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PZ Mon: Influence of Spots on Radial Velocity Measurements

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We present calculations of radial velocity corrections along the phase curve due to influence of the spotted surface of the active giant, PZ Mon. The maximum deviation from a relatively uniformly-bright stellar disk is about 0.20–0.25 km s^{-1}.

1 Introduction

PZ Mon is a K2III chromospherically active variable star of the RS CVn type (Pakhomov et al., 2015). Its activity manifests itself by the presence of cool photospheric spots and modulation of brightness by stellar rotation that provides observable amplitude about $0^{\mathrm{m}}_{.}10$ in the V band with a period of $\sim 34^{\mathrm{d}}_{.}13$. This is a binary system with a low-mass component and an orbital period of $\sim 34^{\mathrm{d}}_{.}15$ (Pakhomov & Gorynya, 2015). The position of main spots responsible for variability is stable (Pakhomov et al., 2017), they are located toward the secondary component (Pakhomov & Gorynya, 2015). Thereby, the axial rotation of PZ Mon and the orbital motion of the low-mass component are synchronous.

The radial velocity (RV) curve of PZ Mon corresponds to a circular orbit and has the amplitude 5.4 km s^{-1} (Pakhomov & Gorynya, 2015). To date, we have 75 RV measurements obtained with five instruments, most of them (64), with the Radial Velocity Meter (Tokovinin, 1987) installed at the Simeiz 1-m telescope of the Crimean Astrophysical Observatory. These measurements have a typical error about 0.2–0.3 km s^{-1}. For others spectrographs, the accuracy is about 0.1–0.7 km s^{-1}. Main observations cover more than nine years from 2011 to 2021; we also have one RV measurement of 1989 from Saar (1998). Despite the accuracy of the data, we have a significant scatter with respect to the theoretical RV curve calculated as the best solution of orbital elements. The rms deviation is 0.97 km s^{-1}. Pakhomov & Gorynya (2018) tried to find the third component in the system, but without success.

On the other hand, the RV deviations can be caused by rotation of the spotted surface of PZ Mon. In this case, the cool spots will contribute less to the total stellar flux, and the velocity field of brighter areas will dominate. Therefore, there will be a shift of the RV with respect to a uniformly bright stellar disk. Considering that the rotation velocity of PZ Mon is 10.5 km s^{-1}, we can expect noticeable shifts.

In this paper, we present calculations of the RV changes during one rotation period of PZ Mon.

2 Model of PZ Mon Surface

We use a model calculated for the multiband extended Johnson photometric system, from U to L (Pakhomov et al., 2018). The model is a map that consists of three areas of different temperatures: the quiet surface ($T_{\rm eff}$=4730 K, ∼40..60% of visible stellar disk), the permanently visible cool spotted area ($T_{\rm eff}$=3500 K, ∼40%), and the warm spotted area ($T_{\rm eff}$=4480 K, ∼0..20%). This model describes all observed features: the shape of photometric curves in all bands, the amplitudes in all bands, the total spectral energy distribution, the intensity of photospheric spectral lines. The map size is 7200×3600 cells.

3 Calculations

For each rotation phase, we transformed the initial map of the stellar surface (l, b – analogues of longitude and latitude) to the polar coordinate system (θ, ϕ) starting at the star's center, where θ=[0 .. $\pi/2$] is the angle between the directions towards the observer and towards the cell of the stellar surface, ϕ=[0 .. 2π] is the positional angle.

The observed intensity of a cell with the coordinates (θ, ϕ) is:

$$\begin{cases} I_{\theta,\phi} = I_0(T_{eff})\ \cos\theta\ \delta A\ \mathrm{limb}(\theta), & \theta < \pi/2 \\ I_{\theta,\phi} = 0, & \theta \geq \pi/2 \end{cases}$$

where $I_0(T_{\rm eff})$ is the intensity of unit area with effective temperature $T_{\rm eff}$ from Bessell et al. (1998); $\delta A = \cos b\, \delta l\, \delta b$ is the area of the cell on stellar surface; $\mathrm{limb}(\theta) = (1-\epsilon) + \epsilon\, \cos\theta$ is the linear limb darkening law from van Hamme (1993); we used the ϵ value for the center of the V band.

The radial velocity of the cell is:

$$V_{\theta,\phi} = V_{\rm eq}\ \sin i\ \sin\phi\ \sin\theta,$$

where $V_{\rm eq}\ \sin i = 10.5\ \mathrm{km\,s^{-1}}$ is the projection of equatorial velocity on the line of sight.

The radial velocity derived from the total stellar flux is intensity-weighted average:

$$V_{\rm rad} = \frac{\sum V_{\theta,\phi}\, I_{\theta,\phi}}{\sum I_{\theta,\phi}}.$$

This value of $V_{\rm rad}$ is the radial velocity of PZ Mon caused not by the real motion of the star but by the rotation of its spotted surface. The RV during one rotation period is shown in Fig. 1 as the solid curve. In this case, we consider radiation in the continuum. However, actual RV measurements are based on shifts of spectral lines. The contribution of quiet and spotted areas will change depending on the atomic data for selected spectral lines. Different lines have different excitation energies E, therefore, different intensities and different temperature dependences. We calculated the profiles of two lines, Fe I λ=5170 Å with E=6.0 eV and Fe I λ=5307 Å with E=1.6 eV (Fig. 2). Each final profile is composed of three profiles calculated for corresponding temperatures (4730, 4480, 3500 K), taking into account the map of the PZ Mon surface. Shifts of the lines with respect to laboratory wavelengths give us the RV changes due to influence of the spotted surface and are shown in Fig. 1.

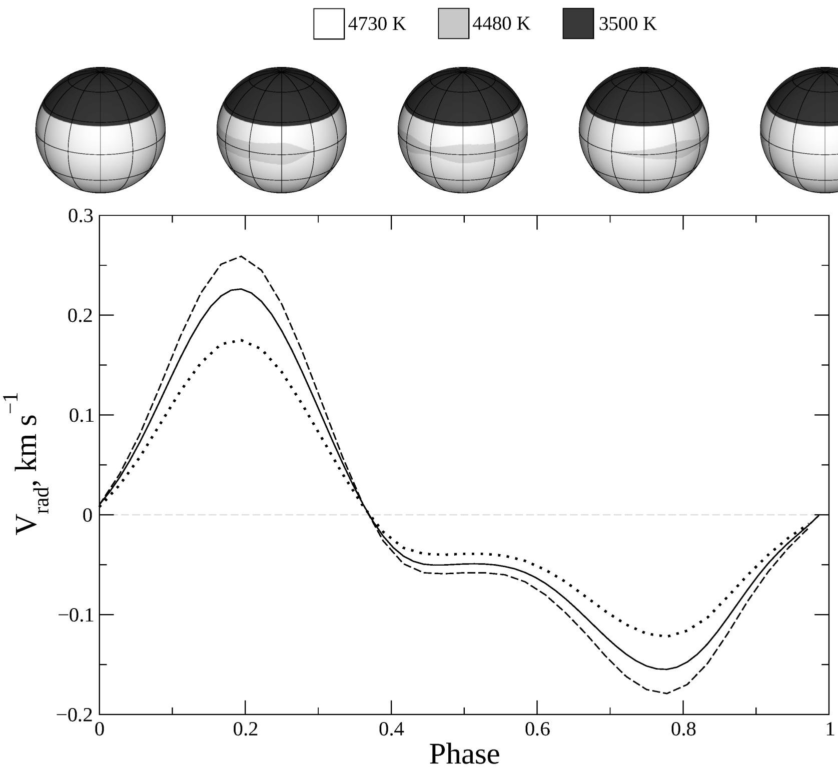

Figure 1. The radial velocity curve of PZ Mon due to influence of spotted surface. *Solid curve:* the case of radiation in continuum. *Dashed curve:* the case of the Fe I 5170 Å spectral line with E=6.0 eV. *Dotted curve:* the case of the Fe I 5307 Å spectral line with E=1.6 eV.

4 Discussion

Radiation of the quiet surface dominates in the V band (provides up to 80%) due to higher temperature and larger area (Fig. 2). The presence of warm spots significantly distorts the rotation profile and leads to RV changes in the direction of quiet surface motion. The cool spot does not affect the RV. Indeed, the photometric solution requires constant area of cool spots. They can be evenly located on the surface of PZ Mon or located at the visible pole. In either case, this gives a symmetrical rotation profile without a shift. Moreover, the contribution of the cool spot is small because of its low temperature.

The map of PZ Mon surface was constructed from photometric data of 2017–2018. However, most of the RV measurements were obtained between 2013 and 2019. Analysis of data from the ASAS and ASAS-SN projects shows no change in photometric behavior. Comparison of several epochs of accurate photometric observations (better than $0\overset{m}{.}01$) reveals some changes (Pakhomov et al., 2018, 2019) in the maximal brightness and the amplitudes. Their main reason is the change of cool spot's size. As seen from the above, the influence of the cool spot on RV measurements is small. The position of warm spots is stable, they define the shape of light curve of PZ Mon and consequently the shape of the RV curve. Thus, calculated RV corrections may apply for our data.

Our calculation shows the maximal effect of 0.25 km s^{-1} using spectral lines with high excitation energy. However, typical energies of most lines are 1..4 eV; this limits the maximum of RV changes by about 0.22 km s^{-1}. All corrected RV measurements convolved with the period of $34\overset{d}{.}15$ are shown in Fig. 3. The accuracy of RV measurements obtained with the Radial Velocity Meter (RVM) is the same or better. Therefore, it is necessary to take into account calculated RV changes to correct the RV measurements. On the other

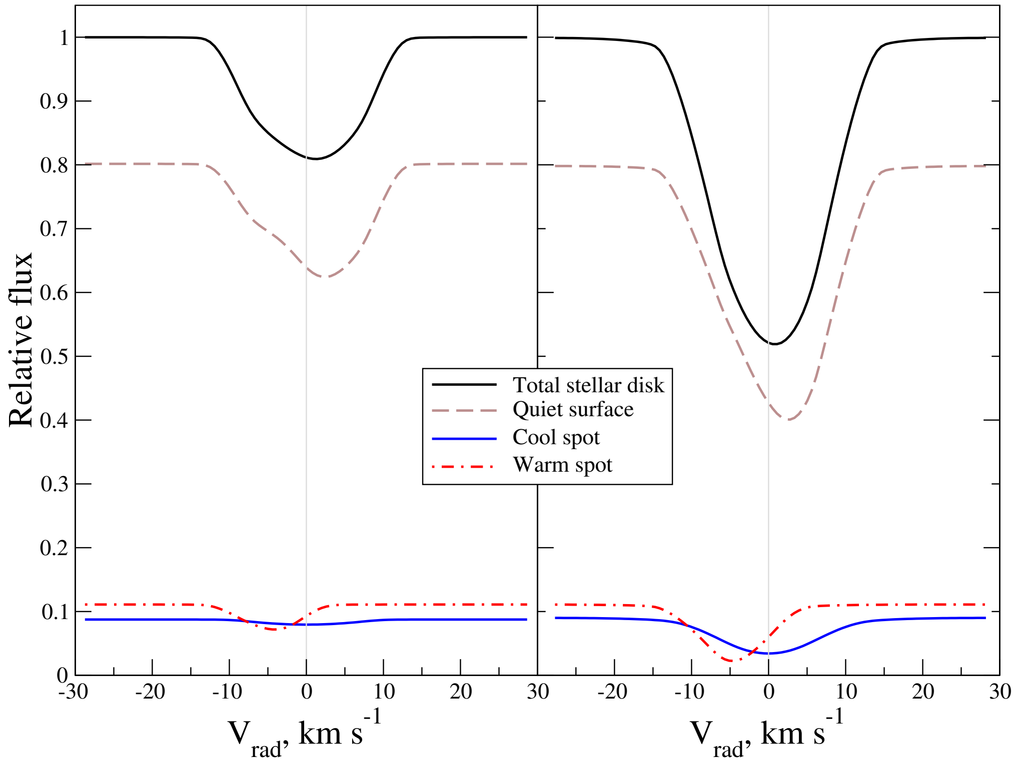

Figure 2. Theoretical profiles of Fe I 5170 Å (*left panel*) and 5307 Å (*right panel*) spectral lines formed in different parts of the spotted surface of PZ Mon for phase=0.1944 with the maximal positive RV shift.

hand, the (O–C) scatter is much larger (0.97 $\mathrm{km\,s^{-1}}$), which requires an explanation.

5 Conclusions

In this paper, we calculated corrections of radial velocities due to influence of the spotted surface of the active giant PZ Mon during one rotation period. The maximal effect is about 0.25 $\mathrm{km\,s^{-1}}$, which is comparable to the accuracy of RV measurements. This influence is noticeable. However, the reason for large (O–C) scatter remains open.

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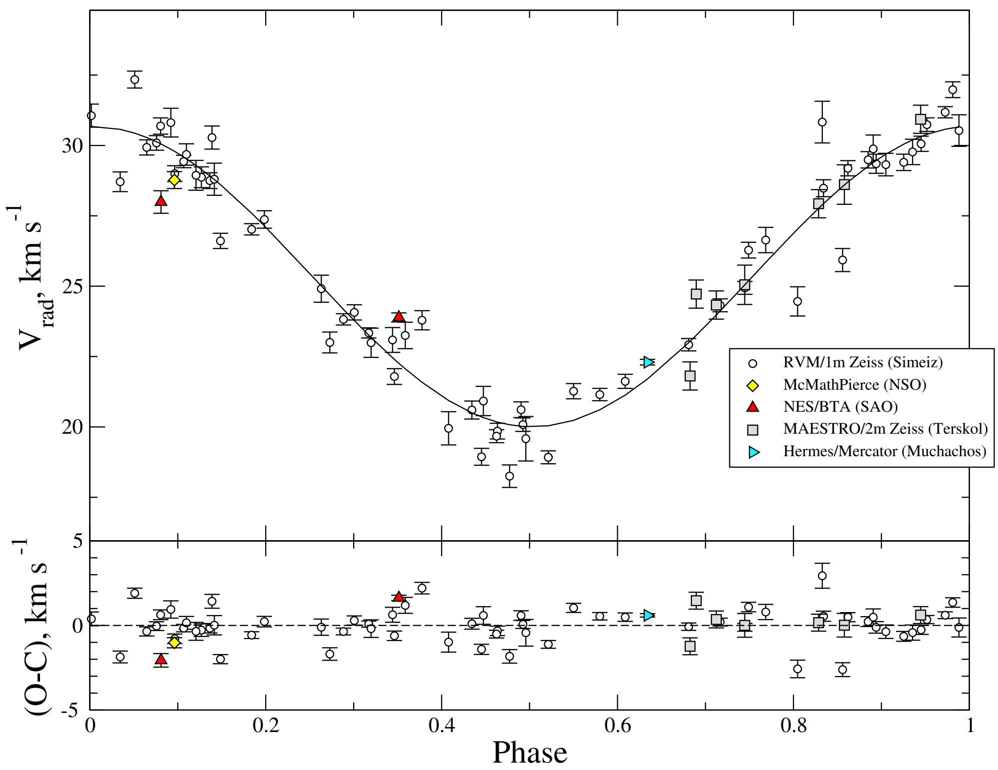

Figure 3. *Top*: Radial velocity curve of PZ Mon corrected for influence of the spotted surface. The orbital solution is plotted as the *solid curve*. *Bottom*: Observation minis calculation (O–C) residuals. The instruments, telescopes, and observatories are identified in the legend.

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