Statistics of magnetic fields on OBA stars

Kholtygin A. F.[1], Hubrig S.[2], Drake N. A.[1,3], Sudnik N. P.[1], Dushin V. V.[1]

[1] *Sobolev Astronomical Institute, St. Petersburg State University, St. Petersburg, Russia*
[2] *Leibniz-Institut fur Astrophysik Potsdam (AIP), Potsdam, Germany*
[3] *Observatório Nacional/MCTI, Brazil*

Abstract Starting from recent measurements, we studied the statistical properties of the magnetic fields of OBA stars. As one of the statistically significant characteristics of the magnetic field we use the average effective magnetic field of the star, $\langle B \rangle$. We then investigated the distribution function $f(\langle B \rangle)$ of the magnetic fields of OBA stars. This function has a power-law dependence on $\langle B \rangle$, with an index of 2–3 and a fast decrease for $\langle B \rangle \leq 300\,$G for B–A stars and $\langle B \rangle \leq 80\,$G for O stars.

1. Introduction

To date, magnetic fields have been detected in about four hundred OBA stars [4, 13, 14]. Upper main-sequence stars with $M > 2M_{\odot}$, without convective envelopes, usually have large-scale, steady magnetic fields. For both OB and less massive A stars, the dynamo mechanism is not effective; this leads one to consider the magnetic fields of those stars as *fossil* remnants in some stable equilibrium configuration. Braithwaite & Nordlund [2] showed by numerical simulations that stable magnetic field configurations do exist under the conditions in the radiative interior of OBA stars.

Nevertheless, the role of dynamo action can be significant. Cantiello et al. [5] find that the Fe convection zone is more prominent for stars with lower surface gravity, higher luminosity and higher initial metallicity. The authors suggest that magnetic fields produced there could appear at the surfaces of OB stars. The clumping in the inner parts of the winds of OB stars could be also connected with the Fe convection zone.

Cantiello & Braithwaite [6] investigated the subsurface magnetism in OB stars, assuming that dynamo action produces the magnetic fields at equipartition in the Fe convection zone. They found that magnetic fields produced there could emerge at the surface via magnetic buoyancy, and concluded that localized magnetic fields could be widespread in those early-type stars that have subsurface convection. Such local magnetic fields could also contribute to global stellar magnetic fields.

Henrichs & Sudnik [8] proposed that local stellar magnetic fields can be responsible for the formation of corotating magnetic loops, which they call *stellar* *prominences*. Those prominences are supposed to explain the cyclical optical wind-line variability in the spectra of O-type stars.

In order to improve our understanding the nature of the magnetic fields of OBA stars, we have studied their statistical properties. This paper describes our sample of stars with magnetic fields and analyses of the magnetic field functions, discusses the results, and presents some conclusions.

2. Magnetic field sample and magnetic field function

Our sample of the magnetic fields for OBA stars includes data presented in catalogues [4, 20], new measurements [10, 11, 12, 13, 14], and measurements from papers cited in [17, 13, 14]. As a global characteristic of the stellar magnetic field we use the *rms* magnetic field:

$$\langle B \rangle = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(B_l^i)^2}, \tag{1}$$

where n is the number of available measurements of the mean longitudinal magnetic field B_l.

To characterize the accuracy of measurements, we use following values:

$$\chi^2/n = \frac{1}{n}\sum_{i=1}^{n}\frac{\left(B_l^i\right)^2}{\left(\sigma_{B_l^i}\right)^2}, \quad \Sigma_{\langle B \rangle} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\sigma_{B_l^i}\right)^2}. \tag{2}$$

Here, $\sigma_{B_l^i}$ is the *rms* error of the field measurement i. As a test of the reality of magnetic field detections, we use the following criteria:

$$\langle B \rangle > 2\Sigma_{\langle B \rangle}, \quad \chi^2/n > 1. \tag{3}$$

The analysis of the differential magnetic field distribution $f(\langle B \rangle)$, or magnetic field function (MFF) [3], is important for understanding the nature of stellar magnetic fields. We determine it via the following formula:

$$N(\langle B \rangle, \langle B \rangle + \Delta\langle B \rangle) \approx N f(\langle B \rangle)\Delta\langle B \rangle, \tag{4}$$

where $N(\langle B \rangle, \langle B \rangle + \Delta\langle B \rangle)$ is the number of stars in the interval of mean magnetic fields $(\langle B \rangle, \langle B \rangle + \Delta\langle B \rangle)$, N is the total number of stars with measured field $\langle B \rangle$ satisfying the criteria (3).

In applying the criteria (3), we selected over 300 B–A stars that have statistically significant fields. The MFFs for those stars are plotted in Fig. 1. They

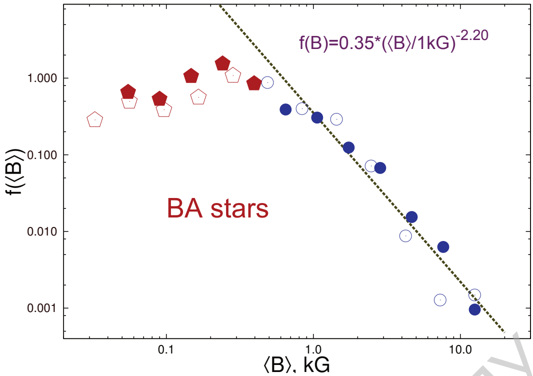

Figure 1. Magnetic field function for B stars (*filled* symbols) and A stars (*empty* symbols). The best fit to the form given in Eq. (5) is represented by the *thick dashed* line. Filled pentagons (for B stars) and empty ones (for A stars) identify data in the $\langle B\rangle < \langle B\rangle^{\rm th}$ region.

can be fitted for $\langle B\rangle > \langle B\rangle^{\rm th}$ with a power law:

$$f(\langle B\rangle) = A_0\left(\frac{\langle B\rangle}{\langle B\rangle_0}\right)^{\gamma}. \qquad (5)$$

$\langle B\rangle^{\rm th}$ is a threshold value of the *rms* field. One sees in Fig. 1 that the difference between the individual MFFs for B and A stars is small. The ensemble of magnetic B–A stars can therefore be described by a unified MFF with parameters $\langle B\rangle_0 = 1\,$kG, $\langle B\rangle^{\rm th} = 300\,$G, $A_0 = 0.35\pm0.08$, and $\gamma = 2.20\pm0.16$. The inference is that a common mechanism for the formation and destruction of the magnetic field can exist in B and A stars.

Only a small fraction of O stars are known to be magnetic. We collected all the measurements of their magnetic fields, B_l. In 19 cases, at least two values of B_l were measured. For those, it was possible to calculate the *rms* magnetic field using Eq. (1).

Fig. 2 shows the magnetic field function for all O stars that have measured magnetic fields. We excluded from the calculation of MFF for O stars the unusual Of?cp star NGC 1624-2, which has an extremely large magnetic field $\langle B\rangle \approx 5\,$kG [21]. For stars with only one field measurement we used the approximation $\langle B\rangle \approx \|B_l\|$ ($\|B_l\|$ is the absolute value of B_l. According to the approach developed in [15, 16] we expect that equality to be valid on average for an ensemble of $n > 3$ magnetic stars.

For O stars, the best-fitting parameter, obtained from a function of the form of Eq. (5), are: $\langle B\rangle^{\rm th} = 80\,$G, $A_0 = 0.036\pm0.015$, and $\gamma = 2.65\pm0.38$. The shape

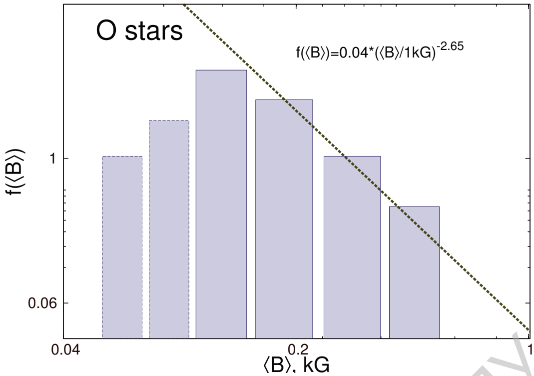

Figure 2. Magnetic field function for O stars. The fit to Eq. (5) is plotted as a *thick dashed* line.

of the fit for O stars is therefore similar to that for B–A stars, but the threshold value $\langle B\rangle^{\rm th}$ is 4 times smaller. Moreover, for O stars the parameter $A_0 = 0.036$ is one order of magnitude smaller than for B–A stars.

3. Discussion

Analysis of Fig. 1 led us to conclude that there is a cutoff in the MFF for $\langle B\rangle < 0.30\,$kG. That cutoff cannot be explained simply by observational selection.

Glagolevskij & Chuntonov [7] proposed an explanation for the relatively small number of stars with measured magnetic fields in the range $\langle B\rangle = 0.20-0.40\,$kG. They suggested that if the mean stellar magnetic field is below some threshold value $\langle B\rangle^{\rm th}$, then the field strength in the stellar atmosphere decreases almost to zero on a short timescale through meridional circulation.

Aurière et al. [1] suggested that there is some critical field strength, above which stable magnetic field configurations can exist, but below it a large-scale field configuration is destroyed through field instabilities.

The latter model could explain qualitatively the existence of a lower boundary in the magnetic field strengths of A stars, and especially of O–B stars, and could also explain why magnetic fields are observed in only a small fraction of OBA stars. If the initial magnetic field strength distribution of intermediate-mass stars were to increase strongly towards weak fields, then after their field formations the large majority of stars would have fields that were weaker than the critical values. The fields of such stars are unstable and would decay rapidly.

The mean effective magnetic field $\langle B\rangle$ was found to decrease with increasing

τ [9], where τ is the relative age of the star on the main sequence. The fading of the magnetic field strength $\langle B \rangle$ of B–A stars with increasing of τ was also confirmed in [18] and [19], and can also explain the cutoff of the MFF at $\langle B \rangle < \langle B \rangle^{\mathrm{th}}$.

4. Conclusions

Magnetic fields have been measured for more than a thousand stars of various spectral types. From a statistical analysis of all the measured magnetic fields for OBA stars, we conclude that the magnetic field function for B–A stars, $f(\langle B \rangle)$, can be described by a power law with a power index $\gamma \approx 2.2$. For $\langle B \rangle < 300\,\mathrm{G}$, the MFF shows a strong decrease. The magnetic field function for O stars is steeper than for B–A stars ($\gamma \approx 2.6$), and the cutoff value $\langle B \rangle^{\mathrm{th}} = 80\,\mathrm{G}$ is smaller.

Acknowledgements. The authors thank Saint Petersburg University for support of this investigation in the framework of the theme 6.38.73.2011. N.A.D. also thanks the PCI/MCTI (Brazil) grant under the project 302350/2013-6.

References

1. Aurière M., Wade G. A., Silvester J. et al. 2007, A&A, 475, 1053
2. Braithwaite J., Nordlund A. 2006, A&A, 450, 1077
3. Bychkov V. D., Monin D. N., Fabrika S. N., Valyavin G. G. 1997, in Stellar Magnetic Fields, Eds. Yu. V. Glagolevskij, I. I. Romanyuk, Special Astrophysical Observatory, p. 124
4. Bychkov V. D., Bychkova L. V., Madej J. 2009, MNRAS, 394, 1338
5. Cantiello M., Langer N., Brott I. et al. 2009, A&A 499, 279
6. Cantiello M., Braithwaite J. 2011, A&A 534, A140
7. Glagolevskij Yu. V., Chuntonov G. A. 2000, in Magnetic Fields of Chemically Peculiar and Related Stars, Eds. Yu. V. Glagolevskij, I. I. Romanyuk, Special Astrophysical Observatory, p. 149
8. Henrichs H. F., Sudnik N. P. 2013, arXiv:1310.5264
9. Hubrig S., North P., Schöller M. 2007, AN, 328, 475
10. Hubrig S., Schöller M., Schnerr R. S. et al. 2008, A&A, 490, 793
11. Hubrig S., Briquet M., De Cat P., et al. 2009, AN, 330, 317
12. Hubrig S., Schöller M., Savanov I., Yudin R. V., Pogodin M. A., et al. 2009, AN, 330, 708
13. Hubrig S., Schöller M., Kharchenko N. V. et al. 2011, A&A, 528, A151
14. Hubrig S., Schöller M., Ilyin I. et al. 2013, A&A, 551, A33
15. Kholtygin A. F., Fabrika S. N., Drake N. A., et al. 2010., Astronomy Letters, 36 370

16. Kholtygin A. F., Fabrika S. N., Drake N. A., et al. 2010, Kin. Phys. Cel. Bodies, 26 181
17. Kholtygin A. F., Drake N. A., Fabrika S. N. 2011, in Magnetic Stars, Eds. I. I. Romanyuk, D. O. Kudryavtsev, Special Astrophysical Observatory, p. 239
18. Kochukhov O., Bagnulo S. 2006, A&A, 450, 763
19. Landstreet J. D., Silaj J., Andretta V., et al. 2008, A&A, 481, 465
20. Romanyuk I. I., Kudryavtsev D. O. 2008, Astrofiz. Byull. 63, 148
21. Wade G. A., Maiz Apellaniz J., Martins F. et al. 2012, MNRAS, 425, 1278