SEMI-EMPIRICAL MODELS OF THE WIND IN COOL SUPERGIANT STARS

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ABSTRACT.

During the past decade the wind velocity as a function of radius of the cool, mass losing supergiants in the ζ Aurigae type binaries has been determined from observations of the density close to the star, the terminal velocity far from the star and near the relatively small main sequence companion (Ahmad and Stencel, 1988). The velocity was found to increase slowly, but steadily, outward. This was in contrast to current models which favor a sudden, fast accelleration close to the surface of the star where the wind reaches sufficient speed to escape form the star and experiences just small changes from there on.

The current work takes the observed velocity function, mass loss rates, and line broadening to infer some properties of the mechanism driving the wind. It is concluded that the most likely candidate to drive such a wind are magneto-hydrodynamic waves. We then proceed to make a semi-empirical Alfvén wave driven wind model starting out with the observed velocity function and mass loss rate. The damping rate of the as a function of radius which is found declines rapidly with radius, unlike any of the predictions from previous models. We also obtain limits on the stellar magnetic field by requiring (1) the temperature to be positive and be lower than 10^5 K, and (2) the wave flux gradient to be negative.

A criterion is obtained for the non-existence of cool winds with a small velocity and velocity gradient. The criterion is similar to that for the existence of cool loops (e.g. Martens and Kuin 1982). Violation of the criterion may explain the sudden atmospheric change from cool (T $<$ 10^5 K) mass loss to a state of low mass loss and coronal X-ray emission.

Key Words: Stars: mass loss, eclipsing binaries, supergiants, winds — Ultraviolet: spectra

1. INTRODUCTION

Our knowledge of the winds from the late type, cool giants and supergiants did not increase as rapidly as for the radiatively driven winds of hot stars. This was due to the difficulty posed by the relatively small velocities attained in the winds of the cool supergiants, and their low luminosity in the UV. Through the study of a special kind of binary, the ζ Aur systems which consist of a hot early type main sequence star and a late type supergiant, the wind properties of the cool supergiant have become better known recently (Ahmad and Stencel 1988, Dupree and Reimers 1987, Hack and Stickland 1987, Schröder 1985).

2. OBSERVATIONS

The relative sizes of the stars in the system are such that the early type B star acts as a light source traveling through the stellar wind of the cool supergiant. The absorption spectrum of the wind along the line of sight is super imposed upon the spectrum of the B-star. In this way the terminal velocity is found from the edge of the absorption profile of Mg II when the B-star eclipses the supergiant. Note that at that time the line of sight only passes through the outermost portions of the supergiant wind. At other phases the spectrum shows evidence for a bow shock in the supergiant wind around the much smaller B-star. From the aberration angle of the bow shock and the known velocity of the B-star in its orbit the actual wind velocity is found at several radii from the supergiant, namely at the distance of the companion star. The cavity carved by the hot corona situated between the bow shock and the B-star results in an absence of wind material at the velocity that the wind typically has at that radius. By comparing the line profiles of MgII at different phases, Ahmad and Stencel (1988) used this signature as an alternative way to find the velocity at the orbit of the secondary.

We have thus a fairly good estimate of the wind velocities in these cool supergiant winds. In figure 1 the velocities, normalised to the terminal velocity, are given. Note that the velocity reaches about half the terminal velocity at a distance corresponding to 1 AU.

Just before first contact, and after third contact, the line of sight to the B star goes through the deepest chromospheric layers. This enabled Schröder (1985) to update earlier chromospheric density models from 1.1 out to two to three supergiant radii. His curve of growth method also obtains values for the turbulent velocities responsible for the line broadening. These velocities can be used to place upper limits on the energy flux in sound waves from the supergiant into the wind.

Mass loss rates were obtained by Ché, Hempe, and Reimers (1983) by modeling the line profiles. These mass loss rates can be combined with the chromospheric density models to a chromospheric velocity profile.

2.1 EVIDENCE FOR MAGNETIC FIELDS

The chromospheric densities do not behave as those belonging to a sperical wind. There has been evidence for a long lasting density enhancement far above the photosphere which Schröder (1983) identifies with a stellar prominence, as well as abnormally low densities in ζ Aur which were compared to a coronal hole in analogy to the sun. These structures suggest the presence of magnetic fields, since magnetic fields provide a simple way to support and insulate regions of different density in a stellar atmosphere.

Since the chromospheric turbulent velocities at 1.1 to 3 stellar radii place upper limits on the sound wave energy flux, we compared that flux with the energy which is required to accelerate the wind from the radius of its companion to infinity. The last flux is easily found because the wind velocity at the companion has been measured, and the mass loss rate and terminal velocity are known. This energy, taken over 4 π radians, exceeds the energy available in chromospheric sound waves. Therefore another source of energy is responsible for accellerating the outermost regions of the wind. Because of the absence of dust, or the absence of the large velocity amplitudes associated with shock waves, we assume the wind is predominantly driven by small amplitude Alfvén waves.

3. SEMI-EMPIRICAL WIND THEORY

The usual approach has been to calculate a wind model under the assumption of a specific damping mechanism for the waves (Holzer, Flå, and Leer 1983), or to adopt a constant damping length (Hartmann and MacGregor 1980, Hartmann and Avrett 1984). We tried the constant damping length approach first and varied the damping length, and the initial wave amplitude and atmospheric density, but were unable to find a model which had a slowly increasing velocity as in figure 1. The smallest normalised gradient was obtained for unacceptably large values of the terminal velocity and had to be rejected (Ahmad and Kuin 1986).

Figure 1. Observed wind velocities and adopted analytic representation

Inspection of the force balance showed, that the dominant terms for the case of a small velocity gradient are gravity and the gradient of the wave energy density. Since the last gradient is a sensitive function of the adopted wave damping, it was clear that the adopted wave damping was incompatible with the observed velocity.

The damping of Alfvén waves is one of todays unsolved problems. For the much better studied solar wind we have still not a good understanding of the wave damping process. It therefore makes much more sense to use our data for the supergiant winds the other way around, and use the observed velocity gradient to study which damping rates are acceptable for driving a wind with Alfvén waves. This does not mean that the final model of the wind is in any way more tentative. For these supergiant winds, where substantial acceleration occurs at distances of 1 AU or more into the wind, the other properties of Alvén waves are called for, like their efficiency in transporting energy over large distances. The damping rate is, through the adoption of the observed velocity profile, then adjusted in just the right way, and we can study the thermal structure and energy balance of a self-consistent model of the wind.

Figure 2. The damping length for several values of the initial wave amplitude. The difference between the drawn and dashed lines is due to a different value for the initial Alfvén speed

As the detailed derivation of Kuin and Ahmad (1987) shows, the basic equations for the wind with Alfvén waves are the same as in the earlier work. What is different is the way the equations are solved. We use the observed velocity as a function of radius, and the observed mass loss rate, with the assumption of conservation of mass, to derive the density as a function of radius. We can then substitute the velocity and density in the force balance to derive the gradient of the total pressure at all radii. The gas pressure can be neglected in first instance, and is easy to introduce during a later iteration. Integrating the gradient of the wave pressure gives then the run of the wave amplitude with radius. The equation for the wave energy density can then be solved to obtain the damping length. Because one integration is involved, we have a free parameter, namely the wave amplitude at a given radius. As figure 2 shows, the damping length solutions are far from constant. We have compared them to several quantities and find that the damping length is almost proportional to the density scale height. The model's wave amplitudes prove to be sensitive to the adopted stellar gravity, and are comparable to the observed turbulent velocities.

4. THE WIND TEMPERATURE

Our choice of the integration parameter for the force balance does not garantee an acceptable solution for the energy balance. Inverting the energy balance, i.e. substituting the wave amplitude, wind velocity and density, gives the required radiative losses as a function of radius. From the required radiation losses the temperature can then be derived. Because the radiation losses are also a function the electron density, we must first determine the electron density.

The electron density was obtained by solving the ionisation balance for a three level hydrogen atom with detailed balance in Ly-α. The radiative loss function at such low temperatures is not very well known. In particular the peak in the optically thin curve due to Ly-α is not appropriate for these winds which are optically thick in this line. We deleted the Ly-α peak in the radiation loss curve. Therefore our model temperatures between 9,000 K and 36,000 K are not very accurate.

We use the requirement that the temperatures are smaller than 10^5 K, and that the electron densities are lower than the upper limits published by Schröder (1986), to derive limits to the integration parameter of the force balance and of the initial value for the Alfvén speed. These can then be used to derive limits for the stellar magnetic field and the initial value of the wave energy flux.

5. THE EXISTENCE CONDITION FOR A COOL WIND

.We can apply the results of the work by Field (1965) on thermal stability to these wind models. The discussion is similar to that for the interstellar plasma, coronal loops (Martens and Kuin 1982), or instabilities in hot stellar winds (Hearn, Kuin, and Martens 1983). The argument is as follows: Once the temperature in the wind rises above 10^5 K, the radiation losses will no longer increase with increasing temperature, as they did at lower temperatures. Unless what is heating the wind suddenly decreases the amount of heating accordingly, the temperature will continue to rise, and the radiation losses per unit volume will continue to decrease. The atmosphere will distend until its increased scale height will offset the radiative losses, or until the losses from free-free emission and brehmstrahlung start to dominate.

This catastrophe from quite moderate to very high wind temperatures puts a limit on the parameters of the cool winds, where we define a cool wind as having a temperature less than 10^5 K throughout the wind. In initial value models of Alfven wave driven winds this condition may be encountered for certain parameter values. In particular it was found that for low values of the mass loss rate no cool solution could be obtained. In the semi-empirical models the condition shows up in a different fashion. We find that the radiation losses required by the force balance, using the observed mass loss rates and velocities become larger than is physically possible. In that case there is no solution for the temperature and the energy balance can not be solved.

We use the semi-empirical models to discriminate between the dominant and the less important terms in the energy balance. Because of the low velocities and temperatures and their gradients many terms in the equation can be neglected. The following crude criterium for the existence of a cool wind solution can then be derived from the energy balance..

$$(\frac{dM_*}{dt}) > /mdot_{crit} = 0.12/(10^{+17}\ g/sec)(\frac{R_*}{10^{+13}\ cm})\ (\frac{V_{esc}^2}{10^{+15}\ cm/sec})\ (\frac{V_\infty^2}{10^{+14}\ cm/sec}) \qquad (1)$$

We suggest that the above requirement may be violated for the coronal gaints and hybrid stars located close to the dividing line in the HR-diagram, and so cause the division into giants with cool, massive winds, or with hot coronae. The appearance of hot coronae when the conditions for the existence of a massive wind are violated, suggests that they arise because the star has a large non-radiative flux at the surface and the most efficient drain, a massive wind, cannot exist.

The results of a test of this idea are presented in figure 3, where for the stars discussed by Drake and Linsky (1986) the mass loss rate was calculated using the correlation of mass loss rate with stellar radius (their figure 3). Using measured mass loss rates or Reimers formula instead does not alter figure 3 very much. The stars with a cool wind all have a massloss rate larger than five times the critical value.