Magnetic Fields in Massive Stars: New Insights

S. Hubrig[1], M. Schöller[2], A.F. Kholtygin[3], L.M. Oskinova[4], I. Ilyin[1]

E-mail: *shubrig@aip.de*

Substantial progress has been achieved over the last decade in studies of stellar magnetism due to the improvement of magnetic field measurement methods. We review recent results on the magnetic field characteristics of early B- and O-type stars obtained by various teams using different measurement techniques.

1 Massive O-type stars with different spectral designations and kinematic characteristics

During the last years, a number of magnetic studies focused on the detection of magnetic fields in massive early B- and O-type stars. The characterization of magnetic fields in massive stars is indispensable to understand the conditions controlling the presence of those fields and their implications for the stellar physical parameters and evolution. Accurate studies of the age, environment, and kinematic characteristics of magnetic stars are also promising to give us new insights into the origin of the magnetic fields. While a number of early B-type stars were detected as magnetic already several decades back, the first magnetic field detection in an O-type star was achieved only 13 years ago, even though the existence of magnetic O-type stars had been suspected for a long time. Indirect observational evidences for the presence of magnetic fields were the many unexplained phenomena observed in massive stars, which are thought to be related to magnetic fields, like cyclical wind variability, Hα emission variation, chemical peculiarity, narrow X-ray emission lines, and non-thermal radio/X-ray emission.

However, direct measurements of the magnetic field strength in massive stars, using spectropolarimetry to determine the Zeeman splitting of the spectral lines, are difficult since only a few spectral lines are available for these measurements. In addition, these spectral lines are usually strongly broadened by rapid rotation and macroturbulence and frequently appear in emission or display P Cyg profiles. In high-resolution spectropolarimetric observations, broad spectral lines frequently extend over adjacent orders, so that it is necessary to adopt order

---

[1] Leibniz-Institut für Astrophysik Potsdam (AIP), Germany
[2] European Southern Observatory, Germany
[3] Astronomical Institute, St. Petersburg State University, Russia
[4] Institut für Physik und Astronomie, Universität Potsdam, Germany

V. Grinin et al. (eds) Radiation mechanisms of astrophysical objects. Yerevan: Edit Print, 2017, pp. 187–196.

shapes to get the best continuum normalization. Furthermore, most of the existing high-resolution spectropolarimeters are operating at smaller telescopes and cannot deliver the necessary high signal-to-noise (SNR) observations for a majority of the massive stars. Especially, O-type stars and Wolf-Rayet (WR) stars are rather faint. Indeed, the Bright Star Catalog contains only about 50 O-type stars and only very few WR stars.

In view of the large line broadening in massive stars, to search for the presence of magnetic fields, the low-resolution VLT instrument FORS 2 – and prior to that FORS 1 – appears to be the most suitable instrument in the world, offering the appropriate spectral resolution and the required spectropolarimetric sensitivity, giving access to massive stars even in galaxies in our neighborhood. Only the Faint Object Camera and Spectrograph at the Subaru Telescope has an operating spectropolarimetric mode, and, pending the commissioning of the PEPSI spectrograph in polarimetric mode installed at the Large Binocular Telescope, no further high-resolution spectropolarimetric capabilities are available on any of the 8–10 m class telescopes.

The first spectropolarimetric observations of O-type stars at ESO started with FORS 1 already in 2005. During a survey of thirteen O-type stars, the discovery of the presence of a magnetic field was announced in the Of?p star HD 148937 [3]. The class of Of?p stars was introduced by Walborn [5] and includes only five stars in our Galaxy. Of?p stars display recurrent spectral variations in certain spectral lines, sharp emission or P Cygni profiles in He I and the Balmer lines, and strong C III emission lines around 4650 Å. In the last years, it was shown that all Of?p stars are magnetic with field strengths from a few hundred Gauss to a few kG. Among them, only two Of?p stars, HD 148937 and CPD–28 2561 are observable from Paranal and, noteworthy, the first magnetic field detections were achieved through FORS 1 and FORS 2 observations [4].

All FORS 1/2 observations of HD 148937 are presented in Fig. 1 together with the ESPaDOnS observations obtained at CFHT [2]. This figure demonstrates the excellent agreement between the FORS 2 and ESPaDOnS measurements, highlighting the outstanding potential of FORS 2 for the detection of magnetic fields and the investigation of the magnetic field geometry in massive stars. Notably, while an exposure time of 21.5 h at the CFHT was necessary to obtain seven binned measurements, the exposure time for the individual FORS 2 observations accounted only for two to four minutes and only 2.3 h were used for the observations at six different epochs, including telescope presets and the usual overheads for readout time and retarder waveplate rotation.

Also the FORS 2 measurements of the mean longitudinal magnetic field of the second Of?p star, CPD–28 2561, were consistent with a single-wave variation during the stellar rotation cycle, indicating a dominant dipolar contribution to the magnetic field topology with an estimated polar strength of the surface dipole B_d larger than 1.15 kG [6]. Interestingly, in the studies of these two Of?p stars, none of the reported detections reached a 4σ significance level. While 3σ detections with FORS 2 can not always be trusted

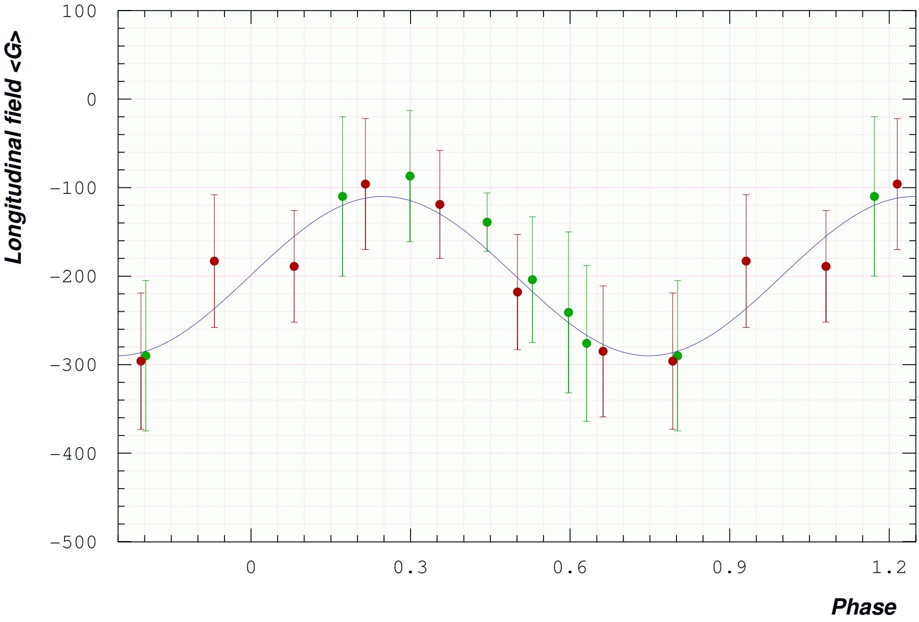

Figure 1: Longitudinal magnetic field variation of the Of?p star HD 148937 according to the 7.032 d period determined by Nazé et al. [1]. Red symbols correspond to ESPaDOnS observations [2], while green symbols are FORS 1 and FORS 2 measurements [3, 4]. Note that the measurement errors for both ESPaDOnS and FORS 1/2 observations are of similar order.

for single observations, they are genuine if the measurements show smooth variations over the rotation period, similar to those found for the Of?p stars HD 148937 and CPD–28 2561. The detection of rotational modulation of the longitudinal magnetic field is important to constrain the global field geometry necessary to support physical modeling of the spectroscopic and light variations.

To identify and to model the physical processes responsible for the generation of their magnetic fields, it is important to establish whether magnetic fields can also be detected in massive stars that are fast rotators and have runaway status. Recent detections of strong magnetic fields in very fast rotating early B-type stars indicate that the spindown timescale via magnetic braking can be much longer than the estimated age of these targets (e.g. [7]). Furthermore, current studies of their kinematic status identified a number of magnetic O and Of?p stars as candidate runaway stars (e.g. [8]). Increasing the known number of magnetic objects with extreme rotation, which are probably products of a past binary interaction, is important to understand the magnetic field origin in massive stars. The star ζ Ophiuchi (=HD 149757) of spectral type O9.5V is a well-known rapidly rotating runaway star, rotating almost at break-up velocity with $v \sin i = 400\,\mathrm{km\,s^{-1}}$ [9]. The analysis of the FORS 2 observations showed the presence of a weak magnetic field with a reversal of polarity [4] and an amplitude of about 100 G. The resulting periodogram for the magnetic field measurements using all available lines showed a dominating peak corresponding to a period of about 1.3 d which is roughly double the period of 0.643 d determined by Pollmann [10], who studied the variation of the equivalent width of the He I 6678 line.

The presence of magnetic fields might change our whole picture about the evolution from O stars via WR stars to supernovae or gamma-ray bursts. Neglecting magnetic fields could be one of the reasons why models and observations of massive-star populations are still in conflict. Another potential importance of magnetic fields in massive stars concerns the dynamics of stellar winds. A few years ago, Hubrig et al. [11] carried out FORS 2 observations of a sample of Galactic WR stars including one WR star in the Large Magellanic Cloud. Magnetic fields in WR stars are especially hard to detect because of wind-broadening of their spectral lines. Moreover, all photospheric lines are absent and the magnetic field is measured on emission lines formed in the strong wind. Remarkably, spectropolarimetric monitoring of WR 6, one of the brightest WR stars, revealed a sinusoidal nature of $\langle B_z \rangle$ variations with a period of 3.77 d with an amplitude of only 70–90 G.

2 Pulsating massive stars

Recent high-precision uninterrupted high-cadence space photometry using a number of satellites (e.g., WIRE, MOST, CoRoT, Kepler, BRITE) led to a revolutionary change in the observational evaluation of variability of massive stars. Supported by results of photometric monitoring, it is expected that a large fraction of massive stars show photometric variability due to either β Cep- or SPB-like pulsations, or stochastic p-modes, or convectively-driven internal gravity waves.

High-resolution spectropolarimetric observations of pulsating stars frequently fail to show credible measurement results, if the whole sequence of subexposures at different retarder waveplate angles has a duration comparable to the timescale of the pulsation variability. As an example, even for the bright fourth magnitude β Cephei star ξ^1 CMa with a pulsation period of 5 h, a full HARPS sequence of subexposures requires about 30 min. In contrast, one FORS 2 observation of the same star lasts less than 10 min. Owing to the strong changes in the line profile positions and the shapes in the spectra of pulsating stars, a method using spectra averaged over all subexposures leads to erroneous wavelength shifts and thus to wrong values for the longitudinal magnetic field.

For the first time, FORS 1 magnetic field surveys of slowly pulsating B (SPB) stars and β Cephei stars were carried out from 2003 to 2008. As a number of pulsating stars showed the presence of a magnetic field, our observations implied that β Cephei and SPB stars can no longer be considered as classes of non-magnetic pulsators. Notably, although the presence of magnetic fields

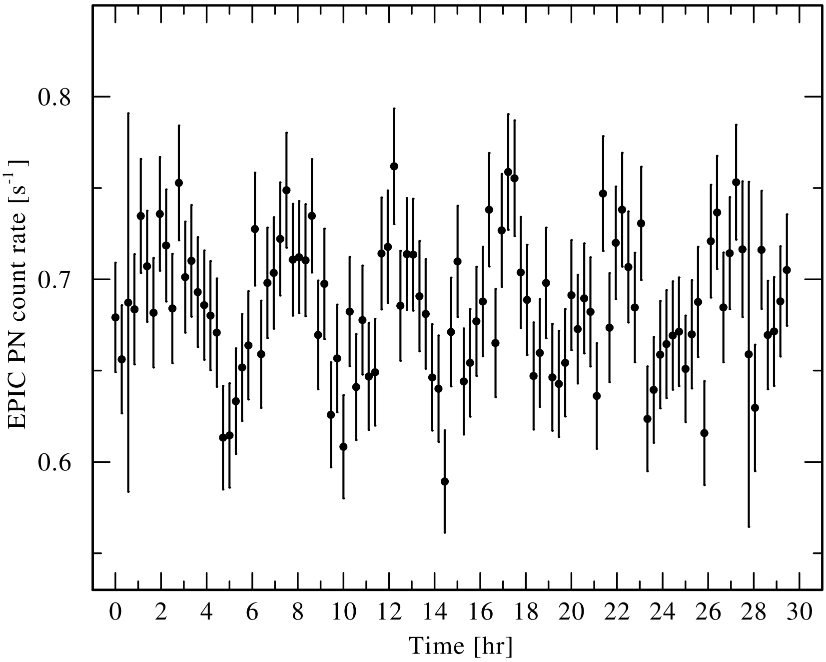

Figure 2: X-ray light curve of ξ^1 CMa in the 0.2 keV – 10.0 keV (1.24 Å – 62 Å) energy band, where the background was subtracted. The horizontal axis denotes the time after the beginning of the observation in hours. The data were binned to 1000 s. The vertical axis shows the count rate as measured by the EPIC PN camera. The error bars (1σ) correspond to the combination of the error in the source counts and the background counts.

in these stars is already known for more than ten years, the effect of these fields on the oscillation properties is not yet understood and remains to be studied. ξ^1 CMa, discovered as magnetic with FORS 1 observations long ago, is still the record holder with the strongest mean longitudinal magnetic field among the β Cephei stars of the order of 300–400 G [12]. Using FORS 2 measurements obtained in service mode in 2009/10, Hubrig et al. [13] detected a rotational modulation of its magnetic field with a period of about 2.19 d and estimated a magnetic dipole strength of about 5.3 kG.

Fully unexpected, observations of this particular star with the *XMM-Newton* telescope revealed for the first time X-ray pulsations with the same period as the stellar radial pulsation [14]. In Figs. 2 and 3, we present the observed X-ray light curve and the X-ray/optical light curves phased with the pulsation period. This first discovery of X-ray pulsations from a non-degenerate massive star stimulates theoretical considerations for the physical processes operating in magnetized stellar winds.

Observations of pulsating stars also allowed the first detection of a magnetic field in another β Cephei star, ϵ Lup [15], which is an SB2 system and recently received attention due to the presence of a magnetic field in both components.

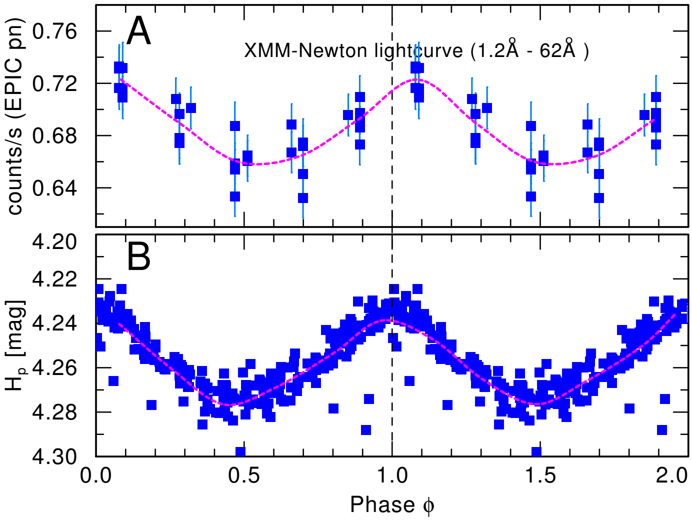

Figure 3: X-ray (upper panel) and optical (lower panel) light curves of ξ^1 CMa, phased with the stellar pulsation period. The X-ray light curve is produced from the data obtained with the *XMM-Newton* EPIC PN camera, using 1 h binning. The dashed red line interpolates the averages in phase bins of $\Delta\phi = 0.1$. The lower panel shows the *Hipparcos* Catalogue Epoch Photometry data. The abscissa is the magnitude $H_{\rm p}$ in the *Hipparcos* photometric system (330–900 nm with maximum at about 420 nm). The dashed red line interpolates the averages.

Since binary systems with magnetic components are rather rare, the detection of a magnetic field in this system using low resolution FORS spectropolarimetry indicates the potential of FORS 2 also for magnetic field searches in binary or multiple systems.

3 Improvements in the measurement techniques

During the last years, the measurement strategy for high-resolution and low-resolution spectropolarimetric observations was modified in many aspects. To measure the mean longitudinal magnetic fields in high-resolution polarimetric spectra obtained with ESPaDOnS, NARVAL, and HARPS, most teams are using the moment technique introduced by Mathys [16] and the Least-Squares Deconvolution (LSD) introduced by Donati et al. [17]. In the last years, Carroll et al. [18] developed the multi-line Singular Value Decomposition (SVD) method for Stokes Profile Reconstruction. The basic idea of SVD is similar to the Principal Component Analysis approach, where the similarity of the individual Stokes V profiles allows one to describe the most coherent and systematic features present in all spectral line profiles as a projection onto a small number of eigenprofiles (e.g. [19]). The excellent potential of the SVD method, especially in the analysis of extremely weak fields, e.g. in the Herbig Ae/Be star PDS 2, was recently demonstrated by Hubrig et al. ([20], right side of their Fig. 4).

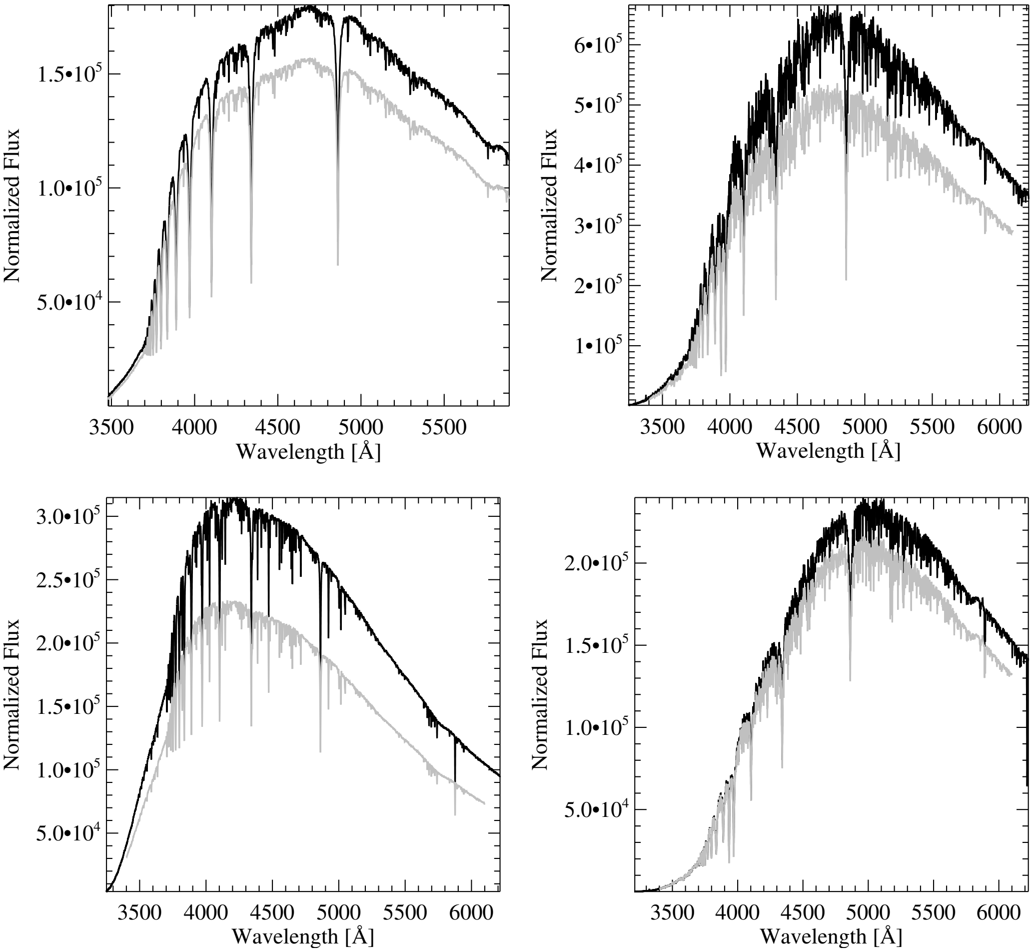

Figure 4: Fluxes extracted by Bagnulo et al. [22] (grey color) compared to those using our own pipeline (black color). The differences in the fluxes are presented (from left to right) for the HgMn star α And, the δ Scuti star HD 21190, the nitrogen rich early B-type star HD 52089, and the Herbig Ae star PDS 2. All these stars were announced in studies by Hubrig et al. as magnetic.

In the reduction process of low-resolution spectropolarimetric observations, Hubrig et al. [21] perform rectification of the V/I spectra and calculate null profiles, N, as pairwise differences from all available V profiles. From these, 3σ-outliers are identified and used to clip the V profiles. This removes spurious signals, which mostly come from cosmic rays, and also reduces the noise. A full description of the updated data reduction and analysis will be presented in a paper by Schöller et al. (*in preparation*).

The mean longitudinal magnetic field, $\langle B_{\rm z}\rangle$, is defined by the slope of the weighted linear regression line through the measured data points, where the weight of each data point is given by the squared signal-to-noise ratio of the Stokes V spectrum. The formal 1σ error of $\langle B_{\rm z}\rangle$ is obtained from the standard relations for weighted linear regression. This error is inversely proportional to the rms signal-to-noise ratio of Stokes V. Finally, we apply the factor $\sqrt{\chi^2_{\rm min}/\nu}$ to the error determined from the linear regression, if larger than 1.

Since 2014, Hubrig et al. [21] also implement the Monte-Carlo bootstrapping technique, where they typically generate $M = 250\,000$ statistical variations of the original dataset, and analyze the resulting distribution $P(\langle B_{\rm z}\rangle)$ of the M regression results. Mean and standard deviation of this distribution are identified with the most likely mean longitudinal magnetic field and its 1σ error, respectively. The main advantage of this method is that it provides an independent error estimate.

A number of discrepancies in the published measurement accuracies has been reported by Bagnulo et al. [22] who used the ESO FORS 1 pipeline to reduce the full content of the FORS 1 archive. The same authors already published a few similar papers in the last years suggesting that very small instrument flexures, negligible in most of the instrument applications, may be responsible for some spurious magnetic field detections, and that FORS detections may be considered reliable only at a level greater than 5σ. However, no report on the presence of flexures from any astronomer observing with the FORSes was ever published in the past. The authors also discuss the impact of seeing, if the exposure time is comparable with the atmospheric coherence time, which they incorrectly assume to be in seconds and not in milliseconds. In the most recent work do the authors present for the first time the level of intensity fluxes for each image and report which spectral regions were used for the magnetic field measurements. However, no fluxes for left-hand and right-hand polarized spectra are available, thus the reproduction of their measurements is not possible. Notably, already small changes in the spectral regions selected for the measurements can have a significant impact on the measurement results [23].

Since the measurement accuracies predominantly depend on photon noise, an improper extraction of the spectra, for instance the use of smaller extraction windows, would explain why Bagnulo et al. [22] disregarded 3σ detections by other authors. Indeed, the inspection of the levels of intensity fluxes for each subexposure compiled in the catalog of Bagnulo et al. [22] shows that their levels are frequently lower, down to 70% in comparison to those obtained in our studies. In Fig. 4 we present the comparison of fluxes for a few stars for which detections were achieved and published by Hubrig et al. during the last years. It is obvious that the detection of weak magnetic fields is especially affected if the extracted fluxes are low. From the consideration of the SNR values presented by Bagnulo et al. [22], we also noted that emission lines are not taken into account during the measurements. The reason for this is not clear to us as there is no need to differentiate between absorption and emission lines: the used relation between the Stokes V signal and the slope of the spectral line wing holds for both type of lines, so that the signals of emission and absorption lines add up rather than cancel.

4 Summary

To increase the reliability of magnetic field detections, but also to carry out a quantitative atmospheric analysis and to probe spectral variability, it is certainly helpful to follow up FORS 2 detections with high-resolution HARPS observations. To our knowledge, the only collaboration that uses FORS 2 and HARPS to monitor magnetic fields is the BOB ("B-fields in OB stars") collaboration [24], which is focused on the search of magnetic fields in massive stars. Combining observations with different instruments allowed the BOB collaboration to report during the last couple of years the presence of magnetic fields in a number of massive stars. As an example, the first detection of a magnetic field in the single slowly rotating O9.7 V star HD 54879 was achieved with FORS 2 and follow-up HARPS observations could show that HD 54879 is, so far, the strongest magnetic single O-type star detected with a stable and normal optical spectrum [25].

References

1. *Y. Nazé, A. Ud-Doula, M. Spano et al.*, Astron. Astrophys., **520**, A59, 2010.
2. *G.A. Wade, G. Grunhut, G. Gräfener et al.*, Mon. Not. Roy. Astron. Soc., **419**, 2459, 2012.
3. *S. Hubrig, M. Schöller, R.S. Schnerr et al.*, Astron. Astrophys., **490**, 793, 2008.
4. *S. Hubrig, M Schöller, I. Ilyin et al.*, Astron. Astrophys., **551**, A33, 2013.
5. *N.R. Walborn*, Astron. J., **78**, 1067, 1973.
6. *S. Hubrig, M. Schöller, A.F. Kholtygin et al.*, Mon. Not. Roy. Astron. Soc., **447**, 1885, 2015.
7. *T. Rivinius, R.H.D. Townsend, O. Kochukhov et al.*, Mon. Not. Roy. Astron. Soc., **429**, 177, 2013.
8. *S. Hubrig, N.V. Kharchenko, M. Schöller*, Astron. Nachr., **332**, 65, 2011.
9. *E. Kambe, R. Hirata, H. Ando*, Astron. Astrophys., **273**, 435, 1993.
10. *E. Pollmann*, Inf. Bull. Var. Stars, No. 6034, 1, 2012.
11. *S. Hubrig, K. Scholz, W.-R. Hamann et al.*, Mon. Not. Roy. Astron. Soc., **458**, 3381, 2016.
12. *S. Hubrig, M. Briquet, M. Schöller et al.*, Mon. Not. Roy. Astron. Soc., **369**, L61, 2006.
13. *S. Hubrig, I. Ilyin, M. Schöller et al.*, Astrophys. J. Lett., **726**, L5, 2011.
14. *L.M. Oskinova, Y. Nazé, H. Todt et al.*, Nature Commun., **5**, 4024, 2014.
15. *S. Hubrig, M. Briquet, P. De Cat et al.*, Astron. Nachr., **330**, 317, 2009.
16. *G. Mathys*, Proc. IAU Coll., **138**, 232, 1993.

17. *J.F. Donati, M. Semel, B.D. Carter et al.*, Mon. Not. Roy. Astron. Soc., **291**, 658, 1997.

18. *T.A. Carroll, K.G. Strassmeier, J.B. Rice, A. Künstler*, Astron. Astrophys., **548**, A95, 2012.

19. *T.A. Carroll, M. Kopf, K.G. Strassmeier, I. Ilyin*, Proc. IAU Symp., **259**, 633, 2009.

20. *S. Hubrig, T.A. Carroll, M. Schöller, I. Ilyin*, Mon. Not. Roy. Astron. Soc., **449**, L118, 2015.

21. *S. Hubrig, M. Schöller, A.F. Kholtygin*, Mon. Not. Roy. Astron. Soc., **440**, 1779, 2014.

22. *S. Bagnulo, L. Fossati, J.D. Landstreet, C. Izzo*, Astron. Astrophys., **583**, A115, 2015.

23. *S. Hubrig, D.W. Kurtz, S. Bagnulo et al.*, Astron. Astrophys., **415**, 661, 2004.

24. *T. Morel, N. Castro, L. Fossati et al.*, The Messenger, **157**, 27, 2014.

25. *N. Castro, L. Fossati, S. Hubrig et al.*, Astron. Astrophys., **581**, A81, 2015.

[*] The color figures are available online in the Proceedings at *http://www.astro.spbu.ru/sobolev100/*.