Polarized Scattering in Strong Chromospheric Lines: Theory and its Confrontation with Observations

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Abstract. We present the current status of modeling scattering polarization in strong lines and compare it to observations. First, we discuss how the emergent polarization profile depends directly on the source function gradient and the anisotropy of the radiation field. This explains naturally the formation of the triplet peak structure often observed in these strong lines. Then, we investigate the Ca ii K line which is of particular interest since it forms high in the chromosphere. The degree of its scattering polarization depends sensitively on atmospheric properties and even provides observational evidence for the presence of cool components in the chromosphere. Therefore, polarized scattering in Ca ii K might provide a long searched for, second observational tool (apart from CO molecules) to access the coolest parts of the chromosphere.

1. Introduction

The peculiar profile structures of strong chromospheric lines in the second solar spectrum such as Na i D2, Ca i 4227 Å, and Ca ii K, have been known for more than two decades (Wiehr 1975, 1978; Stenflo, Baur, & Elmore 1980; Stenflo, Twerenbold, & Harvey 1983a; Stenflo et al. 1983b). Nonetheless, these lines still pose a challenge for theoretical modeling (Rees & Saliba 1982; Saliba 1985; Faurobert-Scholl 1992; Landi Degl’Innocenti 1998; Fluri et al. 2003), while a robust theoretical understanding of their formation is required for exploiting the full diagnostic value of scattering polarization.

In this paper we summarize the basic physical ideas that explain the origin of the triplet peak structure observed in the second solar spectrum of strong lines (Holzreuter, Fluri, & Stenflo 2005, for more details). Then we apply this know-how to the Ca ii K line, where we find evidence for temperature bifurcation in the chromosphere.

2. Basic ingredients for scattering polarization

The radiation field in the solar atmosphere is anisotropic, which breaks the spatial symmetry and gives rise to polarization due to coherent scattering. The degree of emergent scattering polarization results mainly from a mapping of the anisotropy, which itself is due to the gradient of the source function. Basically, positive anisotropy leads to positive polarization while negative anisotropy causes negative polarization. Therefore, we must first understand the anisotropy of the radiation field.
Figure 1. Three simple academic cases of semi-infinite atmospheres showing possible ways of generating anisotropy of the radiation field. (a) Isothermal atmosphere: the boundary at the top causes negative anisotropy within an optical depth of unity just due to the geometry. (b) Milne-Eddington atmosphere: the non-vanishing source function gradient $\nabla S$ gives an additional (positive) contribution to the anisotropy. (c) Layered atmosphere with a transparent gap: the source function $S_1$ of the upper, semi-transparent layer is much smaller than the source function $S_2$ of the lower layer, resulting in a strong anisotropy in the upper layer (from Holzreuter et al. 2005).

Figure 2. Anisotropy of the radiation field in the Na I D₂ line. Left: depth dependence of the anisotropy at various wavelengths across the line: line core (solid); core rise (dash-triple-dotted); polarization minimum (dash-dotted); wing maximum (dashed); and continuum (dotted). These wavelengths, with the exception of the continuum, are indicated by the vertical lines in the right panel (and also in the left panel of Fig. 4). Right: frequency dependence of the anisotropy at various heights: 1800 km (solid); 1000 km (long-dashed); 400 km (dash-triple-dotted); 200 km (dashed-dotted); and $-40$ km (dashed). These heights are indicated by horizontal lines in the left panel.

Figure 1 shows schematically the origin of anisotropy in a stellar atmosphere. The depth dependence of anisotropy is determined mainly by two competing effects (Trujillo Bueno 2001). On one side, the incident radiation field coming back down from the upper hemisphere is limb-brightened within one optical depth from the top, just because the path length is shorter when looking straight up. This gives a negative contribution to the anisotropy even in an
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Figure 3. Contribution function of the Na\textsc{i} D\textsc{2} line for $\mu = 0.1$ (solid) and $\mu = 0.5$ (dotted). The three panels correspond to the wavelengths indicated by the three vertical lines in the left panel of Fig. 4 closest to line center.

Figure 4. Triplet-peak structure formation in strong chromospheric lines. Left: Na\textsc{i} D\textsc{2} for $\mu = 0.1$ (solid) and $\mu = 0.5$ (dotted). Right: theoretical lines for $W_2 = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 1.0$, ordered from bottom to top (thick line for $W_2 = 0$). The dotted line marks a continuum polarization of 0.6%.

isothermal atmosphere. On the other hand, a source function gradient introduces limb darkening of the radiation field incident from the lower hemisphere, which gives rise to positive anisotropy close to the top. The two competing effects result in a typical depth dependence of the anisotropy, as shown in the left panel of Fig. 2, with zero total anisotropy deep in the atmosphere, negative anisotropy around optical depth 1, and positive anisotropy closer to the top (see also Trujillo Bueno 2001). The steeper the source function gradient the more positive the anisotropy is at the top.

Case (c) of Fig. 1 represents a special situation with a gap in the contribution function, which occurs in strong lines around the temperature minimum. The source function in the upper layer (chromosphere) is much smaller than in the lower layer. Thus, the anisotropy becomes particularly large and positive in the upper layer since the hot lower layer is visible only when looking straight down.

3. Origin of triplet peak in the coherent scattering profile

In reality the anisotropy varies in a complex way both with depth and frequency as shown in Fig. 2 for Na\textsc{i} D\textsc{2}. In such a strong chromospheric line all three schematic cases of Fig. 1 are representative at different wavelengths: approximately scheme (a) in the line core; scheme (b) in the wings, including the minima; and scheme (c) in the core rise between the line core and the minima.
The transparent gap assumed by scheme (c) is clearly visible in the Stokes-$I$ contribution function of Na $\text{i} \ D_2$ at wavelengths between minimum and core (middle panel of Fig. 3). Not surprisingly the anisotropy rises in the chromosphere to its highest values at exactly that wavelength (dash-triple-dotted line in left panel of Fig. 2).

We now have all the ingredients to understand the origin of the triplet peak (Fig. 4). When approaching the line center from one of the wings, we first observe increasing polarization due to the transition from continuum to line opacity. Once the line opacity dominates, we would expect an approximately flat polarization profile if the anisotropy remained constant, but that is not the case. In reality, anisotropy drops to form the polarization minima because the source function gradient slightly levels off in the upper photosphere. The core polarization is again larger as a result of the transparent gap around the temperature minimum, which strongly increases anisotropy in the upper layer.

The second solar spectrum contains contributions from continuum, depolarization (just because of line opacity), and intrinsic line polarization (this part has the triplet structure in strong lines). The strength of the line polarization is controlled by the line polarizability, $W_2$, which depends on the quantum numbers of the involved atomic or molecular levels. For $W_2 = 0$ the line only depolarizes the continuum (thick line in right panel of Fig. 4). On top of this “depolarized” line profile we have to add the triplet peak of line polarization when increasing the polarizability $W_2$ (right panel of Fig. 4). The second solar spectrum contains numerous examples of such lines for various $W_2$.

3.1. The role of partial frequency redistribution

Partial frequency redistribution (PRD) is often stated as the main reason for the presence of polarized line wings, and thus for the triplet-peak formation (Rees & Saliba 1982; Faurobert 1987, 1988). However, it should be understood that PRD is a necessary but not sufficient condition for the existence of a triplet peak.

PRD refers to frequency coherence in the atomic rest frame, i.e., the frequencies of the incident and scattered photons are identical. In the observer’s frame the random velocity component of the atoms (usually Maxwellian) leads to Doppler shifts typically of one Doppler width despite strict frequency coherence in the atomic frame. But far in the line wings a shift by one Doppler width is almost negligible and corresponds approximately to frequency coherence.

Therefore, PRD ensures (nearly) frequency coherence, or, in other words, PRD allows us to consider the triplet-peak formation frequency by frequency as a first approximation. It is then the complex depth and frequency dependence of the anisotropy that is responsible for the actual triplet structure.

While PRD does not shape the triplet profile, it is still crucial for the formation of polarization in chromospheric lines, in which basically all contributions to scattering polarization originate from the PRD part of the scattering integral. The line core forms in the chromosphere with a collision rate so low that PRD applies to nearly all scattering events. The wings form deeper in the photosphere with more elastic collisions, which redistribute photons primarily to the line core. Thus, only the fraction of frequency-coherent scattering events (undisturbed by collisions, and described by PRD) contributes to wing polarization.
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4. Temperature bifurcation in Ca II K

Now we apply the acquired knowledge to the diagnostics of the Ca II K line (details in Holzreuter, Fluri, & Stenflo 2006). Figure 5 displays scattering polarization of computed line profiles (same numerical method as in Holzreuter et al. 2005) compared to observations (Gandorfer 2002). We employed two different solar model atmospheres, the average model FALC (Fontenla, Avrett, & Loeser 1993), and the model FALX with a very cool chromosphere (Avrett 1995, his model M_{CO}). Both models are unable to fit observations in the core and near-wing region. In fact, we were not able to fit the observations with a single model atmosphere. All currently available “warm” models such as FALA, FALF, FALP (Fontenla et al. 1993), and others, share the same properties as the FALC profile (smooth, thin solid line, Fig. 5), while cool models result in profiles of the FALX-type (dotted, Fig. 5).

Interestingly, observations can be well fitted with a 2-component model consisting of both the FALC and FALX models (thick solid line in Fig. 5). The fit in the line core is even optimized when assuming a turbulent magnetic field of 8 G, so that the core is depolarized by Hanle effect (Fig. 6).
Such a temperature bifurcation in the chromosphere has already been known and heavily discussed because of the presence of lines of the CO molecule (Noyes & Hall 1972; Ayres & Testerman 1981; Uitenbroek, Noyes, & Rabin 1994; Avrett 1995; Loukitcheva et al. 2004, and many more). However, observational evidence of the cool components were almost exclusively due to molecular lines of CO without independent confirmation.

5. Conclusions

We explained the origin of the triplet peak observed in the second solar spectrum of strong lines by means of source function gradient and anisotropy of the radiation field. Further, we found evidence that scattering polarization in Ca II K can be used as an additional tool besides CO molecules to study the cool components of the chromosphere.

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