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LETTER TO THE EDITOR

No magnetic field in the spotted HgMn star μ Leporis[★]

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ABSTRACT

Context. Chemically peculiar stars of the mercury-manganese (HgMn) type represent a new class of spotted late-B stars, in which evolving surface chemical inhomogeneities are apparently unrelated to the presence of strong magnetic fields but are produced by some hitherto unknown astrophysical mechanism.
Aims. The goal of this study is to perform a detailed line profile variability analysis and carry out a sensitive magnetic field search for one of the brightest HgMn stars – μ Lep.
Methods. We acquired a set of very high-quality intensity and polarization spectra of μ Lep with the HARPSpol polarimeter. These data were analyzed with the multiline technique of least-squares deconvolution in order to extract information on the magnetic field and line profile variability.
Results. Our spectra show very weak but definite variability in the lines of Sc, all Fe-peak elements represented in the spectrum of μ Lep, as well as Y, Sr, and Hg. Variability might also be present in the lines of Si and Mg. Anomalous profile shapes of Ti II and Y II lines suggest a dominant axisymmetric distribution of these elements. At the same time, we found no evidence of the magnetic field in μ Lep, with the 3σ upper limit of only 3 G for the mean longitudinal magnetic field. This is the most stringent upper limit on the possible magnetic field derived for a spotted HgMn star.
Conclusions. The very weak variability detected for many elements in the spectrum μ Lep suggests that low-contrast chemical inhomogeneities may be common in HgMn stars and that they have not been recognized until now due to the limited precision of previous spectroscopic observations and a lack of time-series data. The null result of the magnetic field search reinforces the conclusion that formation of chemical spots in HgMn stars is not magnetically driven.

Key words. stars: chemically peculiar – stars: individual: HD 33904 – stars: magnetic field – starspots – polarization

1. Introduction

Mercury-manganese (HgMn) stars form a subclass of late-B chemically peculiar stars. In addition to a large overabundance of exotic chemical elements, their most extraordinary characteristic is the presence of weak line profile variation that is attributed to chemical spots (Adelman et al. 2002; Hubrig et al. 2006). Despite occasional magnetic field detections claimed for HgMn stars (e.g., Hubrig et al. 2010), all systematic attempts to find magnetic fields using the best available data yielded null results (Shorlin et al. 2002; Folsom et al. 2010; Aurière et al. 2010; Makaganiuk et al. 2011b). The lack of strong magnetic fields distinguishes HgMn stars from the better known strongly magnetic Ap stars, which also exhibit chemical inhomogeneities. Moreover, unlike any other known type of spotted early-type stars, the topology of spots in HgMn stars evolves on a timescale from years (Kochukhov et al. 2007) to months (Briquet et al. 2010). This unusual stellar surface structure-formation phenomenon was only observed for a handful of stars and has received no satisfactory theoretical explanation so far. Additional observational studies are needed to enlarge the sample of known spotted HgMn stars, assess the extent of surface inhomogeneity for a wider range of chemical elements, and relate spots to the possible presence of weak magnetic fields and to other stellar properties.

The third brightest HgMn star, μ Lep (HR 1702, HD 33904, HIP 24305), was a popular target of the model atmosphere and abundance analysis studies of mercury-manganese stars (Smith & Dworetsky 1993; Woolf & Lambert 1999; Adelman & Pintado 2000). Its brightness and a moderate rotational velocity, $v_e \sin i = 15.5–16.5$ km s^{-1} (Dworetsky et al. 1998; Dolk et al. 2003), make μ Lep an ideal object for an investigation of weak line profile variability and for a high-precision magnetic field search.

This star is classified as an α^2 CVn-type star in the General Catalogue of Variable Stars[1] thanks to marginal photometric changes with a period close to 2 d reported by Renson et al. (1976). Subsequent studies did not confirm this variability (Heck et al. 1987; Adelman 1998). Recently Nuñez et al. (2010) mention changes in the Hg II 3984 Å line profile. But apart from this brief report, there have been no previous spectroscopic variability studies of this star. With the exception of an early low-precision polarimetric study by Babcock (1958), μ Lep has previously not been investigated with spectropolarimetry.

[★] Based on observations collected at the European Southern Observatory, Chile (ESO programs 084.D-0338, 086.D-0240).

[1] `http://www.sai.msu.su/gcvs/gcvs/`

Table 1. Journal of spectropolarimetric observations and results of the magnetic field analysis of μ Lep.

Date	Stokes	HJD	$T_{\rm exp}$ (s)	S/N	S/N (LSD)	FAP	$\langle B_z \rangle$(V) (G)	$\langle B_z \rangle$(null) (G)
2010-01-07	*IV*	2455204.7676	4 × 161	750	5700	0.959	-0.7 ± 2.5	5.4 ± 2.5
2011-02-12	*IV*	2455605.6493	8 × 160	1000	8600	0.951	-2.5 ± 1.8	0.1 ± 1.9
2011-02-13	*IV*	2455606.6025	8 × 160	1150	9200	0.994	1.4 ± 1.6	2.7 ± 1.6
2011-02-14	*IV*	2455607.6491	8 × 160	1050	8400	0.948	-0.4 ± 1.8	1.6 ± 1.8
2011-02-16	*I*	2455609.5099	8 × 80	700				
2011-02-17	*I*	2455610.5128	8 × 80	850				

Berghoefer et al. (1996) recognized μ Lep as an X-ray bright object, but the spectral properties of this emission suggest an unresolved late-type, pre-main sequence companion as the origin (Behar et al. 2004). Using adaptive imaging in the infrared Schöller et al. (2010) detect a visual companion at the separation of 0.′′3 from the primary. The K-band luminosity difference of more than 3 mag ensures that the secondary contributes negligibly to the combined radiation at optical wavelengths.

The objective of our study is to investigate the spectral variability and assess the magnetic field properties of μ Lep in the context of a recently discovered HgMn chemical spot phenomenon. Taking advantage of the brightness of this star, we attempt to reach a significantly higher precision both in the line profile analysis and in the magnetic field search than has been achieved for other spotted HgMn stars.

The rest of this paper is organized as follows. Section 2 describes observational data and its reduction. Magnetic field analysis is presented in Sect. 3. The results of our line profile variability study are given in Sect. 4. The paper concludes with a summary and discussion in Sect. 5.

2. Observations and data reduction

The spectra of μ Lep analyzed in this paper were obtained with the HARPSpol polarimeter (Snik et al. 2011; Piskunov et al. 2011) feeding the HARPS spectrometer (Mayor et al. 2003) at the ESO 3.6-m telescope in La Silla. Five observations on different nights were obtained in February 2011. Out of these spectra, three were recorded using the circular polarization analyzer and two were obtained in the non-polarimetric mode. In addition, we reanalyzed our earlier Stokes *IV* HARPSpol observation of μ Lep obtained in January 2010 (Makaganiuk et al. 2011b). All spectra have a resolving power of $R = 115\,000$ and a peak signal-to-noise ratio (S/N) of 700–1000 per 0.8 km s^{-1} pixel at $\lambda \approx 5200$ Å. The information about individual observations, including the UT and Julian dates, Stokes parameters observed, exposure times, and the S/N, is given in Table 1.

Our data cover the wavelength range 3780–6913 Å with a small gap around 5300 Å. Each observation of the star was split into four to eight sub-exposures, each 80–160 s long, obtained with four different orientations of the quarter-wave retarder plate relative to the beamsplitter of the circular polarimeter. The reduction was performed using the REDUCE pipeline (Piskunov & Valenti 2002). The Stokes *V* parameter and the diagnostic null spectrum were deduced with the help of the "ratio method" described by Bagnulo et al. (2009). Other details of the acquisition, reduction, and calibration of the HARPSpol observations of μ Lep can be found in our previous papers devoted to HgMn stars (Makaganiuk et al. 2011a,b).

3. Magnetic field measurements

We used the least-squares deconvolution (LSD) code and the methodology described by Kochukhov et al. (2010) to perform a sensitive magnetic field search for μ Lep. This multiline technique assumes that each intensity or circular polarization line profile is a scaled copy of the common mean line shape and that overlapping lines add up linearly. Under these approximations, the high-quality average Stokes *I* and *V* profiles are derived from observations for a given set of spectral lines (Donati et al. 1997).

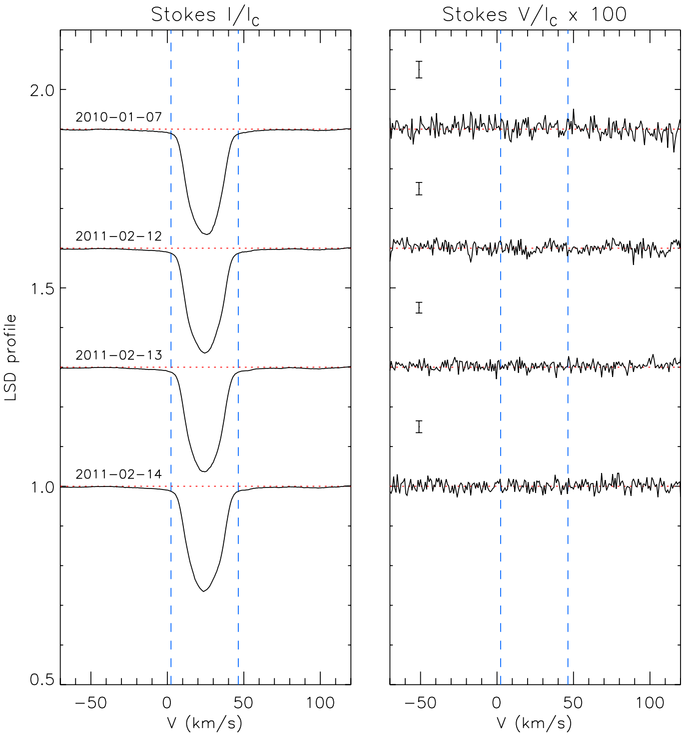

Fig. 1. LSD Stokes *I* (*left panel*) and Stokes *V* (*right panel*) profiles of μ Lep. The profiles corresponding to different observing nights are shifted vertically for clarity. The vertical scale in the Stokes *V* panel is expanded by a factor of 100 relative to Stokes *I*. The error bars for each *V* profile are given on the left side of the panel. The vertical dashed lines indicate the velocity range adopted for the longitudinal magnetic field measurements.

The line mask necessary for applying LSD was extracted from the VALD database (Kupka et al. 1999), assuming stellar parameters $T_{\rm eff} = 12\,750$ K and $\log g = 4.0$ (e.g., Woolf & Lambert 1999), together with the abundances from Adelman & Pintado (2000). The final line mask, obtained after excluding the regions affected by the hydrogen lines and strong telluric features, included 526 spectral lines with a central intensity exceeding 10% of the continuum. This list is dominated by Mn II and Fe II lines. The average wavelength and the mean effective Landé factor are 4769 Å and 1.138, respectively. The application of LSD increases the S/N of the polarized profiles by a factor of ≈8 (see Table 1).

The Stokes *I* and *V* LSD profiles for our four spectropolarimetric observations of μ Lep are presented in Fig. 1. These mean profiles were computed for the velocity range from −70

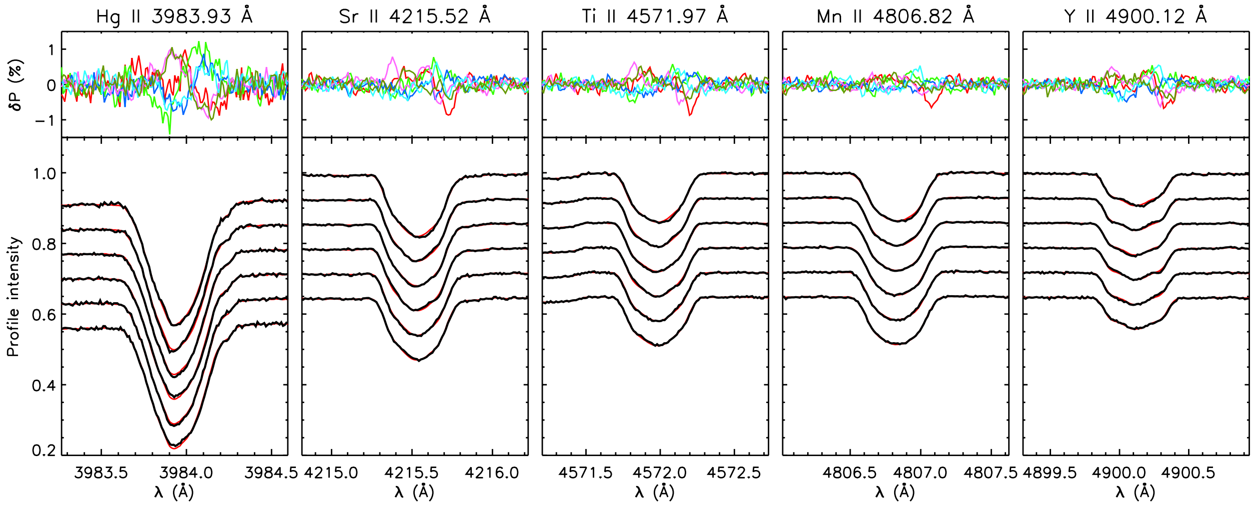

Fig. 2. Variability of individual Hg II, Sr II, Ti II, Mn II, and Y II spectral lines in μ Lep. The spectra corresponding to different observing nights are offset vertically. The mean profile (*thin red line*) is plotted below the time-resolved spectra (*thick black lines*). The upper part of each panel shows residual spectra.

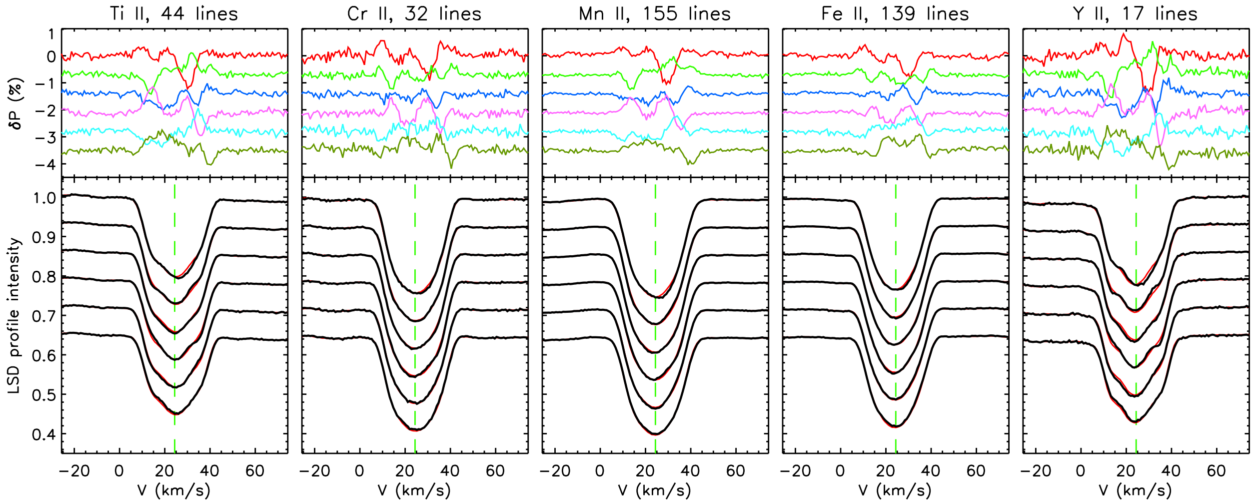

Fig. 3. Variability of the Ti II, Cr II, Mn II, Fe II, and Y II LSD profiles. The ion and the number of lines used for constructing mean profiles are indicated on top. The spectra corresponding to different observing nights are offset vertically. The upper panel in each column shows residual profile variation, while the bottom panel compares the time-averaged (*thin red line*) and time-resolved (*thick black lines*) LSD profiles. The vertical dashed line shows the mean stellar radial velocity.

to +120 km s^{-1}, with a step of 0.8 km s^{-1}, which is close to the mean pixel spacing of HARPS spectra.

There is no evidence of the magnetic signature in any of the LSD Stokes V profiles. The false alarm probability assessment (FAP, Donati et al. 1992) indicates that none of the Stokes V LSD spectra contains a statistically significant (FAP $< 10^{-5}$) or even a marginal (FAP $< 10^{-3}$) signal.

The mean longitudinal magnetic field, $\langle B_z\rangle$, was estimated from the first moment of LSD Stokes V. The profiles were integrated within ± 22 km s^{-1} of the mean radial velocity of the star, 24.38 ± 0.07 km s^{-1}, estimated from LSD Stokes I. The $\langle B_z\rangle$ values range between −2.5 and 1.4 G with an error bar of 1.6–2.5 G. Individual measurements are reported in Table 1. They are entirely consistent with the null hypothesis of no magnetic field. There is no detection of $\langle B_z\rangle$ in the null LSD profiles either, confirming the absence of spurious polarization. The weighted mean of all four $\langle B_z\rangle$ measurements is 0.39 ± 0.93 G, implying a 3σ upper limit of 3 G for the longitudinal field.

4. Line profile variability

A low-amplitude variability is apparent in many individual metal lines in the spectrum of μ Lep. These changes do not exceed 1% of the continuum intensity and require $S/N > 500$ to be detected reliably. Figure 4 shows examples of the variability in individual lines of Hg II, Sr II, Ti II, Mn II, and Y II. The largest amplitude is seen for the Hg II 3984 Å line. In addition, variability is evident in several lines of Sc II. Marginal changes are also present in numerous absorption features of Fe II and Cr II, as well as in a few strong lines of Si II and Mg II.

Aiming to increase the precision of the line profile variability analysis, we applied the LSD technique to individual chemical elements following the multiprofile LSD approach introduced by Kochukhov et al. (2010). The resulting LSD profiles, derived from 17–155 lines, are shown in Fig. 3. The LSD analysis confirms variability in the Fe II and Cr II lines.

The six HARPS spectra of μ Lep available to us are not sufficient for reliably determining the stellar rotational period. But

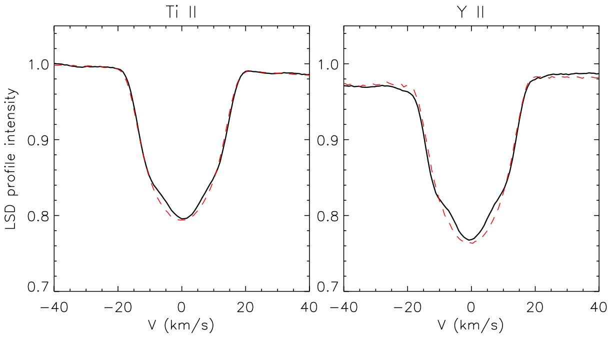

Fig. 4. Comparison of the time-averaged LSD profiles of Ti ii and Y ii derived from observations (*solid black line*) and synthetic spectrum (*dashed red line*).

the absence of a smooth progression of the residual profiles obtained for observations during consecutive nights in February 2011 suggests that rotational period does not exceed a few days. On the other hand, the stellar effective temperature $T_{\rm eff}$ = 12 600 ± 200 K and Hipparcos parallax π = 17.54 ± 0.55 mas (van Leeuwen 2007) yield $R = 3.39 \pm 0.16\,R_\odot$. For this radius value and $v_{\rm e}\sin i = 16 \pm 0.5$ km s^{-1}, the oblique rotator relation predicts a reasonable inclination angle of 30°–75° for the rotation period range of 5–10 d.

5. Discussion

We have detected very low-amplitude line profile variations in the bright HgMn star μ Lep. In contrast to previous studies (Kochukhov et al. 2005; Hubrig et al. 2006; Folsom et al. 2010; Makaganiuk et al. 2011a), these changes were found not only for a few heavy elements but also for all Fe-peak ions represented in the stellar spectrum and, possibly, for the lines of light elements Si ii and Mg ii.

The night-to-night changes of the residual profiles (Figs. 2 and 3) exhibit qualitatively similar, though not identical, line distortions for different elements. This indicates a similar inhomogeneous distribution of various elements. A more extended dataset is required to confirm this conclusion and rule out the possibility of a nonuniform temperature distribution.

The weak line profile variation in μ Lep suggests that low-contrast spots are ubiquitous in HgMn stars and that in many cases their signatures have been missed due to an insufficient precision of the spectroscopic data and lack of systematic time-resolved line profile studies.

Besides the low-amplitude variability discussed above, the time-averaged profiles of the Ti ii and Y ii lines exhibit anomalous triangular cores deviating significantly from the rotational Doppler line shape. This can be interpreted as a signature of a dominant axisymmetric component in the inhomogeneous abundance distribution with an enhancement of both elements at the rotational pole. The peculiar shapes of the average Ti ii and Y ii profiles is not an artifact of the LSD procedure since the LSD profiles derived from the synthetic spectrum using the same line mask do not show any anomaly (Fig. 4).

Spectropolarimetric observations of μ Lep analyzed in our study yield the most precise magnetic field measurements for a spotted HgMn star. It is remarkable that even after reaching the precision of a few G we cannot detect longitudinal magnetic field. The lack of a statistically significant signal in the LSD Stokes V profiles obtained during four different nights also rules out the presence of complex fields similar to those detected in cool active stars with the same instrument, data reduction, and analysis procedures as applied for μ Lep (Kochukhov et al. 2011).

The upper limit of 3 G for the longitudinal magnetic field obtained for μ Lep is much smaller than the equipartition field of ≈100 G expected in the line-forming region of the stellar atmosphere. Thus, it is unlikely that any field below a few G, if exists at all, can influence the accumulation of chemical elements by the atomic diffusion and govern the spot formation process. Time dependence of the radiative diffusion (Alecian 1998) or mixing induced by the hydrodynamical instabilities and circulation are more likely candidates for the mechanism behind the spot formation and evolution in HgMn stars. The similarity of the spot topologies found for different elements in 66 Eri (Makaganiuk et al. 2011a), φ Phe (Makaganiuk et al. 2011c), and tentatively suggested here for μ Lep probably favors the latter hypothesis because diffusion instabilities must produce more diverse surface distributions due to their strong dependence on the radiative acceleration of individual chemical elements.

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References

Adelman, S. J. 1998, A&AS, 132, 93
Adelman, S. J., & Pintado, O. I. 2000, A&A, 354, 899
Adelman, S. J., Gulliver, A. F., Kochukhov, O. P., & Ryabchikova, T. A. 2002, ApJ, 575, 449
Alecian, G. 1998, Contributions of the Astronomical Observatory Skalnate Pleso, 27, 290
Aurière, M., Wade, G. A., Lignières, F., et al. 2010, A&A, 523, A40
Babcock, H. W. 1958, ApJS, 3, 141
Bagnulo, S., Landolfi, M., Landstreet, J. D., et al. 2009, PASP, 121, 993
Behar, E., Leutenegger, M., Doron, R., et al. 2004, ApJ, 612, L65
Berghoefer, T. W., Schmitt, J. H. M. M., & Cassinelli, J. P. 1996, A&AS, 118, 481
Briquet, M., Korhonen, H., González, J. F., Hubrig, S., & Hackman, T. 2010, A&A, 511, A71
Dolk, L., Wahlgren, G. M., & Hubrig, S. 2003, A&A, 402, 299
Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., & Collier Cameron, A. 1997, MNRAS, 291, 658
Donati, J.-F., Semel, M., & Rees, D. E. 1992, A&A, 265, 669
Dworetsky, M. M., Jomaron, C. M., & Smith, C. A. 1998, A&A, 333, 665
Folsom, C. P., Kochukhov, O., Wade, G. A., Silvester, J., & Bagnulo, S. 2010, MNRAS, 407, 2383
Heck, A., Mathys, G., & Manfroid, J. 1987, A&AS, 70, 33
Hubrig, S., González, J. F., Savanov, I., et al. 2006, MNRAS, 371, 1953
Hubrig, S., Savanov, I., Ilyin, I., et al. 2010, MNRAS, 408, L61
Kochukhov, O., Piskunov, N., Sachkov, M., & Kudryavtsev, D. 2005, A&A, 439, 1093
Kochukhov, O., Adelman, S. J., Gulliver, A. F., & Piskunov, N. 2007, Nature Phys., 3, 526
Kochukhov, O., Makaganiuk, V., & Piskunov, N. 2010, A&A, 524, A5
Kochukhov, O., Makaganiuk, V., Piskunov, N., et al. 2011, ApJ, 732, L19
Kupka, F., Piskunov, N., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, A&AS, 138, 119
Makaganiuk, V., Kochukhov, O., Piskunov, N., et al. 2011a, A&A, 529, A160
Makaganiuk, V., Kochukhov, O., Piskunov, N., et al. 2011b, A&A, 525, A97
Makaganiuk, V., et al. 2011c, A&A, submitted
Mayor, M., Pepe, F., Queloz, D., et al. 2003, The Messenger, 114, 20
Nuñez, N. E., González, J. F., & Hubrig, S. 2010, in Magnetic Stars, ed. D. O. Kudryavtsev, I. I. Romanyuk, & A. V. Zyazeva, 109
Piskunov, N. E., & Valenti, J. A. 2002, A&A, 385, 1095
Piskunov, N., Snik, F., Dolgopolov, A., et al. 2011, The Messenger, 143, 7
Renson, P., Manfroid, J., & Heck, A. 1976, A&AS, 23, 413
Schöller, M., Correia, S., Hubrig, S., & Ageorges, N. 2010, A&A, 522, A85
Shorlin, S. L. S., Wade, G. A., Donati, J.-F., et al. 2002, A&A, 392, 637
Smith, K. C., & Dworetsky, M. M. 1993, A&A, 274, 335
Snik, F., Kochukhov, O., Piskunov, N., et al. 2011, in ASP Conf. Ser., 437, ed. J. R. Kuhn, et al., 237
van Leeuwen, F. 2007, A&A, 474, 653
Woolf, V. M., & Lambert, D. L. 1999, ApJ, 521, 414