

# A revisit to model the Cr I triplet at 5204-5208 Å and the Ba II D<sub>2</sub> line at 4554 Å in the Second Solar Spectrum

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**Abstract.** In our previous attempt to model the Stokes profiles of the Cr I triplet at 5204-5208 Å and the Ba II D<sub>2</sub> at 4554 Å, we found it necessary to slightly modify the standard FAL model atmospheres to fit the observed polarization profiles. In the case of Cr I triplet, this modification was done to reduce the theoretical continuum polarization, and in the case of Ba II D<sub>2</sub>, it was needed to reproduce the central peak in  $Q/I$ . In this work, we revisit both these cases using different standard model atmospheres whose temperature structures closely resemble those of the modified FAL models, and explore the possibility of synthesizing the line profiles without the need for small modifications of the model atmosphere.

**Keywords.** line: formation, line: profiles, polarization, radiative transfer, scattering, Sun: atmosphere

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## 1. Introduction

The Cr I triplet at 5204-5208 Å and the Ba II D<sub>2</sub> at 4554 Å are some of the well known chromospheric lines showing prominent polarization signals in the Second Solar Spectrum. The Cr I triplet profiles are governed by  $J$ -state interference (Smitha *et al.* 2012) and the Ba II D<sub>2</sub> line is governed by  $F$ -state interference (Smitha *et al.* 2013b). To model the limb observations of Cr I triplet at  $\mu = 0.15$  ( $\mu = \cos\theta$ , with  $\theta$  being the heliocentric angle), Smitha *et al.* (2012) had to slightly modify FALF, one of the standard model atmospheres of Fontenla *et al.* (1993). This modification, in the form of an increase in the temperature at the continuum formation heights (0-500 km above the photosphere), was necessary to get a good fit to  $Q/I$  in the continuum.

In the case of Ba II D<sub>2</sub> 4554 Å limb observations ( $\mu = 0.1$ ), which were modeled in Smitha *et al.* (2013b), the temperature of the FALX model (Avrett 1995) had to be slightly reduced at the heights where the line center is formed, in order to reproduce the central peak in  $Q/I$ . Subsequently it was shown in Smitha *et al.* (2014a) that although this modified FALX model could reproduce the observations at  $\mu = 0.1$ , it could not reproduce the observations at other limb distances.

In this paper, we explore the possibility of modeling the above two line profiles with the updated FAL models presented in Fontenla *et al.* (2009, referred to as the FCHHT models). A comparison between the temperature structures of the FAL and the FCHHT models is shown in Figure 1 (see also Rutten & Uitenbroek 2012).

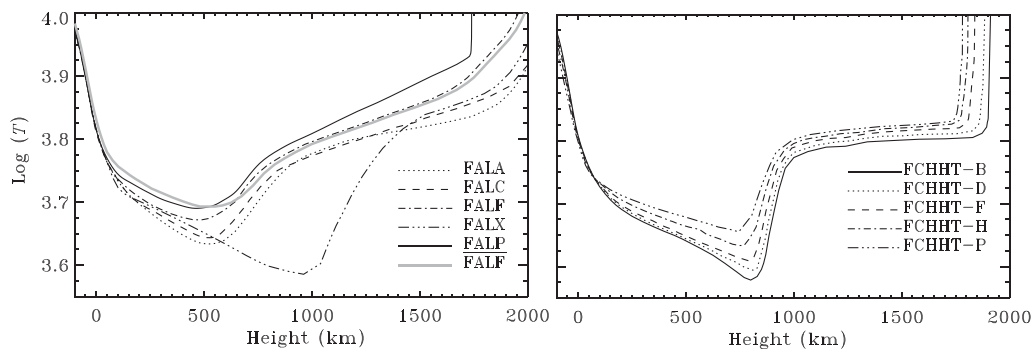


Figure 1. Temperature structures of the FAL and FCHHT models.

## 2. Revisiting the Cr I triplet

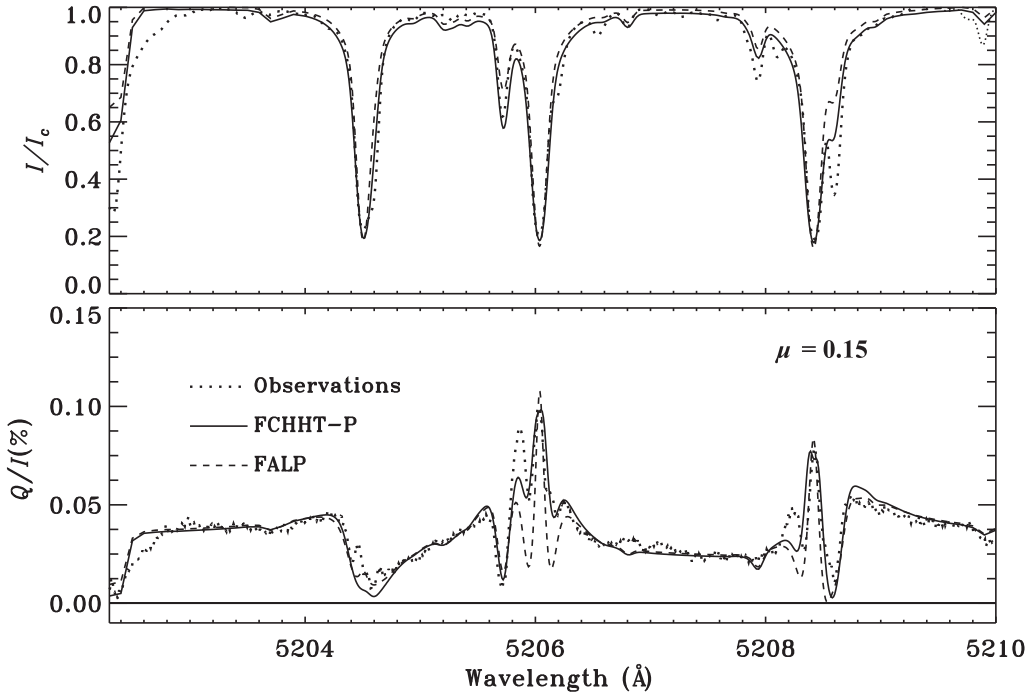
The model atmospheres tried in Smitha *et al.* (2012), namely the FALA, FALC, FALF and FALX, predicted a value of the continuum polarization larger than the one found from observations. This problem of over estimation of the continuum polarization by the one-dimensional model atmospheres was also noted in Stenflo (2005). A similar problem was faced in Smitha *et al.* (2014b) while modeling the Sc II 4247 Å line.

In Smitha *et al.* (2012), to overcome this, the FALF model was modified into  $\overline{\text{FALF}}$  and the temperature was increased in the deeper layers of the atmosphere to reduce the continuum polarization. The FALP model, which is hotter than the FALF model, has a temperature profile similar to the  $\overline{\text{FALF}}$  in these deeper layers. However, the FALP model fails to provide as good a fit as  $\overline{\text{FALF}}$ .

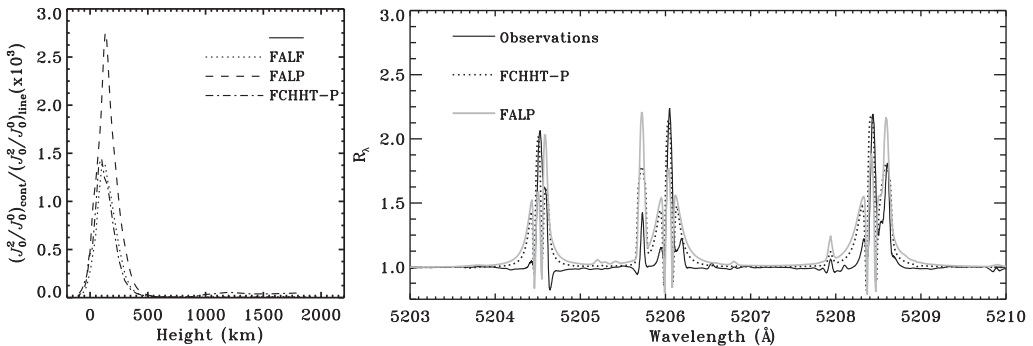
The FCHHT-P model, which represents a plage region and has a temperature structure significantly different from that of the  $\overline{\text{FALF}}$  model, provides a good fit to the Cr I triplet profiles observed in a quiet region. For modeling, we use the partial frequency redistribution (PRD) capable Multi-level Approximate Lambda Iteration code of Uitenbroek (2001) and the PRD theory of  $J$ -state interference described in Smitha *et al.* (2011, 2013a). Further details are described in Smitha *et al.* (2012). A comparison between the profiles from the FALP and FCHHT-P is shown in Figure 2. The microturbulent magnetic field strengths used to get the line center amplitude of the three lines are 0 G, 2.5 G and 1.8 G respectively, for the FCHHT-P model.

The differences in the profiles from the models  $\overline{\text{FALF}}$ , FALP and FCHHT-P can be understood by computing the ratio of the continuum-to-line anisotropy. The left panel of Figure 3 shows this ratio for the 5206 Å line of the Cr I triplet. The FALP model, despite having a temperature structure similar to that of  $\overline{\text{FALF}}$  at continuum heights (left panel of Figure 1), it does not provide as good a fit as the FCHHT-P model (see Figure 2). The FALP model predicts similar anisotropy to  $\overline{\text{FALF}}$  at continuum heights but fails to provide the required continuum-to-line anisotropy ratio which is necessary to obtain a good fit, and this is provided by the FCHHT-P model. Thus the  $\overline{\text{FALF}}$  and FCHHT-P models reproduce the observed Cr I triplet profiles at  $\mu = 0.15$ .

As a further test of the model atmosphere, we compared the observed and theoretical intensity ratio  $R_\lambda = (I/I_c)_\mu / (I/I_c)_{\mu=1}$ . This is shown in the right panel of Figure 3, computed from the FCHHT-P and FALP models.  $R_\lambda$  represents the third solar spectrum described in Stenflo (2015). The FCHHT-P model provides as good a fit to the third solar spectrum as it does to the second solar spectrum. The fit from the FALP model is not as good as the one from the FCHHT-P model. However there are small differences seen between the observed and the theoretical profiles around the 5206 Å and the 5208 Å lines



**Figure 2.** Comparison between the observed and the theoretical Stokes ( $I, Q/I$ ) profiles of the Cr I triplet computed using the FCHHT-P and FALP models at  $\mu = 0.15$ .

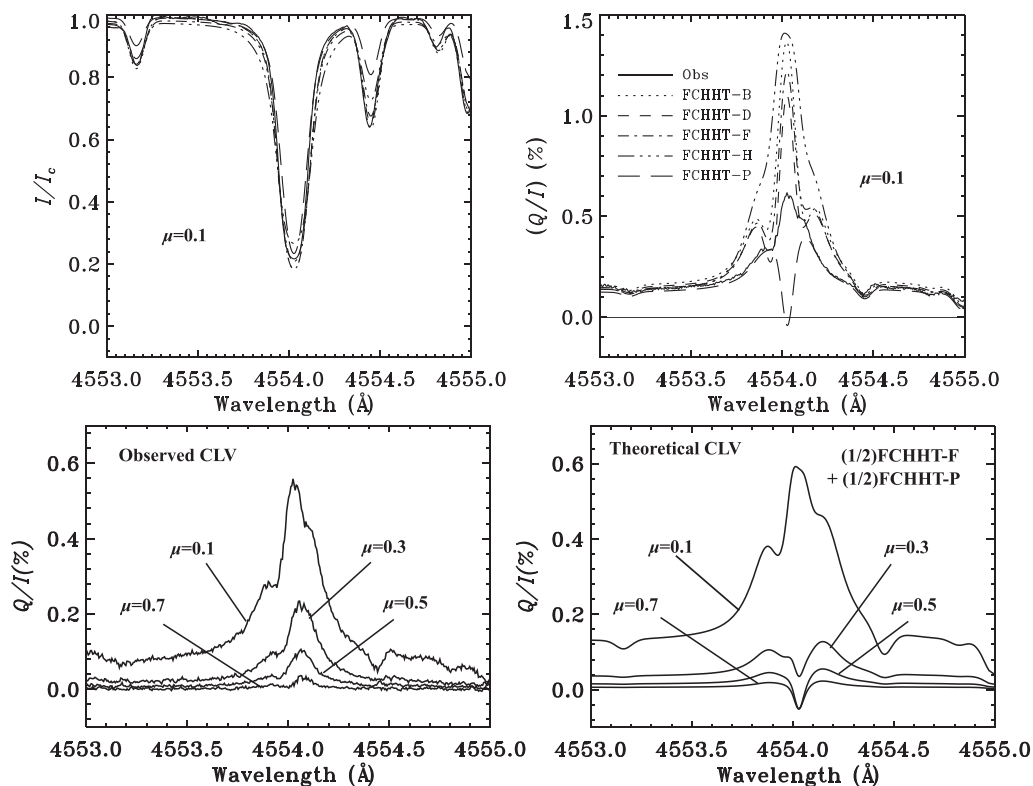


**Figure 3.** *Left panel:* Ratio of continuum to line (5206 Å) anisotropy ( $\times 10^3$ ); *Right panel:* Comparison between the observed (Stenflo 2015) and theoretically computed profiles of the third solar spectrum,  $R_\lambda = (I/I_c)_\mu / (I/I_c)_{\mu=1}$  with  $\mu = 0.15$ .

which may be improved by including the multidimensional effects. Thus the third solar spectrum now provides an additional constraint to test the reliability of the solar model atmospheres.

### 3. Revisiting the Ba II D<sub>2</sub> line

Modeling the ( $I, Q/I$ ) observations of the Ba II D<sub>2</sub> line at  $\mu = 0.1$ , which was attempted in Smitha *et al.* (2013b, see also Smitha *et al.* 2014a), was possible only after a small modification in the temperature structure of the FALX model at heights where the line



**Figure 4.** Comparison between the observed and theoretical ( $I, Q/I$ ) profiles of the Ba II D<sub>2</sub> line computed using the FCHHT models. The profiles from a 2-component model constructed by combining FCHHT-F and FCHHT-P models in equal proportion fits the observations at  $\mu = 0.1$  but fails at higher  $\mu$  values.

core is formed. This modification was necessary to reproduce the central peak formed due to the even isotopes.

In this paper, we have revisited the modeling of this line using the FCHHT models. We find that four of the five models produce the central peak in  $Q/I$ . The intensity profiles from these models match the observed ones well, whereas the  $Q/I$  profiles are broader (see the top two panels of Figure 4). It is possible to combine the two models FCHHT-F and FCHHT-P in equal proportion to build a 2-component model like the one described in Holzreuter *et al.* (2006) and reproduce the observed  $Q/I$  profile at  $\mu = 0.1$  (see the bottom panels in Figure 4). However as  $\mu$  increases, we continue to face problems in reproducing the central peak. At other  $\mu$  values we may need other combinations of the model atmospheres. This demonstrates the possibility of modeling the Ba II D<sub>2</sub> profile without the need for a modification in the standard model atmospheres. However it may not be possible to find a single one-dimensional model atmosphere that fits the observations at all  $\mu$  values.

#### 4. Conclusions

In this work, we have explored the possibility of modeling the chromospheric Cr I triplet at 5206 Å and the Ba II D<sub>2</sub> at 4554 Å line without modifying the standard model atmospheres. The updated FCHHT models are able to reproduce both these cases. While the Cr I triplet can be modeled with the FCHHT-P model, the Ba II D<sub>2</sub> needs a

2-component model constructed by combining the FCHHT-F and FCHHT-P models in equal proportion.

In the case of Cr I triplet, the FCHHT-P model provides as good a fit as the modified model constructed previously. It also provides a good fit to the third solar spectrum with small differences around the centers of the 5206 Å and the 5208 Å lines.

In the case of Ba II D<sub>2</sub> line, the 2-component model constructed in this paper holds its validity only at  $\mu = 0.1$ . For higher  $\mu$  values we need models constructed from other atmospheric combinations. Thus it may not be possible to find a single 1D model atmosphere which can reproduce the observed center-to-limb variation of the Ba II D<sub>2</sub> line profile.

The observed profiles of the Cr I triplet and the Ba II D<sub>2</sub> lines in the second and third solar spectra, and their center-to-limb variations, provide a rich set of complex observational constraints that should ideally be satisfied simultaneously by a given model atmosphere. Our results here indicate that only multidimensional atmospheric modeling can have a chance to simultaneously reproduce these constraints.

### Acknowledgements

We acknowledge the use of the HYDRA cluster facility at the Indian Institute of Astrophysics for computing the results presented in the paper. We are grateful to Dr. Han Uitenbroek for providing his realistic atmospheric modeling code.

### References

- Avrett, E. H. 1995, in: J. R. Kuhn & M. J. Penn (eds.), *Infrared tools for solar astrophysics: What's next?*, Proc. 15th NSO Sac Peak Workshop, p. 303
- Fontenla, J. M., Avrett, E. H., & Loeser, R. 1993, *ApJ* 406, 319
- Fontenla, J. M., Curdt, W., Haberreiter, M., Harder, J., & Tian, H. 2009, *ApJ* 707, 482
- Holzreuter, R., Fluri, D. M., & Stenflo J. O. 2006, *A&A* 449, L41
- Rutten, R. J. & Uitenbroek, H. 2012, *A&A* 540, A86
- Smitha, H. N., Nagendra, K. N., Sampoorna, M., & Stenflo, J. O. 2013a, *JQSRT* 115, 46
- Smitha, H. N., Nagendra, K. N., Stenflo, J. O., Bianda, M., Sampoorna, M., Ramelli, R., & Anusha, L. S. 2012, *A&A* 541, A24
- Smitha, H. N., Nagendra, K. N., Stenflo, J. O., & Sampoorna, M. 2013b, *ApJ* 768, 163
- Smitha, H. N., Nagendra, K. N., Stenflo, J. O., & Sampoorna, M. 2014a, in: K. N. Nagendra, J. O. Stenflo Z. Q. Qu & M. Sampoorna (eds.), *Solar Polarization 7*, ASP Conf. Series 489 (San Francisco: ASP), p. 213
- Smitha, H. N., Nagendra, K. N., Stenflo, J. O., Bianda, M., & Ramelli, R. 2014b, *ApJ* 794, 30
- Smitha, H. N., Sampoorna, M., Nagendra, K. N., & Stenflo, J. O. 2011, *ApJ* 733, 4
- Stenflo, J. O. 2015, *A&A* 573, A74
- Uitenbroek, H. 2001, *ApJ* 557, 389