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Review

Studies of Magnetic Chemically Peculiar Stars Using the 6-m Telescope at SAO RAS

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Abstract: We present a survey of the most important results obtained in observations with the 6-m telescope in the studies of magnetic fields of chemically peculiar stars. It is shown that we have found more than 200 new magnetic chemically peculiar stars, which is more than 30% of their total known number. Observations of ultra-slow rotators (stars with rotation periods of years and decades) have shown that there are objects with strong fields among them, several kG in magnitude. In the association of young stars in Orion, it has been found that the occurrence and strength of magnetic fields of chemically peculiar stars decrease sharply with age in the interval from 2 to 10 Myr. These data indicate the fossil nature of magnetic fields of chemically peculiar stars. About 10 magnetic stars were found based on ultra-accurate photometry data obtained from the Kepler and TESS satellites. A new effective method of searching for magnetic stars was developed. In addition, the exact rotation periods make it possible to build reliable curves of the longitudinal field component variability with the phase of the star's rotation period, and hence to create its magnetic model. The survey is dedicated to the memory of Prof. Yuri Nikolaevich Gnedin.

Keywords: magnetic field; chemically peculiar stars; observation

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1. Yuri Gnedin, a Researcher of Stellar Magnetism

Prof. Yuri Nikolaevich Gnedin is a prominent Russian theoretical physicist. In the field of astrophysics, his studies of the polarized radiation transfer in the inhomogeneous environment, the study of objects with a super strong magnetic field, the polarization and magnetic field of quasars and active galaxy nuclei, and the search for axions and other unusual objects are widely known.

From 1993 to 2015, Yuri Gnedin was the Chairman of the Russian Telescope Time Allocation Committee (RTTAC)[1]. The Committee members develop the scientific program of our several largest telescopes. The RTTAC includes the Russian leading astronomers working in various fields.

The author of this paper worked together with Yuri Gnedin for many years as the scientific secretary of the above Committee. As a rule, RTTAC worked twice a year in SAO RAS and the arrival of the Committee members was an event for the astronomers of the observatory. Each time, open sessions were held, during which leading scientists talked about the latest science news, and telescope time applicants reported on their observation programs. Yuri Gnedin regularly made reports on the most important events in science that have taken place in recent years. His open mindedness allowed him to estimate the importance of the already completed works and the prospects for future research.

Research on stellar magnetism was one of the main areas of his activity. We will mention here some of the main studies: Gnedin et al. [1], Gnedin [2], Gnedin et al. [3–5], and others. Yuri Gnedin's scientific interest mainly was in the studies of objects with strong and very strong magnetic fields (including magnetic white dwarfs and polars).

However, he also solved more general problems associated with stellar magnetism. The classical monograph by Dolginov et al. [6] "Propagation and polarization of radiation in cosmic media" discusses the magnetism of stars of different types, and the more recent paper by Gnedin and Silant'ev [7] summarizes the main theories of the light polarization mechanism by cosmic particles.

His colleagues will be able to write about Yuri Gnedin's papers in the field of theoretical astrophysics in more detail. But he obviously made a great contribution to the development of the origin and evolution of stellar magnetic fields theory. Prof. Gnedin has always supported stellar magnetism studies with the 6-m telescope.

Thanks to the efforts of the staff of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS), the 6-m telescope was equipped for measuring stellar magnetic fields which allowed our scientists to carry out observations of various objects and be among the leaders in this field of science.

2. Studies of Magnetic Stars with the 6-m Telescope

2.1. Some General Issues in the Stellar Magnetism Studies

The study of stellar magnetism is one of the most important areas of research in modern observational astrophysics. The world's largest telescopes are equipped with the appropriate instruments for this purpose. The magnetic field is responsible for a variety of outbursts, explosions, and other manifestations of non-stationarity in our Galaxy and beyond. Techniques for measuring magnetic fields in various objects are still imperfect and insufficiently developed. Often, even the world's largest telescopes are not powerful enough to obtain results of the required accuracy. Therefore, our knowledge of stellar magnetic fields is fairly superficial.

As a theoretician, Yuri Gnedin wondered: how can one find observation evidence of the efficiency of some or other mechanisms of the stellar magnetic field formation and evolution? This question is one of the key questions in modern observational astrophysics.

It is well known that the magnetic field of the Sun has a two-component structure: Hale [8] discovered a strong (2 kG) magnetic field in spots; and only after almost half a century, Babcock [9] found its weak (1–2 G) total surface magnetic field. The process of formation, evolution, and dissipation of the local magnetic field of the Sun spots is perfectly observed and explained in detail. Fields in the spots arise due to convective motions of the magnetized plasma in the Solar atmosphere. The duration of one cycle from occurrence to disappearance of a field takes days or weeks [10,11]. It must be assumed that Solar-like and other stars with convective atmospheres have powerful local magnetic fields formed in their atmospheres.

The nature of formation of the stellar global magnetic field is completely different. Obviously, these are not atmospheric phenomena; they are the result of overall processes occurring in the entire star. But if, by analogy with the Sun, they are weak (of about several G), then the accuracy of modern measurement methods is still too low for a detailed study of such a magnetic field. Therefore, to solve the problem of the large-scale magnetic field formation, it is necessary to find such objects, where global, but strong, fields are observed. Fortunately, such objects exist: chemically peculiar (CP) stars. Babcock [12] discovered strong (measured in kG) coherent magnetic fields in these objects, which were measured with a sufficiently good accuracy making it possible to analyze them.

The methods and techniques of measuring stellar magnetic fields stepped forward compared to those of the time, when Babcock worked. But Babcock's basic ideas are relevant to this day. To study the stellar magnetism, he designed a special differential circular polarization analyzer that split the light beam, entering the spectrograph slit, into two circularly polarized components [9]. Using the longitudinal Zeeman effect, Babcock synchronously obtained two spectra with the opposite orientation of circular polarization. The lines in these spectra are shifted relative to each other in proportion to the magnetic field strength and the Lande factor of the line. By measuring several tens of lines on a photographic plate, Babcock found their average shift and calculated the magnetic field longitudinal component B_e averaged over the entire visible surface. The fact that the spectra were registered in the same photographic plate made it possible to remove numerous small instrumental effects and sharply (by an order of magnitude) increased the accuracy of measurements.

Observing the polarized spectra in different phases of the rotation period, it was possible to build the B_e variations with time and build a field model (if it was strong and close to dipole). When working with photographic plates, it was impossible to achieve more. But with the introduction of CCDs, the accuracy of spectrum measurements has increased dramatically; the signal-to-noise ratio has increased typically by 1–2 orders. It became possible to obtain high-accuracy polarized profiles of spectral lines with details corresponding to the spots of chemical abundance. This made it possible to analyze the line profiles and develop methods of the Doppler and then magnetic imaging [13,14] of chemically peculiar stars.

The Mapping Methods

The mapping methods were first used in the study of chemically peculiar stars, but now they have become widespread in the study of other objects. More information on the history and methods of magnetic field measurements can be found in the series of papers by Romanyuk [15–17].

2.2. Magnetic CP-Stars

It turned out that about 10–15% of all A and B stars of the Main Sequence (MS) have anomalous chemical abundance. Anomalies consist in a significant increase of abundances in some of the selected chemical elements heavier than iron and in a weakening of calcium and light elements. But the most prominent increase is observed in the lines of chromium, strontium, and especially rare-earth elements. Chemically peculiar stars have strong stable magnetic fields that have not changed for decades. How the chemical abundance anomalies and the presence of a magnetic field are related is not completely clear. Do all CP stars have a global magnetic field?

Chemically peculiar stars are easily distinguished by their spectra. Antonia Maury first classified them in 1897 when compiling the Henry Drapper (HD) catalog by eye viewing of low-quality (by modern standards) photographic plates. Subsequently, astronomers, using different methods, found new chemically peculiar stars and the most complete catalog of such objects (which currently has over 8000 stars) was compiled by Renson and Manfroid [18].

Surface chemical anomalies are not uniformly located but in the form of spots or rings. This leads to the observed photometric and spectral variability of the star. Brightness and spectral features of such stars vary repeatedly with a period of axial rotation. Having a limited set of observational characteristics, it becomes possible to describe the star within the frame of the oblique rotator model [19].

The existence of CP stars with strong magnetic fields makes it possible, from an observational point of view, to set the task of studying the formation and evolution of the large-scale magnetic field of these and related objects. In fact, there are many options for the formation of magnetic fields in stars, but two of them stand out particularly [20]:

- the fossil theory, according to which no field is currently generated but we observe only the consequences of earlier processes (it does not matter how and when the field appeared) before the arrival of the star on the Main Sequence [21–24];
- different types of the dynamo theory, according to which the generation also occurs during the life of a star on the Main Sequence [25–27];
- merger scenario, there is growing evidence that interaction in binaries or multiple stars plays a role in the generation in magnetic fields [28].

If the field generation on the Main Sequence does not occur, then magnetic fields of young stars should be greater than those of old ones. And if the dynamo mechanism works, then the field strength should depend on the rotation velocity: it should be higher for fast rotators. All observation tests are built based on these principles [20,29].

Attempts to find correlations of the magnetic field strength with age or with the rotation velocity have been made several times before [30–32] and many others. But no reliable results were obtained. Borra [33] found the field weakening with age from the study of magnetic stars in the Orion OB1 association. Other results were obtained in the paper by Thompson et al. [32], in which the magnetic fields of 13 stars in the Sco–Cen association were measured and no differences were found in two samples of stars of different ages.

The reason for this is the relatively low determination accuracy of the field strength and the lack of magnetic stars with known rotation periods, as well as very large errors in determining the age of stars. To begin with, the process of measuring a magnetic field itself is far from an ordinary procedure. In order to perform such work, a large telescope and special spectropolarimetric instruments are needed. Therefore, magnetic measurements are quite rare. The relative accuracy of measurements rarely exceeds 20% which is an obstacle to the detection of the required weak effects. In addition, the measurement method allows one to obtain the data on the longitudinal field component only. To compare the results for different stars, it is necessary: to obtain a series of observations for each object in different phases of the rotation period and to build the phase variability curve of the longitudinal field B_e. And finally, to build a magnetic field model. Only in this case, it is possible to compare the magnetic fields of different objects. The fields are usually compared at the dipole pole B_p. It is an extremely time-consuming task that requires long-term observations to cover the entire rotation period of a star and complex modeling of a magnetic field, since often the magnetic field variations cannot be described by a simple dipole.

The main spectrographs that perform spectropolarimetric measurements in the world are: FORS1/2[2] at the 8-m VLT telescope, HARPSpol[3] at the 3.6 m ESO telescope, the same-type NARVAL[4] at the 2-m Telescope Bernard Lyot and ESPaDOnS[5] at the 3.6-m CFHT, and Main Stellar Spectrograph (MSS[6] at the 6-m BTA.

For our research at the 6-m BTA telescope, the Main Stellar Spectrograph (MSS) [34] with a circular polarization analyzer has been actively used for more than 40 years [35]. The observation and data reduction methods are described, for example, in the papers by Romanyuk et al. [36], Kudryavtsev et al. [37]. The exposure time is chosen so that the signal-to-noise ratio (S/N) in the spectra exceeds 150–200. The main bulk of the spectra covers the 4450–4950 Å wavelength region with the mean resolution R = 15,000. The instrument allows us to observe the stellar magnetic fields of the magnitude $m_\mathrm{V} = 11^m$. In addition to the magnetic field, the circularly polarized spectra obtained with it can be used to measure the radial velocity V_R and the projected rotation velocity $\mathrm{v}_e \sin i$. But the low resolution of MSS does not permit to estimate $\mathrm{v}_e \sin i$ values for slowly rotating stars: $\mathrm{v}_e \sin i < 20$ km s^{-1}. More than 20 thousand spectra were received with this spectrograph.

The FORS1/2 spectropolarimeter with the spectral resolution R = 2000 is very effectively used to search for faint magnetic stars in clusters of different ages [38]. To date, this instrument allows studying the magnetic fields of the weakest objects, up to the magnitude $m_\mathrm{V} = 13^m$, which is a record for permeability. With other telescopes, it is impossible to observe objects weaker than those observed with FORS1/2.

Besides these instruments, magnetic measurements are being carried out at several other observatories in the world (e.g., [39]), but the amount of data obtained with them is much smaller.

In order to obtain high-quality observed data required for building magnetic and chemical maps of the surface of CP stars, it is necessary to obtain a series of high-resolution spectra in different phases of the rotation period. The HARPSpol (R > 100,000), ESPaDOnS, and NARVAL high-resolution spectrographs (R = 65,000) are intended for observing the four Stokes parameters of magnetic stars for measuring very weak magnetic fields of bright stars with an accuracy of about 1 G [40–42]. The results of observations with these spectropolarimeters are successfully used for magnetic mapping not only of chemically peculiar stars but also of other types of objects [43]. Mapping technique requires long and periodic observations to exclude data redundancy for each object. Such job is not possible to realize with the largest telescopes, because of high pressure to their time. So the work can actually be done with moderate-sized telescopes.

Theoretical calculations have shown that the ohmic decay of a field, if there is no field generation on the Main Sequence, occurs very slowly, the decay time is comparable to the lifetime of a star on it [29]. Since a slow decrease in the magnetic field strength with age is assumed, a large number of high-accuracy observations of MS stars of different ages are required to reveal the effect. So far, the field measurement errors are so large that trends cannot be detected.

Another problem is determining the age of stars. For single stars of the galactic field, errors in the age determination can exceed 100% [44,45]. The age of field stars is determined from the evolutionary tracks based on the effective temperature and surface gravity found using the spectra. The initial data, especially for stars with anomalous chemical abundance, are not very reliably determined. This, in turn, results in large errors in determining the age of CP stars. Since both components (the field and the age) are found with large errors, it has not been possible to find any reliable relationship between these values until now.

The problem of determining the age of CP stars was repeatedly analyzed by John Landstreet and he came to the conclusion that the best solution is to carry out observations of stars in clusters of different ages; in this case, the accuracy and reliability increase significantly. The star is assigned the age of the cluster, in which it is located. Of course, the reliability depends on cluster membership, i.e. on the astrometric data. Results of GAIA essentially improved the quality of astrometric data and in many cases, known members were excluded from clusters.

The search for correlations between the field and the rotation velocity, which is expected by the dynamo mechanism, also presents great difficulties. The number of magnetic CP stars with the determined periods and, hence, the rotation velocities, is still insufficient.

Some tendencies (the faster the rotation is, the stronger the field is) are visible, but since fast rotators are mainly young hot stars, it was not possible to finally give preference to any hypothesis [20]. Summarizing the issue (formed 30 years ago) with studies of the evolution of a large-scale magnetic field, we proposed a large program for studying these objects with the 6-m telescope.

Systematic integrated observations were supposed to be carried out in three main directions.

- Searching for new magnetic CP stars. This is necessary because the available sample of stars was not enough for statistical studies.
- Searching for magnetic stars with very long rotation periods and building the variability curves of the longitudinal field component with the rotation period phase. This is necessary to test the assertion that slow rotators cannot have a strong field, according to the dynamo mechanism. Nevertheless, that could have worked at some other stage of the stellar evolution, so it cannot be excluded.
- Performing a large number of measurements of magnetic fields of young and old stars, members of open clusters of different ages. If there is no generation on the Main Sequence, then the fields of young stars should be systematically large.

This program has been running for over 30 years. Of course, our work was not done in isolation from the rest of the world. Astronomers world-wide have received new impressive results that have made it possible to clarify a lot in the evolution theory of the stellar magnetic field. Below, we present an overview of long-term observations at the 6-m telescope with the results obtained at other telescopes and the conclusions, to which they led.

3. Research Results Obtained from Observations at the 6-m BTA Telescope

Measurements of the magnetic field at the BTA have been carried out since 1977, from the very beginning of the telescope scientific programs. The instruments for magnetic field measurements were developed, manufactured, and implemented in observations by the SAO RAS staff: G. A. Chountonov, I. D. Naidenov, and V. G. Shtol under the leadership of Yu. V. Glagolevskij [46].

By the mid-70s of the last century, Babcock had already completed his observations. Significant contribution to understanding the structure of the magnetic field of CP stars was made by Preston. Angel and Landstreet built and implemented Balmer magnetometer, and its team carried out effective studies of magnetic stars. Magnetic fields of white dwarfs [47] were detected; it was found that stars with anomalous helium lines also have large-scale magnetic fields. An overview of normal A and B stars showed the absence of magnetic fields in them. In this context, observations of magnetic fields began at the 6-m telescope in 1977.

3.1. Search for New Magnetic Stars

By the mid-80s of the twentieth century, 126 magnetic chemically peculiar stars were found [48]. This amount was very small for building various statistical dependencies. Therefore, we started a large program at the BTA with the aim of searching for new magnetic CP stars. However, finding new magnetic stars is not easy. The problem is that the spectra of magnetic CP stars do not actually differ from the spectra of non-magnetic such objects. The Zeeman effect with kilo-Gauss fields has too little influence on spectral lines leading to their insignificant broadening invisible in the moderate spectral resolution observations. Experience has shown that the large fraction of chemically peculiar stars has magnetic fields below the limit of detection [49].

Observing all CP stars indiscriminately with a large telescope to search for their magnetic fields is extremely ineffective. We have proposed a new approach to solving this issue. The point is that using not only the chemical abundance anomalies, but also the energy distribution anomalies of CP stars is necessary. Kodaira and Unno [50] found that wide and short depressions are observed in the continuum of CP stars. The strongest of them is located at the wavelength about $\lambda = 5200$ Å which has a depth of up to 5%.

The most successful, in our opinion, photometric measurements were carried out in the mid-band Geneva system. One of the filters of this system was centered on the region $\lambda = 5200$ Å, which made it possible to carry out numerous observations of different stars. The Swiss astronomers Cramer and Maeder [51] found a correlation between the so-called Z parameter of the Geneva photometric system, which characterizes the depression depth, and the magnetic field strength on the surface of CP stars. The reason for the appearance of such a correlation is not entirely clear; most likely, the effect of magnetic amplification of the lines takes place. Observations of about 30 thousand objects were carried out in the seven-color Geneva system [52], the Z parameters are determined for several thousand CP stars.

A similar system, the Δa photometry, was developed at the Vienna observatory. Mid-band special filters were made, one of them was centered at the wavelength $\lambda = 5200$ Å, and the other two were in the continuous spectrum at a distance of about 200 Å from the center of the depression. A large series of observations was carried out by Maitzen et al. [53] in the specified region. The applicability of photometric methods strongly depends on the spectral type of the studied stars.

Using the photometric data, we have selected more than 100 previously unstudied stars with a strong depression in the continuum, believing that the proportion of magnetic stars among them is more typical. The approach proved to be efficient. In the period from 1998 to 2005, we carried out observations of 96 CP stars with a circular polarization analyzer at the 6-m telescope; and magnetic fields were found for 72 of them for the first time [37]. Thus, 75% of the candidates appeared to be actually magnetic stars. The efficiency of our searches has tripled compared to that with the commonly used method. This allowed our group to become leading in the number of magnetic stars found. More than 10 objects turned out to be stars with very strong magnetic fields, the longitudinal component of which was greater than 3 kG [37,54–57].

By about 2010, we have completed observations of all stars with strong depressions. Unfortunately, our list has been completed. At both Geneva and Vienna observatories, mid-band photometric observations were discontinued. We carried out observations of all objects with strong depressions, the data for which were obtained from observations of the mid-band photometry. Nevertheless, we continued to search for new magnetic stars. We proposed other criteria: strong anomalies and variability of helium lines in hot stars, very strong lines of rare-earth elements for cool ones, the presence of periodic photometric variability, etc. The efficiency of these criteria is not so high, the fraction of successful searches for new magnetic stars has decreased; nevertheless, it amounts to 40–50% of all the observed magnetic star candidates.

We discover about 10 new magnetic CP stars every year. The total number of such objects found by us is more than 200, i.e., more than 1/3 [58] of the total number of currently known magnetic stars. The results are published annually in a series of papers; currently the latest paper is by Romanyuk et al. [36].

Of course, our observatory is not the only in the world, in which searches for magnetic stars are carried out. The world largest telescopes were involved in this work. First of all, the very extensive MiMeS survey should be noted, the purpose of which is to search for the magnetic fields of massive stars. More than 500 objects were observed, 35 new magnetic stars were found [59]. For the first time, large-scale magnetic fields have been found in O stars, similar in structure to the fields of A and B stars. It was found that all five known Of?p stars have magnetic fields. The first, unfortunately unsuccessful attempt was made to detect a magnetic field outside of our Galaxy, in the Magellanic clouds [60].

Another program, "B fields in OB stars (BOB)", is in many ways similar to the previous one. With FORS2 and HARPSpol, they carried out carried out observations of about 70 stars and found that the proportion of magnetic stars is 7%, which is in full agreement with the results of the previous studies [61].

From earlier papers, let us note the paper by Bagnulo et al. [38], in which a large number of magnetic stars were found with the FORS1 VLT in open clusters of different ages. Note that the observations with FORS1 were carried out for stars up to magnitude 13, which are extremely weak and unobservable for other telescopes. This made it possible to study magnetic stars features in dozens of open cluster. It should be noted that the new GAIA data revised membership of large number of stars in clusters. Thus, we can see that the new magnetic CP stars were discovered mainly with the 8-m VLT telescope in the southern hemisphere and with the 6-m BTA telescope in the northern one.

Searches for magnetic stars were also carried out with other telescopes but in much smaller volumes. The number of known magnetic CP stars has now exceeded 600 [58], which allows one to carry out a variety of statistical studies. Resumption the mid-band photometric observations in the depression region at $\lambda = 5200$ Å would help us efficiently speed up the search for new magnetic stars. But new possibilities of spectroscopy have appeared.

The paper by Hümmerich et al. [62] reports the identification of chemically peculiar stars based on the LAMOST spectroscopic survey[7]. Candidates were identified by the spectra based on the presence of a depression at $\lambda = 5200$ Å. The GAIA parallaxes were used to analyze the spatial distribution and their properties in the color-magnitude diagram. The final sample by the authors contains 1002 CP stars, most of them are new discoveries: only 59 objects are in the catalogs of peculiar stars. The ages of all the objects range from 100 million to 1 billion years, the masses range from 2 to 3 $M_\odot$. As a result of this study, the sample of the known CP stars in our Galaxy has been significantly increased. Although, the amount of the found magnetic stars is still insufficient to build their spatial distribution in the Galaxy, few of them have yet been found in open clusters of different ages. But it is already clear that the upper limit of the surface field of these objects is about 34 kG.

More than 60 years ago, Babcock [63] found the star HD 215441 with a magnetic field of 34 kG on the surface. Despite all attempts, it was not possible to find a star with a stronger field. Apparently, fields of greater magnitude cannot be generated during the CP star formation. Magnetic stars are observed in all regions of the Galaxy: in open clusters and in a field of up to 1 kpc. There is no reason to believe that they can not exist farther away, just modern technical capabilities do not allow their observations to be carried out.

To date, no particular regions with a great or small number of magnetic stars in the Galaxy have been found.

The next task to be solved is to find out whether there is a connection between the distribution of magnetic stars and their field strengths with the structure of the Galactic magnetic field. For this purpose, it is necessary to continue the search for new magnetic stars especially distant and, therefore, weak.

3.2. CP Stars with Very Long Rotation Periods

Chemically peculiar stars rotate slower than normal ones, as was shown by Preston [64] and was certainly confirmed later. In normal stars without any spectral variability, one can find only the projected rotation velocities on the line of sight using the line broadening due to rotation.

The chemical abundance anomalies of CP stars are located non-uniformly over their surface. When the star rotates, regions with different chemical abundances fall on the line of sight; therefore, the spectral variability is observed. The variability proved to be periodic and undoubtedly associated with the rotation of the star. For many stars, the period of this variability was determined, and hence the actual rotation velocities on its surface, since the radii of the stars are well known.

After the magnetic field was discovered in CP stars, the large-scale measurements of the longitudinal field component B_e began. It turned out that in a number of cases, the periodic variability indicates very long variability periods: months and years. Preston [65], Preston and Wolff [66] noticed this fact for the first time. The spectral and photometric variability with periods of years and decades cannot be detected. Very small variations that last for many years can be masked by observation systematic errors. The only reliable option is to measure the longitudinal field component. It has been found, in this way, that the rotation period of the star γ Equ is very large: more than 70 years [67].

From the point of view of the dynamo theory of generation of the field at the MS should be a dependence: the faster the star rotates, the stronger the field can be generated. Theoretical calculations are complex and their results depend on many unobservable boundary conditions. Therefore, the theory provides an opportunity for verification in observations: it is necessary to carry out observations of fast and slow rotators and compare their magnetic fields. Such studies have been performed repeatedly before, but have not led to reliable definite conclusions. The main reason is that fast rotators are predominantly young hot stars; there are no slow rotators among them. And slow rotators are older cool stars, among which there are no fast rotators. The second reason is that there are still few stars with known rotation periods. The periods found are often erroneous.

In recent years, owing to spacecraft launches, the situation has been improving; however, there is still little data. Yes, in general, a certain trend is visible: the field decrease with the decrease in the rotation velocity, but it is possible that this is a dependence on temperature and age, and not on the parameters of rotation. To solve this problem, we proposed observing the magnetic field of stars with very long rotation periods: years and decades. If a field is found in such stars, then this will contradict the dynamo theory. The rotation energy in this case is too weak to generate a strong magnetic field.

There were assumptions for such a task. Even Babcock [67] found that the longitudinal magnetic field of the cool peculiar star γ Equ varies very slowly with a probable period of about 70 years. Later, dozens of magnetic observations of this object were carried out. A very long rotation period is confirmed [68,69]; however, an interesting phenomenon was found: over time, observations show an increase in the period. Since even one observation cycle of its magnetic field has not been completed yet, it is not clear whether the rotation of the star slows down or whether the B_e variability curve is anharmonic; and until the full cycle is completed, the exact rotation period of γ Equ is unknown.

The recent rotation periods and the literature on the period estimates can be found in the papers by Savanov et al. [68], Bychkov et al. [69]. The star's rotation period is estimated as 95 years; nevertheless, it has a strong magnetic field, the longitudinal component of which exceeds 1 kG. From the split components, due to the Zeeman effect, it was found that the surface field of the star reaches 4 kG [70]. The presence of such a star was a strong argument against the efficiency of the dynamo mechanism in magnetic CP stars. For a long time, this star was the only one with such characteristics. It was necessary to check whether there were more similar objects. More than 20 years ago, we began a program of searches for and further observations of stars with very long rotation periods. We took the works by astronomer Mathys as a basis, in which he was looking for CP stars with split Zeeman components. The results of his many years of studies are summarized in the comprehensive paper by Mathys [28]. Overall, he found 43 stars with split Zeeman components. This phenomenon can be observed only in stars with a strong magnetic field and very narrow lines in the spectra: the projected rotation velocity on the line of sight $v_e \sin i$ (does not exceed 10 km s^{-1}). Very narrow lines mean either a small value of $\sin i$ (the rotation pole is facing the observer) or very slow rotation.

We have carried out observations of about 15 stars with narrow lines from the lists of the paper by Wade et al. [71]. Among them, three stars with very long rotation periods were discovered. We have carried out observations covering the whole rotation cycle with a period phase. For two more stars, the observations continue. Another star, γ Equ, has been observed for over 70 years all over the world, but the full rotation period has not yet been obtained.

Long-term observations were required to build the variability curve of the longitudinal field component B_e with the phase of the rotation period. The presence of such a phase curve, along with the data on the surface magnetic field obtained from the split Zeeman components, allows one to obtain the data necessary for building a stellar magnetic field model.

We carried out observations with a rotation period phase for three stars, each of which has the longitudinal field component greater than 1 kG. For HD 18078, a rotation period of 1358 days was found. The geometric structure of its magnetic field is in agreement with the first-order collinear model; the dipole axis does not pass through the center of the star. The phase curve of the longitudinal component field B_e is strongly anharmonic which indicates an unusual magnetic structure (for more detail, see the paper by Mathys et al. [72]).

The next star, HD 50169, has been observed in various observatories for 30 years starting with the paper by Babcock [73]. The longitudinal field component was measured with the 6-m telescope; the modulus of the magnetic field from the split Zeeman components was determined at ESO. We found that the rotation period of the star is 29 years. This is the star with the longest period, the observations of which lasted more than one rotation period. In this star, the magnetic field is not symmetrical according to the axis passing through the center of the star [74].

The magnetic field of the chemically peculiar star HD 965 was discovered by us [75]. Further magnetic monitoring showed that the star is a very slow rotator [76]. The results of the HD 965 study are presented in the paper by Mathys et al. [77]. The rotation period of the star is shown to be 16.5 years. The magnetic field is symmetrical to the axis passing through the center of the star. It is well represented as a superposition of collinear dipole, quadrupole, and octupole.

In addition to these three stars, we are measuring two more with very long rotation periods, but it is necessary to carry out observations in all phases in order to build the curve. Recently, Mathys et al. [78] published the results of a study of the rapidly oscillating roAp star HD 166473, whose rotation period is 10.5 years. In all these cases, a magnetic field is observed, the longitudinal component of which exceeds 1 kG. All the objects are cool magnetic stars with effective temperatures of about 7000–8000 K [79]. At least some of them (γ Equ [80], HD 166473) exhibit fast brightness and spectrum oscillations.

We can see that the presence of ultra-slow rotators is a rare phenomenon but not accidental. The fact that we observe exactly ultra-slow rotation and not a cyclic process (like the Solar 11-yr cycle) has been proven repeatedly, for example, in the paper by Mathys [28].

The obtained data indicate that the reference system of magnetic measurements is stable: the data obtained with different telescopes, spectrographs, and using detectors of different types do not lead to principal differences in the data obtained from observations. The standard system of magnetic measurements in SAO is stable for decades and corresponds to the international one.

Available data unambiguously indicate that the generation mechanism cannot create a strong field with such slow rotation: several degrees per year for γ Equ. Thus, the hypothesis of the fossil magnetic field formation receives new weighty evidence.

3.3. Magnetic Fields of Stars in the Association in Orion

Another direction of research, that is actively developing at the 6-m telescope, is observations of chemically peculiar stars in open clusters of different ages. We have selected 17 clusters ranging in age from several million to hundreds of millions of years, of which at least three CP stars are the members. The program implies the magnetic field measurements of about 200 stars, the members of these clusters, in order to study the dependences of the field strength on age. We have completed the observations and analyzed the data obtained for the Orion OB1 association.

In the Orion constellation, at a distance of about 400 pc, there is one of the most famous groups of early-type stars: the Orion OB1 association. The structure of the association is very complex, it consists of various star clusters, gaseous and dust nebulae. Millions of different objects were discovered in it: maser sources, protostars of the τ Tau and Ae/Be Herbig type, OBA stars of the Main Sequence, various emission objects, etc.

Blaauw [81] made the first attempt to analyze the association structure and identified four subgroups: 1a, 1b, 1c, and 1d which differed in age and stellar composition. Subgroup 1a belongs to the northern region of the association, subgroup 1b is the Orion's belt, 1c is the region south of the Orion's belt, and 1d is a very compact area in the center of the association within subgroup 1c.

3.3.1. CP Stars in the Association

The most complete catalog of the association's stellar population is presented in the paper by Brown et al. [82]; it has 814 objects. The number of A and B stars in it is approximately the same (about half) and there is a small number of O stars.

Using various literary sources, in particular the catalog by Renson and Manfroid [18], we selected 85 chemically peculiar stars in the association. We can see that the proportion of such objects in it is 10.4% and corresponds to the average for the whole sample of chemically peculiar stars. Learn more about the star selection from the paper by Romanyuk et al. [83].

The bulk of the selected objects are B stars with strong or weak (in comparison with the Solar abundance) helium lines, with strong silicon lines, as well as early A stars with strong lines of metals and rare-earth elements. The paper by Brown et al. [82] was published before the publication of the results of the HIPPARCOS mission, so we decided check the belonging of objects to the association using parallaxes. The average distance to it is about 400 pc. Using the parallaxes of the HIPPARCOS and GAIA missions, we found that the 23 coolest peculiar stars with strong metal lines do not belong to the association, they are foreground objects and are located at distances from 100 to 300 pc. Thus, for observations with the 6-m telescope, we have selected 62 potentially magnetic chemically peculiar stars.

The association in Orion includes a large number of stars with anomalous helium lines. The researchers could not disregard this fact. Borra and Landstreet [30] first discovered several magnetic stars among objects with strong helium lines in the association. Borra [33] found magnetic braking and magnetic field decay; the evidence was obtained from observations of stars in the association. Based on observations of 13 chemically peculiar stars in the association in Orion, he found that magnetic stars in Orion have magnetic fields stronger than older stars by a factor of the order of three. He found a short decay time (about 100 million years), which he explained by the movements of masses inside the star. But in the paper by Thompson et al. [32], based on studies of magnetic stars in another young association, Sco–Cen, no significant differences were found in the magnetic field strength of young and old stars. Thus, it is unclear whether a rapid decrease of the field strength with age is characteristic only of the association in Orion, or there are some systematic errors in these studies.

Note that both results were obtained with the Balmer magnetometer [47]; classical spectropolarimetry using metal lines was not performed. In any case, these results turned out to be too small in number to solve the problem of the origin of the strong large-scale field and anomalies in the chemical abundance of CP stars. Therefore, we decided to carry out a large-scale program to search for and study magnetic fields in the Orion OB1 association.

3.3.2. Magnetic CP Stars in the Association

The first question that arises concerns the completeness of the sample of chemically peculiar stars in the association. The average distance to it is about 400 pc, which corresponds to the distance module $|V - M_{\rm V}| \sim 8^m$ magnitudes. In the association, the vast majority are B stars with the absolute magnitude $M_{\rm V} = -3\ldots0$ and only three are early A stars. Even taking into account the interstellar and circumstellar extinction, they are all brighter than $m_{\rm V} > 10$ magnitude. Such bright objects are well studied, presented in different catalogs, and the omission of some peculiar star is unlikely. Therefore, we consider the completeness of the sample to be sufficient.

We decided to perform a magnetic survey of all 62 potentially magnetic CP stars in the association. The observations were carried out between 2013 and 2021. The observation results and analysis by subgroups are published in the papers by Romanyuk et al. [84–86]. They present the results of measurements of each CP star in the association subgroups, and describe in detail the methods of observation, data reduction, and analysis. An important feature that should be taken into account is that in most cases only the longitudinal component of the field $B_{\rm e}$ can be obtained in observations averaged over the whole visible surface of the star. In order to estimate the actual field strength in some region on the stellar surface, simulation is required, which cannot be carried out without knowing the rotation period. Therefore, it was decided to use the root-mean-square magnetic field and use χ^2/n (see Romanyuk et al. [85], section: Comments on Individual Stars, formulas 1, 2, 3).

Based on the results of the analysis of the association CP stars, it has been found that the root-mean-square magnetic fields in subgroups 1a and 1c are on average the same, but the reliability of identifying the magnetic stars in subgroup 1c is much higher. And in the Orion's belt in the young 1b subgroup, the magnetic field is almost three times stronger (see Table 1).

Table 1. Root-mean-square fields of magnetic stars in different subgroups of the Orion OB1 association.

Subgroup	**log t**	**$\langle B_{\rm e} \rangle$, G**	**σ, G**	**χ^2/n**
1a	7.0	1286	229	29.8
1b	6.2	3014	212	266.6
1c	6.6	1074	145	92.5

It was also found that the proportion of CP stars in the association relative to all A and B stars drops sharply with age. The youngest 1d subgroup is a separate issue; it contains only three CP stars [87]. It is possible that all these objects are Ae/Be Herbig stars. From one-dimensional spectra, it is difficult to distinguish the indicated objects with the H_α emission from a hot star simply located in the nebula, and emission in H_α is not a signature of a star but the radiation of the nebula itself. To solve this problem, additional high-resolution observations are needed in the H_α region.

We found that the magnetic fields of stars in the Orion's belt (subgroup 1b) are about three times stronger than those in the older 1a and 1c subgroups [86]. The result is consistent with that obtained by Borra [33]. Thus, not only the proportion of magnetic stars in the youngest part of the association, the Orion's Belt, but also the field strength in it is significantly higher than those in other parts of the association. We also note that, contrary to our expectations, the strongest magnetic field for the Orion OB1 association stars is observed not in its center, in the star formation regions, but on its periphery. Two stars with the strongest fields, HD 34736 and HD 37776, are on the periphery. In the Orion Nebula, in the star formation center, there is only one magnetic star HD 37017 with a strong field, the longitudinal component of which is 2 kG.

While working on the magnetic survey of the association, we noticed that among the peculiar stars included in the catalog by Parenago [88], there were very few magnetic stars. The catalog contains the stars from the Great Orion Nebula, all are in subgroups 1c and 1d of the association. One can expect that in the regions with high polarization and circumstellar extinction, in which star formation is apparently taking place, stars with the strongest magnetic fields could be found. However, the situation is exactly the opposite: 12 out of 24 stars of subgroup 1c are included in the Orion Nebula, 3 of them are magnetic and 9 are non-magnetic; 3 CP stars of subgroup 1d are included in the Orion Nebula, and none of them has a strong field. Since there are only 13 magnetic stars in subgroup 1c, it turns out that outside the Nebula we have 9 magnetic and 2 non-magnetic stars. And magnetic stars form in the regions with weak linear polarization and extinction (Romanyuk et al. [86]).

One way or another, we obtain the data about the reliable difference in the magnetic properties of stars inside and outside the Orion Nebula. The proportion of magnetic stars in the nebula is four times smaller and the average magnetic field is two times weaker than those of objects outside it.

By the mid-80s of the last century, mono-channel digital instruments were actively introduced in observations: first reticons and then CCDs. This made it possible not only to study a stellar magnetic field as a whole but also to analyze the polarized profiles of metal lines and, thus, the stellar magnetic field structure.

The paper by Thompson and Landstreet [89] was one of the first, in which they report the discovery of a very strong quadrupole field of the star HD 37776 with anomalously strong helium lines. Subsequently, this star was repeatedly studied and a strong complex field was confirmed. Here, let us note the analysis performed by Khokhlova et al. [90] based on the data obtained from long-term (about 15 years) observations at the 6-m telescope using the Doppler–Zeeman imaging method. A new analysis of the magnetic field structure of the star based on our observations was published in the paper by Kochukhov et al. [91], which also contains the distribution maps of some chemical elements over the surface of the star.

Within the MiMeS project, a new magnetosphere model of the rapidly rotating star σ Ori E was built [92]. The high spectral resolution observations were carried out with the NARVAL and ESPaDOnS spectropolarimeters. The field model built shows significant differences from a simple dipole configuration. Bohlender and Landstreet [93] performed observations and built a field model of the star δ Ori C with strong helium lines.

A total of 31 magnetic stars have been found in the association in Orion. However, the variability curves of the longitudinal component with the rotation period phase were obtained only for the following 25 objects (see Table 2).

For these stars, the rotation periods and fundamental parameters were found and magnetic models were built. Therefore, the Orion OB1 association already has more or less reliable data for making generalization.

Table 2. List of objects, for which the phase curve of the magnetic field variability is built in the Orion OB1 association.

Star	Citation
HD 34736	Semenko et al. [94]
HD 34859	Romanyuk et al. [84]
HD 35177	Romanyuk et al. [84]
HD 35298	Yakunin [95]
HD 35456	Romanyuk et al. [96]
HD 35502	Sikora et al. [97]
HD 36313	Borra [33], Romanyuk et al. [85,96]
HD 36485	Romanyuk et al. [85], Bohlender et al. [98], Yakunin et al. [99]
HD 36526	Borra [33], Romanyuk et al. [96]
HD 36668	Borra [33], Romanyuk et al. [85,100]
HD 36916	Romanyuk et al. [86,100]
HD 36955	Romanyuk et al. [85]
HD 36997	Romanyuk et al. [86]
HD 37017	Borra and Landstreet [30], Bohlender et al. [101]
HD 37058	Romanyuk et al. [86]
HD 37140	Romanyuk et al. [86]
HD 37333	Romanyuk et al. [85]
HD 37479	Bohlender et al. [101]
HD 37633	Romanyuk et al. [85]
HD 37687	Romanyuk et al. [86]
HD 37776	Thompson and Landstreet [89], Kochukhov et al. [91], Romanyuk et al. [102]
HD 40146	Romanyuk et al. [85]
HD 40759	Romanyuk et al. [86]
HD 290665	Romanyuk et al. [85]
HD 294046	Romanyuk et al. [84]

3.4. Mapping the Surface of CP Stars

As we wrote above, after the introduction of CCDs in observations, which allowed obtaining high-accuracy spectroscopic data, methods for analyzing spotted stars using the Doppler–Zeeman imaging methods were developed. Since our data were obtained at the 6-m telescope with a moderate-resolution spectrograph, it can be used for mapping only the stars with very strong magnetic fields, for example, HD 37776. Since new results have been obtained in the analysis with mapping methods, we present here a brief overview of the most important papers in this direction.

The pioneer papers belong to Khokhlova [13], Khokhlova et al. [90], where the main ideas of using methods to solve the inverse problem for reconstructing the maps of the chemical element distribution over the stellar surface using the spectral line profiles are presented. Further, Piskunov and Khokhlova [14] developed the Zeeman–Doppler imaging methods. Piskunov and Wehlau [103] showed that, when a very high S/N ratio is obtained, the stellar surface mapping can also be performed using the moderate-resolution spectra.

Significant contribution to the development of spectroscopy and spectropolarimetry was the creation of the Vienna Atomic Line Data Base (VALD[8]) [104]. This made it possible to unify the analyses performed by different groups of researchers. The further development of the "Spectroscopy made easy" software package by Piskunov et al. [105] made it possible to significantly speed up the estimation of the physical parameters of stars using the method of atmospheric models.

The papers by Piskunov and Kochukhov [106], Kochukhov and Piskunov [107] outline the basic principles of mapping used by the authors. It is shown that calculations require using a cluster of parallel computers. As examples, we present several papers, in which the Doppler–Zeeman imaging of different magnetic CP stars was performed.

In the paper by Kochukhov et al. [108], mapping of the field and distribution of elements over the surface of the star α^2 CVn was fulfilled. It was found that the magnetic field of the star is dominated by the dipole component with small contribution from the quadrupole component. The distribution of elements over the surface is related to the configuration of the magnetic field. Despite critics by Stift and Leone [109], Zeeman-Doppler Imaging (ZDI) remains to be the main method of surface mapping in the case of magnetic CP stars. In the paper by Kochukhov et al. [110], mapping field of 53 Cam based on the results of observations of 4 Stokes parameters is performed. The magnetic field of the star is found to be complex and cannot be described by low-order multi polar expansion. The distributions of spots of some chemical elements over the stellar surface were reconstructed. The paper by Kochukhov et al. [91] presented mapping of magnetic field and some chemical elements of the star HD 37776 with an extremely complex and strong magnetic field. New results were obtained when modeling 4 Stokes parameters. The basic principles and application to specific stars are presented in the paper by Silvester et al. [111].

At the end of the section, let us mention a paper by Yakunin et al. [112] on magnetic and chemical mapping of the star HD 184927 with anomalous helium lines. The fundamental parameters of the star were found, the maps of the distribution of chemical elements and magnetic field were built.

The magnetic and chemical mapping requires a large number of high-accuracy observations with the rotation period phase of the star under study. Therefore, for each object under study, as a rule, maps are built once with very rare exceptions. For the most famous star α^2 CVn, the maps were built several times. However, the accuracy of earlier maps is significantly worse than that of modern ones. Therefore, it is impossible to assess whether there is a measurement of the field structure or the migration of chemical abundance spots over the surface. Most likely there is no migration, because the brightness variability curve of, e.g., α^2 CVn has been perfectly described by the Farnsworth [113] ephemerides for 90 years.

3.5. High-Accuracy Photometry and Variability Searches

Photometric studies are much more common than spectroscopic and magnetic studies. This is mainly due to the greater availability of instruments: it is much easier to build a photometer than a spectrograph, and there is also no need to observe stars with large telescopes. The photometric studies are less informative than spectroscopic ones; however, high-accuracy photometry makes it possible to study the weak variability typical of chemically peculiar stars. The light curves can be used to determine whether the spots of certain chemical elements are hot or cold.

Very slow rotation period variations were found for a number of stars. For the repeatedly mentioned star HD 37776, Mikulášek et al. [114], found that the increase in the rotation period was equal to 18 s over 31 years of observations. In the paper, the data of magnetic observations at the 6-m telescope were used. Soon the second such star HR 7355 was found [115]. New data showed that the rotation period of HD 37776 peaked in 2003 and then began to shorten [116]. The authors explain the phenomenon by the presence of a magnetic outer shell.

Paunzen et al. [117] found the first brightest spotted CP stars in Large Magellanic Cloud (LMC).

A new epoch in the photometry of CP stars began after the successful Kepler, MOST, ASAS, and especially TESS missions. Here, we will not describe many new results obtained from these satellites. Let us turn our attention only to the studies carried out under cooperative agreement with magnetic measurements at the 6-m telescope. In the paper by Mikulášek et al. [118], two variable chemically peculiar stars are studied based on the MOST and Kepler photometry. From the spectra obtained with the 6-m telescope, both were found to be magnetic.

In the fields of the Kepler satellite, (in the paper by Hümmerich et al. [119]) many variable stars have been found, whose light curves resemble those for CP stars. As a result, a sample of 41 stars was obtained, in which the chemical peculiarity was confirmed; 39 stars are new CP stars. The authors consider the stability of the light curve to be the main criterion for selecting CP stars among many thousands of targets.

The paper by Romanyuk et al. [120] presents the results of measurements of the magnetic field of 8 CP stars and one candidate from the Kepler field obtained with the spectropolarimeter of the 6-m telescope. A strong magnetic field has been found in 5 stars, the status of 3 stars is not yet quite clear: additional observations are needed.

The data obtained with the TESS mission intended to search for exoplanets are of particular interest. The MOBSTER collaboration was created to study the variability of massive magnetic stars and intermediate-mass stars using the high-accuracy photometry data from this satellite. David-Uraz et al. [121] presented the first results of studies of magnetic OBA stars carried out by the MOBSTER collaboration. Observations of 19 already known magnetic OBA stars were carried out in sectors 1 and 2 of the TESS mission. The authors determined the exact periods from the newly obtained light curves and compared them with the previously published ones. The advantages of using high-accuracy TESS data were demonstrated. Mathys et al. [122] found long-period CP candidates based on the TESS data. The authors have found 60 such objects in the southern hemisphere, 31 of which are already known to have a long rotation period, and 23 are new discoveries. In the paper by Mikulášek et al. [116], new results obtained for the unique star HD 37776 are discussed. Very high-accuracy data from the TESS satellite showed that the light curve is difficult to reproduce using a standard model with chemical photometric spots and solid-body rotation. It seems that HD 37776 is a unique target among magnetic chemically peculiar stars with no analogs yet found.

4. Conclusions

We demonstrate that the 6-m telescope has been carrying out intense observations of stars of different types for the last 40 years. In this survey, we consider only magnetic chemically peculiar stars.

We have found over 200 new magnetic CP stars. Together with the data obtained in other observatories, there is currently the material on more than 600 such objects. This allowed one to significantly expand the understanding of the magnetic field strength of chemically peculiar stars, their spatial distribution in the Galaxy, in the field, and in open clusters of different ages.

It was found that, starting with a field of approximately 1 kG, the number of magnetic stars decreases with the field increase according to a log-normal law [123]. The upper limit of the field is about 34 kG. The lower limit depends on the determination accuracy and on the instruments and technique used.

Studies of several stars with very long rotation periods have shown that some of them have strong magnetic fields, the longitudinal component of which exceeds 1 kG. For three objects, the phase curves of the longitudinal field component variability were obtained covering more than one rotation period of the star. Therefore, ultra-slow rotation was reliably confirmed. This result is consistent with the theory of the fossil magnetic field of CP stars, which states that the field was generated before the exit of the stars on the Main Sequence.

At the 6-m telescope, extensive observed material was collected on the peculiar stars of the Orion OB1 association: more than 600 moderate-resolution spectra were obtained with a circular polarization analyzer. New important, mainly unexpected, results have been received. We have found that the total number of chemically peculiar stars with strong fields reaches 31, which is 55% of the total number of chemically peculiar stars in the association, which is 2 times greater than usual for the whole sample of these objects. A sharp decrease of the proportion of chemically peculiar stars in the association was found in the age interval from 2 million to 10 million years, as well as a significant decrease in the field strength with age was found. We also observe a sharp fall in the proportion of magnetic stars in the Orion Nebula. However, no strong magnetic field was found in the association for the youngest objects with an age of smaller than 1 million years. It is obvious that the formation of large-scale magnetic fields of chemically peculiar stars occurs in a complex manner. On the whole, our data support the theory of the fossil magnetic field formation in these objects, but the speed of field decay turned out to be unexpectedly large.

We performed a cycle of magnetic observations of stars, photometry of which was carried out at the Kepler and TESS satellites. About 10 new magnetic stars were found. Their phase curves of the longitudinal component variability with the rotation period were built.

Of course, we conduct our research in broad cooperation with scientists from different countries. The conclusions presented here are not only ours. We publish them regularly, the results are widely discussed at Russian and international conferences. Therefore, we believe that the observation results obtained with the 6-m telescope make significant contribution to solving the issue of the origin and evolution of stellar magnetic fields.

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Data Availability Statement: The data supporting reported results about Orion OB1 association can be found at VIZIER database: subgroup 1a (accessed on 25 October 2021): https://cdsarc.cds.unistra.fr/viz-bin/cat/J/other/AstBu/74.55; subgroup 1b (accessed on 25 October 2021): https://cdsarc.cds.unistra.fr/viz-bin/cat/J/other/AstBu/76.39; subgroup 1c, 1d (accessed on 25 October 2021): https://cdsarc.cds.unistra.fr/viz-bin/cat/J/other/AstBu/76.163.

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Abbreviations

The following abbreviations are used in this manuscript:

RTTAC	Russian Telescope Time Allocation Committee
SAO RAS	Special Astrophysical Observatory of the Russian Academy of Sciences
BTA	Big Telescope Alt-azimuthal
FORS	FOcal Reducer and low dispersion Spectrograph
VLT	Very Large Telescope
ESPaDOnS	Echelle SpectroPolarimetric Device for the Observation of Stars
MSS	Main Stellar Spectrograph
TESS	Transiting Exoplanet Survey Satellite
MS	Main Sequence
HD catalog	Henry Drapper Catalogue
CP star	Chemically peculiar star
HIPPARCOS	High Precision Parallax Collecting Satellite
HARPSpol	High Accuracy Radial velocity Planet Searcher
LAMOST	The Large Sky Area Multi-Object Fiber Spectroscopic Telescope
GAIA	Global Astrometric Interferometer for Astrophysics
MOBSTER	Magnetic OBA Stars with TESS:probing their Evolutionary and Rotational properties

Notes

[1] The Committee website (accessed on 25 October 2021): https://www.sao.ru/hq/Komitet/about-en.html.

[2] The FORS1/2 WEB-page (accessed on 25 October 2021): https://www.eso.org/sci/facilities/paranal/instruments/fors.html.

[3] The HARPSpol WEB-page (accessed on 25 October 2021): https://www.eso.org/public/teles-instr/lasilla/36/harps/.

[4] The NARVAL WEB-page (accessed on 25 October 2021): https://tbl.omp.eu/platform/.

[5] The ESPaDOnS WEB-page (accessed on 25 October 2021): https://www.cfht.hawaii.edu/Instruments/Spectroscopy/ESPADONS/.

[6] The MSS WEB-page (accessed on 25 October 2021): https://www.sao.ru/hq/lizm/mss/en/index.html.

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