Doppler imaging of Ap stars

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Abstract. Doppler imaging, a technique which inverts spectral line profile variations of an Ap star into a two-dimensional abundance maps, provides new observational constraints on diffusion mechanism in the presence of a global magnetic field. A programme is presented here with the aim to obtain abundance distributions of at least five elements on each star, in order to study how different diffusion processes act under influence of a stellar magnetic field. The importance of this multi-element approach is demonstrated, by presenting the abundance maps of helium, magnesium, silicon, chromium and iron for the magnetic B9pSi star CU Vriginis.

Key words: Stars: abundances – Stars: chemically peculiar – Stars: magnetic fields – Doppler imaging – Stars: individual: CU Virginis

1. Motivation

The scientific goal of applying the Doppler imaging technique to Ap stars, is to derive observational constraints on the diffusion mechanism in the presence of a stellar magnetic field. Theoretical studies (Michaud et al, 1981; Mégessier, 1984) which predict that certain elements raise, sink or move horizontally in magnetic stellar atmospheres need to be verified. This can only be achieved if an unambiguous correlation between the elemental abundance structures and the magnetic field geometry is obtained. However, two major problems are responsible for difficulties in reaching that goal.

Firstly, Doppler imaging can (presently) only be applied to stars which have a fairly weak magnetic field and hence only the variation of the integrated longitudinal field strength (effective field, $B_{\rm eff}$) is usually determined. This sets only weak limits to the 'real' magnetic geometry. For objects with stronger fields the spectral line profiles are severely influenced by Zeeman broadening and are not mainly caused by abundance variations. This limitation can be avoided by obtaining all four Stokes parameters as a function of the stellar rotational phase. Then Zeeman Doppler imaging codes (Donati, 1995) can be applied to calculate the magnetic field strength and surface orientation in combination with the abundance distribution. But these measurements of the Stokes parameters are not yet available, though strong efforts are made to get them from polarimetry.

Secondly, in the past, only a few elements were mapped, mostly silicon, rarely iron and chromium, not even all of them for each object. Furthermore, these

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maps were based on inversions from single 'unblended' spectral lines, which are difficult to find, especially in cooler Ap stars. This introduced uncertainties leading to a questionable reliability of the derived maps and weakening their relevance to theoretical modelling.

Considering this situation, we focused our programme on the production of abundance maps of up to five and more elements on the surface of each of our target stars. A brief report on the stars and the progress of our project is given hereafter, followed by the presentation of results obtained for the magnetic Ap star CU Virginis.

2. Multi-element Doppler imaging programme

As pointed out before, one crucial limitation of Doppler imaging in the past was that only a few elements were mapped, mostly silicon and occasionally iron and chromium. Furthermore, the number of stars studied was not sufficient to draw general conclusions by relating the abundance maps to the approximate magnetic field structure, thereby providing new constraints on theory (Hatzes 1995). In particular, the abundance maps of elements which are pushed upwards by radiatively driven diffusion should look severely different from those of elements that have a tendency to sink.

Star	HD	Type	Elements
ι Cas	15089	A5pSr	Mg,Ti,Cr,Fe
θ Aur	40312A	A0pSi	Mg,Si,Ti,Cr,Mn,Fe
ϵ UMa	112185	A1pCrEuMn	O,Mg,Si,Ti,Cr,Mn,Fe
CU Vir	124224	B9pSi	He,Mg,Si,Cr,Fe
BP Boo	140728	A0pSiCr	Mg,Si,Ti,Cr,Fe
	153882	A1pCrFe	Cr,Fe
ϕ Dra	170000	A0pSi	O,Mg,Si,Ti,Cr,Fe
ET And	219749	B9pSi	He,Mg,Si,Ti,Cr,Fe

Table 1. Ap stars and the elements which were mapped

Table 1 comprises the present results of our programme. For five more stars, observations were made, which still need to be analyzed or supplemented for missing phases. Presentations of surface images for ι Cas (Kuschnig at al.) and ϵ UMa (Lüftinger et al.) are part of these procceedings. Here, the results for the B9 silicon star CU Vir are presented and discussed.

3. Five elements on the surface of CU Virginis

The spectra of CU Virginis were obtained at Observatoire de Haute-Provence using the AURÉLIE spectrograph, in 1994 and 1995. The spectral resolution of these data is about 2×10^4, and the signal-to-noise ratio is typically 200:1. The abundance maps were calculated using the Doppler imaging technique described by Piskunov & Rice (1993). The input data for mapping are given in Table 2.

	CU Vir
Ephemeris	243178.9025
	$+0\overset{d}{.}52070308 \cdot E$
$v \sin i$	$160\ \mathrm{km\,s^{-1}}$
Inclination	30 deg
T_{eff}	13000 K
$\log g$	4.0

Table 2. Input data for the abundance Doppler imaging of CU Vir

The effective field variation of CU Vir was measured by Borra & Landstreet (1980) and can be modelled to first order by a decentered dipole geometry (Hatzes, 1995).

The helium map (Fig. 1) is characterized by a dominant spot which appears to be at the approximate position of the positive magnetic pole (phase 0.5). Only in the central part of this spot does helium reach the solar abundance; on all other parts of the stellar surface, it is depleted by about 1.5 dex. This result confirms theoretical predictions by Vauclair et al. (1991) which have been obtained by modelling helium abundance in main sequence magnetic stars by introducing a weak wind of ionized metals at the magnetic poles, where the field lines are vertical.

In total contrast to that, silicon (Fig. 2) is strongly depleted in the helium spot but overabundant on the remaining visible surface. In these regions the magnetic field lines are mainly horizontal and as predicted by e.g. Mégessier (1994), silicon accumulates at the magnetic equator band. Chromium and iron have surface structures very similar to that of silicon, but both elements are less enhanced compared to their solar abundances.

However, the magnesium (Fig. 3) distribution differs much from that of the other metals. The main feature is a ring centred at the helium spot (magnetic pole), but with an the overall abundance deficiency of about 1 dex and much less contrast than all other elements.

The helium spot distribution of CU Vir was already found by Hiesberger et al. (1995), on the basis of data obtained in 1980, which is an evidence for the high reliability of this result. Also, the silicon abundance structure confirms earlier results published by Hatzes (1995).

Furthermore, there are strong indications that CU Virginis has slowed down its rotation rate abruptly in the year 1985 (Pyper et al, 1998). This effect has not been found in any other Ap star and no theoretical explanation can be given at the moment.

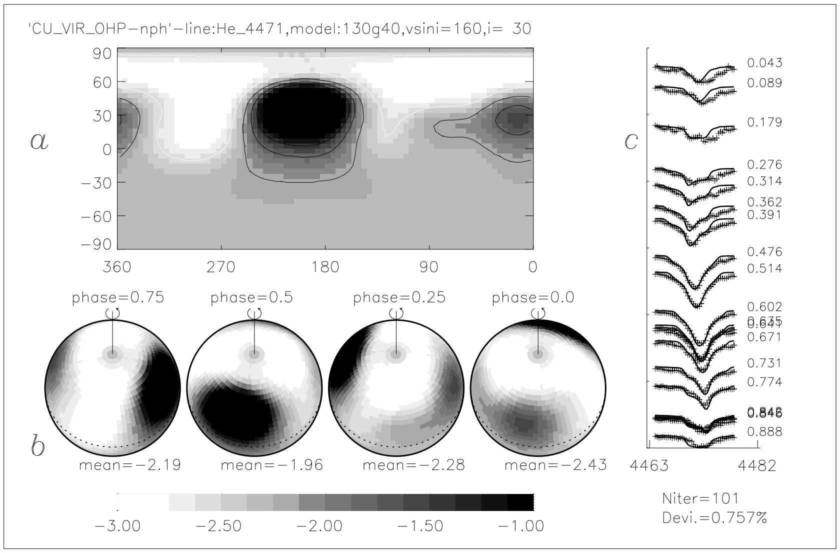

Figure 1. Helium abundance distribution of CU Vir obtained from the He I 4471Å blend.

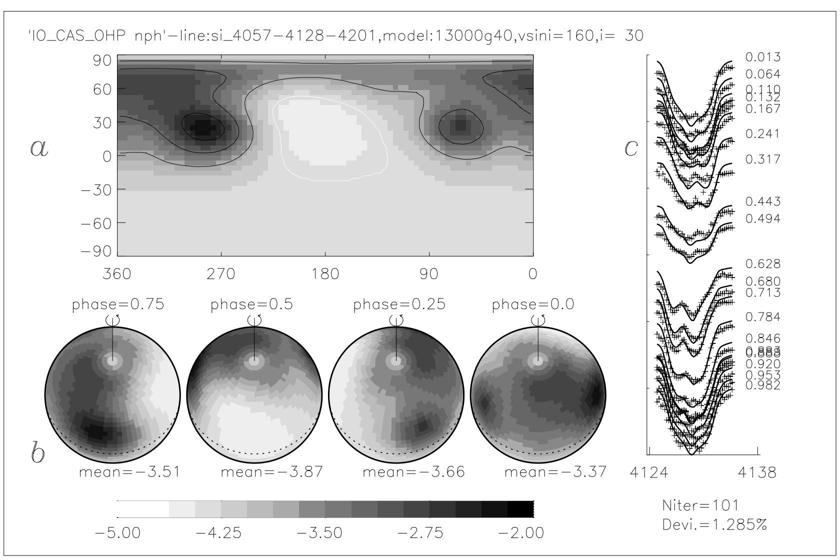

Figure 2. Silicon abundance distribution of CU Vir. More than 20 Si II lines in three separate wavelength regions (4057Å, 4128Å, 4201Å) have been used to calculate this map.

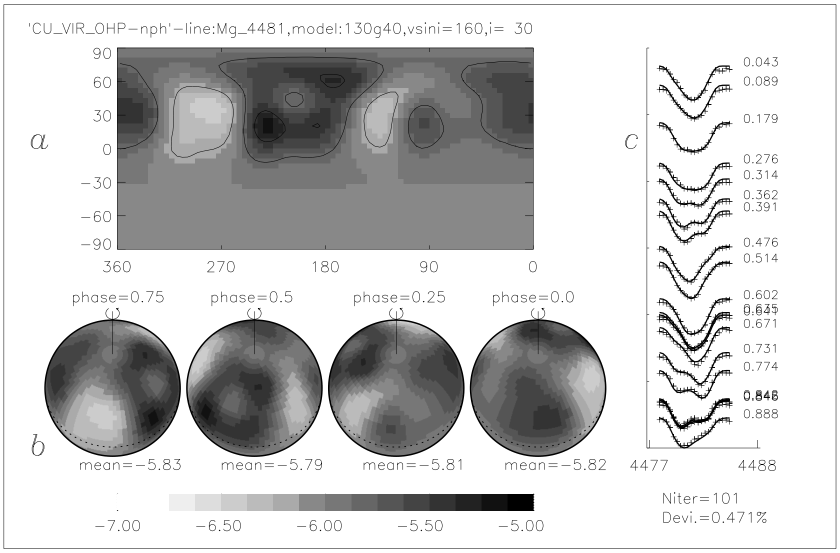

Figure 3. Magnesium abundance distribution of CU Vir obtained for the Mg II 4481Å lines.

Nevertheless, the Doppler imaging results for CU Virgins are a good demonstration of how important it is to obtain the surface distribution of different elements for the same star. CU Virginis is one of the very few objects for which a correlation of the abundance structures and the magnetic field geometry can be given with high significance. Furthermore, it is planned to obtain the abundance distributions for elements like C, N, O and some rare earth species. This should complete the picture and may lead to a detailed theoretical modelling of diffusion processes interacting with the magnetic field of this star.

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