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HGMN STARS: CORNERSTONES FOR OUR UNDERSTANDING OF LATE B-TYPE MULTIPLE STAR FORMATION

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Abstract. The most distinctive feature of HgMn stars is the extreme overabundance of heavy elements in their atmospheres. Furthermore, they show chemical horizontal and vertical inhomogeneities and kG mean quadratic magnetic fields. The topology of these magnetic fields should be rather complex, as we measure only weak mean longitudinal magnetic fields. The connection between these features and their membership in binary and multiple systems is supported by our observations during the last decade.

The most important result achieved in our studies of a large sample of late B-type primaries in spectroscopic binaries and visual multiples is the finding that the vast majority of slowly rotating late B-type stars formed in binary systems with $v \sin i < 70\,\mathrm{km\,s^{-1}}$ and orbital periods between 3 and 20 days become HgMn stars.

Key words: chemically peculiar stars - HgMn stars - binaries - magnetic field - starspots

1. Introduction

Chemically peculiar (CP) stars are main-sequence A and B type stars in the spectra of which lines of some elements are abnormally strong or weak. The class of CP stars is roughly represented by three subclasses: the magnetic Ap and Bp stars, the metallic-line Am stars, and the HgMn stars, which are late B-type stars showing extreme overabundances of Hg (up to 6 dex) and/or Mn (up to 3 dex).

About 150 stars with HgMn peculiarity are currently known (Renson and Manfroid, 2009). Most of them are rather young objects found in young associations such as Sco-Cen, Orion OB1, or Auriga OB1. In contrast to

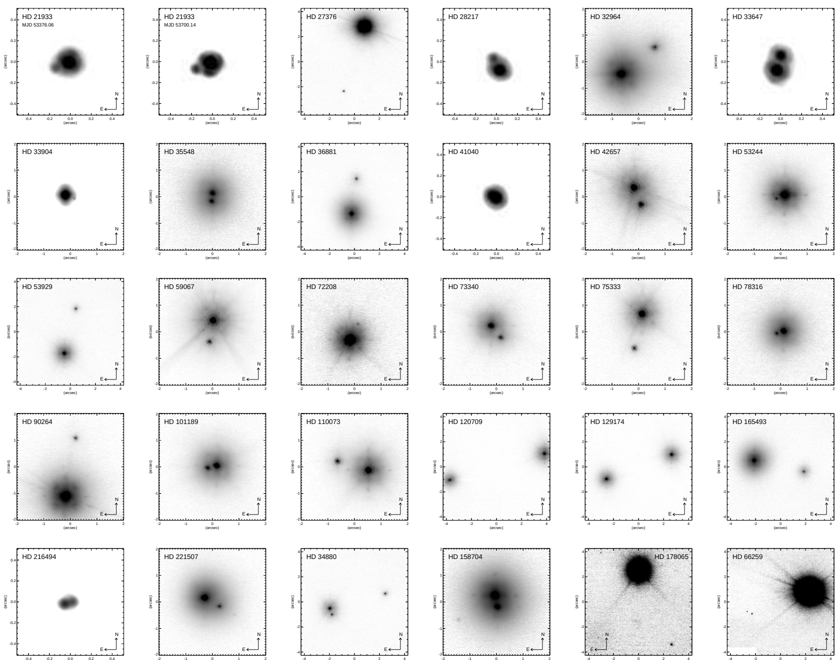

Figure 1: Images of the companions to HgMn stars detected in our VLT/NACO survey.

classical Bp and Ap stars with large-scale organized magnetic fields, HgMn stars generally do not show overabundances of rare earth elements, but exhibit strong overabundances of heavy elements such as W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, or Bi. Another important distinctive feature of these stars is their slow rotation ($\langle v \sin i \rangle \approx 29\,\mathrm{km\,s^{-1}}$, Abt *et al.*, 1972). The number of HgMn stars decreases sharply with increasing rotational velocity (Wolff and Wolff, 1974). Evidence that stellar rotation does affect abundance anomalies in HgMn stars is provided by the rather sharp cutoff in these anomalies at a projected rotational velocity of 70–80 $\mathrm{km\,s^{-1}}$ (Hubrig and Mathys, 1996).

2. Multiplicity

The mechanisms responsible for the development of the chemical anomalies of HgMn stars are not yet fully understood. The abundance patterns may however be connected with binarity and multiplicity. More than 2/3 of the

Table I: Binarity for different stellar types.

Type	Percentage	Reference	SB
A	∼35%	Kouwenhoven *et al.* (2005)	
B	∼30%	Kouwenhoven *et al.* (2005)	
Magnetic Ap	43%	Carrier *et al.* (2002)	Very few SB2
Magnetic Bp	∼20%	Renson and Manfroid (2009)	Very few SB2
HgMn	∼90%	Schöller *et al.* (2010)	2/3
Am	>90%	Renson and Manfroid (2009)	>90%
roAp	24%	Schöller *et al.* (2012)	2 out of ∼45

HgMn stars are known to belong to spectroscopic binaries (Hubrig and Mathys, 1995). Quite a number of HgMn stars belong to triple or even quadruple systems (Cole *et al.*, 1992; Isobe, 1991).

Schöller *et al.* (2010) announced the detection of 33 companion candidates in 24 binaries, three triples, and one quadruple system. The detected companion candidates have K magnitudes between 5.95^m and 18.07^m and angular separations ranging from $<0.05''$ to $7.8''$, corresponding to linear projected separations of 13.5–1700 AU. The companion candidates around HD 21933, HD 33904, HD 53244, HD 53929, HD 66259, HD 72208, HD 90264, HD 101189, and HD 221507 were detected for the first time. Five companion candidates were very likely to be chance projections. The images of the resolved objects are shown in Figure 1. All images are displayed using a logarithmic scale.

Of the 56 HgMn stars studied by Schöller *et al.* (2010), 32 are confirmed SB systems, 11 are potential SB systems, and 38 have visual companions. Only four of the potential SB systems do not have a visual companion. It is especially intriguing that of the 56 HgMn stars in the sample studied, only five stars, HD 37752, HD 38478, HD 63975, HD 70235, and HD 224926 are not known to belong to a binary or multiple system. This results in a multiplicity rate of 91%. Table I shows a comparison between the multiplicity rate for HgMn stars and other types of A and B stars. Only the Am stars have a similarly high binarity and show an even higher percentage of spectroscopic binaries.

In the catalogue of multiple stars by Tokovinin (1997), which compiles data on 728 stellar systems of different spectral types, we found four multiple systems containing HgMn stars. It is compelling that if the relative frequency of HgMn stars in multiple systems is studied, roughly every third system with a primary in the spectral range between B8 and B9 involves a HgMn star.

We note that the inspection of SB systems with a late B-type primary in the 9$^{\mathrm{th}}$ Catalogue of Spectroscopic Binary Orbits (Pourbaix *et al.*, 2004) also indicates a strong correlation between the HgMn peculiarity and membership in a binary system. Among the bright well-studied SB systems with late B-type slowly rotating ($v \sin i < 70\,\mathrm{km\,s^{-1}}$) primaries with an apparent magnitude of up to V≈7 and orbital periods between 3 and 20 days, apart from HD 177863, all 21 systems have a primary with a HgMn peculiarity. Based on this, it cannot be excluded that most late B-type stars formed in binary systems with certain orbital parameters become HgMn stars.

Our observations contribute not only to the understanding of the formation mechanism of HgMn stars, but also to the general understanding of B-type star formation. An interesting result about the combination of long- and short-period systems was presented by Tokovinin (2001). He suggested that the fraction of SBs belonging to multiple systems probably depends on the SB periods. It is much higher for close binaries with 1 to 10 day periods than for systems with 10 to 100 day periods. The statistics of multiple systems is still very poor and much work remains to be done. The current survey of binarity and multiplicity of HgMn stars will help us to understand the connection between close binaries and multiplicity, and especially the formation of close binary systems. To find out which role membership of HgMn stars in multiple systems plays in developing their chemical peculiarities, it would be important in the future to compare the ranges of periods, luminosity ratios, and orbital eccentricities, as well as the hierarchy of multiples, with the same characteristics in normal late B systems. In some binary systems with a HgMn primary, the components definitely rotate subsynchronously (Guthrie, 1986)). It is striking that the majority of these systems have more than two components. Probably the most intriguing and most fundamental question is whether all late-B close binaries with subsynchronously rotating companions belong to more complex systems.

3. Variability

HgMn stars were assumed in the past not to exhibit spectral line variability such as commonly shown by chemically peculiar magnetic Ap and Bp stars.

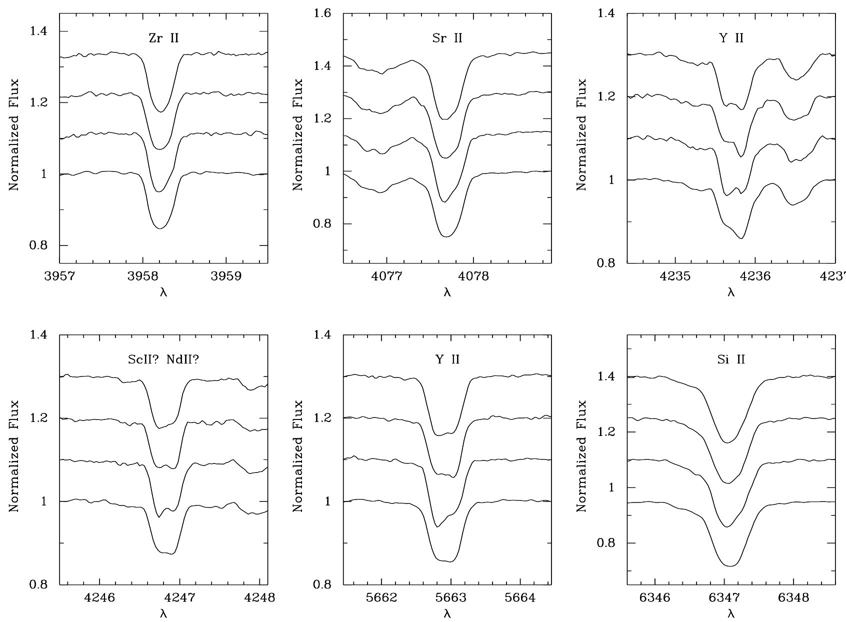

Figure 2: Various degrees of variability of line profiles in the spectra of HD 101189 obtained with FEROS on four different nights. For convenience, individual spectra are shifted in vertical direction.

The aspect of inhomogeneous distribution of some chemical elements over the surface of HgMn stars was, for the first time, discussed by Hubrig and Mathys (1995). From a survey of HgMn stars in close SBs, they suggested that some chemical elements might be inhomogeneously distributed on the surface, with, in particular, preferential concentration of Hg along the equator. In 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 was reported for the binary HgMn star α And by Wahlgren *et al.* (2001) and Adelman *et al.* (2002). They suggested that the spectral variations of the Hg II line at $\lambda 3984\,\text{Å}$ 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 that is concentrated in the equatorial region, in good correspondence with the results of Hubrig and Mathys (1995). The variability of the Hg II line at $\lambda 3984$ Å was interpreted with a Doppler Imaging code revealing high-contrast mercury spots located along the rotational equator. Importantly, recent results (e.g., Nuñez *et al.*, 2011) show that line profile variability is a general characteristic of HgMn stars, rather than an exception. This variability is caused by an inhomogeneous chemical element distribution, and implies that most HgMn stars present a non-uniform distribution of one or more chemical elements (Hubrig *et al.*, 2011). As an example for the variability of HgMn stars, we present in Figure 2 four spectra of the typical variable HgMn star HD 101189, acquired on four different nights with FEROS on La Silla, where spectral lines of several elements exhibit various degrees of variability.

4. Magnetic Fields

Successful searches for magnetic fields in HgMn stars have been carried out over the last 15 years (Hubrig *et al.*, 1999; Hubrig and Castelli, 2001; Hubrig, North, Schöller and Mathys, 2006; Hubrig *et al.*, 2010). In our most recent publication (Hubrig *et al.*, 2012), we have analyzed HARPS and SOFIN polarimetric spectra to search for magnetic fields in HgMn stars with the moment technique developed by Mathys (e.g. Mathys, 1991). This technique allows the determination of the mean longitudinal magnetic field, of the quadratic magnetic field, and of the crossover effect.

41 Eri is a triple system (Hubrig *et al.*, 2001; Schöller *et al.*, 2010), consisting of a close SB2 pair and a companion of $K = 9.9$ at a distance of $5.32''$ and a position angle of $162.5°$. The atmospheric fundamental parameters for both components of the SB2 were studied by Dolk *et al.* (2003), who determined $T_{\rm eff} = 12\,750$ K for the primary and $T_{\rm eff} = 12\,250$ K for the secondary. Our inspection of the spectra belonging to the primary and the secondary revealed that the line profiles of several elements are clearly variable. Both components show typical HgMn peculiarities, but this is the first time that spectrum variability was also discovered in the spectra of the secondary component.

The distribution of the available measurements of the mean longitudinal

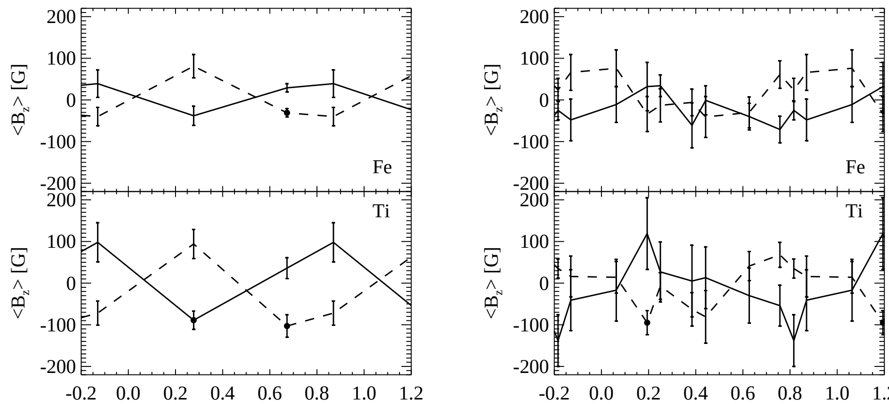

Figure 3: Measurements of the mean longitudinal magnetic field as a function of the rotation phase for 41 Eri (left) and 66 Eri (right). The measurements were carried out separately for the elements Ti and Fe. The solid line denotes the primary component, while the dashed line denotes the secondary component. Filled circles indicate 3σ measurements.

magnetic field over the stellar surface in both components is presented in Figure 3. 3σ detections were achieved using the sample of Ti lines in the spectra of the primary at the rotation phase 0.276 as well as the samples of Ti and Fe lines in the spectra of the secondary at the phase 0.673. An interesting fact discovered in these measurements is that the stellar surfaces with low-abundance element spots that face the companion star show negative magnetic field polarity, while for the opposite hemisphere covered by high abundance element spots, the magnetic field is positive.

66 Eri is an SB2 system with an additional companion of $K = 9.4$ at a distance of $1.613''$ and a position angle of $232.6°$ (Hubrig *et al.*, 2001; Schöller *et al.*, 2010). Ten HARPS polarimetric spectra were obtained over almost two orbital cycles of the SB2 system. Due to a rather large eccentricity of the system, $e = 0.0844$, the rotation period of 66 Eri is not expected to be the same as the orbital period. The period of corotation at periastron is 4.657 d, while the pseudo-synchronous period as defined by Hut (1981), is 5.3015 d. The latter is expected to correspond to the rotation period.

The quality of the polarimetric HARPS spectra is not as good as the spectra of 41 Eri, with S/N mostly between 200 and 300. This could explain

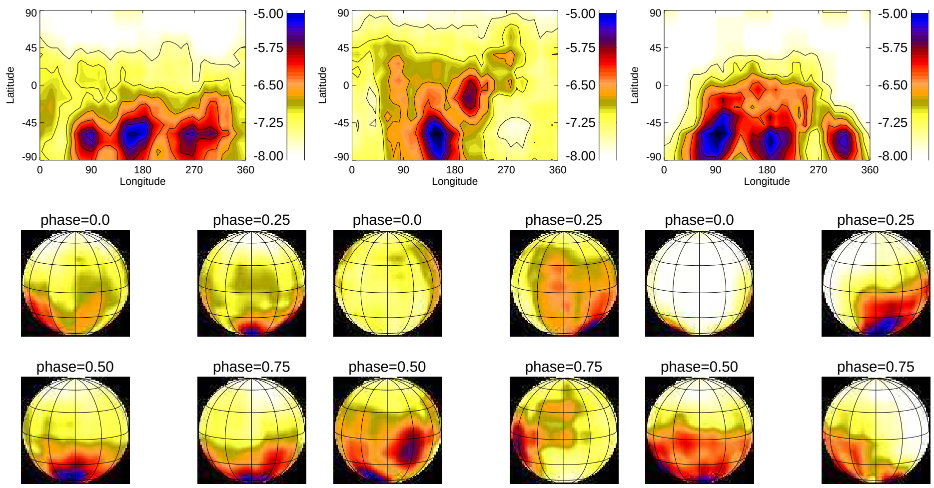

Figure 4: Maps of the abundance distribution for Fe (left), Sr (middle), and Y (right) on the surface of the primary in the system AR Aur.

the larger inaccuracies in the magnetic field determinations and the fact that in our study only one detection at a 3σ significance level was achieved at the rotation phase 0.186 using Ti lines. The distribution of the mean longitudinal magnetic field values measured in both components over the rotation cycle is presented in Figure 3. A comparison of the field distribution with the distribution of elements over the stellar surface presented in Figure 7 in the work of Makaganiuk *et al.* (2011) confirms the pattern already discovered in 41 Eri: A negative mean longitudinal magnetic field is measured at the location of the lower abundance patches, i.e. on the stellar surface facing the companion, and the positive mean longitudinal magnetic field roughly corresponds to the location of the high-abundance patches located on the opposite hemisphere.

The eclipsing system AR Aur (HD 34364, B9V+B9.5V) with an orbital period of 4.13 d at an age of only $4{\times}10^6$ yr belongs to the Aur OB1 association. Since its primary star of HgMn peculiarity is exactly on the ZAMS while the secondary is still contracting towards the ZAMS (e.g. Nordstrom and Johansen, 1994), it presents the best case to study evolutionary aspects of the chemical peculiarity phenomenon (Hubrig, González, Savanov, Schöller, Ageorges, Cowley and Wolff, 2006). The presence of a third body in the system was discovered by Chochol *et al.* (1988).

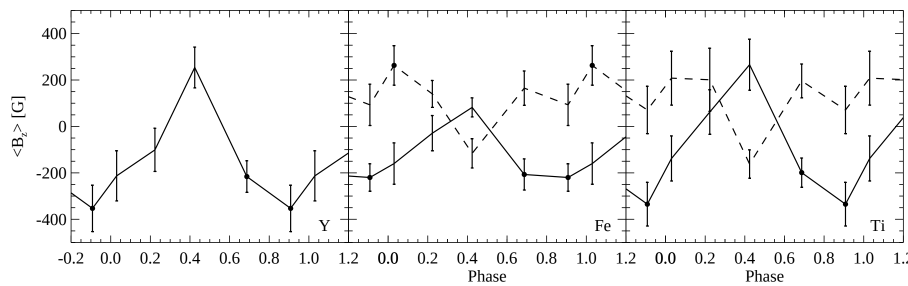

Figure 5: Measurements of the mean longitudinal magnetic field presented as a function of the rotation phase for AR Aur. They were carried out separately for the elements Y, Fe, and Ti (from left to right). The solid line denotes the primary component, while the dashed line denotes the secondary component. Filled circles indicate 3σ measurements.

Measurements of the magnetic field with the moment technique using several elements revealed the presence of a longitudinal magnetic field of the order of a few hundred Gauss in both stellar components as well as a quadratic magnetic field of the order of 8 kG on the surface of the primary star (Hubrig *et al.*, 2012). We acquired five polarimetric observations of AR Aur with SOFIN at the NOT in December 2010. The distribution of the observations was rather random over the rotation/orbital period, allowing us to get a good idea about the surface element distribution. For a DI reconstruction, we selected the following lines: Fe II 4923.9 Å, Sr II 4215.5 Å, and Y II 4900.1 Å. The computed Doppler maps in Mercator and spherical projections based on five different rotation phases are presented in Figure 4 (Hubrig *et al.*, 2012). Similar to previous maps obtained for AR Aur, we again find that the regions with lower abundances of Y and Sr are located on the stellar surface facing the companion, while spots with Y and Sr high abundances appear on the opposite hemispheres.

3σ longitudinal magnetic field detections were achieved for measurements using Ti, Fe, and Y lines in the spectra of the primary in the phases 0.687 and 0.908 as well as for measurements using Fe lines in the spectra of the secondary at the phase 0.030. The variations of the mean longitudinal magnetic field in both components over the rotation cycle presented in Figure 5 display a characteristic behavior similar to that found for the binary stars discussed above. The mean quadratic magnetic field is detected at three different rotation phases in the primary.

Our studies suggest the existence of intriguing correlations between magnetic field, abundance anomalies, and binary properties. In the SB2 systems with synchronously rotating components, 41 Eri and AR Aur, the stellar surfaces facing the companion star usually display low-abundance element spots and negative magnetic field polarity. The surface of the opposite hemisphere, as a rule, is covered by high-abundance element spots and the magnetic field is positive at the rotation phases of the best spot visibility. Although only rather weak longitudinal magnetic fields are detected on the surface of our targets, the numerous 3σ detections of mean quadratic magnetic fields strongly suggest that magnetic fields are present in their atmospheres.

5. Summary

Most, if not all, HgMn stars are members of binary systems. They show distinct element distribution patterns, changing with time, and tied to the secondary component. HgMn stars show weak magnetic fields, with different polarity for regions with over- or underabundance. The vast majority of slowly rotating late B-type stars formed in binary systems with $v \sin i < 70\,\mathrm{km\,s^{-1}}$ and orbital periods between 3 and 20 days become HgMn stars (extracted from Pourbaix *et al.* 2004). Careful studies of HgMn stars are important for the general understanding of B-type star formation in binary systems.

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