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Theoretical Stellar Chromospheres of Late Type Stars

IV. Temperature Minima for Dwarf Stars

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Summary. Theoretical chromosphere models for five late type dwarf stars have been computed with the acoustic heating theory on the basis of the Lighthill-Proudman and mixing length theories. For stars of $T_{\rm eff}$ greater than 5200 K we find good agreement between empirical and theoretical positions of the temperature minima as well as between the semiempirical chromospheric radiation flux and the acoustic flux at the temperature minumum. This supports the validity of the acoustic heating theory. A considerable discrepancy is however found for late type dwarf stars where acoustic flux is clearly missing. This however does not indicate that the acoustic heating theory is wrong but that the theory of acoustic energy production is insufficient for these stars.

Key words: acoustic heating – theoretical temperature minima – chromospheric radiation loss

1. Introduction

In this series of papers we test the ability of the short periodic acoustic heating theory to predict observed parameters of stellar chromospheres. Paper I (Renzini et al., 1977) describes the calculation of the acoustic energy flux which is generated in the convection zone. As argued by Schmitz and Ulmschneider (1979, Paper III) this flux very likely has to be revised upwards by a factor of two to account for the reflection of the inward going acoustic energy. Paper II (Ulmschneider et al., 1977) describes the calculation of shock formation heights carried out using non grey stellar atmosphere models. However the methods used in that work allow only to calculate weak shocks and thus do not permit construction of theoretical chromosphere models. The method of construction of theoretical chromosphere models is discussed by Ulmschneider et al. (1978, 1979) as well as in Paper III. Here the development of acoustic shock waves is followed until the time averaged physical parameters like temperature, pressure, etc. attain a steady state.

In this work good agreement was found between the theoretical heights of the temperature minimum m_T measured in terms of mass column density and the heights m_E derived from semiempirical models of Ayres and Linsky (1975), Kelch (1978), and Kelch et al. (1978) for late type stars with high effective temperature or low gravity. Independently for the same type of stars relatively good agreement was found between the acoustic flux at the temperature minimum F_{MT} and the semiempirical chromospheric radiation fluxes F_E computed on basis of the empirical chromosphere models. However as noted in Paper III discrepancies were found for dwarf stars especially late type dwarfs. That for these types of stars the acoustic flux computed with the Lighthill-Proudman and mixing length theories is insufficient has already been found e.g. by Blanco et al. (1974) who measured Ca II K emission fluxes for a large sample of stars and by Cram and Ulmschneider (1978) who compared empirical temperature minima with shock formation heights. It is thus of great interest to further investigate the dwarf stars especially as new empirical models have recently become available (Kelch et al., 1979).

2. Method and Results

As the method of computation of theoretical chromospheric models on basis of the short period acoustic heating theory has been described in detail elsewhere (Ulmschneider et al., 1978, and Paper III) we do not repeat it here. Table 1 and Fig. 1 show the adopted model parameters and the results of our computations for the five dwarf stars θ Boo, 59 Vir, HD 76151, 61 UMa, and EQ Vir.

To reduce the amount of numerical work we now use a single value $\alpha = 1.25$ of the ratio of mixing length and pressure scale height intermediate between the values 1.0 and 1.5 used in previous work. We calculate models both with the revised and the unrevised initial acoustic fluxes F_{M_0} of Paper I. This revision by a factor of two of the generated acoustic flux is necessary as the inward going acoustic flux very likely is reflected in the convection zone due to the with depth increasing sound speed (Paper III). With the $\alpha^{2.8}$ dependence of F_{M_0} found in Paper I the dependence of theoretical parameters on α can be estimated.

The semiempirical chromospheric H^- radiation fluxes have been calculated as described in Paper III. Here the semiempirical chromosphere models of Kelch et al. (1979) have been used. The values F_{H^-} thus obtained are given in Table 1. For chromospheric radiation loss due to the Ca II H and K and Mg II h and k lines we have used values $F'(K_1)$, $F'(H_1)$ obtained by Linsky et al. (1979). We have assumed that the Mg II and Ca II contributions are equal and that $F'(H_1) = F'(K_1)$ if only the K line flux is given. These fluxes together with the H^- fluxes constitute the semiempirical chromospheric radiation flux F_E given in Table 1.

As for EQ Vir the empirical radiation flux is greater than the initial acoustic flux F_{M_0}, we have calculated cases where this flux is revised upwards by factors of 10 and 100. Interpolating between these results we find that a flux $F_{M_0} = 2.3\ 10^7$ erg cm^{-2} s^{-1} minimizes the discrepancy between m_T and m_E and simultaneously

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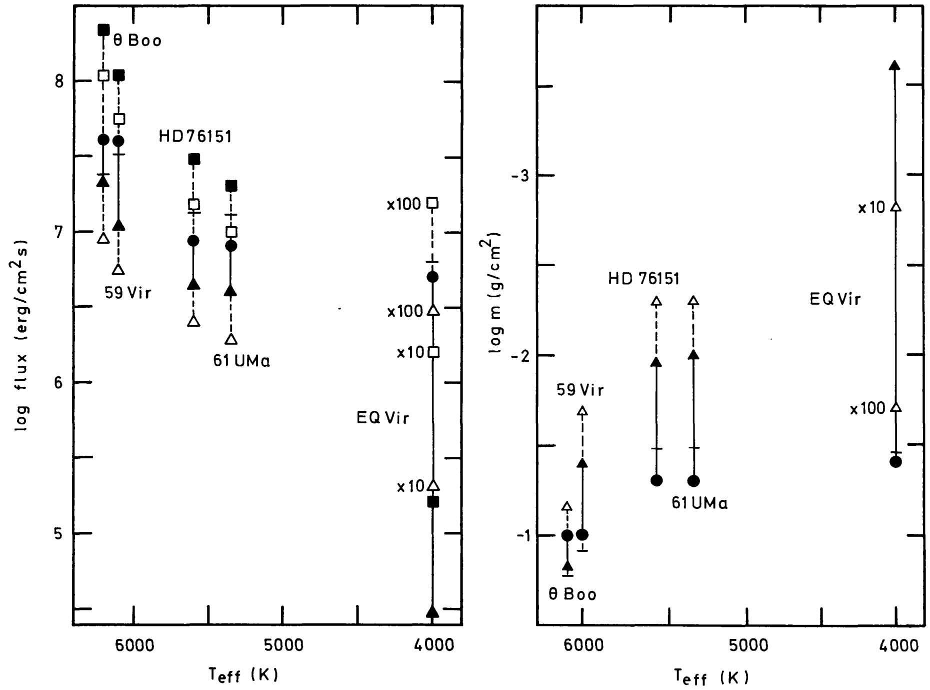

Fig. 1. Theoretical (triangles) and empirical (circles) chromospheric fluxes as well as theoretical (triangles) and empirical (circles) heights m of temperature minima (measured in terms of mass column density) for five stars. Squares indicate initial acoustic fluxes generated in the convection zone and given by Paper I with a revision after Paper III. Open symbols show results for initial acoustic fluxes without this revision. For EQ Vir open symbols indicate results for initial acoustic fluxes revised by factors of 10 and 100. Horizontal bars show results for initial acoustic fluxes chosen such that both the height errors and the flux errors are minimized

Table 1. Adopted model parameters, spectral type, effective temperature $T_{\rm eff}$ and surface gravity g for five stars. The initial acoustic flux generated in the convection zone F_{M_0} (revised by a factor of two) and acoustic period P are evaluated after Paper I. The heights of shock formation m_s, of theoretical temperature minima m_T and empirical temperature minimum heights m_E are measured in terms of mass column density. The acoustic flux at the height of shock formation F_{MS} and at the temperature minimum F_{MT} are compared with semiempirical chromospheric radiation flux F_E. F_{H^-} is the H^- contribution to F_E. T_T is the minimum temperature in the theoretical and T_E in the empirical models. v_T is the velocity amplitude of the acoustic wave at the theoretical temperature minimum. Values in brackets are for the unrevised initial acoustic fluxes F_{M_0} as given by Paper I. For EQ Vir brackets show results for initial fluxes F_{M_0} increased by factors of 10 and 100. All models are based on a ratio $\alpha = 1.25$ of mixing length and pressure scale height

	θ Boo	59 Vir	HD 76151	61 UMa	EQ Vir
Spectral type	F7 IV-V	F8V	G5V	G8V	dK7e
$T_{\rm eff}$ (K)	6200	6100	5600	5350	4000
log g (cm/s^2)	4.0	4.4	4.6	4.5	4.4
F_{M_0} (erg/cm^{2}s)	2.2E8(1.1E8)	1.1E8(5.5E7)	3.0E7(1.5E7)	2.0E7(1.0E7)	1.6E5 [1.6E6, 1.6E7]
P (s)	85	33	19	23	21
m_S (g/cm^2)	1.0E0(3.6E-1)	6.5E-2(3.0E-2)	2.0E-2(8.0E-3)	1.5E-2(7.0E-3)	3.5E-4 [2.0E-3, 3.0E-2]
m_T (g/cm^2)	1.5E-1(7.0E-2)	4.0E-2(2.0E-2)	1.1E-2(5.0E-3)	1.0E-2(5.0E-3)	2.5E-4 [1.5E-3, 2.0E-2]
m_E (g/cm^2)	1.0E-1	1.0E-1	5.0E-2	5.0E-2	4.0E-2
F_{MS} (erg/cm^{2}s)	6.0E7(1.8E7)	1.4E7(6.5E6)	5.5E6(2.5E6)	4.0E6(1.9E6)	4.0E4 [2.5E5, 4.0E6]
F_{MT} (erg/cm^{2}s)	2.1E7(9.0E6)	1.1E7(5.5E6)	4.5E6(2.3E6)	3.2E6(1.7E6)	3.0E4 [2.0E5, 3.0E6]
F_{H^-} (erg/cm^{2}s)	3.8E7	3.3E7	8.8E6	7.8E6	4.8E6
F_E (erg/cm^{2}s)	4.1E7	4.1E7	8.8E6	8.1E6	7.6E6
T_T (K)	4810(4820)	4750(4770)	4440(4450)	4240(4260)	3230 [3200, 3180]
T_E (K)	5250	4770	4350	4190	3240
v_T (cm/s)	1.6E5(1.5E5)	1.3E5(1.2E5)	1.2E5(1.1E5)	1.1E5(1.1E5)	7.0E4 [9.0E4, 1.1E5]
f	1.3	3.1	3.0	3.2	145

between F_{MT} and F_E. We conclude that the theoretical flux F_{M_0} is too small by a factor $f=145$ for EQ Vir. Similarly for the other stars acoustic fluxes fF_{M_0} have been extrapolated from values given in Table 1 such that both the discrepancy between m_T and m_E and the disparity between F_{MT} and F_E are minimized to less than a factor of 1.7. These factors f are given in Table 1 and are always in the direction that more acoustic energy is needed. Note in Fig. 1 and Table 1 for all our stars an increase of the initial acoustic flux F_{M_0} by a factor of two increases the mass column density m_T by a factor of two as well as the acoustic flux F_{MT} by a factor of two.

3. Discussion

a) On the Validity of the Short Period Acoustic Heating Theory

In Paper III we have shown that if the short period acoustic heating theory is valid two conditions must be satisfied simultaneously. Firstly the acoustic waves must produce a theoretical temperature minimum m_T at a height that coincides with the temperature minimum m_E of the empirical chromosphere model. Secondly quite independently, the acoustic flux F_{MT} at the temperature minimum must be sufficient to balance the empirical chromospheric radiation flux F_E. Only the correct heating mechanism will be able to satisfy both conditions. In the present work we have shown that for all stars an initial acoustic flux fF_{M_0} (see Table 1) may be found such that the disparity between m_T and m_E and between F_{MT} and F_E can both be minimized to less than a factor of 1.7.

This naturally depends on the acoustic period of our waves which has been taken as one tenth (Paper I) of the acoustic cut-off period at the top of the convection zone. However Ulmschneider et al. (1978) have shown that the acoustic period did only in a minor way influence the position of the theoretical temperature minimum for the Sun and that m_T is primarily a function of the initial acoustic flux. We thus conclude that our present results give strong support for the validity of the acoustic heating mechanism. This same conclusion has been reached in Paper III where further arguments for the validity of the acoustic heating theory are given. The present work considerably improves the statistical basis in favour of this theory.

In addition to the support for the acoustic heating theory from consideration of m_T, m_E, and F_{MT}, F_E we presently find that except for EQ Vir the Lighthill-Proudman and mixing length theories predict an initial acoustic flux F_{M_0} within a factor of three compared to fF_{M_0}. As shown for the Sun in Paper III (Sect. 3e) a factor of 2.5 in m_T could be obtained from the use of a realistic non grey photospheric model. In addition, as discussed by Gough (1976) and Cram (1977) as well as in Paper III, the large uncertainty of the Lighthill-Proudman and mixinglength theories should be kept in mind. In view of this uncertainty the errors found in Fig. 1 and Table 1 are quite small.

b) Discrepancy for EQ Vir

As found in Paper III for 70 Oph A we again find in the present work that a discrepancy in the acoustic flux exists for late type dwarf stars of $T_{\rm eff} < 5200$ K. Such a discrepancy has already been found by Blanco et al. (1974) by comparing acoustic fluxes with semiempirical chromospheric Ca II K emission fluxes and by Cram and Ulmschneider (1977) who compared m_E and shock formation heights m_s. For late type dwarf stars the heights of shock formation m_S and of the temperature minimum are closely related as is seen in Table 1.

This flux discrepancy is difficult to explain. In Paper III it was suggested that a better treatment of the top of the convection zone including a non grey calculation using additional opacity sources (molecules) might be helpful. The consideration of stratification in the acoustic energy generation (Bohn, 1979) brings a considerable increase of the acoustic flux. Taking stratification into account Bohn (1979) finds for EQ Vir a flux of $F_{M_0}=8.3E5$ erg cm^{-2} s^{-1} for $\alpha=1.25$. This amounts to an increase by a factor of five relative to the value F_{M_0} of Table 1. However it appears that the initial acoustic flux is still too small by a factor of 28.

There is another possibility to explain the flux discrepancy for EQ Vir. Linsky (1979) has pointed out that EQ Vir is a very active chromosphere star. As discussed in Paper III the large difference in Mg II and Ca II emissions between active and quiet chromosphere stars (Linsky, 1979) with smaller $T_{\rm eff}$ and gravity suggests the action of another heating mechanism which is associated with the magnetic field. Strong magnetic fields are expected for late type dwarf stars (Coleman and Worden, 1976) and a possibility for such a mechanism might be more efficient energy generation in the presence of strong magnetic fields (Kulsrud, 1955).

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References

Ayres, T.R., Linsky, J.L.: 1975, *Astrophys. J.* **200**, 660

Blanco, C., Catalano, S., Marilli, E., Rodono, M.: 1974, *Astron. Astrophys.* **33**, 257

Bohn, H.U.: 1979, *Astron. Astrophys.* (to be published)

Coleman, G.D., Worden, S.P.: 1976, *Astrophys. J.* **205**, 475

Cram, L.E.: 1977, *Astron. Astrophys.* **59**, 151

Cram, L.E., Ulmschneider, P.: 1978, *Astron. Astrophys.* **62**, 239

Gough, D.O.: 1976, *Proc.* IAU *Coll.* **36**, R.M. Bonnet, P. Delache, Eds., Clermont-Ferrand, p. 3

Kelch, W.L.: 1978, *Astrophys. J.* **222**, 931

Kelch, W.L., Linsky, J.L., Basri, G.S., Chin, H.Y., Chang, S.H., Maran, S.P., Furenlid, I.: 1978, *Astrophys. J.* **220**, 962

Kelch, W.L., Linsky, J.L., Worden, S.P.: 1979, *Astrophys. J.* **229**, 700

Kulsrud, R.M.: 1955, *Astrophys. J.* **121**, 461

Linsky, J.L.: 1979, (private communication)

Linsky, J.L., Worden, S.P., Mc Clintock, W., Robertson, R.M.: 1979, *Astrophys. J. Suppl.* (to be published)

Renzini, A., Cacciari, C., Ulmschneider, P., Schmitz, F.: 1977, *Astron. Astrophys.* **61**, 39

Schmitz, F., Ulmschneider, P.: 1979, *Astron. Astrophys.* (to be published)

Ulmschneider, P., Schmitz, F., Renzini, A., Cacciari, C., Kalkofen, W., Kurucz, R.: 1977, *Astron. Astrophys.* **61**, 515

Ulmschneider, P., Schmitz, F., Kalkofen, W., Bohn, H.U.: 1978, *Astron. Astrophys.* **70**, 487

Ulmschneider, P., Schmitz, F., Hammer, R.: 1979, *Astron. Astrophys.* **74**, 229