Spots structure and stratification of helium and silicon in the atmosphere of He-weak star HD 21699.

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ABSTRACT

The magnetic star HD 21699 possesses a unique magnetic field structure where the magnetic dipole is displaced from the centre by 0.4 ± 0.1 of the stellar radius (perpendicularly to the magnetic axis), as a result, the magnetic poles are situated close to one another on the stellar surface with an angular separation of 55° and not 180° as seen in the case of a centred dipole. Respectively, the two magnetic poles form a large "magnetic spot". High-resolution spectra were obtained allowing He I and Si II abundance variations to be studied as a function of rotational phase. The results show that the helium abundance is concentrated in one hemisphere of the star, near the magnetic poles and it is comparatively weaker in another hemisphere, where magnetic field lines are horizontal with respect to the stellar surface. At the same time, the silicon abundance is greatest between longitudes of 180 - 320°, the same place where the helium abundance is the weakest. These abundance variations (with rotational phase) support predictions made by the theory of atomic diffusion in the presence of a magnetic field. Simultaneously, these results support the possibility of the formation of unusual structures in stellar magnetic fields. Analysis of vertical stratification of the silicon and helium abundances shows that the boundaries of an abundance jump (in the two step model) are similar for each element; \(\tau_{5000} = 0.8-1.2\) for helium and 0.5-1.3 for silicon. The elemental abundances in the layers of effective formation of selected absorption lines for various phases are also correlated with the excitation energies of low transition levels; abundances are enhanced for higher excitation energy and higher optical depth within the applied model atmosphere.

Key words:
stars:chemically peculiar–
stars:magnetic fields–
stars:atmosphere–
stars:individual: HD 21699

1 INTRODUCTION

HD 21699 (HR 1063) was initially classified by Roman and Morgan (1950) as a B8IIIvar star. Molnar (1972) later performed an analysis of its spectra and determined that helium was extremely deficient (by factor of 5), as a result he classified this star as a He-weak. Shore et al. (1987) refer to HD 21699 as a He-weak silicon star (Sn class - with broad and diffuse He I lines). The Sn class is primarily attributed by Morgan (1977) to the silicon and He-weak star HD 5737. In the classification of Preston (1974) both objects are categorised as chemically peculiar (CP2) stars. Because of the extremely reduced helium abundance, it is possible that HD 21699 has been given an incorrect spectral classification: the MK classification gives Sp = B8, whereas Abt et al. (2002) suggest a spectral class of B8IIImp that corresponds to \(T_{\text{eff}} = 12000\) K, while Glagolevskij (2002) derived \(T_{\text{eff}} = 16100\) K from the analysis of colour indices. Using the spectra obtained with the 6-m telescope, the following parameters were derived by Glagolevskij et al. (2006) by an analysis of the \(H_\delta\) line: \(T_{\text{eff}} = 16000\) K, \(lg g = 4.15\), \(V_t = 0.8\) km s\(^{-1}\).
The period of axial rotation for HD 21699 is $P = 2^4.4765$ (Brown et al. 1985). Using the relation between the equatorial velocity ($\text{km s}^{-1}$), period (days), stellar radius in solar radii ($V = 50.613+R/P$) and the measured value of $\sin i = 35$ km $s^{-1}$ yields an inclination angle of $i = 32^\circ$ (Glagolevskij & Chuntonov 2007). The positive magnetic field maximum 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 = 2445995.529 + 2$^4.49246$).

2 MAGNETIC FIELD MODEL AND VARIABILITY OF HE I AND SI II LINES

It has been shown by Stateva (1995) that a one-spot model for the helium and silicon surface distributions fits the observed periodic equivalent width variations in both He I lines and Si II lines. In this case one large He-weak spot is situated around the positive magnetic pole, while the Si II spot is located at the negative pole, with the surface magnetic field assumed to be due to a centered dipolar field. Analysis of the equivalent widths of the helium and silicon lines show that the maximum values do not occur at the same phase and are in fact opposite. Usually, in a case of centered 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 "peak" in the light curve during one complete rotational period; typically stars with a centered dipolar magnetic field display a double wave (one peak and trough). In the work of Shore et al. (1987) it is mentioned that a similar behavior is noted in the photometric data of two other He-weak sn stars: HD 5737 and HD 79158.

Brown et al. (1985) reported the discovery of magnetically controlled stellar mass outflow in HD 21699 based on IUE observations of the C IV resonance doublet, which is variable on the rotational time-scale of about 2.5 days, but IUE observations of the C IV resonance doublet, which is variable on the rotational time-scale of about 2.5 days, but IUE observations of the C IV resonance doublet, which is variable on the rotational time-scale of about 2.5 days, but IUE observations of the C IV resonance doublet, which is variable on the rotational time-scale of about 2.5 days, but IUE observations of the C IV resonance doublet, which is variable on the rotational time-scale of about 2.5 days, but IUE observations of the C IV resonance doublet, which is variable on the rotational time-scale of about 2.5 days, but IUE observations of the C IV resonance doublet, which is variable on the rotational time-scale of about 2.5 days, but IUE observations of the C IV resonance doublet, which is variable on the rotational time-scale of about 2.5 days, but IUE observations of the C IV resonance doublet, which is variable on the rotational time-scale of about 2.5 days, but IUE observations of the C IV resonance doublet, which is variable on the rotational time-scale of about 2.5 days, but IUE observations of the C IV resonance doublet, which is variable on the rotational time-scale of about 2.5 days, but IUE observations of the C IV resonance doublet, which is...
The signal-to-noise ratio for this spectrum is 300. The SAO spectra are reduced using MIDAS procedures.

We also used spectropolarimetric data (Stokes I and V) obtained with the MuSiCoS (MUlti Slte COntinuous Spectroscopy) spectropolarimeter which was 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 Å (phases = 0.118, 0.322, 0.525). The signal-to-noise ratio for the MuSiCoS spectra is about 400 per pixel.

A complete Stokes exposure is made up of 4 subexposures in which the retarder is rotated by 90 degrees and back. In principle any first order spurious polarization signatures are suppressed to an acceptable level, by switching the beams within the instrument. The MuSiCoS spectra are reduced using the ESPRIT data reduction package (Donati et al. 1997). We only used Stokes I spectra from the MuSiCoS data, which were obtained with observed procedures described in detail by Donati et al. (1999). Stokes V spectra are not discussed here simply because the three available phases are not sufficient to provide additional information about the magnetic field geometry.

In Table 1 we provide the JD, wavelength coverage, S/N and rotational phase for all spectra. The nine spectra obtained with MSS SAO RAS are shown in Fig.1, where we can see variation in intensity of He I 4026 Å, Si II 4128 Å and 4130 Å lines during rotational period.

### Table 1. Data of observed spectra (JD, wavelength coverage, S/N and rotational phase)

| JD          | spectrograph | wavelength cov. | S/N | phase |
|-------------|--------------|-----------------|-----|-------|
| 2453591.6342 | MuSiCoS      | 4490 - 6620 Å   | 0.118 |       |
| 2453594.6357 | "            | "              | 0.322 |       |
| 2453607.630 | "            | "              | 0.525 |       |
| 2453605.510 | NES          | 4500 - 5900 Å   | 0.687 |       |
| 2454072.444 | MuSiCoS      | 4000 - 4240 Å   | 0.023 |       |
| 2454070.182 | "            | "              | 0.116 |       |
| 2454464.188 | "            | "              | 0.195 |       |
| 2454073.167 | "            | "              | 0.314 |       |
| 2454462.189 | "            | "              | 0.393 |       |
| 2454075.558 | "            | "              | 0.470 |       |
| 2454101.155 | "            | "              | 0.543 |       |
| 2454485.251 | "            | "              | 0.646 |       |
| 2454072.208 | "            | "              | 0.928 |       |

### Figure 1.
Nine spectra of HD 21699 obtained with MSS SAO RAS. We can see variation of intensity of He I 4026 Å, Si II 4128 Å and 4130 Å lines during rotational period.

### 5 RESULTS

**HELUM**: The helium lines are weakened in the spectra of HD 21699. Osmer and Peterson (1974) and Vauclair (1975) have shown that the formation of He-weak or He-rich stars depends on the wind power in their atmospheres. If we define VW as the relative velocity of flux with respect to a stellar wind and VD as the velocity of diffusion inside a star, then He-weak stars are formed when VW 

\[ VW > VD \]

as Pavlenko’s (2003) model atmospheres with a reduced He abundance. The atomic lists of VALD (Kupka et al.1999) and Castelli (http://wwwuser.oat.ts.astro.it/castelli/) were used as the input atomic data for the spectrum synthesis. The average abundance of each chemical species (assuming no vertical stratification) was determined by comparing observed spectral profiles to those produced by the models: SYNTTHV code (no magnetic splitting) and SYNTHM code, that takes into account magnetic splitting of lines (Version-04 without stratification). Stratification of chemical elements was determined in a similar vein using the SYNTTHM code (Version-05). Previously, we have determined the contribution function for each line using the code WITA (Pavlenko 1997).

**SiII**: The silicon lines are strengthened in the spectra of HD 21699. This is consistent with the formation of He-rich stars, which are characterized by a higher silicon abundance. The atomic lists of VALD (Kupka et al.1999) and Castelli (http://wwwuser.oat.ts.astro.it/castelli/) were used as the input atomic data for the spectrum synthesis. The average abundance of each chemical species (assuming no vertical stratification) was determined by comparing observed spectral profiles to those produced by the models: SYNTTHV code (no magnetic splitting) and SYNTHM code, that takes into account magnetic splitting of lines (Version-04 without stratification). Stratification of chemical elements was determined in a similar vein using the SYNTTHM code (Version-05). Previously, we have determined the contribution function for each line using the code WITA (Pavlenko 1997).
results for Fig. 2 were obtained using SYNTHM code which takes into account magnetic splitting of spectral lines. The abundance estimates are derived for the visible hemisphere for each phase.

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

For the lower layers, the abundance was derived from the line wings, while for the upper layers it was derived from the line cores. An example of the fit for the He I 4026 A line profile at phase 0.116 (MSS spectrum) is shown in Fig. 3. It is obvious that the line wings are quite sensitive to the helium abundances at the lower atmospheric layers. Therefore, the respective helium abundance can be specified with high confidence, namely with an error of 0.1 dex. Meanwhile, the core of a line provides information about the element abundance in the upper atmospheric layers. However, it provides a somewhat larger error, 0.2 dex. Only by taking into account the He stratification we can get a good fit between the model and the observed diffuse He line profiles for this He-weak sn-type star.

In Fig. 4 we show the vertical stratification of helium for nine phases, derived from the analysis of the He I 4026 A line profiles using the Kurucz model atmosphere 16000/4.0 for the visible hemisphere for each phase.

The results shown in Fig. 4 confirm the theoretical prediction of Vauclair et al. (1991), which predict the enhancement of helium abundance towards a deeper optical depth. In Fig. 5, we can see that as the phase changes, the optical depth \( \tau_{5000} \) corresponds to where the abundance jump behaves inversely to the variation of the He abundance (see Fig. 2).

SILICON: In Table 2, we show estimates of the 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. These values were obtained for the visible hemisphere for each phase without taking into account the silicon stratification.
Table 2. Variation of Si II mean abundance for 4 rotational phases: 0.118, 0.322, 0.525 are from MuSiCoS spectra and 0.687 is from NES spectrum.

| line (Å) | EP(eV) | log N(SiII)/N(H) vs. phase |
|---------|--------|---------------------------|
| 6347    | 8.12   | 0.118 -5.12 -4.92 -4.02 - |
| 6371    | 8.12   | 0.322 -5.12 -4.92 -4.12 - |
| 5041    | 10.07  | 0.525 -4.87 -4.67 -4.02 -4.25 |
| 5055    | 10.07  | 0.687 -5.15 -4.99 -4.55 -4.50 |
| 4673    | 12.84  | -4.37 | |
| 5669    | 14.21  | -4.88 | |
| 5202    | 16.35  | -3.80 | |

Table 3. Variation of mean silicon abundance log N(SiII)/N(H) (without stratification) with rotational phase (including MSS spectra): the phases 0.118, 0.322 and 0.525 Å are taken from Mu-SiCoS spectra, the phase 0.687 is NES spectrum. Wavelengths and EP of spectral lines are given in Table 2.

| Phase | mean 4128, 4130Å, EP=9.84 | mean (MuSiCoS & NES) 8-10eV 12-16eV | Si III 4552Å |
|-------|---------------------------|----------------------------------------|
| 0.023 | -4.90                     | -4.95                                  |
| 0.116 | -4.95                     |
| 0.118 | -5.06                     | -3.92                                  | -3.77        |
| 0.195 | -5.15                     |
| 0.314 | -4.80                     |
| 0.322 | -4.88                     | -3.89                                  | -3.75        |
| 0.393 | -4.50                     |
| 0.470 | -4.35                     |
| 0.525 | -4.16                     | -3.42                                  | -3.77        |
| 0.543 | -4.35                     |
| 0.682 | -4.15                     |
| 0.687 | -4.37                     | -3.72                                  |
| 0.928 | -4.70                     |

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 as suggested by Vauclair et al. (1979).

Table 3 shows a combination of the aforementioned data with the silicon abundances derived from Si II lines 4128 Å and 4130 Å for nine rotational phases using the MSS spectra. Table 2 presents them graphically as a variation of silicon (Si II) abundance with rotational phase. The estimates of log N(Si)/N(H) are derived from the lines of low excitation energies (clear circles) and high excitation energies (shaded circles) stand for the phases 0.118 and 0.322.

Fig. 6 presents the results from Table 3 for the three rotational phases of the observed spectra. The error bar shows the error of the averaged estimates. The error for single abundances was estimated as 0.1 dex.

Fig. 7 shows the fit of Si II lines 4128 and 4130 Å to model profiles, calculated taking into account magnetic broadening and stratification of silicon in the atmosphere. The lines with low excitation energy show an abundance deficit, while the lines with high excitation energy show an excess of silicon for the phases with maximal B_s (0.118 and 0.322).

We also determined Si III abundance from the 4552 Å line using the same model atmosphere 16000/4.0 (see last column of Table 3) for the three phases of MuSiCoS spectra. The results are close to abundances derived from the Si II lines of high excitation energies, justifying the choice of the model atmosphere.

It is remarkable that the abundance estimates derived from the analysis of lines with low excitation energies are in good agreement among themselves for all available spectra (MuSiCoS, NES and MSS). For the phases with minimal B_s (0.525 and 0.687) all the lines show an excess of silicon. Nevertheless, the lines with higher excitation energies still result in higher silicon abundance. They formed at deeper atmospheric layers and as a result we observe an enhancement of silicon abundance there. This is most obvious in the case of the "magnetic spot". In Fig. 7 we show the fit of Si II lines 4128 and 4130 Å to model profiles, calculated taking into account magnetic broadening and stratification of silicon in the atmosphere. Note the relatively good fits of profiles.

Fig. 8 shows an enhancement of silicon abundance towards the deeper atmospheric layers, as predicted by Vauclair et al. (1979). Fig. 9 presents stratification of Si II de...
rived from lines with different excitation energies for the phase of minimal magnetic field.

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 Meggessier (1984). Silicon usually accumulates in the places where the magnetic field lines are predominantly horizontal and where they can oppose the gravitational settling of ionized silicon. In the case of a shifted magnetic dipole, like 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 Tables 2 and 3 and Fig. 6, 7 and 8 it appears that our results confirm the predictions of Vauclair et al. (1979), Alecian and Vauclair (1981) and Meggessier (1984). In the atmosphere of HD 21699 silicon is enhanced in the area

where the field lines are horizontal to the stellar surface. The optical depth of the abundance jump for silicon $\tau_{5000}$ (like to helium) has a tendency to change with phases reversely to the silicon abundance variation (see Figs. 6, 10).

Abundance stratification due to diffusion processes acting in the atmospheres of chemically peculiar stars is studied in the recent work of Monin & LeBlanc (2007). Their self-consistent models show that elements such as Fe, Cr, Si and Ca do 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 $\tau_{5000} = 1$.

6 BASIC CONCLUSIONS

For the first time photospheric chemical element abundances of HD 21699 were obtained during the whole rotational period. Magnetic splitting of spectral lines and elements stratification in the atmosphere were taken into account with line profile modelling. Helium abundance is weakened for the whole stellar surface, which is usual for He-weak stars. Nevertheless, helium has higher abundance in the region of the "magnetic spot" due to the influence of stellar wind, which elevates the helium to the outer layers of the stellar atmosphere, and helium abundance should increase with optical depth in the atmospheres of He-weak stars. (Vauclair et al. 1991).

Silicon is accumulated in the part of the star where the magnetic field lines are predominantly horizontal, as it was predicted by Vauclair et al. (1979), Alecian and Vauclair (1981) and Meggessier (1984). Silicon abundance determined from lines with low excitation energies (8-10eV) appears to be lower in the area of the 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 significantly higher than solar everywhere on the stellar surface. Silicon abundance is lower in the outer parts of the atmosphere and higher in the deeper layers.

The optical depth of the abundance jump (in two-steps model) is near to $\tau_{5000} = 1$. In the cases of He I and Si II, we
can see a tendency to change $\tau_{5000}$ with the phase contrary to abundances, which could be the result of competition between the stellar wind, diffusion, and the local magnetic field geometry that would lead to accumulations of helium and silicon at different depths in the atmosphere.

Since IUE observations of the C IV resonance doublet show existence of magnetically controlled stellar wind in HD 21699 (Brown et al. 1985), one should expect some variations in Balmer lines, similar to that seen in H-alpha in 36 Lyn (Wade et al. 2006) and in many Balmer lines in HD 37479 (Smith et al. 2006) and in many Balmer lines in HD 37479 (Smith and Bohlender, 2007). Unfortunately, due to the incomplete number of observed phases it is difficult to find similar changes in Balmer lines in HD 21699.

7 ACKNOWLEDGEMENTS

We thank V. Tsymbal and S. Khan for the use of their codes: SYNTV and SYNTHM. Many thanks to the referee of the paper, Dr. Bohlender for the very valuable advice and comments. This work was partially funded by the Microcosmophysics program of National Academy of Sciences and National Space Agency of Ukraine and by the Natural Sciences and Engineering Research Council of Canada (NSERC).

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