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Heating of Stellar Chromospheres when Magnetic Fields are Present

P. Ulmschneider[1] and R.F. Stein[2]*

[1] Institut für theoretische Astrophysik, Im Neuenheimer Feld 294, D-6900 Heidelberg, Federal Republic of Germany
[2] Observatoire de Nice, B.P. 252, F-06007 Nice Cedex, France

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Summary. From recent semi-empirical solar models of Vernazza, Avrett and Loeser (1981), from OSO–8 observations and from the stellar Mg II emission line fluxes of Basri and Linsky (1979) constraints on possible chromospheric heating mechanisms are derived. It is shown that a picture where non-magnetic regions are heated by acoustic shock waves and magnetic regions by slow mode shock waves appears to best satisfy the observational facts. For the high chromosphere this mechanism must be supplemented or replaced, possibly by Alfvén wave heating.

Key words: solar chromosphere – stellar chromospheres – acoustic heating – magnetohydrodynamic heating

1. Introduction

In the last few years greatly refined observations of both solar and stellar chromospheres have become available. The new solar data derive mainly from *Skylab* in the EUV wavelength range between 40 and 140 nm. As Vernazza, Avrett and Loeser (1981) have shown, these data can be used to derive semi-empirical models for six different types of regions on the sun. These regions differ mainly in their magnetic flux, that is the fraction of the area pierced by magnetic flux tubes. The derived semi-empirical models thus allow one to study the dependence of the physics of stellar chromospheres on the magnetic field.

That magnetic fields greatly influence stellar chromospheres has also been deduced from stellar Ca II and Mg II emission line observations. Linsky and Ayres (1978) and Basri and Linsky (1979) have shown that for stars of the same effective temperature T_{eff} and gravity g there is no unique Ca II or Mg II emission flux as might be deduced from a purely acoustic wave chromospheric heating mechanism. One observes instead that stars of similar T_{eff} and g exhibit Ca II and Mg II emission fluxes which differ by a factor of 10. This has been interpreted as due to variation in the magnetic field coverage of these stars.

Recently Stein (1981) has described how magnetic fields affect the generation of magneto-hydrodynamic waves by turbulence. The picture that emerges is that of slow mode wave heating of the chromosphere in intense magnetic field areas, acoustic heating in non-magnetic regions, and Alfvén wave heating of the corona. Section 2 describes the empirical evidence, Sect. 3 the theoretical evidence and Sect. 4 gives our conclusions.

2. Empirical Evidence

Recently Vernazza et al. (1981, henceforth called VAL 81) have presented a series of semi-empirical solar models valid for various regions of different magnetic field strength. The lower solar atmosphere appears to consist essentially of areas of weak or no magnetic field strength penetrated by various numbers of isolated narrow flux tubes of strong (~2000 Gauss) magnetic fields (Roberts and Webb, 1978; Stenflo, 1978; Zwaan, 1978). In order to discuss the chromospheric heating mechanism we consider two of the VAL 81 models, A and F, which appear to best represent this essentially two component nature of the solar atmosphere. Model F represents a very bright network element where presumably the magnetic field strength is in the kilogauss range, while model A is valid for a dark point within a cell where there is probably little or no magnetic field strength. Figure 1 shows the temperature structure and the net radiative cooling rate (Avrett, 1981) for models A and F. It has to be kept in mind that the VAL 81 models are based on observations which have a $5'' \times 5''$ resolution and the disparity between models A and F very likely would be much greater if higher resolution observations were used. In addition these models possibly suffer from the approximate manner in which they take into account the dynamical nature of the atmosphere (see Ulmschneider, 1979). Nevertheless these empirical models show interesting features from which one may derive information about the chromospheric heating mechanism. In the following a few of these empirical facts are summarized:

a) The temperature minima occur at roughly the same height ($x_T \simeq 500$ km) in both cases (Fig. 1). The temperature minimum height in the magnetic model F is actually somewhat lower (by $\Delta x_T \simeq 70$ km) than in model A. This relatively small variation of the height of the temperature minimum with magnetic field strength is also seen in stars other than the sun. A well known property of the Wilson-Bappu effect (Wilson and Bappu, 1957; Glebocki and Stawikowski, 1978) is that the relation between the absolute visual magnitude M_v and the width of the emission core of the Ca II K line is largely independent of the age of the star and thus of the magnetic field coverage. Note that the width of the emission core relates to the height of the temperature minimum (see e.g. Ayres, 1979; Ulmschneider, 1979).

Send offprint requests to: P. Ulmschneider

* Permanent address: Physics Department, Michigan State University, East Lansing, MI 48824, USA

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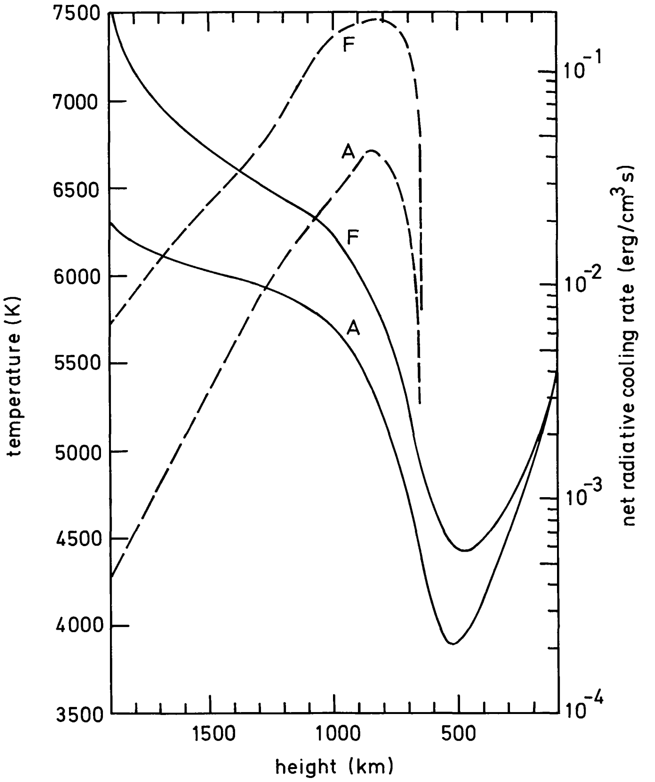

Fig. 1. Temperature (solid, Vernazza et al., 1981) and net radiative cooling rate (dashed, Avrett, 1981) as a function of height in the solar atmosphere. *F* indicates a model for a bright network element and *A* a model for a dark point within a supergranulation cell

b) Model F compared to model A shows a photospheric temperature enhancement which increases from zero in the low photosphere to $T \simeq 500$ K at the temperature minimum. The chromosphere in model F is hotter everywhere by about $\Delta T \simeq 500\ K$ relative to model A.

c) Both models (see Fig. 1) show a rapid onset of net radiative cooling at heights just above the temperature minimum ($x \simeq 600$ km) to values of around $dF_R/dx \simeq 0.1$ erg/cm^3 s. The net radiative cooling rate rises by three orders of magnitude within a distance of only 100 km.

d) The net radiative flux emitted by the chromosphere in model F is a factor of six larger than the flux emitted by model A.

e) In model F the net radiative cooling decreases with height in the chromosphere much more slowly than in model A.

Additional evidence on the chromospheric heating mechanism can be derived from stellar observations. Recently Linsky and Ayres (1978) as well as Basri and Linsky (1979) have presented empirical Ca II and Mg II emission fluxes for a considerable sample of late type stars. From their data these authors derive properties which set stringent conditions on the chromospheric heating mechanism:

f) Linsky and Ayres (1978) as well as Basri and Linsky (1979) conclude that the stellar Mg II flux, $F_{\rm Mg\,II}$, averaged over the whole star shows no apparent dependence on the gravity of the star.

g) The observed flux $F_{\rm Mg\,II}$ shows a dependence on the effective temperature $T_{\rm eff}$ of the stars (Basri and Linsky, 1979; Fig. 3) roughly like

$$F_{\rm Mg\,II}/\sigma T_{\rm eff}^4 \simeq 1.32\ 10^{-19}\ T_{\rm eff}^{3.78} \qquad (1)$$

h) There are stars which have the same $T_{\rm eff}$ and gravity but emit fluxes $F_{\rm Ca\,II}$ and $F_{\rm Mg\,II}$ which differ by a factor of ten.

Finally Athay and White (1978, 1979) as well as Bruner (1978) have analysed OSO–8 observations of line profiles to determine the nonthermal velocity. They conclude that:

i) The acoustic flux in the higher chromosphere and lower transition layer appears to be small ($\sim 10^4$ erg/cm^{2}s) compared to the total transition layer and coronal energy loss rate ($\sim 5\ 10^5$ erg/cm^2 s). These authors point out that an Alfvén wave flux sufficient to heat the corona would be consistent with their observations.

Mein and Schmieder draw similar conclusions from their observations of Mg II and Ca II lines in the visible (Mein, 1981).

3. Theoretical Evidence

a) Formation of the Temperature Minimum

For the sun as in all *S*-type chromosphere stars the height of the temperature minimum and the height of shock formation are intimately correlated (Schmitz and Ulmschneider, 1981; see also Ulmschneider, 1979, 1981). The empirical lowering of the temperature minimum height in the magnetic model F as compared to model A [empirical fact (a)] is consistent with an enhanced wave flux emerging in the magnetic regions [fact (d)]. It is well known that if one increases the initial acoustic flux at the top of the convection zone the height of the temperature minimum decreases (see e.g. Ulmschneider et al., 1978). For acoustic waves, as shown in Fig. 2, that height depends quite sensitively on the initial acoustic flux. A factor of six increase in the acoustic flux which corresponds to the difference of the chromospheric flux between models A and F lowers the temperature minimum height by about $\Delta x = 220$ km, which is considerably larger than $\Delta x = 70$ km seen in the empirical models. How can this discrepancy be explained? Clearly the approximations made in the computation of Fig. 2, neutral gas, vertical monochromatic acoustic waves with grey LTE radiation and the Kurucz (1979) opacity table, are quite severe. For example radiation transfer computed in a non-grey manner would obviously modify the amount of photospheric radiation damping. But there is another explanation which points towards slow mode waves. Two processes decrease the amplitude of slow mode waves and thus retard the process of shock formation: First, in slow mode waves energy is stored as magnetic as well as compressional and kinetic energy, leading to a decrease of the velocity amplitude relative to acoustic waves for the same energy flux. Second, spreading of the flux tube with height distributes the wave energy over an increasingly greater area and hence also decreases the amplitude of the wave. The height of shock formation x_S for slow mode waves in model F is thus expected to be much closer to the height x_S in model A than for purely acoustic waves. The photospheric temperature enhancement [fact (b)] is presently not well understood. Here the nonlinearity of the Planck function for waves with large amplitude (Schmitz and Ulmschneider, 1981) and the short period wave spectrum could be important.

b) The Low Chromosphere

Theoretical chromospheric models (Ulmschneider et al., 1978; Stein and Klein, 1980, unpublished) with acoustic wave heating and grey-LTE radiative cooling show that shock dissipation by short period acoustic waves increases rapidly above the tempera-

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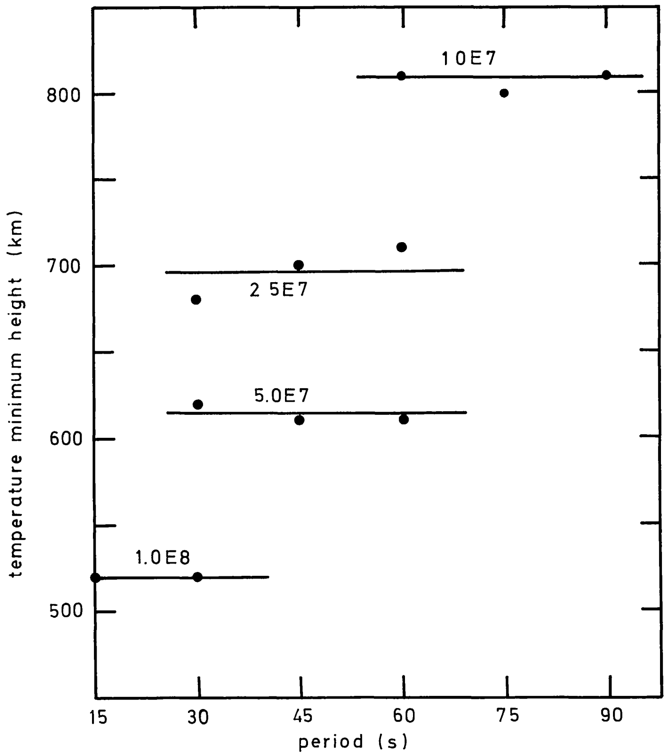

Fig. 2. Temperature minimum heights (dots) in theoretical chromosphere models generated by acoustic shock wave heating. The heights depend little on the wave period. The initial acoustic flux (in erg/cm^{2}s) at the top of the convection zone is shown as parameter. Lines are mean heights. The theoretical models are produced in the same manner as described by Schmitz and Ulmschneider (1981)

ture minimum in roughly one quarter wavelength from incipient shock formation to a fully developed shock, and has the correct magnitude to balance the radiative losses calculated by VAL 81 [0.1 erg/cm^3 s, empirical fact (c)]. Thus acoustic waves and slow MHD waves (which are essentially acoustic waves channeled by the magnetic flux tubes) presumably provide the energy input for the low chromosphere in non-magnetic regions and strong magnetic flux tubes respectively. That waves of higher energy generate hotter chromospheres [fact (b)] is a regular feature of the above cited theoretical models.

c) The High Chromosphere

The heating of the high chromosphere is more difficult to explain. On the one hand, the observations of Athay and White (1978, 1979) as well as Bruner (1978) and Mein (1981) show that the acoustic flux in the upper chromosphere is possibly quite low, although there are large uncertainties (Ulmschneider and Bohn, 1981). On the other hand, it can be seen from Fig. 5 of Ulmschneider et al. (1978) that once shock waves are formed they rapidly dissipate their energy. Calculations of Stein and Vernazza (1980, unpublished) moreover show that because of their dissipation in shocks, short period purely acoustic waves quite generally have difficulties transporting energy to the upper chromosphere [empirical fact (e)]. Long period acoustic waves cannot transport enough energy either, because they are evanescent in the temperature minimum region. Although these calculations are quite crude it appears that heating both from acoustic and from slow mode waves operates mainly in the lower and middle chromosphere. Thus both empirical and theoretical considerations seem to point to another heating mechanism for the high chromosphere.

This possibly missing magnetic type, heating mechanism [constraints (e), (i)] ties in nicely with the presence of large wave fluxes of Alfvén waves as shown by Stein and Leibacher (1980) as well as Stein (1981). In our discussion of wave generation below we show that slow mode and Alfvén waves are both very efficiently produced, much more efficiently than acoustic or fast mode waves. If a dissipation mechanism for Alfvén waves could be found, possibly along the lines of Ionson (1978) and Wentzel (1979) or through mode coupling as suggested by Uchida and Kaburaki (1974), a coherent picture of the acoustic and magnetohydrodynamic wave heating of stellar chromospheres and possibly even coronae would emerge. While some authors view the transport and dissipation of energy in terms of current flow and dissipation, in most cases this is equivalent to MHD wave propagation and dissipation. Magnetic flux emergence is, however, a different mechanism, which alters the magnetic field geometry.

d) Wave Generation

Our comparison of observational and theoretical evidence so far suggests that the low chromosphere is heated by acoustic type slow mode waves in strong flux tubes and purely acoustic waves in nonmagnetic regions, while the upper chromosphere and the corona is heated by Alfvén waves. Let us now consider the generation of these waves.

In field free regions the acoustic emission is produced predominantly by a quadrupole type volume deformation of gas elements enforced by the convective bubbles. Because the generation for fast mode waves is essentially isotropic, as for acoustic waves, one has a quadrupole type generation. For slow mode and Alfvén mode waves which are restricted to propagate along the field lines one has monopole type energy generation. The slow mode waves are produced by bubbles that produce sausage type deformations of flux tubes while the Alfvén waves are produced by bending and twisting of the flux tubes. For more details on magnetic tube waves see Spruit (1981 a, b).

Following Stein (1981) the wave flux generated by turbulent motions in the convection zone of cool stars is

$$F_M^{\mathrm{Acoust}} \simeq \varrho u^3 \left(\frac{u}{s}\right)^5 \tag{2}$$

in non-magnetic regions (which is the well known Lighthill formula) and in strong magnetic flux tubes is

$$F_M^{\mathrm{Fast}} \simeq \varrho u^3 \left(\frac{u}{a}\right)^5, \tag{3}$$

$$F_M^{\mathrm{Slow}} \simeq \varrho u^3 \left(\frac{u}{s}\right), \tag{4}$$

$$F_M^{\mathrm{Alfvén}} \simeq \varrho u^3 \left(\frac{u}{a}\right) \tag{5}$$

for the fast mode, slow mode and Alfvén mode fluxes. Here ϱ is the density, u the mean convective velocity, s the sound velocity and a

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1982A&A...106....9U

the Alfvén velocity. Numerical constants in Eqs. (2)–(5) are assumed to be of order unity.

From these admittedly crude estimates it appears that slow and Alfvén mode waves, due to the monopole nature of their generation are much more efficiently produced than acoustic waves. Since in the sun $s \simeq a$ at the visible surface, and $u/s \simeq 1/4$, the efficiency of slow and Alfvén wave generation is 100 times that of acoustic waves. This readily explains our constraint (d) that the radiation flux from the magnetic model F is considerably larger than from the non-magnetic model A. The magnetic enhancement of wave energy generation is also consistent with the variation of the Ca II and Mg II emission flux of stars of similar T_{eff} and gravity [empirical fact (h)]. Here similar stars have different ages and thus different magnetic field coverage.

We can estimate the actual magnitude of these wave energy fluxes. For late type stars with efficient convection one has at the top of the convection zone

$$F_{\mathrm{total}} = \sigma T_{\mathrm{eff}}^4 \simeq F_{\mathrm{conv}} = \frac{5}{\alpha} \varrho u^3. \qquad (6)$$

It is possible, following Stein (1966, p. 18, 1981) as well as Renzini et al. (1977), to use hydrostatic equilibrium to estimate ϱ and with Eq. (6) to estimate u at the top of the convection zone using an opacity law of

$$\kappa = 1.376\ 10^{-23} p^{0.738} T^5\ (\mathrm{cm}^2\,\mathrm{g}^{-1}) \qquad (7)$$

(Ulmschneider et al., 1978) which is a fit to more elaborate opacity tables of Kurucz (1979). One finds with $\alpha = 1.25$

$$\varrho \sim 1.51\ 10^{-8} g_4^{0.575} T_{\mathrm{eff}4}^{-3.88}\ (\mathrm{g\,cm}^{-3}), \qquad (8)$$

$$u \sim 2.11\ 10^6 g_4^{-0.192} T_{\mathrm{eff}4}^{2.63}\ (\mathrm{cm\,s}^{-1}). \qquad (9)$$

Here $g_4 = 10^{-4}\,g$ and $T_4 = 10^{-4}\,T$. [Note that in Eq. (11) of Renzini et al. (1977) are misprints.]

Together with the sound speed

$$s = (\gamma RT/\mu)^{1/2} \simeq 1.03\ 10^6 T_4^{1/2}\ (\mathrm{cm\,s}^{-1}) \qquad (10)$$

and the Alfvén speed

$$a = B/(4\pi\varrho)^{1/2} \simeq 2.30\ 10^6 B_3 g_4^{-0.288} T_4^{1.94} (\mathrm{cm\,s}^{-1}), \qquad (11)$$

where γ is the ratio of specific heats, R the gas constant, μ the mean molecular weight and B the magnetic induction ($B_3 = 10^{-3} B$) one obtains from Eqs. (2)–(5) the acoustic and magnetohydrodynamic wave fluxes (Renzini et al., 1977; Stein, 1981)

$$F_M^{\mathrm{Acoust}}/\sigma T_{\mathrm{eff}}^4 \simeq 9.1\, g_4^{-0.959} T_{\mathrm{eff}4}^{10.6}, \qquad (12)$$

$$F_M^{\mathrm{Fast}}/\sigma T_{\mathrm{eff}}^4 \simeq 0.2\, g_4^{0.479} T_{\mathrm{eff}4}^{3.44} B_3^{-5}, \qquad (13)$$

$$F_M^{\mathrm{Slow}}/\sigma T_{\mathrm{eff}}^4 \simeq 0.5\, g_4^{-0.192} T_{\mathrm{eff}4}^{2.13}, \qquad (14)$$

$$F_M^{\mathrm{Alfvén}}/\sigma T_{\mathrm{eff}}^4 \simeq 0.2\, g_4^{0.096} T_{\mathrm{eff}4}^{0.69} B_3^{-1}. \qquad (15)$$

It is suggestive to compare these dependencies with those derived from the Mg II emission fluxes [facts (f) and (g)]. Unfortunately a direct comparison is not possible as the theoretical fluxes are valid for the top of the convection zone while the Mg II emission fluxes, aside from being only one of many loss mechanisms, pertain to the chromosphere. Highly idealized calculations of the propagation of acoustic waves (e.g. Stein and Schwartz, 1972, 1973; Schmitz and Ulmschneider, 1980a, b) show that in many stars a large amount of radiation damping occurs in the photosphere. Capella ($\alpha = 1.5$) for example loses a factor of 51 of the acoustic flux by radiation damping in the photosphere, Arcturus ($\alpha = 1.5$) a factor of 34, Pollux ($\alpha = 1.5$) a factor of 9, the sun ($\alpha = 1.5$) a factor of 7 and 70 Oph A ($\alpha = 1.5$) a factor of 5. In spite of the considerable uncertainty in these calculations due to the many approximations made it is clear that photospheric radiation damping will lead to a considerable modification of both the T_{eff} and the gravity dependence for acoustic waves. Similar although possibly smaller modifications are expected for slow mode waves. Nevertheless a crude comparison of the theoretical fluxes given by Eqs. (12)–(15) with the Mg II observations [facts (f), (g)] shows that contrary to the acoustic fluxes, which have rather large T_{eff} and gravity dependences, the slow mode waves show both a reduced T_{eff} and a very small gravity dependence. Since on the sun Mg II emission occurs mainly in the network, we expect that on other stars one would primarily see the effect of slow mode waves. Thus our heating picture appears consistent with the empirical constraints (f) and (g). In view of missing information about the details of the magnetic field coverage (strength and filling factor) of stars however we want to emphasize the great uncertainty of the present picture. In particular agreement between MHD wave generation dependence on T_{eff} and g and UV flux measurements requires that there be no strong correlation of the average magnetic field coverage with T_{eff} or g. Yet the present picture could nicely explain the well-correlated stellar UV and X-ray emission recently found by Ayres, et al. (1981).

4. Conclusion

The heating mechanism of stellar chromospheres has to satisfy observational facts summarized in Sect. 2. These constraints have been deduced from the detailed semi-empirical solar models A and F of VAL 81, from OSO-8 observations, from solar Ca II and Mg II observations in the visible as well as UV, and from the behaviour of stellar Ca II and Mg II emission line strengths.

It was found that one of the most stringent conditions, (c), namely that for the sun the net radiative cooling rate just above the temperature minimum rises by three orders of magnitude within a height distance of only 100 km to a value of about 0.1 erg/cm^3 s, can be satisfied if the formation and dissipation of hydrodynamic shocks is assumed. As this conclusion must be valid for both the magnetic model F and the non-magnetic model A one arrives at the following heating picture of the lower and middle chromosphere: Non-magnetic regions are heated by acoustic shock waves as has been thought previously. Magnetic regions assumed to exist in flux tubes of small diameter with intense magnetic field strength are heated by slow mode shock waves. These slow mode waves are generated much more efficiently than acoustic waves (Stein, 1981), because the magnetic field channels the gas motions along the flux tube leading to monopole emission. Different magnetic field coverage of stars leads to different average wave flux generation and explains the Mg II and Ca II emission flux variation [constraint (h)]. The acoustic nature of slow mode waves explains the close similarity found in the temperature structure of both models A and F [facts (a)–(c)]. In a way almost the same mechanism is working in magnetic and non-magnetic regions. The gravity dependence of the Mg II emission flux in stars, observed to be small [constraint (f)], is explained by the small gravity dependence found for the slow mode wave-flux generation.

For the high chromosphere, empirical and theoretical evidence indicates insufficient heating by the acoustic and slow mode waves [constraint (i)]. Alfvén waves, whose energy flux is comparable to that of the slow waves [Eqs. (14) and (15)], but which dissipate over a longer distance, can supply the needed

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1982A&A...106....9U

energy to the corona. However, the heating must involve some additional process (such as coverage of the star by magnetic flux tubes, Alfvén wave transmission to the corona, of Alfvén wave dissipation) that varies with stellar properties. The observed x-ray flux in cool stars, $F_x \propto T_{\rm eff}^{-2}$, Vaiana et al. (1981) show that $L_x \simeq$ const, while Allen (1973) shows that the stellar radius $R_* \propto T_{\rm eff}$, so $F_x \propto L_x R_*^{-2} \propto L_x T_{\rm eff}^{-2}$. Note the mistaken sign in Eq. (36) of the Stein (1981) paper). This has a very different dependence on effective temperature than the Alfvén flux generation in strong magnetic field regions. The present acoustic, slow mode and Alfvén wave heating picture would nicely explain the well-correlated stellar UV and X-ray emission recently found by Ayres et al. (1981).

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