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Evolution of magnetic field of massive stars

A. S. Medvedev[1], A. F. Kholtygin[2], S. Hubrig[3], S. N. Fabrika[1], G. G. Valyavin[1], M. Schöller[4] and O. A. Tsiopa[5]

[1] *Special Astrophysical Observatory, Russia*
(E-mail: a.s.medvedev@gmail.com)

[2] *Saint-Petersburg State University, Russia, (E-mail: afkholtygin@gmail.com)*

[3] *Leibniz-Institut für Astrophysik Potsdam (AIP), Potsdam, Germany*

[4] *European Southern Observatory, Garching, Germany*

[5] *Main (Pulkovo) Astronomical Observatory, Russia*

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Abstract. We model the evolution of massive magnetic stars in the Galaxy using our own population synthesis code. A comparison of our model magnetic field distribution with that obtained from an analysis of measurements of magnetic fields shows that both model and real distributions can be approximated by a log-normal law with a mean $\log(B) = 2.5$. Based on this comparison we conclude that the magnetic flux variations of OBA stars on the main sequence (MS) are very slow. The shape of the magnetic field distribution for O, B and A stars appeared to be similar. This means that the mechanisms of the generation of their magnetic field are probably identical.

Key words: stars: magnetic field – stars: evolution – stars: early type

1. Introduction

Studies of the age, environment, and kinematic characteristics of magnetic stars are promising to give us new insight into the origin of the magnetic fields (e.g. Hubrig et al., 2011, 2013; González et al., 2017). The first magnetic field detection in an O-type star was made in 2002 by Donati et al. (2002) only.

The recent systematic surveys BOB (The B fields in OB stars; Morel et al., 2014) and MiMeS (The Magnetism in Massive Stars; Wade et al., 2016) significantly enhanced the number of known magnetic OBA stars in comparison with $\sim$500 OBA stars with confirmed magnetic field in the catalog by Bychkov et al. (2009). The fraction of massive magnetic stars was found about of 6 – 7% only (Wade et al., 2014; Schöller et al., 2017).

Measuring of magnetic fields in hundreds of OBA stars open the possibility to study the magnetic field distribution (MFD) for different types of stars (e.g. Kholtygin et al., 2010a) which is important to understand the nature of the magnetic field of massive stars. An employment of the real MFD showed that some previous ideas about the magnetic field evolution can be incorrect. In this paper we consider the evolution of the magnetic fields and fluxes of OBA stars at the main sequence stage.

2. Model

The first step of our modelling is a creation of the initial ensemble of stars supposing that a total number of stars in the ensemble is $N_{\rm tot}$ and the stellar masses $M \in [M_{\rm min}, M_{\rm max}]$. The stellar mass distribution at the Zero-Age-MS (ZAMS) is described by a power law with an exponent of -2.3 (Kroupa, 2002). The appearance time t_* of each star at ZAMS is generated using the uniform distribution in the range $[0, T]$, where T is the total simulation time. The simulation time T has to be at least three times longer than the main sequence lifetime $\tau_{\rm MS}$ of a least massive star in the ensemble. The stellar birthrate λ is supposed to be constant.

Evolution of the stars in our ensemble is simulated using the single-star evolution code SSE by Hurley et al. (2000). This code is based on analytical approximations of evolutionary tracks by Pols et al. (1998). Our population synthesis code is created on the base of the Astrophysical Multipurpose Software Environment[1] (AMUSE) developed by Pelupessy et al. (2013).

The magnetic field of a star in our model is defined via the net magnetic flux Φ at the stellar surface: $\Phi = \int_S |B_r| dS$. Here B_r is the radial projection of the B-field and dS is a surface element. We use the root-mean-square (*rms*) field $\mathcal{B}$ instead of $B_{\rm d}$ as the main characteristic of stellar magnetic fields. If N is the total number of the field measurements B_l^k $(k = 1 \ldots N)$, then the *rms*-field is given by the formula (e.g. Bohlender et al., 1993):

$$\mathcal{B} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} \left(B_l^k\right)^2}. \tag{1}$$

The phase-averaged ratio $\mathcal{B}/B_{\rm d}$ and its asymptotical behaviour at $N \to \infty$ were investigated by Kholtygin et al. (2010a). They demonstrated that in the case of a dipole configuration the *rms*-field $\mathcal{B}$ weakly depends on random values of the rotational phase ϕ, inclination i and the angle β between magnetic and rotational axes. Following this paper we adopt $\Phi = 4\pi R^2 \mathcal{B}$, $\mathcal{B} \approx 0.2 B_{\rm d}$. We assume the lognormal distribution of the net magnetic fluxes:

$$f(\Phi \mid t = 0) = \frac{1}{\sqrt{2\pi} \ln 10 \Phi \sigma} \exp\left\{ -\frac{1}{2} \left(\frac{\log \Phi - \langle \log \Phi \rangle}{\sigma} \right)^2 \right\}, \tag{2}$$

where Φ is the net magnetic flux, $\langle \log \Phi \rangle$ is the mean value of the $\log \Phi$, σ is the width (in dex) of the distribution.

We chose the lognormal distribution of the magnetic fluxes mainly due to similarity between the lognormal and empirical distributions derived from real samples of magnetic stars (e.g. Medvedev et al., 2017). A lognormal magnetic flux distribution (magnetic flux function) can be generated due to of multiple

[1] see http://www.amusecode.org for details

merging of the protostars at the stage of the evolution before MS (see for details Medvedev & Kholtygin, 2017). Observational evidences imply that the magnetic fields of Ap stars can be decayed (e.g. Landstreet et al., 2008). According to Kholtygin et al. (2010b) the dissipation of magnetic fields can be described by the exponential function: $\Phi(t) = \Phi(0)e^{-\tau/t_{\rm d}}$.

3. Statistical criteria

Suppose that we want to analyse some empirical magnetic field distribution derived from a sample of N_* stars, using our model. Let n_i be the number of stars in each of N bins of the empirical distribution and let e_i be the expected number of stars, given by our model. Unfortunately, the number of known magnetic massive stars is not large. Therefore, the standard χ^2 statistics is not suitable for the analysis of empirical distributions. Instead we use the C-statistics, introduced by Cash (1979). In our model we use the following modification of the C-statistics:

$$C = 2\sum_{i=1}^{N_{\rm bins}} \left[e_i - n_i + n_i(\ln n_i - \ln e_i)\right]. \tag{3}$$

This form of C-statistics is often used in X-ray astronomy especially in cases when the number of photons is low (e.g. Arnaud, 1996).

Humphrey et al. (2009) found that the C-statistics allows to find unbiased estimates of fitting parameters even if a number of counts in data is low. However they also noted the main problem associated with the C-statistics that there is no simple way to implement a goodness-of-fit test. For example, in our model we first find the minimum of C-statistics using the Nelder-Mead algorithm and then find confidence intervals for fitting parameters using Monte-Carlo simulations. Hence in a recent paper, Kaastra (2017) presented the analytical and numerical approximations of expected values and variances for the C-statistics that can be used to evaluate the goodness-of-fit.

Additionally, the C-statistics can be expanded for simultaneous fitting of different samples of empirical distributions. If N is the number of samples and N_k is the number of bins in k-th sample, then we get

$$C_{\rm sim} = 2\sum_{k=1}^{N}\sum_{i=1}^{N_k}\left[e_i^k - n_i^k + n_i^k\Big(\ln n_i^k - \ln e_i^k\Big)\right]. \tag{4}$$

4. Results and Conclusions

Results of simultaneous fitting are presented in Fig. 1. For the model without dissipation of magnetic field we find: $\langle\log\Phi\rangle = 26.45^{+0.05}_{-0.05}$, $\sigma = 0.50^{+0.04}_{-0.05}$, $C/{\rm dof} = 39.1/53$ (here “dof” denotes “degrees of freedom”). For the model with $\tau_{\rm d} = 0.5$ the corresponding values are: $\langle\log\Phi\rangle = 26.87^{+0.05}_{-0.07}$, $\sigma = 0.35^{+0.04}_{-0.09}$,

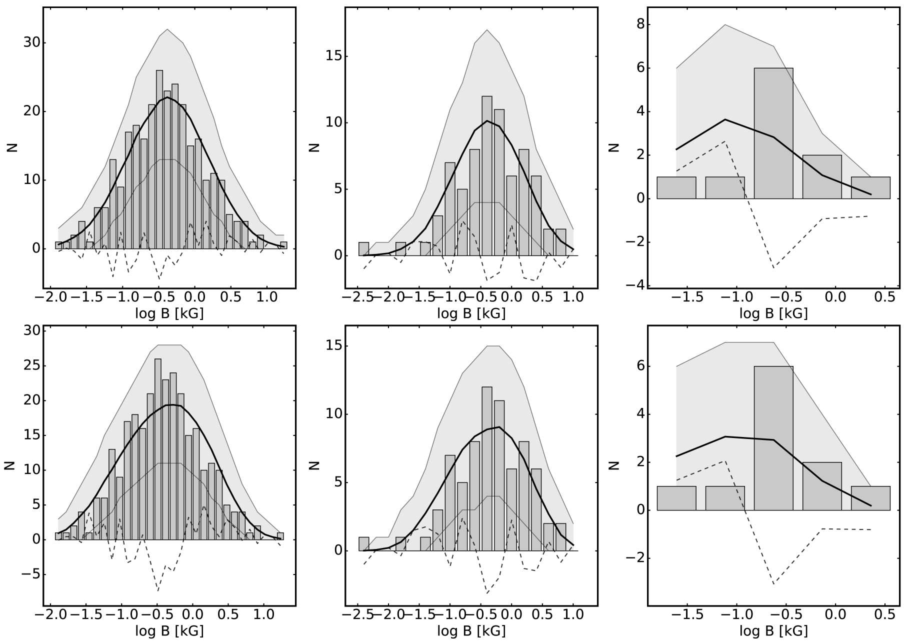

Figure 1. Simultaneous fitting of the magnetic field distributions for BA, OB and O-type stars (from left to right) for the model without dissipation of magnetic fields (*upper panel*) and for the model with dissipation parameter $\tau_{\rm d} = 0.5$ (*lower panel*). The gray histograms represent the empirical data, while the black lines and dashed lines show the mean model distribution and residuals. The gray filled area corresponds to the 95% confidence limits for possible variations.

$C/\mathrm{dof} = 48.3/53$. Our results show that all three empirical distribution of magnetic fields can be fitted with a common magnetic field function.

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References

Arnaud, K. A. 1996, in ASP Conf. Ser., Vol. **101**, *Astronomical Data Analysis Software and Systems V*, ed. G. H. Jacoby & J. Barnes, 17

Bohlender, D. A., Landstreet, J. D., & Thompson, I. B. 1993, *Astron. Astrophys.*, **269**, 355

Bychkov, V. D., Bychkova, L. V., & Madej, J. 2009, *Mon. Not. R. Astron. Soc.*, **394**, 1338

Cash, W. 1979, *Astrophys. J.*, **228**, 939

Donati, J.-F., Babel, J., Harries, T. J., et al. 2002, *Mon. Not. R. Astron. Soc.*, **333**, 55

González, J. F., Hubrig, S., Przybilla, N., et al. 2017, *Mon. Not. R. Astron. Soc.*, **467**, 437

Hubrig, S., Schöller, M., Ilyin, I., et al. 2013, *Astron. Astrophys.*, **551**, A33

Hubrig, S., Schöller, M., Kharchenko, N. V., et al. 2011, *Astron. Astrophys.*, **528**, A151

Humphrey, P. J., Liu, W., & Buote, D. A. 2009, *Astrophys. J.*, **693**, 822

Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, *Mon. Not. R. Astron. Soc.*, **315**, 543

Kaastra, J. S. 2017, *Astron. Astrophys.*, **605**, A51

Kholtygin, A. F., Fabrika, S. N., Drake, N. A., et al. 2010a, *Astronomy Letters*, **36**, 370

Kholtygin, A. F., Fabrika, S. N., Drake, N. A., et al. 2010b, *Kinematics and Physics of Celestial Bodies*, **26**, 181

Kroupa, P. 2002, *Science*, **295**, 82

Landstreet, J. D., Silaj, J., Andretta, V., et al. 2008, *Astron. Astrophys.*, **481**, 465

Medvedev, A. & Kholtygin, A. 2017, in ASP Conf. Ser., Vol. **510**, *Stars: From Collapse to Collapse*, ed. Y. Y. Balega, D. O. Kudryavtsev, I. I. Romanyuk, & I. A. Yakunin, 265

Medvedev, A. S., Kholtygin, A. F., Hubrig, S., et al. 2017, *Astron. Nachr.*, **338**, 910

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

Pelupessy, F. I., van Elteren, A., de Vries, N., et al. 2013, *Astron. Astrophys.*, **557**, A84

Pols, O. R., Schröder, K.-P., Hurley, J. R., Tout, C. A., & Eggleton, P. P. 1998, *Mon. Not. R. Astron. Soc.*, **298**, 525

Schöller, M., Hubrig, S., Fossati, L., et al. 2017, *Astron. Astrophys.*, **599**, A66

Wade, G. A., Grunhut, J., Alecian, E., et al. 2014, in IAU Symp., Vol. **302**, *Magnetic Fields throughout Stellar Evolution*, ed. P. Petit, M. Jardine, & H. C. Spruit, 265–269

Wade, G. A., Neiner, C., Alecian, E., et al. 2016, *Mon. Not. R. Astron. Soc.*, **456**, 2