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Evolution of large-scale magnetic fields of chemically peculiar stars

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Abstract. We studied the magnetic field of chemically peculiar stars in the young Orion OB1 association and in other five older clusters. We have found new evidence of the validity of the relic origin of the magnetic field. In the Orion OB1 association, the magnetic field values and the occurrence frequency of magnetic stars are systematically higher than in older groups. There is no magnetic field generation during the life of a star on the main sequence. The observations were carried out using the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences. We studied the magnetic field of about 80 stars. More than 1000 spectra were obtained with the circular polarization analyzer on the BTA Main Stellar Spectrograph.

Keywords: stars: magnetic field, chemically peculiar

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1 Introduction

Currently, about 600 magnetic chemically peculiar (CP) stars are known. Their physical parameters do not differ from the normal ones of the same spectral classes. The main differences are the presence of a large-scale magnetic field, slower rotation, depressions at the continuum level and anomalies in the chemical abundance of elements.

There are various hypotheses for the large-scale field origin: theories of relict origin, dynamo, "stellar mergers", etc. (Moss 1989; Mestel 2003; Schneider et al. 2019). However, it is still not clear which theory confirms one or another hypothesis of the formation of a magnetic field.

The solution to the problem lies in observing the magnetic field of chemically peculiar stars, constructing and analyzing the dependencies of the field on various parameters, in particular, on age. In most cases, chemically peculiar stars are field objects. Despite the availability of fairly accurate parallaxes from the Gaia and Hipparcos missions, a number of difficulties remain in estimating the physical parameters of these stars. Therefore, by plotting them on the Hertzsprung-Russell diagram, we can only indirectly assess their evolutionary status; the error in age determined in this case will be about 100%. On the other hand, to estimate the age of stars in clusters, one can select the most suitable evolutionary tracks (Bagnulo et al. 2006). Therefore, since 2010, we have been carrying out a comprehensive program of studying the magnetic field of stars—members of open clusters of different ages at the 6-m telescope of the SAO RAS.

2 Magnetic field of stars

2.1 Method of determination

As a result of observations, we obtain only the longitudinal component of the magnetic field averaged over the entire visible surface, which varies with the rotation period of the star. Therefore, the problem arises—what kind of global magnetic field does this star have? Theoretically, this problem can be solved as follows: perform quite a lot of observations in different phases of the rotation period and construct a phase curve of longitudinal field variability, which can then be simulated, and find the magnetic field value at any point on the surface of the star. This approach is quite difficult to implement in practice due to the need to obtain a large number of observations for stars, for which, for the most part, rotation periods are unknown. However, it is worth noting that recently this problem has been actively solved with the help of the Kepler and TESS space missions (Hümmerich et al. 2018). Therefore, to estimate the magnitude of the star's magnetic field, one can use its root-mean-square value $B_{\rm rms}$. To confirm the magnetic field presence in a star, we use the χ^2/n criterion. The star can reliably be considered magnetic at a value of $\chi^2/n > 5$. The field $B_{\rm rms}$, its error $\sigma_{\rm rms}$ and the criterion χ^2/n are calculated using the following formulas:

$$B_{\rm rms} = \left(\frac{1}{n}\sum_{i=1}^{n} B_e i^2\right)^{1/2}, \quad \sigma_{\rm rms} = \left(\frac{1}{n}\sum_{i=1}^{n} \sigma_i^2\right)^{1/2}, \quad \chi^2/n = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{B_e i}{\sigma_i}\right)^2. \qquad (1)$$

The accuracy of our measurements at the MSS depends on the stellar physical parameters, in particular, on its rotation speed and the number of lines in the spectrum. For cold stars with slow rotation, field determination errors usually do not exceed 100 G, and for hot stars with a high rotation speed and a small number of lines, errors can exceed 500 G.

2.2 Magnetic stars in the Orion OB1 association

One of the most studied groups in the solar vicinity is the Orion OB1 association. Inside it, Blaauw (1964) identified four regions: subgroups 1a, 1b, 1c and 1d, which differ in age and stellar composition. Brown et al. (1994) carried out the most detailed analysis of the stellar population of the association, and provided the results of the analysis for 814 stars of spectral types O–F.

Romanyuk et al. (2013) identified 85 chemically peculiar stars in the association and showed that all 23 Am stars from this list are foreground objects and do not belong to the association. Taking into account the conditions above, we selected 56 poorly studied chemically peculiar Ap/Bp stars in the association to search for their magnetic field. For this purpose, more than 600 spectra of association stars were obtained with the circular polarization analyzer (Chountonov 2016) at the BTA Main Stellar Spectrograph (MSS) (Panchuk et al. 2014) in the period 2010–2022.

The results of these studies were published in a number of works (Romanyuk et al. 2019, 2021a,b), which are summarized by the publication Semenko et al. (2022).

South of "Orion's belt", the Great Orion Nebula was observed. Of the 27 CP stars from subgroups 1c and 1d of the association, 15 are members of the Nebula. Of these, only three stars have been found to be magnetic, and 12 (80%) are non-magnetic. On the contrary, of the 12 stars located outside the nebula, 10 stars (83%) are magnetic and only two are non-magnetic. We believe that many of the young stars may be Herbig Ae/Be objects.

2.3 Magnetic field of CP stars in other clusters

Having completed our observations in the Orion OB1 association, we began a program of magnetic star's research in older clusters. At the beginning, we conducted a study in the open cluster Pleiades and in the kinematic group of the same name (Romanyuk et al. 2023b). In the Pleiades, we identified four CP stars, in which we did not detect a magnetic field. We further analyzed three clusters: IC 4756, α Per (Melotte 20) and NGC 7092 (Romanyuk et al. 2023a), and none of the 13 stars show field B_{rms} greater than 1 kG. We presented the conclusions of the analysis of these clusters in more detail in Romanyuk et al. (2024).

In this paper, we present the analysis results of two more open clusters: Melotte 111 (Coma Berenices) and the younger Trumpler 37 ($\log t = 7.05$).

In the open cluster Melotte 111 from the WEBDA database we identified eight candidates for mCP stars. However, as a result of our analysis, a magnetic field was detected in only three of them. The average value of the cluster's magnetic field is less than 500 G.

The age of the open cluster Trumpler 37 corresponds to the subgroup 1a in the Orion OB1 association. The WEBDA database indicates that only seven stars are chemically peculiar from this cluster. Having carried out their spectropolarimetric observations, we discovered that the classification for this cluster in the database turns out to be erroneous: among the seven objects there is not a single chemically peculiar one, all of them have strong emission lines and the absence of a magnetic field.

3 Results

We have summarized all the results obtained from the analysis of CP stars in the Orion OB1 association and other clusters in Table 1 and Fig. 1. The columns of the table indicate the names of the studied cluster and subgroups of the Orion OB1 association, arranged in increasing order of their age $\log t$, which was taken from the WEBDA database, the number of chemically peculiar stars N_{CP} and magnetic CP stars N_{mCP}, mean magnetic field and its error.

We conclude that chemically peculiar stars are not found in all open clusters. The conditions for star formation in different regions of the Galaxy could be different. This is perfectly illustrated by Fig. 1b, which shows the obtained dependence of the magnetic field on age.

Table 1. Results of the average magnetic field measurements of the studied clusters and subgroups of the Orion OB1 association.

Cluster	$\log t$ [yr]	$N_{\rm CP}$	$N_{\rm mCP}$	$\langle B_{\rm rms}\rangle \pm \sigma$ G
Orion OB1b	6.23	15	11	1831 ± 197
Orion OB1c	6.66	24	13	1060 ± 132
Orion OB1a	7.05	14	7	909 ± 197
α Per	7.81	6	1	440 ± 140
Pleiades	8.06	3	1	121 ± 46
NGC 7092	8.41	5	0	0 ± 140
Melotte 111	8.65	8	3	340 ± 60
IC 4756	8.90	2	1	310 ± 140

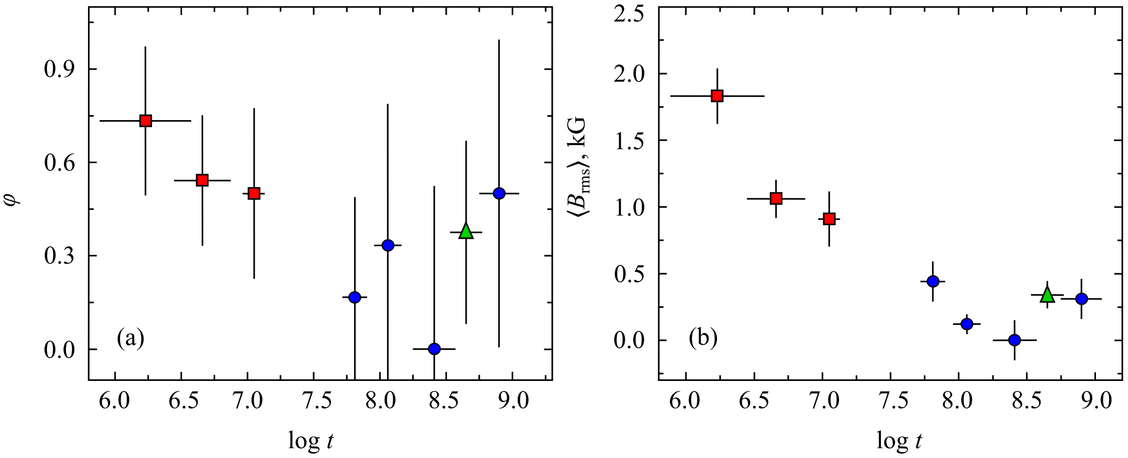

Fig. 1. Dependence of the fraction of magnetic CP stars (a) and the average magnetic field (b) on age. In the figures, red squares show the values of the Orion OB1 subgroups, blue circles show values of characteristics of the clusters α Per, Pleiades, NGC 7092 and IC 4756, green triangle are the values of parameters of the newly studied Melotte 111 cluster.

4 Summary

As a result, we analyzed the magnetic field of 77 chemically peculiar stars that belong to the Orion OB1 association and other older clusters α Per, Pleiades, NGC 7092, Melotte 111 and IC 4756.

For the first time, the magnetic field of 14 stars in the Orion OB1 association was discovered by us. In total, we and our foreign colleagues found 31 magnetic CP stars in the association, which is 55% of all CP stars in it. Noteworthy is the segregation of magnetic CP stars inside and outside the Orion Nebula. To explain this phenomenon, we proposed a new hypothesis: the magnetic field decrease is not caused by its rapid decay, but is the result of the influence of different conditions during its formation in our Galaxy at different times. However, to confirm our results, we need to supplement our studies with clusters and groupings of different ages.

We have shown that the fraction of magnetic stars and the magnitude of the magnetic field of CP stars in the young Orion OB1 association are significantly greater than in five older groups (Fig. 1a). We see that no magnetic field is generated on the main sequence (Fig. 1b). The large-scale field of Ap/Bp stars was formed at the stages of evolution before the main sequence. Chemically peculiar stars are not found in all open star clusters, as demonstrated by the relatively young open cluster Trumpler 37. The Orion OB1 association is likely unique, where special conditions for the formation of magnetic stars have developed.

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