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Rotationally-modulated photometric variations of magnetic CP stars – theoretical aspects

J. Krtička[1], Z. Mikulášek[1], J. Zverko[2], J. Žižňovský[2] and P. Zvěřina[1]

[1] *Institute of Theoretical Physics and Astrophysics, Masaryk University, Brno, Czech Republic*

[2] *Astronomical Institute of the Slovak Academy of Sciences, Tatranská Lomnica, Slovak Republic*

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Abstract. We study theoretical aspects of the light variability of magnetic chemically-peculiar stars, using HD 37776 and HR 7224 as the test cases for our understanding of the light variability. We are able to reproduce their light curves from the known distribution of surface elements. We show that the light variability of these stars is mainly due to the inhomogeneous surface distribution of overabundant silicon, iron and helium.

Key words: stars: chemically peculiar – stars: early-type – stars: variables: other – stars: atmospheres – stars: magnetic

1. The light variability of magnetic CP stars

The light variability of magnetic CP stars (mCP) proves to be a useful means both for a precise determination of their periods and for the study of changes of their spectral energy distributions (see Mikulášek *et al.*, 2008). Extensive studies of photometric, spectroscopic and magnetic field variations show that they are closely related to the inhomogeneous distribution of chemical elements and magnetic fields on the surfaces of mCP stars.

Despite the fact that the photometric variations are one of the main sources of information regarding the rotational periods of the mCP stars, modelling of their light curves has been rather scarce. The literature mentions several different sources which may influence the light variations of these stars, such as line-blanketing (Molnar, 1973), bound-free transitions (Peterson, 1970), surface temperature differences (e.g., Weiss *et al.*, 1976) and magnetic field (e.g., Khan, Shulyak 2008). One of the first attempts to model the light variability of mCP stars was that of Krivosheina *et al.* (1980), who were able to reproduce successfully the observed *vby* light variations of CU Vir by modifying the temperature gradient in the regions where silicon was overabundant.

2. HD 37776

In order to investigate how to model light curves in the presence of uneven surface distribution of chemical elements, we selected HD 37776. This helium-strong star HD 37776 is a member of the Ori OB1b association, and has a surface magnetic field with a strong quadrupolar component (Thompson & Landstreet, 1985). The surface distribution of helium, silicon, oxygen and iron was derived by Khokhlova *et al.* (2000) from Zeeman Doppler imaging. According to their analysis, silicon and helium are overabundant within spots, whereas oxygen and iron are underabundant everywhere on the surface.

Even though this star displays a strong rotational braking (Mikulášek *et al.*, 2008), we accepted in this study the linear ephemeris derived by Adelman (1997) (and which was also used by Khokhlova *et al.* (2000) in their surface mapping), as a fair approximation to the real situation.

2.1. Model atmosphere and synthetic spectrum

We assumed a fixed effective temperature $T_{\text{eff}} = 22\,000\,\text{K}$ and surface gravity $\log g = 4.0$ (CGS). Model atmospheres were computed using the code TLUSTY (Hubeny, Lanz 1995), with the silicon and helium ionic models from Lanz and Hubeny (2007). We considered plane-parallel model atmospheres in LTE. Lighter elements were included only while the influence of iron-peak elements was neglected since, according to Khokhlova *et al.* (2000), iron is underabundant in the atmosphere of HD 37776.

The synthetic spectrum, as the source of photometric colours, was computed using the code SYNSPEC. Bound-free and bound-bound transitions for the same ions as in the model-atmosphere calculations were taken into account.

We calculated Eddington fluxes $H(\lambda, Y, Z)$ for a grid of 80 model atmospheres with 10 different helium (Y) and 8 different silicon (Z) abundances (λ is the wavelength). The flux $H_c(Y, Z)$ in a colour c is obtained by a convolution of $H(\lambda, Y, Z)$ with the transmissivity function of filter c, where c stands for each of the filters in the *uvby* system.

We divided the visible stellar surface into 90×360 elements in latitude and longitude, respectively. The local abundances of helium and silicon in each surface element were set in accordance with the maps of Khokhlova *et al.* (2000). The abundances of other elements were (for simplicity) assumed fixed and equal to the solar values. Consequently, the flux $H_c(\Omega)$ is a function of spherical coordinates Ω on the stellar surface. The fluxes emerging from the elements were interpolated in a grid of fluxes for the 80 models. For more details, see Krtička *et al.* (2007).

2.2. Influence of chemical peculiarity on emergent flux

As a result of the greater opacity in the models with enhanced abundance of either helium or silicon, the local temperature in outer parts of the atmosphere increases owing to backwarming. The line-transitions influence the atmosphere's temperature only for $\tau_{\text{ross}} \lesssim 10^{-3}$, where the stellar atmosphere is basically transparent in continuum. Consequently, the main influence of the enhanced

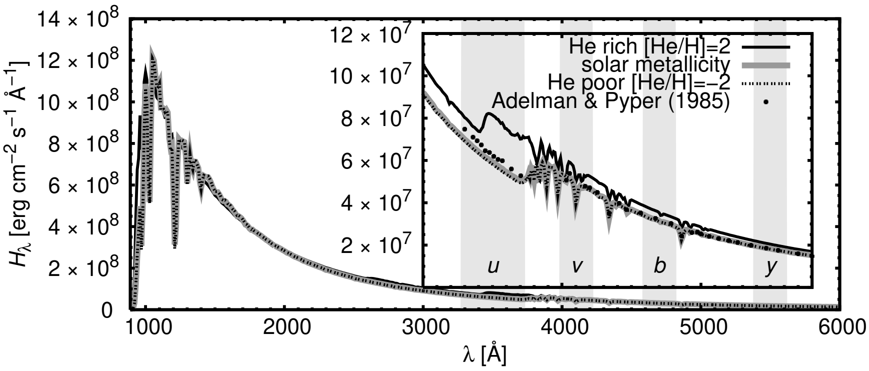


Figure 1. The emergent flux from atmospheres with different helium abundances. The flux was smoothed by a 10 Å Gaussian filter. The passbands of the *uvby* photometric system are also shown. The photometric region has also been enlarged, and overplotted. For reference we include the observed mean flux derived by Adelman and Pyper (1985) which we normalise using the predicted solar-abundance flux at 5000 Å.

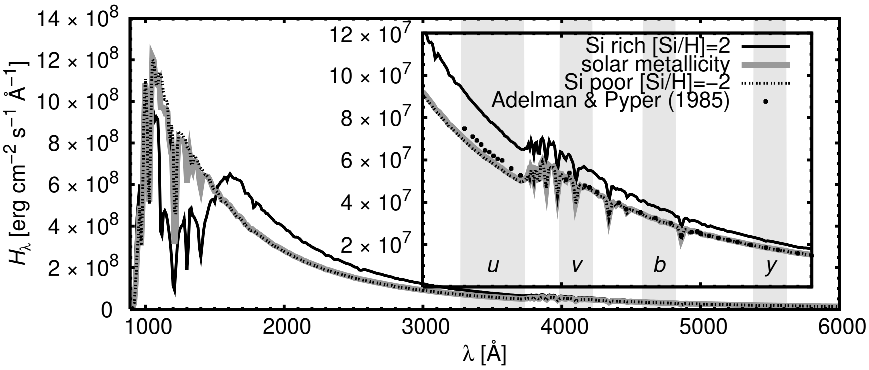


Figure 2. As Fig. 1, but for silicon.

abundance of helium and silicon on the temperature stratification of the atmosphere (in the region of photometric flux formation, i.e. for $0.1 \lesssim \tau_{\mathrm{ross}} \lesssim 1$) is due to bound-free transitions. In the case of silicon overabundance, the bound-free transitions from the higher excited levels of Si II and Si III contribute significantly to the continuum opacity in the wavelength region where most of the flux is radiated from the atmosphere of HD 37776, i.e. in the far UV region of the Balmer continuum.

The radiative flux emerging from the model atmosphere depends on the silicon and helium abundances, as can be seen in Figs. 1, 2. For solar chemical composition, the Balmer jump is visible. With increasing silicon abundance, the opacity in the ultraviolet (UV) region below roughly 1600 Å increases (mainly through to bound-free silicon transitions and partly through bound-bound transitions). The flux from this UV region is then redistributed towards longer wavelengths, partly into the optical region. Consequently, the regions in which silicon is overabundant are brighter in the *uvby* bands than those in which silicon is underabundant. A very similar situation also occurs in the case of helium overabundance: regions with helium overabundances are also brighter in the *uvby* bands than those with lower helium abundances. Decreases in helium and silicon abundances below the solar values outside the bright spots do not significantly influence the flux in *uvby*. We therefore expect only bright spots to occur on the stellar surface.

2.3. Simulation of the light variations

Since helium is the dominant element in the majority of regions on the surface of HD 37776, we started studying the light variations caused by this element only. Because the most helium-rich regions appear on the visible disk during the light minimum of the observed light variations, and because the helium overabundance induces the brightening of the stellar surface (Fig. 1), the predicted light variations caused by helium are practically in antiphase with the observed ones. Consequently, although helium contributes significantly to the light variability of the star being studied, there has to be another mechanism which dominates its optical variability.

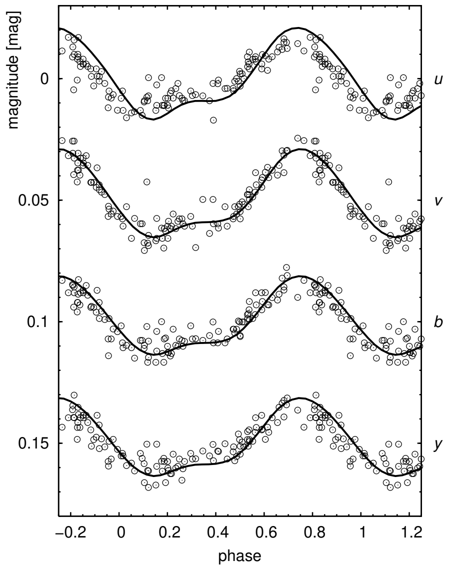
The fact that silicon is overabundant in the observed disc around the phase $\varphi = 0.75$, when the star reaches its light maximum, together with our finding that silicon-rich regions are bright, leads us to deduce that it is silicon which is the main cause of the variability of HD 37776. To test that, we calculated the light curve of taking into only account the uneven distribution of silicon. However, the amplitude of the light curve is then too large compared with the observed one; nevertheless, there is a good correspondence between the shapes of the observed and computed light curves.

Light curves computed for abundance changes in both silicon and helium are shown in Fig. 3. There is a very good agreement between the predicted and observed light curves in both shape and amplitude.

We therefore conclude that the observed light variability of HD 37776 can be successfully simulated by assuming an uneven surface distribution of individual elements, principally silicon and helium.

3. HR 7224

In order to study further the nature of the light variability of mCP stars we selected the Si–star HR 7224 (HD 177410 = EE Dra). The distribution of silicon and iron on the surface of this star was derived by Lehmann *et al.* (2007). For



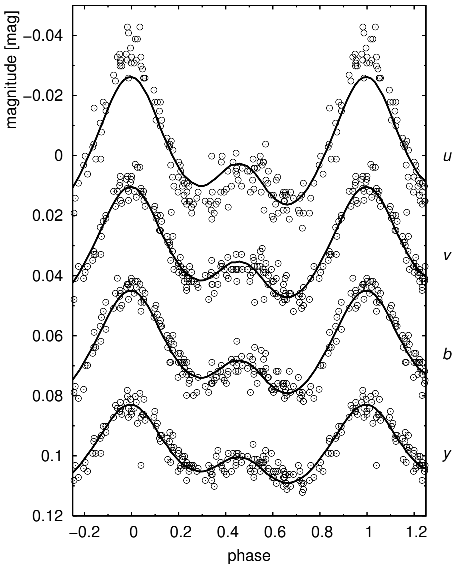


Figure 3. Left: The simulated light variations of the He-strong HD 37776 in different colours, derived by taking into account the uneven distributions of Si and He on its surface (solid line), compared with individual *uvby* observations of Pedersen, Thomsen (1977), Adelman and Pyper (1985), and Adelman (1997). Right: The same for the Si-star HR 7224.

the atmosphere modelling we selected the same atomic data as Lanz, Hubeny (2007), i.e. we also included iron. We adopted the fixed effective temperature and surface gravity $T_{\rm eff} = 14\,500\,{\rm K}$ and $\log g = 4.2$ (CGS) given by Lehmann *et al.* (2007).

The preliminary simulated light curves are given in Fig. 3. There is a good agreement between theoretical and observed light curves. Both silicon and iron contribute significantly to the light variability. In Fig. 4 we plot the logarithm of the ratio of model-atmosphere fluxes for two different iron abundances. In this plot the depression at 5200 Å is clearly visible, supporting the idea of Khan and Shulyak (2007) that this feature is mainly due to numerous iron lines.

4. Conclusions

We have shown (Krtička *et al.*, 2007) that the light variability of HD 37776 is due to the uneven distribution of silicon and helium. The use of the silicon model based on the Opacity Project data (Seaton *et al.* 1992; Butler *et al.*, 1993) has been a valuable asset for obtaining a good agreement between theory and observation.

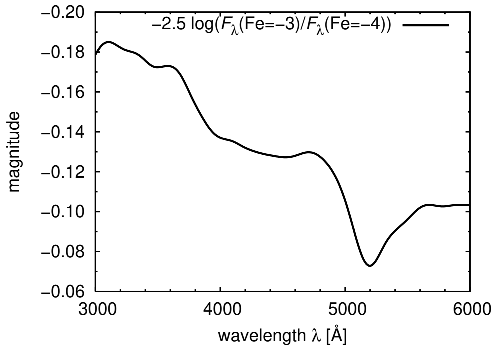


Figure 4. Comparison of heavily-smoothed model atmosphere fluxes calculated for two different iron abundances, showing the depression at 5200 Å.

Silicon is likely to be a causal factor in the light variability of other mCP stars with surface overabundances of silicon. This is supported by the comparison of observed and simulated light curves of the star HR 7224.

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