COMPREHENSIVE STUDIES OF MAGNETIC CP STARS IN SHAMAKHY ASTROPHYSICAL OBSERVATORY

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1. Introduction.

In the sixties of the twentieth century, important discoveries were made in astronomy: quasars, pulsars, and supernovae of our galaxy were discovered. As it has already become known, the magnetic field plays a particularly important role in the formation and evolution of these interesting objects and the universe in general. It is known that the magnetic field in the universe to one degree or another determines many physical processes, or plays a noticeable role in the formation of objects that make up the universe. By this time, a number of stars with strong magnetic fields were discovered. Strong magnetic fields in stars (Be≥200 G) were first measured by Babcock in 1947 using the Zeeman Effect. Stars with a strong common magnetic field have a number of interesting features, the most surprising of which are strong anomalies in the chemical composition of the atmospheres of these stars. Subsequently, such stars were called magnetic chemically peculiar (MCP) stars. This article focuses on these very stars, the study of which has become one of the priority areas of astrophysics in the second half of the twentieth century.

The commissioning of the 2-meter ShAO telescope (1966) and the Coude focus in 1969 (spectrographs with a dispersion of 4-8 Å/mm) made it possible to expand the range of tasks in the field of astronomy. The Cassegrain focus of the 2-meter telescope was mainly used to study faint brightness of variable stars and galaxies. And in the Coude focus, with the help of a high-resolution spectrograph, observations of supergiant stars, solar-type stars, magnetic stars, planets and other objects were started.

Since 1969, at the proposal of the Chairman of the Astronomical Council of the USSR Academy of Sciences, Academician E.R. Mustel’s topic included ShAO topics on the study of magnetic stars in 1970-1979 formed the basis of the Coude focus observational program of the 2-meter ShAO telescope. To conduct comprehensive research of magnetic stars in 1970, at the initiative and proposal of the leaders of the Astronomical Council of the USSR Academy of Sciences, E.R. Mustel and A.G. Masevich’s consent was obtained for the establishment of an observational station at the Central Institute of Astronomy of the Academy of Sciences of the GDR (TsIA AN GDR) in the ShAO. A 35 cm photoelectric telescope was installed on the territory of ShAO to conduct parallel observations of magnetic stars in 10 colours (λλ 3400-8000 Å). An agreement was signed on cooperation between the Academies of Sciences of the USSR and the German Democratic Republic in the field of research of magnetic stars. Thus, the program for the spectroscopic and photometric studies of magnetic AR- stars begins, which is carried out at the Shamakhy Astrophysical Observatory in cooperation with the Central Institute of Astronomy of the Academy of Sciences of the GDR and the Astronomical Council of the USSR Academy of Sciences. In July 1973, a meeting was held on the physics of magnetic AR stars, and in June 1976, on the physics of magnetic stars, Subcommission No. 4 of the problem commission “Physics and Evolution of Stars” of multilateral cooperation of the academies of sciences of socialist countries summed up the ongoing research on this topic.

Complex (spectral, photometric and magnetic) studies of magnetic chemically peculiar (MCP) stars conducted in the ShAO can historically be divided into two periods: 1. 1969-1998, 1998-2019. Below are some of the most important results of research on MCP - stars obtained at different stages of research.

2. Organization of work and used devices for the study of magnetic stars

In 1967-69 the observations of two magnetic stars α And and π Boo were started on telescopes of the Crimean Astrophysical Observatory (ZTSh and AZT-11 KrAO) by S.G. Aliyev together with V.L. Khokhlova (Senior Researcher, Astrosoviet of the Academy of Sciences of the USSR) [1].

The first observations of magnetic stars in the ShAO corresponded to the summer of 1969. A large number of high-quality spectrograms of the stars HD 19832 (56 Ari) and HD 220825 (χ Psc) were obtained this season. The observations were carried out in the Coude focus of a 2-meter telescope, on III camera of a diffraction spectrograph (dispersion 4 Å/mm). The excellent image quality (0.7 seconds) and the high quality of the telescope optics made it possible to obtain the spectra of the studied objects with an exposure of 20–30 min [2].

To carry out the cooperative program, a working group for the study of magnetic stars is organized in the ShAO, which includes the following ShAO employees: Aslanov I.A. (leader), Aliev S.G., Glushenko L.O., Rustamov Y.S., Khalilov V.M., Shakirzade A.A. etc. A joint program of observations and studies of magnetic stars of various types (Table 1), and their comparison stars, is being compiled.

Since 1970, a large number of MCP spectra of stars have been obtained by the working group [2]. listed in table 1, evenly covering their estimated periods of rotation. For joint research, part of the obtained spectral material for AR stars (HD19832, HD34452, HD65339, HD140160) was presented to the Astronomical Council of the USSR Academy of Sciences (V. Khokhlova and others.), To the Autonomous Okrug of the USSR Academy of Sciences (Yu.V. Glagolevsky) and to the Astronomical Observatory of the Bulgarian Academy of Sciences (D. Kolev).

A large amount of the obtained spectral material required automation of the processing of spectrograms. This problem was partially solved by the programs developed at that time for automatic processing of spectrograms using a computer (BESM-4) by employees of the ShAO and the Astrosovet of the USSR Academy of Sciences [3,4].

To automate the processing processes in the workshops of ShAO, a three-channel two-beam microphotometer was manufactured, which significantly reduced the processing time of spectrograms [5].

In parallel with spectral observations, the TsIA AN GDR conducted 10 colour photometric observations using a 35cm photometric telescope. Using these observations, we studied changes in brightness and colour in the wavelength range $\lambda\lambda$3400-8000 Å and determined (or refined) the values of the periods of a number of magnetic stars, which were included in the cooperative program of complex research [6]. In 1972, a double photometric reflector with a diameter of 40 cm was installed in the ShAO. The TsIA AN GDR [7].

In July 1972, in order to measure the magnetic fields of stars, the Zeeman analyzer manufactured in the workshops of TsIA AN GDR was installed in the Coude focus of a 2-m telescope. The λ / 4 plates used in the construction made it possible to operate in the short-wave portion of the spectrum from λ4200 A to λ5500A. In front of the analyzer, an instrumental polarization compensator was installed, similar to a Bowen compensator. In June 1973, a second analyzer was installed, which differs from the first in that instead of the λ/4 plate, two λ/8 plates were installed, rotating relative to each other, as in the Bowen compensator. As a result, the scope of the analyzer was expanded from λ3900 to λ6300 Å [8].

In order to measure Zeeman splitting, as well as radial velocities from line profiles in the workshops of ShAO, an attachment was made for the coordinate measuring instrument «Ascorecord » [9], similar to the Golnov attachment. This made it possible to see the line profile on the oscilloscope screen and precisely point to any point and take measurements regardless of the width, shape and intensity of the measured lines. The prefix made it possible to measure radial velocities and magnetic field strengths with an accuracy of Δ Vr = 1.5 km / h and ΔH = 150-200 Gauss, respectively.

Table 1. Observation program for selected magnetic stars.

№	Number HD	m_v	S_p	Type of peculiarity	V sini km/s	Be (Gauss)	Amount spectra
1.	19832 56 Ari	5.65	AOp B8p	Si, Cr, Sr	200 140	-400/+550 -340/+380	13 (4 Å/mm)
2.	34452	5.39	B8p B4p	Si, He	65 80	?	18(4 Å/mm)
3.	65339 53 Cam	6.0	A2p			-5000/+4000	12(4 Å/mm)
4.	108662 17 Com	5.4	A0p	Sr, Cr	35 40	-1150/+360 -1100/+450	10(4 Å/mm)
5.	108945 21 Com	5.4	A2p A3p	Sr Cr	65 70	0/+400	23(4 Å/mm)
6.	124224 CU Vir	5.6	B8p	Si, Cr	130 118	-600 -437/+811	8(4 Å/mm)
7.	133029	6.19	B9p A0p	Si, Cr, Sr	20 40	+3270/+1150 +4065/+2900	19(4 Å/mm) 5(10 Å/mm)
8.	137909 β CrB	3.72	F0p	Sr, Cr ,Eu		-800/+840	14(4 Å/mm)
9.	140160 χ Ser	5.26 5.30	A0p	Sr, Eu, Cr	82	+760/-1840	25(4 Å/mm)
10	140728	5.48	B9p A0p	Sr, Cr	84 109	+310/-1080	16(10Å/mm)
11.	148112 ω Her		A0p	Cr, Eu	-	-	25 (4 Å/mm)
12.	184905	6.5	B9p B7p	Si λ4200	51	~3000	18(4 Å/mm)
13.	193722	6.15	B9p B7p	Si λ4200	42 60	+/-	20(4 Å/mm) 10(10Å/mm)
14.	220825 χ Psc	4.90	A0p A2p	Sr, Cr Eu, Si	48 38	-400/+200 ?	24(4 Å/mm)
15.	224801 GG And	6.25	B9p	Cr, Sr Si, Eu	49 55	?	12(10Å/mm)

In 1974, the Coude focus (III chamber, dispersion 4-8 Å/mm) was equipped with an electron diffraction image converter (EDIC) developed at the All-Union Scientific and Research Institute of Optical and Physical Measurements to study rapid changes in individual lines of magnetic stars using nuclear emulsions significantly increasing information content in comparison with conventional emulsions [10, 11].

The commissioning of the echelle spectrometer for the Coude focus of the 2-m telescope in 1999 made it possible to expand the range of tasks in the study of magnetic stars (the study of weaker objects, fast variability, etc.) [12].

3. The results of studies of MCP - stars in the period of 1969-1998

Spotting of the surface of a star used to be familiar only to astronomers - solar cells. The angular diameter of the Sun is 0.5 degrees, which allows you to observe small details (spots) on its surface. And the angular diameters of the closest magnetic stars are approximately 0.001 sec. arcs. Since the angular resolutions of modern telescopes, including the 2-meter ShAO telescope, do not exceed 0.5 sec. arcs, it is impossible to select individual local areas in the image of a star as a spot on its surface. However, the movement of the spots due to the rotation of the star (hard rotation) should lead to variability of the profiles and Doppler shift of the observed spectral lines. This effect makes it possible to study local properties and to determine the distribution of elements over the surface of the star from the observed line profiles.

If a star has a (one) compact spot in which the abundance of a certain (peculiar) element will be much (0.5 dex) greater than in the adjacent region, then during the rotation of the star, periodic changes in the equivalent widths and radial velocities will be observed in its spectrum.

Usually on the surface of Ap stars there are several (n>2) spots and lines of appreciable intensity are not always formed in the spot, the line profiles look much more complicated than in the above scheme. With low accuracy and resolution of the photographic recording of the spectrum due to noise and depending on the orientation of the axis of rotation with respect to the observer, difficulties arise with the separation of lines into components. It follows that in order to unambiguously separate complex line profiles into components and, based on their research, to obtain maps of the distribution of chemical elements over the surface of a star, it is first necessary to obtain high-quality spectra with high spectral and temporal resolution.

The high quality of the obtained spectrograms and the good spectral resolution of the Coude spectrograph of the 2-m telescope [10, 13] made it possible to apply the technique of separating complex line profiles of various peculiar elements (Si, Sr, Eu, Cr, etc.) into components, and use this method to analyze the inhomogeneous structure of the atmospheres of Ap stars [14].

The method of localizing peculiar elements on the surface of Ap stars and moving them in accordance with the inclined rotator hypothesis was adopted to explain the spectral variability of magnetic stars.

The results of further studies showed that these components are real (not a defect in observations and photographs) and are formed in separate local areas - in the "spots" on the surface of the Ar - star. After separation of the components, their radial velocities Vr and equivalent widths Wλ are measured. Then, using the phase relations Vr and Wλ, the surface structure of the star is revealed. Thus, for the first time, observer astronomers were able to determine the uneven distribution of chemical (peculiar) elements over the surface of magnetic Ap stars. This served as the basis for obtaining a map of the distribution of chemical elements on the surface of magnetic Ap stars [15–18].

From the spectra of 13 Ap stars uniformly covering the periods of rotation, the behaviour of the Balmer lines has been studied. It was found that the equivalent widths of hydrogen lines show periodic changes and are one of their common properties [19]. Determined from the Hγ and Hδ lines, the number of atoms in the second quantum state (lgN_2H) and the electron concentration (n_e) in all the studied stars vary with the period of rotation of the star. They are compared with the available light curves. It was revealed that for these stars at the moment of minimum brightness, the Balmer lines are wider and deeper than at the moment of maximum brightness [20]. For some stars, periodic changes in radial velocities and equivalent widths of hydrogen lines were found [21, 22]. It was shown that for all the studied stars, the electron concentration has a minimum in those places where spots with an increased concentration of one or another element are located and it was concluded that the most intense spot on the surface of the star is responsible for the minimum lg n_e. It was noted that in the spectra of some of the observed stars, the core of the hydrogen lines has a complex profile [22].

For the classical magnetic CP star HD 220825, differential studies of the contours of hydrogen lines were carried out. It was found that the largest changes show the central (nuclear) parts of the studied lines. Similar results were obtained for magnetic stars, α^2CVn and εUMa [23]. It is concluded that the change in the central part of the hydrogen lines is mainly caused by the difference in physical conditions and chemical composition from the normal part of the atmosphere in the upper atmosphere in the peculiar regions of the studied stars [23, 24].

The nature of the change in the equivalent widths of hydrogen lines in the spectra of MCP stars was studied, the composition of which included almost all types of peculiarity with different values of the magnetic field and rotation speeds (see Table 1). For each star studied, the relative values of the equivalent widths (Wλ/Wλ (media)) of the hydrogen lines (H5 - H14) were calculated. The dependences were constructed between the quantities (Wλ/Wλ (cf.)) and the wavelength λ for the phases corresponding to the spot regions (maximum) (φP) and normal regions (φN) of the atmosphere of the studied stars. As a result, it turned out that all the constructed dependency graphs are divided into two groups. For the first group of stars in the spot region (φP), the relative values of Wλ increase with wavelength, while the opposite is observed for the second group. All the stars belonging to the first group turned out to be silicon stars, the second group included other types of stars, mainly Cr, Sr, Eu stars [25].

It was found that for the first group of stars, changes in the relative intensity of hydrogen lines are mainly due to the anomalous content (excess) of silicon in the atmospheres of these stars. In the case of the second group, the main role is played by other peculiar elements, especially rare earths, as a result of which there is an additional absorption (cover effect) in those areas of the atmosphere where on average the higher terms ($n \geq 10$) of the Balmer series are formed [25].

Studies of MCP stars with different rotation periods were carried out in order to find possible relationships between the rotation speed of the studied stars with their character of variability. Particular attention was paid to the study of fast rotators (HD 19832 (56 Ari), HD 124224 (CU Vir) and HD 220825 (χ Psc)). It is known that rotation speed, and not a magnetic field, is a determining factor for maintaining the field and the atmosphere stability of MCP stars, diffusion of chemical elements, leading to anomalies in the chemical composition in the atmospheres of these stars. In addition to slow rotation, the magnetic field creates additional atmospheric stability. The following are the results of a study of rapidly rotating, MCP stars.

HD 19832 (56 Ari) The rotation period of this star is P = 0.728d. Based on high-quality spectrograms obtained with a 2-meter ShAO telescope (dispersion 4 A/mm), this star was studied taking into account the peculiarity effect. For processing, several un banded lines of the following peculiar elements He I, Si II, Cr II, Sr II, Fe II, and Eu II were selected. In order to reveal the spotted structure of the star's atmosphere, we constructed phase curves of the parameters ($W\lambda$, $\Delta\lambda$, Ro) of the spectral lines, magnetic field, and brightness (in a 10-colour photometric system). By comparing the phase curves, we determined the phases that correspond to the largest peculiar (φP = 0.25-0.30) and normal region (φN = 0.5-0.55) on the surface of the star. In the phase φ = 0.25-0.30, most spectral lines are divided into several components. It was shown that all the observed hydrogen lines show synchronous changes, and the amplitude of the variations increases with an increase in the number of these lines. The phase of the maximum of peculiar elements (Si II and others) and the brightness of the star coincides with the phase of the minimum intensity of the H and He lines. It was revealed that a spot with a ten-fold deficit of He is located near the positive pole of the magnetic field [26].

The spectra of the rapidly rotating star HD 124224 (CU Vir) were studied in a similar way [27]. Using a comprehensive study, the phases (φ) corresponding to the largest peculiar (P) and relatively normal (N) regions of the atmosphere were determined, where φ(P) = 0.5-0.6 and φ(N) = 0.15-0.25. It was found that the lines of hydrogen and helium change in antiphase with the lines of silicon, the brightness of the star, and the magnetic field. It was revealed that in the central part of the Hα lines there is a weak emission, which is not typical for stars of the Main Sequence [27].

Based on a large number (about 30) of high-quality (4 Å/mm) spectrograms, the period ($P=0^d.583$) of the spectral variability of a rapidly rotating magnetic star (χ Psc) was determined. This period value differs little from the period value ($P=0^d.5803$) which was found from photometric observations (see [18] and references therein). In the spectra of this star, the lines of the molecular band of CH 4310 were detected and changes in their intensities were detected. It was shown that changes in the intensity of the molecular band of CH λ4310 in the spectra of the χ Psc star occur in antiphase with changes in the intensity of hydrogen lines [28].

The issues of electron density distribution over the atmosphere depth for MCP stars χ Psc were considered. For various magnetic stars (see Table 1), the electron densities were determined at various depths ($\tau_\lambda \approx 0.24$, $\tau_\lambda \approx 0.7$) of the atmosphere. It was found that the electron densities for the normal region hardly differ from the atmosphere of normal stars of the same spectral classes. In the upper atmosphere ($\tau \leq 0.2$), the value of log ne (nm) for the region of spots is less than for the normal region of the atmosphere of the studied stars. In the lower atmospheric layers (τ = 0.5-0.7) of the studied stars, the electron densities in the region of spots are higher than in areas without spots [29, 30].

Behavior of the KCa II line from the spectra of 8 Ap stars was investigated by Aslanov and others. [31]. It is shown that the calcium lines show variability with a rotation period. The variability of the calcium lines is explained by a combination of several reasons, the main of which may be different thicknesses of the absorbing layer in different places of the star's atmosphere and the presence of spots with an anomalous concentration of peculiar elements.

Lines of heavy elements were found in the spectra of magnetic stars HR465, HD108662 and HD224801 [32]. The presence of heavy elements (Pm, Os, W, U, etc.) in the atmospheres of magnetic stars is of great importance, since the elements of the r process are formed by fast neutron capture. These results can be of great importance for solving many problems, especially about the occurrence of chemical anomalies in magnetic stars.

Detailed spectral studies have revealed lines of the elements of the r process in the spectra of the MCP star χ Psc [33]. High-resolution spectrograms were used to search for lines of r-process elements. The main objective of the study was to identify the presence of lines of lanthanides and actinides, as well as lines of other radioactive chemical elements (Z> 57). Using the example of a fast-rotating star HD 220825 (χ Psc), identification of spectral lines was carried out. It was revealed that the nature of the change in the lines of the r - process is significantly different from those for the lines of other elements for which Z <56. The observed fact is, as it were, an additional confirmation (argument) of the presence of the lines of the r - process in the spectra of the studied stars. It is shown that the lines of heavy elements are not observed in all phases of the rotation period of this star. It was found that the peculiar regions for heavy and other elements do not coincide, which often leads to a disagreement of the results in the identification of lines in the spectrum of a magnetic star.

Stronger lines Pm, Pb, W and U are in the ultraviolet region (λ <3000 Å) of the spectrum. The «Astron» space station launched in 1983, on board of which the ultraviolet telescope UVT was installed, made observations of a number of Ap stars (HR465, 73Dra and χ Cnc). The UVT spectrometer recorded in the range λλ2000-3000 Å with a spectral resolution of 0.4 Å [34]. In the UV spectra of the observed Ap stars, lines of heavy elements, Pb II λ2203.53, W IIλ2204.48, UII λ2556.19, etc., were detected, which confirmed the conclusions made earlier by ShAO employees about the presence of heavy elements in the atmospheres of Ap stars.

In 1974-1976 almost synchronous spectral and photometric observations of the 15 Vul metal Am star were carried out with a 2-meter ShAO telescope and a double photometric reflector of the observation center TsIA AN GDR in ShAO, respectively. Based on these observations, for the first time, both spectral and photometric variations were found in a representative of the metallic Am star 15 Vul, with a period of 14 days [35]. It was revealed that the spectral and photometric behaviour of this star are similar to classical magnetic stars (HD40312, 17 Com, χ Psc, etc.) [36].

A detailed identification of the spectral lines was carried out for the star χ Psc. About 2000 spectral lines were detected and identified in the spectrum of this classical magnetic star in the region of 3700-4700 Å and their central depths were measured. At the same time, the lines in the spectra of the normal star Leo (A2V) were identified. As a result, it turned out that the number of observed lines in the spectrum of the magnetic star χ Psc is approximately eight times larger than for the normal Leo star. The identification results for χ Psc can be used to identify lines in the spectra of magnetic stars for spectral classes B8-A4 [37].

Based on 24 spectrograms with a high spectral resolution (4 Å/ mm), the chemical composition of the MCP star HD220825 (χ Psc) was determined. Using the growth curve method, it was found that there is a calcium deficiency in the atmosphere of this star, carbon is normal, most of the other elements are in excess (see Table 2) [38].

For most Ap stars, the brightness variation coincides with the rotation period of these stars within the measurement accuracy ((Δφ = ± 0.05). However, the results of photometric and spectral observations indicate the presence of short-term changes in Ap stars that do not coincide with the rotation period.

For star HD 108945, which is part of a joint research program, brightness changes with an amplitude of $0.^{m}015$ occurring with a period of 32 minutes were found even earlier, and the rotation period of this star is $P = 1^{d}.03$. The results of the 2-m telescope conducted at the Coude focus using EPI and a three-cascade image intensifier UM -92 spectral observations of a number of magnetic stars (17 Com, 21 Com, HD148112, HD133029, HD224801, etc.) showed the complexity and ambiguity of the problem of studying short-term changes in Ap - stars. The exposure time of the spectrograms obtained with EPI (20 min) did not allow us to detect rapid changes with periods of less than 30 minutes. At the same time, the quality of the spectrograms made it possible to identify a number of features inherent in Ap - stars. The analysis of short-term changes showed that fast changes in Ap stars have both periodic (pulsation) and irregular (flare) character, which may be caused by pulsation in the upper atmosphere of the star and flare activity in areas with a high content of chemical elements (spots) respectively [39].

Table 2. The chemical composition of some magnetic stars.

Z	element	ℓgE				
		αAnd	πBooA	HD184905	χ Psc	Sun
2	He	-1.5	?	- 1.0	?	- 0.85
6	C	-3.3	-3.2	- 3.40	- 3.60	- 3.48
7	N	-	-	-	- 4.26	- 3.99
8	O	?	?	-	- 3.40	- 3.11
12	Mg	-4.6	- 5.8	- 3.60	- 3.45	- 4.46
14	Si	-4.5	- 4.00	- 3.50	- 2.46	- 4.49
15	P	-4.8	- 4.70	-	- 5.35	- 6.57
16	S	-	-	?	- 3.74	- 4.79
20	Ca	-5.2	- 5.50	- 5.40	- 6.74	- 5.68
21	Se	-7.5	- 7.50	-	- 8.30	- 8.94
22	Ti	-	- 7.50	- 5.34	- 6.00	- 7.05
23	V	-	-	?	- 6.70	- 8.04
24	Cr	-7.5	- 7.9	- 5.40	- 3.80	- 6.77
25	Mn	-4.7	- 4.5	-	- 5.35	- 6.65
26	Fe	-6.6	- 6.6	- 3.02	- 3.55	- 4.37
27	Co	-5.3	- 5.3		- 6.20	- 7.12
28	Ni	-	-	-	- 4.90	- 5.79
38	Sr	07.0	- 7.2	- 5.80	- 6.70	- 9.14
39	Y	-6.0	- 5.9	- 7.20	- 7.90	- 9.80
40	Zr	-	-	-	- 8.40	- 9.44
60	Nd	-	-	-	- 8.04	- 10.54
62	Sm	-	-	-	- 8.24	- 11.04
63	Eu	-	-	- 7.2	- 8.45	- 11.53

Emission components were detected in the nuclei of hydrogen and other lines (K Ca II, Sm II, etc.). An analysis of the changes led to the conclusion that pulsating shells may exist around these stars and that these stars have an active chromosphere. Periodic short-term changes were also found in stars HD9996, 17 Com, 21 Com, HD224801. The found periods ranged from 36^m to 6h 41^m. Observations of irregular variations associated with emission in some lines of peculiar elements indicate that areas with a high content of a chemical element (in spots) show flare activity [39].

Work has begun in the ShAO to determine the chemical composition of some typical magnetic superlattices - stars: HD358, HD129174, HD193722, HD184905, and HD220825 and others [1,14,38].

Table 2 shows the results of determining the chemical composition for various types of magnetic CP - stars α And, π BooA, HD184905, and χ Psc stars. Here, in the last column, the content of elements in the atmosphere of the Sun is given. Based on the table 2, we can draw the following conclusions. In the atmosphere of α And and π BooA, the largest excess is observed for P and Mn in the range of 1.5 - 2.5 dex ,whereas for the last two stars, the maximum anomalies are found for the elements Sí, Sr, Cr, Eu, Nd, and other lanthanides.

Analysis of the results of the table 2 shows that for all the studied magnetic stars, the anomalies in the element content increase with increasing atomic weight (or atomic number of the chemical element). The results of determining the chemical composition of the studied magnetic stars were used in various monographs [40,41].

For all these stars, the temperatures of excitation and ionization were determined. The excitation temperature was determined by the shift of the multiplets of FeII, MnII, SíII, CrI, CrII, etc. Moreover, the accuracy of determining the temperature varies within ± 500 degrees, depending on the selected line [37]. The T_{ion} value was determined from the lines of atoms and ions of the above chemical elements, using the parameters obtained in [1.41]. Comparison of the obtained T_{exc} and T_{ion} values with the T_{eff} estimates show that the ratio of these values (T_{eff} / T_{ion} / T_{exc} = 1: 0.89: 0.82) is the same as that of normal stars of the main sequence of the same spectral classes (B8-A2).

Despite the observed anomalies in the chemical composition, the global characteristics of magnetic stars (energy distribution in the spectrum, hydrogen line intensities, photometric indices, etc.) are not very different from the corresponding characteristics of normal stars of the same spectral class. An analysis of the chemical composition of Ar stars has shown that the abnormal (peculiar) elements are an order of magnitude higher than the same elements in the solar atmosphere [40].

To study the nature and origin of the family of magnetic CP stars, it is necessary to conduct comprehensive studies of a fairly large number of typical representatives of MCP stars. For this purpose, for further research, the program included typical representatives of various magnetic CP stars: HD 40312, HD 34452, HD 196502, HD 201601, etc.

Based on 60 photographic spectrograms obtained in 1978-1986 for the star HD 40312 (θAur), the period $P = 3^d.6188$ was found, which equally satisfied all photometric, spectral, and magnetic observations of the star [42].

It was found that the amplitudes of changes in the relative values of the equivalent (W_λ / W_λ (cf.)) widths of the hydrogen lines increase with the wavelength. This means that in the spotted regions the distribution of physical parameters (T_{eff}, P = Pg + Pe, ρ) and the peculiarity effect over the depth of the atmosphere are not uniform, as was obtained for most MCP stars. Two peculiar regions were found on the θAur surface, which are located at longitudes of 30 and 200 degrees. The most peculiar region is located at the positive pole (L=200°) of the magnetic field [43].

Magnetic field measurements are of particular importance for the study of chemically peculiar stars and other space objects. Using comparisons, it was found that for all magnetic Ap stars, the periods of variation of the spectrum, brightness, and magnetic field coincide within the measurement accuracy ($\Delta\varphi$ = 0.05) [40].

Based on the well-known fact that all magnetic stars have chemical anomalies, we can conclude that there is a connection between the presence of a magnetic field and the phenomenon of chemical peculiarity. For this purpose, a rich observational material was obtained at the Coude focus of the 2nd m telescope of the ShAO using the Zeeman analyzer for measuring the magnetic fields of Ap stars. For some of the stars, these observations covered the entire period of rotation of the star (βCrB, HD 148112), and for some stars, materials covering individual phases were obtained (HD108662, HD108945, HD220825, etc.) [44–47].

As a result of the studies, it was found that for these stars, the regions with maximum concentrations of chemical (peculiar) elements and the extremum of the magnetic field coincide [43, 45].

Measurements of the magnetic field of the star β CrB showed that the magnitude of the magnetic field along the lines of various chemical elements varies with the rotation period, however, the magnitudes of the magnetic field vary greatly. It was found that in a fixed phase, the magnetic field strength depends on the optical depth of spectral line formation [44, 46].

For the first time in world practice, it was possible to measure the magnetic field over wide spectral lines with a complex component structure (HD148112) and it was possible to measure the magnetic field in individual spots on the surface of the star [46].

It was shown that in the spectra of Ap stars HD108662, HD108945, and HD 148112 obtained using the Zeeman analyzer, the line intensities in the spectra of different polarizations are different [46, 47].

According to literature data and magnetic field measurements from Zeeman spectrograms obtained with a 2 m telescope ShAO, it was shown that β CrB stars have long-term periodic changes in the magnetic field with a period of 350 days [47].

The period from 1998 to 2019

To solve a number of problems, in the second stage of the study, including briefly periodic changes in Ap stars, observations were started using an Echelle spectrometer with a CCD camera on the 2m telescope ShAO (1998-99). The introduction of a CCD matrix into observations made it possible to record more accurate spectral details and increase the accuracy of observations by more than an order of magnitude. Using an Echelle spectrometer with a CCD camera, it is possible to obtain spectra with high temporal and spectral resolutions that allow one to study pulsation and other processes in MCP stars.

Three relatively bright stars (χPsc, γ Equ, θ Aur) were selected in the research program. The exposure time for these stars ranged from 3 to 8 minutes, depending on image quality. It was found that in the atmosphere of γ Equ there are fast short-term oscillations of the pulsation type with a period of about 12 minutes, which are seismic in nature. All measured values (Vr¸ Wλ¸ Δλ/2¸ Ro) showed synchronous changes with the pulsation period, which confirms the reality of the existence of non-radial pulsations in the atmosphere of this star. The greatest variations are found for the lines of chromium and Eu, which is the main peculiar element in the atmosphere of this star [48, 49].

An analysis of the results of studying short-term oscillations in the studied magnetic stars shows that these processes are not radial and are seismic in nature. Multi-periodic oscillations occur not at all phases, and not on the entire surface of the star, but arise only in local areas - in spots where there are pronounced anomalies of the chemical composition and a strong magnetic field (Be ≥200 G) [50].

For the first time, fast short-term oscillations were detected in the atmosphere of a magnetic Ap star χ Psc, with a period of $P_2 = 0^{d}.0119 \pm 0.0008$ (17 minutes); Analysis of briefly periodic oscillations over 1.5 - 2.0 hours shows a monotonic increase, or complete extinction of the amplitude of the fast oscillations, depending on the phase of the axial rotation of this star. The radial velocities and intensities of individual lines vary to varying degrees with the phase both for the period $P_1 = 0^{d}.583$ and $P_2 = 17$ min, and the largest amplitudes are found for the lines of the main peculiar elements SrII, CrII, and EuII [50].

Based on a large number of (80) CCD spectrograms, seismicity and pulsation studies were performed for the θ Aur star. However, the search results for quasiperiodic changes did not yield a positive result. It was learned that the magnetic field is clearly variable, but the number of observations is insufficient to construct periodic changes [51].

In the period from 1998 to 2019, comprehensive studies of various MCP stars were continued taking into account the peculiarity effect [52].

The effective temperatures and the radii of various magnetic stars were determined based on the peculiarity (spotting) effect [53]. The program included representatives of various magnetic CP stars of class B4-F0. To take into account the peculiarity effect, using complex observations for the selected stars, the most peculiar (spotted) and normal regions on the surface of each star were determined [54]. To determine the effective temperature (Te), the H_γ and H_δ line profiles corresponding to the most peculiar (P) and normal region (N) of the star's atmosphere were selected. At the same time, colour indicators (B-V) were used. It was found that, depending on the type of peculiarity and magnetic field, the values of Te found for the peculiar region are on average 500–1500 K larger than in normal regions of the atmosphere studied by MCP stars.

The radii found from the values of T_{eff} (N) [53] (normal region) better correspond to the values obtained by other methods [55].

It is concluded that the temperature differences obtained for the peculiar and normal regions are associated not only with magnetic fields, but also with anomalies in chemical composition, i.e. the peculiarity effect in spotted regions on the surface of MCP stars [56].

For 30 different magnetic CP stars in the range of the spectral classes B2-A9 (17000 > Te> 7500), the axial rotation velocities were determined - $v_e sini$ [57]. For this, high-quality (4 Å/mm) spectral materials obtained with a 2 m ShAO telescope were used. Unlike other works, the determination of the axial rotation speed was carried out taking into account the peculiarity effect. For comparison purposes, $v_e sini$ values were also determined for normal stars of the same spectral classes. As a result, it was found that, on average, the rotation speeds of the studied magnetic CP stars are approximately 2–3 times lower than the $v_e sini$ values for normal stars of the same spectral classes.

1. It was found that the average dependences of $v_e sini$ on the spectral class are not monotonic, and there are noticeable maxima and minima. The main minima fall on the spectral intervals A0-A3 and B8-A2, as is the case for normal stars [57].
2. There is a general tendency for $v_e sini$ to decrease with the transition from earlier to later spectral classes. Using the results of published works, it is concluded that the process of deceleration of rotation of magnetic stars can mainly be completed before the stage of quasistatic compression of these stars begins [58].

For a statistical study of magnetic CP stars, of particular interest are the definitions of the quantitative spectral (P (E)) and photometric peculiarity indices (Δα, z) of these stars [59]. For this purpose, for 20 different magnetic CP stars in the range of spectral classes B4-A9 (16000>T_{eff} >7500K), quantitative spectral indices of peculiarity P = W(P)/W(N) were determined from the selected lines of the peculiar elements Si, Mn , Cr, Sr and Eu. For this, the equivalent line widths of these elements were determined for the spot region in the spectra of magnetic and normal stars W (N) with the same T_{eff}. The found values of P(E) characterize a quantitative measure of the line amplifications of the element in question in the spectrum of an MCP star [60]. It was found that the highest peculiarity indices are shown by rare-earth stars, for which the value P (Eu) = 4.5-6.0. The found values of the P indices make it possible to compare the spectral (P) and photometric (according to Maitsen and Z in the Geneva system) peculiarity indices in order to detect new magnetic CP stars [60].

In order to detect a possible connection with the magnetic field, graphs were constructed of the relationship between the peculiarity indices (P and Δα) and the surface magnetic field (Bs). It was found that the spectral (P) and photometric (Δα) peculiarity indices increase with increasing magnetic field to 5 kQ. Subsequently, an increase in the field sets in, i.e. a further increase in the magnetic field no longer affects these parameters [61].

For 30 different magnetic CP stars of spectral classes B0-F0, Balmer jumps (D) and their relations with effective temperatures were determined. It was shown that the maximum of D values for magnetic stars is shifted toward lower temperatures, by about 700-1000 K, in comparison with normal stars. The following conclusions are received:

1. Comparison of the dependences of the Balmer jump D on T_{eff} shows that the behaviour of the Balmer jump on temperature is the same for normal and magnetic stars. However, in magnetic stars, Balmer jumps are reduced compared to normal stars, as was previously noted by Glagolevsky et al. [62].
2. It has been revealed that the course of decreasing the Balmer jump in the considered temperature range of 7000–25000 K is uneven. The largest anomalies (ΔD = 0.04-0.06) are found in the temperature range T_{eff} ≈9000K and T_{eff}=10000-12000K, respectively, which are associated with the peculiarity type of MCP stars.
3. It was found that the decrease in the Balmer jump D is mainly due to the peculiarity effect, which is characteristic of magnetic stars [63].

Based on ten colour photometric observations of various MSC stars of class B0-F0, studies were conducted on the nature of changes in their brightness [64].

Phase light curves have been building based on photometric materials, obtained in 10 colours for different magnetic CP stars. As a result of the analysis of light curves, it was found that all phase dependences are divided into three groups:

1. The brightness of the early (B8-B0) MCP stars in the whole observable region, change in phase with close in the magnitude of amplitude, which associated with the transfer of blocked energy from the ultraviolet region to the visible range of the spectrum.
2. The brightness amplitudes for the second group of the investigated stars change in different rays significantly and in the region λλ5000 5500Å decreases to the minimum value. This is explaining by the occurring of depression in the continuum at the atmosphere of these stars.
3. It was obtained that the brightness variation in antiphase for magnetic A2-F0 stars is due to the blocking of lanthanide lines in the visible range of the continuum, particularly in the range of depression (λ5200 Å) [64].

On the basis of the materials obtained in the 10-colour photometric system, the light curves of more than 30 different (B0-F0) magnetic CP -stars are analyzed. As a result, the following main conclusions were obtained:

1. The shine of the early (B8-B0) stars in the entire observable region varies in phase with a close amplitude.
2. Amplitudes of light in different rays vary significantly, and in the region of depression 5200 Å , the brightness amplitude decreases to a minimum value.
3. For cold (A2-F0) magnetic CP-stars, the brightness in the short-wave ($\lambda < 5000$Å) and long-wave ($\lambda > 5500$ Å) rays varies in antiphase due to the blocking energy in the continuous of the lines rare-earth elements in visible region.

The main cause of various changes in the brightness of magnetic CP-stars during the period is apparently the transfer of blocked energy from the ultraviolet region to the visible region of the spectrum backwarming (retrothermal) effect, magnetic line blanketing effect and blocking energy in the continuous of the lines by rare-earth elements in visible region [65].

The main, important results obtained in the ShAO on research of MCP stars:

1. For all magnetic CP stars, the hydrogen lines of the Balmer series show periodic changes and are one of the common properties, regardless of their individual characteristics; All magnetic CP stars by the nature of the change in the intensity of the H lines with a wavelength are divided into two groups:
   a) for the first group of stars, the amplitude of the change in the intensity of the H-lines increases with the wavelength;
   b) for the second group, an inverse relationship is observed.
2. Using high-quality spectrograms obtained at the Coude focus of 2 m of the ShAO telescope, the coordinates (L, φ) of individual spots on the surface of the studied magnetic stars were determined.
3. The distribution of electron densities over the depth of the atmosphere for all magnetic stars in the region of spots and without spots differs significantly from each other.
4. Using Zeeman spectrograms obtained with the 2m ShAO telescope, magnetic fields were measured for some (HD108662, HD108945, HD220825, etc.) program stars with wide spectral lines ($\lambda \geq 0.4$ Å).
5. An analysis of the results of studying short-term changes in some of the studied magnetic stars shows that these processes are not radial, but are seismic in nature.
6. The effective temperatures T_{eff} and the radii of various magnetic stars of class B4-F0 are determined, taking into account the peculiarity effect. It was found that, depending on the type of peculiarity and intensity of the magnetic field, the value of T_{eff} in the spot region is on average 500–1500 K higher than in normal atmospheric regions of the studied MSC stars.
7. Using spectra with high spectral resolution (4 Å/mm) for MCP stars of classes B4-A9, quantitative spectral indices of peculiarity P (E) were determined from the lines of peculiar elements Si, Mn, Cr, Sr and Eu. It was found that the highest peculiarity indices are shown by rare-earth stars, for which the value of P (E) = 4.5-6.0. It was found that the value of P (E) and the photometric indices of peculiarity increase with an increase in the magnetic field to 5 KG and further saturation occurs in an increase in the field.

8. For 27 different magnetic stars, the $v_e sini$ axial rotation velocities were determined from the half-widths of the MgII, FeII, HeII line for the spot region (P) and the normal region of the atmosphere. It was revealed that the $v_e sini$ value for MCP stars is approximately 2–3 times smaller than that of normal stars of the same spectral classes. It is concluded that the process of deceleration of the axial rotation speed of MCP stars is completed, apparently, before the stage of quasi-statistical compression of the star begins.
9. The Balmer jumps (D) of MCP stars of spectral classes B2-F0 were determined, where it was found that the value of D for MCP stars is reduced by approximately D = 0.04-0.06 with respect to normal stars of the same spectral classes. It is shown that the decrease in the Balmer jump is due to the peculiarity effect in the spotted regions on the surface of these stars.
10. According to 10 colour photometric observations, it was revealed that for some cold MCP stars (A2-F0) of the Sr, Cr, Eu type, the brightness changes in antiphase in different rays. This is explained by the fact that in the visible region (depression region λ5200 Å) the spectrum is blocked by lines of rare-earth elements, the excess of which reaches 5-6 dex. For these stars, the absorbed energy (brightness reduction) in the region λλ5000-5500Å by lines of rare-earth elements is not accompanied by its increase due to the retrothermal effect, but is reradiated in the red region (λ> 10000 Å) of the spectrum.
11. The main cause of various changes in the brightness of magnetic CP-stars during the period is apparently the transfer of blocked energy from the ultraviolet region to the visible region of the spectrum backwarming (retrothermal) effect, magnetic line blanketing effect and blocking energy in the continuous of the lines by rare-earth elements in visible region.

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