Statistics of magnetic field measurements in OB stars

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Abstract. We review the measurements of magnetic fields of OB stars and compile a catalog of magnetic OB stars. Based on available data we confirm that magnetic field values are distributed according to a log–normal law with a mean log(B) = 2.53 and a standard deviation σ = 0.54. We also investigate the formation of the magnetic field of OBA stars before the Main Sequence (MS).

1. Introduction

The origin of magnetic fields in massive stars is still poorly known. Many authors argued that magnetic fields could be fossil, or it may be generated by a strong binary interaction in stellar mergers, or during a mass transfer or common envelope evolution. The answers to questions related to the origin and evolution of magnetic fields in massive stars require therefore additional efforts in this field.

2. Statistical Characteristics of Magnetic Fields

As the most convenient characteristic of the stellar magnetic field we use the rms magnetic field

\[ \langle B \rangle = \sqrt{\frac{1}{n} \sum_{k=1}^{n} (B_k^z)^2} \]  \hspace{1cm} (1)

where we sum over all measured values of mean longitudinal magnetic fields \( B_k^z \) for a given star. Here \( k \) is the running number of the individual observation, \( n \) is the total number of observations. Kholtygin et al. (2010) showed that in the case of dipole field configuration the rms field value \( \langle B \rangle \) depends weakly on the rotational phase \( \phi \) of observations, the rotation axis inclination angle \( i \), and the angle \( \beta \) between the rotational axis and the axis of magnetic dipole. This conclusion holds for quadrupole and other field configurations. As a measure of reality of the measured field values we use the
criterion (4) presented by Kholtygin et al. (2010). This criterion is equivalent to the condition that the absolute value of the measured magnetic field $|B_z|$ is 3 or more times larger than the error of the measurements at least for one field measurement.

2.1. Distribution of Magnetic Fields

The analysis of a differential magnetic field distribution $f(\langle B \rangle)$ (the magnetic field function) introduced by Fabrika et al. (1997) is important for understanding the origin of stellar magnetic fields. The function $f(\langle B \rangle)$ is defined as follows:

$$f(\langle B \rangle) \approx \frac{N(\langle B \rangle, \langle B \rangle + \Delta(\langle B \rangle))}{N\Delta(\langle B \rangle)}, \quad (2)$$

where $N(\langle B \rangle, \langle B \rangle + \Delta(\langle B \rangle))$ is the number of stars in the interval $(\langle B \rangle, \langle B \rangle + \Delta(\langle B \rangle))$, $N$ is the total number of stars with real measured $rms$ field $\langle B \rangle$. At present, only for about one dozen of O-type stars the presence of a magnetic field is confirmed using high- and low-resolution spectropolarimetry. For remaining 10 stars the presence of a weak magnetic field is still under debate (Hubrig et al. 2011, 2013).

The calculated by us function $f(\langle B \rangle)$ for all O stars with measured magnetic fields, including data by (Hubrig et al. 2011, 2013) is given in Fig. 1 (left panel) and can be fitted with a power law $f(\langle B \rangle) = A_0 \left(\frac{\langle B \rangle}{\langle B \rangle_{H}}\right)^{\gamma}$, where $A_0 = 0.035$, $\gamma = -2.78$ for $\langle B \rangle > \langle B \rangle^H = 100$ G. The magnetic field function $f(\langle B \rangle)$ for BA stars was also fitted with a power law by Kholygin et al. (2015) for $\langle B \rangle > \langle B \rangle^H = 300$ G. They obtained $A_0 = 0.35 \pm 0.06$, and $\gamma = 2.09 \pm 0.13$. It means that the average magnetic fields of O-type stars are 8 – 9 times weaker than those for BA stars.

At $\langle B \rangle < \langle B \rangle^H$ the magnetic field function greatly reduced relative to the power law. The relatively small number of stars with $\langle B \rangle < \langle B \rangle^H$ was interpreted by Lignières et al. (2014) as an evidence of the magnetic desert in this field region as a result of the bifurcation between stable and unstable large scale magnetic field configurations.

To clarify this issue we calculated the magnetic field distribution function using all suitable data from the catalogue by Bychkov et al. (2009). We fit the magnetic field
distribution by log–normal law instead of a power one. The result of our fit is presented in Fig. 1 (right panel). We do not see the magnetic desert at least for BA stars. The number of measured magnetic fields for O stars is too small to check if the log–normal law is better than the power one for these stars.

Recently Fossati et al. (2015) created the histogram of the distribution of the dipolar magnetic field strength for the magnetic massive stars using their new measurements and did not detect the magnetic desert for intermediate-mass stars. They argued that the relatively weak fields might be more common than currently observed.

3. Magnetic field generation before the Main Sequence

The population synthesis model of the magnetic field evolution for O and BA stars (Medvedev & Kholtygin 2015) showed that the present-day distribution of the magnetic fields of OBA stars can be reproduced assuming that the initial magnetic field distribution at the ZAMS obeys the log–normal law. For the sake of convenience the authors used the magnetic fluxes $F \approx 4\pi \langle B \rangle R_\ast^2$ for stars with known values of $\langle B \rangle$ instead of their magnetic fields. All obtained initial distributions of the magnetic fluxes at ZAMS were also fitted with log–normal law. Recently Medvedev & Kholtygin (2016, this issue) show that parameters of the initial magnetic flux distribution can be chosen the same both for O and BA stars. The mean logarithm of the initial magnetic fluxes at ZAMS for all OBA stars in the model without magnetic field dissipation (model I) is $\bar{F} = 26.45$ with the standard deviation $\sigma = 0.50$, while for model II with a dissipation time $T_d = 1/2T_{MS}$ $\bar{F} = 26.87$ and $\sigma = 0.35$. Here $T_{MS}$ is the star lifetime on the MS.

![Figure 2](image)

Figure 2. Distribution of generated magnetic fluxes for model I (left panel) and model II (right panel) at the ZAMS. Thick dashed lines show the initial magnetic flux distribution in the population synthesis model by Medvedev & Kholtygin (2015). The nature of the log–normal distribution of magnetic fluxes for OB and BA stars is enigmatic. To explain this we can use the main idea by Ferrario et al. (2009) that mergers of protostars might play an important role in the formation of magnetic field of massive stars. Developing this idea, we assume that the magnetic field is not formed in a final merging of the protostars, but in multiple merging events of protostars and planetesimals.

Suppose that there was $N$ cycles of merging before ZAMS and after act $i$ of merging the magnetic flux of star $\langle F \rangle_i = \alpha_i \langle F \rangle_{i-1}$, where $\alpha_i$ is the coefficient of the field
amplification and $\langle F \rangle_{i-1}$ is the stellar magnetic flux at the cycle $i-1$. The amplification coefficients are supposed to be uniformly distributed in the interval $[a, b]$, where $a$ and $b$ are constant. The initial magnetic flux $\langle F \rangle_{i=0} = F_0$ supposed to be identical for all stars. In Fig. 2 we demonstrate the result of our modeling of the magnetic flux distribution at ZAMS. We fixed a value $N = 20$ and fitted the parameters $a$, $b$ and $F_0$ only. The obtained optimal parameters are $a = 1.0$, $b = 2.49$, $F_0 = 7.9 \times 10^{21}$ G cm$^2$ for model I and $a = 1.0$, $b = 1.88$, $F_0 = 7.0 \times 10^{23}$ G cm$^2$ for model II. The total field amplification ratio $F_N/F_0 \approx 3.5 \times 10^4$ and $F_N/F_0 \approx 10^3$ for models I and II respectively.

4. Conclusions

We show that the magnetic filed distribution for early BA-type stars can be described with the log–normal law. This means, in particular, the absence of a magnetic desert at least for early-type stars. From our considerations we can conclude that multiple dynamo action during merging of protostars and planetesimals can be responsible for the generation of magnetic fields before the MS.

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