MAGNETIC CONFINEMENT, ALFVÉN WAVE REFLECTION, AND THE ORIGINS OF X-RAY AND MASS-LOSS “DIVIDING LINES” FOR LATE-TYPE GIANTS AND SUPERGIANTS

R. ROSNER
Astronomy and Astrophysics Center and Enrico Fermi Institute, University of Chicago, 5640 Ellis Avenue, Chicago, IL 60637

C.-H. AN
Applied Research, Inc., 5025 Bradford Boulevard, Huntsville, AL 35805

Z. E. MUSIELAK
University of Alabama in Huntsville, Huntsville, AL 35899

AND

R. L. MOORE AND S. T. SUESS
NASA Marshall Space Flight Center, Huntsville, AL 35812

Received 1990 December 12; accepted 1991 February 18

ABSTRACT

We discuss a simple qualitative model for the origin of the coronal and mass-loss dividing lines separating late-type giants and supergiants with and without hot, X-ray-emitting corona, and with and without significant mass loss. The basic physical effects we appeal to are the necessity of magnetic confinement for hot coronal material on the surface of such stars—which turns out to imply that any matter in “open” regions must be relatively cool—and the large reflection efficiency for Alfvén waves in cool exponential atmospheres. Our model assumes that the magnetic field geometry of these stars changes across the observed “dividing lines” from being mostly closed on the high effective temperature side to being mostly open on the low effective temperature side.

Subject headings: magnetic fields — stars: coronae — stars: mass loss — stars: winds — stars: X-rays

1. INTRODUCTION

The physics underlying the activity and mass loss of giant and supergiant stars has remained elusive. Perhaps most puzzling of all is the presence of “dividing lines” in the H-R diagram which roughly separate evolved late-type stars into distinct classes, namely, stars with and without emission characteristic of high-temperature material (the “coronal dividing line”; Linsky & Haisch 1979; Simon, Linsky, & Stencel 1982; Ayres et al. 1981; Maggio et al. 1990; Haisch et al. 1990) and stars with and without substantial mass loss (the “mass-loss dividing line”; cf. review by MacGregor 1983). In this Letter, we address the joint problem, namely, how one can account for the coincidence of the relatively sudden onset of large mass-loss rates with the equally sudden disappearance of emission associated with high plasma temperatures (viz., the “X-ray dividing line”). In this context it is essential to note that these “dividing lines” are not especially well defined but rather refer to finite-width bands in the H-R diagram within which the transitions in behavior alluded to above occur (cf. Maggio et al. 1990; see also review of “hybrid stars” and the general question of dividing lines in Dupree 1983).

Perhaps the most difficult of these issues to resolve are the characteristics of the observed winds (see reviews by Dupree 1983 and MacGregor 1983). These winds are significantly different from the well-observed solar wind, as well as from the massive outflows associated with massive early-type stars. In particular, observed winds from late-type evolved stars tend to have rather low terminal speeds (of the order of several tens of kilometers per second) as well as large mass-loss rates (which can attain values not too dissimilar from those associated with earlier type stars). To understand why these particulars are difficult to account for, we recall that any theory for accelerating such a wind must satisfy two constraints:

1. The mechanism must deposit enough energy below the sonic point of the outflow to balance radiative losses, and to lift the gas out of the star’s gravitational potential well, in order to satisfy the observed mass flow rates.

2. The mechanism cannot deposit significant momentum above the sonic point, because, if it did, the flow could not remain relatively slow as is observed.

It is possible to construct models based on wave heating and momentum deposition which satisfy these constraints (cf. Hartman & MacGregor 1980), but, as pointed out by Holzer, Fla, & Leer (1983), such models suffer from the fatal defect that the necessary wave damping lengths are not only ad hoc but need to be extremely finely tuned in value. Indeed, as discussed by MacGregor (1983), the problem of how these two constraints can be met within the context of a physically plausible...
model remains unsolved. In this Letter we describe a model for the outer atmospheres of late-type evolved stars which appears to meet most of the constraints applied to date, and is based upon the application of models for Alfvén wave propagation in stellar atmospheres of this type (see review by Rosner, Low, & Holzer 1986 and the recent discussion by An et al. 1990).

2. CORONAL FORMATION

We first address the problem of coronal formation for these evolved stars, a topic reviewed in some depth earlier by Rosner, Golub, & Vaiana (1985). To begin with, we note that we do not have any better information on the mechanisms for heating the outer layers of giant stars than for the Sun, and that since we do not as yet know how the Sun’s outermost atmosphere is heated, we are not likely to be better off in the stellar case. However, whereas one could imagine a several million degree solar corona without the need of invoking magnetic fields (and indeed early models of the Sun’s corona were exactly of this type), this is impossible for giant stars. The reasoning is as follows: Consider the escape temperature for a typical GO giant, say with $M_\ast \approx 10^4 M_\odot$ and $R_\ast \approx 10^8 R_\odot$ (Allen 1973),

$$T_{\text{esc}} \approx 10^{-1.2} T_{\text{esc, Sun}},$$

where $T_{\text{esc, Sun}} (\approx 10^7 K)$ is the escape temperature for the Sun; for a G5 giant, the corresponding escape temperature is approximately $10^{-1.7} T_{\text{esc, Sun}}$. Clearly, such stars cannot have a solar-like multi-million-degree corona in the absence of some confining force other than gravity, i.e., stellar magnetic fields (cf. Rosner, Tucker, & Vaiana 1978; Holt et al. 1979). That is, if one were to try to heat the outer layers of such stars to coronal (several million degree) temperatures, then the gas would be simply entirely unconfined in the absence of nongravitational forces, and would expand freely at the sound speed (this is entirely unlike a thermally driven wind, which exists for coronal temperatures well below the escape speed; viz., Parker 1963). It therefore seems inescapable that X-ray-emitting giants and supergiants must have the X-ray-emitting gas confined by stellar magnetic fields.

Now consider the giants and supergiants without observed X-ray emission (i.e., stars for which the upper bounds on observed X-ray emission lie well below typical detection levels for the observed stars). Possible explanations for why no X-ray emission is seen from these stars involve (1) a change in magnetic field configuration (e.g., the absence of magnetic field configurations capable of confining coronal gas, were it to exist); (2) the presence of absorbing matter (associated with, for example, its own massive wind) which obscures emission from hot coronal matter (assuming that it is in fact still present); or (3) a change in the thermodynamic properties of the outer atmospheres of such stars—for example, a change in the stability property of the “hot” corona.

The available spectral information for these stars (cf. Maggio et al. 1990) does not show any evidence for increased extinction as one approaches the dividing line from high stellar effective temperatures; indeed, there is no evidence whatever that we are aware of supporting the second type of explanation. The third model—especially that originally proposed by Antiochos & Noci (1986)—cannot be disposed of as an explanation of the emission dividing lines on the basis of presently available data; therefore, it, as well as the first explanation (lack of magnetic confinement), are left as plausible explanations for the absence of coronal emission on the low stellar effective temperature side of the dividing lines. As we show in a moment, however, these two alternatives do differ in explaining the coincidence of the wind dividing line and the emission dividing lines.

Finally, we note as an aside that the analogy between stars on either side of these dividing lines and solar active regions and coronal holes is not really appropriate. That is, it has been suggested that simply “opening” the magnetic field topology on the surface of giants and supergiants is sufficient to produce a cool wind in the regions of open field topology, analogous to the transition of closed field regions in solar active region complexes to the open field topology in solar coronal holes (cf. Linsky & Haisch 1979). The reason this analogy is defective is that in the case of the Sun, the plasma at coronal heights within coronal holes is still at coronal temperatures [albeit at much smaller densities—hence the reduction in X-ray brightness in these regions—and slightly reduced temperatures, from $(2-3) \times 10^6 K$ to $\approx 1.5 \times 10^6 K$; cf. Maxson & Vaiana 1977]. In contrast, the argument presented in this section shows that in the case of giants and supergiants, any plasma in “open” regions must be cooler than the escape temperature of these stars, and hence must be substantially cooler than coronal temperatures (and thus cannot produce a thermally driven wind at the observed large mass-loss rates; cf. § 1).

3. WIND FORMATION

Now, given the change in surface magnetic confinement properties, can we tie the disappearance of emission from high-temperature matter to the onset of large mass outflows? In this section, we focus on this problem.

To begin with, we note that models which account for the emission dividing lines by appealing to a change in the dominant stable atmosphere, from a “hot” coronal state to a “cool” chromospheric state, do not have any obvious or natural means of tying this change to the onset of winds. In contrast, we will now show that lack of confinement, which naturally leads to a relatively cool outer atmosphere in the “open” regions, then naturally leads to vigorous outflows.

It has long been known that reflection of Alfvén waves in stellar atmospheres becomes significant when the wavelength of the propagating wave becomes of the order of (or larger than) the local Alfvén speed scale height of the background medium (see earlier discussions by, for example, Ferraro & Plumpton 1958; Hollweg 1978; Heinemann & Olbert 1980; and the review by Rosner et al. 1986). Indeed, as pointed out by Leer, Holzer, & Flá (1982), the WKB approximation usually employed in problems involving wave propagation in stellar atmospheres breaks down precisely under such circumstances for waves with periods of the order of a minute or longer. For the simplest case, namely, an exponential atmosphere which is also plane-parallel, Ferraro & Plumpton (1958) showed that analytical solutions for Alfvén waves may be obtained, which depend on the gradient of the Alfvén speed,

$$V_A = \frac{dV_A}{dR} = \frac{V_A}{h}$$

(1)

(the last relation is the definition of the Alfvén speed scale height $h$). These solutions have the property that in the short-wavelength limit (in which $h/(V_A/\omega) \gg 1$), there is essentially no reflection; this limit is obtained for atmospheres in which the typical scale height is large compared with the wavelength of the dominant energy-carrying waves, e.g., the wavelength of waves at the peak of the wave power spectrum; and, con-
versely, there is strong reflection in the opposing limit \( h/(V_A/\omega) \ll 1 \).

Now, consider a star with a corona. The atmosphere for such a star can be modeled to lowest order by a two-layer description (Leer et al. 1982; see Rosner et al. 1986 for an abbreviated discussion), consisting of two distinct adjacent layers. The lower layer, corresponding to the photospheric and transition region layers in an actual star, is characterized by a small Alfvén speed scale height \( h = h_1 \ll V_A/\omega \) for \( \omega \) at the peak of the wave power spectrum because of both the low temperature of the photospheric region and the small spatial extent of the temperature transition region (i.e., the transition region thickness is much smaller than the local pressure scale height, so that the density varies inversely with the temperature in this layer, and hence experiences a 100-fold decrease in the same region in which the temperature increases 100-fold). In contrast, the overlying layer, corresponding to the coronal region, is characterized by the Alfvén speed scale height \( h = h_2 \), with \( h_2 \gg V_A/\omega \) for \( \omega \) as above. One can then show that all waves with wavelength \( \lambda > h_1 \) will be strongly reflected as long as \( h_1 \) obeys this inequality, but that the reflection efficiency quickly drops to zero as \( h_1 \to h_2 \). The strong inequality would seem to apply to the evolved stars with coronae, and so one would expect a significant wave pressure exerted by the reflected waves at the transition region level; but will all this really matter to the structure of these stars' coronae? We contend that the answer is no: that is, since magnetic fields must be present to confine the hot gas against pure thermal expansion (i.e., for these stars, the presence of a transition region implies the existence of high-temperature matter, which because of its high temperature barely notices the gravitational well due to the underlying star), the wave pressure just discussed (exerted by the longer period waves) very likely does nothing of consequence except to modify the radial stratification of the hot matter; as for the shorter period waves, which can penetrate into the coronal gas, these may well be involved in the coronal heating process.

Consider now the case of giants and supergiants with no coronae. By the above argument, these are stars for which magnetic fields have proved to be ineffective in confining hot gas, had any been present. As above, we can now consider the effect of Alfvén waves on the resulting cool outer atmospheres (e.g., we still assume that the stars in question have surface magnetic fields, albeit fields which are too weak to confine hot coronal gas). This sort of case has been studied explicitly by means of numerical calculations by An et al. (1989, 1990), in which the characteristics of Alfvén waves in a hydrostatic, isothermal, and spherically symmetric atmosphere with purely radial background magnetic fields were considered. In this atmosphere, the density falls off exponentially with distance from the stellar surface,

\[
\rho = \rho_* \exp \left[ -\alpha \left(1 - \frac{R_*}{R}\right) \right],
\]

where \( \alpha \) is a constant, given by

\[
\alpha = \frac{\frac{1}{2} \frac{GM_*}{kT/m} \frac{R}{R_*}}{H} = \frac{R}{R_*} \frac{R_*}{H_*},
\]

and where \( R \) is the radius, and \( H = kT/mg \) is the density scale height at \( R \) (all other quantities have their customary meanings, e.g., \( T \) is the temperature, and so forth). Quantities evaluated at the base of the stellar atmosphere, i.e., at stellar radius

![Fig. 1.—Variations of the Alfvén velocity, \( V_A \) (normalized by its value at the stellar surface, \( V_{A*} \)), with radius \( R \) (normalized by its value at the stellar surface, \( R_* \)) for four different values of \( \alpha \). A steep gradient in the Alfvén velocity (corresponding to strong wave reflection) sets in at \( \alpha > 10 \).](figure)

Thus, we see that in such an atmosphere the Alfvén speed increases steeply with radius above the base (see Fig. 1) for sufficiently large \( \alpha \) (which, for given \( M_* \) and \( R_* \), requires a sufficiently low atmospheric temperature); this suggests the possibility of reflection, as discussed above. Indeed, detailed calculations for such an atmosphere by An et al. (1990), based on numerical solution of the linearized wave propagation equations, show evidence both for the continuous reflection process in such an atmosphere (this distinguishes reflection in a cool, uniform-temperature, stratified medium from reflection in an atmosphere with a transition zone, where the reflection is completely dominated by the sharp spatial gradient in density at the temperature transition point) and for the associated strong local body force, which results from the locally enhanced wave pressure gradient in the reflection region for \( H/(V_A/\omega) \ll 1 \) (An et al. 1990).

A feeling for this effect can be gained from Figure 1, in which the gradient in the Alfvén velocity clearly becomes very steep when \( \alpha > 10 \) (for fixed \( \omega \) and for a single-layer, spherically symmetric atmosphere model). The sensitivity of this result to the temperature of the background medium can be seen by considering as an example a typical K5 supergiant \( (M_* = 16 M_\odot, R_* = 400 R_\odot) \), and evaluating \( \alpha = 4.6 \times 10^4/T \) for three different temperatures, \( T = 1.5 \times 10^4, 2.3 \times 10^4, \) and \( 4.6 \times 10^4 K \) (we obtain \( \alpha = 30, 20, \) and 10, respectively; these three values for \( \alpha \) correspond to the three curves in Fig. 1). This specific sensitive dependence of the Alfvén velocity on the temperature indicates that conditions for effective Alfvén wave

© American Astronomical Society • Provided by the NASA Astrophysics Data System
reflection by a uniform temperature atmosphere occur exactly

where the stars indeed segregate (described by the parameter \(a\)) across the dividing line, we plot only those stars which were observed, and for which we are able to evaluate a, as defined in the text (the value of a for each star is as expected on the basis of the proposed model.

In order to illustrate changes in Alfvén wave reflection (described by the parameter \(a\)) across the dividing line, we plot in Figure 2 the H-R diagram for giants, with values of \(a\) indicated for each star. It is seen that the stars indeed segregate into two classes, located on either side of the dividing line, namely, stars with \(a > 20\) and \(a < 10\). This segregation largely reflects the difference in the peak temperature reached in the outer atmospheres of the stars on either side of the dividing line shown in this figure. The key point is, however, that, according to Figure 1, wave reflection should be much stronger for values of \(a > 20\) than for \(a < 10\). Thus, it appears that wind acceleration effects resulting from mode reflection near the base of the atmosphere occur for stars both to the right and to the left of the dividing line in the H-R diagram, but that only in the case of the “open” atmospheres to the right of the dividing line is it possible for this reflection to lead to an outflow.

4. CONCLUSIONS

We have suggested that changes in surface magnetic field configuration as one moves along the giant and supergiant tracks in the H-R diagram can play the central role in account-

ing for the coincidence of relatively sudden absence of stellar X-ray emission and onset of large mass-loss rates observed for stars located on the giant and supergiant branches in the H-R diagram. In this picture, the coincidence of the dividing lines for mass loss and coronal emission arises as follows: first, coronal emission from hot plasma must arise from magnetically confined gases; second, given a change in magnetic topology, we show that any plasma residing on the stellar surface in magnetically “open” regions must be relatively cool; third, because such cool outer atmospheres have a small Alfvén speed scale height, they must experience strong Alfvén wave reflection at their base, thus leading to a wind. Our model does, however, leave one major issue unresolved: we have not identified the reason why evolved stars to the right of the coronal dividing line ought to have “open” magnetospheres, and stars to the left ought to have “closed” magnetospheres. Unfortunately, the answer to such issues lies in the domain of stellar magnetic dynamo theory, which is at present ill-equipped to provide the solution.

Attractive features of our suggestion are that the momentum deposition by reflected Alfvén waves occurs below the sonic critical point, and that the mode damping beyond the reflection point may well be very small (so that the further acceleration of the wind is minimal, as required by the observed low terminal velocities). These considerations are of course the very desiderata which motivated our study in the first place. Nevertheless, the suggestions just discussed here call for detailed computations and, in particular, more detailed calculations of Alfvén wave reflection in atmospheres of late-type giants and supergiants with an actual “open” atmosphere which allows for outflows. An important missing element in our discussion (aside from the underlying, presumably dynamo-related cause of the change in field topology) is consideration of the energetics; that is, it also remains to be shown that the model described here is capable of balancing the observed radiative losses from the atmosphere and the massive winds of late-type evolved stars. Finally, we note that the forthcoming ROSAT results will provide a significant increase in the number of evolved stars near the dividing lines for which X-ray observations will be available. This increase will allow far more decisive tests of the nature of the dividing lines—their “breath” in effective temperature and the overlap in the various types of dividing lines.

We thank J. Linsky for discussions of the IUE observations, and an anonymous referee for several very helpful comments. This research was supported by the Solar Science Branch of NASA/MSFC under grant NAS8-36955 (Z. E. M.) and by the Space Plasma Theory Program at the University of Chicago (R. R. and Z. E. M.).

REFERENCES

Parker, E. N. 1963, Interplanetary Processes (New York: Interscience)