THE ASTROPHYSICAL JOURNAL, 353: L39–L43, 1990 April 20

STOCHASTIC SHOCK WAVES AS A CANDIDATE MECHANISM FOR THE FORMATION OF THE He I λ10830 LINE IN COOL GIANT STARS

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Received 1989 October 6; accepted 1990 January 29

ABSTRACT

We investigate whether strong shocks produced in time-dependent stochastic wave models can explain the formation of the He I λ10830 line in cool giant stars. Our exploratory research is based on the *ab initio* chromosphere model for Arcturus published by Cuntz in 1987, who found that a stochastic distribution of wave periods leads to overtaking and merging of shocks, which occasionally produce very strong shocks with temperatures larger than 40,000 K in the postshock regions. These temperatures can easily produce a significant population in the $2s\,^3S$ state by electron collisional excitation. The λ10830 line occurs in absorption when the densities in the shocks exceed $\gtrsim 10^7$ cm^{-3}.

Subject headings: line formation — radiative transfer — shock waves — stars: chromospheres — stars: late-type

I. INTRODUCTION

For many years a major unsolved problem regarding the atmospheric structure of cool giant stars has been the formation and the time-dependent behavior of the He I λ10830 line. Linsky and Haisch (1979) and Simon, Linsky, and Stencel (1982) determined that the cool half of the Hertzsprung-Russell (H-R) diagram is divided into two distinct regions: F–M dwarfs and late-F through early-K giants are characterized by prominent chromospheric ($T \lesssim 10^4$ K) and higher temperature (2×10^4–2×10^5 K) emission lines in far-ultraviolet *IUE* spectra, whereas single red giants later than about K2 III and supergiants later than about G5 Ib are characterized by generally weaker chromospheric emission and little or no evidence for higher temperature species. In the Sun, the higher temperature emission lines (i.e., C IV λλ1548, 1551) originate in the transition region lying at the base of the corona.

Various authors have suggested that the apparent absence of C IV emission in the cooler stars implies no hot coronal plasma, and the line in the H-R diagram which separates the two regions has been termed the coronal dividing line (CDL). Ayres *et al.* (1981) used the *Einstein* IPC to confirm the reality of the proposed CDL: Stars to the left typically have measurable *Einstein* X-ray fluxes, but those to the right do not. Upper limits set in $f_X/f_{\rm bol}$ and surface flux are only $\sim 1\%$ of the Sun's X-ray flux for the brightest *noncoronal* stars (e.g., α Boo, α Sco, and α Ori). Haisch (1987) and Judge (1987) have reviewed the history of the CDL as determined by a variety of observational criteria.

On the other hand, O'Brien and Lambert (1979, 1986) and Lambert (1987) observed 60 cool (late-F through M) giant and supergiant stars in the He I triplet ($2s\,^3S$–$2p\,^3P^o$) spectral region at 10830 Å. An important result was that most of the early-K–type giant stars have a *constant* λ10830 absorption profile similar in shape to the Sun and to their prototype, β Gem (K0 III), a relatively inactive *coronal* star. Stars to the right of the CDL, the *noncoronal* stars, show *highly variable profiles* in He I λ10830. α Boo (K2 IIIp), for instance, showed profiles which varied between a P Cygni shape, a *pure* absorption feature, and no feature at all (O'Brien and Lambert 1979). Lambert (1987) showed a sequence spanning about 6 weeks in which the profile varied smoothly from a P Cygni profile (very weak emission) to a broad, shallow, blueshifted absorption line. These changes represent evidently the evolution of a single "event." Lambert interpreted it as rotational modulation as an active region crossing the line of sight. However, one could argue just as well for the growth and decay of an active region.

Zarro and Zirin (1986) found a strong observed correlation between X-ray fluxes from *Einstein* and He I absorption equivalent widths for a large number of late-type *coronal* stars. They postulated (as did Zirin 1975, 1976) that high-energy (e.g., EUV and X-ray) photons from the corona irradiate the chromosphere and photoionize He I, and subsequent recombinations then populate the metastable $2s\,^3S$ state (~ 20 eV) leading to an absorption line. Solar observations also suggest this picture (Harvey *et al.* 1975). Although He I λ10830 is formed at chromospheric depths in these stars, it is clear that the He I *line is related in some way to the coronal X-rays.*

II. POSSIBLE EXCITATION MECHANISMS

One possible explanation for the formation of the He I λ10830 line is therefore photoionization by X-rays. Ayres *et al.* (1981) determined the X-ray flux upper limits with the *Einstein* IPC for several giants on the cool side of the CDL. α Boo was one of these noncoronal stars observed, with $f_X/f_{\rm bol} < 3 \times 10^{-9}$ as an upper limit. The IPC energy band lies between 0.1 and 4 keV (124–3 Å). The bound-free edge of helium ionization from the ground state lies at 504 Å (0.025 keV). The photoionization cross section for He I at 125 Å is 6% the value of the cross section at the ionization limit and falls to 2% of band head strength at 80 Å.

In order to test whether X-ray photoionization is responsible for the He I λ10830 line in cool giant stars, we have made test calculations with the semiempirical chromospheric model of Arcturus given by Ayres and Linsky (1975). Synthetic spectra of the He I λ10830 line were generated with the PANDORA radiative transfer code (Vernazza, Avrett, and Loeser 1973, 1976, and 1981). We found that the semiempirical chromospheric model produces no apparent λ10830 line. However, if an additional X-ray flux (as observed from Earth) of 2×10^{-14} ergs cm^{-2} s^{-1} over an energy range of 0.03–0.2

keV (flux was kept constant over frequency in this preliminary calculation) is postulated, a profile with a FWHM of 0.38 Å and a central depth of $0.97F_{\rm cont}$ is produced (an equivalent width, W_λ, of 22 mÅ). Increasing the X-ray flux to 2×10^{-13} ergs $\rm cm^{-2}\ s^{-1}$ (i.e., approximately the upper limit set by *Einstein*, $f_X = 1.5 \times 10^{-13}$ ergs $\rm cm^{-2}\ s^{-1}$) leads to a line with a FWHM of 0.4 Å and $F_0 = 0.85F_{\rm cont}$ ($W_\lambda = 80$ mÅ), which is similar in strength to some of the observed absorption profiles of α Boo (O'Brien and Lambert 1986; Lambert 1987). To justify the presence of such a X-ray flux, deeper observations are urgently needed (perhaps by *ROSAT*).

Another possible mechanism for producing the He I line in noncoronal stars is collisional excitation by thermal electrons. A large emission measure of plasma hotter than 40,000 K is required, however, to populate sufficiently the $2s\,^3S$ state: This could be achieved in an extended cool corona ($10^5 < T < 10^6$ K) or in an atmosphere with hot shocks. He I *emission* is observed in some cool giants and supergiants, which suggests that an extended region of hot plasma exists off the limb. Some of these stars also show He I absorption followed by episodes of emission. Noncoronal stars typically show evidence for massive cool stellar winds (Stencel 1978; Stencel and Mullan 1980*a*, *b*). α Boo, for example, displays evidence for episodic mass motions in the He I λ10830 line (O'Brien and Lambert 1986).

Meanwhile, Cuntz (1987) has generated a model atmosphere for α Boo with a nonlinear, time-dependent acoustic wave calculation. His model shows that the dissipation of mechanical wave energy leads to an increase of the mean atmospheric temperature with height up to chromospheric values in the outer layers of the star. Cuntz allows the wave period to change stochastically in the short period range, which produces supersonic flows leading to episodic mass loss. His wave model shows a quite interesting behavior: Due to the stochastic change of the wave periods, shocks with different strengths are produced. The speeds of these shocks are usually different, which leads to an overtaking and merging of shocks. Since an overtaking shock has the combined strength and therefore an increased speed, it overtakes more and more shocks in front of it and attains a very large strength. The momentum transfer of these strong shocks causes episodic mass loss. Furthermore, the energy dissipation of the strong shocks produces high temperatures in the postshock regions. Occasionally, temperatures larger than 40,000 K, necessary to populate the $2s\,^3S$ state by electron collisional excitation, are reached. In addition, stochastic shock waves could also explain the time-dependent behavior of the He I λ10830 line in K giant stars like Arcturus, since the highly variable profiles of the He I λ10830 line in these stars are strong evidence for the presence of atmospheric outflows and inflows (O'Brien and Lambert 1986), and the stellar wind flows in the stochastic wave model of Arcturus presented by Cuntz (1987) often show the same behavior.

We suggest that stochastic shock wave models for the chromospheres of late-type giant stars could explain the presence of the He I λ10830 line. Such models produce gas temperatures larger than 40,000 K, which could excite sufficient numbers of electrons to the metastable $2s\,^3S$ state. We check whether stochastic shocks can account for the He I line in cool giant stars by generating synthetic λ10830 line spectra from the Cuntz models of α Boo at various times when large shocks form. However, we emphasize that we are not trying to fit the observed λ10830 spectrum of Arcturus; these calculations are made merely to determine whether stochastic shocks can produce an observable He I feature. The synthetic spectra are calculated with the non–LTE radiative transfer code PANDORA with additional continuous opacities included for cool stars (Luttermoser *et al.* 1989).

III. METHOD

We begin by selecting various epochs of the *ab initio* Arcturus model of Cuntz (1987), which is based on time-dependent stochastic wave calculations. His model assumes that each shock wave covers the entire surface and is not distributed across a few active regions. Figure 1*c*[1] of Cuntz, called model 1 in this *Letter*, and some additional models with shock strengths and locations based on his Figure 3, are used for this exploratory research. A radiative equilibrium photospheric model representative for Arcturus ($T_{\rm eff} = 4250$ K, $g = 50$ cm $\rm s^{-1}$, and one-third solar metal abundance; Johnson *et al.* 1977) is attached to selected depths of the 800 zone hydrodynamic model at the various epochs. The depths corresponding to temperature maxima and minima are selected, as well as additional depths from the postshocked material of the main shock, for a total of 55 depths. This *reduced* model atmosphere is used as a *snapshot* of the time-dependent model in the radiative transfer calculations.

The equations of radiative transfer and statistical equilibrium are solved with the PANDORA code for the various atmospheric models. We use the following iterative procedure for the synthetic spectrum calculations: (1) A three-level hydrogen model atom is used in a static, plane-parallel atmosphere. Hα is treated explicitly, and Lyα and Lyβ are assumed to be in detailed balance. Balmer and Paschen photoionization rates are approximated with input radiation temperatures of 4000 K. (2) A three-level hydrogen atom is used in a static, spherically symmetric medium. All transitions are handled in detail. (3) A 13 level neutral helium atom with 23 bound-bound transitions is used for both a plane-parallel and spherically symmetric medium. All photoionizations and recombinations to each level are included, with cross sections for the various transitions obtained from Mathisen (1984). Although the He I λ10830 feature is a triplet, with lines at 10829.08 Å, 10830.25 Å, and 10830.34 Å, it is treated here as a single line at $\lambda_{\rm air} =$ 10829.95 Å. *Einstein A*-values for He I were obtained from Kono and Hattori (1984), and electron excitation rate coefficients for transitions involving the $2s\,^3S$ state were obtained from the compilation of Mendoza (1983). For this preliminary investigation, the macroscopic velocity field is included in the source function and line profile calculations only for model 5 of Table 1. All other atomic and molecular opacities are treated assuming LTE.

Sphericity effects are negligible in the radiative transfer calculations due to the small extent of the emitting regions ($<0.02\ R_*$). The initial assumption of detailed balance in the Lyman lines overestimates the population densities of the second and third levels of hydrogen by a factor of 3 in the main shock of model 1. This Lyman-line "draining effect" was also noticed in a chromospheric model of the cool carbon star TX Psc (Luttermoser 1988; Luttermoser *et al.* 1989) (see these references for further discussion of this phenomenon).

[1] Please note a temperature typo in this figure.

IV. RESULTS AND DISCUSSION

Model 1 does not produce any signature of the He I line. Although the temperatures in the main postshock region is high enough to collisionally excite the $2s\,^3S$ state, the density is too low to produce sufficient opacity for this line. Whereas model 1 has a shock front of 42,000 K at a height of 2.7×10^6 km above the continuum emitting region, a model based on Figure 1*d* of Cuntz (1987) has a 80,000 K shock at 4.1×10^6 km above the photosphere. Again the opacity is too low, even at this high temperature, to produce a He I λ10830 line.

Now, we start to compute additional models with various atmospheric shock structures. We introduce strong shocks at various depths in the atmosphere, in agreement with Figure 3 of Cuntz, and generate synthetic spectra. Figure 3 of Cuntz displays minimal and maximal shock strengths in his time-dependent stochastic wave calculation as a function of height. He found that shocks with strengths larger than 2.5, which is the strength of the main shock in our model 1, are occasionally produced at atmospheric heights beyond 1.1×10^6 km. The shock strengths and locations in his wave model depend completely on the stochasticity of the wave field introduced in the atmosphere. The wave periods used in his calculations cover the wave period range deduced by Bohn (1981, 1984) in his study of acoustic energy generation in stellar convective zones.

Table 1 displays characteristics of each shocked atmosphere and lists the equivalent width of the calculated line profile. We begin by increasing the temperature of the main shock of model 1 from 42,000 to 80,000 K (model 2). This produces a weak feature but not enough to be observable. We next take model 1 and introduce a 50,000 K shock at 1.2×10^6 km above the photosphere (model 3), which is four orders of magnitude higher in density than the large shock of model 1. This model, however, produces an emission continuum from the He I $2s\,^3S$ metastable state, which would have easily been seen by the *IUE* satellite (a flux level of 10^{-6} ergs cm^{-2} s^{-1} Å^{-1} at 2600 Å as seen from Earth for α Boo), and produces hydrogen Balmer emission lines. Since this obviously cannot be a representative shock structure for a star like Arcturus, we reject this model.

We next bring this 50,000 K shock outward to a depth of 1.8×10^6 km above the photosphere (model 4) which has no noticeable effect on the continuum longward of the Lyman limit and no effect on the Balmer lines. This scenario produces a He I λ10830 line with a FWHM of 0.80 Å and a central depression of 0.071 times the continuous flux—much too large compared with observations. Next we construct a model with a 40,000 K shock at 2.3×10^6 km above the photosphere (model 5). The He I λ10830 line produced by this model is similar to profiles observed in Arcturus (FWHM = 0.33 Å, $F_0 = 0.78F_{\rm cont}$). The Balmer lines and all UV, visual, and IR continua display their normal photospheric appearence. The emission measure of the material at 40,000 K is 6.7×10^{24} cm^{-5}; this is consistent with the emission measure diagnostics from far-UV lines of Arcturus (Judge 1986). Table 1 displays the calculated emission measure of the main shock which can be compared with Figure 3 of Judge.

In order to investigate the density and temperature parameter range for shocks that produce reasonable He I λ10830 lines, we increase the temperature of the shock of model 5 to 65,000 K (model 6). This produces a line similar to that of the 40,000 K shock, although it is slightly deeper (i.e., $F_0 = 0.75F_{\rm cont}$). We next reduce the temperature of the main shock to 40,000 K at 2.5×10^6 km above the photosphere (model 7). The strength of the He I line decreases by a factor of 3 with respect to model 6. Finally, model 8 is constructed which introduces the main shock of 40,000 K at 2.0×10^6 km above the continuum. This model generates a He I λ10830 line which mimics the average observed absorption feature.

We select model 5 to compute a synthetic spectrum of the λ10830 line with the velocity field included in the source function and line profile calculations. The velocity field is originally set by Figure 1*c* of Cuntz (1987). However, since the temperature structure is altered in model 5 from this model, we scale the velocity field with the relation $u_{\rm new} = (T_{\rm new}/T_{\rm old})^{1/2}u_{\rm old}$. Surprisingly, the velocity field shifts the line blueward by only $\sim$3 km s^{-1}, whereas the shock velocity is 40 km s^{-1}. In addition, the line weakens by one-third (equivalent width of 51 mÅ) with respect to the static model. Figure 1 shows the temperature structure of model 5 and a comparison between the profiles of this line for the static and dynamic cases. For such a weak absorption line, approximately 30% of the flux originates from the postshock region in the static calculation with the rest of the flux coming from the continuum deep below. However, with the velocity field included in the calculations, most of the photons which originate in the postshock region are redistributed into the line wings. Since the line center photon flux is only slightly less than the nearby continuum flux for this weak line, the Doppler-shifted photons are not apparent against the bright continuum. However, their

TABLE 1

MODEL CHARACTERISTICS

Model	Main Shock Temperature (K)	Main Shock Height[a] (10^6 km)	Main Shock Hydrogen Density (cm^{-3})	Main Shock Column Mass (g cm^{-2})	Emission Measure (cm^{-5})	He I λ10830 Equivalent Width[b] (mÅ)
1	42,000	−2.7	1.6×10^5	2.6×10^{-7}	3.0×10^{23}	0.
2	80,000	−2.7	1.6×10^5	2.6×10^{-7}	3.0×10^{23}	0.
3	50,000	−1.2	3.3×10^9	6.1×10^{-5}	1.4×10^{29}	...[c]
4	50,000	−1.8	1.7×10^8	3.1×10^{-6}	3.5×10^{26}	740.
5	40,000	−2.3	1.7×10^7	5.3×10^{-7}	6.7×10^{24}	77.
6	65,000	−2.3	1.7×10^7	5.3×10^{-7}	6.7×10^{24}	83.
7	40,000	−2.5	6.0×10^6	3.6×10^{-7}	1.6×10^{24}	30.
8	40,000	−2.0	9.0×10^7	1.7×10^{-6}	1.1×10^{26}	135.

[a] The negative sign indicates the distance above the continuum formation depth at 5000 Å.
[b] The values for the observed absorption feature in α Boo range from 0 to 240 mÅ.
[c] Not calculated due to model rejection from Balmer lines—probably very large.

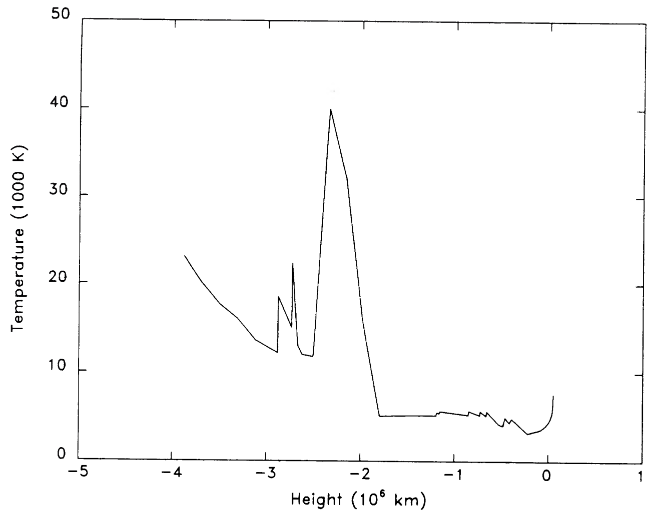

FIG. 1*a*

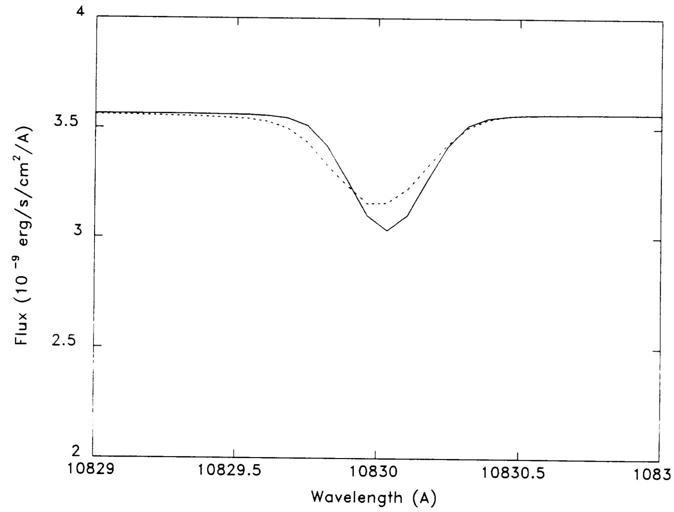

FIG. 1*b*

FIG. 1.—(*a*) Temperature structure of model 5 and (*b*) the resulting synthetic spectra of the He I λ10830 line for the static calculation (*solid line*) and the calculation made with the macroscopic velocity field included in the source function and line profile (*dashed line*). Note that the profiles are not convolved with any instrument profile and that the flux has been scaled to the angular size of Arcturus.

absence is noticed at line center since their contribution to the emergent flux is reduced with respect to the continuum as compared to the static calculation. As a result of this radiative transfer effect, optically thin *absorption* lines formed in a shock are not necessarily good diagnostics of the shock structure.

V. CONCLUSIONS

We investigated whether strong shocks can account for the formation of the He I λ10830 line in *noncoronal* giant stars. We found the following results:

1. The absorption profiles seen in the spectrum can be reproduced without sensibly changing the hydrogen photospheric spectra for a variety of shock temperatures greater than 40,000 K. They are not very sensitive to temperature once that threshold is reached.

2. The shock strengths needed in the radiative transfer computations are in agreement with stochastic *ab initio* models.

3. These high-temperature shocks do not form too low in the atmosphere ($z < 2.0 \times 10^6$ km above the photosphere) since such shocks would produce large Balmer emission lines and a neutral helium emission continuum in the UV—neither of which is seen in the observed spectra of these types of stars (i.e., Arcturus).

4. High-temperature shocks formed at large distances from the photosphere ($z > 2.7 \times 10^6$ km) cannot produce the He I λ10830 line because of the low densities which produces little collisional excitation.

5. Radiative transfer effects in a moving medium weaken the optically thin He I λ10830 line with respect to a static calculation for the same temperature-density stratification, and the line central wavelength does not reveal the true velocity of the shock.

6. Emission measures calculated from the models which reproduce the observed spectra are consistent with those determined by far-UV *IUE* spectra for these stars.

Some problems are evident in these calculations. Since the opacity of the λ10830 line is too small in the outermost layers to form an observable line, even for an 80,000 K shock, it is not obvious why this line is occasionally seen in emission in noncoronal stars. In addition, the observed strong blueshifts are not reproduced. Lambert (1987) suggested that the variation seen in the He I line of Arcturus may have a 78 day periodicity; however, the Cuntz model has a spectrum of waves introduced with stochastically changing periods with a Gaussian distribution centered at 1.4×10^4 s (~4 hr) with a standard deviation of 1.0×10^4 s. Due to shock merging, the repetition time for the shocks increases with height reaching values between 2.0×10^4 s and 5.0×10^4 s in the He I line formation region. However, since many shocks cannot produce the He I line because of their small strength, the theoretical time scale for the variation time of the He I line lies perhaps between 1.0×10^5 s (~1 day) and 1.0×10^6 s (~10 days). (O'Brien and Lambert 1979, 1986 report a 1 week variability which is closer to the theoretical estimate.) The theoretical time scale of the line profile variations in the hydrodynamic model was not calculated but is probably too small to reproduce the observations.

Despite this criticism, we found strong evidence that time-dependent stochastic waves are indeed a promising candidate mechanism for the formation and time-dependent behavior of the He I λ10830 line in cool giant stars. Short-period shock waves are present permanently in the atmospheres of cool giants because they are produced by the stellar convective zones. Since short-period shock waves are capable of forming the λ10830 line, we thus found a working mechanism which fits excellently in actual time-dependent chromosphere models for these stars (e.g., Ulmschneider 1989). Nevertheless, stochastic wave calculations, which treat the propagation of the waves and the formation of important chromospheric emission lines in a consistent manner, are urgently needed.

As mentioned before, our models do not predict *emission* features and strong blueshifts given by observations. This result suggests that *magnetic fields* might play an important role in the λ10830 formation region. On the other hand, we have not yet computed improved stochastic wave models for stars like Arcturus which take into account long-period wave modes. We anticipate that long-period wave modes lead to more extended chromospheric shells which are characterized by a much smaller decrease with height of the atmospheric density. These models might be dominated by spherical symmetric effects which can perhaps explain why the He I λ10830 line occurs sometimes in emission.

The authors acknowledge financial support by the National Aeronautics and Space Administration (grant NGL 06-003-057 to the University of Colorado). M. C. acknowledges financial support by the Deutsche Forschungsgemeinschaft (Projects Cu 19/1-1 and Cu 19/1-2). D. G. L. would like to thank E. H. Avrett and R. Loeser for use of the PANDORA code. We are grateful to P. G. Judge, J. L. Linsky, and D. L. Lambert (the referee) for helpful comments on the manuscript.

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