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Stellar Spottedness Models

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ABSTRACT: Starspots are one of the most important characteristics of stars with solar-type activity. This paper briefly outlines the history of studying these structures, from a single round spot in the middle of the past century to the present-day three-component stellar surface consisting of the quiet photosphere, cold spots, and hot faculae. Particular attention is given to the zonal spottedness model proposed and developed in Crimea, which is practically unknown to our foreign colleagues due to the fact that almost all the studies on this model have been published in Russian.

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1. Introduction

Low-temperature regions on the surface of lower main-sequence stars – the so-called starspots – are a key characteristic of stars with solar-type activity. The idea that cold starspots, similar to those on the Sun, are responsible for the variable brightness

of stars was first proposed in the 19th century. However, systematic studies of starspots have been initiated after electrophotometry became the dominant method in stellar photometry, producing stellar light curves with an accuracy of hundredths of a magnitude and higher. Such data allowed the light curves of stars with a single spot to be represented by selecting four parameters: two coordinates, the size and temperature of the spot. Spots on red dwarf stars were actually discovered in 1949 by Kron (1952) from slight distortions in the light curve of the binary system YY Gem that violated the shape of the light curve typical of eclipsing systems. Figure 1 shows the results of electrophotometry for two flaring red dwarfs with noticeable spottedness.

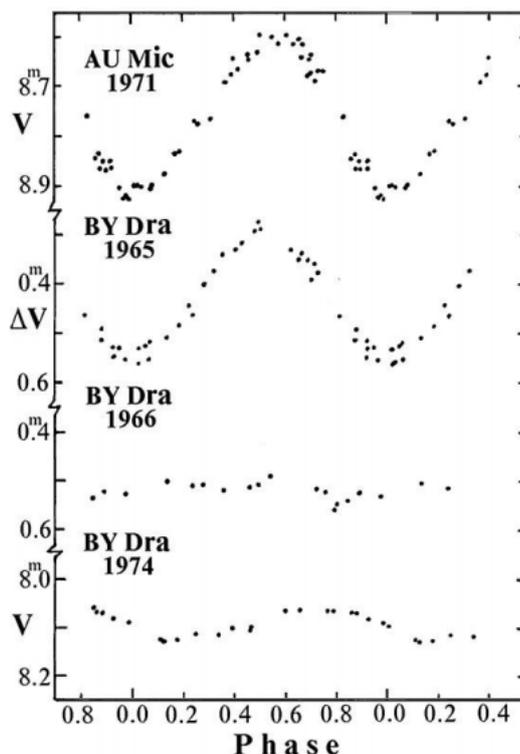


Figure 1. Brightness variations of two red dwarfs caused by their spottedness (Rodonó, 1980).

The first step in modeling starspots was taken by Krzeminski (1969): he “collected” all inhomogeneities into a single spot, “lowered” its temperature with respect to the unperturbed photosphere by 350 K – by two spectral subtypes – and estimated the spot size required for the observed photometric effect: approximately 10% of the stellar surface. The result of Krzeminski has inspired the construction of a number of spottedness models for red dwarf stars.

By increasing a number of parameters sought, models with two spots were proposed. Among them, much attention was given to a model suggested by La Fauci and Rodonó (1983). The attempts to construct models with three spots yielded no significant results. All of the aforementioned models with a small number of spots are currently hardly used, having been replaced by multispot models with a quite new physical approach and different mathematical ideologies. Four of them are briefly described below. Particular attention is given to the zonal spottedness model. Being proposed and developed in Crimea, it remains practically unknown to foreign colleagues due to the fact that almost all the studies on this model have been published in Russian.

2. Matrix Light Curve Inversion

Wild (1991) should be excluded proposed a purely photometric method for imaging stars using Matrix Light curve Inversion (MLI). This method does not imply in advance the number and shape of spots, while the stellar surface is divided into numerous small regions, and the uniqueness of their brightness distribution is found using a regularization procedure. At an

appropriate inclination of the stellar rotation axis to the line of sight and a light curve recorded at different wavelengths, the method allows one to find high-latitude spots, often detected by Doppler imaging described below. Being inferior in resolution to Doppler imaging, MLI has an advantage in using numerous archival data, in the comparative simplicity of obtaining new observations and in the absence of strict requirements for stellar rotation rates and spectral resolution.

The MLI method has become widely applied with the appearance of panoramic data from the Kepler satellite. Savanov and Strassmaier (2008) developed an original MLI program for reconstructing temperature inhomogeneities at the stellar surface, incorporating a statistical approach proposed by Terebizh (2004) to the solution of the inverse problem. Photometric imaging proved to be particularly effective in constructing maps of stellar surfaces with two or more spots based on data acquired by spacecrafts. Examples of such studies are published in the following papers: Croll (2006), Mosser et al. (2009), Huber et al. (2010), Frasca (2011), Silva-Valio and Lanza (2011), Fröhlich et al. (2012), Harrison et al. (2012), Gizis et al. (2013), Notsu et al. (2013), Savanov (2015), Savanov and Dmitrienko (2018).

3. Doppler imaging

The spectral Doppler imaging method has become widely used in studying stellar spottedness. According to this method, the stellar surface is divided into dozens of regions, and a spectral line widened due to a significant rotation of the star is also divided into a number of narrow stripes. The special algorithms were proposed to connect these regions and stripes, using a series of high-resolution spectrograms for different rotation phases. A region that corresponds to a stripe of reduced intensity should be considered as a starspot with defined coordinates, size, and temperature. The Doppler imaging method can only be applied to fairly bright stars with significant rotation in order to reliably estimate the intensity of relatively narrow stripes, and this limitation is quite significant for faint flaring stars.

Doppler imaging has revealed a significant diversity of starspot latitudes: there are stars with high-latitude and polar spots and without them, with spots predominantly at mid- and equatorial latitudes, and with spots extending from the equator to high-latitude regions. There are cases where imaging for different spectral lines yields different maps of spottedness and differentiates maps constructed from observations at different epochs. Stars with variations in differential rotation have been detected.

Numerous results from Doppler imaging of stars are summarized in reviews by Berdyugina (2005) and Strassmaier (2009).

Regardless of the results of Doppler imaging, photometric imaging remains relevant. Firstly, photometric investigations cover longer time periods and are therefore more appropriate for searching for activity cycles, differential rotation, and other long-term effects. Secondly, some stars with low rotation rates are generally inaccessible to Doppler imaging, and only photometric investigations are suitable for searching for statistical dependences of starspot parameters over a wide range of stellar global characteristics. Thirdly, the final result of Doppler imaging is significantly affected by the choice of lines under study, the precise determination of the star's rotation rate and inclination angle of its axis, the selection of model atmosphere parameters, the contribution of chromospheric activity, the appropriate choice of integration grid, etc. And finally, looking at the results of Doppler imaging based on the same initial data but obtained by different methods, one can only be surprised by the repeated statements that Doppler imaging results depend weakly on the method used to solve the inverse problem. Upon closer examination, Doppler imaging remains a kind of art, whereas a rougher estimate of spottedness parameters from photometric observations is free from numerous additional input data required and ambiguity in the choice of the calculation method.

4. Zonal Model of Stellar Spottedness

As is known, the distribution of sunspots across the surface of our star commonly reveals two bands, symmetric relative to the equator, with a high density of these structures. Postulating an identical surface structure for flaring stars, in a series of papers

at the Crimean Astrophysical Observatory in the late 20th century, Alekseev and Gershberg (1996, 1997) proposed studying the spottedness of such stars not based on the parameters of individual spots but on the general characteristics of these spottedness bands. In the simplest case, such a zonal model is determined by four independent parameters: the distance of the dark bands from the equator, φ_0 ; mean spot latitude, $\langle\varphi\rangle$; temperature; and the parameter of band inhomogeneities in longitude. Such a model corresponds to a star with a single active longitude.

The approach to calculating these spottedness parameters from multicolor photometric observations was described in the monograph by Alekseev (2001): measurements at brightness maxima and minima were taken from BVRI observations, and four zonal model parameters were determined from this excessive system of eight integral equations. In the mentioned monograph, Alekseev summarized the initial results of such studies. He examined 338 zonal models for 25 red dwarf stars in the spectral type range G1–M4.5e and detected certain physically significant correlations between the global parameters of stars and their spot characteristics (see Fig. 2).

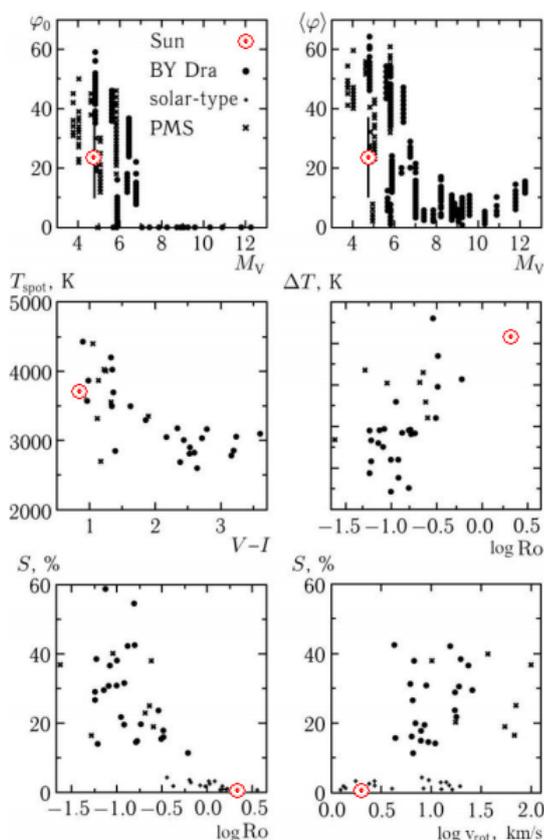


Fig. 2. Comparison of the calculated parameters of stellar zonal spottedness models (the distance from the equator to the spottedness bands, φ_0 ; the mean latitude of the spottedness band, $\langle\varphi\rangle$; the spot temperature, T_{spot} ; temperature differences between the photosphere and spots, ΔT ; and the degree of spottedness of the stellar surface, S) and global stellar parameters (absolute stellar magnitude, M_V ; rotation rate, v_{rot} ; and Rossby number) (Alekseev and Gershberg, 1996).

The top two graphs show the dependences of the distance of spottedness bands from the star's equator φ_0 and the mean latitude of bands $\langle\varphi\rangle$ on the absolute luminosity M_V . For stars with absolute luminosities $M_V > 7^m$, zonal model calculations reveal the merging of two supposed equatorially symmetric bands into a single equatorial band. On hotter stars, the spots shift toward mid-latitudes and occupy a wider latitude range. As noted by Obridko, Sokolov, and Katsova (2023), stars with a single

equatorial spottedness band and two equatorially symmetric bands should have different magnetic field structures. These graphs also demonstrate that sunspot parameters are located in the region of starspot localization.

The second pair of graphs shows spot temperatures and temperature differences between the quiescent photosphere and spots in relation to the $V-I$ color and the logarithm of Rossby number. The left graph reveals a consistent trend in spot temperatures, from 4000 K for solar-type stars to 2500–3000 K for the coldest M dwarfs. A comparison of the temperature differences between the photospheres and spots, ΔT , with the global parameters of the stars revealed that, on average, this difference reaches 2000 K for hot stars and 300 K for cold stars. The dependence on Rossby number is less reliable here, but the solar symbol is localized along the continuation of the starspot localization.

Note that Alekseev and Gershberg (2021) recently found a correlation between starspot temperatures, determined within the zonal spottedness concept, and the temperatures of the corresponding quiescent photospheres.

The bottom pair of graphs shows the spottedness areas, but no clear dependence of this parameter on global stellar parameters is seen. This is likely because spottedness area is the least stable parameter of stellar activity, and there is no reason to expect its correlation with stationary global stellar parameters.

For those 10 of the 25 stars considered, for which photometric imaging had been previously conducted, the spot areas and temperatures found within the zonal models were in satisfactory agreement with the corresponding previously obtained estimates. Subsequent multicolor photometric observations in Crimea (Alekseev and Kozlova, 2003) and in Kourovka (Kozhevnikova et al., 2004; Alekseev and Kozhevnikova 2017, 2018) were also successfully represented within the zonal spottedness model.

For several of the most spotted stars, for which the calculated zonal models revealed distinct spottedness bands, Livshits et al. (2003) and Katsova et al. (2003) found systematic shifts of the lower boundaries of these bands toward the equator as the activity cycle evolves. Thus, based on the concept of zonal spottedness models, they constructed spot drift diagrams similar to solar Maunder butterfly diagrams (see Fig. 3).

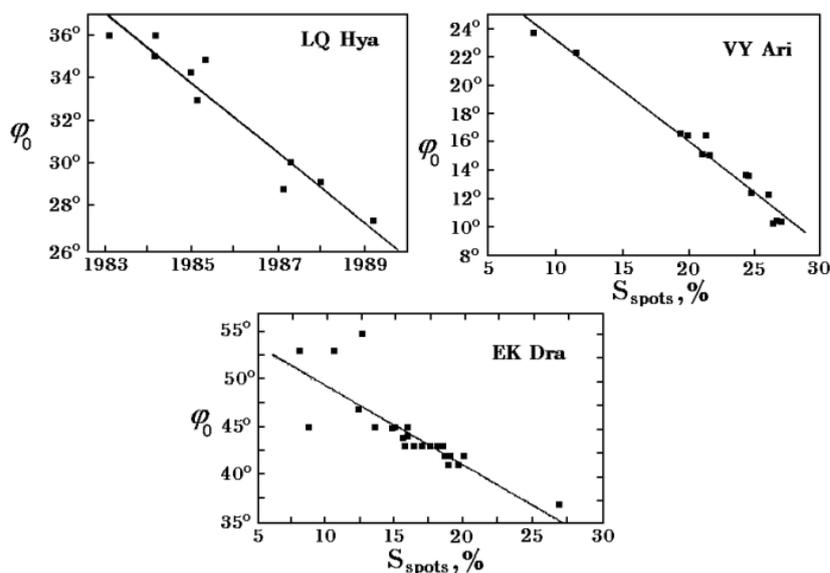


Fig. 3. Evidence of stellar cycles: based on the zonal spottedness model i.e. stellar analogues of Maunder butterflies (Katsova et al., 2003; Livshits et al., 2003).

Bruevich and Alekseev (2007) estimated the spottedness of a number of stars with activity levels close to solar ones and found that it increases from the solar level of 0.3% to 1–5% for HK stars (stars from the HK project) and then sharply increases to 20–35%. The authors found a close relationship between the area of spots and X-ray emission intensity of stars.

Alekseev (2006) successfully applied the zonal spottedness concept to variables of other types: RS CVn, FK Com, and T Tau. Using the zonal spottedness concept, Grankin and Artemenko (2009) presented variations in the light curves of the T Tauri star V410 Tau over eight consecutive observing seasons (see Fig. 4).

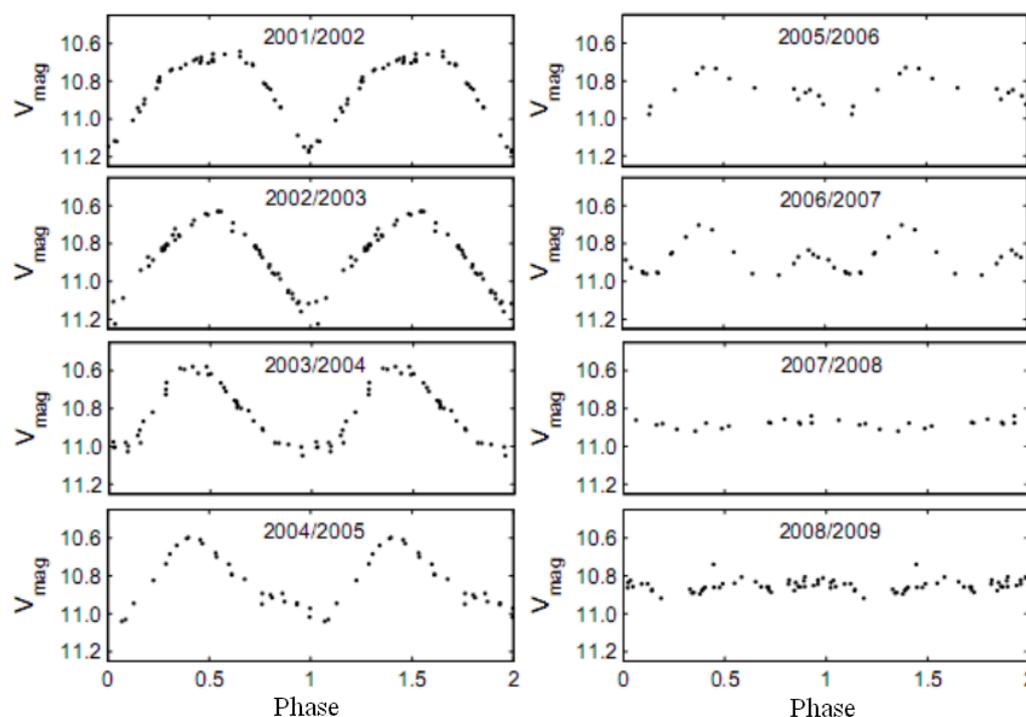


Fig. 4. Light curves of one of the brightest and most active T Tauri stars, V 410 Tau, over eight consecutive observing seasons: spot asymmetry in longitude was noticeable in the first four, while it was almost invisible in the last four observing seasons (Grankin and Artemenko, 2009).

Thus, the zonal spottedness concept proved to be highly effective in studying nonstationary stars: physically significant correlations in stellar spottedness parameters have been detected within its framework, which are not seen in studies using other methods. Unlike two- and three-spot models, zonal model calculations do not include any hierarchical idea of spottedness structure, that is, it does not predetermine which spot will be the main one and which ones will be secondary. However, a method for studying stellar spottedness in which hierarchical conception is essential has been recently proposed by Sagynbayeva et al. (2025).

Unfortunately, the existing algorithm for searching for zonal spottedness parameters has a disappointing drawback: among many hundreds of zonal spottedness models calculated, there is none with polar or high-latitude spots, although such spots were not ruled out in advance when calculating model parameters. However, such spots are quite common in the results of the aforementioned Matrix Inversion and Doppler imaging methods. Attempts to overcome this drawback have been undertaken for many years. Thus, Alekseev (2008) examined a zonal model not with a linear variation of spottedness in longitude but with a more complex, double-humped variation, introducing additional definable parameters into the model. Physically, this meant considering two simultaneously active longitudes on a star, and the author presented the extreme points of the light curves for 25 stars

at 679 epochs with an accuracy of no worse than $0^m.01$. However, the recalculated four input model parameters remained practically unchanged. The absence of high-latitude spots in the zonal model remains an open issue. Its solution is likely to be found by solving integral equations on a topologically more complex spatial structure.

5. Three-component stellar surfaces

The uniformity of the solar surface is violated not only by dark spots but also by bright faculae, with the latter often having higher energy than spots; thus, maximum solar radiation occurs during periods of maximum spottedness. This circumstance stimulated the consideration of three-component stellar surfaces: the quiescent photosphere, spots, and faculae.

Lanza et al. (2009) explored the photometric properties of the G7V star CoRoT-Exo-2a and obtained a continuous light curve over 142 days with an accuracy that is unprecedented at that time. Using regularization by the maximum entropy method, they searched for the effects of cold spots and hot faculae, resulting in the construction of a model with two active longitudes, with the distance between them changing by 80° over the observation period. The contribution of faculae turned out to be much smaller than on the present-day Sun.

Analyzing the high-precision light curves of ϵ Eri and κ^1 Cet, Gondoin (2008) suspected that their variations can determine not only dark stellar spots but also bright faculae. Savanov (2009) estimated the relative area of faculae and cold spots on these stars to be small and concluded that long-term brightness variations in stars younger than the Sun are primarily caused by spots, whereas the contribution of facula fields becomes more noticeable in older stars.

Frasca et al. (2010) analyzed photometric monitoring of the young solar-type rotator HD 171488 (V889 Her) with $P_{\text{rot}} = 1.337$ days and presented the B and V band light curves by two large high-latitude spots and bright faculae.

Johnson et al. (2021) published the first analysis of the expected photometric features of magnetoactive G–M stars with hot faculae and cold spots. The theory developed by them is based on light curves in various photometric bands and relies on differences in the visibility of spots and faculae at different distances from the disk center and on the limb-darkening effect of the disk.

6. Conclusions

Over 75 years since the discovery of starspots, several dozens of thousands spotted stars have been identified, and significant progress has been made in understanding these structures: namely, the development of methods for estimating their basic parameters and the detection of their connections with global stellar characteristics and with other manifestations of stellar activity. To date, the evolutionary epoch of the appearance of starspots on stars and the nature of their changes during stellar evolution have been determined.

Among the stellar spottedness models briefly reviewed above, the original zonal spottedness model deserves special attention: being proposed and developed in Crimea, it is practically unknown to foreign colleagues because papers on this topic have been mainly published in Russian. However, as noted above, the algorithm of this model requires further development.

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