)

COMPLEX STUDIES OF MAGNETIC CP STARS. III.ANALYSIS OF VARIABILITY AND EVOLUTIONARY STATUS MAGNETIC CP - STARS θ AUR

S. H. Aliyev [a*], ***V. M. Khalilov*** [a], ***Z. M. Alishova*** [a]

[a] *N.Tusi Shamakhy Astrophysical Observatory of Azerbaijan National Academy of Sciences, Shamakhy, Azerbaijan*

Based on complex observations, the characters of the photometric, magnetic and spectral variability, with a period of $\mathrm{P} = 3^{\mathrm{d}}.6188$, of the magnetic CP of the star θ Aur = HD 40312 were studied. The phase curves of the magnetic field (B_e), brightness (V) and equivalent widths ($\mathrm{W}\lambda$) of the lines of peculiar elements ($\mathrm{Si, Cr, Sr,}$ etc.) are constructed, by means of which the phases corresponding to the maximal peculiar (P) and normal region (N) on the surface of the star are determined. It is revealed that all phase dependences are synchronous; that is, the extrema of the values of $\mathrm{Be, V}$, and $\mathrm{W}\lambda$ coincide within the error ($\varphi = \pm 0.05$). Hydrogen line profiles ($\mathrm{H}\gamma, \mathrm{H}\delta$) were used to determine the fundamental parameters ($\mathrm{T_e}$ and $\log \mathrm{g}$) for the normal ($T_\mathrm{e} = 8800$ K, $\log g = 3.65$) and peculiar ($\mathrm{T_e} = 9800$ K, $\log g = 3.90$) regions on the stellar surface. The effective temperature was also determined from the photometric indices ($\mathrm{T_e} = 10100$ K and 9500 K).
The location of the star θ Aur on the Hertzsprung-Russell diagram has been established, and thus its evolutionary status has been determined. It was found that the star HD 40312 is located closer to the upper boundary (TAMS) of the MS band.
Key words: Variability magnetic chemically peculiar stars – evolutionary status.

1. INTRODUCTION

To study the nature of peculiar effects and the origin of the family of magnetic chemically peculiar stars (MCP stars), it is very important to carry out compre-

)AJAz:2023_2_72.pdf
* E-mail: sabirshao5@gmail.com

http://doi.org/10.59849/2078-4163.2023.2.72

hensive studies for a sufficiently large number of typical representatives of these stars.

The common properties of MCP stars are that their spectra contain anomalously strong lines of a large set of chemical elements (Si, Cr, Sr, Mn, Eu, etc.), the presence of a powerful magnetic field, and relatively low axial rotation velocities ($\mathrm{V} \sin i \leq 60$ km/s) compared to $\mathrm{V} \sin \mathrm{i} \approx 170$ km/s for normal stars of the same Main Sequence (MS) spectral types.

So far, there is no clear picture of the evolution of MCP stars during their stay on the Main Sequence. The question of the evolution of the intensity of magnetic fields in MCP stars has not yet been confirmed by sufficiently reliable observational data. Of particular interest are also questions about changes in chemical anomalies and velocities of axial rotation of MSR stars during their stay on the MS.

Of particular interest is the question of possible changes in the course of evolution of peculiar characteristics - powerful magnetic fields and chemical anomalies in magnetic stars, in clusters of different ages. Clearly, cluster membership provides the age parameter. Therefore, the problem of studying the atmospheric parameters and the evolution of MCP stars belonging to clusters of different ages seems natural.

This paper presents mainly the results obtained for θ Aur (HD40312). The star θ Aur = HD40312 = HR2095 is one of the brightest magnetic stars ($M_{\mathrm{v}} = 2.7$) of spectral class B9-A0p with the type of peculiarity SiCr.

The purpose of the work is to determine the nature of spectral and other variability as well as the evolutionary status of the MCP of the star θ Aur (HD40312). To compare the data obtained with the results obtained for magnetic stars of this type of peculiarity of different ages.

2. OBSERVATIONS AND PROCESSING

To date, a large number of spectra have been obtained in two versions: a) classical photographic spectra with a dispersion of 4Åmm; b) CCD spectra that are obtained using echelle spectrometers installed in the focus of Coude, and Cassegrain, Photographic spectrograms were obtained in Coude focus is the 2nd Shao Telescope. A large number of high-quality spectrograms with a dispersion of 4/mm were obtained . [1]

Over the course of three nights, about 50 CCD spectrograms of the star θAur were obtained using an echelle spectrometer installed in the focus of the Coude 2-m telescope SHAO NAS of Azerbaijan with the use of CCD matrix with 530x580 elements [2].

In 2021, another 12 CCD spectrograms with a resolution of R = 55000 and two spectra with a resolution of R = 27500 were obtained using ShaEES. Detailed information on the equipment and processing techniques is presented in [3].

On the basis of spectral, magnetic and photometric observations, an analysis of the variability and evolutionary status of the magnetic CP-stars of θ Aur was carried out.

Complex observations have shown that it is a photometric, spectral and magnetically variable star with a period of P = $3^{d}.619$ [4].

3. SPECTRAL VARIABILITY

With the help of the obtained spectrograms, line equivalent widths (W_λ) for Si II, Fe I,FE, II, Cr I, II, Ti II, Sr II, Ca II, etc. were measured. Phase curves equivalent widths Wλ for the above elements are constructed [4]. As an example, fig. 1 shows the phase curves of the quantities W_λ for Hδ, Si II and Cr II. As you can see, a double wave is observed on all phase curves of the W_λ.

Equivalent widths of W_λ line for all examined specified elements change synchronously. On all phase curves there are two maxima, which are associated with the presence of two peculiar regions on the surface of the star.

4. PHOTOMETRIC VARIABILITY

Photometric studies of the star's brightness variability were carried out by Adelman [?] in the Strömgren (uvby) system. Over the course of several years, 47 photometric observations were carried out for this star. It has been shown that changes in the brightness of the star occur synchronously with the period P = $3^{d}.6188$ [?]). The amplitude of changes in the filter is $u = 0.07$, in the filter $v = 0.035$, in the filter $b = 0.04$ and in the filter y = 0.035, respectively.

Although the equivalent widths of different peculiar elements (Cr, Si) change in phase, there is phase mixing ($\Delta\varphi \leq 0.07$). (see Fig. 1). This may indicate that the centers of maximum concentration of the regions of these peculiar elements are located at different distances from the pole of the magnetic field.

5. MAGNETIC FIELD VARIABILITY

In the spectrum of stars, θ Aur lines are $\approx$ 1Åwide, which does not allow, measuring the magnetic field by photographic method along metal lines. Therefore, magnetic field measurements were performed by photoelectric method along lines with hydrogen [5]. The authors of this work observed a variable magnetic

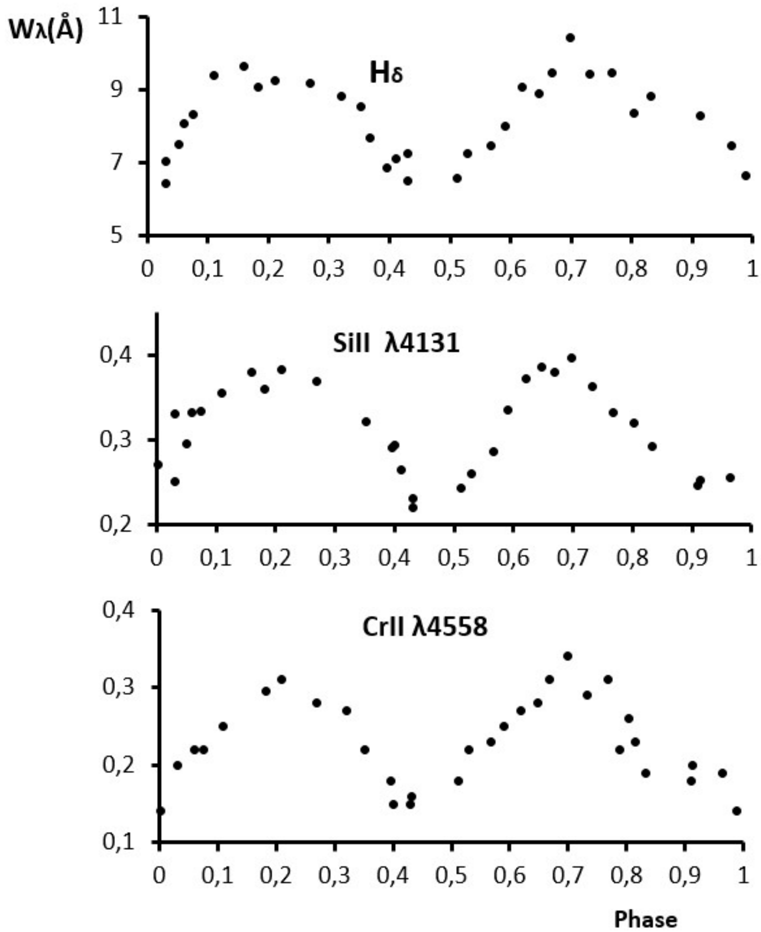

Fig. 1. Phase curves of W_λ values for $H\delta$, Si II $\lambda 4131 A^\circ$ and Cr II $\lambda 4558 A^\circ$

field (+400/−275Gs), which varies with the period $3^d.618$. According to [7], we have constructed phase curves of the magnetic field (see Figure 2). It can be seen from Fig. 1 that there are two maxima on the phase dependencies of B_e values ($\phi_1 = 0.15 - 0.20$ and $\phi_2 = 0.75 - 0.80$).

Hubrig [6] observed the magnetic field using Babcock methods and obtained 9 Zeeman spectrograms in the spectral range λ3800 Å-λ4650 Å with 4Å/mm dispersion. Measurements of the effective magnetic field ($B_e = +1375/-1270 \pm 75$Gs) were carried out along the metal lines Si II, Fe I, II, Cr I, II, Ti II. On the basis of these observations, we built phase curves of the magnetic field (see Fig. 2). Comparison of the results of works [5] and [6] shows that the measured value of the effective magnetic field intensity along the lines of peculiar elements is about three times more than obtained along the lines of hydrogen. This observed fact is explained by the fact that, unlike hydrogen, peculiar elements are concentrated in peculiar (in spotted) regions where the poles of the magnetic field are located.

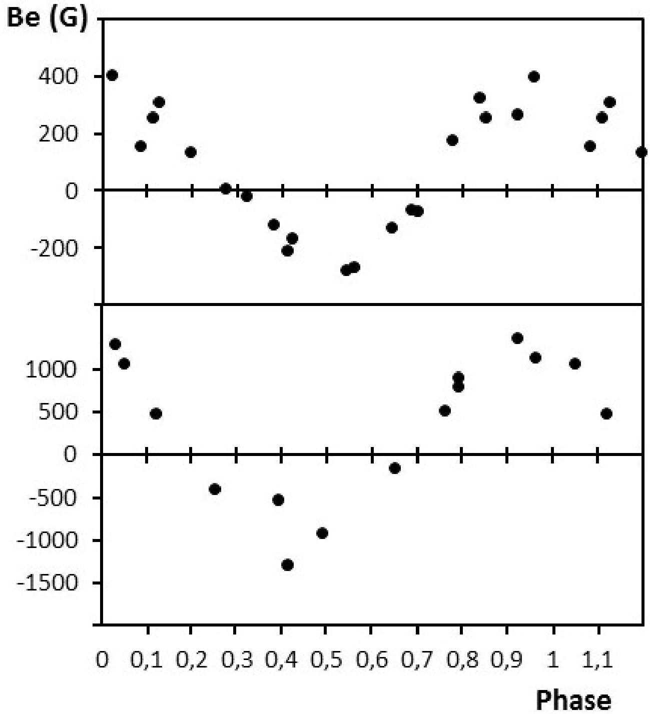

Fig. 2. Phase dependencies of magnetic field strength for a star θ Aur

6. PECULIARITY-P(E) SPECTRAL INDICES.

Quantitative spectral indices of peculiarity characterize the measure of amplification of the lines of the chemical element in the magnetic spectrum of CP stars; then eats the ratio equivalent to the line width ($W\lambda$) of the element in question for a magnetic star to its ($W\lambda$) from the spectrum of a normal star with the same Te and Sp. Thus, the P(E) = $W_\lambda(P)/W_\lambda(N)$ index characterizes to a certain extent the degree of anomaly of the chemical composition [8]. The values found for P(E) are shown in the last row of Table 1 .

7. EVOLUTIONARY STATUS

Landstreet et al. [8] noted that average magnetic field in magnetic stars decreases with increasing age of these stars. Therefore, it can be assumed that the different values of the magnetic field of the group of evolved stars (TAMS) and young stars comparison (ZAMS) may be the result of evolution. To confirm this explanation, more research is needed on new members of this group of stars. Therefore, determining the evolutionary statuses of magnetic chemically peculiar stars is an urgent issue and determining their exact positions on the Hertzsprung - Russell diagram is of particular interest to the physicist and evolution of these stars.

To determine the evolutionary status of a HD40312 star, its luminosity was calculated using standard ratios.

$$\log\left(\mathrm{L}*/\mathrm{L}_{\odot}\right) = 0.4\left(\mathrm{M}_{\odot} - \mathrm{M}_{*}\right) \tag{1}$$

- where the $M_{\odot}$ absolute magnitude of the Sun is $4^{m}, 8$ and $\Delta M_{bal} = -0^{m}.1$ Using the found values of luminosity and effective temperature, the location of the star under study was determined on the Hertzsprung-Russell diagram (Fig. 3) and thereby its evolutionary status was determined.

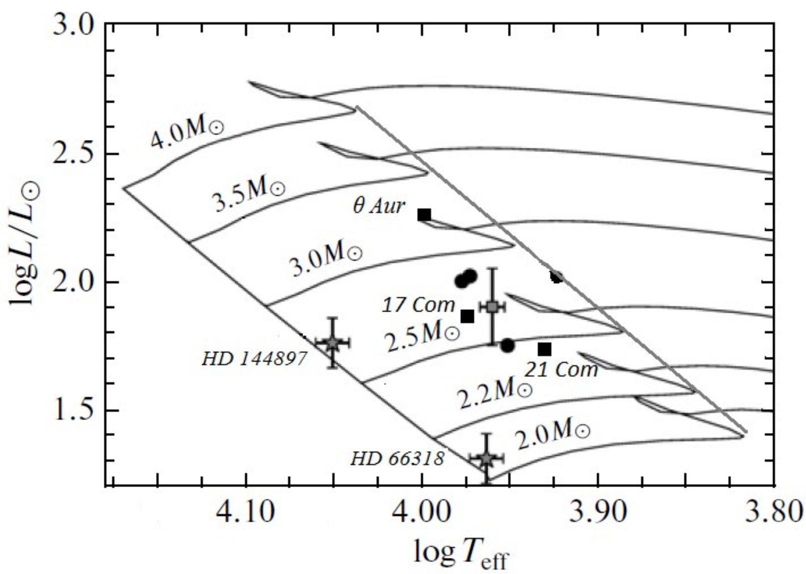

Fig. 3. Hertzsprung-Russell diagram with marked positions of the star θ Aur ■ and comparison stars HD 66318, HD 144897

Table 1. Main parameters for peculiar (P) and normal (N) region atmosphere of magnetic CP-star θ Auriga.

№	Parameters	P	N	Data of the Literature
1	The phases correspond to the peculiar (P) and normal (N) regions of the atmosphere.	$0.15 - 0.20$	$0.48 - 0.52$	-
2	T_{eff} (K) and log g found by $H\gamma$ profiles and Hffi	9800 ± 200 K 3.65	8800 ± 200 K 3.91	10100 [11] 9900 [9]
3	T_{eff} (K) found by photometric indices.	10100 ± 150 K	9500 ± 150 K	10100 [7]
4	Radius $R/R_\odot$ found by T_{eff}(P) and T_{eff} (N)	3.90 $R\,[R_\odot]$	3.55	3.6 [9]
5	Effective magnetic field (Be) measured by Zeeman analyzer (Gauss)	$+1375/{-1270}$ ± 75Gs	< 50G	[6]
6	Value of value Be measured by means of hydrogen magnetometer. (Gs)	$+270/{-370}$ ± 55Gs	≈ 10G	[5]
7	Luminosity Log $L^*/\ L_\odot$	2.44	2.31	2.42 [10]
8	Pecularity spectral indices P (E) for SiII, MnII, CrII, SrII.	2.60; 1.60; 1.50; 1.05		2.55; 1.5 1.60 [7]

In this diagram, (■) with an arrow marks the position of the θ Aur star. It is located next to previously studied advanced MCP stars marked with black circles. From Fig. 3 it can be seen that the θ Aur star is a devolving star, which is approaching the end of life on the GP. The same group includes a number of old stars, such as HD 8441, HD 5797, HD 40711, HD 103498, HD 204411 etc. This group of stars is characterized by strong and numerous lines of elements of the iron peak in the spectra. However, the lines of the peculiar elements Si, Cr and Ca are somewhat weakened compared to young stars (comparison). In the diagram, stars with strong magnetic fields (HD66318 and HD144817) are indicated by asterisks. These young stars have strong magnetic fields (Be $\geq$ 3000 Gauss), in the spectra of which high contents are observed, both elements of the iron peak and peculiar elements Si, Cr and Ca. These young stars were chosen for comparison with the evolving MCP stars.

8. CONCLUSION.

It was revealed that all phase dependences of the magnetic field (Be), brightness (V) and equivalent widths (W_λ) of the lines of peculiar elements (Si, Cr, Sr et al.) are synchronous; that is, the extremes of the quantities Be, V and W_λ within the error range ($\varphi = \pm\ 0.05$) coincide. According to the oblique rotator model, it is possible to tell that on a surface of the star θ Aur most peculiar areas which are located in phases $\varphi \approx 0.15 - 0.20$ and $\varphi \approx 0.48$ - 0.52 on a star surface.

According to the oblique rotator model, the phase of the main maximum ($\varphi \approx 0.15 - 0.20$) of the phase curves of the values Be, V, and Wλ corresponds to the largest peculiar (P) region, and the phase of the minimum ($\varphi \approx 0.48 - 0.52$) (relatively) to the normal (N) region on the surface of the star (see Table 1). The results of complex studies allowed us to establish the location of the θ Aur star on the Hertzsprung-Russell diagram and thereby determine its evolutionary status. It is located next to the evolved MCP stars that are approaching the end of life on the MS. In the spectra of this group of magnetic stars, the lines of peculiar elements, compared to young MCP stars, are somewhat weakened. Stars of this group have weak magnetic fields that are not characteristic of magnetic CP stars [8]. It was obtained that during the evolution of MCP stars θ Aur the magnetic field and peculiarity indices P(E) of peculiar elements are reduced in comparison with young magnetic CP stars corresponding to the spectral class. The results of our study, basically, do not contradict the assumption of Landstreet et al. [8] that the average magnetic field value in magnetic stars decreases with increasing age of these stars.

Based on the observational facts presented above, the following conclusions can be drawn.

1. By means of comparison of phase dependences of intensity of magnetic field, peculiar elements and gloss were revealed that on a surface of a star of θ Aur there are two most peculiar areas which are located in phases $\varphi \approx 0.2$ and $\varphi \approx 0.7$ on a star surface.

2. Obtained, measured value of effective magnetic field intensity along lines of peculiar elements is approximately three times more than obtained along lines of hydrogen.

3. It has been established that the θ Aur star is located closer to the upper border (TAMS), which is approaching the end of life on the MS.

REFERENCES

1. Aliev S. G., Rustamov J. N., Spectrophotometric study of the magnetically variable peculiarstar HD 40312, Circular ShAO, 1989 № 86, 3-8.

2. Aliev S. G., Ismailov N. Z. Spectral variability of the Ap star θAur, Proceedings of the international conference “Tusi-800”, Prikuli, October 4-7, 2001, 221-223.

3. Mikailov Kh. M., Musaev F. A. et all, Shamakhy Fiber Echelle Spectrograph, Kinematics and Physics of Celestial Bodies, 2020, **36**, № 1, 22-36.

4. Aliev S. G. Comprehensive study of the magnetic CP star θ Aur, News of the ANAS series Physics, Astronomy. 2007, №5, 170-177. Adelman S. J. Stromgren uvby Photometry of the Magnetic Chemically Peculiar stars HR 1643, θ Aur, 49 Cam and HR 3724, Publications of the Astronomical Society of the Pacific, 1997, 9-14.

5. Borra E. F, Landstreet J. D. The magnetic fields of the Ap-stars. Astrophys.J. Suppl. 1982, **42**, 421-426.

6. Hubrig S., The magnetic field of Theta Aur. Stellar magnetism, Sankt- Petersburg nauka, 1992, 201-206.

7. Kopylov I. M., Quantitative spectral indices of the peculiarity of CP stars of the upper part of the Main Sequence, Astrophysical research. 1987, №24, 44-67.

8. Landstreet J. D., Bagnulo S., Andretta V., Silaj J., Fossati L., Wade G. A., Evoloution of the maqnetic fields of magnetic Ap stars during the main sequence phase, Magnetic stars, 2011, 14-22.

9. Aliev S. G. Determination of temperatures and radii of magnetic CP stars taking into account inhomogeneity. Kinematics and Phys. celestial bodies 2009, №6, 250-253.

10. Kochukhov O., Bagnulo S., Evolutionary state of magnetic chemically peculiar stars, Astronomy and Astrophysics, 2006, **450**, 763-775.

11. Kochukhov O., Shultz M., Neiner C., Magnetic field topologies of the bright, weak-field Ap stars θAurigae and ξUrsae Majoris, Astronomy & Astrophysics, 2019, **621**, 47, 1-19.