocities to the very large observed final velocities. What is being argued about, sometimes rather hotly, is what causes the mass loss, or at least what accelerates the flow to supersonic velocities so that the radiative forces may finish the work.

In the session which follows, the four main theories of mass loss from hot stars will be discussed. The physical basis of these theories is really rather different, and the conclusions that they draw about the physical conditions of the expanding envelope is very different indeed.

Since the original work of Morton, many high quality observations have been made with the Copernicus satellite, and now the I.U.E. satellite is producing more. One of the most important observations with Copernicus was of O VI in τ Scorpii by Rogerson and Lamers (1975). τ Scorpii is a B0 V star. Later O VI was observed in many OB stars. O VI cannot be explained by pure radiative equilibrium models for these stars and its observation is the first clear evidence that the outer layers of hot star atmospheres have some sort of mechanical heating. Three of the four theories for mass loss explain the formation of O VI by different physical processes and this is the main cause of the very different temperatures deduced by the theories from the ultraviolet observations.

The first theory is a development of the radiative equilibrium, radiation pressure driven theory of mass loss of Lucy and Solomon (1970).

Castor, Abbott and Klein (1975) found a way round the objection of Marlborough and Roy (1970).

They pointed out that these resonance lines are also found in the photosphere and they are saturated which substantially reduces the radiative force associated with them. As the atmosphere expands and accelerates the lines desaturate and the radiative force becomes greater. They produced a model wherein the velocity gradients in the subsonic part of the flow are so small that the lines are sufficiently saturated to reduce the outward radiative force to less than the inward force due to gravity. The objection of Marlborough and Roy is thereby overcome and the flow can accelerate to supersonic velocities. Once supersonic, the velocity gradient becomes large giving a strong acceleration from the desaturated resonance lines. They used the Sobolev approximation to relate the radiative force to the velocity gradient. Their model has a rapid acceleration, so that the critical point, the point where the flow attains supersonic velocities, is right at the surface of the star.

The observation of O VI has caused some difficulty for this theory. It shows that the assumption of radiative equilibrium is not valid. More recent work by Castor, which will be discussed in the following session, has shown that the O VI observations can be explained if the atmosphere is mechanically heated up to 60 000 K and the expanding atmosphere is optically thick in the continuum.

The second theory is that the mass loss is a hot coronal stellar wind of the Parker type, which was proposed by Hearn (1975). To explain the observed mass loss rates, the critical point of the Parker solution must be near the surface of the star, and this means coronal temperatures from 3 to 9 million K. The corona is small in extent, and beyond the corona the expanding atmosphere is in radiative equilibrium. It is in this radiative equilibrium region that the observed resonance lines are formed and where the flow is accelerated by radiative forces up to the final expansion velocities. But the mass loss is determined by the hot coronal wind mechanism which accelerates the flow to supersonic velocities. The extent of the corona must be very small indeed. The lower limit for the X-ray measurements of ζ Puppis by the ANS satellite means that its corona cannot be greater than about 40 000 km thick. Cassinelli, Olson and Stalio (1978) came to a similar conclusion from an analysis of the Hα line profiles. There is also a physical reason why the corona should be small in extent. In the solar corona the high coronal temperature is maintained to great distances from the Sun by thermal conduction of heat from the base of the corona where it is heated. The corona round an OB supergiant will have an electron density which is 10^2 or 10^3 times greater than the solar corona. This means that the radiated energy losses, which are proportional to the electron density squared, are 10^4 or 10^6 times greater than in the solar corona. These losses are just too great for thermal conduction to maintain the corona beyond the region where it is directly heated. Olson (1978) and Cassinelli and Olson (1978) have shown that the O VI observations can be explained by Auger ionization of O IV in the radiative equilibrium region outside the corona by X-rays emitted by the corona.

The third theory is a combined coronal, radiation pressure model proposed by Rogerson and Lamers (1975). The result of Marlborough and Roy (1970) that the subsonic-supersonic solution disappears if the outward radiative force is greater than the inward force due to gravity is true for an isothermal corona. Lamers showed in his thesis that in the presence of a large positive temperature gradient, such as in the transition region between the corona and the photosphere a subsonic-supersonic flow can occur. In this case the critical point lies in the transition region. The consequences of this theory have not been worked out. Lamers and Morton (1976) have shown that the O VI observations of ζ Puppis can be explained by a collisional ionization model. This requires an electron temperature of about 2 10^5 K throughout the expanding atmosphere out to about 10 stellar radii. In τ Scorpii only the inner region of the atmosphere is at 2 10^5 K (Lamers and Rogerson).

The fourth theory of mass loss was proposed by Cannon and Thomas (1977). They use the de Laval Nozzle analogy of a stellar wind. The shape of a nozzle has to be designed to fit the input and output conditions of the nozzle. If the shape of the nozzle is not perfect then shocks will form in the flow. Now the nozzle equivalent to a radiative equilibrium stellar atmosphere is a very long thin nozzle with the throat far away from the star. This nozzle does not give the perfect match for the observed mass loss rates from OB stars. Therefore shocks will form in the flow just above the photosphere and it is these shocks that heat the corona. This is quite different from the Parker theory. The Parker theory shows that mass loss is a consequence of an extended hot corona. Cannon and Thomas say that the corona is heated as a consequence of the mass loss. To some extent their work is more a criticism of the other theories than a theory of mass loss. They take the mass loss rate as an observed quantity and investigate the effects of this mass loss on the stellar atmosphere. They do not calculate a mass loss rate. They believe that the mass loss rate is determined by the dynamical processes below the photosphere, the subphotospheric non-thermal storage modes in their language, and that until the dynamics is completely understood it is impossible to calculate a mass loss rate.

These are the four theories which will be discussed in the following session. During this session it was clear that everyone now agrees that the outer layers of hot star atmospheres have mechanical heating. How they might be heated was not discussed. This is clearly a field which needs more work.

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DISCUSSION FOLLOWING HEARN

Lamers: In your original version of the coronal model, the corona was very extended. After the revisions by Cassinelli the corona is much thinner. This means that the escape-velocity in the new coronal models is much larger than in your original model, and consequently the temperatures have to be higher in order to reach the critical point close to the star. What is the coronal temperature that you require to explain the observed mass loss rates by gas pressure in a thin corona?

Hearn: For a star such as ξ Orionis a temperature of about 3.5×10^6 K, and as high as 9×10^6 K for ξ Pup. The model given by Cassinelli et al. uses a corona of 5×10^6 K to explain the observations. This is not a hydrodynamically consistent model. But the interpretation of the observations is not sensitive to the coronal temperature, and a coronal temperature of 9×10^6 K in the model of Cassinelli et al. would not make a great difference.