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Paschen is partially Back

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Abstract. We present a discussion of the partial Paschen-Back (PB) effect in magnetic Ap stars. An overview of the theory is illustrated with examples of how splittings deviate non-linearly from the simple Zeeman picture; normally forbidden "ghost lines" appear in strong fields. Resulting asymmetric stellar Stokes profiles for a dipolar magnetic geometry are shown for the Fe II $\lambda\,6149$ line and it is established that PB lines may be subject to wavelength shifts. Modelling of Stokes profiles in the PB regime opens exciting new diagnostics.

Key words: atomic processes – magnetic fields – line : profiles – stars : chemically peculiar – stars : magnetic fields

1. Introduction

The discovery in 1897 by P. Zeeman of the splitting of spectral lines in magnetic fields has provided astrophysicists with a a valuable diagnostic tool. Following the pioneering work of G.E. Hale (1908) on sunspots, Zeeman observations have been carried out on all kinds of magnetic structures found throughout the solar atmosphere, leading to a deeper understanding of the role of magnetic fields in atmospheric dynamics. The later discovery by Friedrich Paschen and Ernst Back (1921) of the transition in very strong magnetic fields from the anomalous Zeeman effect to the normal Zeeman effect has had much less impact. Indeed, even in fields of 0.4 T as encountered in sunspots, very few spectral lines of special astrophysical interest are affected by the Paschen-Back (PB) effect and so only a handful of atomic lines have been analysed for PB signatures (see e.g. Engvold *et al.*, 1970; Socas Navarro *et al.*, 2004).

When H.W. Babcock (1960) discovered a 3.4 T field in the upper main sequence chemically peculiar (Ap) star HD 215441, it should have been obvious that a lot of atomic transitions would find themselves somewhere between the Zeeman and the PB regime (the partial or incomplete PB effect). However, not until much later was any thought spent on this problem (Kemic, 1975; Stift, 1977). A major discussion of the partial PB effect and a line profile modelling attempt is due to Mathys (1990). Landolfi *et al.* (2001) had a look at the PB effect on hyperfine splitting and predicted how this would affect the interpretation of observations.

In strongly magnetic Ap stars, it turns out that high-resolution spectra of the Zeeman doublet of Fe II at 6149 Å cannot be fitted with synthetic line profiles calculated in the Zeeman approximation. Mathys (1990) attributed the observed non-symmetric relative intensities of the two components and their shift in wavelength (relative to the magnetic null lines of iron) to the partial PB effect: at 2 T the magnetic splitting attains about 35% of the distance between the nearest fine structure levels of the lower term. We decided to have a close look at this particular iron line which is heavily used in magnetic field measurements, to model it in detail for realistic stellar atmospheres and various magnetic geometries, and to search for other spectral lines affected by the partial PB effect.

2. Theory and computational tools

The vector model of the Zeeman effect assumes that the spin-orbit interaction between L and S is stronger than their interaction with the magnetic field B. The total angular momentum is $J = L + S$ and J precesses about the magnetic field vector B, leading to $2J + 1$ magnetic sublevels characterised by the quantum number M. When instead the magnetic splitting by far exceeds the fine-structure splitting, both L and S first interact with the magnetic field, and J is no longer a good quantum number. The partial (incomplete) PB effect is situated between these 2 extrema; splitting and relative component strengths depend non-linearly on magnetic field intensity. The energy values of the levels (the eigenvalues) and the corresponding eigenvectors now have to be calculated by diagonalisation of a set of matrices. See Sect. 3.4 of the beautiful monograph by Landi Degl'Innocenti and Landolfi (2004) for details.

Thanks to multi-core architectures, detailed stellar polarised line synthesis in the partial PB regime has become affordable. Derived from the Stokes code COSSAM (Stift, 2000) CossamPaschen is the first code ever to allow the correct modelling of a multiplet in the partial Paschen-Back regime. Which means realistic stellar atmospheres, a sophisticated oblique rotator model in the stellar case (Stift, 1975), component by component opacity sampling (CoCoS) (Stift, 2005), and the Zeeman Feautrier solution to the polarised RTE (Alecian, Stift, 2004). Blending with the other transitions in the spectrum (these are treated in the Zeeman approximation) is fully taken into account. CossamPaschen requires lots of computer memory because splittings and relative subcomponent intensities go non-linearly with field strength; so for each point on the stellar surface (depending on field geometry and on rotation we need several $10^2 - 10^3$ points) the exact splittings and relative intensities for the given local field strength have to be determined by diagonalisation of the set of matrices outlined above and stored in appropriate data structures. The object-oriented approach (Stift, 1998 a, b) based on Ada95 greatly facilitated the necessary modifications.

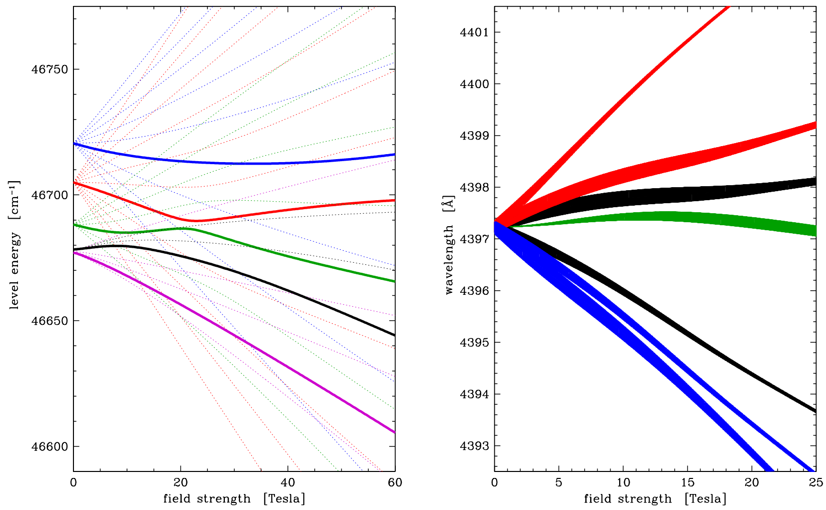

Figure 1. (Left) Avoided crossings in a Cr I ^5D term. **(Rright)** Splitting pattern and intensities of the Cr I line at 4397.229 Å.

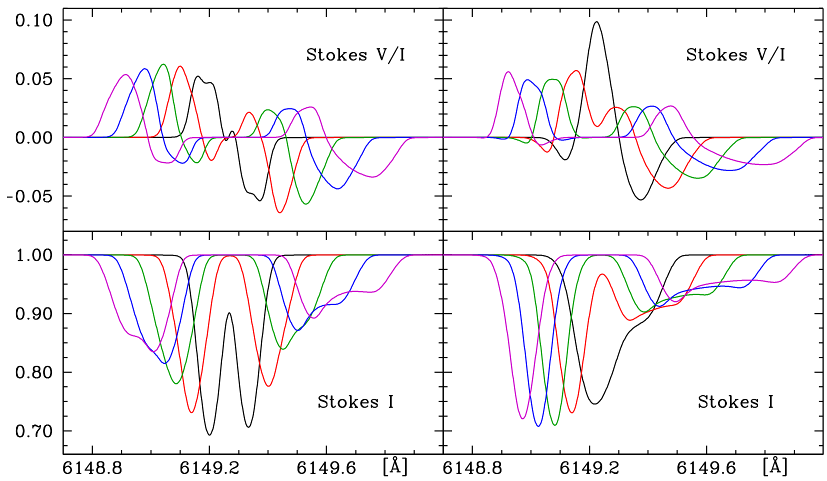

Figure 2. (Left) Stokes I and V profiles of the Fe I λ 6149 line for an oblique rotator model (as explained in the text). No rotation, the results pertain to field modulus values of $H_s = 1.43$, 1.14, 0.86, 0.57 and 0.29 T. **(Right)** The same, but for $v \sin i = 5\,\mathrm{km\,s^{-1}}$.

3. Level splittings

In the PB regime the splittings of the energy levels in a multiplet change in a non-linear and asymmetric way with magnetic field intensity. So do the relative intensities of the subcomponents. The smallest distance between adjacent levels of the ^4D term of Fe II multiplet 74 (to which the well-known line 6149 Å belongs) is about $4.0\,\mathrm{cm}^{-1}$ and deviations from linear Zeeman splitting are revealed for fields ≥ 0.7 T. In the Li I λ 6707 doublet (just $0.34\,\mathrm{cm}^{-1}$ fine structure splitting) asymmetries can occur at much lower field strengths (0.2 T) but the relative intensities are affected even earlier: the two π-components differ by 20 % at 0.05 T, the respective blue and red σ-components by 10 %.

Sometimes we encounter "avoided crossings", so familiar to helioseismologists. Sublevels of a spectroscopic term which have the same value of M must not cross, whereas the others are free to do so. This is beautifully illustrated for the $M = -1$ levels of a Cr I ^5D term (Fig. 1 right). Such avoided crossings are of course reflected in exotic splitting patterns (Fig. 1 left).

4. The profile of the Fe II λ 6149 line

This famous line, belonging to multiplet 74 of Fe II, is at the basis of most determinations of H_s, the field modulus integrated over the visible hemisphere of a magnetic star. Mathys (1990) has already drawn attention to the observed asymmetry of the line profile in the strongly magnetic Ap star HD 126515 which cannot be explained in the Zeeman approximation (the rotation is almost negligible), and he invoked the partial Paschen-Back effect as an explanation. Fig. 2 shows PB profiles in Stokes I and V for a simple centred dipole oblique rotator model and for $v \sin i = 0$ (left) and $5\,\mathrm{km\,s}^{-1}$ (right panel). With $i = 90°$and obliquity $\beta = 90°$, the star is seen at phase $\phi = 0.125$, i.e. the dipole axis is inclined by 45°towards the line-of-sight. Without rotation, the doublet becomes aysmmetric already at $H_\mathrm{s} = 0.29$ T; at $H_\mathrm{s} = 1.43$ T the red component is quite broad and shallow, the blue component narrower and deeper. The Stokes V profiles are not quite as asymmetric.

With moderate rotation of a mere $v \sin i = 5\,\mathrm{km\,s}^{-1}$, the profiles change drastically, and the asymmetry becomes even more pronounced. For the strongest fields displayed in Fig. 2 (8.6 - 14.3 T) we encounter a very narrow blue component and an extremely extended red component (with the ratio of the respective FWHM approaching a value of 4). These huge asymmetries are reflected to a lesser degree in the Stokes V profiles. Detailed modelling of such profiles should provide fascinating diagnostic capabilities.

Fortunately, despite these spectacular profile changes due to the PB effect, the distance between the respective centres-of-gravity of the blue and the red component of λ 6149 remains almost exactly the same as in the Zeeman regime. Measurements of H_s made in the past thus do not have to be revised.

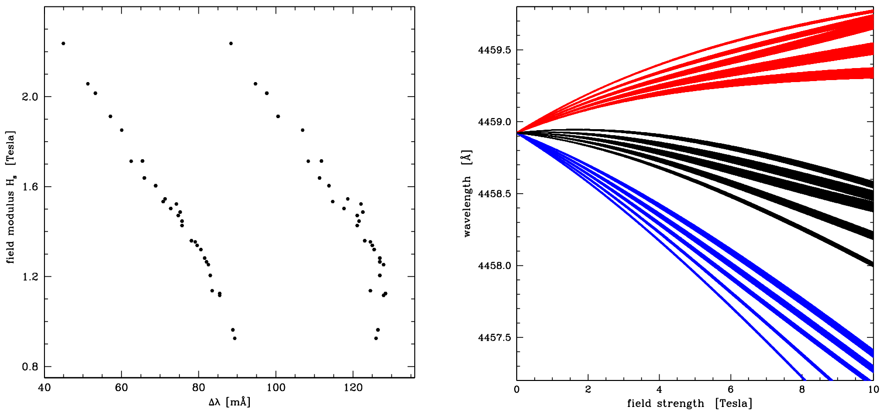

Figure 3. (Left) Wavelength shift of the centre of gravity of the combined Fe II $\lambda\,6147$ and $\lambda\,6149$ lines as a function of mean field modulus H_s. The abundance difference between the 2 sets of points is 1 dex. **(Right)** Splitting pattern and intensities of the Cr I "ghost line" at 4458.92 Å, belonging to multiplet 127.

4.1. Line shifts

Line shifts in Stokes I are a natural consequence of the non-linear splittings and the field-dependent relative intensities of the Zeeman subcomponents. Taking 30 different oblique rotator models with $H_s = 0.9 - 2.2$ T, we find a fairly tight relation between H_s and the shift of the centre of gravity of the $\lambda 6147, 6149$ blend from its zero field position. Largely insensitive to geometry, the relation strongly depends on line strength. Fig. 3, left, displays the results for 2 abundances differing by 1 dex. The set of points to the right corresponds to the higher abundance and the maximum displacement of about 125 mÅ occurs near $H_s = 1.2$ kG. Such shifts in conjunction with the strong profile variations could erroneously be interpreted as resulting from inhomogeneous element distributions.

5. Ghost lines

In their monograph, Landi Degl'Innocenti and Landolfi (2004) discuss in some detail the appearance in the incomplete Paschen-Back regime of lines which are forbidden under the usual selection rules but which originate from J-mixing of the various levels of a term. The strength of these lines is a strong function of field intensity. and many of them can result in having a strength comparable with that of the allowed lines when the field exeeds 10-20 T.

Multiplet 127 of Cr I, in addition to the 12 allowed lines, gives rise to 13 ghost lines. The strength of these lines starts from 0 at $B = 0$, and at 10 T they are $1-10$ orders of magnitude weaker than the allowed lines. Fig. 3b shows the nicely non-linear behaviour of the $\lambda\,4458.92$ ghost line. It is as yet not clear whether any ghost lines belonging to strong multiplets of overabundant elements could possibly be observed – as suggested by Mathys (1990) – in Ap stars, where parts of the surface can exhibit fields of $3-5$ T.

6. Conclusions and outlook

A number of atomic lines observed in strongly magnetic Ap stars manifest asymmetries and line shifts that cannot be modelled in the Zeeman regime and have to be ascribed to the partial Paschen-Back effect. We can show that these are not just some exotic few because no less than 846 lines originate from a single Cr I term with fine structure splittings $0.25-2.77\,\mathrm{cm}^{-1}$. We think that whenever magnetic splittings become of comparable size, a full PB treatment of the whole multiplet containing this term is warranted and we illustrate this with the first ever realistic Stokes profile modelling of the Fe II $\lambda\,6149$ line. Expecting exciting new diagnostic possibilities thanks to such improved modelling, we have started further explorations in this fascinating new field.

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