MAGNETIC-LOOP MODEL FOR Be STARS
(Review Paper)

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ABSTRACT

The magnetic-loop model for a stellar mantle is described and it is shown how this model may be used to understand the differences in spectrum and change of spectrum which are observed for main-sequence stars having effective temperatures in the range from 2.5 x 10^4 to 3.0 x 10^4 K.

It is suggested that the difference in spectrum between a shell star such as Gamma Cas when it is in an active state and a Wolf-Rayet star may be due to a difference in environment.

I. INTRODUCTION

Any acceptable model for a Be star must explain why the spectra of Be stars differ in well known specific details from the spectra of normal, absorption-line stars of about the same mass, luminosity, and effective temperature, and from the spectra of stars with abnormally strong emission lines but about the same mass, luminosity, and effective temperature. Let me direct your attention to two groups of stars in the main-sequence band: those having T_{eff} in the range from 2.5 x 10^4 to 3.0 x 10^4 K and those with T_{eff} from about 1.2 x 10^4 to 1.5 x 10^4 K.

Normal main-sequence stars of the first group have spectral types near B0 V or B1 IV, Be stars of this group have spectral types such as B0 IVe or B1 IVe, while extreme emission-line stars of the group are given Wolf-Rayet types. All these stars probably have masses in the range from 10 to 15 $M_\odot$. Specific examples are Tau Sco or Upsilon Ori, Gamma Cas or 59 Cyg, and HD 192103 (WC8) or HD 191765 (WN6). Among the cooler stars one can think of normal B5 IV or B6 III stars such as Tau Her or Zeta Dra, Be/shell stars such as Theta CrB, Kappa Dra, or Pleione, and some of the Herbig Be/Ae stars, for instance, AB Aur. These stars may have masses in the range from 2 to 4 $M_\odot$.

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Any successful model must be able to account for the observed fact that some stars change from purely absorption spectral types to Be or Be/shell spectral types at intervals of the order of months to decades and vice-versa. On the other hand, stars which show dominant emission-line spectra (the Wolf-Rayet and the Herbig Be/Ae stars) seem to retain that type of spectrum at all times, although relatively small changes in the shapes and intensities of the emission lines are observed from time to time. In the interests of brevity I shall not quote references supporting these generalizations.

One point that I wish to make is that the spectroscopic changes which we are discussing may not be so much due to global changes in internal stellar structure resulting from the passage of time (stellar evolution) as to changes in certain superficial factors. The most important of these superficial factors appears to be the presence of weak, locally distributed magnetic fields in the atmospheres of B stars. The magnetic-loop model for Be stars attempts in a qualitative way to make it understandable that spectroscopic changes of the types known for Be stars occur, yet no fundamental change in the stellar properties seems to have taken place. Changes are not conspicuous in the spectra of "normal" absorption-line stars, nor in the spectra of extreme emission-line stars. This may happen because the conditions controlling the atmosphere in these cases are not close to the dividing mark which causes spectroscopically detectable changes in the physical state of the stellar atmosphere. On a scale from 1 to 3 in possessing significant atmospheric structure controlled by locally distributed magnetic fields, I would put normal B stars at 1, Be stars at 2, and extreme emission-line stars at 3.

When magnetic field lines traverse a low-density plasma such as is found in the atmospheres of all B stars, magnetohydrodynamic (MHD) interactions occur which may transfer energy from a mechanical source, such as the turbulent motion in the photosphere or subsurface convection zone of the rotating star to the plasma in the form of heat, and which may transfer outward directed momentum to the plasma enabling some of the plasma to escape from the gravitational control of the star. Escaping plasma is called a wind. There is no evidence indicating that the winds from main-sequence stars are necessarily spherically symmetric.

Information about the mechanisms which may be active and about what may occur can be found in studies of the MHD behaviour of the solar wind and of laboratory plasmas. The fact that stars rotate is important for determining where the expelled ionized plasma appears to go in the volume seen around a star by a stationary, distant observer. If the density of line photons emitted from the plasma projected against the sky in the neighbourhood of a star is sufficiently great, an emission line will be observed added to the normal absorption-line spectrum of the star. If there is sufficient plasma projected in front of the disk of a star and it contains atoms/ions in the lower states of intrinsically strong lines additional, usually rather sharp, absorption lines will be observed added to the spectrum of the star. One may infer the physical state of the line emitting/absorbing plasma near the star by comparing the relative intensities of lines sensitive to the electron temperature and density and to the local radiation field. Any aceptable model for a Be star must be able to account for how this physical state is generated.

Changes in spectrum imply changes in the physical state of the plasma in the vicinity of the star. Accounting for the variability of Be stars implies accounting for changes of the physical state of the plasma seen by a distant observer to be near the star. For convenience I shall call the line-emitting and absorbing plasma near the star the stellar mantle. The mantle will generate some continuous opacity also. I will not discuss that topic here because of limitations of space.

The plan of this paper is first to deduce the major differences in the most important parameters of the mantles of normal B0/B1 stars, of B0/B1 Be stars, and of Wolf-Rayet stars and then to describe the properties which an acceptable model must have. The properties of late B-type stars with emission-line spectra will probably scale from what is found for hot Be stars.

II. THE PHYSICAL STATES OF THE MANTLES OF STARS WITH $2.5 \times 10^4 < T_{eff} < 3.0 \times 10^4$ K

The stars Tau Sco and Upsilon Ori are examples of stars in this group which have very inconspicuous mantles. The only evidence for the presence of a mantle is weak, shortward wings on the resonance lines of C IV, N V, and O VI. We infer that the mantles contain little material in the cone of sight and that the electron temperature may be rather high ($5 \times 10^4 < T_e < 10^5$ K) in the mantle. There is insufficient material projected against the sky to generate detectable emission lines.

The spectrum of Gamma Cas when this star is in an active state shows readily detected emission lines of the Balmer series of H, emission lines of He I and Fe II, and of spectra of a similar level of excitation. At some epochs the emission lines are accompanied by relatively sharp, essentially undisplaced absorption cores. The intensity of the emission line at He II λ4686 is marginal, if detectable at all, and no significant sharp absorption core is formed in He II. The resonance lines of C IV may show weak "wind" troughs; sharp, shortward displaced absorption components appear sometimes. The positions and strengths of the discrete absorption components change independently of the emission lines in

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the visible spectrum. The resonance lines of N V and Si IV behave in comparable manner to the C IV lines, but no conspicuous mantle-formed absorptions or emissions are seen in the resonance lines of C II at 1335 A. The observed changes in the spectrum of Gamma Cas have been reported by Doazan (1982). I take these to be typical of what may be observed for hot Be stars.

The spectra of Wolf-Rayet stars differ from those of normal B0/B1 stars with emission lines in being dominated by broad emission lines. The emission line He II λ4686 is the strongest line in the photographic region in the case of WN stars while it is weaker in WC stars; the emission at HeI λ5876 is significant but weaker in all Wolf-Rayet stars than the line at λ4686; strong emission lines of the ions of C, N, and O and of the fourth and fifth spectra of the metals are seen. The ultraviolet spectra of Wolf- Rayet stars are dominated by broad, strong emission lines. The resonance lines of C IV, Si IV, and N V show strong "wind" troughs in many Wolf-Rayet stars. Narrow discrete, shortward displaced absorption components can be detected for some resonance lines. On the whole, the most easily detected components are displaced shortward by less than about 100 km s^{-1}; they seem to come from the structured ring nebula which is detected around many Wolf-Rayet stars. Ring nebulae are also detected around some O stars; these ring nebulae tend to be smooth (Heckathorn, Bruhweiler, and Gull 1982). It is significant that the ring nebulae detected around Wolf-Rayet stars are structured. The fact that discrete components such as seen in the spectrum of Gamma Cas and of 59 Cyg (Doazan 1982) are not readily detected for Wolf-Rayet stars may be a result of the high level of saturation of the "wind" troughs seen in Wolf-Rayet spectra and of the complexity of the emission-line blends which occur.

Typically the mantles of normal B0/B1 main-sequence stars contain very little material and they appear to have a high electron temperature, perhaps in the range from 5 x 10^4 to 10^5 K. The mantles of hot Be stars contain quite a lot of material and the electron temperature is low, of the order of 10^4 K, while $N_e \sim 10^{11}$ cm^{-3} (see below). Bhatia and Underhill (1986) have shown that the mantles of Wolf-Rayet stars are moderately dense, $N_e \sim 10^{10}$ cm^{-3}, while the electron temperature is high, $T_e \sim 10^5$ K. Wolf-Rayet stars have easily detected winds. These differences in T_e, N_e, and in wind visibility are what cause the differences in spectrum denoted by the differences in nominal spectral type between these three types of star which have about the same T_{eff}. All of these stars illuminate their mantles with the same radiation field, namely that which emerges from a main-sequence star with T_{eff} in the range from 2.5 x 10^4 to 3.0 x 10^4 K. In the range of wavelength important for ionizing H and He, this radiation field can be represented by B_ν (2.5 x 10^4 K).

Bhatia and Underhill (1986) have predicted relative energies in lines of H, He I, and He II formed in a mantle in which there is a velocity gradient. From this material, plus additional calculations, the information shown in Figure 1 has been assembled. This figure substantiates the conclusions of Bhatia and Underhill (1986) about the physical state of the mantles of Wolf-Rayet stars; it also allows one to estimate roughly the physical state of the mantle of Gamma Cas at a time when the emission lines are strong. At that time, the energy seen in He II λ4686 appears to be less than that in He I λ5876 by at least a factor 3. This fact rules out $N_e = 10^9$ or 10^{10} cm^{-3} and points toward $N_e \leq 10^{11}$ cm^{-3} with $T_e < 5 \times 10^4$ K. Because the energy detected in He I λ5876 probably is comparable to that detected in Hβ (to my knowledge no quantitative results have been published about this) and because many Fe II emission lines are seen, one would estimate that $T_e < 2 \times 10^4$ K. Quantitative measurements of the relative energies in He II λ4686, He I λ5876, and Hβ would allow closer estimates to be made of T_e and N_e. The chief point which I wish to make here is that the difference between the mantles of Wolf-Rayet stars and those of hot Be stars is chiefly one of difference in T_e, and of the density of material flowing from the star in a wind. For Wolf-Rayet stars $T_e \sim 10^5$ K, while for hot B stars $T_e < 2 \times 10^4$ K. The density in the mantles may be comparable: 10^{10} to 10^{11} cm^{-3}. There is no quantitative information about the densities in the winds from the three types of star, although the winds of Wolf-Rayet stars are much more visible than those from Be stars. This points to a difference in density and, perhaps, one of T_e in the wind. The emission lines appear to be formed chiefly in plasma which has a symmetrical velocity distribution with respect to the star. Wide emission lines as known for Wolf-Rayet stars, suggest turbulent plasma. Less extreme differences in T_e, N_e, and wind density may account for the differences in spectrum between cool Be stars and Herbig Be stars. The broad, shortward displaced, flat-bottomed troughs of resonance lines in the spectra of Wolf-Rayet stars point to large turbulent velocities in the mantles of Wolf-Rayet stars.

Unpublished calculations by Bhatia and Underhill (using the method of Bhatia and Underhill 1986) of the relative strengths of the resonance lines of C II and C IV to the strengths of He I λ 5876 and He II λ4686 in the mantle of a B0 star indicate that in Be stars like Gamma Cas emission at 1335 A in the C II lines may be weakly present. No emission is to be expected at the wavelengths of the C IV resonance lines. No observations of C II or CIV emission in the spectrum of Gamma Cas have been reported. The presence of strong interstellar absorption lines of C II would make it difficult to detect the expected weak emission line. The presence of detectable C IV emission points towards a high electron temperature in the mantle, as occurs for Wolf-Rayet stars. Emission in the C II resonance lines has been observed for the B2 Ia star χ^2 Ori and for the B2 Ib star 9 Cep (see Figures 4-7, 4-11, and 4-16 of Underhill 1982).

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III. THE MAGNETIC LOOP MODEL FOR Be STARS

Underhill (1983) described a model for Be stars consisting of a low density wind and a disk generated by the magnetohydrodynamic (MHD) interactions which may occur as a star with extruding, magnetically supported plumes rotates rapidly. Numerical and analytical studies of the mantles of rotating stars with external magnetospheres (Pizzo 1982; Nerney and Suess 1985; Korzhov, Mishin, and Tomozov 1985; Wang and Robertson 1985) provide a quantitative base for the statements of Underhill.

Underhill's model consists of (1) arcades of magnetic loops which form helmet-type structures in the equatorial band of the star, and of (2) coronal-hole-type structures, emmanating from weak unipolar magnetic regions which are chiefly distributed at polar latitudes. The coronal-hole-type structures provide source areas for a general stellar wind. Wind particles may also be released from the magnetic loops as reconnection across small areas takes place when the surfaces of the loops undulate and move about owing to the buffeting of the footpoints of the loops by turbulent elements in the photosphere of the star. In addition, magnetic reconnection may take place near the tops of some arcades releasing parcels of plasma from particular spots above the photosphere. These parcels will have trajectories such as those described by Underhill and Fahey (1984). When the source points have an appropriate orientation with respect to the distant, stationary observer, shortward displaced components of resonance lines will be formed in the spectrum of the star. The lifetime of the discrete components will depend on the angular velocity of the star, on the height of the source point, on the line-of-sight acceleration experienced by the parcels, and on the length of time during which a source point remains open.

Observations of the solar wind and the solar corona give examples of the types of closed and open magnetic structures which may form in the mantle of a rotating star with a magnetosphere. The solar wind has a sectored structure. It consists of a few long-lived streams of plasma moving at fast and slow speeds. These streams, when viewed from the rotation axis of the star form an expanding spiral. The streams emmanating from coronal-hole-type structures expand radially more rapidly than do the streams which come from source areas associated with primarily closed magnetic structures. Studies of the solar wind (e.g. Korzhov, Mishin, and Tomozov 1985) indicate that in the interaction areas between fast and slow streams Kelvin-Helmholtz instabilities may develop in places where the plasma β (the ratio of gas pressure to magnetic pressure) is greater than unity. In these volumes turbulence may generate extra heating of the plasma. At intermediate distances from the Sun, the plasma β may exceed 1. Far from the Sun (outside the earth at about 200 $R_{\odot}$), β becomes small again and the flow is less turbulent. Eventually at distances of

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the order of 45 AU, the wind structure becomes disorganized and joins the interplanetary medium under shock conditions.

The behaviour of the solar wind presents an example of how a low-density wind from a rotating star with locally distributed surface magnetic fields may behave. In the extreme case of a rapidly rotating neutron star with a strong magnetic field, the magnetosphere and the wind may develop long vortices and loops as the wind impinges on a surrounding plasma disk of modest density coming from a companion star (Wang and Robertson 1985). The plasma into which the magnetosphere of the rotating star tries to expand becomes shredded and a disk-like, turbulent body of plasma forms near the star compressing the magnetosphere of the neutron star. This gives one example of how the boundary conditions into which the magnetosphere of the rotating star tries to expand affect the structure of the resulting mantle. Kuperus and Ionson (1985) have discussed how electro-dynamic coupling of the disk to the photosphere of the star may generate very hot bodies of plasma in which X rays are created.

Both types of example, namely the Sun which presents us with the case of a low-density mantle which interacts weakly with its surroundings, and that of the rotating neutron star in a plasma flow which has strong interactions give information which is useful for accounting for the differences in behaviour observed between early-type Be stars and Wolf-Rayet stars. The magnetic loop model is an attempt to find out how far the physics of magnetohydrodynamics may go in providing information about the mechanisms which may cause the physical state of the mantle to occur and to change on the time-scales which are observed.

To maintain a mantle which radiates emission lines as strong as are seen for Gamma Cas during an active period at an electron temperature of the order of 10^4 K requires energy to be deposited in the mantle at a rate which will replace the energy lost by radiation in lines and continua. Possibly this is at a rate of the order of 0.1 L_* , see Underhill (1982). To maintain a mantle at a high electron temperature ($T_e \sim 10^5$ K) and replace the energy lost in emission lines and continua, as for a Wolf-Rayet star, requires energy to be deposited at a rate of the order of 0.1 to 0.3 L_* . Thus a significant amount of energy is being deposited steadily in the mantles of Be and Wolf-Rayet stars. Because the winds from Wolf-Rayet stars appear to be denser than those of Be stars, it appears that more outward momentum is deposited in the mantle of a Wolf-Rayet star than in the mantle of a Be star. The greater-widths of the emission lines of Wolf-Rayet stars in comparison to the widths of the emission lines of Be stars points to greater turbulence in the mantles of Wolf-Rayet stars than in the mantles of Be star. Any acceptable model for the mantles of B stars must be able to account for these different types of behaviour, as well as for the fact that many B stars have a very inconspicuous mantle.

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IV. DISCUSSION

a) Cases to be discussed

The topic to be discussed in the following paragraphs is how the magnetic-loop model allows one to understand how the same underlying star can generate four different types of mantle. We note that in each case the mantle lies in the same gravitational field (that due to a star with a mass of the order of 10 $M_\odot$), and in the same radiation field (that which emerges from a main-sequence star with effective temperature in the range from 2.5 x 10^4 to 3.0 x 10^4 K). In this discussion I am not concerned with volumes of plasma that have an appropriate density to emit forbidden lines. It is straight forward to extend the model to handle that case.

A type A mantle is inconspicuous, thus difficult to detect. It represents what is seen for a normal early B-type star and what is present when a Be star has lost its emission lines.

A type B mantle is the type of mantle which a Be star has when the star shows LS-coupling permitted emission lines. Specifically, there is enough plasma around such a star in such a state as to generate emission lines, at least Hα , but there is not enough material projected in front of the disk of the star to give rise to detectable, rather sharp absorption cores.

A type C mantle, in addition to consisting of plasma which gives rise to LS-coupling permitted emission lines, has enough plasma projected in front of the disk of the star to generate relatively sharp, more or less stationary absorption lines. The density in this plasma is sufficiently low that NLTE physics is required if one is to account for the relative strengths of the absorption lines, but it is not so low that LS-coupling forbidden lines have significant strength. A type C mantle represents the mantle of a shell star.

The vast body of spectroscopic knowledge about B stars, Be stars, and B-type shell stars demonstrates that the mantle of a B star can change from Type A to Type B to Type C and vice-versa in an interval of the order of a few months. Nevertheless, the mantle may stabilize at Type A, Type B, or Type C for decades. In fact except for those rare cases where the type of mantle is related to the periodic motion of two stars in an orbit about each other, there is no way of predicting when the mantle will change its type. The detailed spectroscopic changes seen over a limited interval of time sometimes suggest increasing or decreasing density and increasing or decreasing electron temperature. Sometimes small inflow line-of-sight velocities are seen (< + 20 km s^{-1}); in some cases outflow line-of-sight velocities are seen which may lie in the range from - 20 to - 100 km s^{-1} or so. In the visible spectral

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range one does not see motions which exceed the velocity of escape from the photosphere of the star. The wings of the ultraviolet resonance lines sometimes suggest velocities of outflow exceeding the velocity of escape. Discrete, displaced absorption components may occur at large outflow velocities or they may occur at nearly undisplaced velocities. Discrete components come and go in the case of all Be stars in which they are observed; they have not been observed at inflow line-of-sight velocities.

Type D mantles are those of the strong-emission-line stars. The amount of material in the mantle and its degree of ionization may change a little from time to time. In the case of Wolf-Rayet stars, T_e and turbulence are high in the mantle and a significant wind can be detected. Type D mantles are not known to change from Type D to Types A, B, or C.

b) Properties of the magnetic-loop model which make this model of interest for further consideration

The density in the magnetic loops and open structures which make up the model is dependent on the mechanism which injects plasma into the loops at the footpoints of the loops. This mechanism is not understood for the Sun so it cannot be described here. However, solar observations show that dense loops and loops containing little material can co-exist in one object. The density in the several parts of the model is locally controlled and the pattern need not be spherically symmetric. In fact, if the Sun is a guide, the distribution of bipolar and unipolar regions on the stellar surface is never symmetrical in detail, although the N and S hemispheres, more or less, reflect each other.

The equilibrium value of the electron temperature which occurs in the magnetically confined plasma or in escaping plasma which carries magnetic lines of force with it can be low ($\sim 10^4$K) or high ($\sim 10^5$ K). The T_e achieved will be the result of a balance between the heating and cooling processes which occur. The dominant cooling processes appear to be the escape of line and continua photons which have been generated in the plasma of the mantle. We noted above that in the case of Be stars and of Wolf-Rayet stars, one needs to supply energy at a rate of at least the order of 0.1 L_* just to replenish the energy lost by radiation each second. This is in addition to the amount of energy which must be supplied to establish and maintain the electron temperature of the mantle at its apparent value. More outward directed momentum and more turbulence appears in the mantle of a Wolf-Rayet star than in the mantle of a Be star.

Studies of the solar mantle indicate that the solar mantle is heated as a result of irreversible micro processes which occur when magnetic field lines are present in the plasma of the mantle and there is a field of motion at the base of the mantle,

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see Ionson (1984) for a synthesis of the relevant theory. There is no consensus of opinion about which are the most important processes for tranfering energy and momentum from an internal source. The result of the action of the micro processes which take place in the presence of small magnetic fields appears to be the transfer of mechanical energy and momentum which originate in the convective zone of the Sun to the plasma of the mantle. The lengths of the regions in which standing magneto-acoustic waves can be set up are believed to be important parameters for determining the relative heating in different structures. Propagating magneto-acoustic waves transfer momentum to the plasma, but little heat. Another factor of importance is the amplitude of the motion of the plasma in the underlying dense photosphere. These motions describe an internal reservoir of mechanical energy and momentum.

The arguments of Bohm-Vitense (1986) indicate that the pressure scale height of the region of the mantle which is heated by mechanical energy coming from the interior of the star may control whether T_e is low or high in the extended mantle. Low T_e can occur when the pressure scale height is large. The pressure scale heights of the photospheres of B stars tend to be large in comparison to the pressure scale height of the solar atmosphere. This points towards lower T_e in the mantles of B stars than in the solar mantle.

It is also true (see, for example, Wang and Robertson 1985 and Kuperus and Ionson 1985) that electrodynamic effects can transfer energy and momentum to the plasma of the magnetosphere of a star from an external, unmagnetized source such as an accretion disk or other plasma into which the magnetosphere of the star is expanding. It is found that the environment of a star may react on the mantle of the star if the environment has a sufficient density relative to the particle density in the mantle.

In the case of B0/B1 stars the deposit of a significant amount of energy and momentum is needed to generate mantles described as Types B, C, and D. In these cases one may ask whether some part of the required energy and momentum may be transferred to the plasma of the mantle as a result of electrodynamic coupling to an external source of mechanical energy or whether all the observed energy and momentum come from inside the star. The magnetic-loop model has the capability of taking account of both types of process. This capability has not yet been exploited by making numerical models.

The generation of Type A mantles requires relatively little energy and momentum to be deposited in the mantle in addition to what is needed to maintain the outer stellar atmosphere in radiative and hydrostatic equilibrium. Processes such as those which are active in the Sun may suffice. Stars of types B0/B1 do possess convection zones due to the second ionization of He just under their photospheres. However, the solar-like problem has not

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yet been studied quantitatively for B stars.

To change from a Type A mantle to a Type B mantle requires the deposit of enough momentum to form an extended mantle with a density of somewhat less than 10^{11} cm^{-3} as well as the deposit of enough energy to maintain this plasma at about 10^4 K. No large amount of turbulence appears to be generated; the lines are not unusually broad. About 0.1 L_* is needed just to replace the energy radiated in the spectrum of emission lines and continua of a Be star. It is doubtful that solar-like processes are efficient enough to cause this state of affairs.

A change in the rate of deposition of energy and momentum in the mantle of at least a factor 10 appears to be required in order to change from a Type A mantle to a Type B. The theory formulated by Ionson (1984) suggests that if the magnetic field in a loop increases while the properties of the underlying convective zone remain unchanged, then the heating may become more efficient. Ionson does not treat the problem of depositing momentum in the mantle. The source of mechanical energy which is the source of heat and momentum can, in principle, lie within the star or external to the star, cf. Kuperus and Ionson (1985), Wang and Robertson (1985).

The change to a Type C mantle may be chiefly the result of depositing more outward directed momentum in the parts of a Type B mantle near the equator of the star than occurs with a Type B mantle. This may lead to the formation of a disk. In any case, the magnetic-loop model has the capacity for handling this situation.

Although the indicated detailed electromagnetic interactions have not yet been worked out, we do know from the studies of the Sun and of rotating neutron stars that electrodynamics has the capacity of transfering energy and momentum to a plasma from a mechanical source. Very energetic events are known to occur in magnetized laboratory plasmas. The problem with B stars is to so arrange things that explosive events do not occur frequently. The presence of magnetic lines of force allows the deposit of energy and momentum in <u>local</u> regions of the mantle. Forces such as stellar rotation and radiation pressure act globally; with them one has no discrimination in latitude or azimuth.

The magnetic-loop model can account for changes in the physical state of the mantle (detected by changes in the emission and absorption lines formed in the mantle) having time scales of the order of days, months, and decades. Time scales of the order of days may be generated by the rotation of a photosphere spotted in a non uniform manner with unipolar and bipolar magnetic regions. Balona and Engelbrecht (1986) have noted that some Be stars may have spotted disks. Time scales of the order of months to decades may be generated by the emergence and subsidence of magnetic flux extruded from the surface of the star as changing conditions in the stellar interior cause the internal dynamos in the subsurface convection zone to react to the ever changing boundary conditions on the outside of the star.

The types of change in mantle conditions known for the Sun appear to be sufficient to account for the types of change seen in the spectra of Be stars. Although the results of the possible MHD interactions between the outer atmospheres of B stars and their photospheres (or external sources) result in mantles in which the physical state differs in some respects (chiefly T_e) from that of the solar mantle, this fact does not imply that different physics is needed to account for the different observed cases.

In the case of the Type D mantles of Wolf-Rayet stars, enough energy must be deposited in the mantle to heat the plasma of the mantle to about 10^5 K and to maintain the radiative losses of 0.1-0.3 L_*. In addition, enough momentum must be added to the plasma to (1) generate a mantle which has a radius of the order of 100 R_* (Bhatia and Underhill 1986), (2) generate macroturbulence of several hundred km s^{-1}, and (3) drive a readily detected wind. Greater heating suggests the presence of more closed-loop magnetic structures with relatively short lengths than in the case of relatively cool mantle. One wonders, in the case of Wolf-Rayet stars, whether the additional source of mechanical energy and momentum is to be found outside the star rather than inside the star. Such a source could be the reason why the T_e and state of turbulence of the mantles of Wolf-Rayet stars exceed those of B0e stars. Is it possible that the source is the environment into which the mantle attempts to expand?

The small spectroscopic changes shown by some Wolf-Rayet stars in intervals of the order of a day or two and the small changes which have been noted to occur in a year or two may be due to the rotation of a spotted photosphere and to the emergence and subsidence of the stellar magnetic field, respectively. Most Wolf-Rayet stars do not show unpredictable changes on time scales of decades. This may be related to the facts that many Wolf-Rayet stars are enmeshed in a structured ring nebula (Heckathorn Bruhweiler, and Gull 1982) and that ring nebulae have radii of the order of a few parsecs (Kwitter 1984). Consequently the motion of the Wolf-Rayet star will not change the relationship of the star to its surrounding environment in an interval of time of the order of a decade. Gross changes in those parts of the energy and momentum deposits which come from interactions with the surroundings are not expected to change by a significant amount in intervals of the order of the time during which Wolf-Rayet stars have been observed intensively. In the case of Be stars, the environment may be more ephemeral and have a finer scale. Only sometimes will the environment provide an adequate interaction to generate the conditions needed for a Be-type spectrum to arise.

Population I Wolf-Rayet stars appear to be as young as the O and B stars with which they are associated. It is, perhaps, possible that Wolf-Rayet stars are stars which occluded larger than normal magnetic fields as they were formed (thereby creating more and stronger internal dynamos than for B0 stars in their neighbourhood). Because this means that these stars were formed in an unusual part of the interstellar medium, they may be surrounded by a denser than normal interstellar medium. Ring nebulae may represent a "chicken-and-the-egg" situation. The picture which I envisage resembles the scenario discussed by Pudritz and Norman (1986) for protostellar objects. The chief difference is that the central object is massive enough to generate a radiation field corresponding to T_{eff} in the range from 25,000 to 30,000 K.

Population II Wolf-Rayet stars are the central stars of planetary nebulae. These unusual central stars are, perhaps, the remnants of cool giants which had larger than normal internal magnetic fields. According to recent ideas (see, for example, Volk and Kwok 1985) the mantles of the central stars of planetary nebulae do expand into a denser than normal surrounding medium. If the energy and momentum seen in a Wolf-Rayet spectrum has been transferred to the mantle of the star from outside the star, it can be understood that some central stars show Wolf-Rayet type spectra while others do not. According to the ideas discussed here, a Wolf-Rayet spectrum can only develop when larger than normal magnetic fields are present in the stellar mantle to react with the denser than normal plasma in the immediate neighbourhood of the star.

Because the magnetic-loop model postulates the presence of all the ingredients needed for electrodynamic transfer of mechanical energy and momentum to a plasma, this model has promise. In any emission-line object where an amount of energy and momentum comparable to that in the radiation field of the star has to be transferred to the plasma of the mantle, the magnetic-loop model may be useful.

I leave this topic here. The magnetic-loop model is still in a heuristic state. The circumstantial evidence suggesting that electrodynamics has much to do with what is observed for emission-line stars is sufficient to make it expedient that the MHD problems which I have sketched be studied.

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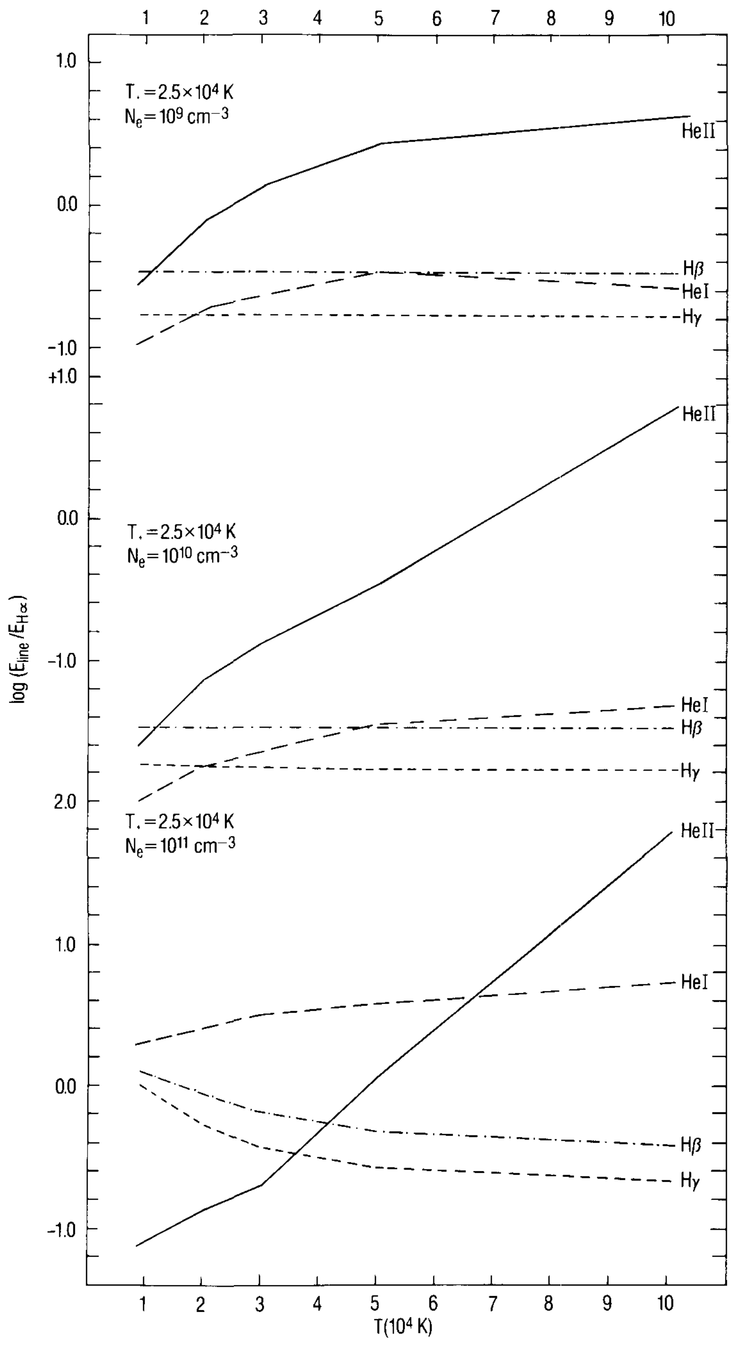
FIGURE CAPTION

Fig. 1.- The predicted relative strengths of Hβ , Hγ He I λ5876, and He II λ4686 as functions of N_e and T_e in model mantles. The relative abundance by number of H to He is 10. All calculated energies are expressed in terms of the energy radiated in Hα.



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DISCUSSION FOLLOWING UNDERHILL

Snow:

If the circumstellar material around Be stars is remnant material left over from the star's formation, what has happened to the dust that would have been mixed in with this gas? Most Be stars show no evidence of circumstellar dust.

Underhill:

I believe that the phase I am describing involves only the last, most filamentary stage of the remnant cloud. The dust has been blown away by radiation pressure. When the star has just turned on, the central star is buried in free-free emission and dust emission; it is an infrared source. I am suggesting that Be stars represent the last stages of the interaction between the environment and the star.

Henrichs:

The discrete components are also observed in many supergiants. Would you infer from this that the magnetic fields are also active in this case? These stars are likely older than 10^7 years.

Underhill:

The study by Underhill and Fahey (1984) is directed at B- type supergiants and interpreting their persistent discrete components. We inferred that small magnetic fields were present in the form of bipolar magnetic regions. It takes 10^{11} years for a primordial magnetic field to decay.

Collins:

Shouldn't magnetic braking slow this model down on a timescale that would be seen as a systematic correlation of $< vsini >$ with cluster age? How large a mean surface field do you envision?

Underhill:

The magnetic fields I am thinking about are small ($<$ few hundred gauss) fields on the surface of the star. There is no net dipole field. Magnetic braking is small for such configurations. In addition, I suspect that the Be stars are in early stages of evolution across the main-sequence band. I have not investigated the braking timescale relative to the evolutionary timescale, but I suspect that intervals of the order of 10^6 years are relevant.

Friend:

The presence of tangled magnetic fields on the solar surface seems to be due to the fact the surface is convectively unstable. To what do you attribute the presence of these fields on much hotter stars?

Underhill:

There is a convective zone in B stars just below the photosphere. It is due to the second ionization of He; it was first recognized by Underhill in 1949. It is not necessary to go over to an adiabatic temperature gradient when modeling the atmospheres of B stars because the radiative and adiabatic temperature gradients differ little (owing to the effects of radiation), and because convection is not a significant method for transporting energy through B-type atmospheres. I attribute locally distributed magnetic fields on the surface of B stars to the action of dynamics formed in the surface convection zones of B stars. One has to assume that when the B star formed it included a small primordial magnetic field.

Alvarez:

The magnetic field on the sun is *not* the most important physical parameter that enters into the energy balance of the solar corona (extended envelope). I agree that it is important to include the open magnetic fields as regions where the stellar winds will do their work. The "active" magnetic fields may be the regions where the variability of the star might start.

Underhill:

The presence of magnetic lines of force is essential to facilitate the transfer of energy and momentum from the mechanical energy source in the convective zone of the sun to the plasma of the solar corona and wind. Without magnetic fields the solar corona would not exist.

van den Heuvel:

You say that in Be and WR stars the energy source of the activity is not in the interior but in the mantle. This worries me. This is quite different from the case of the sun where the energy for heating the coronal loops finally is derived from the interior energy source: this energy is converted partly into convective motions which finally end up in mechanical energy which heats the corona. If you don't have something like this in your Be or WR model, your only possible energy source is rotation, but this source will be soon depleted if you have to extract $\sim 10^{37}$ ergs/s from it, which you need to energize their emitting mantles. The rotational energy contained in a 10 solar mass star with a radius of 5 solar radii, rotating at 400 kms^{-1} at its equator is about 10^{48} ergs. At an energy loss rate of 10^{37} erg/sec this reservoir will be depleted in 3000 years, which seems far too short to explain that some 20 percent of the early B stars are Be stars.

Underhill:

It appears that my statements were not quite clear. What I meant to say was that the coupling factor to the internal energy source is so inefficient that one has also to consider coupling to a large external source of mechanical energy. The coupling to the internal mechanical energy still goes on. It is supplemented by a significant addition from an external source in certain cases.