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Spurious Doppler maps from noisy spectra and zero-field inversions★

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ABSTRACT

Empirical abundance maps derived with the help of Zeeman Doppler mapping are found to be at variance with the predictions of numerical models of atomic diffusion in magnetic atmospheres of ApBp stars. Although theory has often been made responsible for this lack of agreement, direct spectral synthesis based on the published abundance maps reveals that all the chemical inhomogeneities claimed for HD 3980 are entirely spurious, and those of HD 50773 to a large extent. In the former case, this is shown to be due to the neglect of a strong magnetic field, and in the latter case, due to noisy spectra in combination with considerable rotational broadening and ensuing strong line blending. Doppler maps for other magnetic ApBp stars could be affected by similar problems. It is also pointed out that the patchy, extreme overabundances in HD 3980 cannot be reconciled with the theory of stellar atmospheres.

Key words: line: profiles – stars: abundances – stars: chemically peculiar – stars: individual: HD 3980, HD 50773 – stars: magnetic field.

1 INTRODUCTION

Over the past decades, a fair number of ApBp stars have been analysed by means of Zeeman Doppler mapping (ZDM), resulting in an impressive array of abundance maps – and of magnetic maps when Stokes *V* profiles or preferentially *QUV* profiles are available in addition to Stokes *I*. On the other hand, diffusion theory has also progressed and has resulted in predicted stratification profiles of several chemical elements as a function of effective temperature, magnetic field angle and field strength (Alecian 2015). As it turns out, all the published results of ZDM seem to be at variance with the predictions of numerical diffusion models. Overabundances are rarely found around the 'magnetic equator' – where magnetic lines are tangent to the stellar surface – as predicted by theory, the correlation between magnetic field direction or strength with abundances is often poor or outright non-existent. This has led authors to conclude that the discrepancies between empirical abundance maps and theoretical predictions have to be imputed exclusively to an alleged lack of up-to-date theoretical models (Nesvacil et al. 2012, hereafter NL) or that important details are missing from the theory relating to the formation of horizontal abundance structures and the magnetic field (Silvester, Kochukhov & Wade 2014).

There is so far only one paper (Stift & Leone 2016) dealing in some detail with the capabilities of ZDM codes in the recovery of abundances under non-optimal conditions or possibly erroneous assumptions such as inversions based on a single line or zero-field inversions of the spectra of strongly magnetic stars. We have no intention to discuss here these results, neither will we ask at this point whether it can be legitimate to assume unstratified overabundances (even extreme ones) and underabundances in the ZDM analysis when on the other hand there is ample empirical evidence for stratifications in ApBp stars (see the review by Ryabchikova 2008). Instead, we have chosen to shed new light on a long-standing problem by direct forward line synthesis based on the published abundance maps. In Section 2, we illustrate how difficult in fact it is to determine meaningful abundance maps from 'noisy' [of insufficient signal-to-noise (S/N) ratio] spectra, and we show in Section 3 that zero-field inversions of stars with strong magnetic fields have to result in spurious maps. Finally, in Section 4, we draw attention to arguments brought forward in support of published maps – which, however, are in contradiction with the essentials of ZDM – and we point out the fundamental incompatibilities of these maps with basic stellar atmospheric physics.

2 NOISE AND SPURIOUS MAPS

To evaluate the effect of significant noise in Doppler mapping, we refer to the case of HD 50773. Lüftinger et al. (2010, hereafter LU10) have carried out a Doppler mapping analysis of this star, resulting in maps of a couple of metals, ranging from Mg to Cu.

★ Based on observations obtained at the Telescope Bernard Lyot (USR5026) operated by the Observatoire Midi-Pyrénées, Université de Toulouse (Paul Sabatier), Centre National de la Recherche Scientifique (France).
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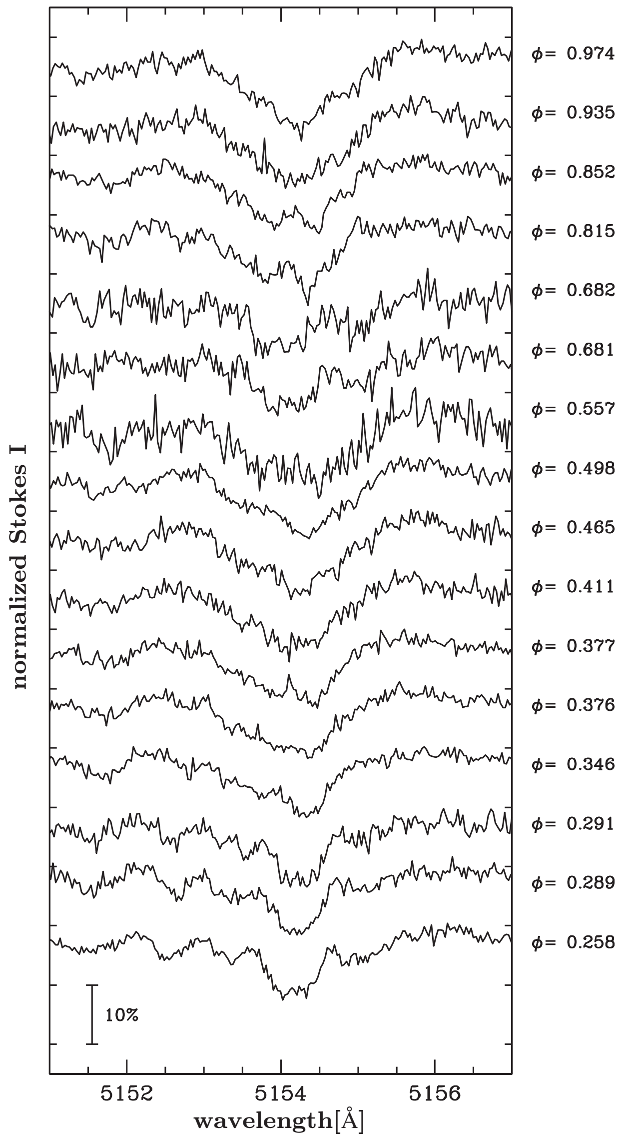

Figure 1. The spectral interval 5151–5157 Å of the Narval spectra (see the footnote to the title) used by Lüftinger et al. (2010) in the Doppler mapping study of HD 50773.

Since these maps have appeared a number of times in various reviews and lectures (e.g. Kochukhov 2014) in addition to the front page of A&A, they figure among the Doppler maps best known to the general astronomical public. According to table 1 of LU10, the *peak* S/N ratio of the spectra used in the inversion ranges from 64 to 170, with a mean value of about 120. Despite the low S/N ratio, LU10 have presented maps for elements like Ni and Cu, based on just one line each, with maximum abundance contrasts of a mere 0.5 and 1.1 dex, respectively. According to LU10, the Ni I λ5510.003 line is heavily blended with Cr, Fe and Y, and the Cu II λ5153.230 line with Cr, Ti and Fe. This makes HD 50773 a natural choice for a reassessment of the limits to the capabilities of ZDM when based on 'noisy' spectra.

Fig. 1 shows the interval 5151–5157 Å of the 16 Narval spectra used by LU10. To visualize the nature of the problem, one simply has to compare pairs of spectra made at almost the same phase, as for example at $\phi = 0.289$, 291, $\phi = 0.376$, 377 and $\phi = 0.681$, 682. It is obvious that a statistically optimum fit to the profile at phase 0.289 will not really fit the profile at phase 0.291 (see the top of Fig. 2). As far as the λ 5510 blend is concerned – the Narval spectra are plotted in Fig. 3 – the same holds true for phases 0.681 and 0.682 (see the top of Fig. 1). In view of these low S/N ratios, only spectral variations above a threshold of some >1 per cent of the continuum could be considered statistically significant and suitable for ZDM. Do the Ni and the Cu lines meet these conditions, and

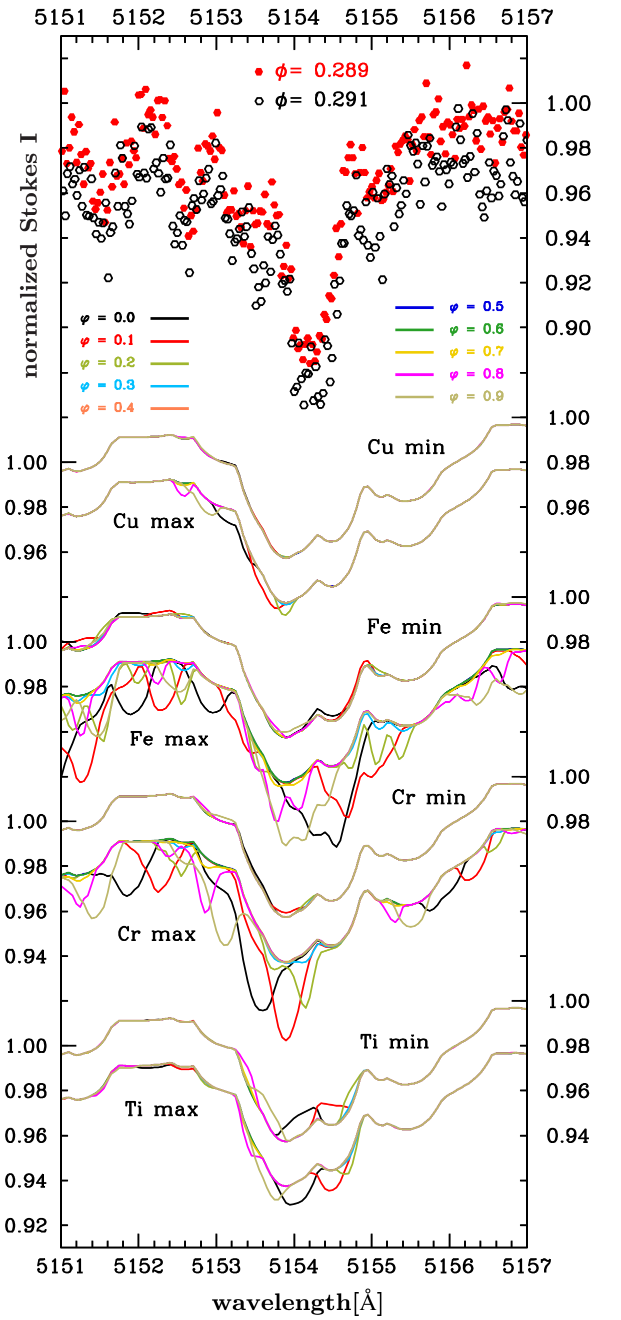

Figure 2. Spectral variations with phase φ (offset from ϕ) due to a spot at 20° latitude, with a radius of 20°. The spot is assumed to feature in turn the respective maximum and minimum abundances of each of the four elements in question (Ti, Cr, Fe, Cu), with solar abundances for the other 91 elements. The observed Narval spectra at two almost identical phases ϕ are also shown. Maximum visibility of the spot occurs at $\varphi = 0.0$, the spot remains invisible at phases $\varphi = 0.4$, 0.5, 0.6.

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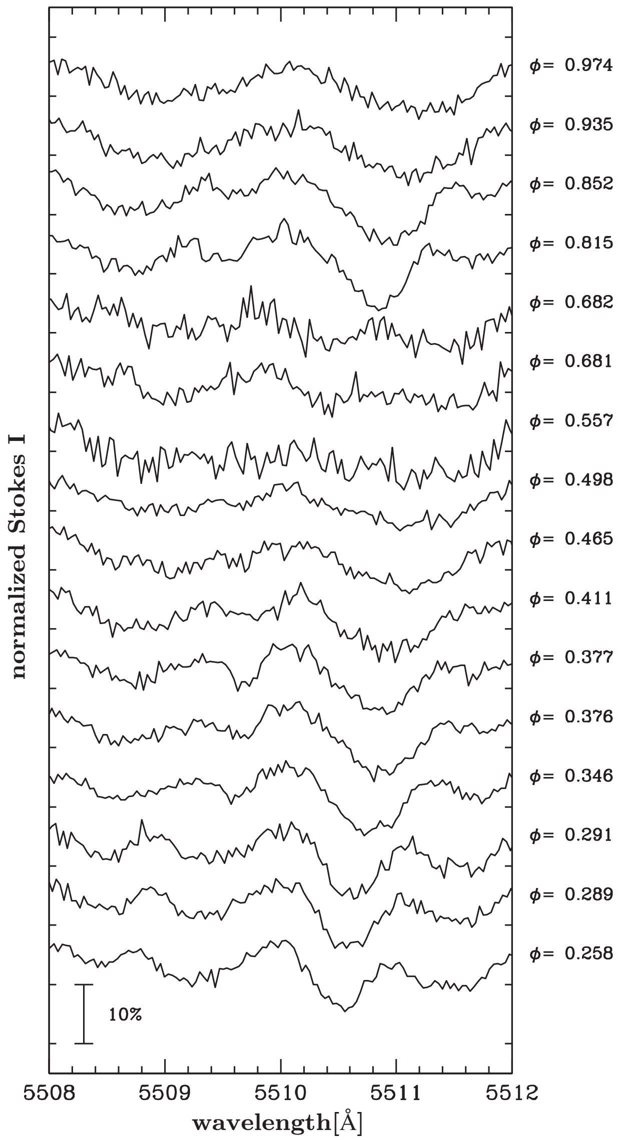

Figure 3. The spectral interval 5508–5512 Å of the Narval spectra used by Lüftinger et al. (2010) in the Doppler mapping study of HD 50773.

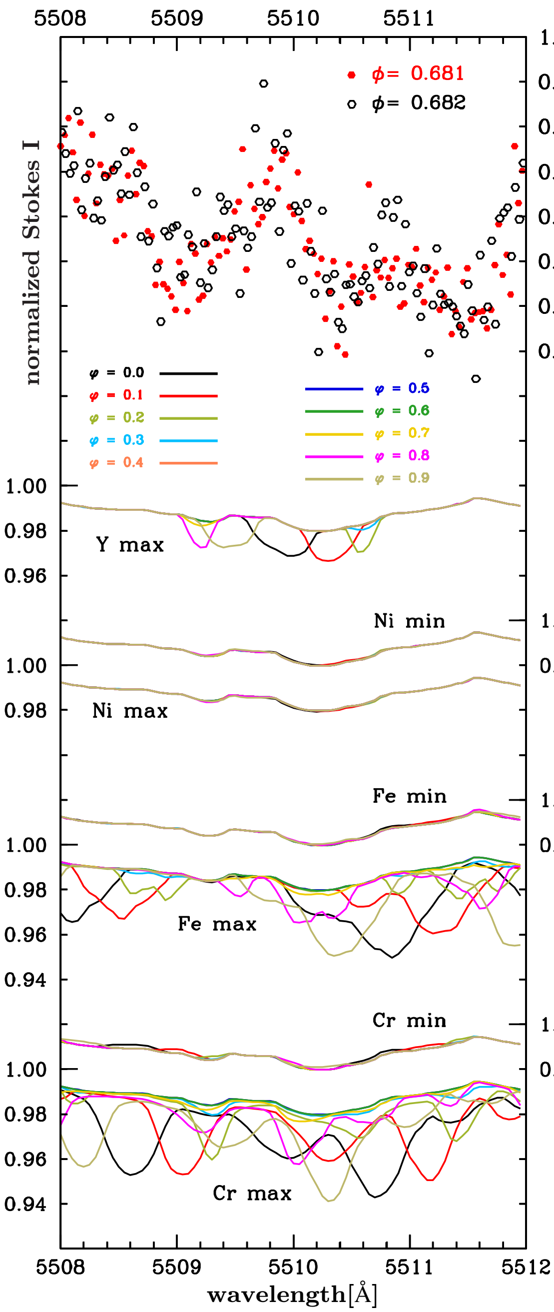

Figure 4. Similar to Fig. 2 but displaying the spectral variations of Cr, Fe, Ni and Y in the interval 5508–5512 Å. Narval spectra at two almost identical phases ϕ are also shown.

what is the actual signal of the respective Ni and Cu spots published by LU10?

Figs 2 and 4 give the answer. Adopting the stellar parameters listed by LU10 and assuming a Cu spot at 20° latitude with a radius of 20°, we modelled the variations of the blend containing the Cu II λ5153.230 line, assuming solar abundances for the rest of the chemical elements. We consider two limiting cases: a 'monolithic' spot with the maximum Cu abundance claimed by LU10 and the same spot with the minimum abundance. As it turns out, the spectrum variations due to the maximum spot are well below the 1 per cent mark, the minimum spot is altogether undetectable. Looking at the same spectral interval, but modelling solely Ti (in a similar way to Cu), one sees small variations from both the minimum spot and the maximum spot, both of the order of the photon noise. Repeating this exercise for Cr, the minimum spot is undetectable, whereas the signal of the maximum spot is quite pronounced. The Fe contribution to the blend behaves similarly, but with more than one line involved. It is important to be aware of the fact that in the Doppler mapping procedure that has led to the published Ti and Cu maps, both the contributions of Cr and of Fe to the blend have been modelled with lines found elsewhere in the spectrum. The λ5510 blend reveals equally interesting insight into what can be detected and what cannot even be guessed at. Both the minimum and the maximum Ni spots for example leave a signal which reaches a few 10^{-3} of the continuum at most and which is completely swamped by the signatures of the respective Cr, Fe and Y maximum spots. Not a single minimum spot of the four elements can be distinguished from the solar abundance stellar surface. Even the most cursory glance at the observed spectra at phases 0.681 and 0.682 will convince the experienced spectroscopist that modelling of the blend will lead to exceedingly uncertain results.

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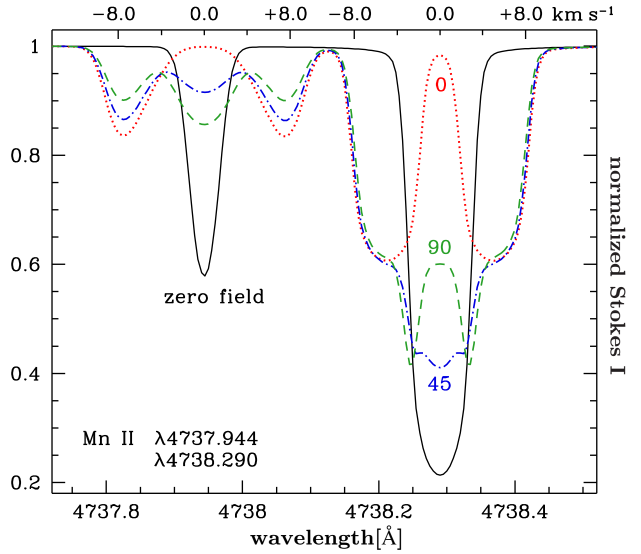

Figure 5. Zeeman splitting of the Mn II lines at λ4737.944 and λ4738.290 in a 7 kG magnetic field. Shown are the cases of a longitudinal field (dotted profile), a transverse field (dashed) and the intermediate case of 45 ° (dash–dotted). The full line gives the unsplit lines. For illustrative purposes, we have also given velocities with respect to the unsplit positions of the two lines.

Let us push this analysis further. In LU10, it is stated that the Doppler code makes it possible to simultaneously calculate abundance maps of several chemical elements even from blended spectral lines, but this statement deserves some qualification in view of the strong interdependence between the various maps. Let us begin with the Fe map which is derived from four lines in 'noisy' spectra, three of these lines forming a blend at λ5400 (see table 6 of LU10). This Fe map is used in the modelling of the λ5510 blend, resulting – together with two more Cr lines – in a Cr map, but at the same time also in an Ni map and in a Y map, the latter together with one more Y line which in turn is blended with Fe. The Fe map and the Cr map (which depends to some degree on the Fe and the Y maps) have to be taken into account for the mapping of Ti and of Cu. Unless one were prepared to assume that a perfect fit to the Cr and the Fe profiles could be obtained at the 0.1 per cent level, any signal apparently originating from spatial inhomogeneities in Ni or Cu must of necessity be dominated by errors in the Cr and Fe maps, resulting in entirely spurious maps. Given the marginal signature of minimum and maximum Ti spots, little faith can be placed in the corresponding map. The same holds probably true for Y. How far the maps of Cr and of Fe reflect the intrinsic abundances cannot be said at any reasonable level of certainty.

3 NEGLECTING MAGNETIC FIELDS

Stift (1996) showed that in ZDM, the adoption of an incorrect magnetic field geometry leads to spurious abundance structure, even more so when the field is neglected altogether. The resulting horizontally non-homogeneous abundances are due to the effect of 'magnetic intensification' (Stift & Leone 2003) – i.e. the splitting and ensuing desaturation of the spectral lines – but these abundances bear no relation to the magnetic field strength and/or orientation. Rather are they a consequence of the entirely unphysical and unpredictable response of the regularization function used in ZDM to the Zeeman splitting of the local line profiles. The analysis of HD 3980 by NL constitutes an interesting case of Doppler mapping that does

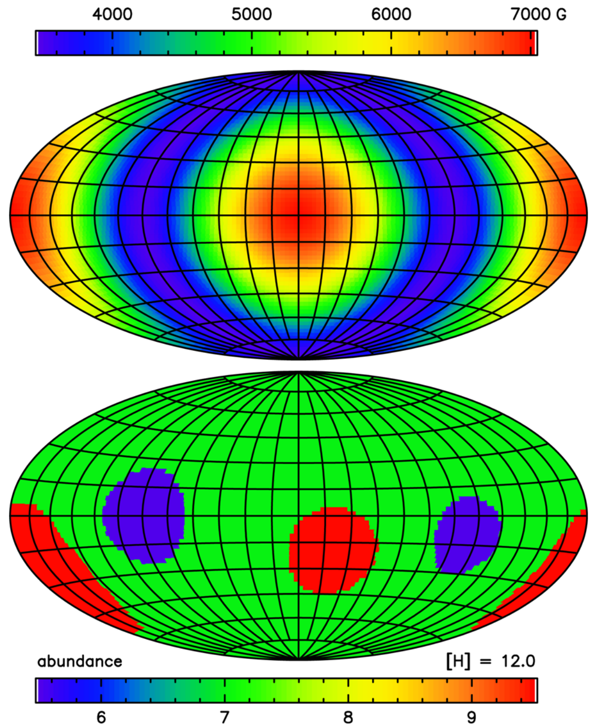

Figure 6. A Hammer equal-area projection of the magnetic geometry and the distribution of the manganese spots in a simple model of HD 3980. Top panel: the respective positions of the magnetic poles in the equatorial plane. The wedge indicates the absolute field strength (in Gauss). Bottom panel: there are two spots with an overabundance of 4.6 dex relative to solar, two spots with an underabundance of 0.4 dex, the remaining surface being overabundant by 1.6 dex. The wedge indicates the adopted abundances on a scale with [H] = 12.0.

not take into account a 7 kG magnetic field; it is therefore well suited for a reassessment of empirical zero-field maps in strongly magnetic stars.

A close look at the two Mn II lines used by NL in a field of B = 7 kG reveals large Zeeman splittings as shown in Fig. 5 (a similar most instructive plot for all four Stokes parameters can be found on page 30 of Kochukhov 2014). At a given wavelength, intensity values can differ hugely between the unsplit lines and the Zeeman-split lines at various field angles. In the longitudinal field case, intensities at the respective positions of the unperturbed lines attain a level very close to the continuum. Conversely, at ±5–6 km s^{-1} from the centre of the λ4738.290 line – where normally the line disappears in the continuum – substantial opacity comes from the σ-components. The λ4737.944 line behaves similarly but displays a larger Zeeman splitting; maximum opacity from the σ-components is now found at ± 7–8 km s^{-1}. The missing signal from the line centre in a zero-field inversion will be interpreted by the ZDM algorithm as a sign of an extremely low abundance, the signal from the σ-components as coming from spots. To complicate things, these spurious spots would be located at different positions for the two lines. There can be little doubt that zero-field inversions for stars with strong magnetic fields like HD 3980 have to fail.

It is not difficult to verify this conjecture. We approximate the published Mn maps with two major spots featuring a 4.6 dex overabundance relative to the solar values, two spots with a 0.4 dex underabundance and a remaining surface overabundant by 1.6 dex (Fig. 6). Adopting the suggested magnetic field parameters, the

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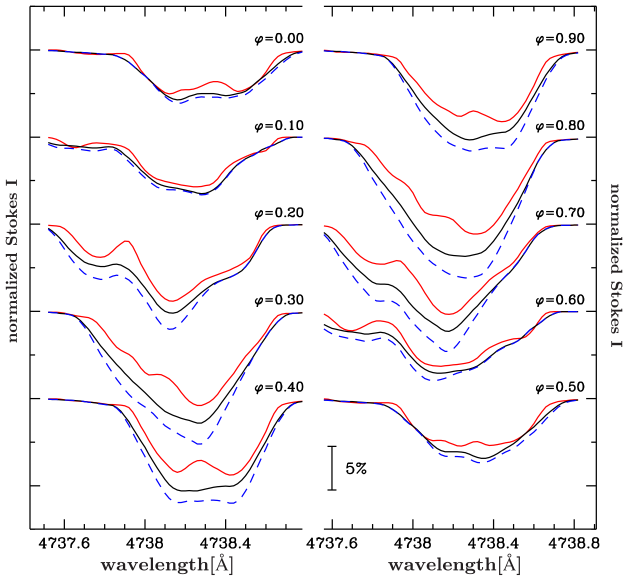

Figure 7. Predicted profiles of the manganese doublet in HD 3980. The profiles in black have been calculated with the magnetic field geometry postulated by NL, with a polar field strength of $B_p = 7$ kG. The red profiles pertain to a zero-field synthesis. If appropriate metallicity-dependent local atmospheres were used in the line synthesis as postulated by Stift, Leone & Cowley (2012), one would obtain the dashed blue profiles.

effect of the magnetic field on the Stokes *I* profiles can be modelled in a straightforward way. The results for 10 different phases are displayed in Fig. 7. Over more than half the rotation period, large discrepancies are found between the non-magnetic profiles and the profiles calculated with the field of the dipole lying in the equatorial plane. If in addition, we apply an estimate of the impact of the huge overabundances of elements like Si, Cr, Fe, Mn on the local atmospheric structure – for a more detailed discussion of the latter problem see Stift et al. (2012) – the discrepancies become even larger. In the light of these findings, it cannot come as a surprise that the abundances of silicon (equal to hydrogen) and manganese (equal to helium) determined by NL are so extreme in some spots; their spurious nature is beyond reasonable doubt – not least because their existence is physically impossible as becomes immediately clear from a comparison of the respective pressure scaleheights in the spots and their surroundings.

4 PROFILES, EQUIVALENT WIDTHS AND STELLAR ATMOSPHERES: SOME CAVEATS

Despite the huge differences in the angle-dependent Mn profiles shown in Fig. 5, the equivalent widths differ by less than 7 per cent because of the large Zeeman splitting. Does this mean that (as argued by NL) we can safely neglect the magnetic field in Doppler mapping because of the small impact of the magnetic field on equivalent widths and apparent abundances? To do so would constitute a violation of the very foundations of ZDM – which is all about wavelength shifts due to rotation and to magnetic splitting. The exact shapes of the local line profiles have to be known, not the equivalent widths or similar quantities. This has amply been made clear in many papers (e.g. Vogt & Penrod 1983) and in lectures (e.g. Kochukhov 2014). There is also an instructive video to be found on http://astars2013.inasan.ru/presentations/4_06/Lueftinger/Theresa/di.mpg demonstrating the signatures of two spots on a line profile.

One may thus rightfully be puzzled by the fact that in the analysis of HD 3980 (Nesvacil et al. 2012), carried out with the help of the fully magnetic INVERS12 code, the effects of neglecting the strong magnetic field have not been estimated by means of a simple forward synthesis run of INVERS12, adopting the actual magnetic field. Resorting instead to line synthesis runs with the SYNTH3 and the SYNTHMAG codes, comparing non-magnetic to magnetic equivalent widths and determining the resulting apparent abundances, NL are advancing arguments that bear no relation to the workings of ZDM.

In this context, one is reminded of the zero-field results published for HR 3831 (Kochukhov et al. 2004), another star with a substantial magnetic field of about $B_p = 2.5$ kG. One of the most striking characteristics of these maps are the huge abundance contrasts displayed for a number of chemical elements, reaching 7 dex for Ba, 6.3 dex for Na, 6.2 dex for Pr, 6.1 dex for Mn and Y, and between 4 and 5.5 dex for a couple of other metals. Incidentally, the maps for the five elements with the largest contrasts are all based on single-line or dual-line inversions (for the problems associated with single-line inversions see Stift & Leone 2016). Since none of the many stars with magnetic field and abundances determined simultaneously has ever been shown to exhibit such astonishing behaviour, it is not unreasonable to surmise that the neglected magnetic field may be at least partly responsible for the strikingly high-contrast abundance structures of HR 3831. The credibility of the abundances maps is not exactly enhanced by the quality of the profile fits; the differences predicted versus observed profiles can reach and even exceed 5 per cent of the continuum intensity in several lines of the elements C, Mg, Si and Na.

Taking the overabundances of various elements in HD 3980 as determined by Nesvacil et al. (2012) at face value – Si being as abundant as hydrogen in some spots, and Mn and O as abundant as He – we are confronted with a situation incompatible with basic physics. In these spots, the mean molecular weight of the gas is about $\mu \approx 35$, more than 25 times the value for solar abundances of $\mu = 1.26$. The local pressure scaleheight inside the spot would thus be just 1/25 of the scaleheight of the surroundings. In a system consisting of such an extreme stellar spot and the 'normal' atmosphere, horizontal pressure equilibrium would be established almost instantaneously. In order to ensure that the very slow diffusive motions – of the order of a few centimetres per second – may build up truly enormous abundances of O, Si, Ca, Cr, Mn and Fe over time-scales of hundreds of thousands of years, one has to invoke some stabilizing force. The only possible lateral support would come from a very strong magnetic field, but in order to operate, the material would need to be mostly ionized, which is unrealistic for mid- or late A-type stars.

We know little to nothing about the magnetic field geometry of HD 3980, so it makes sense to look elsewhere for empirical evidence concerning the relation between field strength, geometry and overabundances. In 53 Cam (Piskunov 2008, Figs 3 and 4), the largest overabundance and the most remarkable underabundance of Fe are both found at positions on the stellar disc that can be considered extremely strong magnetic poles with $\boldsymbol{B} > 20$ kG. The spot with the second largest Fe overabundance is found not far from the 'magnetic equator' and there is no vertical field to horizontally confine the strong Si spots situated near the 'magnetic equator'. We thus conclude that the alleged existence of extreme abundance configurations in HD 3980 is in contradiction with basic principles of stellar atmospheric physics and also points towards an entirely spurious nature of the published Doppler maps.

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5 CONCLUSIONS

In order to assess the reliability of the published Doppler maps of HD 3980 and of HD 50773, one is not obliged to have recourse to ZDM codes. Without a detailed and extensive comparison of the performance of rival codes one could never be absolutely sure that for the same set of data they would converge to the same solution. It rather makes sense to choose forward synthesis, based on the published abundance maps, to see what the predicted line profile variations would look like in the presence or absence of a magnetic field, and/or how their amplitudes compare to the noise in the observed spectra. In Wade et al. (2001), it has been shown that the polarized line synthesis algorithms underlying INVERS12 on one hand and COSSAM on the other hand yield identical results, so the reliability of our findings is not expected to become the subject of dispute.

It turns out that the signals from the low-contrast Ni and Cu spots published by Lüftinger et al. (2010) are swamped by the noise of the Narval spectra of HD 50773 which are of insufficient S/N ratio. Our results also suggest that it is highly unlikely that any observational constraints for the theory of radiative diffusion in magnetic stars could ever be deduced from the modelling of profile variations of heavily blended, noise-ridden spectral lines in a fast rotator. In a similar vein, zero-field inversions applied to strongly magnetic stars, for example, HD 3980 (Nesvacil et al. 2012) must of necessity lead to spurious abundance maps – which in the case of this particular star are demonstrably irreconcilable with textbook stellar atmospheric physics. Hence, claims and conclusions based on such empirical zero-field inversion abundance maps cannot possibly constitute challenges to present-day diffusion theory. For an overview of a couple of other major problems arising in ZDM, we refer to Stift & Leone (2016).

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REFERENCES

Alecian G., 2015, MNRAS, 454, 3143
Kochukhov O., 2014, Surface Cartography of the Sun and Stars, Besançon, 2014. Uppsala University, Sweden
Kochukhov O., Bagnulo S., Wade G. A., Sangalli L., Piskunov N., Landstreet J. D., Petit P., Sigut T. A. A., 2004, A&A, 414, 613
Lüftinger T. et al., 2010, A&A, 509, A43 (LU10)
Nesvacil N. et al., 2012, A&A, 537, A151 (NL)
Piskunov N., 2008, Phys. Scr., 133, 014017
Ryabchikova T., 2008, Contrib. Astron. Obs. Skalnate Pleso, 38, 257
Silvester J., Kochukhov O., Wade G. A., 2014, MNRAS, 444, 1442
Stift M. J., 1996, in Strassmeier K. G., Linsky J. L., eds, Proc. IAU Symp. 176, Stellar Surface Structure. Kluwer, Dordrecht, p. 61
Stift M. J., Leone F., 2003, A&A, 398, 411
Stift M. J., Leone F., 2016, ApJ, in press
Stift M. J., Leone F., Cowley C. R., 2012, MNRAS, 419, 2912
Vogt S. S., Penrod G. D., 1983, PASP, 95, 565
Wade G. A., Bagnulo S., Kochukhov O., Landstreet J. D., Piskunov N., Stift M. J., 2001, A&A, 374, 265

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