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Stellar wind flows in M-type supergiants produced by stochastic shock waves

ABSTRACT

I present first results of a novel ab–initio model for the formation and time–dependent behavior of chaotic stellar wind flows in M-type supergiants produced by stochastic shock waves. Stochastic shocks are closely related to the physical structure of the stellar convective zones. For my wave models I have taken the stellar parameters of α Orionis. My wave models show time–dependent episodes of momentum and energy deposition produced by strong shocks generated by merging of shocks in the stochastic wave field. I also show that the limiting shock strength behavior found in monochromatic wave models does not apply to stochastic shock waves. The stochastic variation of the energy dissipation by the shocks might also explain irregular variabilities observed in chromospheric emission lines in many M-type supergiants.

INTRODUCTION

M-type supergiants located to the right of the coronal dividing line are characterized by chromospheric structures and chaotic stellar wind flows. For α Orionis, observations suggest the presence of infalling and outstreaming atmospheric flows (Boesgaard & Magnan 1975, Boesgaard 1979, Bernat 1981, Querci & Querci 1986, among others) and episodic chromospheric heating events (Toussaint & Reimers 1989). The broad variety of observational results suggests that different components moving at different radial velocities are present, but the direction of the flow apparently alternates between infalling and outfalling motion, possibly as a result of dramatic events such as sporadic mass ejections, or simply a consequence of stellar pulsation or waves. Jorás (1989) presented a detailed study of atmospheric features in α Orionis, providing evidence for the complicated dynamics which occur.

Explaining the observational results through ab–initio modeling is challenging. As a step toward accomplishing this, I apply the model of Cuntz (1987), which assumes deposition of mechanical energy and momentum in outer atmospheric layers due to the propagation of stochastic shock waves. I extend this model to M-type supergiant stars. This is motivated by results of previous studies which show that the outer atmospheric heating in M-type supergiants is expected to be entirely dominated by nonmagnetic heating, because the relatively weak chromospheric emission of these stars depends only on their effective temperatures (Johnson 1987, Judge 1989, Judge & Stencel 1991, Dupree 1991). A similar result for slow–rotating single K giant stars was presented by Schrijver (1987 a,b). Hartmann & Avrett (1984) computed an ab–initio model for the outer atmosphere of α Orionis based on Alfvén wave dissipation, which could explain some of the observed properties. However, the relevance of this model remains uncertain due to the lack of magnetic field measurements.

METHOD

I have used an Eulerian one–dimensional, spherically symmetric, time–dependent radiation hydrodynamic code based upon the method of characteristics (Cuntz & Ulmschneider 1988). The code is suitable to the study of propagating shocks, which are treated as discontinuities. Boundary conditions for incoming and outgoing shocks are solved. Ionization of hydrogen is explicitly taken into account. Radiation damping is considered in the effectively thin plasma approximation using a Cox and Tucker type law given by Judge & Neff (1990). Judge (1990) presented theoretical arguments that the effectively thin plasma approximation should work well for chromospheric layers of the inactive, low–gravity star studied here. For my wave model I have taken the stellar parameters of α Orionis which are assumed to be $T_{eff} = 3900$ K, $R_* = 860\ R_\odot$, and $\log g_* = -0.4$ (Tsuji 1989). The initial atmosphere of the model extends from 1.1 up to 1.4 R_*. The atmospheric extent has been chosen to encompass the scale length where the major part of the mechanical energy dissipation of the stochastic shock waves occur. Wave models computed to deduce the magnitude of time–averaged mass loss rates must certainly be based upon much more extended atmospheric shells.

RESULTS AND DISCUSSION

For my study I start with a monochromatic wave model computed for a fixed wave period of $2\ 10^6$ s and a fixed initial wave amplitude of 0.30 Mach. Then I start to introduce shock waves with stochastically changing wave periods in the short–period range. The shape of the wave period distribution is assumed to be Gaussian centered at 2 10^6 s with a standard deviation of 5 10^6 s. Negative periods have been omitted. The peak value of the wave period distribution has been chosen according to the results of traditional acoustic energy generation models (Bohn 1981, 1984). Figure 1 shows a snapshot of a time–dependent wave computation obtained 1.9 10^7 s after allowing the wave period to change stochastically. The atmospheric model is characterized by a complicated hydrodynamic structure containing a nonuniform distribution of 6 shocks with different strengths. The shock strengths M_{sh}, the shock speeds U_{sh}, and the post–shock temperatures $T^{(2)}$ for the model are listed in Table 1. The table shows that both the shock strengths and the shock speeds differ substantially and change non–monotonically with height.

This result is a clue to the basic physics which is going on: after allowing the wave period to change stochastically, shocks with different strengths are introduced into the atmosphere. Different shock strengths cause different shock speeds, which lead to interacting, overtaking and merging of shocks (*"shock–cannibalism"*). Since the strength of an overtaking shock combines with the shocks it engulfs, its speed increases, so it overtakes more and more shocks in front of it and attains an even greater strength. Consequently, the amount of momentum and energy deposition that occurs in the atmospheric layer varies drastically. The direction of the flow alternates between infalling and outflowing motions depending on the strengths of the shocks and the hydrodynamic history of the flow. In the snapshot presented here, shock number 3 (counted from outside to inside) is the major cannabalizing shock. This shock will soon overtake the two shocks in front of it.

A further interesting result is obtained by the behavior of radiation damping. My time–dependent stochastic wave model shows that the radiation damping function is strongly peaked behind the shocks and is not directly related to the structure of the time–averaged atmosphere. The radiation losses decrease with increasing atmospheric height showing that the waves behave more and more adiabatically when propagating outward. The post–shock temperatures $T^{(2)}$ in my atmospheric model range from 4690 K up to 7280 K. The mean thermal structure of the atmosphere is somewhat similar to that of the semiempirical chromosphere model of Basri et al. (1981), who computed a semiempirical chromosphere model for α Orionis based upon the Ca II K and Mg II h,k emission lines from IUE spectra. They found a smooth increase of the atmospheric temperature starting from 2820 K in the temperature minimum layer up to 7000 K at a column mass density of 1.0 10^{-6} g cm^{-2}.

In order to get further insight into the physics of time–dependent stochastic wave models, I have plotted the minimal and maximal shock strengths as func-

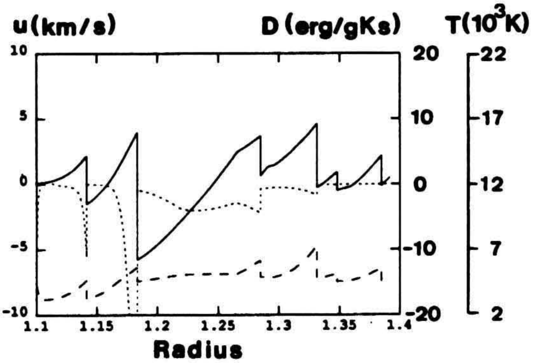

Fig. 1 A snapshot of a time–dependent stochastic wave computation. The flow speed u (solid line), the temperature T (dashed line), and the radiation damping function D (dotted line) are shown as functions of height.

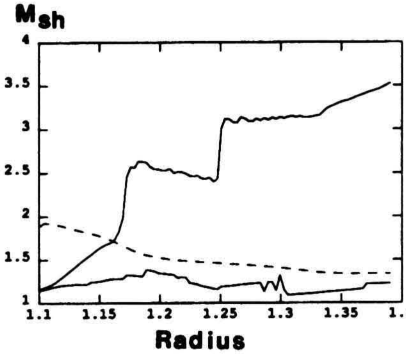

Fig. 2 Minimal and maximal shock strength (solid lines) in a time–dependent stochastic wave computation as functions of height. The run of the limiting shock strength (dashed line) is also shown.

Table 1 SHOCK DATA

SHOCK NUMBER	M_{sh}	U_{sh} (km s^{-1})	$T^{(2)}$ (K)
1	1.23	8.9	5600
2	1.14	7.8	5150
3	1.52	11.1	7280
4	1.57	10.2	6170
5	2.20	7.2	5650
6	1.45	7.1	4690

tions of the atmospheric height (Fig. 2). I have introduced 16 stochastic wave periods into the atmospheric layer covering a timespan of 6.9 10^7 s. The minimum wave period I introduced was 1.2 10^6 s, and the maximum was 1.6 10^7 s. Due to overtaking and merging of shocks, different shock strengths are found at the same atmospheric height. For the outer boundary point of the atmosphere the shock strengths differ from 1.22 to 3.53. This result is extremely impressive when I compute the respective energy dissipation rate for the shocks. Since the energy dissipation rate behaves as $(M_{sh}-1)^2$, a difference by a factor of 130 is produced by the stochastic nature of the flow. It is also obvious that the limiting shock strength behavior, as found in monochromatic wave models with waves having a fixed initial amplitude (e.g., Cuntz & Ulmschneider 1988), no longer exists, when stochastic shocks are considered. I show the predicted limiting shock strength using data from the time–averaged atmosphere model. Changes in the mean sound speed (due to the thermal atmospheric structure) and in γ (due to the ionization of hydrogen) and the height–dependency of the gravity have been explicitly taken into account.

CONCLUSIONS

I have computed a novel ab–initio model for the outer atmosphere of α Orionis which includes chromospheric heating and the generation of chaotic stellar wind flows. The chromospheric temperatures are found to be similar to those temperatures given by the semiempirical chromosphere model of Basri et al. (1981). The atmospheric dynamics are extremely complicated. Stochastic variations of energy and momentum deposition occur. I found that the atmosphere is neither in static (nobody would expect this!) nor dynamic equilibrium, but in time–dependent stochastic disequilibrium. The time average of the atmospheric flow speed can easily be related to the microturbulent velocity, a velocity which is required in classic stellar atmosphere models. I also showed that the limiting shock strength behavior found in monochromatic wave models (the waves must also maintain a fixed initial wave amplitude in these models!) no longer exists, when stochastic shocks are considered, because the atmospheric dynamics lead to the formation of shocks with different strengths at the same atmospheric height.

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