Contrib. Astron. Obs. Skalnaté Pleso **38**, 191 – 200, (2008)

Magnetic fields, spots and weather in chemically peculiar stars

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Received: November 30, 2007; Accepted: December 17, 2007

Abstract. New observational techniques and sophisticated modelling methods have led to dramatic breakthroughs in our understanding of the interplay between the surface magnetism, atomic diffusion and atmospheric dynamics in chemically peculiar stars. Magnetic Doppler images, constructed using spectropolarimetric observations of Ap stars in all four Stokes parameters, reveal the presence of small-scale field topologies. Abundance Doppler mapping has been perfected to the level where distributions of many different chemical elements can be deduced self-consistently for one star. The inferred chemical spot structures are diverse and do not always trace underlying magnetic field geometry. Moreover, horizontal chemical inhomogeneities are discovered in non-magnetic CP stars and evolving chemical spots are observed for the first time in the bright mercury-manganese star α And. These results show that in addition to magnetic fields, another important non-magnetic structure formation mechanism acts in CP stars.

Key words: stars: abundances – stars: atmospheres – stars: chemically peculiar – stars: magnetic fields – stars: starspots

1. Introduction

Chemically peculiar stars are privileged astrophysical laboratories for investigation into the structure formation processes taking place in the surface layers of stars. Unlike the turbulent atmospheres of cool solar-type stars or mass loss-dominated envelopes of massive stars, atmospheres of slowly rotating main sequence A and B stars are very stable, and this in turn allows several remarkable processes to operate in these stars. The most prominent characteristic of many CP stars is the presence of strong fossil magnetic fields at their surfaces and in interiors. Moreover, due to the atmospheric stability, further enhanced by the magnetic field, chemical segregation processes, determined by the competition between gravitational settling and radiative levitation, can operate efficiently. These processes are responsible for conspicuous non-solar chemical abundance patterns observed in CP stars and can also lead to strong vertical abundance gradients in the line-forming regions. The balance between gravitation and radiation pressure is affected by the magnetic field and hence prominent horizontal chemical inhomogeneities emerge at the surfaces of CP stars. Rapid pulsational variability in cool Ap stars, also related to non-solar chemistry and the presence of strong magnetic field, adds dynamical aspect to the intricate picture of the CP-star phenomenon. Various manifestations of this unique and poorly understood combination of complex surface properties of CP stars are readily observed in the form of periodic light and spectrum variation, anomalous line profile shapes, significant Zeeman broadening, circular and linear polarization in spectral lines. With some effort these observables can be interpreted in terms of local magnetic field strength and orientation, horizontal and vertical abundance maps, and time-dependent pulsation velocity field. The resulting extensive information on the surface structures and atmospheric dynamics is often utterly unique and is usually inaccessible for other kinds of stars, making CP stars the only source of crucial direct evidence and powerful observational constraints on the physical processes governing chemical diffusion, emergence and evolution of large-scale magnetic field. At the same time, the complexity and remarkable diversity of the phenomena observed in the atmospheres of CP stars drive the development of new astronomical instrumentation, modelling techniques and computer codes. On this background continuing efforts of many CP-star specialists, with enthusiastic support from the rest of the stellar community, have led to the revival of this research field in the last decade. New discoveries have overturned some of the old paradigms, generally resulting in a more complex, yet also more interesting picture of chemically peculiar stars.

In this review I highlight recent progress achieved in the studies of magnetic fields and horizontal chemical inhomogeneities in CP stars. The closely related topics of chemical stratification and magnetoacoustic pulsations in roAp stars are dealt with in other contributions (Sachkov *et al.*, 2008).

2. Magnetic fields

Multipolar fits to the phase curves of magnetic observables (Landstreet, Mathys 2000; Bagnulo *et al.* 2002) is a common technique to infer information about the large-scale structure of the magnetic fields in CP stars. Reasonably successful application of this modelling method to many stars over the last few decades is often taken as an indication that magnetic topology in most CP stars is close to a centered dipolar structure, sometimes with an offset or a small quadrupolar contribution. However, one cannot guarantee that this conclusion is not an artifact of the *a priori* low-order multipolar field assumption, applied to often quite sparse set of field modulus and longitudinal magnetic measurements. Indeed, a number of studies that attempted to incorporate information on linear polarization in multipolar modelling (Leroy *et al.*, 1996; Bagnulo *et al.*, 2001) have demonstrated that significant deviations from the dipolar field geometry are present in many stars. Another concern is fundamental non-uniqueness of multipolar modelling, which sometimes yields widely different results, depending on what particular type of several common field parameterizations is adopted (Kochukhov, 2006). Thus, a multipolar fit to the phase curves of magnetic observables is generally unable to give direct information on the stellar magnetic

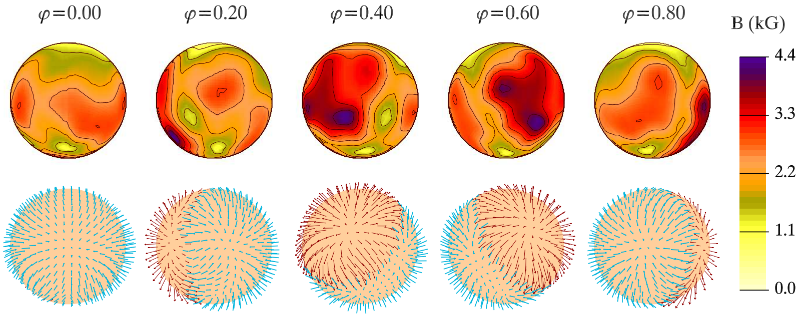

Figure 1. Magnetic field topology of α^2 CVn inferred with the help of magnetic Doppler imaging in all four Stokes parameters (Kochukhov and Wade, in preparation). The upper row of spherical plots shows distribution of the field strength, the lower row presents the map of field orientation. The star is shown at the inclination angle $i = 120^{\circ}$ for five rotation phases.

field topology. It only characterizes the basic statistical properties (the mean and few lowest moments) of the surface distribution of magnetic field modulus and the line of sight field component.

The ultimate breakthrough in answering the question, what does the CP-star magnetic field really look like, was achieved with the help of high-resolution four Stokes parameter observations, secured by Wade *et al.* (2000). They have obtained measurements of circular and linear polarization in the profiles of individual metal lines for several bright Ap stars using the MuSiCoS spectropolarimeter These data are being interpreted with the Magnetic Doppler imaging (MDI) method. Developed by Piskunov and Kochukhov (2002) and thoroughly tested by Kochukhov and Piskunov (2002), this new implementation of Doppler imaging allows one to obtain self-consistent maps of magnetic field and chemical spots through the regularized inversion of the rotationally modulated Stokes $IQUV$ time series. This technique makes possible a robust reconstruction of the magnetic maps without any *a priori* (e.g. multipolar) assumptions about magnetic field geometry.

Kochukhov *et al.* (2004 a) applied MDI to the MuSiCoS observations of 53 Cam, constructing the first stellar magnetic map based on observations in all four Stokes parameters. The outcome of the magnetic inversion for 53 Cam was rather unexpected: it was found that this Ap star hosts a surprisingly complex magnetic field, which cannot be approximated by any low-order multipolar topology. Subsequently we have carried out MDI with the MuSiCoS four Stokes parameter spectra of another well-known CP star, α^2 CVn (Kochukhov and Wade, in preparation). The result of the magnetic inversion from the Cr and Fe lines is presented in Fig. 1. Unlike 53 Cam, α^2 CVn shows a more subtle deviation from the dominant dipolar field configuration. Nevertheless, the small-scale features, such as the two magnetic spots visible at phase $\varphi \approx 0.5$, are required to reproduce variation of the Stokes parameter spectra. Remarkably, these fine details of the surface magnetic field distribution could be inferred only when Stokes Q and U profiles are employed for magnetic mapping. The highest quality observations of traditional integral magnetic observables, aided with the high-resolution Stokes I and V spectropolarimetry, apparently do not contain information sufficient to resolve the small-scale magnetic topologies (Kochukhov *et al.* 2002; Khalack, Wade 2006; Lüftinger *et al.*, 2008). It is therefore conceivable that the typical field structure of magnetic CP stars contains contributions both from a global, dipolar-like component and from much smaller spatial scales.

The small number of stars analysed up to now with the MDI technique leaves open the question of short-term stability of the newly discovered complex magnetic elements, as well as possible evolutionary and star-to-star scatter in the relative importance of large *vs.* small-scale magnetic structures. Evidently, repeated mapping of selected CP stars and substantial expansion of the sample of stars with detailed magnetic maps is needed. This is becoming feasible thanks to the recent commissioning of the two new spectropolarimeters, NARVAL and ESPaDOnS, installed at Pic-du-Midi and CFHT. Compared to MuSiCoS, these instruments tremendously improve the S/N, wavelength coverage and resolution of the Stokes parameter spectra. We are using both spectrographs in a long-term observing campaign (Silvester *et al.*, (2008) to collect observations needed for exploring in detail the field topology at various spatial scales and for probing intrinsic changes of the small-scale field structures.

3. Chemical spots

Since the formulation of the oblique rotator model (Stibbs, 1950) and the first attempts to determine the distribution of chemical elements based on the rotational modulation of radial velocity and equivalent widths of variable spectral lines (Deutsch, 1958), the studies of chemical non-uniformities have become an important part of CP-star research. Inspired by the phenomenon of chemical spots, the powerful technique of Doppler imaging (DI) was developed for CP stars (Goncharskij *et al.*, 1982) and then extended to the problems of mapping temperature inhomogeneities, magnetic fields and pulsation velocity field.

Over the years the DI technique was repeatedly applied to study spots of individual elements in selected stars (e.g., Rice *et al.*, 1997; Hatzes, 1997). However, the emerging recent trend is to perform multi-element abundance DI studies, covering large number of elements in a self-consistent manner. Such spatially-resolved abundance analyses provide a more representative and comprehensive picture of the surface chemical inhomogeneities. Ongoing investigations, pursuing multi-element mapping of cool Ap stars HD 24712 (Lüftinger *et al.*, 2008) and HD 3980 (Obrugger *et al.*, 2008), were presented at this meeting. Another examples of such studies can be found in Lüftinger *et al.* (2003) for ε UMa

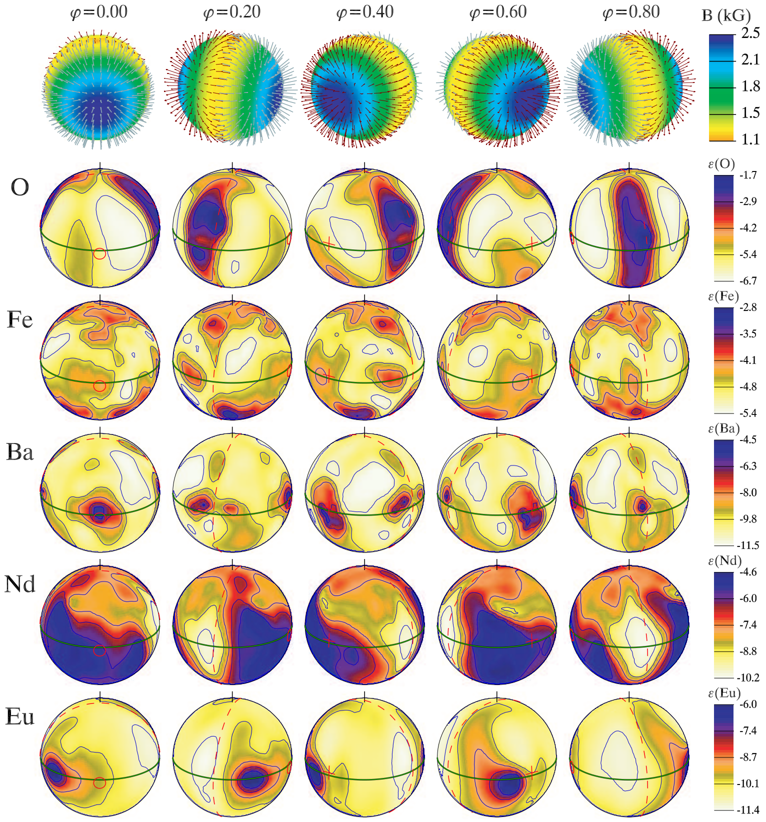

Figure 2. Surface magnetic and chemical structure of the roAp star HD 83368. The upper row shows dipolar magnetic field topology of the star. Five lower rows present surface distribution of O, Fe, Ba, Nd and Eu (Kochukhov *et al.*, 2004 b). In each plot the star is shown at the inclination angle $i = 68°$ for five rotation phases.

and in Kochukhov *et al.* (2004 b) for the prototype rapidly oscillating Ap star HD 83368. Five of the 17 abundance maps reconstructed in the latter study are presented in Fig. 2. Chemical maps shown in this plot illustrate an extremely wide range of behaviour observed for different elements in the same star. Some species, for instance O I, show global features, obviously related to the symmetry of the dipolar magnetic field component. Other elements, for example Fe and Ba, are distributed in a considerably more complex surface pattern, defying a simple interpretation in terms of underlying magnetic field geometry.

Another important feature of modern multi-element DI maps is the discrepancy in the surface distribution of elements with similar atomic weights, in particular different rare-earth elements (REEs). Old DI studies of REE spots in hot magnetic stars (e.g. Goncharskij *et al.*, 1983), typically limited to Eu, have inferred overabundance of this element at the magnetic poles. It is not uncommon to meet an overly simplistic and misleading generalization of these results to all REEs in all Ap stars. Modern DI studies have probed distributions of REEs other than Eu (Kochukhov *et al.*, 2002, 2004 b) and have clearly rejected the notion of a common surface structure of heavy element spots. As seen on the example of HD 83368 (Fig 2), Eu spots are small and high-contrast, but are displaced from the magnetic poles of that particular star. At the same time, Nd and Pr, responsible for many strong variable lines in the Ap-star spectra, exhibit markedly different surface distribution, dominated by the ring of relative underabundance rather than a clearly defined polar spot.

The diversity and occasional extreme complexity of the chemical maps derived in recent studies of spotted Ap stars suggest that chemical diffusion operates in different regimes for different elements and ions. For some species radiative forces, modulated by the magnetic field, are overwhelming and create large-scale features. For other elements radiative acceleration may be more finely balanced by gravity and hence the observed local abundance may be easily perturbed by small local variations of magnetic field and atmospheric structure. Moreover, the presence of chemical overabundances at the intersection of magnetic and rotational equators (cf. Ba in HD 83368) hints that magnetically-channeled mass loss plays a non-negligible role in the process of chemical spot formation.

The question of possible time variation of the chemical spot geometry in magnetic stars has not received sufficient attention. The light curve stability of the photometrically variable CP stars (Adelman, Kaewkornmaung, 2005) and a sequence of Si Doppler maps produced for 56 Ari (Ryabchikova, 2003) show no evidence of surface structure changes over the time span of several decades. However, only the largest spatial scales are probed in these studies and, therefore, no data can currently exclude evolution of the small-scale abundance structures resolved in modern DI studies.

At the same time, it is becoming clear that under the right circumstances radiative diffusion can produce chemical spots rather quickly compared to the stellar evolutionary time scales. The search for progenitors of Ap/Bp stars among the Herbig Ae/Be objects (Wade *et al.*, 2007) has revealed a number of infant magnetic CP stars. For one such object – the B9 primary of the HD 72106 system – Doppler mapping carried out by Folsom *et al.* (2008). shows well-developed typical Ap-star abundance spots, despite the fact that the star has completed less than 1.5% of its main sequence life, and possibly still has not reached ZAMS.

4. Chemical weather

The classification scheme of the upper main sequence CP stars has traditionally relied on the dichotomy between the magnetic and non-magnetic peculiar stars (Preston, 1974). The former (Ap/Bp stars) possess strong organized magnetic fields, inhomogeneous horizontal abundance distributions, and show large-amplitude photometric and spectroscopic variation. The latter (Am and HgMn stars) were thought to be constant and lack magnetic fields and chemical spots, sharing with their magnetic counterparts only the unusually slow rotation. Repeated searches for magnetic fields in Am and HgMn stars have failed to produce any detection of a large-scale Ap-like or small-scale solar-like field, even when the highest quality spectropolarimetric data were used and the errors of the effective field measurements were brought down to 30–50 G (Shorlin *et al.*, 2002). Rare reports of the photometric variability of Am and HgMn stars were always refuted with higher quality data (Adelman, 1993), while claims of marginal line profile changes (Malanushenko, 1996; Zverko *et al.*, 1997) were not considered convincing. The observational situation has changed radically with the discovery of mercury abundance inhomogeneities in the brightest HgMn star α And (Adelman *et al.*, 2002). Careful observations of this broad line star have demonstrated large-amplitude variability of the Hg II 3984 Å line and allowed to measure rotation period of a HgMn star for the first time. The mercury line variability, established beyond any doubt, was interpreted with a Doppler imaging code. The resulting map showed a series of high-contrast mercury spots, located along the rotational equator. This remarkable discovery of the new type of spotted structure has questioned our understanding of the basic properties of HgMn stars and their differentiation from the magnetic CP stars. One can speculate that the stellar properties change continuously from strongly magnetic Bp to HgMn stars and that weak magnetic fields, present in the latter class, could be responsible for the chemical inhomogeneities in α And. However, this hypothesis did not withstand the test of very high-precision spectropolarimetric observations of α And carried out by Wade *et al.* (2006), who proved that no line of sight field stronger than 10 G can be detected in this star. The dipolar field strength in the atmosphere of α And is thus constrained to be below the equipartition limit of ≈ 250 G. Such a field is unlikely to affect chemical diffusion and, even if present at the epoch of star formation, is expected to decay rapidly due to shearing by the differential rotation (Auriér *et al.*, 2008).

It was soon demonstrated that the spots on α And are not unique. Kochukhov *et al.* (2005) have surveyed a small group of HgMn stars with T_{eff} and $v \sin i$ close to those of α And, finding signatures of spotted Hg distribution in two (HR 1185, HR 8723) out of five stars studied. Hubrig *et al.* (2006) have confirmed tentative finding of Zverko *et al.* (1997) that the Hg II 3984 Å line in the primary component of the eclipsing SB2 HgMn binary star AR Aur shows intrinsic changes. Furthermore, Hubrig *et al.* (2006) also reported variability of Y, Zr and Pt in AR Aur A. Our independent spectropolarimetric observations of this system have confirm these results and also showed that no global magnetic field is present on either component of AR Aur.

Thus, it appears that chemical inhomogeneities are widespread among HgMn stars and that previous failures to notice them are largely related to a small

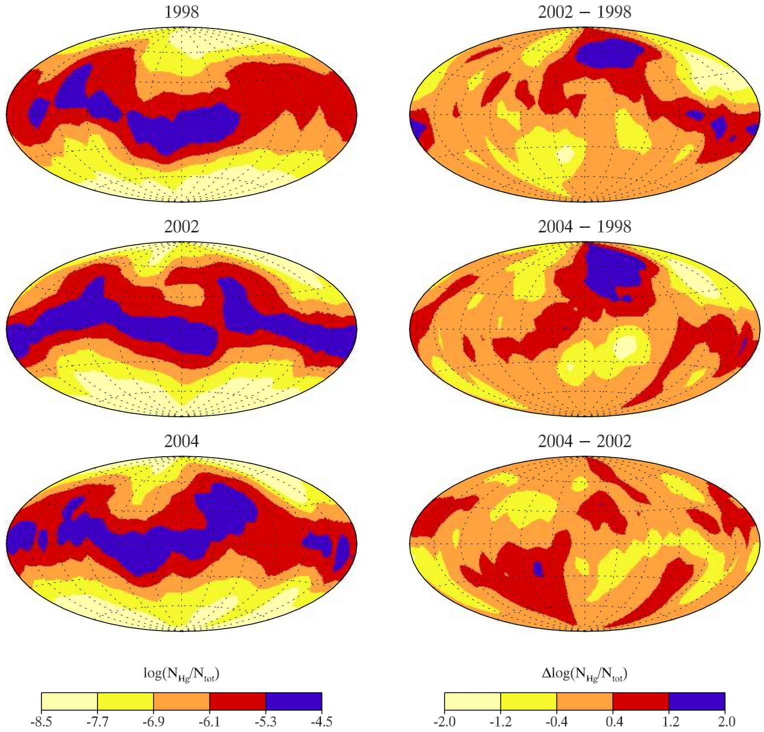

Figure 3. Evolution of mercury inhomogeneities in the atmosphere of HgMn star α And (Kochukhov *et al.*, 2007). This figure shows Hammer-Aitoff projection of Hg maps for three different epochs covering the time span of 7 years. *Left:* abundance distributions for years 1998, 2002 and 2004. *Right:* pairwise difference of the Hg maps.

number of repeated observations of the same targets and traditional focus on the sharp-lined stars, for which the spectrum variations are much harder to detect. Although the reality of chemical spots in HgMn stars has been convincingly established, the physical interpretation of this phenomena remains uncertain. A possible key to understanding the spottedness of HgMn stars is provided by our follow up study of α And (Kochukhov *et al.*, 2007). Using exceedingly high-quality spectra ($S/N > 1000$), we have reconstructed a series of Hg Doppler images, covering the time span of 7 years. The resulting chemical maps for the three different epochs are shown in Fig. 3. It is evident that the Hg spot topology changes slowly over time. This is the first ever observation of evolving chemical structure at the surface of any star. Our breakthrough finding suggests that the process responsible for the Hg spot formation in α And is fundamentally different from the interplay of strong magnetic field and radiative diffusion acting in Ap/Bp stars. In contrast to the latter objects, in HgMn stars we find an unstable surface structure, created without magnetic field participation.

Kochukhov *et al.* (2007) have suggested that theoretically expected (Michaud *et al.*, 1974) fine balance of the gravitational force and radiative pressure in the Hg-rich layer in the upper atmosphere of α And can be disrupted by hydrodynamical instabilities or by the time-dependent diffusion effects (Alecian, 1998). Thus, the structure of mercury clouds is governed by a stochastic process, similar to the cloud weather in planetary atmospheres. Detailed theoretical calculations are however required to assess feasibility of this hypothesis.

The discovery of mercury cloud weather in α And and detection of chemical inhomogeneities in other HgMn stars has important implications for our understanding of the properties of various classes of spotted CP stars. On the one hand, chemical weather effects can be present in magnetic stars, partly explaining the observed diversity of abundance distributions. On the other hand, large discrepancies of the heavy element abundances in HgMn stars of the same mass and age (e.g., Smith, 1997) and in the nearly equal components of the close binary systems (e.g., Zverko *et al.*, 1997; Catanzaro, Leone 2006) can be attributed to the slow variation of the surface abundances under the influence of the same process that acts in α And. If different stars are observed at different phases of their long-term "weather cycle", the inferred star-to-star scatter in the average abundances may be essentially random or only weakly related to the fundamental stellar properties. In this context the discovery of spotted distribution for precisely those elements (Hg, Pt, Y, Zr) which show the most extreme abundance anomalies *and* large star-to-star scatter is not coincidental.

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