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GENERATION OF MASS LOSS IN K GIANTS: THE FAILURE OF GLOBAL OSCILLATION MODES AND POSSIBLE IMPLICATIONS

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ABSTRACT

It is a well-established observational result that many inactive K giant stars show global oscillation modes, which lead to low-amplitude photospheric velocity variations. It is the purpose of this paper to investigate whether these modes are also relevant to the outer atmospheric dynamics, including the generation of mass loss. We find that this is not the case as most of these modes remain evanescent ("mode trapping"). Nonlinear effects are negligible as the wave amplitudes remain very small. The failure of these modes to produce mass loss (as well as the failure of acoustic modes previously studied) should be considered as strong evidence that the mass loss in these stars cannot be initiated by a nonmagnetic process. This result is of particular interest as the chromospheric heating in most of these stars seems to be fully attributable to acoustic energy dissipation.

Subject headings: stars: individual (α Bootis) — stars: magnetic fields — stars: mass loss — stars: oscillations

1. INTRODUCTION

K giant stars are well-studied objects, and a broad variety of observational results exists. In the case of Arcturus (α Boo = HD 124897 = HR 5340; K1.5 III), important information about the thermodynamic structure of the outer atmosphere has been obtained by analyzing *IUE* (Ayres & Linsky 1975; Judge 1986; Ayres et al. 1986) and *ROSAT* data (Ayres, Fleming, & Schmitt 1991). Many of these stars have been considered as inactive as they have chromospheric emission losses consistent with the basal flux limits of Schrijver (1987) and Rutten et al. (1991) and do not possess detectable coronae. It has been found that Arcturus as well as other inactive K giants have extended chromospheres with temperatures between 5000 and 20,000 K, perhaps accompanied by tiny layers at somewhat higher temperatures. Furthermore, moderately large mass-loss rates on the order of 10^{-9} $M_\odot$ yr^{-1} (or somewhat below) also exist. The final flow speeds of the winds have also been determined. It was found that the flow speeds of the winds are relatively low, probably not exceeding 50 km s^{-1} (see, e.g., Judge & Stencel 1991 and references therein). Despite the broad variety of observational and theoretical results, however, the basic process(es) responsible for generating the mass loss are still not understood.

A classic proposal which might explain some of these observations was made many years ago by Hartmann & MacGregor (1980), who studied the response of the outer atmospheric layers of Arcturus to the passage of energy and momentum fluxes in the term to Alfvén waves. Hartmann & MacGregor found that the dissipation of Alfvén waves with an energy flux of 3×10^6 ergs cm^{-2} s^{-1} and a magnetic field strength of ~ 10 G leads to a mass-loss rate of $\sim 10^{-9}$ $M_\odot$ yr^{-1}. The final flow speed of the wind in these models was ~ 60 km s^{-1}, and the adopted atmospheric temperature was 5000 or 10,000 K, depending on the model calculated. Consequently, the theoretical wind models of Hartmann & MacGregor have been considered as a big success because all these results were relatively close to the observational values. Nevertheless, the Alfvén-wave-driven wind model for Arcturus by Hartmann & MacGregor as well as a similar model for Betelgeuse by Hartmann & Avrett (1984) suffered from serious technical restrictions, which include the choice of the damping length of the waves as a free parameter, the restrictive treatment of the atmospheric thermodynamics, and the so-called WKB approximation. Some of these approximations have meanwhile been overcome. Rosner et al. (1991) have calculated improved models, which include Alfvén wave reflection. MacGregor & Charbonneau (1995) have investigated effects of non-WKB waves in models somewhat appropriate to Betelgeuse.

Further studies for the generation of mass loss in stars like Arcturus were given by Cuntz (1990), who studied the propagation of short-period acoustic shock waves. The models of Cuntz show strong time-dependent episodes of momentum and energy deposition, which give rise to substantial chromospheric heating. Unfortunately, these models failed completely in producing significant mass loss because of the small damping length of the acoustic energy flux. It was found that the mass-loss rates remain very low (i.e., between 10^{-14} and 10^{-16} $M_\odot$ yr^{-1}, depending on the model parameters). Significant mass-loss rates could only be produced, when periods larger than 5.6×10^5 s (6.5 days) were adopted. The mass-loss rates were found to be between 10^{-10} and 10^{-11} $M_\odot$ yr^{-1}, which is still consistent with observations. Nevertheless, all these results should be considered as very uncertain, because the initial wave amplitudes in these models were chosen arbitrarily. Furthermore, Cuntz (1990) has ignored the influence of radiative damping which is particularly relevant at low atmospheric heights.

All these uncertainties should be viewed as a strong reason to revisit the heating and mass loss in the outer atmospheres of cool giants. It is our basic goal to study the propagation of the low-amplitude radial pulsation modes found by observations. In the case of Arcturus, a broad range of low-amplitude radial velocity variations has been detected in various observational monitoring programs. Belmonte et al. (1990) have performed a

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2 week program to analyze the range of photospheric acoustic oscillations. They found a large range of modes between ~1 and ~80 μHz. The clearest peak was found at a frequency of ~4.3 μHz (period ~2.7 days) with an amplitude of 60 m s^{-1}. Belmonte et al. also presented some evidence for a ~1.4 μHz (period ~8.3 days) peak, which is possibly attributable to the fundamental pulsation period of this star. Note, however, that this frequency peak was considered as extremely uncertain because of the ~11 day observational time span. Also note that the period which corresponds to this frequency peak is clearly beyond the so-called acoustic cutoff period, which can be estimated as $2.2 \pm 0.9 \times 10^5$ s (or 2.5 ± 1.0 days), assuming a stellar gravity of $\log g = 1.5 \pm 0.15$ (Peterson, Dalle Ore, & Kurucz 1993). When a gravity of $\log g = 1.7$ is adopted (as in our models), an acoustic cutoff period of $\simeq 1.2 \times 10^5$ s is found.

A further observational program leading to the detection of low-amplitude radial velocity variations in Arcturus is that of Hatzes & Cochran (1994). Hatzes & Cochran have taken measurements over 8 consecutive nights in 1992 June. A detailed analysis based on nonlinear least-square fitting revealed three significant periods at 2.46, 4.03, and 8.52 days. The associated amplitudes were 54, 30, and 14 m s^{-1}. These results again confirmed the presence of radial pulsation. Low-amplitude radial velocity variations have also been found in other stars. In the case of K giants, results have been given by M. A. Smith (1982, 1983), P. H. Smith, McMillan, & Merline (1987), Cochran (1988), Walker et al. (1989), and Irwin et al. (1989).

2. THEORETICAL MODEL CALCULATIONS

The computation of wave modes initiated at the inner boundary of an atmospheric slab has been discussed in previous papers of P. Ulmschneider and his group (see, e.g., Ulmschneider et al. 1977; Ulmschneider, Muchmore, & Kalkofen 1987; Rammacher & Ulmschneider 1992) and therefore does not need to be described again. We note that the one-dimensional time-dependent hydrodynamics equations are solved consistently using the method of characteristics. At the top of the atmosphere, a transmitting boundary is used. At the bottom of the atmosphere, disturbances are introduced by means of a piston. The disturbances considered are chosen according to the photospheric oscillation modes observed by Belmonte et al. (1990) and Hatzes & Cochran (1994). In the case of this study, the waves are computed in the adiabatic approximation.

Belmonte et al. have identified 19 acoustic modes in the range of 0.146 and 8.32 days. As found by Cuntz (1990), short-period modes with periods less than 6.5 days are most likely unimportant for driving mass loss because of the small damping length of the mechanical energy flux. On the other hand, short-period modes can be converted into long-period modes due to mode-mode interaction as demonstrated by Rammacher & Ulmschneider (1992), Fleck & Schmitz (1993), Sutmann & Ulmschneider (1995b), and others. Therefore, we computed models also containing shorter wave periods. Our first model, which is Frequency Model 1 (FM 1), contains the following four frequencies: 8.32, 2.71, 1.71, and 1.27 days. In our second model (FM 2), we omitted the 8.32 day frequency as the existence of this frequency is very uncertain (see above). In FM 3, we used the three frequency peaks derived by Hatzes & Cochran (1994). Hatzes & Cochran also identified a frequency peak at 8.52 days, but with an amplitude a factor of 3 smaller than the corresponding 8.32 days peak in the Belmonte et al. series. Hatzes & Cochran also considered this peak as a possible artifact caused by the limited number of observations. Consequently, we computed a further model (FM 4), in which this frequency point was dropped. The data we used are summarized in Table 1. Based on these data, we synthesized the motion of the piston using the formalism given by Sutmann & Ulmschneider (1995a, b). In this procedure this piston movement is described as a linear superposition of wave modes with randomly chosen phase shifts. The most important difference is that the velocity amplitudes are not calculated from a prescribed mechanical energy flux, but taken from Belmonte et al. and Hatzes & Cochran according to the observations.

We still have to discuss the calculation of the initial atmosphere model. We computed an initial atmosphere model appropriate to Arcturus. In order to simulate the effect of a steady temperature increase due to short-period heating, we adopted the semiempirical chromosphere model of Ayres & Linsky (1975). This model extends over a distance of 5×10^{-2} R_*. The density at the inner boundary point is 1.58×10^{-8} g cm^{-3}, and the temperature at this point is 3935 K. After a temperature minimum of 3200 K, the temperature encounters a steady increase up to 10,000 K. This temperature structure is used for our initial atmosphere. Note, however, that we do not treat the ionization of hydrogen as we assume an ideal gas. The atmosphere is also assumed as plane-parallel. For the effective temperature we take $T_{\rm eff} = 4250$ K, and as gravity we use $\log g = 1.7$. Both values are close to the determinations of Peterson et al. (1993).

Now we discuss our results. As noted before, we have calculated four models with different sets of oscillation frequencies. These models are referred to as FM 1, FM 2, FM 3 and FM 4, respectively. As the number of frequency points considered are not the same in all of our models, we cannot expect the same mechanical energy flux to be introduced into the atmospheric slab. After numerical integration, which also considers the phase shifts between density and velocity, we find energy fluxes

TABLE 1

INPUT DATA

Observation	P (days)	A (m s^{-1})	FM 1	FM 2	FM 3	FM 4
Belmonte et al. 1990..........	8.32	43.20	x	...	...	...
	2.71	60.24	x	x	...	...
	1.71	13.47	x	x	...	...
	1.27	12.32	x	x	...	...
Hatzes & Cochran 1994......	8.52	14	...	...	x	...
	4.03	30	...	...	x	x
	2.46	54	...	...	x	x

of 2.27×10^3, 9.72×10^2, 1.20×10^3, and 8.50×10^2 ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in FM 1 to FM 4. This result shows that omitting the 8.5 days frequency point in both series reduces the mechanical energy flux by about 25%. We evaluated the displacement of the gas elements as function of atmospheric height. We found that the displacements remain very small. We also found that no significant transportation of mass occurs. At large atmospheric heights, that is beyond nine pressure scale heights, large-scale oscillations with a frequency consistent with the acoustic cutoff frequency of $\simeq 1.2 \times 10^5$ s are found. The phase shifts between velocity and gas density mostly equal π. Consequently, no significant transport of energy can occur. The wave modes considered remain essentially evanescent ("mode trapping"). Also note that the thermodynamic structure of the initial atmosphere remains essentially unchanged because the temperature fluctuations never exceed a few K. This result should be compared with results from acoustic wave models given by Ulmschneider, Schmitz, & Hammer (1979) and Cuntz & Muchmore (1989). These acoustic wave models treat the propagation of waves generated by stellar convection. Ulmschneider et al. found significant atmospheric temperature fluctuation up to 1000 K due to the presence of shocks. In the models of Cuntz & Muchmore, which also include the formation and destruction of molecules, hot and cool layers are formed, which differ in temperature by up to 5000 K.

Next, we evaluated the behavior of the mechanical energy flux with atmospheric height for the wave models computed (see Fig. 1). We found that in the inner part of the atmosphere, the wave energy fluxes decrease exponentially as the velocity amplitudes of evanescent waves remain constant and the mass density falls exponentially with height. In the outer part of the model, the wave energy fluxes are constant. This is due to the fact that some of the modes originally evanescent start to become propagating. This behavior is due to the increase in the sound speed, which shifts the acoustic cutoff period to higher values ($P_{\mathrm{cut}} \sim c$). Most significantly, we checked whether low-amplitude radial velocity variations can support mass loss. We found that this is not the case. The energy required to lift the wind out of the gravitational potential of the star remains many orders of magnitude below the wind energy flux constrained by observations (see Judge & Stencel 1991, and references therein). Judge & Stencel evaluated the energy and momentum requirement of cool star winds including that of Arcturus. They noted that the lines observed by Smith et al. (1987) as well as Belmonte et al. (1990) are associated with an energy which is ~20 times greater than the energy required to drive the wind. We note, however, that the energy flux used in this study has been computed by ignoring the phase shifts between velocity and density. This approach is incorrect in the case of linear waves but nevertheless quite reasonable in the case of shock waves. In order to assess this possibility, we recalculated the wave energy flux of FM 1 ignoring the velocity-density phase shifts. In this case, we were able to identify significantly higher energy fluxes in all parts of the atmosphere. Nevertheless, the energy needed to drive the wind is still unavailable.

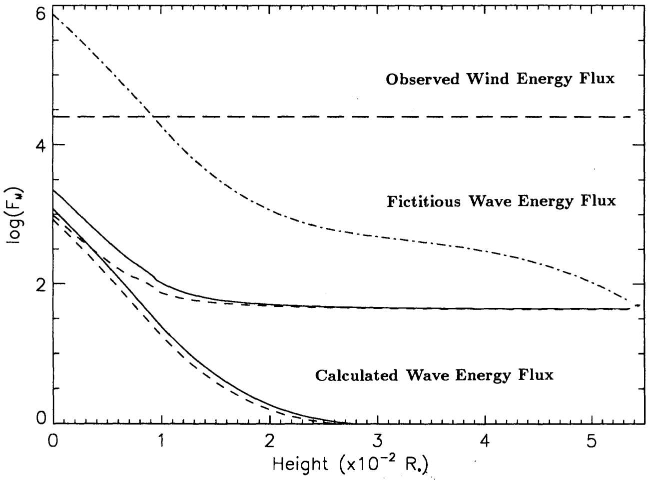

FIG. 1.—Behavior of various energy fluxes. The upper solid and short-dashed lines denote the wave energy flux of FM 1 and 2, respectively. The lower solid and short-dashed lines denote the wave energy flux of FM 3 and 4. The dashed-dotted line denotes the fictitious wave energy flux of FM 1, which has been computed ignoring the phase shifts between the density and gas velocity. The long-dashed line refers to the wind energy flux required to lift the wind out of the gravitational potential of the star. The value of this quantity has been deduced by Judge & Stencel (1991). The authors argue that this value is uncertain by a factor of 3.

3. CONCLUSIONS

It has been the purpose of this *Letter* to investigate whether low-amplitude radial velocity variations which are present in many K giant stars have significant influence on the outer atmospheric dynamics of these stars, including the generation of mass loss. As a standard example we used Arcturus. Arcturus shows a broad range of long-period photospheric oscillation modes due to radial oscillations. We studied a total of four models using observational data from Belmonte et al. (1990) and Hatzes & Cochran (1994). The response of the atmosphere due to the excitation of the wave modes considered was treated in the adiabatic approximation. As initial atmosphere we used the semiempirical chromosphere model of Ayres & Linsky (1975). The outer part of this model shows a temperature increase with atmospheric height, which allowed us to consider the effect of chromospheric heating. We found the following results:

1. The response of the atmosphere shows that most of the wave modes considered remain evanescent ("mode trapping"). The propagation of energy into higher atmospheric layers remains marginal. Nonlinear effects are negligible because of the small wave amplitudes. The outer parts of the atmosphere show large-scale oscillations with a frequency consistent with the acoustic cutoff frequency. At large atmospheric heights some of the wave modes originally being evanescent start to become propagating. This behavior is caused by the increase of the sound speed with atmospheric height as the acoustic cutoff frequency is shifted to higher values.
2. It has been our ultimate goal to study whether the low-amplitude photospheric velocity variations considered can substantially impact the outer atmospheric dynamics. We found that apart from the excitation of the acoustic cutoff frequency this is not the case. Regarding the atmospheric thermodynamics, we found that the oscillation modes considered are much less relevant than other modes, including (magneto-) acoustic wave modes which are generated by stellar convection and rotation.
3. We also checked whether low-amplitude radial velocity variations can support mass loss. We found that this is not the case as the energy required to lift the wind out of the gravitational potential of the star remains many orders of magnitude

below the wind energy flux constrained by observations (see Judge & Stencel 1991, and references therein).

4. As a test case we recalculated the wave energy flux for FM 1 by ignoring the phase shifts between the atmospheric density and the velocity. This fictitious wave energy flux can somewhat simulate the propagation of shock waves although remarkable differences in the dissipation of energy remain. We found again that the energy necessary to drive the wind is unavailable.

5. Earlier studies for the generation of mass loss in stars like Arcturus were given by Cuntz (1990), who studied the propagation of short-period acoustic shock waves. The models of Cuntz give rise to significant chromospheric heating, but fail in producing significant mass loss. Cuntz found mass-loss rates between 10^{-14} and 10^{-16} $M_\odot$ yr^{-1}, depending on the model parameters. By considering the results given in this paper, it is safe to say that mass loss in stars like Arcturus cannot be initiated by a nonmagnetic mechanism.

6. We argue that our results are also relevant to other inactive K giant stars, which also show the presence of radial velocity variations with a similar range of frequencies and amplitudes. Relevant observations have been obtained by Walker et al. (1989) and others.

The results obtained are also relevant because of another reason: Schrijver (1987) and Rutten et al. (1991) argued that inactive K giants like Arcturus should be referred to as chromospheric basal flux stars as the chromospheric energy losses (particularly those of Mg II and Ca II) in these stars coincide with the basal flux limits. This result is usually interpreted as strong evidence that the chromospheric heating in these stars is due to acoustic energy dissipation and not associated with magnetic fields. Based on the results presented it is obvious that even so-called chromospheric basal flux stars are expected to have a certain level of magnetic activity at least to support the mass loss occurring. In the case of α Tau (K5 III), a further inactive K giant star, fully resolved *HST*-GHRS profiles of C II] have meanwhile become available. These observations allow the first spectroscopic measurement of chromospheric turbulence in a cool giant. The magnitude of turbulence has been determined as about 24 km s^{-1} (Carpenter et al. 1991), which is much larger than found in the acoustic wave models of Judge & Cuntz (1993). Judge & Cuntz argued that other effects not included in the models might also be present in this star. The suggested possibilities include (1) nonstandard wave modes given by photospheric radial oscillation modes, (2) three-dimensional turbulence and/or horizontal flows (perhaps due to gravity modes overshooting bubbles), and (3) effects due to magnetic energy dissipation. Based on the results presented, the first possibility should now be dropped. Further studies are needed.

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