SPOTS STRUCTURE AND STRATIFICATION OF SOME CHEMICAL ELEMENTS IN THE ATMOSPHERE OF He-WEAK STAR HD 21699

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1.Introduction

HD 21699 (HR 1063) was initially classified by Roman and Morgan (1950) as B8IIIvar star. Molnar (1972) has performed analysis of its spectra and determined that helium was extremely deficient (by factor of 5). Therefore, he classified this star as a He-weak type. Shore et al. (1987) refer to HD 21699 as He-weak silicon star (sn class - with broad and diffuse He I lines).

Extremely reduced helium abundance in HD 21699 results in the incorrect spectral classification. The MK classification gives Sp = B8. Abt et al. (2002) suggest a spectral class B8IIIpMn, that corresponds to T_{eff} = 12000 K, while Glagolevskij (2002) has derived T_{eff} = 16100 K from the analysis of color indices. Using the spectra obtained with 6-m telescope, the parameters T_{eff} = 16000 K, lg g = 4.15, $V_t = 0.8$ km/s are derived by Glagolevskij et al. (2005) from analysis of the H_δ line.

Period of the axial rotation for HD 21699 is P = $2^d.4765$ (Brawn et al. 1985). The relation between the equatorial velocity, period and stellar radius ($V = 50.613 * R/P$) and the measured value of v sin i= 35 km/s yields the inclination angle $i = 32°$ (Glagolevskij & Chuntonov, 2007). The positive maximum of effective magnetic field occurs at the phase $\phi = 0$, and the negative extremum occurs at $\phi = 0.4$ according to the ephemerides of Glagolevskij & Chuntonov (2007) for initial phase:

JD = 2445595.529 + $2^d.49246$

2. Magnetic field model

A one-spot model for helium and silicon surface distribution has been shown by the work of Stateva (1995) to fit observed periodic variations of equivalent widths of He I lines and Si II lines. One large He-weak spot is situated around the positive magnetic pole, while Si II spot is located at the negative pole. A central dipole model for surface magnetic field has been assumed in this work. Analysis of the equivalent widths of helium and silicon lines shows that the peaks of their plots do not coincide in phase, rather they are opposite. Usually, in a case of central magnetic dipole the abundances of the same element are equal in the vicinity of both magnetic poles.

UBV photometry (Percy, 1985) shows only a single wave of the light curve during the rotational period, while stars with a magnetic field of centered dipole always have a double wave. In the work of Shore et al. (1987) it is mentioned that a similar behavior in the photometric data is seen in two other He-weak sn stars: HD 5737 and HD 79158.

Brown et al. (1985) has reported discovery of magnetically controlled stellar mass outflow in HD 21699 basing on IUE observations of the C IV resonance doublet, which is variable on the rotational time-scale of about 2.5 days. He has found only one jet from the only one magnetic pole.

An additional study of the surface magnetic field for this star has been performed by Glagolevskij & Chuntonov (2007) using a model of the spatially distributed magnetic charges (Gerth & Glagolevskij, 2000) . The measurements of H_β line with the Zeeman polarimeter (Brown et al., 1985) have been employed to reconstruct the magnetic field model.

It is shown that a better agreement between the observed and calculated curves of the equivalent widths of He I and Si II lines for HD 21699 can be reached with a model where the dipole is displaced across its magnetic axis from the stellar center by a factor $a = 0.4 + 0.1$ of stellar radius. Therefore, the magnetic poles appear to be close to one another on the stellar surface (they are separated by 55°, not by 180° as it would be in a case of central dipole). The big "strong" helium spot coincides with the average position of the two magnetic poles, while the "weak" spot is located in the opposite side of the star (Glagolevskij & Chuntonov, 2007).

Phase dependence of the equivalent widths of He I and Si II lines shows extreme values at phases that correspond to the passage through visible meridian of zero magnetic field between the magnetic poles. The intensity of helium lines reaches its maximum at the magnetic poles, while the intensity of silicon lines reaches here its minimum. Silicon abundance is maximal in the regions where magnetic field is predominantly tangential to the stellar surface.

The behavior of atomic diffusion does not depend on the sign of magnetic field nor does the abundance of chemical species in a magnetic spot depend on the field' sign. Observed data show that despite of the intensities of helium lines are weakened in all rotational phases, they still are unmistakably increased in the magnetic spot. On the contrary, silicon lines are more weak in the spot than on the opposite part of stellar surface. Due to averaging over the visible hemisphere and owing to the close location of both magnetic poles to each other, the only one wave of intensity variation in spectral lines is observed for the investigated chemical species. For the same reason we observe the only one wave for the variability of photometric light curve and of average surface magnetic field Bs. Respectively, only one jet of stellar wind, common from both poles, is observed.

3. Variability of He I and Si II line's intensity with rotational phases

HD 21699 is a unique star due to the nature of the surface magnetic field distribution. Due to close location of positive and negative magnetic poles to each other, the common "magnetic spot" are situated on one-half of stellar surface with predominantly vertical magnetic field lines (Glagolevskij & Chuntonov, 2007). Meanwhile, on the other hemisphere the magnetic field lines are horizontal. Such a configuration of the magnetic field is convenient to perform analysis of abundance surface distribution for those chemical species which are concentrated around the magnetic poles (He I and others) and those which are concentrated in the area with the horizontal magnetic field lines (Si II and others). It provides also a unique opportunity to study the variability of mean abundances with rotational phase and the vertical distribution (stratification) of chemical species in stellar atmosphere depending on the structure of magnetic field.

HD 21699 is very suitable star for studying the atomic diffusion of chemical species in the atmospheres of CP stars because its surface can be simply divided on two parts: one where the magnetic field lines are horizontal to the stellar surface and another where they are predominantly vertical.

4. Observation data and treatment

The spectra used in this study are obtained with the 6-m telescope of Special Astrophysical Observatory of Russian Academy of Sciences (SAO RAS) with the main stellar spectrograph (MSS) equipped by slicer of 14 cuts and have spectral resolution R = 15000. The signal-to-noise ratio is 2000. Ten spectra in the region 3900-4300 A cover uniformly the whole rotational period. One more spectrum has been registered with Nasmyth Echelle Spectrometer (NES) for the resolution of 40000 in the range 4500-5900 A (the phase=0.687). The signal-to-noise ratio for this spectrum is 400. SAO spectra are reduced using MIDAS procedures.

Additionally we used spectra obtained with the MuSiCoS spectropolarimeter which is installed on the 2-m Bernard Lyot telescope at the Pic du Midi Observatory in France. MuSiCoS is a table-top cross-dispersed echelle spectrograph which is fed by two optical fibres from the polarimeter, mounted in the cassegrain focus, with resolution R = 35000 and wavelength coverage from 4500 to 6600 A (phases=0.118, 0.322, 0.525). For the MuSiCoS spectra signal-to-noise ratio is about 400 per pixel.

A complete Stokes V exposure is made up of 4 subexposures in which the retarder is rotated by 90 degrees and back. By switching the beams within the instrument, in principle any first order spurious polarization signatures are suppressed to an acceptable level. The MuSiCoS spectra are reduced using the ESPRIT data reduction package (Donati et al., 1997).

5. The spectra modeling and results

Synthetic spectra for HD 21699 are calculated with the code SYNTHM of S.Khan (2004) and SYNTHV of V.Tsymbal (1996). We use Kurucz' model atmosphere with parameters $T_{\rm eff}$ =16000 K and $\log g$ =4.0 as well as Pavlenko' model atmosphere with reduced He abundance. The atomic lists of VALD and

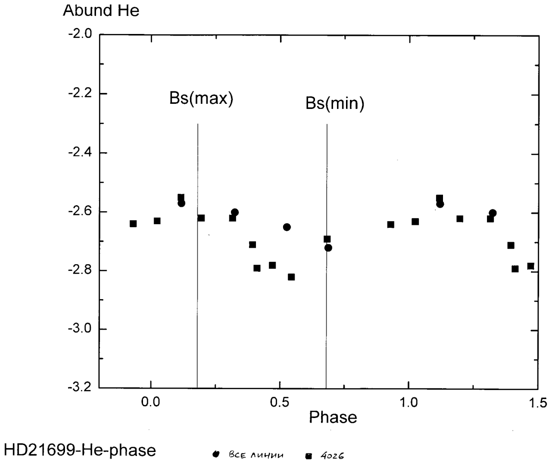

Figure 1: Variability of the helium abundance (log N(He)/N(H)) with rotational phase. The circles present averaged abundance deduced from analysis of He I lines (see Table 1), while the squares stand for abundance deduced from analysis of He I line 4026A. Mean error for all abundance estimates is about ± 0.1dex.

Castelli (http://wwwuser.oat.ts.astro.it/castelli/) are employed to simulate the spectra. Average abundance of chemical species (assuming no vertical stratification) is determined with the help of SYNTHV code (no magnetic splitting) and SYNTHM code (Version-04, that takes into account magnetic splitting of lines). Stratification of elements is determined from the best fit of calculated by SYNTHM (Version-05) line profiles (wings and cores) to observed ones. Previously, we have determined the contribution function for each line using the code WITA (Pavlenko, 1997).

HELIUM: The helium lines are weakened in the spectra of HD 21699. Osmer and Peterson (1974) and Vauclair (1975) have shown that formation of He-weak or He-rich stars depends on the wind power in their atmospheres. If we define that VW is a velocity of flux relative to wind and VD is the velocity of diffusion inside a star, then He-weak stars are formed when VD > VW. It is clear from Fig. 1 that on the whole surface of HD 21699 helium appears to be deficit. Nevertheless, in the area of "magnetic spot" the helium abundance is comparatively higher, than that derived for the opposite side.

For those parts of stellar surface, where magnetic lines are horizontal, only He I (not He II) vertical diffusion can be efficient. There the abundance of helium must be higher than on the magnetic poles, where the field lines are vertical, because there is no resistance to the diffusion of He I and He II atoms. The fact that intensity of He I lines on the magnetic poles is higher than on the opposite side supports the idea of a sufficiently strong wind on the magnetic poles. The observed data justify presence of a powerful wind from

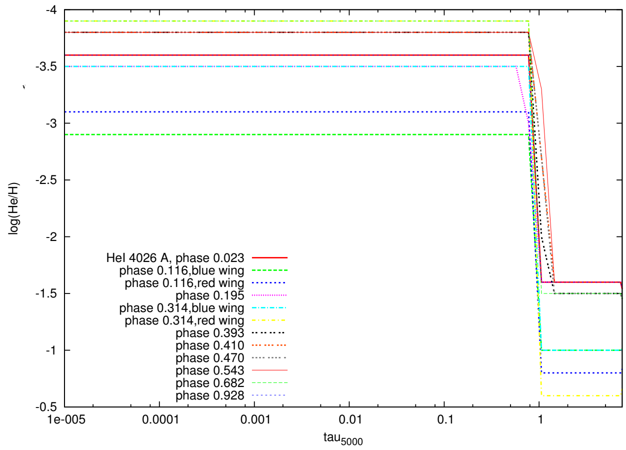

Figure 2: Helium vertical stratification (in the frame of two-step model) from the analysis of He I 4026A line for various rotational phases (in phases 0.928, 0.023, 0.116, 0.195, 0.314 helium abundance is close to its maximum, while in phases 0.393, 0.410, 0.470, 0.543, 0.682 helium abundance is close to its minimum).

the "magnetic spot" of HD 21699 (magnetically structured jets, Brown et al. 1985).

We have assumed the two-step approximation for vertical stratification of chemical species in the atmosphere of HD 21699 (see, for example, Ryabchikova et al., 2005). In Fig. 2 we show vertical stratification of helium for 10 phases, derived from analysis of He I 4026 A line profiles (for the lower layers the abundance is derived from line wings, while for the upper layers it is derived from line cores).

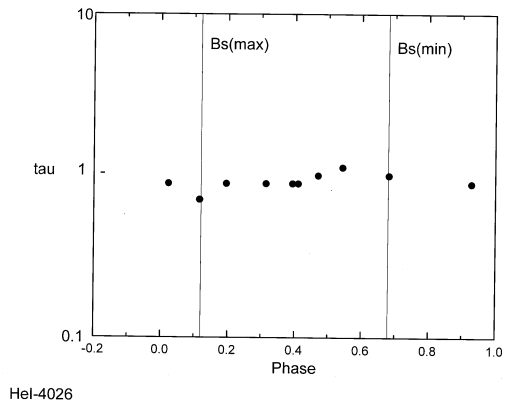

Figure 3: Optical depth τ_{5000} of the abundance jump versus rotational phase for the line He I 4026 A.

The results shown at Fig. 2 confirm theoretical prediction of Vauclair et al. (1991) about enhancement of helium abundance towards the deeper optical depth. We can see in Fig. 3 that optical depth τ_{5000} of the abundance jump does not vary with the rotational

Table 1: Variation of Si II mean abundance with rotational phase (MuSiCoS and NES spectra)

line (A)	E"	log N(Si)/N(H)			
	phase	0.118	0.322	0.525	0.687
6347	8.12	-5.12	-4.92	-4.02	-
6371	8.12	-5.12	-4.92	-4.12	-
5041	10.07	-4.87	-4.67	-4.02	-4.25
5055	10.07	-5.15	-4.99	-4.55	-4.50
4673	12.84	-3.87	-3.82	-3.52	-3.70
5669	14.21	-4.15	-4.05	-3.55	-3.75
5202	16.35	-3.75	-3.80	-3.20	-3.70

phase.

SILICON: In Table 2 we show estimates of silicon abundance derived from MuSiCoS and NES spectra for seven Si II lines with various excitation energies (in the range of 8-16 eV) of the lower transition level for 4 rotation phases. It is easy to track an apparent increase of the derived silicon abundance with the rise of excitation energy (i.e. towards the deeper atmosphere). This tendency supports the idea of vertical stratification of silicon abundance, which was announced by Vauclair et al. (1979).

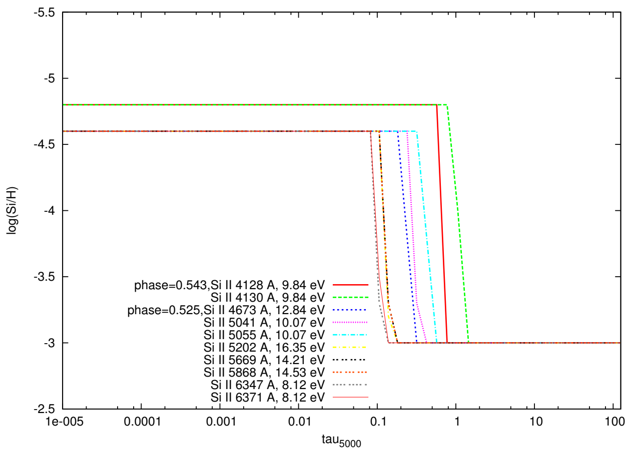

Figure 4: Vertical stratification of silicon for the phase 0.525, where Bs reaches its minimum and Si II abundance rise to its maximum.

Table 2 shows combination of the aforementioned data with the silicon abundances derived from Si II lines 4128 A and 4130 A for ten rotational phases using the MSS spectra. Taking into account the level -4.49 dex of solar abundance for silicon (Grevesse et al 2007), it appears that the lines with low excitation energies show abundance deficit, while the lines with high excitation energy show excess of silicon for phases with maximal Bs (0.118 and 0.322). It is remarkable that the abundance estimates derived from analysis of the

Table 2: Variation of mean silicon abundance log N(Si)/N(H) (without stratification) with rotational phase (including MSS spectra): * 8-10 eV - lines 6347, 6371, 5041, 5055 A are taken from MuSiCoS spectra lines 5041, 5055 A - from NES SAO spectra; ** 12-16eV - lines 4673, 5202 and 5669 A are taken from NES spectrum (phase 0.682).

Phase	mean 4128, 4130A	mean eshelle (MuSiCoS & NES)		
		9.837 eV	8-10eV*	12-16eV**
0.023	-4.90			
0.116	-4.95	0.118	-5.06	-3.92
0.195	-5.15			
0.314	-4.80	0.322	-4.88	-3.87
0.393	-4.50			
0.410	-4.35			
0.470	-4.35			
0.543	-4.35	0.525	-4.16	-3.42
0.682	-4.15	0.687	-4.37	-3.72
0.928	-4.70			

lines with low excitation energies are in good agreement between themselves for all available spectra (MuSiCoS, NES and MSS). For the phases with minimal Bs (0.525 and 0.687) all the lines show an excess of silicon. Nevertheless, the lines with higher excitation energies still result in higher abundance.

Fig. 4 shows enhancement of silicon abundance towards the deeper atmospheric layers, as it was predicted by Vauclair et al. (1979). In the Fig. 5 we can see dependence of optical depth τ_{5000} at the Si II abundance jump from rotational phase. The case of non-uniform silicon distribution on the surface of magnetic stars is discussed in the works of Vauclair et al. (1979), Alecian and Vauclair (1981) and Megessier (1984). Silicon is usually accumulated in the places where magnetic field lines are predominantly horizontal and they oppose the gravitational settling of ionized silicon. In the case of a shifted magnetic dipole, as for HD 21699, the side opposite to the magnetic poles has a large area with horizontal magnetic field lines, where silicon should be concentrated. Meanwhile, it has to be weakened around the magnetic poles.

From the Tabl. 1, 2 and Fig. 4 it appears that our results confirm the predictions of Vauclair et al. (1979), Alecian and Vauclair (1981) and Megessier (1984). In the atmosphere of HD 21699 silicon is enhanced in the area where the field lines are horizontal to stellar surface. The optical depth of abundance' jump for silicon (as for helium) is approximately the same for the all rotational phases ($\tau_{5000} = 1$, see Fig. 5).

Abundance stratification due to diffusion processes acting in the atmospheres of chemically peculiar stars is studied in the recent work of Monin & LeBlanc

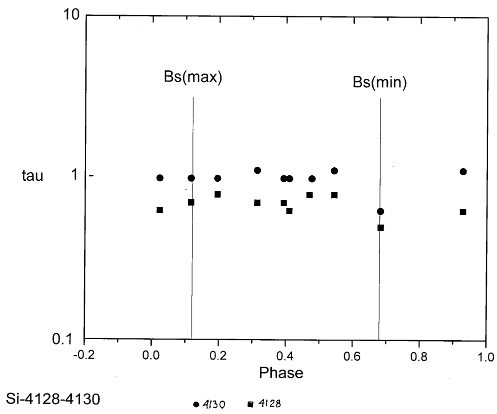

Figure 5: Optical depth τ_{5000} of the abundance jump versus rotational phase for the Si II lines 4128 A and 4130 A.

(2007). Their self-consisting models show that elements such as Fe, Cr, Si and Ca indeed accumulate at large optical depths, while they are dramatically underabundant in the upper atmosphere. The transition zone for iron in their models is located around optical depth $\tau_{5000} = 1$.

7. Basic conclusions

– For the first time the chemical element abundances in the atmosphere of HD 21699 are obtained during the whole rotational period, not only for a one phase.

– Silicon is accumulated in the part of star, where the magnetic field lines are predominantly horizontal, as it was predicted by Vauclair et al. 1979, Alecian & Vouclair 1981 and Meggessier 1984.

– Silicon abundance determined from lines with low excitation energies (8-10eV) appears to be lower in the area of magnetic poles and is approximately solar in the region with horizontal magnetic lines. The lines with high excitation energies (12-16eV) also show enhancement of silicon abundance for the region with horizontal magnetic lines, but this abundance is everywhere significantly higher than the solar one.

– Silicon abundance is lower in the outer parts of the atmosphere and higher in the deeper layers.

– Helium abundance is weakened on the whole stellar surface, which is usual for He-weak stars. Nevertheless, helium has higher abundance in the region of "magnetic spot" due to the influence of stellar wind, which elevates it to the outer layers of stellar atmosphere (Vauclair et al. 1991).

– The optical depth of abundance' jump (in two-steps model) is approximately $\tau_{5000} = 1$.

– The optical depth of abundance' jump for He and Si does not change during the period of stellar rotational.

– Our results support theoretical prediction of Vauclair et al. (1991) that helium abundance should increase with optical depth in the atmospheres of He-weak stars.

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