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WAVE HEATING AND RANGE OF STELLAR ACTIVITY IN LATE-TYPE DWARFS

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ABSTRACT

Theoretical time-dependent and two-component chromospheric models for late-type dwarfs are constructed based on acoustic and magnetic wave heating mechanisms. The models are used to predict the theoretical range of chromospheric activity for these stars. Comparison of this range with the one established observationally shows that the wave heating alone can explain most but not all of the observed range of stellar activity.

Subject headings: stars: activity — stars: chromospheres

1. INTRODUCTION

It is now well established that all late-type stars show chromospheric activity, which is typically identified with the presence of emission in the cores of the Ca II H + K and Mg II $h + k$ spectral lines. The observed activity varies significantly for a given spectral type (e.g., Linsky 1980; Schrijver 1987; Rutten et al. 1991; Stępień 1994; Baliunas et al. 1995). The fact that stars of the same spectral type have different levels of stellar activity is attributed to the presence of surface magnetic fields. Observations show that stars are more active when a larger portion of their surface is covered by magnetic fields and that the activity is most prominent in rapidly rotating stars (Noyes et al. 1984). For stars that rotate very slowly, a minimum chromospheric line core emission flux has been observed (Schrijver 1987; Rutten et al. 1991); this type of activity is usually referred to as "basal flux."

Direct measurements of stellar magnetic fields show that the photospheric magnetic flux increases when the stellar rotation rate increases (Saar & Schrijver 1987; Saar 1996; Jordan 1997). According to Saar (1998), there is growing evidence for inhomogeneous and locally strong magnetic fields in atmospheres of chromospherically active stars, but detailed distributions are not currently known. For solar-type stars (e.g., Linsky et al. 1992), it is very likely that their magnetic structures resemble those known from the Sun, where there are two main regions of strong magnetic fields: sunspots and magnetic flux tubes located primarily at the boundaries of supergranules (e.g., Solanki 1993).

From these observational results, two basic and currently unsolved theoretical problems can be identified. The first is to predict theoretically the distribution of magnetic fields on the surface of a star with known rotation rate. This requires a first-principle theory of stellar dynamos, which is not yet available (e.g., Weiss 1994). The second is to identify the basic physical processes that are responsible for the heating of stellar atmospheres and explain the observed range of stellar activity. In this Letter, we address the second problem. Our approach is to construct theoretical chromospheric models and use them to predict the range of stellar activity. Obviously, to construct these models, we must specify the magnetic field coverage and the heating mechanisms operating in stellar chromospheres.

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According to Narain & Ulmschneider (1996), the various proposed heating mechanisms can be divided into two main categories: hydrodynamic (acoustic and pulsational waves) and magnetic (MHD waves and magnetic field dissipation). Currently, the mechanisms that heat the different layers of stellar atmospheres are still poorly known. However, recent *Solar and Heliospheric Observatory* observations imply that small magnetic loops are being perpetually generated in the solar atmosphere and then very quickly disappear by releasing their energy through magnetic reconnection; note that reconnections will also generate MHD waves. These short-lived loops form what is called a "magnetic carpet" (Schrijver et al. 1997), and its energy content seems to be sufficient to heat the solar corona. One may speculate that similar magnetic carpets exist on other solar-type stars, but it is unclear how important this carpet is for the heating of a given stellar chromospheric layer. Thus, we assume that the acoustic and magnetic wave-heating mechanisms dominate in stellar chromospheres and that all wave energy needed for this heating is generated in the stellar convection zones.

In this Letter, we describe new theoretical time-dependent and two-component chromospheric models of late-type dwarfs. The models are based exclusively on the wave heating, and they are used to compute the resulting range of stellar activity. By comparing this range with the observations, we are able to determine the role played by acoustic and magnetic waves in the heating of chromospheres of stars of different activity. The comparison shows that the wave heating alone can explain most but not all of the observed range of stellar activity.

2. THEORETICAL CHROMOSPHERIC MODELS

Our theoretical time-dependent and two-component chromospheric models take into account nonmagnetic regions (heated by acoustic waves) and magnetic flux tubes (assumed uniformly distributed and heated by longitudinal tube waves). The coverage of the stellar surface by magnetic fields (area filling factor) is a free parameter in these calculations. The initial wave energy fluxes are input parameters for the models, and they are calculated using convection zone models (see below). A time-dependent magnetohydrodynamic code based on the method of characteristics is used to compute the propagation of both acoustic waves in a plane-parallel atmosphere (e.g., Ulmschneider et al. 1977; Buchholz, Ulmschneider, & Cuntz 1998) and longitudinal waves along the magnetic flux tubes (e.g., Herbold et al. 1985). Simultaneously with these wave calculations, we compute radiative losses in the H^- continuum and in the Mg II and Ca II emission lines by solving the appropriate radiative transfer equations together with the

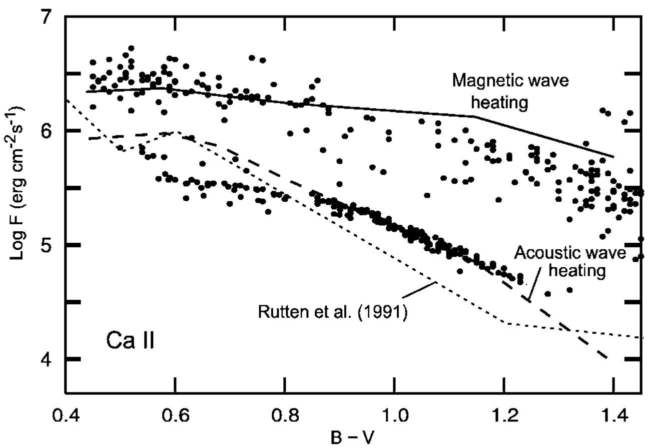

FIG. 1.—Total observed Ca II H + K line core emission fluxes of minimum flux stars and most active dwarfs are shown as filled circles, compared with theoretical fluxes for pure acoustic wave heating (*dashed line*) and for magnetic wave heating in flux tubes, which at photospheric height have an area filling factor of $f = 0.4$ (*solid line*). Also shown is the basal flux limit by Rutten et al. (1991, Fig. 5).

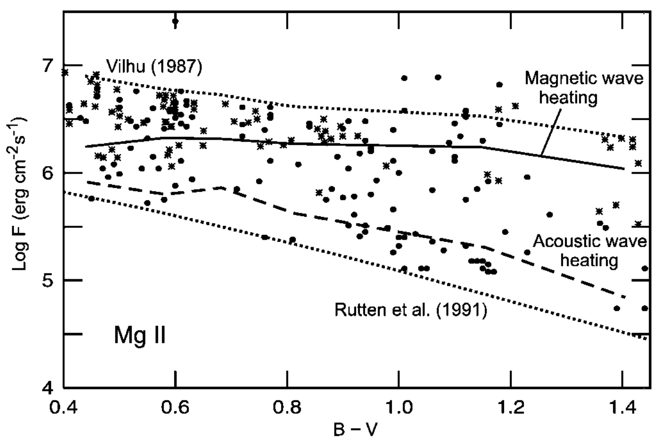

FIG. 2.—Total observed Mg II $h + k$ line emission of stars by Vilhu (1987; *asterisks*) and Rutten et al. (1991; *filled circles*), compared with theoretical fluxes for pure acoustic wave heating (*dashed line*) and for magnetic wave heating in flux tubes, which at photospheric height have an area filling factor of $f = 0.4$ (*solid line*). Also shown are the saturation and basal flux limits given by Vilhu (1987) and Rutten et al. (1991, Fig. 5), respectively.

statistical equilibrium equations for non-LTE populations (Ulmschneider 1991; Hünerth & Ulmschneider 1995). The time-dependent energy balance between the wave dissipation due to shocks and the emitted radiative losses determines the local values of temperature, density, and pressure in the magnetic and nonmagnetic stellar atmosphere regions (Fawzy 2001). It must be noted that early versions of these models have been used by Buchholz et al. (1998) to predict theoretically the level of the basal flux and by Cuntz et al. (1999) to study the decrease of chromospheric activity with stellar rotation for K2 V stars.

Our chromosphere models are computed using the best currently known stellar wave energy fluxes. To obtain these fluxes, stellar convection zone models are calculated using a stellar envelope code described by Bohn (1984) and later modified by Ulmschneider, Theurer, & Musielak (1996). To run this code, we must specify the basic stellar parameters, namely, g, $T_{\rm eff}$, metallicity, and the mixing-length parameter α, which is assumed to be 2 in all calculations described in this Letter (e.g., Ulmschneider, Musielak, & Fawzy 2001). Having obtained the convection zone models, the acoustic (Musielak et al. 1994; Ulmschneider et al. 1996) and longitudinal tube wave energy fluxes (Musielak, Rosner, & Ulmschneider 2000; Ulmschneider et al. 2001) are computed and then used as the initial input to our theoretical models. As already recognized by Spruit & Roberts (1983), the efficiency of the generation of transverse tube waves is much higher than that for longitudinal tube waves. There have been several attempts to estimate the amount of energy carried by transverse waves in the solar atmosphere (Choudhuri et al. 1993a, 1993b; Muller et al. 1994; Huang, Musielak, & Ulmschneider 1995). Recently, Musielak & Ulmschneider (2001a, 2001b) used an analytical approach to compute the transverse wave energy fluxes for late-type stars. The obtained results show that these difficult to dissipate wave fluxes are more than 1 order of magnitude higher than those carried by longitudinal tube waves. To account for this wave mode, we assume that 16% of the generated transverse wave energy is converted into longitudinal wave energy by the process of nonlinear mode coupling (e.g., Ulmschneider, Zähringer, & Musielak 1991; Zhugzhda, Bromm, & Ulmschneider 1995), and this extra energy is added to the initial longitudinal wave energy flux (increasing it by a factor of 5) to serve as an input parameter for our theoretical models of the magnetic areas.

3. CHROMOSPHERIC ACTIVITY

A series of theoretical chromospheric models has been calculated for late-type dwarfs with the magnetic filling factor ranging from 0.0, for purely acoustically heated chromospheres, to 0.4, for both acoustically and magnetically heated chromospheres. In the former case, the models describe stars that show the basal flux level of chromospheric activity, while for the latter case the models describe active stars. Since our models are based on uniformly distributed magnetic flux tubes, assuming filling factors higher than 0.4 appears unrealistic because the turbulent flows outside the tube (which generate the magnetic waves) might then be impaired. Hence, the maximum wave heating in these models occurs when the filling factor $f = 0.4$. This means that our theoretical range of chromospheric activity (measured by the emerging fluxes in the emission cores of the Ca II H + K and Mg II $h + k$ lines) corresponds to a variation of the filling factor from $f = 0.0$ to 0.4. By comparing this range with the observational range, we are able to answer the important question: *Can our wave-based theoretical models account for the observed range of chromospheric activity in late-type dwarfs?*

The emerging fluxes in the Ca II H + K and Mg II $h + k$ emission lines resulting from the theoretical chromospheric models are computed using a radiative transfer code based on partial redistribution and utilizing a modified operator splitting method (Ulmschneider 1994). A ray-tracing method through the forest of expanding flux tubes similar to Rammacher & Ulmschneider (1989) is used to calculate the emerging radiative flux from both magnetic and nonmagnetic regions of our models. The emerging fluxes for acoustic waves ($f = 0.0$) and magnetic (plus acoustic) waves ($f = 0.4$) in the Ca II and Mg II emission lines are shown in Figures 1 and 2. To judge the significance of this comparison, it should be noted that the theoretical emission fluxes were computed completely on first principles, specifying only $T_{\rm eff}$, g, α, (solar) metallicity, and f. Thus, these theoretical computations carry all systematic inaccuracies in the wave flux generation calculations, the chromospheric wave modeling, and radiation treatments.

Figure 1 shows Ca II H + K line observations of stars (*filled circles*) with very low or high core emission fluxes mostly from Duncan et al. (1991) and Henry et al. (1996), recalibrated if necessary after Noyes et al. (1984). Also shown is the basal flux limit from earlier work by Rutten et al. (1991, Fig. 5, *dotted line*), which is significantly higher for hotter stars than our low-emission stars. It is seen that the observational range of activity for a given spectral type is almost 1 order of magnitude for hot stars and 2 orders of magnitude for cool stars. Except for hot stars, the observed minimum agrees fairly well with the theoretical emission flux of nonmagnetic stars, which are heated purely by acoustic waves (see also Buchholz et al. 1998). In view of the uncertainties of the theoretical and observed emission fluxes, the saturation limit for the most active stars is also fairly well reproduced by magnetic wave heating models ($f = 0.4$), which consists of heating by acoustic waves, longitudinal waves, and mode-coupled transverse waves. This shows that wave heating, in principle, is able to account for the observed chromospheric Ca II line-core emission fluxes, both in terms of the absolute flux as function of spectral type and the variability caused by different area filling factors of the magnetic field coverage.

Figure 2 shows observed emission fluxes in the Mg II $h + k$ lines for late-type stars taken from Vilhu (1987; *asterisks*) and Rutten et al. (1991; *filled circles*). Also indicated (*dotted line*) is the basal flux limit from Rutten et al. (1991, Fig. 5). Similar to the Ca II fluxes, it is seen that the basal flux limit agrees within about a factor of 3 with the emission flux of nonmagnetic stars that are heated purely by acoustic waves (see also Buchholz et al. 1998). However, the maximum magnetic wave heating for our most active stars ($f = 0.4$) appears to be systematically below the observed saturation limit given by Vilhu (1987, *dotted line*). Although most of the observed variability of the chromospheric emission seems to be covered by varying the filling factor f, this gap appears to be persistent and independent of the effective temperature. This suggests that most of the chromospheric emission activity in Mg II can be explained by magnetic wave heating but that for the most active stars an additional nonwave magnetic heating mechanism appears to be at work.

That we can explain the entire observed range of the chromospheric activity of the Ca II emission and partly the range of the Mg II emission can be attributed to the fact that the Ca II H + K lines are formed much lower in the atmosphere than the Mg II $h + k$ lines. It seems that the magnetic wave heating gets progressively weaker with height in the chromosphere and that at great height in addition coronal heating mechanisms (like reconnective heating) appear to contribute. This suggests the following scenario: the base of the chromosphere is produced by pure acoustic (shock) heating, the lower and middle chromosphere (with an increasing importance of the magnetic flux tubes due to the photospheric filling factor and the geometrical spreading) are heated by longitudinal tube waves (shocks), and the high chromosphere receives additional nonwave magnetic heating (e.g., by reconnective heating).

4. CONCLUDING REMARKS

A coherent picture of the heating of the outer atmospheres of late-type stars appears to be now slowly emerging. Turbulent gas motions in the surface convection zones of these stars give rise to acoustic waves that, upon propagating into the outer stellar layers, quickly steepen into shock waves due to the strong density gradient. The postshock temperature peaks of these waves produce the emission cores in the Ca II H + K and Mg II $h + k$ lines. These core emissions occur in all stars regardless of rotation and produce the basal flux limit. With increasing rotation, stars are progressively covered by magnetic fields and have an increasing area filling factor at photospheric heights.

External turbulent gas flows in the convection zone perturb the magnetic flux tubes and generate longitudinal, transverse, and torsional magnetic waves. Of these, longitudinal waves behave like acoustic waves and form shocks when propagating along the magnetic flux tubes, which spread with height until they fill out the entire available space. By mode-coupling (Zhugzhda et al. 1995), part of the transverse wave energy is converted to longitudinal waves, and the same must happen for torsional waves. Unfortunately, the energy generation of torsional waves is presently unknown. Assuming that a fraction of 0.3 of the transverse wave flux becomes available as longitudinal waves, a maximum amount of heating in the magnetic flux tubes for stars with a filling factor $f = 0.4$ has been computed. We find that this heating is sufficient to explain magnetic chromospheres up to the level of the Ca II H + K line formation.

However, the magnetic wave heating appears to be insufficient when in the high chromosphere the level of Mg II $h + k$ line core formation is reached and coronal heating mechanisms (like reconnective heating by microflares) appear to contribute. As the role of the dissipation of torsional waves is not clear, the exact amount of reconnective heating necessary cannot be reliably determined. In addition, it is not known whether reconnective heating operates mainly by direct dissipation or by the generation of magnetic waves. There are indications that magnetic reconnection occurs in small magnetic loops, the so-called magnetic carpet (see § 1). Moreover, there are stellar observations of the C IV line by Wood, Linsky, & Ayres (1997) that support the picture of a transition of wave heating to reconnective heating in the chromosphere-corona transition layer.

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