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Magnetic Fields and Dynamical Evolution of Chemical Spots on the Surface of HgMn Stars

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Abstract. The discovery of exotic abundances, chemical inhomogeneities, and weak magnetic fields on the surface of HgMn stars, which are frequently the primaries in spectroscopic binaries, has important implications not only for our understanding of the formation mechanisms of stars with Hg and Mn peculiarities themselves, but also to the general understanding of the B–type star formation. The recent results on the Doppler mapping of several elements on the surface of HgMn stars at different epochs, and magnetic field measurements suggest new directions in the studies of these stars to be followed in view of improving our understanding of the physical processes occurring in their atmospheres.

Key words: stars: abundances – binaries: eclipsing – binaries: spectroscopic – stars: chemically peculiar – stars: individual: AR Aur – stars: magnetic field – stars: spots

1 Introduction

Over the last years, we have performed extensive spectroscopic studies of the upper–main sequence spectroscopic binaries with late B–type primaries (spectral types B7 – B9) with the goal to understand why the vast majority of these stars exhibits certain chemical abundance anomalies in the atmospheres, i. e. large excesses of P, Mn, Ga, Br, Sr, Y, Zr, Rh, Pd, Xe, Pr, Yb, W, Re, Os, Pt, Au, and Hg, and underabundances of He, Al, Zn, Ni, and Co (e. g., Castelli & Hubrig 2004b). Strong isotopic anomalies were detected for the chemical elements Ca, Pt, and Hg with patterns changing from one star to another (Hubrig et al., 1999; Castelli & Hubrig, 2004a; Cowley et al., 2008). Observationally, these stars are characterised by the low rotational velocities $\langle v \sin i \rangle \leq 29$ km/s (Abt et al., 1972). Evidence that stellar rotation does affect abundance anomalies in HgMn stars is provided by a rather sharp cutoff in such anomalies at projected rotational velocities of 70 – 80 km/s (Hubrig & Mathys, 1996).

Intrinsic photometric variability has been difficult to detect. More than 2/3 of the HgMn stars are known to belong to spectroscopic binaries (Hubrig & Mathys, 1995) with a preference of orbital periods in the range between 3 and 20 days. It is striking that the inspection of SB systems with a late B–type primary in the 9$^{\text{th}}$ Catalogue of Spectroscopic Binary Orbits (Pourbaix et al., 2004) indicates a strong correlation between the HgMn peculiarity and its membership in a binary system. Among the bright well–studied SB systems with late B–type slowly rotating ($v \sin i < 70$ km/s) primaries with apparent magnitudes of up to $V \approx 7$, and orbital periods between 3 and 20 days (apart from HR 7241) all 21 systems have a primary with a HgMn peculiarity. Based on this fact, it is very likely that the majority of slowly rotating late B–type stars formed in binary systems with certain orbital parameters become HgMn stars. This indicates that careful studies of these peculiar stars are important for the general understanding of B–type star formation in binary systems. Since a number of HgMn stars in binary systems are found at the zero age main-sequence (ZAMS) (e. g., Nordstrom & Johansen, 1994; González et al., 2006, 2010), it is very likely that the timescale for developing a HgMn peculiarity is very short.

The origin of the abundance anomalies observed in HgMn stars is still poorly understood. In situ the chemical separation, under gravitational and radiative forces is accepted as the basic explanation of the abundance anomalies in the upper main sequence chemically peculiar stars. The abundance pattern of HgMn stars indicates the influence of non–nuclear processes. In all the stars there is an odd–Z anomaly at yttrium ($Z = 39$), which is more abundant than its even–Z neighbours (Guthrie, 1971; Adelman et al., 2001). Just as significant as the odd–Z anomalies are the two highly fractionated even–Z neighbors: Kr and Sr, and Xe and Ba. Kr is usually more abundant than Sr by ~ 3 dex, and Xe is more abundant than Ba by ~ 4 dex (e. g. Cowley et al., 2010). The elements Sr and Ba are typically associated with the s–process, and their failure to show enhancement immediately excludes the relevance of that process. On the other hand, the solar system r–process shows excesses of Te and Xe, as well as Os and Pt. These elements are usually overabundant in the HgMn stars. Clearly, there is no neutron–addition scheme that would produce such a severe fractionation in the atmospheres of these stars. A recently suggested model supposes that exotic r–processed material fell on the surface of these stars, and then was subject to in situ differentiation (Cowley et al., 2010). In any case, a strange abundance pattern of HgMn stars suggests both the mass transfer to explain the enhanced r–process elements, and some type of processing in the stars themselves. On the other hand, the abundance patterns can be the signatures of separation in the magnetised atmosphere itself.

2 Dynamical Evolution of Chemical Spots on the Surface of HgMn Stars

As much as 2/3 of the HgMn stars are known to belong to the spectroscopic binaries, the variation of spectral lines observed in any HgMn star is usually explained to be due to the orbital motion of the companion. The aspect of inhomogeneous distribution of some chemical elements over the surfaces of HgMn stars has been, for the first time, discussed by Hubrig & Mathys (1995). From a survey of HgMn stars in close SBs, it was suggested that some chemical elements might be inhomogeneously distributed on the surface with, in particular, preferential concentration of Hg along the equator. In the close SB2 systems, where the orbital plane has a small inclination to the line of sight, a rather large overabundance of Hg was found. By contrast, in stars with orbits almost perpendicular to the line of sight, mercury is not observed at all. The first definitively identified spectrum variability that is not caused by the companion has been reported for the binary HgMn star α And by Wahlgren et al. (2001) and Adelman et al. (2002). They suggested that spectral variations of the Hg II line at λ 3984, discovered in high–dispersion spectra are not due to the orbital motion of the companion, but produced by the combination of the 2.8–d period of rotation of the primary and a non–uniform surface distribution of mercury, which is concentrated in the equatorial region, in good correspondence with the results of Hubrig & Mathys (1995). The variability of the Hg II line at λ 3984 was interpreted with a Doppler Imaging code revealing high–contrast mercury spots, located along the rotational equator. Using the Doppler Imaging reconstruction of the spectroscopic time series obtained over seven consecutive years, Kochukhov et al. (2007) suggested the presence of a secular evolution of the mercury distribution.

The zero–age main–sequence (ZAMS) eclipsing binary AR Aur (HD 34364, B9 V + B9.5 V) with an orbital period of 4.13 d at an age of only 4×10^6 years presents a particularly interesting case for forging connections between different chemically peculiar star classes. The primary and the secondary eclipses are nearly total, since its orbital inclination is 88.5°, and the radii of both stars are almost equal (Nordstrom & Johansen, 1994). Chochol et al. (1988) discovered a third body in the system. The existence of the as yet unseen third star with a mass of at least $0.51\,M_{\odot}$ has been inferred from a light–time effect in the observed photometric minima with a period of 25 – 27 yr. Nordstrom & Johansen (1994) studied the parameters of this multiple system in detail through an analysis of the available light and radial velocity curves. They concluded that the secondary star is still contracting towards the ZAMS, while the primary star appears to be exactly on the ZAMS. Hubrig et al. (2006a) carried out a spectroscopic study of AR Aur using nine high–quality, high–resolution spectra obtained with the Ultraviolet and Visual Echelle Spectrograph (UVES), providing convincing evidence that the line profiles of several elements are variable on the surface of the primary component. The problem of analysing the component spectra in the double–lined spectroscopic binaries is difficult, but, fortunately, in the past few years several techniques for spectral disentangling have been developed. For each observed phase we applied the procedure of decomposition described in detail by González & Levato (2006).

Doppler maps for the elements Mn, Sr, Y, and Hg using nine spectra of AR Aur observed at the European Southern Observatory with the UVES spectrograph at UT2 in 2005 were for the first time presented at the IAU Symposium 259 by Savanov et al. (2009). Motivated by the results of the recently published work on the spectroscopic time series of another HgMn star, HD 11753, which revealed noticeable temporal changes in the surface distribution of several elements, indicating a dynamical chemical spot evolution (Briquet et al., 2010, see also the contribution of Korhonen et al. in this proceeding), we decided to prove the presence of a dynamical evolution of spots on the surface of AR Aur (Hubrig et al., 2010). New spectroscopic data were obtained in the course of a multi–site campaign at the end of 2008 and the beginning of 2009, using the Coudé Spectrograph of the 2.0 m telescope of the Thüringer Landessternwarte (TLS) (Oct. 2008 – Feb. 2009) and the SES spectrograph of the 1.2–m STELLA–I robotic telescope at the Teide Observatory (Nov. – Dec. 2008). The results of the reconstruction for both sets, (SET1 for the UVES spectra and SET2 for the recent observations) are presented in Figures 1 and 2, respectively. The adopted stellar parameters, $T_{\rm eff} = 10\,950$ K, $\log g = 4.33$, were those employed by Nordstrom & Johansen (1994). The inspection of the resulting Fe and Y distribution maps, separated by four years shows that Fe is overabundant by up to +1.5 dex, and Y is overabundant by up to +3.9 dex in several spots. The solar values for abundances in the units used in Figures 1 and 2 are −4.50 for Fe and −9.79 for Y (Grevesse et al., 2010). The positions and shapes of the spots with the highest Fe overabundance slightly changed from 2005 to 2009, and the level of the Fe overabundance shows a significant increase, especially in the spot, located close to the equator at the phases of 0.50 – 0.75, and in the polar spot at the phases of 0.75 – 0.83. In the Y maps, the evolution of overabundance, shape, and position of the spots appears much more remarkable, revealing a region of huge overabundance having a shape of a belt, which is broken around phase 0. Intriguingly, in this phase we observe the hemisphere which is permanently facing the secondary. Such a behaviour is likely observed also for Sr in the UVES spectra and was discussed in our previous study (Hubrig et al., 2006a).

Including AR Aur, the whole sample of HgMn stars studied with Doppler Imaging consists now of only three HgMn stars. All of them showed a presence of evolutionary changes in the element distribution. Clearly, future element distribution reconstructions using the Doppler Imaging technique are necessary to improve our understanding of the physical processes, occurring in late B–type binary systems with HgMn primaries.

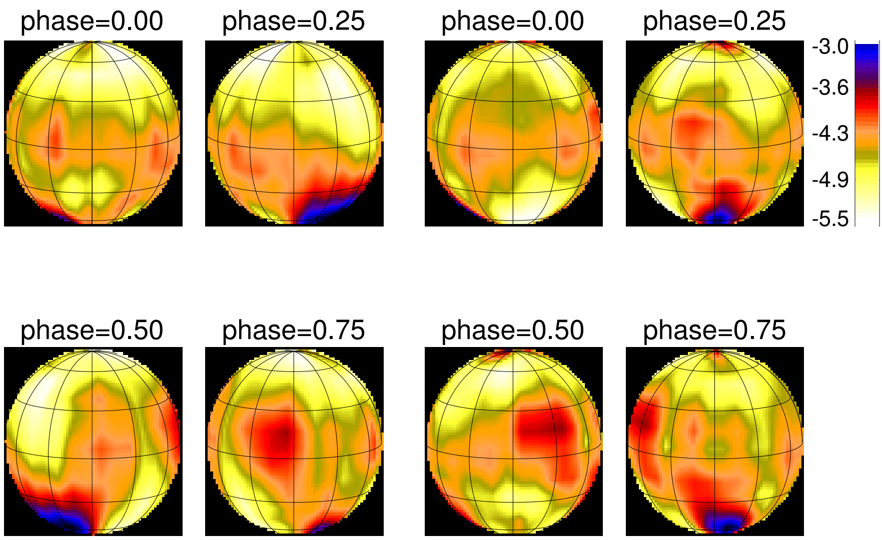

Figure 1: The Fe abundance map of AR Aur, obtained from the Fe II 4923.9 Å line for the SET1 (left) and SET2 (right)

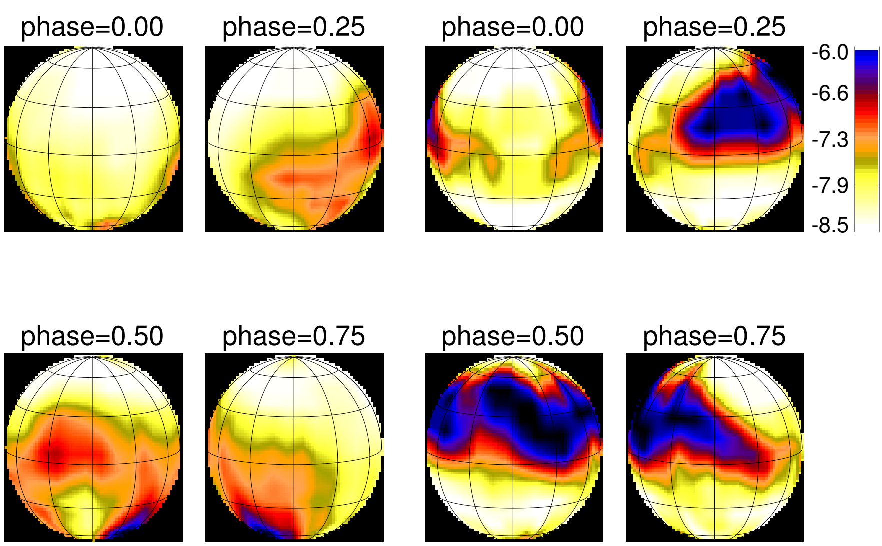

Figure 2: The Y abundance map of AR Aur, obtained from the Y II 4900.1 Å line for the SET1 (left) and SET2 (right)

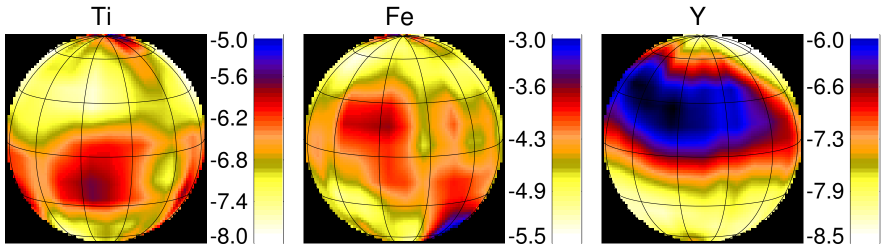

Figure 3: The element distribution from the Ti II 4563.8 Å line, the Fe II 4923.9 Å line, and the Y II 4900.1 Å line for AR Aur at the time of our magnetic field measurement (phase 0.622).

3 Magnetic Field Measurements in HgMn Stars

Typically, inhomogeneous chemical abundance distributions are observed only on the surface of magnetic chemically peculiar stars with large–scale organised magnetic fields. In these stars, the abundance distribution of certain elements is non–uniform and non–symmetric with respect to the rotation axis. The most widespread method to detect a magnetic field is to obtain polarimetric spectra, recorded in the left and right–hand polarised light to measure the mean longitudinal magnetic field. Another approach to establish the presence of magnetic fields in the upper main sequence stars is to study the mean quadratic magnetic field or the relative magnetic intensification of the two Fe II lines of mult. 74, λ 6147.7 Å and λ 6149.2 Å. For a few HgMn stars, Hubrig & Castelli (2001) showed evidence for a relative magnetic intensification of these lines, produced by different magnetic desaturations induced by different Zeeman–split components. A few unsuccessful attempts to detect mean longitudinal magnetic fields in HgMn stars have been made by several authors using the line addition technique, called the Least–Squares Deconvolution (e. g., Shorlin et al., 2002; Folsom et al., 2010). In this technique, the average line profiles are calculated for several hundreds of spectral lines not considering the inhomogeneous element distribution on the surface of HgMn stars. Furthermore, this technique does not allow to measure other moments of the magnetic field using the moment technique.

A longitudinal magnetic field of the order of a few hundred Gauss was detected in four out of 17 studied HgMn stars by Hubrig et al. (2006b) using the low–resolution ($R = 2000$) circular polarisation spectra, obtained with the FORS1 at the VLT. This small sample of HgMn stars also included the spectrum of a variable HgMn star α And, for which a magnetic field of about a few hundred Gauss was detected. Very recently, we obtained spectropolarimetric observations of AR Aur at the rotation phase 0.622 with the low-resolution camera of the SOFIN ($R \approx 30\,000$) in spectropolarimetric mode. Since most elements are expected to be inhomogeneously distributed over the surface of the primary of AR Aur, magnetic field measurements using the moment technique were carried out for samples of Ti, Cr, Fe, and Y lines separately. A longitudinal magnetic field at a the level higher than 3σ of about a few hundred Gauss was detected in Fe II, Ti II, and Y II lines, while a quadratic magnetic field $\langle B \rangle = 8284 \pm 1501$ G at 5.5σ level was measured in the Ti II lines. No crossover at the 3σ confidence level was detected for the elements studied. Further, we detect a weak longitudinal magnetic field, $\langle B_z \rangle = -229 \pm 56$ G in the secondary component using a sample of nine Fe II lines. In Fig. 3 we present the distribution of Ti, Fe, and Y at the phase 0.622 of the element distribution for the SET2, which was obtained at the time closest to our spectropolarimetric observation. Obviously, the spots of higher Fe, Ti, and Y concentration are well visible at this phase.

The only longitudinal magnetic field measurements carried out for AR Aur were reported recently by Folsom et al. (2010), who used the LSD technique to combine 1168 lines of various elements. No magnetic field was detected in their analysis of the polarimetric spectra obtained in 2006. One possibility for this non–detection could be related to an unfavorable element spot configuration, or

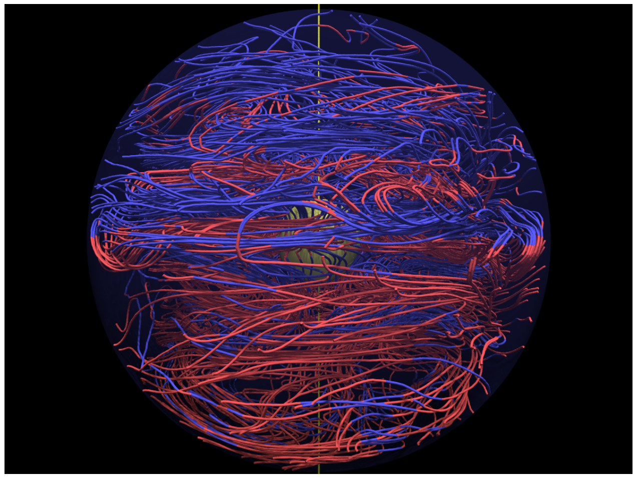

Figure 4: A 3D simulation of magnetic field lines after the onset of MRI. Blue shows radial magnetic field $B_r < 0$, while red stands for $B_r > 0$.

even to the absence of some element spots at the epoch of their observations, since the authors report that no variability of the Ti and Fe lines was detected. Strangely enough, although the authors are aware of the inhomogeneous distribution of elements on the surface of AR Aur, no Zeeman signature analysis has been done on such elements separately. Since a kind of symmetry between the topology of magnetic fields and the element distribution is expected, the method of using all element spectral lines is not advisable and leads to doubtful results.

4 Summary

The recent survey of spectral variability of 28 single–lined HgMn stars by Nuñez et al. (see the contribution of Nuñez et al. in this proceeding) revealed that the line profile variability is a general characteristics of HgMn stars. Most stars in the studied sample present a non–uniform distribution of one or several chemical elements. However, for only three stars the surface element distribution and its evolution over different time scales was studied until now. It is presently a fundamental question whether magnetic fields play a significant role in the development of anomalies in HgMn stars, which are frequently members of binary and multiple systems. Answering this question is also important for the understanding of the processes, taking place during the formation and evolution of B stars in multiple systems in general. A scenario of how a magnetic field can be built up in the binaries has been presented some time ago by Hubrig et al. (1998), who suggested that a tidal torque, varying with depth and latitude in a star induces the differential rotation. The differential rotation in a radiative star can be prone to magneto–rotational instability (MRI). Magnetohydrodynamical simulations by Arlt et al. (2003) revealed a distinct structure for the magnetic field topology, similar to the fractured elemental rings, observed on the surface of HgMn stars. The initial model differential rotation was hydrodynamically stable (Taylor–Proudman flow), but the introduction of a magnetic field excites the MRI on a very short time–scale, compared to the time–scale of microscopic magnetic diffusion. Although the fields are not very strong, complex surface patterns can be obtained from the nonlinear, nonaxisymmetric evolution of the MRI. In Fig. 4 we present a 3D simulation of magnetic field lines after the onset of the MRI.

Our studies, carried out in the past few years confirm that HgMn stars remain the intriguing targets with respect to their temporally evolving anomalies and puzzling topologies of magnetic fields. However, the results achieved in a few individual studies do not yet allow evaluating the theoretical models of the origin of chemical anomalies, and their link with the magnetic field geometry on the stellar surface. Future element distribution reconstructions via the Doppler Imaging technique and magnetic field measurements, using the lines of elements concentrated in the spots for a larger number of stars are necessary to improve our understanding of the physical processes, occurring in the atmospheres of HgMn stars.

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