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THEORETICAL BASAL FLUX LIMITS FROM ACOUSTIC WAVE CALCULATIONS

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ABSTRACT Based on acoustic energy generation calculations for a series of late-type main sequence stars, we performed improved acoustic wave calculations and, using new spectral line codes, simulated theoretical basal flux values for Mg II and Ca II lines assuming both CRD and PRD. Comparing these fluxes with the observed values from basal flux stars, we find good agreement between theory and observation. This strongly suggests that acoustic waves are the basic chromospheric heating mechanism for main sequence stars. Poor agreement of the CRD fluxes particularly for Mg II shows that the CRD assumption is bad.

INTRODUCTION

It is known for some time that there are two types of heating mechanisms for stellar chromospheres, a magnetic mechanism which is correlated with stellar rotation and a possible acoustic mechanism which does not depend on rotation (Schrijver 1987). This acoustic mechanism was long suspected to be responsible for the minimal emission observed in the cores of strong chromospheric lines and which in the HR-diagram leads to an empirical basal chromospheric emission flux line populated by stars with very low rotation rates (Ulmschneider 1990, 1991). For more rapidly rotating stars increasing amounts of magnetic heating are supposed to add emission on top of this basal acoustic heating. To test the basal acoustic heating picture we have performed a series of theoretical evaluations, starting with the acoustic energy generation calculations of Bohn (1981, 1984), continuing with acoustic wave propagation and shock development computations and finally simulating chromospheric line profiles and fluxes which are then compared with observations. To take such a series of theoretical steps is satisfying because it follows the sequence of physical events which occur in the stars, but is also dangerous because systematic errors could accumulate over the many steps.

BASIC ASSUMPTIONS AND COMPUTATIONAL METHODS

For a series of main sequence stars (c.f. Tab. I) we have taken acoustic energy fluxes F_M from convection zone calculations of Bohn (1981, 1984). For our monochromatic wave calculations we have chosen wave periods P which

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correspond to the maximum of the acoustic frequency spectrum (Bohn 1981, Ulmschneider 1991). One finds that P is roughly equal to 1/5 of the acoustic cutoff period. Tab. I shows these initial data. For our acoustic wave propagation calculations the time-dependent hydrodynamic equations and the radiative transfer and statistical rate equations for the H^- continuum as well as the Mg II k and H Lyα lines (as representative chromospheric emitters) are solved simultaneously, using the method of characteristics. After completion of the wave calculations, CRD and PRD line profiles (=WM profiles) are computed for selected phases of the wave using new operator splitting methods of Buchholz et al. (1994) for CRD and of Ulmschneider (1994) for PRD. Before the start of the wave calculations radiative equilibrium atmosphere models are calculated. For these models, CRD and PRD line profiles (=RE profiles) are also computed. The difference between the WM and RE profiles was integrated over frequency, converted to flux values and multiplied by two to account for the total Ca II H+K and Mg II h+k line emissions.

TABLE I Selected stellar models, acoustic fluxes and wave periods.

Star	$T_{\rm eff}(K)$	log g	$F_{\rm M}$ (erg cm^{-2}sec^{-1})	P(sec)
F5 V	6440	4.34	$6.56 \cdot 10^8$	50
G0 V	6030	4.39	$3.26 \cdot 10^8$	45
G5 V	5770	4.49	$1.88 \cdot 10^8$	40
K0 V	5250	4.49	$7.53 \cdot 10^7$	35
K5 V	4350	4.54	$1.14 \cdot 10^7$	26
M0 V	3850	4.59	$1.84 \cdot 10^6$	22

RESULTS AND DISCUSSION

Figure I shows snapshots of wave calculations for several indicated main sequence stars, together with the emerging WM line profiles of Ca II K and Mg II k both for CRD and PRD. Note that the initial radiative equilibrium model is also seen, together with the RE line profiles. All models show the limiting shock strength behaviour. After a shock is fully developed, the shock strength remains essentially constant, despite the fact that the density decreases rapidly towards greater height. The temperature inversion starts at the point of shock formation, leading either to a slowly increasing, with height, mean chromospheric temperature structure or to elevated temperature plateaus. At great height the rapid temperature rise indicates the onset of the transition layer.

Particularly for the CRD profiles it is seen that the RE background strongly decreases and that the profiles narrow with later spectral type. Note that the wavelength scale for the K5V star is different from that of the F5V and G5V stars in Fig. I. The narrowing of the emission core is due to the relative decrease of the electron density despite the increase of the gas pressure towards later spectral type on the main sequence. In addition, the PRD emission is strongly tied to the Doppler core of the line as discussed by Cuntz, Ulmschneider and Rammacher

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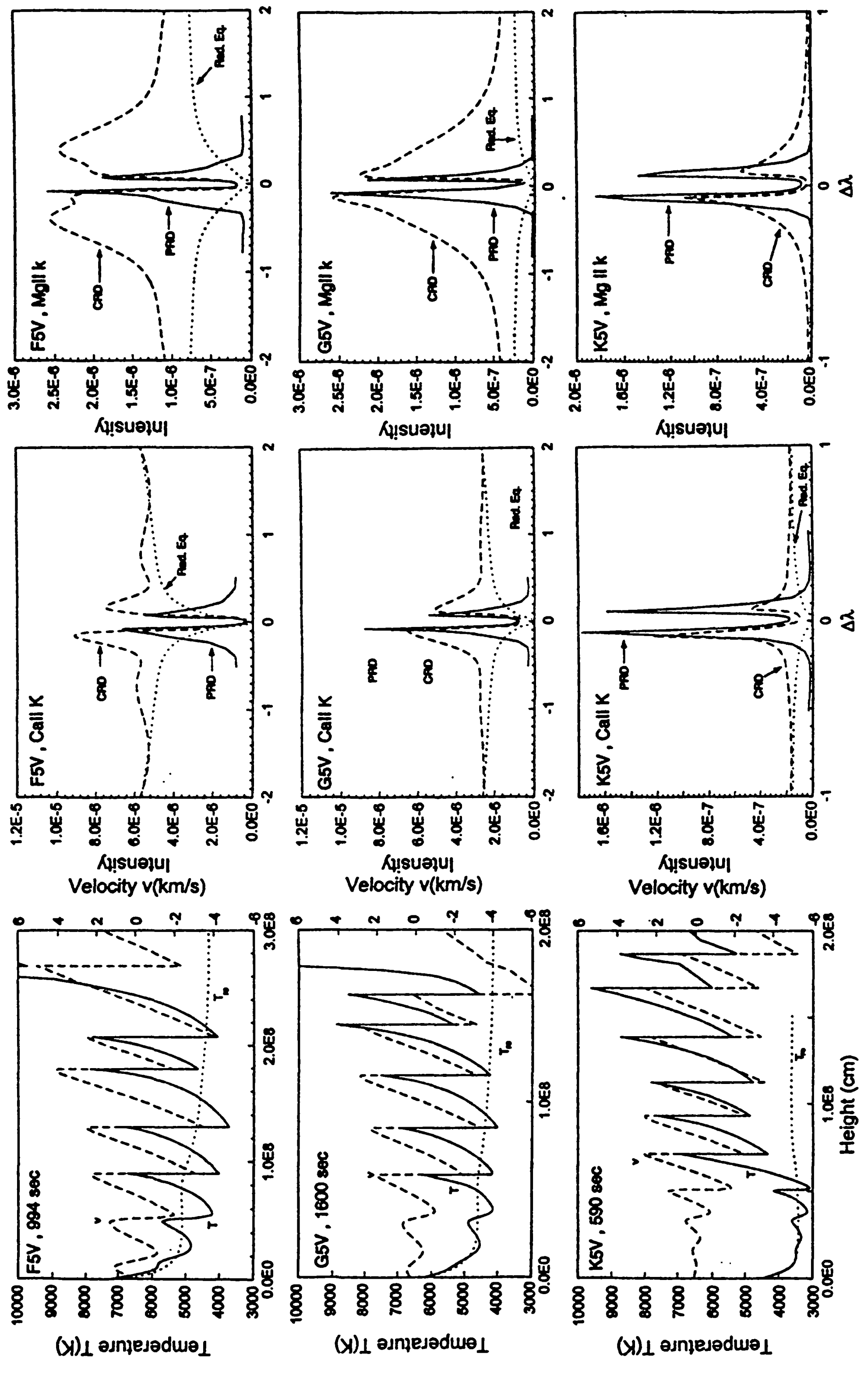

FIGURE I Snapshots of wave calculations for late type main sequence stars. Intensities are in erg/ cm^2 s sr Hz.

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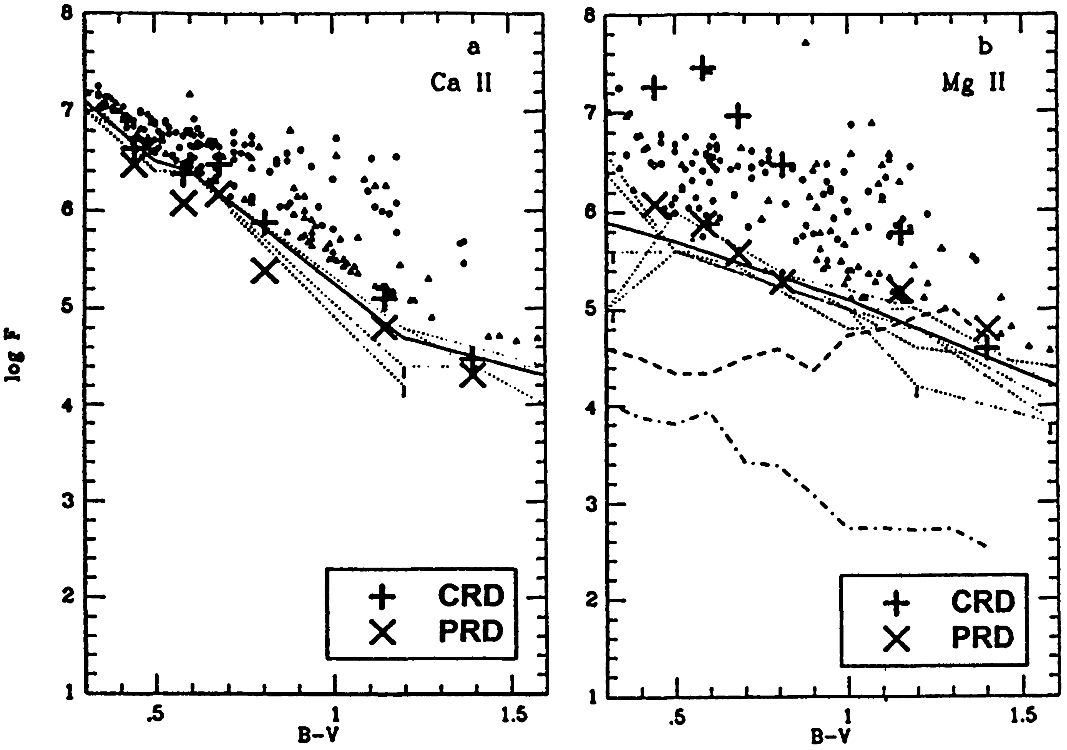

FIGURE II Theoretical emission fluxes compared with empirical fluxes of Rutten et al. (1991).

(1994), and thus narrows with decreasing T_{eff}. The theoretical emission fluxes obtained as discussed above are given in Tab. II and for comparison are plotted in Fig. II, together with empirical fluxes by Rutten et al. (1991). It is seen that our PRD fluxes agree rather nicely with the observed basal flux line. The CRD results, particularly in the Mg II case, appear to be far too large. As other work (Hünerth and Ulmschneider 1994) also shows that CRD fluxes greatly overestimate the true emission fluxes, we conclude that the CRD assumption is bad and should be avoided in future computations. In addition, as pointed out by Schrijver (1993, private communication) the Ca II values of Rutten et al. include some RE background and thus for comparison with our values should be moved downward in Fig. II. This improves the agreement of our values wi th the Ca II observations.

It is possible that the theoretical emission flux, derived from a jumpy atmospheric wave model changes with the phase of the wave. Calculations for different phases, however, do not show much variation of the emission flux. The relatively good agreement of our theoretical PRD fluxes with the basal flux line thus appears to be strong evidence for acoustic waves as the basic heating mechanism of chromospheres. This support of the acoustic heating picture has to be seen together with similar results for giants (Cuntz and Ulmschneider 1994, this volume, Ulmschneider 1989).

Despite the obvious limitations of our present exploratory calculations, where not too well known acoustic fluxes and periods had to be used and where monochromatic wave computations instead of full acoustic spectrum calculations

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TABLE II Theoretical basal emission fluxes for main sequence stars based on acoustic wave calculations.

Star	B - V	log F_{basal}			
		CaII CRD	CaII PRD	MgII CRD	MgII PRD
F5 V	0.44	6.6	6.5	7.3	6.1
G0 V	0.58	6.4	6.1	7.5	5.9
G5 V	0.68	6.5	6.2	7.0	5.6
K0 V	0.81	5.9	5.4	6.5	5.3
K5 V	1.15	5.1	4.8	5.8	5.2
M0 V	1.40	4.4	4.3	4.6	4.8

were performed, we consider our present results as the first definite proof that acoustic heating seems to be important in all late-type stars. This result was already suspected much earlier. It is a basic fact that all turbulent convection zones invariably generate acoustic waves. But there is a crucial point: is the generated acoustic energy, in view of the other mechanisms, significant enough for the heating of the stellar chromospheres? The result of the present work is that acoustic heating definitely is important.

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