OUTFLOWING ATMOSPHERES ACROSS THE HR DIAGRAM

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Abstract

The principal factors governing the modelling of stellar atmospheres are reviewed, and it is noted that modern observations, which span wavelengths from 1000 Å to several mm, reveal parts of stars which are not included in the classical models. The evidence across the HR diagram shows that four components may be present in addition to the photosphere, namely a hot chromosphere/corona, a cool extended atmosphere of atoms and ions, dust, and an escaping wind. Some suggestions are made concerning the direction future research might take in order to solve the problems that are not handled successfully by classical methods of modelling stellar atmosphere.

I. INTRODUCTION

The only thing that reaches us from stars is radiation. Until recently we were restricted to observing only the radiation which reaches the surface of the Earth and our appreciation of that was, and is, severely modified by the types of detectors and dispersing devices available to us. Most of what will be reviewed here is concerned with interpreting spectroscopic observations of stars in wavelengths from about 1000 Å to a few millimeters.

Information obtained from ground-based telescopes is still our prime source of information, but observations made from space have been decisive in making us aware that the classical models of the stars and the interstellar medium, which were developed to interpret observations obtained in the limited visible wavelength range, are no longer adequate. Now that we can detect parts of stars that 30 years ago were invisible to us, it is appropriate that we review the modelling process which is the basis of our understanding of stars. Our intention is to obtain a sharp and deep understanding of stars, their formation and their evolution. Stars are the building blocks of the universe and their study is absorbing.

One starting definition is in order. By photosphere, I mean the moderately dense layer which, in visible wavelengths (4000 to 7000 Å), is seen to be opaque and to define the limb of a star or the Sun. It is the deepest layer which we can observe directly from the surface of Earth. Parts of the outer atmospheres around the various types of star which we shall mention have been given different names. We shall speak of chromospheres and coronas, meaning structures somewhat like those known for the Sun. Their temperatures are higher than the effective temperature of the star. We shall speak of shells around B stars and around some M-type supergiants. The planetary nebulae and the circular gaseous nebulae which surround a few Wolf-Rayet stars can be considered to be extreme examples of shells. A typical characteristic of a shell is that the electron temperature there is cooler than the effective temperature of the central star.

There are two factors which strongly influence the character of all models of stars. The first is the need for simplicity if the details are to be worked out, and the second is the character of the body of observational data which is available at the time the models are defined. The first constraint has been loosened greatly in recent years owing to the capability of modern computers to handle complex problems of large extent. However, it is still a real constraint. The second factor has been completely changed by the present availability of spectroscopic observations of stars and of nebulae over practically all of the electromagnetic spectrum.

The classical model of a star postulates a sphere of gas in hydrostatic equilibrium under the attraction of gravity due to the mass of the star. A flux of radiation, generated by nuclear reactions in the center of the star, traverses the model atmosphere and emerges as a spectrum. The usual geometry for model atmospheres is plane parallel layers. Usually there are no sources of energy in the model atmosphere except the radiation field, but a few models take energy carried by convection into account in a simplified way. The model star is situated in empty space. Interaction with the surrounding interstellar medium is not taken into account when specifying the boundary conditions for classical models of stellar atmospheres.

Improved model atmospheres should be constructed to describe the physical state of the outer layers of a stellar atmosphere starting from the full forms for the equations describing the conservation of mass, momentum and energy in the stellar atmosphere, taking care to eliminate only the least essential terms. These equations are discussed in the Appendix. First let us see what patterns of physical structure are suggested by spectroscopic observations of stars in all parts of the HR diagram. The classical equations for model atmospheres result from ignoring all terms in the conservation equations which describe changes in time and which take account of a flow velocity and its rate of change.

II. STRUCTURES BETWEEN THE PHOTOSPHERE AND THE INTERSTELLAR MEDIUM

In the center of a star, where the energy is generated, the temperature and density are high. As one moves outwards in the star, the temperature and density decrease until one reaches the photosphere, which comprises those layers seen in visible light. We now know that more or less extensive, rather low density gaseous layers exist outside the photospheres of most stars. Rough spectroscopic diagnostic analysis permits us to recognize five outer parts of the star: the photosphere, a hot chromosphere/corona, a cool extended atmosphere of atoms and ions, a very cool extended atmosphere containing dust, and an escaping wind. The relative linear sizes of the various components and their densities are probably quite different for stars of different spectral types, but most likely the order outwards from the photosphere is the same for all stars. The order given above is plausible and we will adopt it. The wind may *originate* in the hot chromosphere/corona; it may be *detected* at any part of the extended atmosphere, detection depending on the availability of a sensitive indicator in the available part of the stellar spectrum. The relative sizes of the various structures are controlled by the heating and cooling mechanisms which are active and the mechanisms which control the input of outward directed momentum.

It may be a major problem to *detect* any or all of the above components for any given star, but we shall work from the hypothesis that each component exists. Once we have noted what we know to exist, we shall consider the constraints present observations place on any model for the star and its interaction with its environment.

An overview of the known outer structures of stars follows with an indication of typical temperatures and densities in some of the above regions. Most of the temperatures have been estimated from the shape of the continuous spectrum, from the total flux received from the star, or from the relative intensities of lines from two or three stages of ionization of abundant elements. It is more difficult to estimate densities. They are usually found by interpreting line shapes and strengths by means of theoretical models for the atmosphere. The presence of forbidden lines, usually in emission, indicates an ionized plasma having a number density less than 10^9 cm^{-3}. The break off of the Balmer series for B-type shell spectra suggests densities of the order of 10^{10} to 10^{11} cm^{-3} for shells, while for B-type supergiant atmospheres the density in the photosphere seems to be about 10^{12} cm^{-3}. For early-type main-sequence stars the density in the photosphere is of the order of 10^{14} cm^{-3}. These values may be compared with those for the Sun of 10^{16} cm^{-3} in the photosphere, about 10^{14} in the low chromosphere and about 10^9 at the base of the corona.

The outer structures around stars generally are considered to be spherical in shape. However, Be and B-type stars with shells are known to show intrinsic polarization. This fact, together with the observed shapes of the emission lines of H and Fe II strongly suggests that the outer atmospheres of these stars are disc-like. The extent of the material and its density in the equatorial plane perpendicular to the axis of rotation of the star are believed to be significantly greater than in the direction parallel to the axis of rotation of the star. The amount of material in these outer structures and the radial-velocity pattern shown by this material is known to change in intervals from days to years for many Be and shell stars. However, some B stars seem to have been essentially constant in their behaviour for the 50 to 100 years over which they have been observed.

A search for spectroscopic changes which occur in minutes to hours has been made for only a few stars. Too little information is at present available on the rapid changes seen in some stellar spectra to make any generalizations at this time. The line profiles for some stars definitely do change in minutes. Thus the observation of a grossly constant spectrum should not be interpreted to mean that the atmospheres of the stars are quiescent. Most of the stars which show emission lines in their spectra are irregular light variables of small range. Not all light-variable stars, however, are known to have emission lines in their spectra.

Wolf-Rayet, O and Of stars: The photospheres of Wolf-Rayet stars are difficult to observe; they are considered to furnish a continuous spectrum corresponding to an effective temperature near 30,000 K on which the emission lines are seen. A few particular emission lines are associated with a shortward displaced absorption component (see Underhill 1968). The physical state of the photospheres of O and Of stars of all spectral types and luminosity classes from subluminous stars to supergiants are deduced from the strengths of the absorption lines of He I and He II. The effective temperatures range from about 30,000 to 50,000 K. Heap (1977a,b) and Pottasch *et al.* (1978) have shown that the effective temperatures of some central stars of planetary nebulae may be as high as about 70,000 K; the values of log g for the central stars with O-type spectra are about the same as those for normal, galactic O stars.

The evidence for hot chromospheres/coronas around O-type stars comes from the ultraviolet spectrum where shortward displaced strong absorption lines of O VI, N V and other high ions are found, see, for instance, the review by Snow and Morton (1976). The hot gas is seen to be moving with velocities exceeding the velocity of escape; the flow velocity is well above thermal velocities, whatever choice one makes for the electron temperature in the hot gas. Both Wolf-Rayet stars (Cohen, Barlow, and Kuhi 1975) and O stars (Barlow and Cohen, 1977) have infrared excesses indicating the presence of a cool extended region with $T_e \backsim 10^4$ K, and some WC9 stars are known to show a cool dust-containing shell where the electron temperature may be near 10^3 K. The superthermal winds from Wolf-Rayet stars are conspicuous and may be detected by the visible line spectrum. Those of the O stars, including some central stars of planetary nebulae which show Wolf-Rayet-type emission lines, are also fairly conspicuous Several criteria pointing towards the presence of an escaping wind are now recognized in the visible spectral region of O-type spectra.

B-type stars. The photospheres of these stars are readily studied for all subtypes by means of the absorption-line spectrum of the visible region. The effective temperatures run from about 10,000 K at type B9.5 V to about 31,000 K at type B0 V, see Underhill *et al.* (1978). A hot chromospheric/coronal region may be inferred from the presence of absorption lines from high ions in the ultraviolet spectra of many B5 and earlier main-sequence and supergiant stars, see Snow and Morton (1976) and Lamers and Snow (1978). Underhill *et al.* (1978) have demonstrated that the visible absorption-line spectra of the B-type supergiants indicate the presence of a hot chromospheric/coronal layer in supergiants. The B-type supergiants are known to have infrared excesses (Barlow and Cohen 1977) which indicate the presence of extended cool outer atmospheres for these stars. The spectroscopic phenomena attributed to the shells of Be and shell stars, as well as the known strong emission in Hα and various hydrogen continua, give ample evidence that a large, cool extended atmosphere may exist at times around main-sequence and near main-sequence B stars. There are no visible observations suggesting that the material in this cool structure is flowing from these stars at *escape* velocities. Some of the flow velocities seen, for instance, in Balmer progressions of active shells, exceed typical thermal velocities which are of the order of 10 km s^{-1} . The lifetimes of extended shells can be days to years. Snow and Marlborough (1976) and Marlborough (1977) have found evidence in the ultraviolet spectra of a few Be stars for a modest rate of mass loss.

Escaping winds are readily detected for B-type supergiants; they are not conspicuous for main-sequence and near main-sequence B stars. There is evidence for irregularities in the flow, see, for instance, York *et al.* (1977) and Snow (1977).

The [BQ] stars form a special group of Be stars which are enmeshed in a presumably very large envelope. The density of this envelope is sufficiently low that *forbidden* lines of Fe II and other ions are seen. The composition of the emission-line spectrum usually suggests electron temperatures in the range 8,000—10,000 K in this extended structure. Some of the [BQ] stars are known to have a cool, dust-containing envelope where the temperature may not exceed about 10^3 K. The spectra of the [BQ] stars frequently are variable, which suggests that the extended envelopes are not static.

A group of Ae/Be stars lying in obscured regions and illuminating nebulosities has been observed quite extensively. These may be very young stars. They seem to fall into two groups : (1) a group which has emission lines with P-Cygni character indicative of outflow velocities of the order of 150 to 200 km s^{-1} and (2) a group which shows emission lines of hydrogen plus absorption lines attributable to a cool overlying shell as for a conventional Be star. High-resolution observations of the Hα lines of these objects and polarization studies, see, for instance, Garrison and Anderson (1977, 1978) show that changes occur in fairly short intervals and that these stars are clearly surrounded by dynamic, cool extended atmospheres. They are associated with dust clouds, are irregularly variable and have infrared excesses and are associated with molelcular line emission. The outer layers of these stars seem to be interacting with the surrounding interstellar medium.

Supergiant and main-sequence A stars; Ap, Am stars :

The photospheres of the A stars have temperatures in the range from about 8,000 to 10,000 K. There is evidence for outflow at escape velocity for α Cyg , A2 Ia, see, for instance, Lamers, Stalio and Kondo (1978). The observations tabulated by Rosendhal (1973) of variable Hα profiles for a number of A-type supergiants may be interpreted in terms of outflow. Freire *et al.* (1977) have searched the spectrum of α Lyr, A0 V, from the ultraviolet to the near infrared for evidence of outflow or of a hot chromospheric/coronal layer and have found none. However, Johnson and Wisniewski (1978) have observed that the Ca II and O I lines in the infrared spectrum of α Lyr have small shortward shifted emission satellites, which suggest that Vega has a relatively thin extended atmosphere which may be expanding at about 50 km s^{-1} . Other main-sequence A stars observed by Johnson and Wisniewski do not show the Ca II and O I lines in emission. However, other observers, for instance, Griffen (1978) and Freire *et al.* (1978), have not been able to confirm the observations of Johnson and Wisniewski. The Am and Ap stars are known for their stable spectra, although cyclic changes, sometimes attributed to the rotation of spots, are known for the Ap stars. Among the A stars, only the supergiant α Cyg is surely known to have an escaping atmosphere. Because some of the A stars are relatively nearby, lack of detection of outer structures for these stars indicates that if such structures exist for A stars, the amount of material in the structures is much less than for a typical B star. A few A-type stars are known to have shells like those of Be stars, for instance, 14 Comae. The temperatures in such shells are cool, around 7000 K.

Supergiant, giant and main-sequence F and G stars :

The effective temperatures of these stars lie in the range 5000 to 8000 K. A chromosphere and corona are known for the Sun (rather easily observed because of the nearness of the Sun); the fact that the spectra of most of these stars contain emission lines of Ca II, see, for instance, Dravins (1976), for a brief summary of recent observations, is usually taken to mean that a chromosphere is present. The Delta Cephei variables have particularly strong emission lines of Ca II, so presumably they have substantial chromospheres. The dominant emission-line character of the spectra of some T Tauri stars leads to the inferred presence of significant chromosphres/coronas for these stars also. A possible indicator of the presence of a corona is the presence of the He I 10830 Å line in absorption or emission in late-type stars. Observations of He I 10830 in 198 stars of many spectral types have been summarized by Zirin (1976). who concludes that the intensity of He I 10830 must be more or less proportional to the amount of energy deposited in stellar chromospheres/coronas by non-thermal processes. Reimers (1977) has summarized information on the existence of winds from a few G supergiants. A low density wind is known to be escaping from the Sun, but a wind of this tenuous character cannot be detected for stars with our present techniques. There is a little observational evidence for a large cool envelope surrounding the F and G supergiants 89 Her and ρ Cas. Clearly, a cool envelope must exist around all F and G stars with coronas, for a high-temperature coronal regime will extend only as far from the stellar photosphere as the rate of energy input is sufficiently great to maintain a high electron temperature. At large distances from the photosphere, the gas will cool by radiation. Eventually its temperature will approach that of the surrounding interstellar medium. It is a difficult observational problem to detect such a cool extended envelope.

Supergiant, giant and main-sequence K and M stars: The effective temperatures of these stars lie in the range 2500 to 5000 K. Ultraviolet spectra have furnished evidence for the presence of emission lines formed in the hot chromospheres of α Boo and other K giants; the presence of chromospheres in most of these stars is inferred, as for the F and G stars, from the occurrence of emission lines of Ca II. Also for these stars, according to Zirin, the He I 10830 Å line may indicate the presence of a corona. Substantial hot flare regions occur on the discs of dMe variables. There is a large body of data, reviewed by Reimers (1975), which demonstrates the presence of extensive, cool circumstellar atmospheres surrounding M giants and supergiants. Some shells contain dust. Velocity gradients are known to occur in these circumstellar shells and the escape velocity is superthermal. The observation of broadened emission-profiles from microwave lines of SiO and HC_5N attests to the fact that an optically thick sphere of gas is expanding uniformly from some M-type and other red supergiants at about 20 km s^{-1}, see, for instance, Morris and Alcock (1977), McGee *et al.* (1977). The cool shells surrounding M supergiants are very large and they may be traced to more than 500 stellar radii (Bernat 1977 ; Bernat *et al.* 1978). It has long been known that large superthermal velocities are seen deep in the chromosphere of 31 Cyg, K1 Ib, during the partial phases of the eclipse (McKellar *et al.* 1959). Reimers (1977) gives evidence for variations in the flow velocities shown by the circumstellar lines around a number of K stars. Quite clearly, the extended, cool atmospheres around the late-type stars are not static structures. Hagen (1978) has shown that the ratio of dust to gas varies from star to star and she notes that the mechanism causing mass loss in the M giants and supergiants may be something other than radiation pressure on grains.

III. PROBLEMS REQUIRING STUDY

A. Significant characteristics of outer atmospheres: The most significant thing about the outer atmospheres of stars is that the state variables, (electron temperature, density, state of motion) of the gas, detected by means of spectral lines, frequently change in rather short intervals of time. For instance, weak satellite components due possibly to non-radial pulsation, occur next to the normal photospheric absorption lines of sharp-lined O and B stars (Smith 1977; Smith and Karp 1978) and their displacements change in a few hours; the displacement of H α and the relative strengths of its emission and absorption components in O, B and A supergiants are known to change irregularly in days to months; the velocity fields seen in some Be and shell stars and the strengths of the absorption lines usually change slowly, but systematically in times of the order of 6 to 10 years, although significant changes can occur in a few weeks. In other stars, particularly in binary stars where one is seeing the material flowing between the two stars, changes are known to occur in days. Our observations are still too incomplete to document fully the rates of change which occur and the sizes of the changes.

Three facts are certain: (1) conspicuous changes can occur in minutes in the outer atmospheres of stars, (2) luminous stars and some main-sequence stars continuously produce modest changes in their atmospheres in times from a few days to a few months, and (3) the Be and/or shell phenomenon is more varied in its temporal characteristics than the changes seen in supergiants or in non-radially or radially pulsating stars.

We infer that the state variables change because the shape, intensity and displacement of the lines, which reveal the outer atmosphere, change. It is by no means clear whether the observed spectroscopic changes are primarily due to changes in electron temperature, in density or in line-of-sight motion. Probably all three factors are interlocked. What causes the changes is unknown. They may be accompanied by changes in the brightness of the star.

A second important generalization about the outer atmospheres of stars is that winds moving at escape velocity are usually more easily visible at any given spectral type for supergiants than they are for main-sequence stars. Winds are known to occur for some low-luminosity stars, the Sun, for instance, and for some central stars of planetary nebulae. It is interesting that the visible spectra of Be and shell stars do not give evidence for a wind escaping from the star, although there is evidence for outward and inward directed motion which changes slowly, and sometimes for velocity gradients in the observed part of the outer atmosphere. The escaping outer atmospheres of B-type supergiants can usually be seen in H α and sometimes in other strong lines accessible from the surface of Earth.

An analysis of the shapes of the ultraviolet lines of O and B stars with winds suggests that the acceleration to escape velocity takes place close to the photosphere. In the case of 31 Cyg, K1 Ib, sharp Ca II lines with large line-of-sight velocities are sometimes seen on lines of sight which pass close to the photosphere, (*i.e.* at times near second and third contact), suggesting that the propulsion force is particularly strong near the photosphere. Van Blerkom (1978), however, has interpreted the shapes of the hydrogen lines of P Cygni to mean that in this star the acceleration to escape velocity occurs slowly. He thinks two types of wind occur : one which is accelerated to escape velocity rapidly near the photosphere, and one which receives acceleration to escape velocity over a long path length.

A third significant fact about the outer atmospheres of stars is that the spectra of practically all stars, when looked at carefully, give evidence for the presence of a hot chromosphere/corona lying outside the photosphere. The real difficulty is to find appropriate spectroscopic features to reveal the, perhaps, small amount of material which is at a high temperature. When appropriate indicators of chromospheric/coronal conditions can be observed, often in the ultraviolet, a hot layer is usually detected.

B. Propulsion forces ; Since the rate of flow in outer atmospheres and the densities and temperatures which occur change, sometimes quite rapidly, it is clear that the propulsion mechanism, which accelerates stellar winds, is not some global force such as radiation pressure or the centrifugal force resulting from the rotation of the star. In fact, some of the observations of flow in outer stellar atmospheres are suggestive of motion in jets. Global forces such as radiation pressure or centrifugal force may facilitate the outward propulsion of material by partially annulling the effects of gravity, but forces of this type cannot change rapidly and coherently over the disc of the star.

An attractive source of propulsion, which could be variable, is offered by magnetic fields. In the case of the Sun, eruptive prominences are seen from time to time. These are suggestive of the type of phenomenon which might be considered. However, the theory of such propulsion has not been worked out satisfactorily even for the Sun. There is no evidence for the presence of magnetic fields in the atmospheres of B-type supergiants, but on the other hand, it is not possible at this time to prove that magnetic fields are not present. To prove whether appropriate magnetic fields exist for stars with variable winds is a problem that will require high-resolution spectroscopy for its solution.

It is a question for speculation whether the propulsion mechanism is the same or different for young stars and for old stars. Certainly both types of star have winds. A clue might be obtained by examining the temporal behaviour of winds from young and from old stars and seeing whether it is the same or different.

C. Kinetic energy carried away by a wind : If the wind is spherically symmetric and material is conserved in spherical shells, then it is easy to show that the fraction of the stellar luminosity which is carried away as kinetic energy of the escaping particles is $0.0082\dot{M}v/l$, where $\dot{M}$ is the rate of mass loss in units of 10^{-6} solar masses per year, v is the observed velocity of the wind in units of 10^3 km s^{-1}, and l is the luminosity of the star in units of $10^4 L_{\odot}$. For stars with bolometric absolute magnitudes near -5.0, flow velocities of 1000 km s^{-1}, and $\dot{M} = 10^{-6}$ solar masses per year, about one per cent of the luminosity is lost as kinetic energy. Presently available estimates of $\dot{M}$, v and l for stars in all parts of the HR diagram indicate that the loss of energy in the form of kinetic energy of the escaping particles is small relative to the energy being radiated by the stars.

Studies of the evolution of massive stars with mass loss (see, for instance, Chiosi *et al.* 1978), show that by the time a star has lost 10 per cent of its mass, its position in the HR diagram is significantly different from where it would have been had evolution without mass loss occurred. The calculated evolution of massive model stars with mass loss shows that most mass is lost while the star is in the main-sequence band. Once the star starts hydrogen shell burning, it moves quickly to the red-giant regime and loses little more mass. The evolution of low-mass stars with mass loss has not been studied.

D. Heating of outer atmospheres: There is growing observational evidence that hot chromospheres/coronas exist outside the photospheres of all stars in all parts of the HR diagram. The sizes of these hot regions, their extent and density, are not known and the estimates of typical electron temperatures are very uncertain. This is because appropriate diagnostic methods for inferring the state variables when flow occurs are at present rudimentary. It is, however, clear that energy is deposited in the outer layers of stars from a source, or sources, in addition to the radiation field flowing from the star (see, for instance, Hearn 1975).

The heating of the solar chromosphere and corona is not yet fully understood. Until this problem is solved, it seems unlikely that a satisfactory theory for the heating processes in the outer atmospheres of stars will be found. One can think of two sources of energy: mechanical energy, such as that carried in convection elements and in acoustic waves, and the energy contained in a magnetic field, or in Alfvén waves. A problem in physics which requires solution is how, under the density and flow conditions believed to exist in the outer layers of stars, to transfer the stored mechanical/magnetic energy available in the interior of the star to the gas of the outer atmosphere so that it shows up as internal energy of the gas and in the form of line radiation.

The problem of understanding the physics of stellar atmospheres in which the flow of matter occurs and of finding how the flow affects the state variables, in particular the temperature, has been studied by Cannon and Thomas (1977). They emphasise that the mass flow which is observed must originate from small outward directed motions in the subatmosphere and they show that the part of the atmosphere near the critical point, where the flow velocity is approaching the local thermal velocity, is unstable against the production of acoustic waves.

Another approach has been taken by Cassinelli and his colleagues (see Cassinelli 1978), who have shown that X-rays from a small, low lying, very hot region can account for the numbers of high ions of the light elements which are inferred to be present in the winds from hot stars, and yet not violate the observed upper limits presently existing on the amount of X-rays produced by hot stars. The X rays must originate from some mechanism, probably one associated with the acceleration of particles. This facet of the problem has not yet been worked out in detail.

APPENDIX: THE CONSERVATION EQUATIONS AND THEIR USE

The equations which govern the construction of models for the atmospheres of stars are the equation of state

$$P_g = NkT = \rho a^2, \qquad (1)$$

where N is the particle density per unit volumm, ρ is the mass density per unit volume, and a is the thermal velocity which is equal to $(kT/m)^{\frac{1}{2}}$. Here m is the mass of a typical particle. In the conservation equations, we have substituted ρa^2 for the gas pressure, P_g, which is seen in some formulations of these equations. There $\underline{u}$ represents a three-dimensional flow velocity.

The conservation of mass from shell to shell during the flow requires that

$$\frac{\partial \rho}{\partial t} + \nabla . \rho \underline{u} = 0 ; \qquad (2)$$

the conservation of momentum requires that

$$\frac{\partial \underline{u}}{\partial t} + \underline{u} . \nabla \underline{u} = -\frac{1}{\rho} \nabla \left(\rho a^2 \right) + \underline{F} + \underline{f} ; \qquad (3)$$

and the conservation of energy (energy exchange) requires that

$$\frac{\partial E_g}{\partial t} + \underline{u} . E_g + \rho a^2 \frac{\partial}{\partial t} \left(\frac{1}{\rho} \right) + \rho a^2 \underline{u} . \nabla \left(\frac{1}{\rho} \right) = G - L. \qquad (4)$$

In eq. (3), $\underline{F}$ is the total body force per unit mass acting on the fluid while $\underline{f}$ is the total boundary force per unit mass acting on a fluid element; it is usually put equal to zero. In eq. (4), E_g is the internal energy of the gas per unit mass while G is the rate of energy gain per unit mass of the gas and L is the rate of energy loss.

Usually steady-state situations are considered; thus the partial derivatives with respect to time are put equal to zero and only the spatial variations of the state variables are considered. The components of $\underline{F}$ should include the attraction due to gravity from the mass of the star itself as well as any perturbations resulting from the presence of a companion, the force on a fluid element due to radiation pressure on atoms, ions and dust and the Lorentz force, if a magnetic field is present. If viscous forces are significant, they sould be included in this term. The rates G and L, as well as the internal energy E_g, depend on the radiative processes which occur in the outer atmosphere, on the energy exchange involving motion such as convection, collisions of atoms, ions and electrons, and interactions with acoustic waves or Alfvén waves. Energy exchanges resulting from the interaction of a magnetic field with the electrons and ionized particles of the outer atmosphere should also be included. The conduction of heat has to be considered in some density-temperature-velocity regimes. In so-called LTE model atmospheres, the distribution of atoms, ions and electrons over their possible states of ionization and excitation is calculated by means of the Boltzmann and Saha laws; in non-LTE models, these distributions are calculated using the equations of statistical equilibrium.

All presently published theories of stellar winds assume a variation of temperature and pressure (density) with the spatial coordinates which is given by previous knowledge. The authors then work from eqs. (1), (2) and (3) to find the resulting velocity field. The effects of radiation pressure in hot stars have been discussed, for instance, by Lucy and Solomon (1970), Cassinelli and Castor (1973), Thomas (1973) and by Castor, Abbott and Klein (1975). The conclusions obtained are dependent on the functional form which is assumed for the acceleration due to radiation pressure and on the assumed temperature law. The only other force acting is gravity. The achievement of Castor, Abbott, and Klein in being able to support a large rate of mass loss for hot stars by radiation pressure due to resonance lines results primarily from the ad-hoc formula they adopt for g_{rad}, which among other assumptions, assumes the presence of a large velocity gradient and a strong *continuum* of radiation near the wavelengths of the ultraviolet resonance lines of the ions of the light elements. Since the photospheres of most stars are observed to be effectively in hydrostatic equilibrium, thus $\underline{u}$ (photosphere) ≈ 0, yet winds originating in the outer atmosphere are observed at supersonic velocity, $\underline{u}$ (shell) $>>$ a (shell), it is clear that an acceleration through the critical point in the flow where $\underline{u} = a$ must occur. To solve this problem in a physically consistent manner will require use of eq. (4) as well as eqs. (1), (2) and (3).

A useful rule of thumb regarding the retention of the terms containing $\underline{u}$ and $\nabla \underline{u}$ in eqs. (2), (3) and (4) is that when $\underline{u}$ is less than about 0.3a, these terms may be neglected. When $\underline{u}$ exceeds about 0.3a, their affect on the physical state of the model atmosphere may become significant. One well known procedure for taking this point into consideration is the introduction of a term representing the rate of change of "turbulent pressure" into eq. (3) when models of supergiant atmospheres are constructed.

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ANNOUNCEMENT

The twenty second COSPAR meeting will be held at Bangalore, India, between May 29 to June 9, 1979. Among other things, the following symposia are planned:

1. Vikram Sarabhai Symposium on Space and Development.
2. Symposium on Gamma Rays.
3. Symposium on Equatorial Aeronomy.
4. Symposium on Formation and Evolution of the Solar System.

In addition, discussions on the following special topics will also be held during Open Meetings of the Working Groups :

1. Informal presentation and discussion of recent results and prospects on Space Research in Astrophysics.
2. Search for extra-terrestrial intelligence.
3. Organic molecules in space.
4. Venus and the outer planets.

Further details can be obtained by writing to :
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