A MECHANISM FOR THE INCREASE IN STELLAR WIND MASS LOSS FROM GIANTS ACROSS THE "DIVIDING LINE"

C. H. AN
Applied Research, Inc.
Huntsville, AL 35805, U.S.A.

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

R. ROSNER
University of Chicago
Chicago, IL 60637, U.S.A.

R. L. MOORE and S. T. SUSS
Marshall Space Flight Center
Huntsville, AL 35812, U.S.A.

ABSTRACT: We suggest that reflection of Alfvén waves in atmospheres of late-type giants may be important in the acceleration of the massive winds from these stars and in explaining the existence of "dividing lines".

INTRODUCTION
Understanding the physics underlying the activity and mass loss of giant and supergiant stars has remained elusive. Perhaps most puzzling of all is the apparent appearance 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 (Linsky and Haish 1979; Ayres et al. 1981; Maggio et al. 1989), and stars with and without substantial mass loss (cf. MacGregor 1983). In this paper, we address the latter problem, namely how one can account for the relatively sudden onset of large mass loss rates as one moves along the giant branch in the H-R diagram.

The basic problem is simply stated (and well-summarized by MacGregor 1983): First, one must account for the onset of substantial mass loss as one varies the effective temperature along the giant branch; second, one must account for the particulars of these stellar outflows. The latter 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 giants 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 simply note that any theory for accelerating such a wind must satisfy two constraints:

1. The mechanism must deposit enough energy below the sonic point in order to balance radiative losses, and to lift the gas out of the star's potential well to satisfy the observed mass flow rates.
2. The mechanism cannot deposit significant momentum above the sonic point (because if it did, then 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 and MacGregor 1980), but as pointed out by Holzer, Fla., and 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 paper, we apply a model for Alfvén wave propagation in stellar atmospheres which appears to resolve these difficulties in part.

THE MODEL AND RESULTS

The calculation carried out is based on a very simple model for a star’s magnetized outer layers, namely an isothermal, hydrostatic, and spherically symmetric atmosphere in which a purely radial magnetic field is embedded. We assume that Alfvén waves are generated at the base of this atmosphere, and integrate the MHD equations of motion for the subsequent wave propagation in the overlying layers. The key new element in these calculations is a detailed treatment of wave reflection when the wavelength of the propagating mode becomes of order (or larger) than the local density scale height \( h (= kT/mHg) \) of the background medium (An et al. 1989, 1990), where \( T \) is the atmosphere’s temperature and \( g \) is the effective surface gravity. Now, in the case at hand, the atmosphere’s density falls off with distance from the stellar surface as \( \rho = \rho_\ast \exp[-\alpha(1 - R_\ast/R)] \), where

\[
\alpha = \frac{GM_\ast}{kT/mR_\ast} = \frac{R_\ast}{h} \left( \frac{R}{R_\ast} \right)^2,
\]

and \( R_\ast \) is the stellar radius. Since the Alfvén speed varies as \( V_A = V_A \ast R_\ast^2 \exp[\alpha(1 - R_\ast/R)]/2 \), it is evident that such an atmosphere has a rather steep gradient in its Alfvén speed for low atmospheric temperatures (quantities evaluated at the base of the atmosphere are indicated by a “\( \ast \)” subscript). As a consequence, a given mode’s wavelength will also experience a corresponding steep increase in this atmosphere; and it is this increase which leads to strong mode reflection and wave trapping. A side effect of this wave trapping is the imposition of a strong local force on the atmosphere (due to the locally-enhanced wave pressure gradient in the reflection region). We suggest that this force may be the responsible agent for wind acceleration in late-type evolved stars; in particular, explicit integration of the Alfvén wave equation for an atmosphere of the type described above shows precisely the effects just alluded to.

Interesting features of this model include the fact that depending on the value of \( \alpha \), the momentum deposition in the outflow can occur fairly close to the stellar surface; that the position of maximal momentum deposition (as well as the amplitude of maximal momentum deposition) is entirely decoupled from the natural damping length of these waves; and that the mode damping subsequent to 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 desirata which motivated this study in the first place. An important missing element in our calculations is consideration of the energetics; that is, it remains to be shown that the model described here is also capable of balancing the observed radiative losses.
Figure 1: H-R diagram for evolved stars observed with the IUE and Einstein Observatories. We plot only those stars which were observed, and for which we are able to evaluate $\alpha$, as defined in the text (the value of $\alpha$ for each star is given in parentheses). It is striking that with the exception of the two "hybrid" stars, stars segregate in the value of $\alpha$ exactly as expected on the basis of the proposed model.

In order to illustrate a consequence of the natural coupling of the position of the maximal momentum deposition to the atmospheric scale height, we plot in Figure 1 the H-R diagram for giants, with values of $\alpha$ indicated for each star. With only a few exceptions, the stars indeed segregate into two classes, located on either side of a "dividing line", namely stars with $\alpha > 20$ and $\alpha < 10$. This result is not unexpected, since 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 of our calculations is, however, that they show very strong reflection effects for values of $\alpha > 20$, and much reduced effects for $\alpha < 10$; thus, it appears that wind acceleration effects resulting from mode reflection near the base of the atmosphere is indeed restricted to the stars to the right of the "dividing line". This result provides the basis for continued investigation of the energetics of the model presented here.

REFERENCES