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Dependence of starspot temperatures on the spectral type and luminosity of stars

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ABSTRACT

The paper considers the spottedness models for 54 stars with solar-type activity at different evolutionary stages (stars of different spectral types and luminosity classes). We note the dependence of starspot temperatures on the temperature of the undisturbed photosphere for stars at each stage of evolution (young post T Tau stars, dwarf stars on MS, and evolved giants). A weak dependence of starspot temperatures on the evolutionary stage of stars is shown. The general analytical expression for estimating starspot temperatures by the temperatures of undisturbed photospheres is obtained.

Key words: stars, starspots

Cold spots in the photospheres of late-type stars, along with powerful sporadic flares, extended coronae and chromospheres, are manifestations of solar activity in stars with outer convective envelopes. Studying such activity is the subject of solar-stellar physics research, allowing one to extend the pattern of solar magnetism to stars with a wide range of parameters: masses ranging from 1.5 to 0.05 $M_{\odot}$, ages from millions to billions of years, axial rotation periods ranging from hours to many tens of days, and evolutionary statuses ranging from young T Tauri stars to highly evolved giants. On the other hand, studying general patterns of stellar magnetic activity provides insights into the Sun as a well-studied specific case, validating common assumptions and exploring deeper the subtle processes of stellar magnetism.

The only star where we can easily study photospheric spots with high spatial resolution is the Sun. For all other stars, we have to use indirect methods to gather information about the presence of starspots and their physical parameters. The first method for independent estimation of starspot temperatures was proposed by Vogt (1981) based on simultaneous photometric observations in two passbands, V and R. Later Poe, Eaton (1985) demonstrated that the best-fit bands are V and I bands. The method used in both studies was applicable to stars of spectral types G–K, including both dwarfs and giants. Six years later, Gershberg et al. (1991) modified the Vogt – Poe – Eaton method for M dwarfs and successfully applied it to determine spot parameters on the flaring star EV Lac. This method is still in use, at least for estimating spot temperatures in first approximation. Further refinement of spot temperatures is achieved using various image reconstruction methods, such as the maximum entropy method (Messina et al., 1999), Occam's method (Berdyugina et al., 2002), or the least squares method (e.g., Savanov, Strassmeier, 2008).

Other methods for determining spot temperatures are based on spectral observations. The most promising one is the Doppler imaging method. The initial concepts of this method were proposed by Deutsch (1958) and Khokhlova (1975), with the first observational profile analysis of the spotted star being carried out by Vogt, Penrod (1983). However, since the method deals with subtle changes in spectral lines, it requires a high signal-to-noise ratio (about 300–400) and a significant axial rotation velocity of a star $v \sin \iota$ to make a line profile as accurately as possible, imposing strict constraints on the selection of target stars. For slowly rotating stars, Doppler imaging transitions into a simpler method called LDR, which examines changes in the depths of photospheric lines and allows for a straightforward estimation of the temperature and relative area of spots (e.g., Catalano et al., 2002). The third spectral method for estimating the temperature and relative area of spots is based on studying molecular bands that are atypical for the quiet photosphere of the target star but typical for cooler spotted areas. These are usually bands of titanium oxide TiO (Hünemörder, Ramsey, 1987) and hydroxyl OH 1.563 μm (O'Neal, Neff, 1997).

For spotted dwarfs, the main number of studies has been carried out using multicolor photometry. The first robust statistical characteristics of spot parameters of such stars were obtained within the zonal spottedness model proposed and developed at the Crimean Astrophysical Observatory (Alekseev, Gershberg, 1996a, b, c, 1997; Alekseev, 2008). In this model, it is assumed that, similar to the Sun, spots are located on stars along two bands parallel to the equator, and the star's rotation with inhomogeneous distribution of spots in longitude produces a photometric effect similar to the effect of continuous spottedness bands with variable width. From the results of the initial calculations of zonal models, it was inferred, in particular, that the spotted areas have temperatures

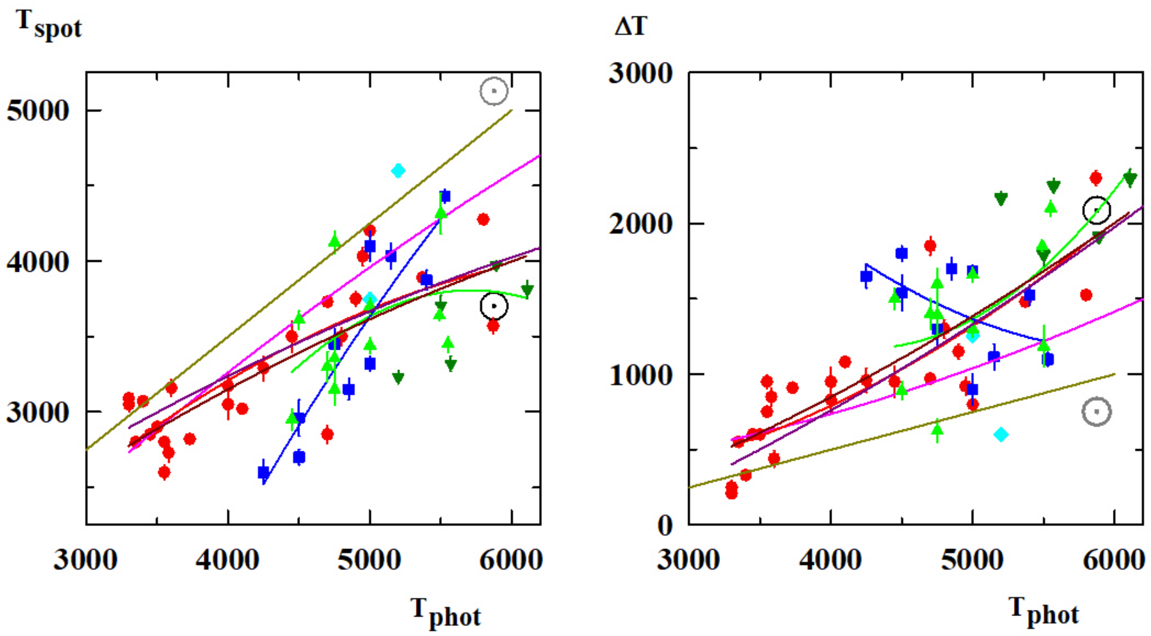

Fig. 1. Dependence of spot temperatures on photospheric temperatures. Red circles and dashed line represent calculations by Alekseev, Kozhevnikova (2017, 2018) and their quadratic approximation (1). Green symbols and line show giant stars, blue squares and line show young stars. The dark red solid line represents the approximation of the entire array of our calculations (4). The dark pink dash-dotted line is the approximation by Berdyugina (2005); pink, the approximation by Herbst et al. (2021); dark yellow, the calculations by Savanov, Dmitrienko (2019). Symbols ⊙ denote the temperatures of sunspot umbrae (black symbol) and penumbrae (gray symbol).

ranging from 4000 K for solar-type stars and 2500–3000 K for the coldest M dwarfs, whereas the temperature differences between the undisturbed photosphere and spots reach 2000 K for hot stars and 300 K for cold stars (Alekseev, 2001, 2008).

Alekseev, Kozhevnikova (2017, 2018) developed the zonal spottedness models for 26 dwarf stars of spectral types G–M over the entire period of their photometric observations. The results of these calculations are shown by red circles in Fig. 1. The left panel of the figure shows spot temperatures for different photospheric temperatures, while the right panel shows the temperature differences between the quiet photospheres and spots for different photospheric temperatures. The red dashed line represents a second-order curve approximation:

$$T_{\rm spot} = (-8.69 \cdot 10^{-5})(T_{\rm phot})^2 + 1.252\, T_{\rm phot} - 409.2, \quad (1)$$

drawn through these points (Alekseev, Gershberg, 2021). The root mean square deviation from the curve amounts to 280 K. In this study, we supplemented the sample of dwarfs with calculations for 18 evolved giants: 5 short-period systems of the RS CVn type (dark green triangles pointing downwards), 2 fast-rotating giants of the asymptotic branch of the FK Com type (green-blue diamonds), and 11 classical systems of the RS CVn type (green triangles pointing upwards). The calculations we used are detailed in Kozhevnikova, Alekseev (2015) and Alekseev, Kozlova (2013). The green solid line represents a second-order approximation:

$$T_{\rm spot} = (-3.392 \cdot 10^{-4})(T_{\rm phot})^2 + 3.876\, T_{\rm phot} - 7266. \quad (2)$$

Blue squares denote the calculations of spot temperatures for 10 stars that have just left the T Tau stage (post T Tauri stars) based on the data in Alekseev (2014), Alekseev, Kozlova (2001), Kozhevnikova et al. (2018). The blue solid line shows the approximation of these data:

$$T_{\rm spot} = (-1.524 \cdot 10^{-4})(T_{\rm phot})^2 + 2.892\, T_{\rm phot} - 7016. \quad (3)$$

The entire array of our data is approximated by the curve

$$T_{\rm spot} = (-4.058 \cdot 10^{-5})(T_{\rm phot})^2 + 0.8295\, T_{\rm phot} + 481.9 \quad (4)$$

(dark red solid line), with a root mean square deviation of points amounting to 350 K.

Irrespective of the Crimean results, in an extensive review on solar and stellar spots, Berdyugina (2005) examined the existing methods for estimating their temperatures, including, along with multicolor photometry of the target stars, the following spectroscopic methods: Doppler imaging, modeling of molecular bands, and the depth ratios of spectral lines. For 29 stars of different spectral types and luminosity classes, the author obtained a dependence of spot temperatures on the photospheric temperatures, qualitatively similar to ours, denoted by the dark pink dash-dotted line in Fig. 1:

$$T_{\rm spot} = (-3.58 \cdot 10^{-5})(T_{\rm phot})^2 + 0.751\, T_{\rm phot} + 808. \quad (5)$$

It is worth noting that the work provides for EK Dra two significantly different estimates of spot temperatures obtained by two different methods – Doppler imaging and analysis of molecular bands of titanium oxide. The latter estimate is close to ours. Herbst et al. (2021) slightly modified

Berdyugina's method and calculated starspot temperatures for the same sample of stars, obtaining a similar dependence:

$$T_{\rm spot} = (-3.58 \cdot 10^{-5})(T_{\rm phot})^2 + 0.801\,T_{\rm phot} + 666.5. \quad (6)$$

We can see that the red, dark red, and dark pink lines in Fig. 1 are almost coincident. These dependences are consistent with the umbrae of sunspots. Additionally, Herbst et al. (2021) extended Berdyugina's sample to 45 objects of different luminosity classes with photospheric temperatures ranging from 3300 to 6400 K. Their results are presented in Fig. 1 by the pink line:

$$T_{\rm spot} = (-3.58 \cdot 10^{-5})(T_{\rm phot})^2 + 1.0188\,T_{\rm phot} - 239.3. \quad (7)$$

Up to photospheric temperatures of 4900 K, it almost coincides with our red curve, then it starts to deviate upwards, and the deviation reaches about 500 K around 5500 K. The corresponding error bar width, according to their estimates, ranges from 470 K for M stars to 680 K for G stars.

According to the latest measurements by Savanov, Dmitrienko (2019) of 15 giant stars using Doppler imaging and photometry of exoplanet transit over spots, a more gradual change in the temperature difference between the quiet photosphere and the spot ΔT from the photosphere temperature was obtained. According to their estimates, the temperature difference ΔT decreases from about 1000 K for G0 stars to 200 K for M4 stars (dark yellow line), and this dependence is consistent with the penumbra of sunspots. It is worth noting that some stars in our sample, such as IN Com, AR Psc, V775 Her, LQ Hya, AB Dor, also fit well into this dependence.

Thus, we conclude that the methods we apply to determine starspot temperatures based on photometric BVRI observations primarily indicate the temperatures of spot umbrae. These temperatures are almost independent of the evolutionary status of the star and are primarily determined by the temperature of the photosphere. It can be considered that the dependences we have identified (4) and similar ones (5) and (6) are universal for stars of different luminosity classes, and they can be recommended for direct estimates of the temperature of starspot umbrae based on the effective temperatures of photospheres. The found dependences also satisfy the estimates of the temperature of sunspot umbrae. On the other hand, the spot temperature measurements used by Savanov, Dmitrienko (2019) and Herbst et al. (2021) likely account more the contribution of the penumbra and are primarily applicable to the estimates of its temperature. The estimates of the temperature of sunspot penumbrae also satisfy the dependence found by Savanov, Dmitrienko (2019).

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