STELLAR WIND THEORIES

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1. GENERAL

The term stellar wind is used nowadays to describe any more or less continuous mass loss from a star. With the observations made with satellites in recent years it is becoming clear that most stars are undergoing this form of mass loss, though its magnitude can be very different from one star to another. The term stellar wind does not include the more eruptive forms of mass loss such as novae, the ejection of mass in shells or mass loss as a result of flares.

Stellar winds are maintained by energy and momentum deposited in the outer layers of a stellar atmosphere. The deposition of energy causes the heating of a chromosphere and corona, so that the theory of stellar winds cannot really be separated from the theory of coronal heating. Energy and momentum can both be deposited by the same mechanism. For example if a corona is heated by the dissipation of a wave which deposits energy, the same wave can change the momentum of the mean flow through wave pressure and this can happen even in the extreme case of no dissipation of the wave.

The foundation of the theory of stellar winds was laid by Parker (1958) in his theory of the solar wind. A useful review of this work has been given by Parker (1965). The theory of the solar wind in its simplest form is deduced from the equation of motion combined with the equations of continuity and state.

The equation of motion for a stationary expanding atmosphere is

$$\rho v \frac{dv}{dr} + \frac{dp}{dr} + \frac{GM\rho}{r^2} = 0 \,, \tag{1}$$

where ρ is the density of the gas and v is its velocity measured at a radial distance r from the centre of the star. p is the gas pressure, M is the mass of the star and G is the gravitational constant.

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 591–600.

The equation of continuity with spherical symmetry is

$$\frac{1}{\rho}\frac{d\rho}{dr} + \frac{1}{v}\frac{dv}{dr} + \frac{2}{r} = 0 \qquad (2)$$

and the equation of state is

$$\frac{p}{\rho} = \frac{RT}{\mu} = c^2 , \qquad (3)$$

where R is the gas constant, T is the temperature and μ is the mean atomic weight of the gas. c is then the isothermal sound speed.

These equations give

$$\frac{1}{v}\frac{dv}{dr}\left(v^2 - c^2 \right) = \frac{2c^2}{r} - \frac{dc^2}{dr} - \frac{GM}{r^2} . \qquad (4)$$

If the velocity v is equal to the isothermal sound speed the left hand side of the equation is zero. The only solution which goes from velocities less than the isothermal sound speed (subsonic) to velocities greater than the isothermal sound speed (supersonic) with velocity gradients that are not infinite is that solution in which the right hand side of the equation goes to zero simultaneously with the left hand side. At this point the equation has a singularity and this point is called the critical point.

Parker showed that if the temperature of the corona falls more slowly with distance than 1/r a hydrostatic corona cannot satisfy the boundary condition that the pressure tends to zero as the distance tends to infinity and therefore the corona must expand. Further he showed that of the possible dynamic solutions only the solution which passes through the critical point can satisfy that boundary condition. He thus predicted that the solar corona would expand to supersonic velocities, a prediction later confirmed by satellite measurements.

The wind is driven by the expansion of gas which converts the internal energy of the gas into work available for accelerating the gas and overcoming gravitational attraction. If the temperature gradients are negligible in equation 4, the critical point is the point where the total energy of the gas is just sufficient to take the gas to infinity where it arrives with zero temperature and zero velocity. A finite velocity and temperature at infinity requires further energy and momentum to be deposited in the gas beyond the critical point.

The Parker theory does not by itself predict a mass loss rate. The theory determines a velocity distribution with distance given a temperature distribution. It cannot predict a mass loss rate because the density has dropped out of equation 4. The reason for this is that the Parker theory does not contain an energy balance equation. So that to predict a mass loss rate one has to solve equations 1, 2 and 3 consistently with an energy balance equation which requires a knowledge of the mechanisms heating the corona.

We know now that to describe properly the stellar winds observed from a wide range of stars more physics has to be included in the equations. A magnetic field can cause a multiplicity of critical points because there are three characteristic sound speeds instead of one. It can also cause geometries which do not have spherical symmetry. The energy transfer between protons and electrons can be so slow that a one fluid model is no longer valid and separate equations for the temperatures of the protons and electrons are necessary. A thorough review of many of these problems has been given by Hollweg (1978).

Further the equation of motion must be modified to include momentum transfer resulting from radiation pressure and wave pressure. The radiation pressure can come from absorption of the stars radiation by continuous or line opacity or by dust. The wave pressure can result from the propagation of any sort of magnetohydrodynamic wave, though Alfvén waves and sound waves are probably the most important.

There are limits to what contribution direct momentum transfer can make to the stellar wind. Marlborough and Roy (1970) looked at the Parker solution modified by an extra force on the gas directed outward. They showed that if this extra force everywhere exceeds the force due to gravity the Parker solar wind solution going through the critical point disappears. Thus it is not possible to generate a stationary stellar wind with a transition to supersonic velocities by large steady forces alone. Their work was directed to hot stars where the radiative force associated with resonance lines is very large, but their conclusions are quite general. But once the flow is supersonic a large outward force can produce a large acceleration of the flow. (Cassinelli and Castor, 1973).

No matter what extra terms are included in the basic equations, all the work based on the Parker theory has one thing in common: it is assumed that the solution for the velocity distribution goes through the critical point, or if there are more than one critical point that it goes through one of the critical points. This approach has been criticised by Cannon and Thomas (1977) (see also Thomas, 1978). Cannon and Thomas suggest that the mass loss from a star is determined by the dynamical processes below the photosphere, and as this imposed mass loss moves out into regions of lower density the outward velocity of the flow rapidly achieves the sound speed and generated shocks. These shocks dissipate energy and heat the corona. In the Parker theory the stellar wind and mass loss are a result of a corona. In the Cannon and Thomas theory the corona is a result of the mass loss. The Parker theory is essentially a theory of stationary flow, and Parker (1965) maintains that the flow through the critical point is stable against perturbations. Cannon and Thomas maintain that the flow through the critical point is not stable and that instabilities in the trans-sonic region will grow. Their theory is a completely time dependent theory which cannot be represented by a stationary solution.

This has raised the question of variability in stellar winds. There is increasing observational evidence of variability in stellar winds on short and long timescales. However these observations are not in themselves proof that the stationary solutions are not valid representations of the mean flow. One expects perturbations in the stationary flow to exist. If a corona is heated by wave motions or instabilities one would expect perturbations to propagate outward in the stellar wind causing short period variability. In some cases the perturbations in the supersonic wind may grow in energy (MacGregor et al., 1979) but again this need not invalidate the stationary solution. One must be equally cautious in the interpretation of long period changes in the stellar wind. One knows from the Skylab observations that much of the solar wind comes out of the coronal holes. It is clear from all these observations that if the solar wind were measured at a distance so great that the Sun is a point source, the magnitude of the solar wind measured would vary considerably depending on the coronal holes pointing at the observer. This would produce variations related to the 11 year solar cycle and well as to the 27 day rotation of the Sun.

At the same time these arguments are not proof that the stationary solutions are valid representations of the mean stellar wind. It is clear that further work is needed to elucidate the nature of the variations observed in stellar winds to see whether perturbations of a stationary flow or a completely time dependent flow can explain them.

Finally a very different description of mass loss from stars has been given by Andriesse (1979). He has calculated the mass loss rate from fluctuation theory and the order of magnitude that he derives is in reasonable agreement with the measured mass loss rates for a wide range of stars. However the physical basis of his calculation is obscure.

2. STELLAR WINDS FROM HOT STARS

The nature of stellar winds from hot stars was an important topic discussed at the IAU Symposium 83 on "Mass loss and evolution of 0 type stars" held on Vancouver Island in June 1978. A panel discussion was held of the various theories. A summary of a JILA workshop has been given by Cassinelli et al. (1978). A further review has been given by Cassinelli (1979). A short review has also been given by Cassinelli in the report of commission 36.

The important modification to the Parker solution which needs to be made for hot stars is the large outward force resulting from the absorption of photospheric radiation by the resonance lines of ions in the stellar wind. It is now agreed that these large forces are responsible for the acceleration of the stellar wind up to the large final velocities. Velocities as high as 3000 km s^{-1} are observed.

What was so uncertain at the Vancouver meeting was the temperature structure of the expanding envelope of hot stars. Four models were

https://doi.org/10.1017/S1539299600004482 Published online by Cambridge University Press

discussed. The first given by Castor (1978) was a development of the work of Castor, Abbott and Klein (1975) and Lucy and Solomon (1970). In this model the radiative forces from the resonance lines are responsible for the mass loss. The Castor, Abbott and Klein model was a radiative equilibrium model. This was modified by Castor (1978) who showed that the observed O VI lines could be explained if the atmosphere was heated mechanically up to 60 000 K and if the atmosphere is optically thick in the continuum. The second model was the warm wind model of Lamers and Morton (1976) and Lamers and Rogerson (1978). In this model the expanding envelope has a temperature of about $2\ 10^5$ K thoughout and the O VI lines are explained by collisional ionization. The mass loss is also driven by radiation pressure. The third model has a small hot corona surrounded by an expanding envelope near radiative equilibrium. Such a model was first proposed by Hearn (1975). It was refined by Cassinelli, Olson and Stalio (1978) who showed that the corona could not be much more than a tenth of a stellar radius thick, and by Cassinelli and Olson (1978) who showed that such a corona with a temperature of $5\ 10^6$ K could explain the observed O VI lines by Auger ionization of the surrounding envelope by X-rays emitted from the corona. The fourth model was the time dependent model of Cannon and Thomas (1977). Apart from predicting a corona no specific model has been worked out. Cannon and Thomas (1977) maintain this is impossible until the dynamics of the motions below the photosphere are understood.

Since the Vancouver meeting reports of measurements of X-rays with the Einstein observatory (Harnden et al., 1979) appear to confirm that hot stars have a hot corona. The spectral distribution and intensities seem quite consistent with the model of Cassinelli and Olson (1979). A $5\ 10^6$ K corona is not hot enough to be responsible for the mass loss by itself and clearly the radiative forces are important. However Lamers, Paerels and De Loore (1979) have found O and Of stars with the same bolometric magnitude have significantly different mass loss rates, a result that has been confirmed by Conti and Garmany (1979) with a larger sample of stars. Lamers, Paerels and De Loore (1979) conclude that the differences in mass loss cannot be explained by differences in chemical composition, mass or rotation and that the mass loss rate is not determined by the effective temperature and luminosity alone.

With the Einstein observatory evidence of hot coronae round OB supergiants it is tempting to ascribe these differences in mass loss to differences in mechanical heating of the corona, but the way in which the mechanical heating and the radiative forces interact to determine the mass loss is just not understood at present.

There is now clear evidence that the winds from hot stars are variable over both short and long time scales. See Wegner and Snow (1978), Snow and Hayes (1978), Stalio et al. (1979) and the references in these articles. The interpretation of these variations is uncertain. More theoretical work is required on the variations in stellar winds and a comparison with the observations to see whether the observations are consistent with a perturbed stationary stellar wind or with a fully time dependent model.

3. THE SOLAR WIND

The original theory of the solar wind (Parker, 1965) combined with an energy balance of heating only by conductivity seemed to agree with the observations of the average solar wind quite well. The temperature predicted at the Earth's orbit agrees quite well with the observed electron temperature but the predicted velocity was about 20% too low. Two fluid models were developed by Sturrock and Hartle (1966) and Hartle and Sturrock (1968) in which the protons and electrons have their own energy equations. These models gave proton temperatures that were too low and electron temperatures that were too high. The expansion velocity was about the same as that obtained from the one fluid model.

However a substantial push to the theory of the solar wind has been given by the Skylab observations. A description of much of the work related to coronal holes has been given in the Skylab solar workshop series (Zirker, 1977). In an observation of a polar coronal hole Munro and Jackson (1977) found that below 3 solar radii the geometry formed by the magnetic field was far from radial, having a strongly diverging shape. They also found that the main acceleration of the flow out of the coronal hole occurs between 2 and 5 solar radii, becoming supersonic between 2 and 3 solar radii. Further Cushman and Rense (1976) have measured outward velocities at the base of a coronal hole of 16 km s^{-1}.

It has been known for some time that the high speed streams in the solar wind come from coronal holes (Krieger et al., 1973). The Skylab observations have shown that much and perhaps all of the solar wind comes from coronal holes, and this implies much larger mass loss rates from coronal holes than are measured from the average solar wind.

These large velocities and mass loss rates cannot be explained by the simple Parker theory. One explanation for them that has been explored is the greater than radial divergence of the geometry which has now been observed by Munro and Jackson (1977). Kopp and Holzer (1976) have investigated this effect using a polytropic equation of state. They find that a rapidly diverging geometry gives extra critical points nearer to the sun's surface than the critical point for radial geometry. This can cause the wind to become supersonic at a point which is much lower in the atmosphere than with radial geometry. Holzer (1977) has made a rather more general study of the nature of multiple critical points. The work of Kopp and Holzer has been extended to a wind heated by thermal conduction alone by Steinolfson and Tandberg-Hanssen (1977). Although a divergent geometry can increase the expansion velocities near the Sun, it appears it cannot alone increase the final velocity of expansion or the mass loss rate. To do this more energy or momentum must be deposited in the flow.

The observation of Munro and Jackson (1977) that the main acceleration of the wind in a polar coronal hole occurs between 2 and 5 solar radii has stimulated a further study of how momentum may be added directly to the wind and in particular of the effect of the wave pressure of Alfvén waves. It had already been suggested by Alazraki and Couturier (1971) and Belcher (1971) that wave pressure of Alfvén waves propagating through the solar corona could make a significant difference to the solar wind. Jacques (1978) has calculated the effect of Alfvén wave pressure on coronal models assuming conduction heating and on models with a polytropic equation of state. He concludes that the addition of Alfvén wave fluxes of 10^5 erg cm^{-2} s^{-1} makes it possible to construct coronal models that match the densities and velocities at the Earth's orbit of the high speed streams in the solar wind which also have reasonable electron densities near the Sun.

A similar conclusion has been found by McWhirter and Kopp (1979) for a model using an isothermal corona extending from 2 to 5 solar radii. However they could not find a consistent model including the low corona and transition region because the reflection of Alfvén waves at the transition region was so strong that the gradient of the Alfvén wave pressure at the transition region prevented a stable solution. This problem was also found by McWhirter, Thonemann and Wilson (1975, 1977) in a coronal model heated by sound waves.

4. WINDS FROM LATE TYPE STARS

The observations of mass loss from late type stars have been reviewed by Reimers (1978), Merrill (1978) and Moran (1976). Some of the theoretical work on stellar winds in late type stars has been reviewed by Weymann (1978). A review of both observations and theory has been given by Cassinelli (1979). A short review has also been given by Reimers in the report of commission 36.

It is for late type stars that the theory of stellar winds is the most uncertain, and virtually all the modifications to the basic Parker theory that have been applied to hot stars and the solar wind have been used in an attempt to explain the observed mass losses from these stars.

An interesting observation has been made with IUE by Linsky and Haisch (1979). They find one group of stars which have emission lines consistent with a transition region and presumably with a corona. The other group of stars, which lie to the top and to the right of the Hertzsprung-Russell diagram, show lines formed at temperatures no hotter than 20 000 K . This means that either these stars have no coronae or that the transition region lies at such a low density that the emission lines are below the detection level.

For the stars which show a transition region the simple Parker theory is a possible explanation of the observed mass loss rates.

The stars which do not show a transition region present a much greater problem to the theorist. The application of the simple Parker theory to M supergiants for example had already been criticised by Weymann (1978). He also discusses other extra processes which may be added to the theory such as Alfvén wave pressure, radiation pressure due to molecular opacity and radiation pressure due to dust. Haisch, Linsky and Basri (1979) have explored stellar wind models for Arcturus, which is one of the stars not showing transition region lines, with temperatures no higher than 20 000 K with deposition of momentum in the stellar wind by radiation pressure of Lyman α in the chromosphere and wave pressure from Alfvén waves in the outer regions. However these models, like the original Parker theory, use a prescribed temperature distribution and further work is necessary to show whether these solutions are consistent with a proper energy balance equation.

The dividing line in the Hertzsprung-Russell diagram between stars with and without transition lines lies near the supersonic transition locus predicted by Mullan (1978). He calculated from a mixture of observations and theory the region in the Hertzsprung-Russell diagram where the critical point in the simple Parker theory will be at the base of the corona. The stellar winds in the region beyond this supersonic transition locus will be supersonic from the surface of the star as opposed to the regions below the locus where, as in the case of the Sun, there is an extended region of subsonic flow above the surface of the star before it reaches the critical point and becomes supersonic. Mullan argues that when the critical point comes down to the base of the corona spicules will inject matter into the region of the critical point thereby increasing discontinuously the mass loss. Since the chromospheric densities are typically 50 times greater than densities at the base of the corona he predicts a 50 fold increase in the mass loss on crossing the supersonic transition locus.

Increasing the density alone at the critical point by a factor of 50 will not increase the mass loss. A 50 fold increase in energy and momentum transfer is also needed to bring this extra mass flow to infinity. Without that extra energy and momentum either the corona will be choked and the stellar wind with it, or the base of the corona will move to lower densities such that the available energy can maintain the corona and the stellar wind. It is of couse possible that the spicules can also feed the extra energy into the base of the corona, but because of thermal conductivity that would also increase the stellar wind for those coronae in which the critical point had not yet reached the base of the corona, and consequently one would not expect any discontinuous increase in mass loss across the supersonic transition locus.

ACKNOWLEDGEMENTS

I am very grateful to Dr. J.P. Cassinelli and Dr. D. Reimers for sending me copies of their reviews before publication. They have made my task much easier. I am grateful to Dr. H.J.G.L.M. Lamers, Mr. F.B.S. Paerels and Dr. C. de Loore for details of unpublished work, and to Mr. N.P.M. Kuin for discussions of the effect of diverging geometries.

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