Chemical Stratification in Magnetic Ap Stars

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Abstract. We report powerful new optical diagnostics of chemical stratification in the outer layers of magnetic Ap stars, along with preliminary modeling of the vertical abundance distributions and discussion of the implications of these results.

1. Introduction

Most, and perhaps all, A and late-B type (or tepid) stars exhibit anomalous star-to-star variations in the photospheric abundances of various chemical elements. These chemical peculiarities are understood within the framework of microscopic chemical diffusion: competition between gravitational settling and radiative levitation is believed to result in the selective diffusion of various trace elements into (or out of) the line-forming region (Michaud 1970). The peculiar spectra of tepid stars directly reflect the resultant accumulation or depletion of these elements. Amongst the magnetic tepid stars these effects become the most striking, indicating that the magnetic field plays an important (but presently unclear) role in element concentration. Chemical stratification represents an obvious equilibrium consequence of diffusion as ions are concentrated in some atmospheric layers and depleted in others, and has been investigated previously by a few authors: Babel (1992) and Babel & Lanz (1992) compared optical vs. UV abundances to explore chemical stratification of several elements in the magnetic Ap star 53 Cam. Babel (1994) studied the peculiar profile of the Ca II K line in spectra of a sample of magnetic Ap stars to constrain the vertical abundance distribution of calcium. Savanov & Kochukhov (1998) used the systematic variation in opacity through the Hβ line wing to study the stratification of Cr in several magnetic stars. These studies, although limited in extent, illustrate the potential utility of stratification as a tool for testing models of element
Figure 1. The Fe II λ4923.9 region in the spectrum of β CrB. This figure illustrates our systematic failure to fit the profiles of weak and strong lines with a uniform vertical abundance distribution. **Open Circles** – observed spectrum **Thin curve** – best uniform abundance fit to wings of Fe II λ4923.9, [Fe/H] = +1.2 **Dashed curve** – best uniform abundance fit to core of Fe II λ4923.9, [Fe/H] = −1.0 **Thick curve** – Best two-zone stratified Fe model. Note the much improved fit to Fe II λ4923.9 and to the Fe I/II λ4924 blend provided by the stratified model.

transport, including its exploitation as a sensitive probe of related atmospheric processes such as mixing and mass loss.

2. New optical diagnostics of chemical stratification

As a serendipitous result of two ongoing studies of the optical spectra of magnetic tepid stars, we have identified clear and ubiquitous new evidence for atmospheric chemical stratification:

1. We observe important systematic differences amongst abundances inferred from weak versus strong absorption lines of a given ion. These differences (e.g. Bagnulo et al. 2001) are often as large as 1-2 dex, are evident throughout the entire optical spectrum of magnetic tepid stars, and represent the most effective diagnostic of stratification discovered to date. This phenomenon, which is always manifested as weak lines indicating larger abundances than strong lines (in exactly the opposite fashion of microturbulence) is illustrated in Fig 1.

2. We fail systematically to fit the profiles of highly saturated metallic absorption lines. This effect (e.g. Cowley et al. 2000; Bagnulo et al. 2001), which is always manifested as line wings being much broader than expected given the abundance inferred from the line core, is also illustrated in Fig. 1.

3. We observe an unacceptable conflict between temperatures determined from spectral energy distributions versus those determined from ionisation balance. This is manifested as large systematic differences amongst abundances inferred from lines of different ions of the same element, and is especially obvious for the rare earths (e.g. Gelbmann et al. 2000).
4. We observe very high excitation lines of Fe II and Cr II \((E_l > 10 \text{ eV})\) in the spectra of relatively cool stars, consistent with large overabundances of these elements in atmospheric layers near \(\log \tau_{\text{std}} \approx 0.0\).

Some or all these of phenomena have so far been confidently detected in the spectra of \(\beta\) CrB, 53 Cam, 33 Lib, HD 101065 (Przybylski's star), HD 24712, HD 166473 and \(\gamma\) Equi. Because of the variety, magnitude and characteristics of the phenomena, we cannot attribute them to uncertainties in the structure of the atmosphere, to microturbulence, non-LTE effects, or magnetic desaturation. Furthermore, no simple non-uniform surface distribution of abundances seems able to explain the observations, either individually or generally. Chemical stratification, on the other hand, provides a single, simple explanation for all of the observed phenomena.

3. Modeling strategy and first results

The detection of chemical stratification, and the subsequent determination of vertical abundance distributions, was accomplished using two independently-developed magnetic spectrum synthesis codes: Zeeman2 (Wade et al. 2001), employed by Wade and Bagus, and SynthMag, employed by Ryabchikova and Piskunov. Both codes adopt the same basic two-zone model of the vertical abundance distribution, first introduced by Babel (1994). Using this schematic framework we are able to reproduce simultaneously the observed strengths of weak and strong lines, as well as the profiles of highly saturated lines. We also find that we are generally able to reconcile the ionisation balance with the atmospheric parameters determined from the spectral energy distribution.

To date, the cool A9p SrCrEu star \(\beta\) CrB has been studied in the greatest detail. We presently have vertical abundance distributions confidently determined for Fe, Cr and Ca. Figure 1 shows observed and calculated spectra for \(\beta\) CrB, illustrating poor agreement of the observations with vertically uniform models (thin and dashed curves) and the quality of fit provided by the stratified models (thick curve) for the particular case of Fe. Table 1 lists the parameters describing the recovered vertical abundance distributions of \(\beta\) CrB. These empirical distributions are in reasonable agreement with the theoretical distributions reported by Babel (1992) (however those calculations were obtained for a somewhat hotter stellar model.)

4. Implications and applications

The new observations have widespread impact:

1. Abundance studies of magnetic stars: A tentative conclusion of this study is that most, and possibly all, magnetic tepid stars exhibit chemical stratification. This suggests that abundance studies of magnetic stars undertaken without taking this phenomenon into account may be completely misleading.

2. Convection & mixing: Many abundance analyses implicitly show that the effects of stratification are not obviously apparent in the spectra of (non-magnetic) normal and Am stars. A natural (although not necessarily valid!) hypothesis inferred from these results is that stratification occurs only in the
Table 1. Parameters describing vertical abundance distributions of Fe, Cr and Ca for β CrB. This table lists recovered parameters of the two-zone models: ε₀ (abundance in upper zone), Δ (abundance difference between zones) and τ₀ (standard optical depth of zone transition), as well as the number of lines n used in the determination. Note that for all elements the zone transition τ₀ occurs at approximately the same standard optical depth, and that the full range of vertical abundance Δ is about 3 dex.

<table>
<thead>
<tr>
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<th>ε₀</th>
<th>Δ</th>
<th>τ₀</th>
<th>n</th>
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<tr>
<td>Fe</td>
<td>-5.8</td>
<td>3.2</td>
<td>-0.7</td>
<td>10</td>
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<tr>
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<td>2.8</td>
<td>-0.6</td>
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</tr>
<tr>
<td>Ca</td>
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<td>-0.7</td>
<td>5</td>
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magnetic tepid stars due to suppression of convection by the magnetic field. Testing this hypothesis will be a major theme of this investigation.

3. Accuracy of stellar atmosphere models: Accurate chemical abundances and abundance distributions have important consequences for opacities in stellar atmosphere models.

4. Weak stellar winds: as exploited by Babel (1992, 1994), chemical stratification provides a sensitive probe of the weak mass loss of main sequence A stars. This will represent another important theme of this investigation.

Unfortunately, a major current impediment to this study is the paucity of atmospheric equilibrium abundance distribution calculations. We underscore the importance of such calculations, and urge renewed effort in this direction.

References