VIRTUAL AND SPURIOUS SURFACE STRUCTURE ON AP STARS

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1. Introduction

Modelling of magnetic Ap type stars has a long and distinguished history. The Oblique Rotator Model (ORM) – a dipole inside the star, its axis not aligned with the rotation axis – proposed by Babcock (1949a) provides a simple yet flexible enough paradigm for the modelling both of the magnetic and the spectral line variations of these stars. Deutsch (1958) developed a method to derive surface composition distributions from magnetic field measurements in conjunction with line strength variations but subsequent investigators concentrated either on the magnetic field or on the abundance distributions. Hardly ever was the question of consistency between field and composition mapping addressed – Landstreet (1988) constitutes the exception. In abundance mapping, Doppler imaging (Vogt et al. 1987) has meanwhile replaced most other approaches and is credited with fairly reliable results. But can one really carry out such mapping, as done by Hatzes (these proceedings) without accounting for the magnetic field and can these zero-field abundance maps and their relation to the magnetic configuration be compared to the predictions of diffusion theory? Did Landstreet ever have a real chance of disentangling magnetic and abundance effects using intensity (Stokes I) profiles only? What is the probability of obtaining spurious surface structure from intensity Doppler imaging of Ap stars?

2. Magnetic intensification and virtual surface structure

In a transverse magnetic field the equivalent width of a spectral line increases over the field free value due to Zeeman splitting an ensuing desat-

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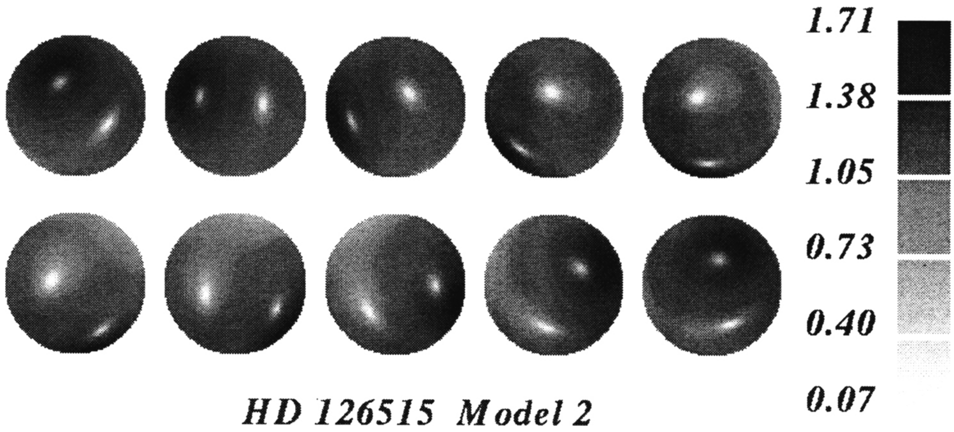

Figure 1. Phase dependent virtual surface structure of HD 126515 calculated for Stift & Goossens' (1991) low inclination ($i = 25°$) ORM. The Eulerian angles $\alpha = 70°$, $\beta = 65°$ and $\gamma = 50°$ describe the direction of the dipole axis relative to the rotational axis, $x_2 = 0.25$ and $x_3 = 0.20$ are the displacements of the dipole from the centre of the star in and perpendicular to the equatorial plane respectively (in units of stellar radius); normalised dipole strength $m = 0.658$ Tesla. Phases run from left to right and from top to bottom; abundance enhancements derived for a Zeeman triplet are given in dex.

uration. This effect, called magnetic intensification by Babcock (1949b), plays an important role in many Ap stars where magnetic fields constitute the dominating line broadening mechanism. It can be expected to be at least partially responsible for the observed variations in shape and equivalent width of metal lines of moderate strength, since spatially inhomogeneous transverse field components are present over large portions of the visible hemisphere (at least for the dipolar and quadrupolar magnetic field distributions characteristic of Ap stars). The respective differences between magnetic and non-magnetic line widths depend linearly on the magnetic field modulus, but the equivalent widths change in a strongly non-linear way with magnetic field strength and direction, depending on Zeeman pattern and saturation. Keep in mind that it is the field direction in the observer's frame that enters the equation of radiative transfer for polarised light, not the magnetic geometry in the corotating frame!

The analysis of Ap star spectra shows that the observed equivalent widths of the lines of a number of elements, interpreted in terms of abundance, are not compatible with solar metallicity values. Apparent overabundances – which frequently vary with magnetic phase – can be attributed either to true abundance surface structure or to magnetic intensification (or to both): the former corotates with the star, the latter depends in a complex way on the instantaneous projected magnetic geometry in the observer's frame. Note that surface temperature inhomogeneities (rarely if ever considered) would lead to similar enhancements and variations.

What does virtual surface structure look like for strongly magnetic Ap stars? Analysing the local equivalent widths purely in terms of abundance anomalies, one arrives at the phase dependent maps for HD 126515 displayed in Fig. 1. Local virtual abundances are found to exceed the true abundance by up to 1.7 dex over large parts of the stellar disk; depending on Zeeman pattern and field, enhancements may attain 2 dex in other models. Only close to those comparatively small regions where the field is almost longitudinal do we find near zero enhancement, giving the overall impression that we are dealing with spots. A systematic investigation, using also less extreme field strengths and geometries, reveals that at constant geometry maps change with field strength in a non-linear way and that there is no apparent rotation of virtual structure, only some kind of libration. The changes with phase of virtual structure misleadingly suggest that the star is seen almost pole-on, regardless of the actual inclination.

3. Virtual structure and Doppler imaging

Consider an Oblique Rotator with uniform surface chemical composition. With high resolution, the observer would see phase dependent equivalent width variations over the stellar disk, interpretable in terms of abundance patches as discussed above and displayed in Fig. 1. From the libration however it would become immediately clear that the observed structure was not corotating. In integrated light this information is no longer available: virtual structure, Doppler-shifted by rotation, yields line profile variations which could as well result from true surface structure. Is the signature of librating virtual structure in Stokes I sufficiently different from the signature of true inhomogeneities to enable us to distinguish between these scenarios?

A related question concerns the modification of the results of Doppler imaging when the effects of magnetic intensification are accounted for in an approximate way. In effect, for many Ap stars, magnetic measurements are available and one may envisage mapping the true surface structure after applying appropriate corrections derived from a magnetic model of the star. Leroy et al. (1996) have shown that with reasonable constraints, a unique model can be derived by considering the integrated longitudinal field H_e, the integrated field modulus H_s and the QU-loops (frequency-integrated linear polarisation) simultaneously, but the availability of such complete data sets is the exception. H_e alone hardly places any restrictions on the possible model parameter combinations; addition of the QU-loops or of H_s observations becomes necessary for meaningful modelling. For the great majority of Ap stars with suspected or with poorly determined magnetic

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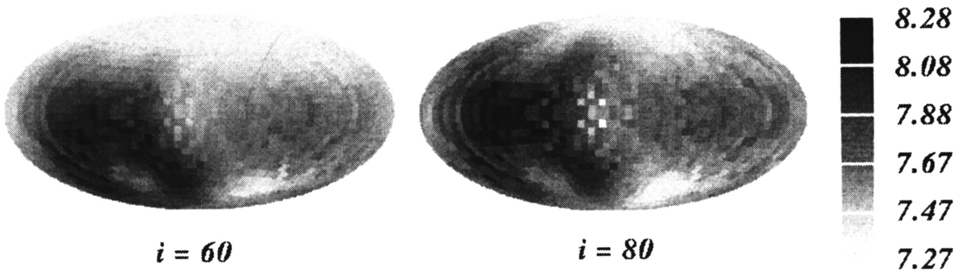

Figure 2. Spurious abundance maps (in dex) obtained from the zero field inversion of Stokes I profiles synthesised for an ORM with uniform abundance $\epsilon = 7.4$ and $i = 70°$, $\alpha = -90°$, $\beta = 0°$, $\gamma = 0°$, $x_2 = 0.20$, $x_3 = 0.00$ with $\mathbf{m} = 0.075$ Tesla and $v \sin i = 20$ km/s. The inclinations adopted for the inversion are given below the respective Hammer equal area projections, $v \sin i$ is the same as for the synthesised profiles.

fields we thus cannot compensate at all for magnetic intensification; compensation won't be overly reliable for most stars with strong fields. What kind of worst-case scenarios must we then expect in the analysis of moderate line-profile variations of Ap stars when field strength and geometry can only be guessed at?

4. Spurious structure and Doppler imaging: facts and conjectures

Neglecting the magnetic field or accounting for it in an approximate way corresponds to an erroneous assumption as to the local intrinsic line shapes, known to lead to spurious or distorted surface structure (Unruh & Collier Cameron 1995). Further development of this argument in the context of the exclusive analysis of Stokes I profiles leads to the following conjectures:

- There is virtually no guarantee against misinterpretation of magnetically induced spectrum variations in terms of spurious surface composition inhomogeneities: the signature of *librating virtual* structure can be indistinguishable from the signature of *corotating* structure.
- The judicious selection of a fairly large number of lines with greatly differing Zeeman patterns might forestall such misinterpretation but necessitates profile fitting to a very low value of χ^2.
- Relaxing the latter requirement as practised by Landstreet (1988) who tolerates systematic discrepancies of up to 20% in several lines amounts to discarding this information.
- Spurious structure will result from the adoption of magnetic geometries which do not exactly correspond to the true field distribution. This holds in particular for strong magnetic fields.
- Even the adoption of a magnetic field geometry totally at variance with the true one may lead to a reasonably looking map.

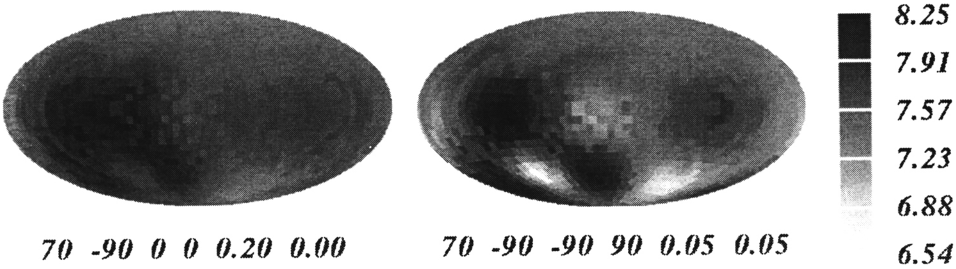

Figure 3. Comparison between spurious abundance maps obtained from the inversion of Stokes I profiles synthesised for an ORM with uniform abundance $\epsilon = 7.4$ and $i = 70°$, $\alpha = -90°$, $\beta = 0°$, $\gamma = 0°$, $x_2 = 0.20$, $x_3 = 0.00$, $\mathbf{m} = 0.075$ Tesla and $v \sin i = 20$ km/s. The magnetic geometries adopted for the inversion are given below. On the left, the map has been obtained with $\mathbf{m} = 0.000$ Tesla (i.e. zero field inversion), on the right with $\mathbf{m} = 0.050$ Tesla (i.e. magnetic field incorrectly taken into account).

– Magnetic fields can distort true abundance structure almost beyond recognition making it virtually impossible to recover it.

For the present study, large-scale software development proved necessary. A spectrum synthesis code capable of calculating integrated Stokes profiles for an ORM and a variety of surface abundance and magnetic field distributions is described elsewhere (Stift 1995). This code and a (Zeeman) Doppler imaging code which uses the same input physics and which correctly takes into account magnetic intensification (Fensl, private communication) are both written in Ada83, resulting in dramatically enhanced efficiency, understandability and modifiability. Stokes profiles were synthesised for a variety of field strengths and Zeeman patterns, using many different ORMs, including centred dipole, decentred dipole and tilted decentred dipole models (see Stift 1975); abundance distributions ranged from uniform to spots and smooth large scale variations. The numerical noise was less than 10^{-3} throughout, the minimum resolution 0.05 Å, i.e. twice the resolution attained by Landstreet (1988). Doppler imaging was carried out under different assumptions, involving all combinations of correct or incorrect inclination, approximate or altogether neglected magnetic fields.

In the following I shall only discuss results obtained from inversion of profiles where the magnetic field – alone or in combination with the abundance distribution – gives rise to a signature in I which exceeds the numerical noise by factors of 20-70 and even higher. Given the fact that identical physics and spatial grids are used for synthesis and reconstruction and that the profiles are fitted to 0.003 (rms), the results will thus reflect the response of the maximum entropy image reconstruction to the effects of the magnetic field; they cannot simply be attributed to poor conditioning. Compare my strict requirements to those of Landstreet (1988) whose 'reasonably unique'

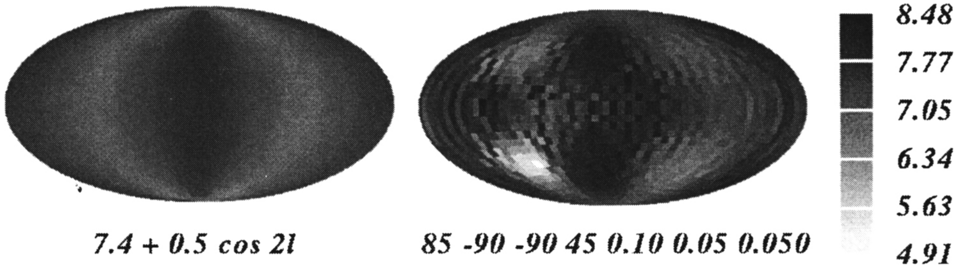

Figure 4. Spurious abundance map obtained from the inversion of Stokes I profiles synthesised for an ORM with abundance distribution $\epsilon = 7.4 + 0.5 \cos 2l$ (shown on the left) where l is the stellar longitude and $i = 85°$, $\alpha = -80°$, $\beta = 0°$, $\gamma = 0°$, $x_2 = 0.15$, $x_3 = 0.15$ with $\mathbf{m} = 0.075$ Tesla and $v \sin i = 15$ km/s. The map on the right is derived with an incorrect magnetic model given below in the order $i, \alpha, \beta, \gamma, x_2, x_3$ and $\mathbf{m}$.

best-fit models suffer from systematic discrepancies between theoretical and observed line profiles of between 13% and 20% (see his Figs. 1-3).

5. Magnetic fields and spurious surface structure: the results

The Doppler imaging results behave very much as anticipated. In particular, it can be demonstrated that virtual structure due to magnetic intensification can be misinterpreted: zero field inversion of Stokes I profiles synthesised with uniform surface composition and moderate to strong fields ($\geq$0.1 Tesla) not infrequently result in spurious corotating abundance structure as displayed in Fig. 2. Depending on the inclination value adopted for the inversion, this spurious structure shifts in latitude but with relatively little overall change; rarely does it relate to the magnetic field geometry. A comparison between two worst-case scenarios in Fig. 3 reveals that it is as dangerous to adopt an incorrect magnetic model (derived for example from H_e only) as to neglect the magnetic field altogether; both maps do not exhibit any abnormal spatial variations indicative of their spurious nature. How can one then establish the validity of the zero field approach (or of a particular adopted field geometry) in intensity Doppler imaging of some arbitrary star? Whereas non-convergence of the inversion scheme or an excessively patchy stellar abundance map may be taken as signs of errors, the converse is not true! It emerges from my calculations that any *a posteriori* justification based solely on a successful inversion and a beautiful abundance map is worthless. Without detailed circular or linear polarisation data it appears impossible to make sure that the worst-case scenarios invoked above will not actually happen.

It may surprise the attentive reader who is tempted to relate this spurious structure to the underlying virtual structure (as e.g. shown in Fig. 1)

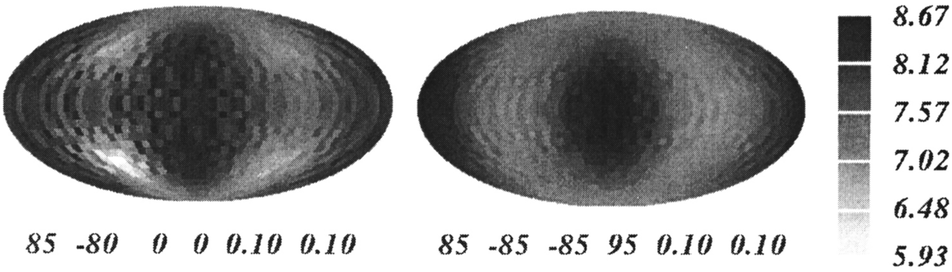

Figure 5. Spurious abundance map obtained from the zero field inversion of Stokes I profiles synthesised for two ORMs with abundance $\epsilon = 7.4{+}0.5 \cos 2l$ and magnetic model parameters as given below; $\mathrm{m} = 0.075$ Tesla and $v \sin i = 15$ km/s. True and assumed inclinations are identical. Compared to the original distribution, the apparently successful reconstruction on the right exhibits a much larger range in abundance (6.81-8.67).

to see a comparatively weak stellar field of only 0.150 Tesla polar strength yield apparent abundance enhancements of up to 0.9 dex as displayed in Fig. 2. Beware of such a fundamental conceptual mistake: spurious composition structure is not governed by the physics of magnetic intensification! Spurious abundances can be much higher than virtual abundances because they constitute the sometimes entirely unphysical response of a particular regularisation function to the spectral signature of the magnetic field!

Analysis of a large number of different models reveals that as a rule magnetic fields seriously distort true abundance maps. As demonstrated in Figs. 4-5, the intrinsic $7.4{+}0.5 \cos 2l$ composition pattern is not recovered in the presence of a magnetic field of the order of 0.1 Tesla. Both an incorrectly adopted magnetic geometry and zero field inversion yield a spurious increase in the amplitude of the spatial abundance variations; curiously depleted patches can develop, accompanied by the emergence of extended regions of considerable element-enhancement. Still, there is nothing really strange about the maps in Figs. 2-5; one even encounters Doppler imaging results that look "better" than the true abundance maps.

6. Conclusions: what can be done

Magnetic fields, whether neglected or taken into account in an approximate manner, can have a highly adverse effect on intensity mapping. Unfortunately, even magnetic fields of less than 0.1 Tesla exhibit this unpleasant behaviour. Thus only the ill-advised will try to map a magnetic star with a poorly determined magnetic field and with moderate spectrum variations. Even for well-observed Ap stars, it remains more than doubtful whether 'reasonably unique' abundance distributions can be derived from Stokes I profiles only. In stars with fields exceeding 0.5 Tesla this would require an inordinately accurate magnetic model; because the latter cannot be obtained without prior knowledge of the abundance map, Landstreet (1988) has proposed an iterative approach with alternate field and abundance determinations. Pending a proof that the solution converges towards the *correct* result for arbitrary large-scale field and abundance distributions, and in view of my calculations presented above, I am inclined to view Landstreet's scheme with the greatest scepsis. Having established that most conjectures listed in section 4 are really hard facts I want to conclude with a few more *conjectures* which will be the subject of subsequent papers:

- The interaction between the projected magnetic field variations, rotation and true surface structure is so complex and non-linear as to make it illusory to derive *a posteriori* corrections to be applied to zero field composition maps.
- For the same reasons, one cannot *in general* expect an iteration procedure to converge towards the correct result unless the magnetic starting model is almost indistinguishable from the correct one.
- It is not legitimate to compare abundance (or equivalent width) maps from zero field inversions with the magnetic geometry, correlating over- or under-abundances with the magnetic poles or the equator.
- Unique abundance maps require the inclusion of detailed $IQUV$ intensity, linear and circular polarisation profiles – or at least intensity profiles and integrated QUV measures – in *simultaneous* Doppler imaging of magnetic field and composition structure.

Remember: It is better to have no map than to have a spurious map!

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