Testing opacities using the SED variability of chemically peculiar stars

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Abstract. Opacity variations across stellar surfaces are the key process producing the spectral energy distribution (SED) variability in chemically peculiar (CP) stars. The opacity variations are caused by the presence of surface spots with enhanced (or depleted) abundances of chemical elements. Simulations of the SED variability of chemically peculiar stars with abundances derived from Doppler mapping provide a detailed test of the continuum (bound-free) and line opacities in the model atmospheres. The effect of opacities on the SED is most pronounced in the ultraviolet region. We simulate the ultraviolet and visual SED variability of selected chemically peculiar stars using model atmospheres calculated for actual surface abundances and compare the predicted SEDs with observational results. We show that the simulations can reliably predict the observed SED and its variability provided that complete bound-free and bound-bound opacities are used. Therefore, the variability of chemically peculiar stars may serve as a test of opacities included in model atmospheres.

1. Introduction

In upper-main sequence chemically peculiar (CP) stars the processes of radiative diffusion and gravitational settling significantly modify the chemical composition of stellar envelopes (Michaud et al. 2015). The light variability of CP stars was detected in the beginning of the 20th century by Guthnick & Prager (1914). This type of the light variability is essentially ubiquitous among magnetic CP stars (Abt & Golso 1962). It has become clear that the light variability in CP stars is a result of a presence of surface spots and is modulated by the stellar rotation. However, unlike cool stars, the spots on the surfaces of CP stars have the same effective temperature as the rest of the stellar surface. Instead, the photometric variability of CP stars results from the presence of surface spots with peculiar chemical composition, and flux redistribution due to bound-free (Peterson 1970; Lanz et al. 1996) and bound-bound transitions (Wolff & Wolff 1971; Trasco 1972; Molnar 1973).

Hence the spots of Ap stars are best described as opacity spots, in contrast to the temperature spots of cool stars. Therefore, detailed opacity calculations are necessary for the modelling of the light variability of CP stars. Moreover, the comparison of predicted and observed light variability may serve as a test of the opacities due to individual atoms. We demonstrate this for three CP stars.

2. SED and light curve modelling

The spectral energy distribution (SED) and the light curve modelling are based on the surface abundance maps derived from the Doppler mapping. The method of Doppler mapping is an inversion technique that enables us to derive the surface distribution of elements from the spectroscopic line variations observed at different rotational phases. For given stellar parameters, we calculate model atmospheres and synthetic spectra for abundances derived from the Doppler mapping. For the modelling of the stellar atmospheres we use either the TLUSTY (Lanz & Hubeny 2007) or the ATLAS codes (Kurucz 2005) and for the modelling of the stellar spectra we use the SYNSPEC code.

For each rotational phase, we derive the emergent flux (SED) and the magnitudes in individual photometric filters from the emergent specific intensities integrated over the visible stellar surface. The resulting SEDs and light curves are compared with IUE flux distributions and observed photometric variations.

3. HD 37776

The helium-strong star HD 37776 (V901 Ori) is a hot CP star. The rotational period of this star is about 1.5 days (Mikulášek et al. 2011). For our modelling we use the helium and silicon surface abundance distributions derived from spectroscopic line variations using the Doppler mapping method by Khokhlova et al. (2000).

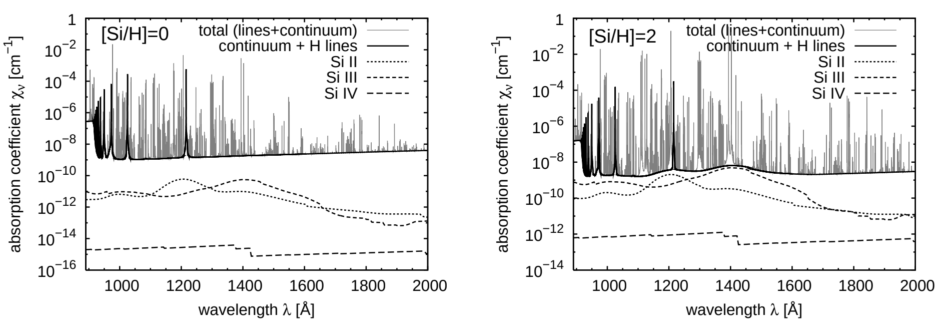

Figure 1. Typical absorption coefficient for HD 37776 atmosphere. *Left:* Solar chemical composition. *Right:* Enhanced abundance of silicon (by a factor of 100).

The overabundance of silicon in the surface spots of HD 37776 is so high that silicon may dominate the opacity in certain ultraviolet (UV) regions (see Figure 1). Consequently, the silicon bound-free absorption affects the emergent flux and redistributes the flux from the far-UV region to the near-UV and optical regions (see Figure 2). As a result, the silicon-rich regions are relatively bright in the optical regions and relatively dark in the far-UV regions. Helium affects the flux distribution in a similar way, but the helium-rich surface spots are located in different regions of the stellar surface than silicon rich spots.

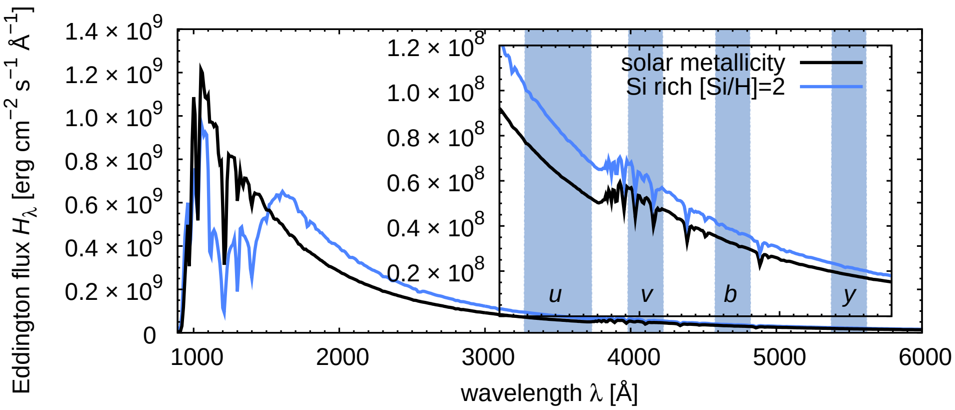

Figure 2. Comparison of the emergent fluxes from an atmosphere with a solar chemical composition and from an atmosphere with enhanced silicon abundance. The inset shows the detailed flux distribution in the region of Strömgren *uvby* colours.

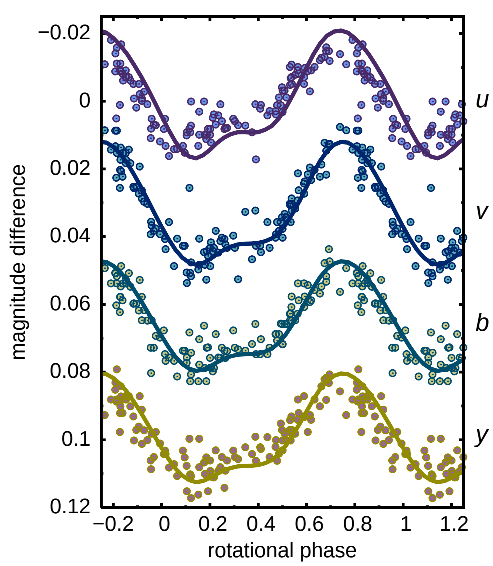

Figure 3. Comparison of observed (dots) and predicted (lines) light variability of HD 37776 in Strömgren photometric filters.

In the light curve of HD 37776, light variations due to silicon overcome variations due to helium (Krtička et al. 2007). Because the maximum silicon abundance appears on the stellar surface around phase $\phi \approx 0.75$, the visible light curve has a maximum around the same phase. The simulated light curve agrees nicely with the observed light curve obtained by Adelman & Pyper (1985). Our additional tests showed that such satisfacrory agreement could be obtained only by including all levels of the corresponding silicon ions derived within the Opacity Project (Seaton et al. 1992).

4. CU Vir

For the modelling of the light variability of CU Vir we used He, Si, Cr, and Fe surface abundance maps derived from spectroscopy by Kuschnig et al. (1999). We compared the derived light and SED variations with observations derived by Pyper et al. (1998) and IUE (see Krtička et al. 2012).

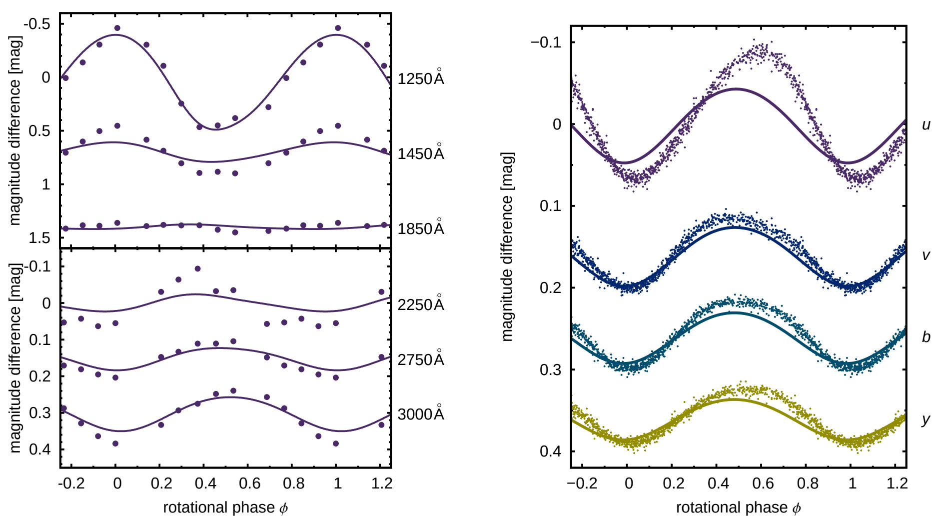

Figure 4. Predicted light curves of CU Vir in comparison with observation. *Left:* Variations in selected UV bands. *Right:* Variations in Strömgren photometric filters. The remaining differencies are most likely caused by some additional element(s).

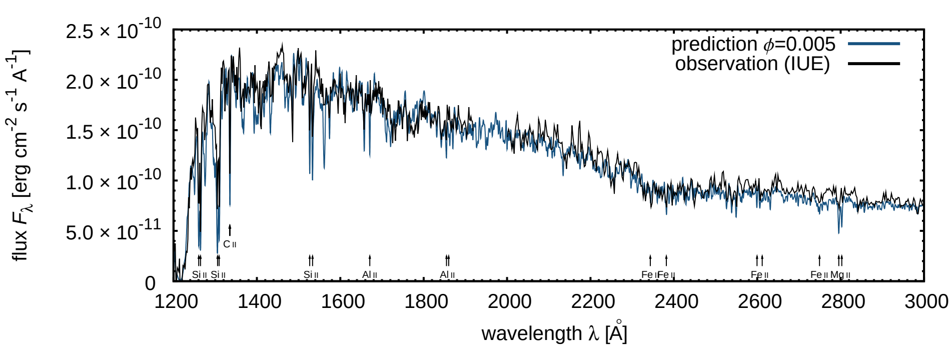

Figure 5. Comparison of the calculated and observed SED for phase $\phi = 0.005$

The light curve of CU Vir is dominated by bound-free transitions of silicon (Butler et al. 1993) and bound-bound transitions of iron and chromium (Kurucz 2005). These processes lead to the redistribution of flux from the far-UV to near-UV and optical regions. Therefore, surface regions that are overabundant in silicon, iron, or chromium are bright in the optical regions. These elements account for most of the variability of CU Vir (see Figure 4). It is also possible to compare the SED at individual rotational phases with observations and to test the opacities in detail (Figure 5).

5. a Cen

V761 Cen (a Cen) belongs to the brightest CP stars of the southern sky. For the modelling of the light variability of this star we used He, N, O, Si, and Fe surface distribution derived from Doppler mapping.

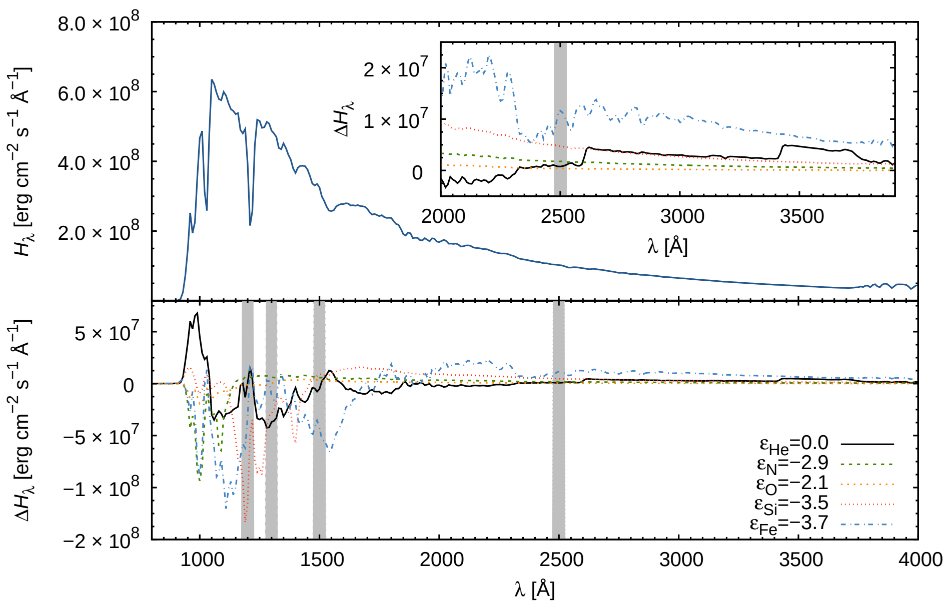

Figure 6. *Upper:* SED for a Cen parameters for solar chemical composition. *Lower:* The difference between the SED calculated for the enhanced composition of a given element and the SED calculated for solar chemical composition. The near-UV region is enlarged in the inset.

Individual elements influence the SED in different wavelength regions (see Figure 6). Therefore, the light variability in individual UV regions in Figure 7 tests the opacity of different elements. The light variability at 1200 Å is given mostly by silicon. At 1300 Å both silicon and helium contribute, however because the surface abundances of these elements are nearly anticorrelated, the amplitude of the light variability at 1300 Å is relatively small. The light variability at 1500 Å is dominated by iron lines, whereas at 2500 Å iron lines and bound-free transitions of silicon dominate. In general, the predicted light variations nicely agree with IUE observations.

6. Conclusions

The light variability of CP stars is caused by flux redistribution in the abundance spots combined with stellar rotation. The redistribution is connected to opacity variations

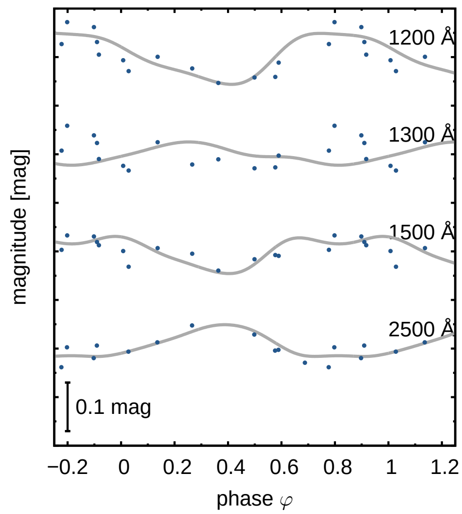

Figure 7. Comparison of observed (IUE, dots) and predicted (lines) UV light variability of a Cen

with abundance due to helium and silicon bound-free transitions and iron and chromium line transitions. The observed and predicted light variations typically agree nicely providing an additional test of opacities due to individual ions.

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