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Surface mapping of the young solar-like star V1358 Ori with the updated SpotDIPy code

E. Bahar[1,2], **İ. Özavcı**[1,2], **E.B. Yorulmaz**[1,2], **G.A.J. Hussain**[3] and **H.V. Şenavcı**[1,2]

[1] *Department of Astronomy and Space Sciences, Faculty of Science, Ankara University, Beşevler TR-06560 Yenimahalle, Ankara, Türkiye (E-mail: enbahar@ankara.edu.tr)*

[2] *Ankara University, Astronomy and Space Sciences Research and Application Center (Kreiken Observatory), İncek Blvd., TR-06837 Ahlatlı bel, Ankara, Türkiye*

[3] *European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands*

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Abstract. New features integrated into the open-source Doppler imaging code SpotDIPy were introduced, with an application performed on the young solar-like star V1358 Ori. A three-temperature approximation was adapted to the SpotDIPy code to reconstruct regions on the stellar surface that are both cooler and hotter than the photosphere. Additionally, the code was updated to enable simultaneous solutions of both spectroscopic and photometric data. The code has been improved both in terms of performance and user interface. The high-resolution spectra and the TESS light curve of V1358 Ori were simultaneously modeled for the first time using the new version of SpotDIPy, resulting in the surface brightness distribution of the star.

Key words: magnetic activity – starspots – solar-like stars

1. Introduction

The study of stellar surface brightness distributions, particularly in young solar-like stars, is crucial for understanding magnetic activity and its evolution. Although interferometry is applied for direct imaging of a limited number of stars, most stars require indirect techniques such as Doppler imaging, which is known as the only method capable of producing high-resolution surface brightness distributions. In this context, SpotDIPy (Bahar et al., 2024), an open-source code, was developed to generate surface brightness distributions using Doppler imaging and light curve inversion techniques. Initially, the code was based on a two-temperature model that accounted for cool spots and the photosphere. It was later extended to a three-temperature model by incorporating hot spots as well, enabling a more comprehensive representation of surface brightness distribution. Additionally, SpotDIPy now supports simultaneous Doppler imaging and light curve inversion, which was applied to V1358 Ori to derive its surface brightness distribution.

2. SpotDIPy code

SpotDIPy is a Python-based Doppler imaging and light curve inversion code based on a three-temperature approximation. It has been designed to be as simple and user-friendly as possible, while offering a powerful interface for visualizing the results. Some of the key features of SpotDIPy are listed below.

- Constructs a surface grid consisting of surface elements with approximately equal areas, taking into account the oblateness of the star due to its rotation. Additionally, it incorporates the effect of gravity-darkening as described by Espinosa Lara & Rieutord (2011).
- Calculates limb-darkening effects for the relevant wavelength range or passband, based on each surface element's temperature, surface gravity (logg), and metallicity values using $ExoTiC\!-\!LD$ (Grant & Wakeford, 2024) Python package.
- Generates synthetic spectral line profiles considering the effects of macroturbulence and the instrumental profile.
- Accounts for differential rotation in the inversion process.
- Determine specific stellar parameters (such as *vsini*) using the grid search technique.

3. Observations

V1358 Ori was observed using the NARVAL high-resolution (R ≈65000) echelle spectropolarimeter, mounted on the 2-meter Bernard Lyot Telescope at the Observatoire Midi-Pyrénées, Pic du Midi, France, between January 3 and 16, 2019. A total of 10 spectra were obtained from PolarBase (Donati et al., 1997; Petit et al., 2014), covering approximately 1.5 stellar rotations. The light curve data were obtained from the TESS space telescope (Ricker et al., 2015), specifically using observations that coincided with the temporal coverage of the spectroscopic data.

4. Analyses and results

The surface brightness distribution of the star V1358 Ori was obtained using the SpotDIPy code by simultaneously modeling spectral line profiles and light curve data. Since the accuracy of the surface brightness distribution derived from Doppler imaging is highly dependent on the signal-to-noise ratio (SNR) of the data, high SNR average line profiles were generated using the Least Squares Deconvolution technique (Donati et al., 1997). The input parameters required for Doppler imaging were adopted from the study by Kriskovics et al. (2019). While Kriskovics et al. (2019) used a range of temperatures in their Doppler imaging analysis, our approach employs a three-temperature model. Specifically, we adopted the quiet photosphere temperature of 6040 K from Kriskovics et al. (2019), and used the minimum and maximum spot temperatures reported in that study, 4500 K and 6400 K, as the representative temperatures for the cool and hot spot regions, respectively. Differential rotation was not considered in our Doppler imaging analysis. Given that the time span of our spectral and photometric data is approximately 1.5 stellar rotations (about 2 days), the effect of differential rotation are expected to be negligible within this time frame. The best-fit results obtained from the simultaneous analysis are shown in Figure 1, 2, and 3.

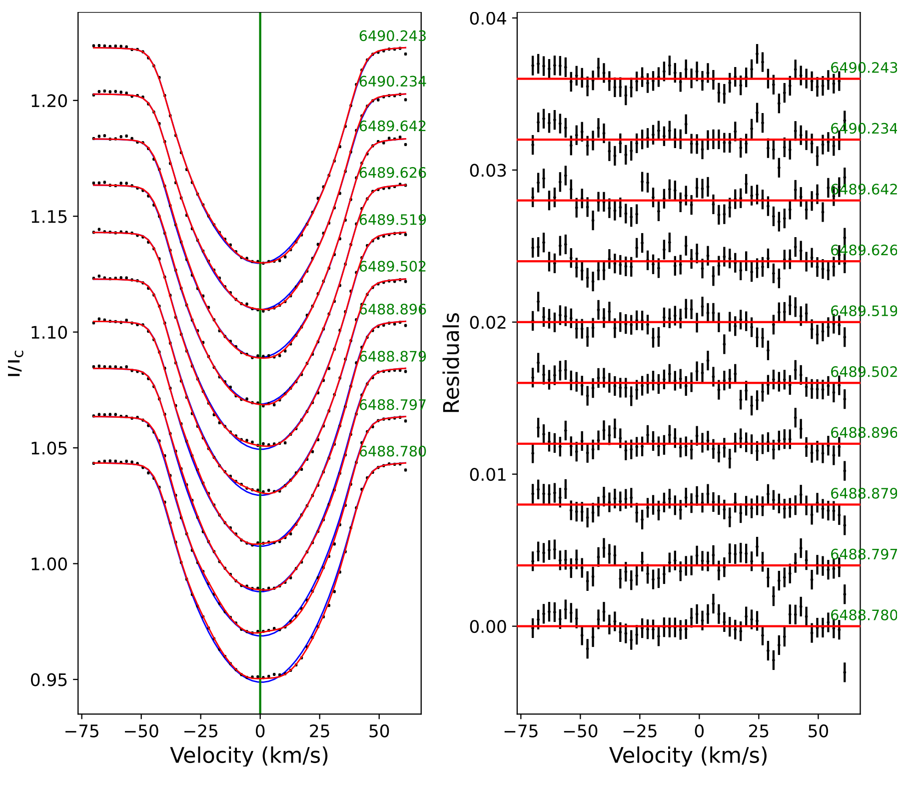

Figure 1. Left: the observed spectral line profiles (black dots), spotted model (red lines), and spotless model (blue lines). Right: residuals.

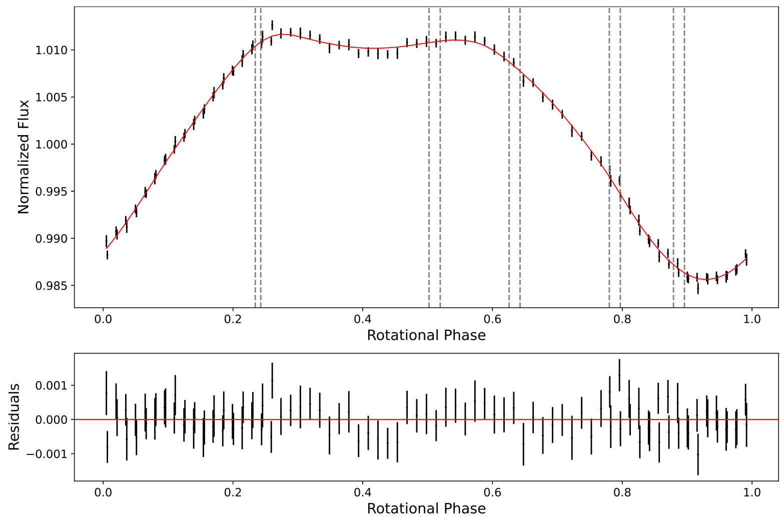

Figure 2. Top: the observed light curve (black dots) and the spotted model (red line). Vertical dashed lines corresponding to the mid-phase of the observed spectral data used in the Doppler imaging analysis. Bottom: residuals.

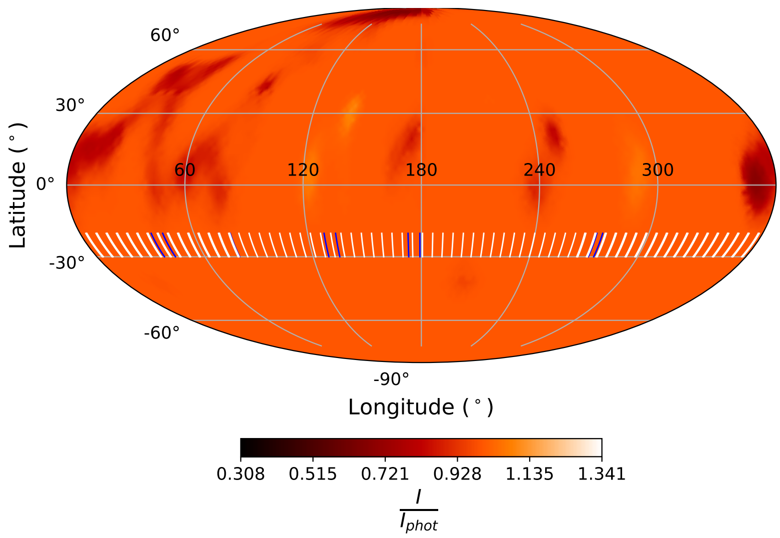

Figure 3. The surface brightness distribution map of V1358 Ori in Mollweide projection. The white and blue stripes show the distribution of photometric and spectral data used in this study along stellar longitude, respectively.

5. Conclusion and future work

In this study, using the SpotDIPy code, we obtained the surface brightness distribution of the young solar-like star V1358 Ori, revealing cool spots primarily at mid and high latitudes, especially near the equator. The results, derived from high signal-to-noise ratio (SNR) data, offer valuable insights into the star's magnetic activity. It is important to note that the uneven phase distribution of the spectral data, with a maximum phase gap of 0.347, may result in the appearance of artificial spots on the resulting map. The latest version of SpotDIPy has been upgraded to simultaneously model both spectral line profiles and light curves for single stars based on a three-temperature approximation. In the future, we plan to expand SpotDIPy's capabilities to generate surface brightness distributions for binary stars. SpotDIPy is available on GitHub (https://github.com/EnginBahar/SpotDIPy).

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