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A Non-LTE Analysis of Doppler Imaging Lines

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Abstract:

Doppler imaging studies have revealed that most stars with high activity levels have polar spots. Although their existence is corroborated by spectroscopic and photometric measurements, and although theoretical models have been produced that include polar spots, their existence remains controversial. Based on a NLTE radiative transfer analysis of the most-used Doppler-imaging lines we reject the claim that chromospheric activity might be responsible for the features in the spectral lines that are commonly interpreted as polar spots.

1. Introduction

Doppler imaging has become an important and powerful tool for investigating the distribution and evolution of long-lived stellar surface features, viz., starspots. It exploits the fact that, in the spectrum of a rapidly-rotating star, there is a correspondence between wavelength position in a spectral line and spatial position on the stellar disk. Due to this correspondence, a feature that traverses the stellar disk can produce a bump or a dip that moves across the observed line profile in time (e.g., Vogt & Penrod 1983).

The Doppler imaging technique is only applicable to stars within a certain, rather high, rotation velocity range, which therefore show extremely high activity levels. On many of these stars, unlike the comparatively very quiet Sun, there seem to exist rather large, stable and long-lived polar spots. Even though a theoretical explanation for their existence has been given (Schüssler & Solanki 1992; Schüssler et al. 1996) and notwithstanding the host of (polarized) spectroscopic and photometric evidence (e.g., Strassmeier 1990; Donati et al. 1992; Hatzes et al. 1996), they have been subject to controversy ever since they were found.

The spectral signature of polar spots is a nearly time-independent and stationary filling in of the observed line core (e.g., Strassmeier 1990), measured either relative to the computed (non-)LTE line profile (assuming a "reasonable" stellar model atmosphere) or to the appropriately broadened line profile of a slowly-rotating star of similar spectral type. Both types of reference profiles need to be treated with caution, since the high rotation rate may influence the star's atmosphere in subtle ways. That this might happen is suggested by the observation that several lines that are considered photospheric in non-active cool stars show chromospheric emission cores in more active stars. In particular, it

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has been claimed that emission related to chromospheric activity may be responsible for most or all of the filling in that is observed in the central parts of Doppler-imaging lines (Byrne 1992; Strassmeier et al. 1993).

We present a non-LTE analysis of the formation of the most-used Doppler-imaging lines in cool star model atmospheres with a chromospheric temperature rise. When chromospheres come into play, proper non-LTE radiative transfer computations are required to obtain the line profiles; most line profiles used in Doppler imaging analyses are computed under the simplifying assumption of LTE. We suspect that in the case of a chromospheric temperature rise the LTE assumption may lead to the same filling in of the line core that is commonly interpreted as due to a polar spot.

Wavelength Air, [Å]	Excitation [eV]	$\log(gf)$	quiet Sun: $\tau_{\nu_0} = 1$ @	
			$\log(\tau)$	Height [km]
Ca I 6122.226	1.89	–0.41	–2.72	410
Ca I 6166.440	2.52	–1.02	–1.40	210
Ca I 6439.083	2.52	0.47	–2.80	420
Ca I 6462.570	2.52	0.31	–2.65	400
Ca I 6717.687	2.71	–0.61	–1.54	230
Fe I 5497.526	1.10	–2.85	–3.65	550
Fe I 6141.727	3.60	–1.54	–0.89	130
Fe I 6157.733	4.07	–1.19	–1.52	230
Fe I 6165.363	4.14	–1.48	–1.04	150
Fe I 6173.341	2.22	–2.99	–1.86	280
Fe I 6180.209	2.73	–2.71	–1.41	210
Fe I 6411.658	3.65	–0.79	–2.90	440
Fe I 6430.856	2.18	–2.02	–3.17	480
Fe I 6546.252	2.76	–1.62	–2.61	400

Table 1. The set of Doppler-imaging lines. In addition to the excitation energy and the oscillator strength of each line, we list the location where the line core optical depth τ_{ν_0} reaches unity in the quiet Sun model T5780, both in terms of the standard optical depth τ at 5000 Å as well as in terms of geometrical height above $\tau = 1$. The oscillator strengths for the Ca I lines are obtained through the TOPbase database system that gives access to the Opacity Project atomic data (http://vizier.u-strasbg.fr/OP.html), and the Fe I line oscillator strengths are from the compilation by Fuhr et al. (1988). The values listed compare favorably with the ones obtained by Thévenin (1990) from LTE line profile fits, except for the Ca I 6439.083, Ca I 6462.570 and Fe I 6141.727 lines, for which ours are significantly larger.

1998ASPC..154.1959B

2. The Lines and the Model Atmospheres

We investigate the sensitivity of the profiles of the Ca I and Fe I Doppler-imaging lines (Table 1) to chromospheric activity and, at the same time, make a comparison between the LTE and non-LTE profiles of those lines. More "exotic" lines, such as the Na I D doublet, the Mg I b triplet and even Hα, have been proposed or used for Doppler imaging, but those lines are much wider and much stronger than the lines of Table 1, implying that they will inevitably be affected by the presence of a chromosphere. Unruh & Collier-Cameron (1997) show that stellar surface structures obtained from Doppler imaging with the Na I D_1 line have less high-latitude structure and give more consistent light curves of AB Doradus than photospheric lines, suggesting that a consistent treatment of chromospheric emission effects is warranted for stronger lines. Even the weakest Doppler-imaging lines in our sample show polar spots, and it is more challenging to explain how in those lines chromospheric activity could produce features that mimic a polar spot.

Our starting point is the quiet Sun, modeled by means of the $T_{\rm eff} = 5780$ K ODF line blanketed radiative equilibrium (RE) model T5780 (Edvardsson et al. 1993). Line profiles computed from that model are compared with the observed profiles to verify that the atomic data, in particular the oscillator strengths of the lines, are not too far off. An exact line fit is unnecessary, since we only compare theoretical profiles from atmospheres with and without a chromospheric temperature rise. Chromospheric activity is included in the form of plage, i.e. magnetic flux tubes; the FAL-F model (Fontenla et al. 1991) serves as a flux tube atmosphere. Both models are represented in the left panel of Fig. 1.

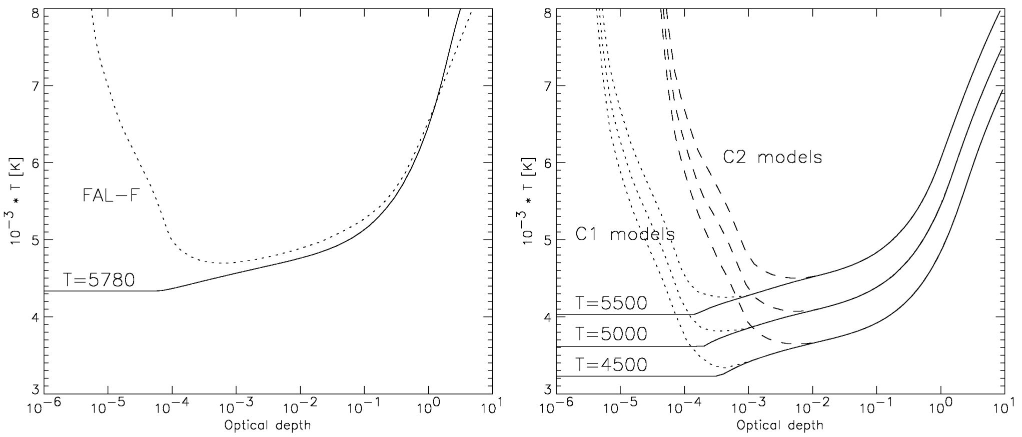

Figure 1. The solar (left panel) and stellar (right panel) atmosphere models used. All radiative equilibrium models had to be slightly modified for the purpose of these computations, because in their original form the upper limit of the atmospheres was not high enough. They have been extended with an isothermal layer at the top.

The stellar models used are shown in the right panel of Fig. 1. The non-active stars (solid curves) are represented by line blanketed radiative equilibrium models at $T_{\rm eff}$ = 4500, 5000 and 5500 K. The chromospheric models of set C1 (dotted curves) are constructed in an ad hoc way by adding the height-dependent temperature difference ΔT (with a slight shift so that the chromosphere starts near $\tau = 10^{-3}$, where τ is the optical depth at 5000 Å) between the solar models FAL-F and T5780 to the temperature of the non-active stellar models. In addition, a set of C2 models (dashed curves), with significantly stronger chromosphere, is constructed by applying the ΔT values shifted inward by a decade in optical depth.

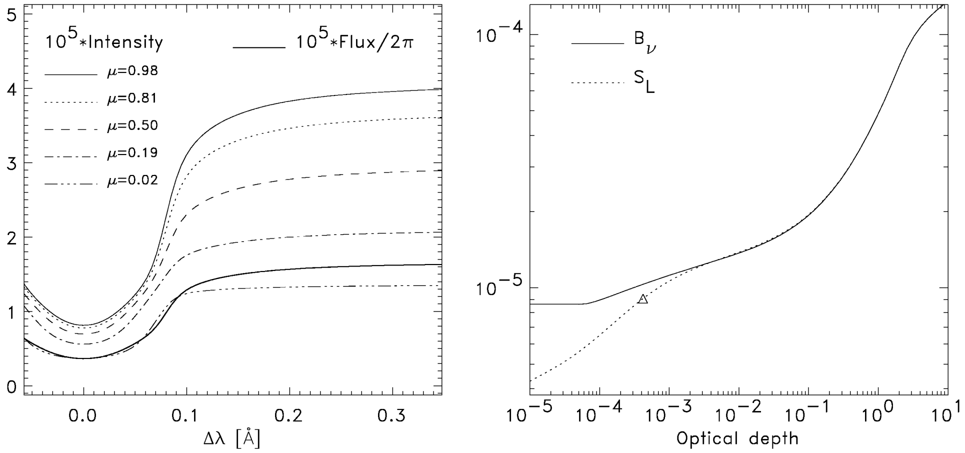

Figure 2. Line formation diagnostics for the Fe I 6430.856 line. Left: intensity and flux (surface-integrated intensity) profiles. Right: Planck function B_ν and line source function $S_{\rm L}$; the triangle indicates the location of line center optical depth unity.

3. The Sun as a Reference Point: a Dead End

We used the Sun as a starting/reference point in our computations. From the formation heights listed for the quiet Sun (Table 1), it is obvious that none of the lines is strong enough to even start feeling the chromospheric temperature rise. Additionally, the T5780 model is so well-behaved in the photosphere, that LTE line formation computations would have resulted in nearly identical results. As an example, Fig. 2 shows the basic formation properties of one of the strongest lines in the list, Fe I 6430.856. This line is formed entirely in the photosphere, and is not affected by chromospheric activity at all. Not even very close to the limb ($\mu = 0.02$) is there any sign of chromospheric emission in the line profile. The deep location of the line center optical depth unity (the triangle in the right panel of Fig. 2) indicates that the line source function equals the Planck function throughout the line formation region, i.e. the line source function is in LTE. Additionally (not shown), the lower level populations are close to their LTE values throughout the atmosphere, so that the line opacities are in LTE as well. In conclusion: the non-LTE line formation results can only differ slightly from the LTE results. This actually holds for all our lines.

1998ASPC..154.1959B

4. Active Cool Stars

With decreasing temperature, the strength of the lines in our sample, all neutral metal lines, increases and their formation region rises, so that it is expected that their sensitivity to activity could be drastically different in cooler stars.

Most non-LTE line source functions don't follow the chromospheric temperature rise at all or just very slightly: they are in general only weakly height-dependent in those layers, so that changes in line optical depths due to the addition of a chromospheric temperature rise are not reflected strongly in the line profiles. The line shape is therefore largely preserved. The LTE line source functions, on the other hand, do follow the temperature rise, and give rise to emission cores that may be stronger than in the NLTE line profiles, if the latter are present at all. By far the most prominent chromospheric signature, and for that matter also the most promising one as far as line shape is concerned, is seen in the Fe I 6430.856 line in the very coolest model and with a strong (C2) chromosphere.

Figure 3 shows the intensity in that line as a function of position in the line and position angle μ on the stellar disk, both for the case of the standard 4500 K RE model (left panel) and for that model with the C2 chromosphere (right panel).

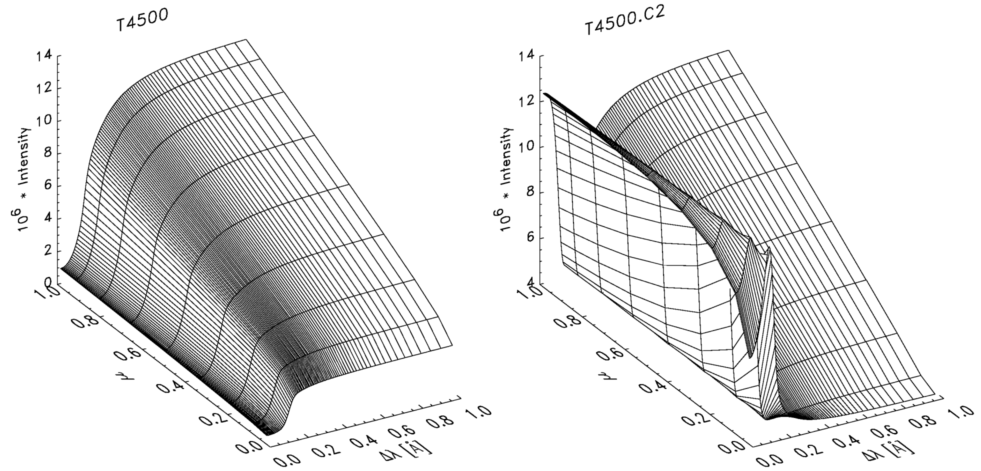

Figure 3. Wavelength and position angle dependence of the intensity in the Fe I 6430.856 line from the 4500 K model without and with a chromosperic temperature rise.

This line shows a very pronounced chromospheric emission feature already at disk center ($\mu = 1$). This is just what one needs to obtain filling in of the line core in rapidly-rotating stars.

Figure 4 shows what the flux profile of that line looks like for a star that rotates at 30 km s^{-1}. The atmosphere is supposed to consist of two components, the RE model at $T_{\rm eff} = 4500$ K and the C2 plage model constructed from that, in varying (uniform) surface coverage fractions.

Figure 4 clearly shows that the the line profile of the intensity integrated over the stellar disk, appropriately Doppler shifted to account for the fast rota-

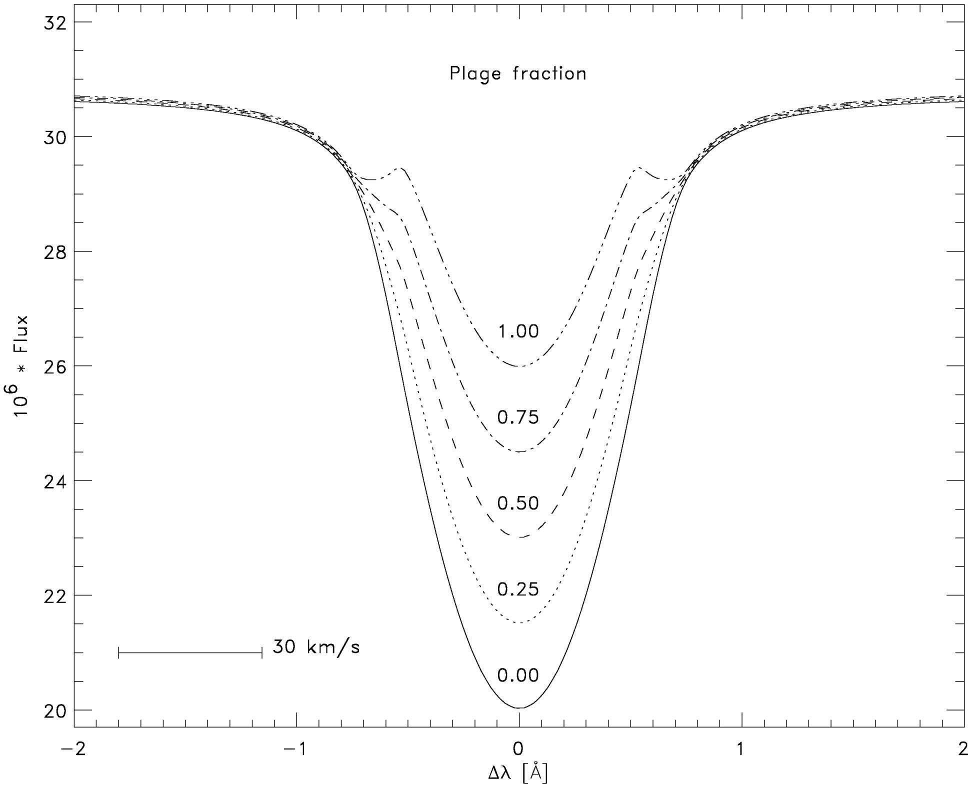

Figure 4. Profiles of the Fe I 6430.856 line on a 4500 K star with varying amounts of chromospheric activity. Note the width of the line, which results almost entirely from the rotational Doppler shifts. The plage fraction indicates the fraction of the surface that is covered by chromospheric activity, uniformly distributed.

tion of the star, is very sensitive to chromospheric activity. Unfortunately, the activity affects a rather large part of the profile instead of just filling in the line core. With the current type of chromosphere models it therefore seems impossible to obtain a flat-bottom line profile that otherwise looks very similar to the flux profile of a non-active star (with the same rotation velocity).

5. Conclusion

We computed Doppler-imaging lines for a number of model atmospheres without and with a chromospheric temperature rise in an attempt to show whether the line center flux enhancement that is seen in fast-rotating active stars and that is generally attributed to polar spots, could also be caused by chromospheric emission.

The example of the Fe I 6430.856 line shows that the present models are unable to produce such enhancement. Considering that these conclusions are not very dependent upon the exact line shape, it is expected that chromospheric models of the type considered here, which result in line profiles of similar type, are unable to produce the required enhancement.

Essentially, what one should look for are processes that preferentially enhance the intensity at or very near line center and much less in the line wings, and that only near disk center. We see two ways to obtain such enhancement:

- A spatially constrained line source function enhancement, e.g., from some local heating process. It is difficult to model such structure, and, unless these hot blobs occur over a fairly large height range, they cannot explain why line center enhancements occur in stronger as well as weaker lines.
- The current profiles have been computed under the assumption that complete redistribution (CRD) is valid. In the cooler models the line formation occurs in higher layers and it may well be that partial frequency redistribution (PRD) may have to be applied to obtain correct line profiles. It has been shown, that PRD profiles can indeed satisfy the requirement that the intensity enhancement should preferentially occur near line center and be strongest near disk center. Even so, for the weaker lines, CRD should be ok.

Neither of the two options provides a satisfactory explanation why the flux enhancement occurs both in strong and in weak lines. In conclusion: chromospheric activity *cannot* provide an alternative explanation for the observed filling in of the line core.

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