Chromospheric models of Solar Type Stars: The Vaughan Preston Gap

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Abstract.
We built different models for stars of the same spectral type than the Sun but with different levels of chromospheric activity, to study the response of the S index of activity built from the emission of the Ca II H and K lines to changes in the chromospheric structure. We found that the fact that there are many stars with either strong or week emission, but few with intermediate values of S, the so called Vaughan-Preston gap, can be due to a discontinuity in the response of the Ca II lines to chromospheric heating.

1. Introduction

Perhaps the largest observational study of chromospheric activity is the one started in 1966 at the Mount Wilson Observatory (herafter MW), which at present includes more than 2200 stars in the spectral range between F and early K. This study uses a four channel spectrometer to measure the emission in the core of the H and K lines of Ca II and in two continuum windows nearby. Emission in these lines, by analogy with the Sun, is assumed to be well correlated with surface magnetic fields and, therefore, with activity.

Qualitative studies of this data by Vaughan and Preston (1980) suggested that a "gap" in chromospheric emission exists for stars in the range $0.45 \leq B - V \leq 1.0$ (see also Durney et al 1981, Middelkoop 1982). There are relatively large numbers of stars in this color range with either strong or weak chromospheric emission, but relatively few with moderate emission.

In a survey of Ca II emission in southern solar-type stars, Henry et al. (1996) also found a bimodal distribution, although they considered it "more of a transition zone that a gap", and that "there is not a complete absence of stars" in it.

Much has been speculated on the origin of this gap, ussually called the Vaughan-Preston (VP) gap in the literature. For example, since chromospheric activity decreases with increasing stellar age, the VP gap could represent a change in the nature of activity at a certain stellar

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age (Knobloch et al. 1981, Soderblom 1982). Similarly, Hartmann et al (1984) interpreted the break in chromospheric activity as a fluctuation in the locar stellar birthrate, so that the gap area results from a slowly varying star formation rate.

Alternatively, since activity is closely related to stellar rotation through the stellar dynamo generating the surface magnetic fields, Durney et al (1981) suggested that the VP gap can be due either to a rapid spindown at some point of stellar evolution, in such a way that there is a certain range of rotation period which is rarer than the rest, or to an abrupt change of the efficiency of the dynamo for a given rotation period. Other interpretations in terms of dynamo theory can be found in Soon et al. (1993) and Baliunas et al. (1996).

Brandenburg et al (1998) also proposed a break in the rotation period around age 2-3 Gyr, roughly at the VP gap. Rocha-Pinto and Maciel (1998) suggested that the transition from active to inactive stars across the VP gap is related to an abrupt change in the metallicity distribution of these stars.

In the present paper we investigate the response of the Ca II emission to changes in the thermal structure of the stellar chromosphere, to investigate whether the abrupt change in emission implied by the VP gap can be due not to a discontinuity in chromospheric heating, but in the response of the lines to this heating. In Section 2 we present our models and explain how our calculations were made. In Section 3 we present the results, and in Section 4 we discuss the implications.

2. The computations

To investigate the response of the Ca II lines to the changes in the chromospheric structure induced by stellar activity, we built a set of chromospheric models for stars with the same photospheric structure than the Sun and different activity levels. To do so, we started from the solar model C of Vernazza et al. (1981), as modified in the temperature minimum region by Avrett (1985, see also Maltby et al. 1986), and later in the transition region by Fontenla et al (1993). We then generated more active stellar chromospheres shifting inwards the T vs. log(m) structure in the chromosphere, down to the height below T_{min} where the original temperature is higher. Some of our models are shown in Figure 1.

This way of building plausible single-component, plane-parallel models of the chromosphere of active solar-like stars have been used before in different studies of activity (see Andretta and Giampapa 1995 and references therein). It essentially increases the amount of material in

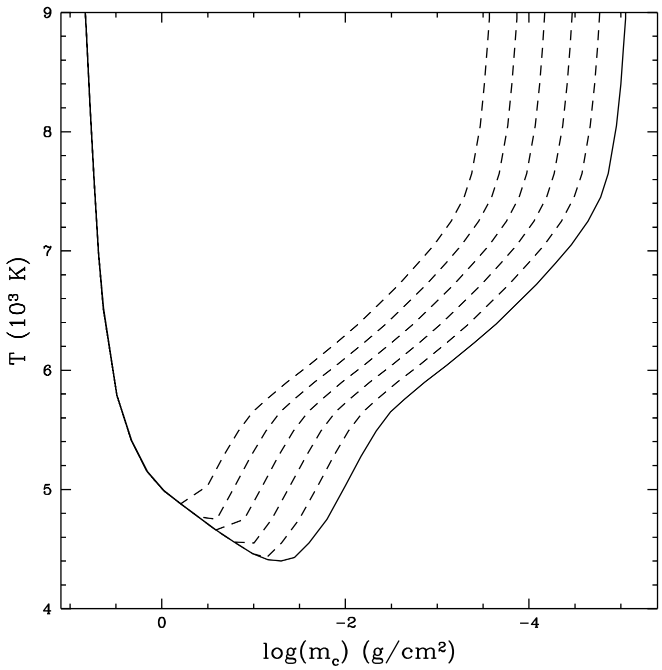

Figure 1. The atmospheric models. The full line is the quiet Sun model C of Fontenla et al. (1993), and the dashed lines are the models built by shifting this model by $\Delta \log \mathrm{m}$ =0.3, 0.6, 0.9, 1.2 and 1.5.

the chromosphere, and has the advantage of reducing the number of free parameters characterizing activity to only one, the amount $\Delta \log \mathrm{m}$ by which the thermal structure has been shifted, or, alternatively, the value $\mathrm{m_c}$ giving the position of the transition region.

Once the T vs. log(m) table was built in this way, we self consistently computed an atmosphere in hydrostatic equilibrium and solved the transfer and statistical equilibrium equations for hydrogen, to obtain total and electron densities at every height. This was done using the computer code Pandora, kindly provided by Dr. E. H. Avrett (see Avrett & Loeser 1992 for an explanation of the program). Finally, we computed the Ca II populations, and the H and K line profiles. The atomic model for Ca II is the same one used by Falchi and Mauas (1998). In particular, we computed the profiles of the Ca II K and H lines with the Partial Redistribution (PRD) treatment explained in that paper, where we showed that if Complete Redistribution (CRD) is assumed the $\mathrm{K_1}$ minimum is twice as intense as the one computed in PRD. As the changes introduced by the CRD assumption might be

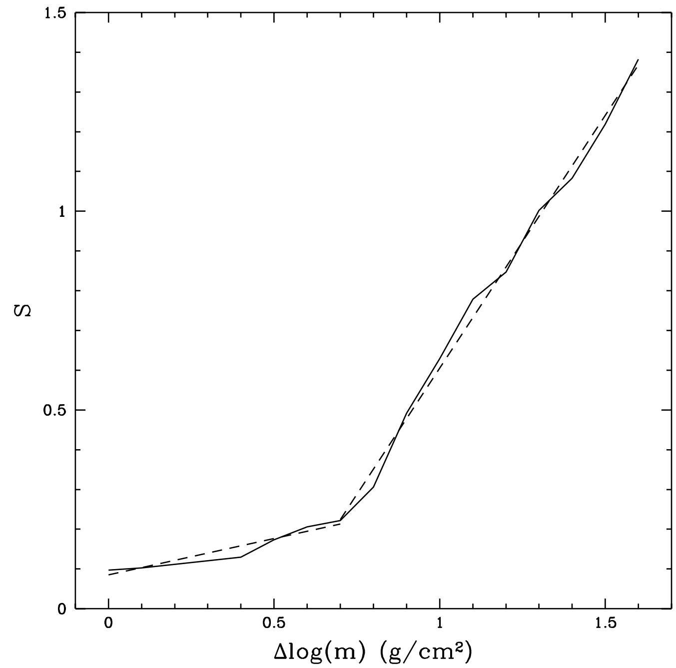

Figure 2. The response of the Ca II K S index to the different atmospheric models of Fig. 1. Also shown as dashed lines are the linear fits to the two different regimes (see text).

larger than the ones obtained modifying the atmospheric models, it is important to compute the K and H lines in PRD if they are going to be used for this kind of modeling.

From the computed profiles, we computed an S index similar to the one observed at the MW observatory. This index is defined as the ratio of the flux in two triangular bandpasses of 1.09 Å FWHM centered at the H and K lines, relative to two 20 Å "continuum" bands centered at 3901 and 4001 Å. Here, we mimic the result obtained with the filters, by integrating the computed flux with a triangular function of the right width, and dividing by the solar flux in the same continuum regions than the MW filters, as given by the solar flux Atlas by Kurucz et al. (1984).

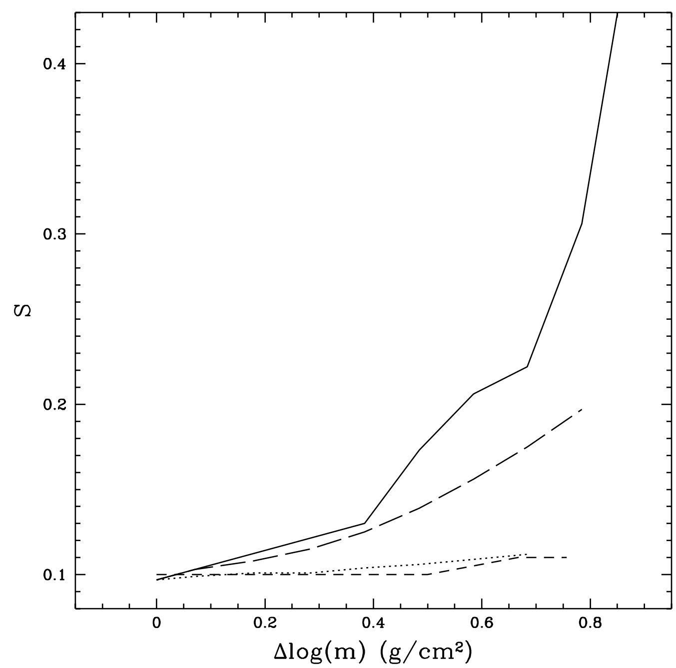

Figure 3. The response of the Ca II K S index to the different models built changing locally the atmospheric structure. The full line is the same curve shown in Fig. 2. The dotted, short-dashed and long-dashed lines represent models built by shifting downwards the chromosperic plateau, the transition region, or the first chromospheric rise by $\Delta \log \mathrm{m}$ from the quiet Sun model.

3. The results

The results are shown in Figure 2, where the computed value of S is shown as a function of $\Delta \log \mathrm{m}$. It can be seen in the figure that the activity index has a bimodal behavior: from the quiet Sun model to the model with $\Delta \log \mathrm{m}$ =0.7, S varies following the linear relation S= $0.19.\Delta \log \mathrm{m} + 0.085$, with a correlation coefficient $r = 0.958$. At this point, the S vs. $\Delta \log \mathrm{m}$ relation changes slope, and growths much more rapidly, as S= $1.27.\Delta \log \mathrm{m} - 0.66$, with $r = 0.997$. In fact, our next model, with $\Delta \log \mathrm{m}$ =0.8, is already just above the VP gap, with S=0.31. Both fits are shown in Fig. 2 as dashed lines

This change in behavior can explain why there is a much larger number of stars with $S < 0.2$, since all stars having $\Delta \log \mathrm{m} < 0.7$ are in this region, and stars already having $\Delta \log \mathrm{m} > 0.8$ are already above the gap. In other words, this can explain the lower end of the VP gap.

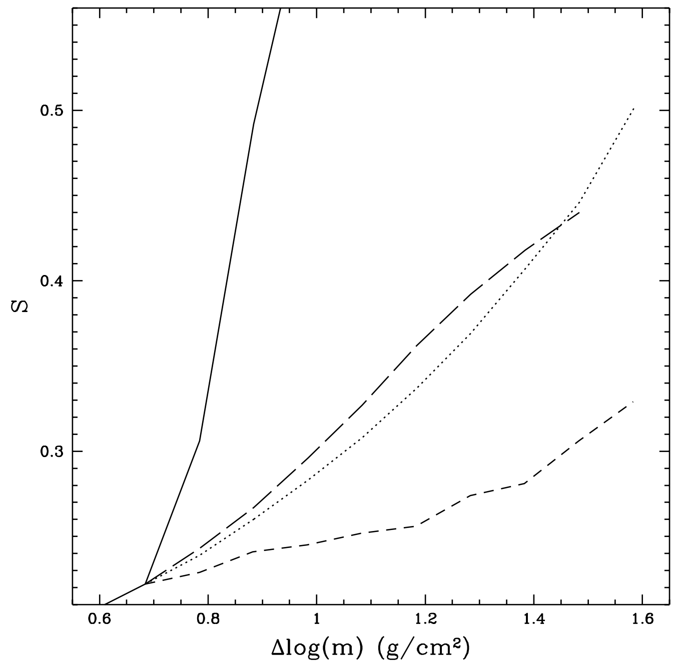

Figure 4. Idem Fig. 3, but for models built starting from the model just below the VP gap (i.e. the model with $\Delta \log \mathrm{m} = 0.7$).

As can be seen in Figure 1, the models we have built change globally in the chromosphere: they have different temperature minima T_{min}, different positions of the first chromospheric rise from T_{min} to the chromospheric plateau, different temperatures in this plateau, and different positions of the transition region. To study which of these changes in the model are responsible for the behavior of the S index in each part of Fig. 2, we built several sets of models changing locally the model characteristics, in a similar way to the models shown in Fig. 1.

In other words, starting from the quiet Sun model C, or the models just below and just above the VP gap, we built different sets of models, shifting inwards the transition region, the chromospheric plateau (which is similar to increasing the temperature in this region), or the first chromospheric rise (which also resulted in an increase in T_{min}). The values of S computed for the nine sets of models are shown in Figures 3 to 5.

For example, in Figure 3 we plot the computed S for the three sets of models built starting from the quiet Sun model, against the

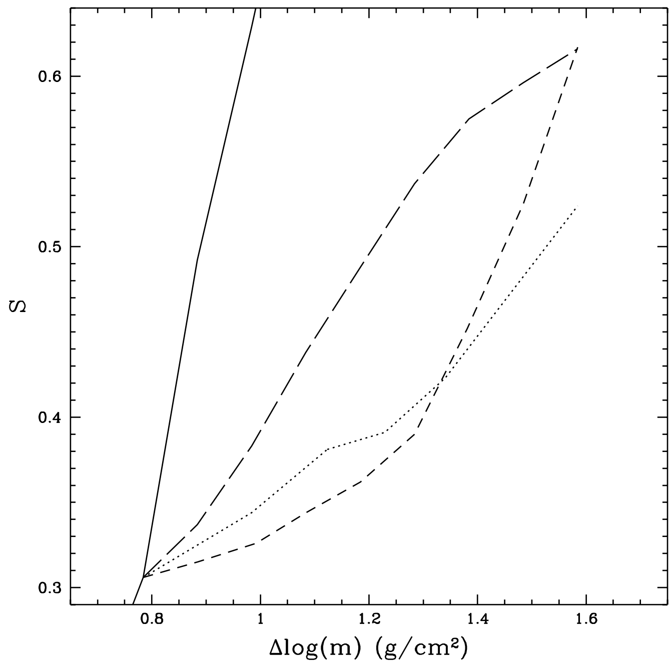

Figure 5. Idem Fig. 3, but for models built starting from the model just above the VP gap (i.e. the model with $\Delta \log \mathrm{m}$ =0.8).

displacement $\Delta \log \mathrm{m}$ from the quiet Sun model. It can be seen that, for these models with lower activity, neither the shifting of the transition region nor the heating of the chromosphere affect the value of S, which is almost solely dependent on the structure of the T_{min} region.

Figure 4 is a similar plot, but for the three models built starting from the model just below the VP gap, with $\Delta \log \mathrm{m}$ =0.7. To facilitate the comparison between figures, the scales are the same than in Fig. 3. It is worth noting that in this region all three changes affect the value of S. Here, the changes in the position of the transition region are as effective as the changes in the structure of the T_{min} was in the least active models, and the changes in T_{min} and the temperature of the chromospheric plateau are twice as important. Considering that the results in Fig. 2 are the combined effect of all these changes, it can be easily understood why the change in behavior.

In Figure 5 we show the reponse of different types of chromospheric heating starting from a model already above the VP gap, with $\Delta \log \mathrm{m}$ =0.8. Here the Ca II lines are even more sensitive to changes in the T_{min}

region, or to the shifting of the transition region, while the response to the heating of the chromosphere remains the same. In particular, the curve corresponding to the change in $T_{\min}$ has a slope three times larger that the one in Fig. 3.

However, these models changing the $T_{\min}$ region are probably not very realistic, since at this point the modifications of the original model reach regions very deep in the low chromosphere or high photosphere, down to $z = 200km$ above the height where $\tau_{5000\mathring{A}} = 1$.

4. Discussion

The main result of this work can be seen in Fig. 2. There we show that the response of the Ca II H and K line emission to activity is not linear throughout the observed range of activity. In particular, the most frequently used indicator of activity, the index S built in MW, has a break at $S \approx 0.2$, and changes abruptly slope, which increases by a factor of 6.

This behavior suggests that the existence of the lower end of the VP gap is due, not to a discontinuity in the response of activity with rotation, or age, or of the rate of star formation in the past, but of the response of the Ca II line emission with chromospheric heating.

The existence of the upper region, of active stars, is probably due to an effect of saturation in the heating, and in particular to the fact that is not possible to heat further the upper atmosphere, at least not without changing the spectral type of the star.

It is worth pointing out the value of S where the break occurs, S≈ 0.2, has been found to separate active and quiet regions in the Sun by LaBonte (1986). Also, in an observational study of the profiles of the K line, Cincunegui and Mauas (2002) found that this value is a threshold between the moderatly active stars which present the Ca II lines in emission from the inactive stars which have them in absorption.

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