THE He I $\lambda$10830 LINE IN ARCTURUS PRODUCED BY
STOCHASTIC SHOCKS

MANFRED CUNTZ and DONALD G. LUTTERMOSER
Joint Institute for Laboratory Astrophysics, University of Colorado,
Boulder, Colorado 80309

Abstract We investigate whether strong shocks produced in time-
dependent stochastic wave models can explain the formation of the He I
$\lambda$10830 line in a cool giant star like Arcturus. Our exploratory research
is based on the work of Cuntz who found that stochastic waves lead
to overtaking and merging of shocks producing occasionally very strong
shocks with temperatures larger than 40,000 K in the post-shock regions.

INTRODUCTION

O'Brien and Lambert (1979, 1986) and Lambert (1987) surveyed sixty cool (late
F through M) giant and supergiant stars and found that most of the early K-
type giant stars have a constant He I $\lambda$10830 line profile similar in shape to
the Sun and their prototype, $\beta$ Gem (K0 III), a relatively inactive coronal star.
Non-coronal stars like Arcturus, on the other hand, show highly variable profiles
in He I $\lambda$10830, although the equivalent width of the line shows no dramatic
change from timescales up to one week.

There are two different mechanisms which can produce the He I $\lambda$10830
in a non-coronal star: photoionization by X-rays and collisional excitation by
thermal electrons. Photoionization by X-rays alone can probably not work be-
because the X-ray fluxes available in these stars may be too small. We have made
test calculations using the semi-empirical Arcturus model of Ayres and Linsky
(1975) assuming incident X-ray fluxes weaker than the Einstein upper limits
measured by Ayres et al. (1981). Realistic He I profiles were only obtained
when the X-ray flux was increased to the upper limit set by Einstein.

Another possible mechanism for producing the He I line in non-coronal
stars is collisional excitation by thermal electrons. However, a large emission
measure of plasma hotter than 40,000 K is required to populate sufficiently
the 2s $^3S$ state. This could be achieved in an extended cool corona, however
evidence for such a corona is not observed in this star (e.g., Linsky and Haisch
1979; Simon et al. 1982). On the other hand, ab-initio stochastic wave models
for the chromosphere of Arcturus show temperatures larger than 40,000 K in
the post-shock region of strong shocks, which can be achieved by shock merging
(Cuntz 1987). We suggest that these strong shocks can possibly explain the He I
$\lambda$10830 line in stars like Arcturus.
METHOD

We select various epochs of the time-dependent stochastic Arcturus wave model of Cuntz (1987) with shock strengths and locations in agreement with the stochastic behavior of the flow. The He I $\lambda 10830$ line is computed solving the equations of radiative transfer and statistical equilibrium with the PANDORA code (Vernazza, Avrett, and Loeser 1981; Luttermoser et al. 1989). We use the following iterative procedure for the synthetic spectrum calculations: (1) A 3-level hydrogen model atom is used in a static, plane-parallel medium. $H-\alpha$ is treated explicitly and Ly-$\alpha$ and Ly-$\beta$ are assumed to be in detailed balance. Balmer and Paschen photoionization rates are approximated with input radiation temperatures of 4000 K. (2) A 3-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. All other atomic and molecular opacities are treated assuming LTE.

RESULTS AND DISCUSSION

Figure 1 shows a model with a 40,000 K shock at $2.3 \times 10^6$ above the photosphere. The resulting spectrum of the He I $\lambda 10830$ line is similar to some line strengths observed in Arcturus (equivalent width of 77 mA). The Balmer lines and UV, visual, and IR continua all display normal photospheric appearance. The emission measure of the material at 40,000 K that produced the observed He I $\lambda 10830$ line is $\sim 10^{24} - 10^{25}$ cm$^{-5}$, which is consistent with the emission measure of Arcturus determined by far-UV lines (Judge 1986). When the velocity field is included in the source function and the line profile calculations, the line is shifted blueward by only $\sim 3$ km s$^{-1}$, whereas the shock velocity is 40 km s$^{-1}$. As well, the line actually weakens by a third (equivalent width of 51 mA) with respect to the static model due to radiative transfer effects.

In order to investigate the density and temperature parameter range for shocks that produce reasonable He I $\lambda 10830$ lines we have computed additional models (Cuntz and Luttermoser 1990). We find 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. There is little sensitivity to temperature once that threshold is reached. (2) 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 spectrum of Arcturus. (3) High temperature shocks formed at large distances from the photosphere ($z > 2.7 \times 10^6$ km) cannot produce the He I $\lambda 10830$ line due to the low densities. Unfortunately, we cannot reproduce observed $\lambda 10830$ emission features. We plan to generate improved stochastic Arcturus wave models which take into account long period wave modes.
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REFERENCES


![Graph](image_url)

Figure 1: The synthetic spectrum of the He I λ10830 line for our model. The dashed and solid lines indicate the profiles with and without the macroscopic velocity field included in the source function and line profile calculation, respectively.