Surface Mapping of the Young Solar-like Star V1358 Ori with the Updated SpotDIPy Code

Engin Bahar, İbrahim Özavcı, Eda B. Yorulmaz, Gaitee Hussain, Hakan V. Şenavcı

A Young Solar Analog Star: V1358 Ori

Table 2. Fundamental astrophysical parameters of V1358 Ori.

$T_{\rm eff}$	6040 ± 25 K
$\log g$	4.44 ± 0.04
[Fe/H]	0.04 ± 0.02
$v_{\rm mic}$	3.0 ± 0.5 km s^{-1}
$v_{\rm mac}$ (computed)	3.6 km s^{-1}
$v \sin i$	38 ± 1 km s^{-1}
Distance	52.0 ± 1.3 pc
$M_{\rm bol}$	$4.23^{\rm m}{}^{+0.06}_{-0.05}$
$L/L_{\odot}$	$1.62^{+0.09}_{-0.07}$
$R/R_{\odot}$	1.17 ± 0.03
Inclination	$60 \pm 10^{\circ}$
$P_{\rm rot}$	1.3571 d
NLTE Li abundance	2.27 ± 0.05

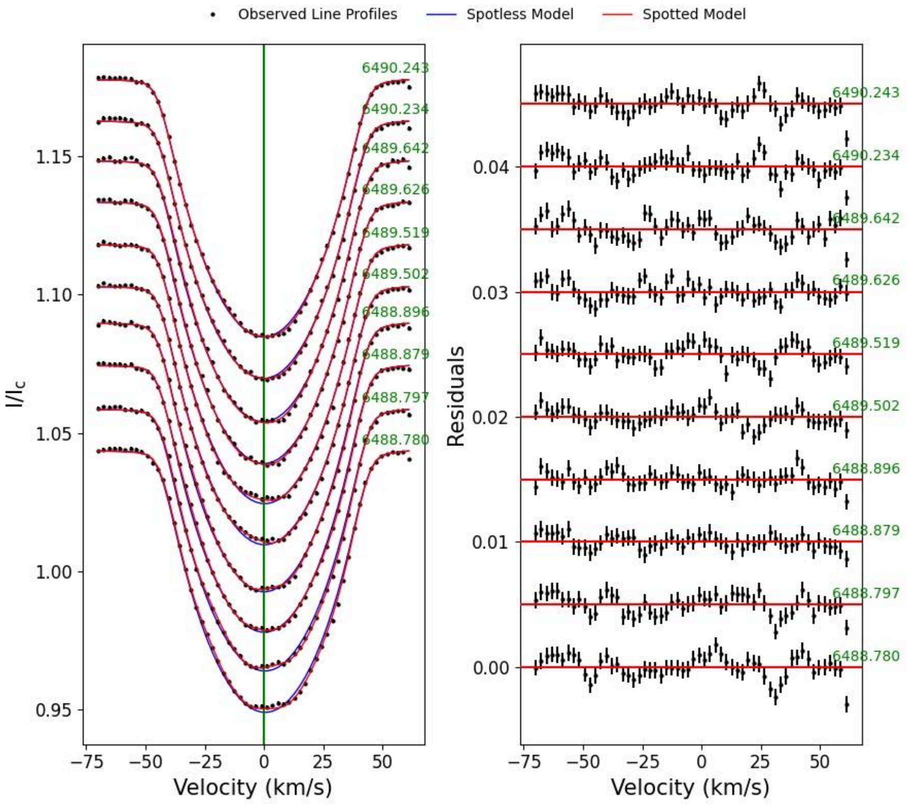
Kriskovic et al. (2019)

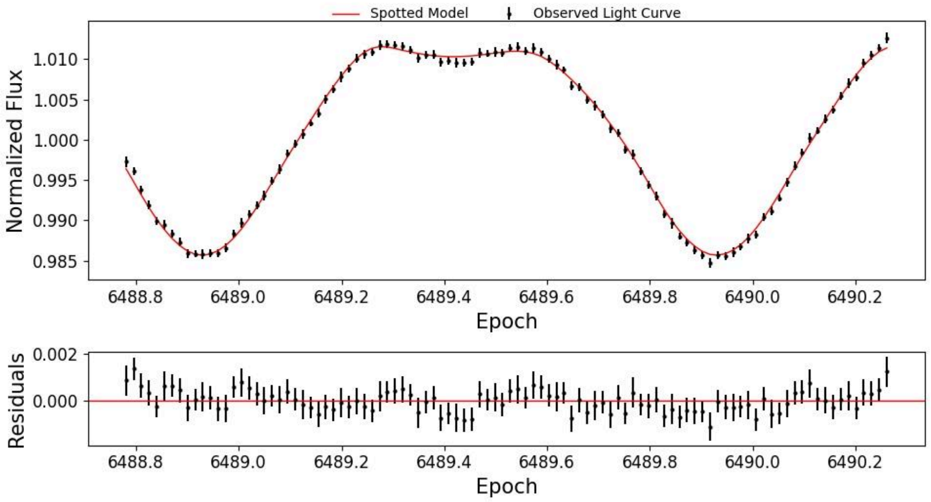
We performed simultaneous Doppler imaging and light curve inversion analysis of V1358 Ori using the spectroscopic and photometric data.

The star is a rapidly rotating, young solar-like star. Such stars are crucial for understanding the early stages of magnetic activity in the Sun.

V1358 Ori: Observations and Models

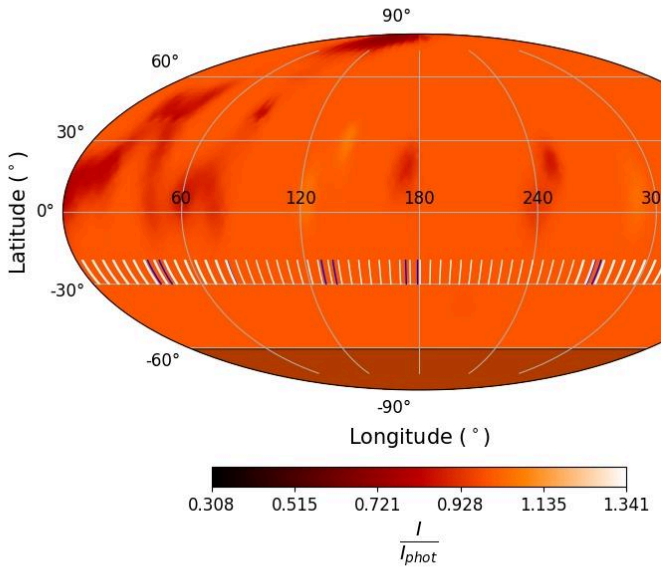
For Doppler imaging, we utilized high-resolution spectra obtained from the Narval spectrograph. Additionally, the TESS light curve was employed for light curve inversion. Both spectral and light curve data cover same time span.

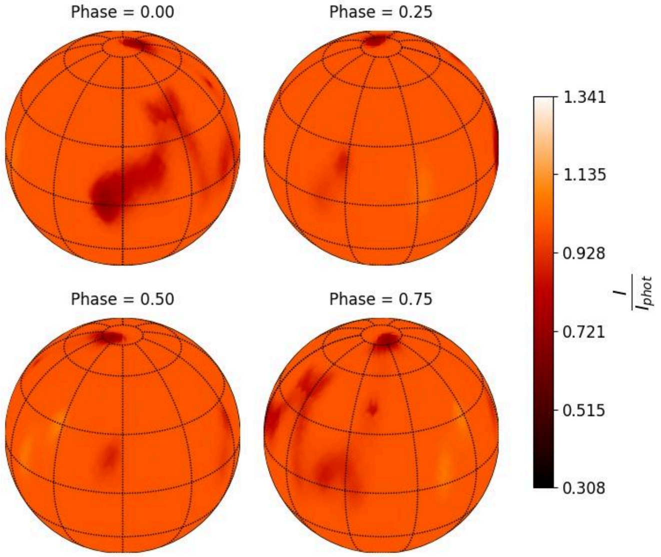




V1358 Ori: Surface Brightness Distribution

Cool spots are mainly seen at mid and high latitudes, especially near the equator.





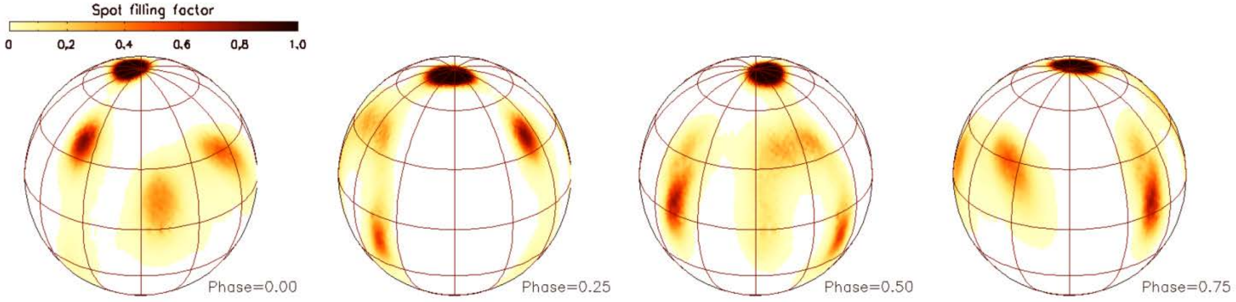
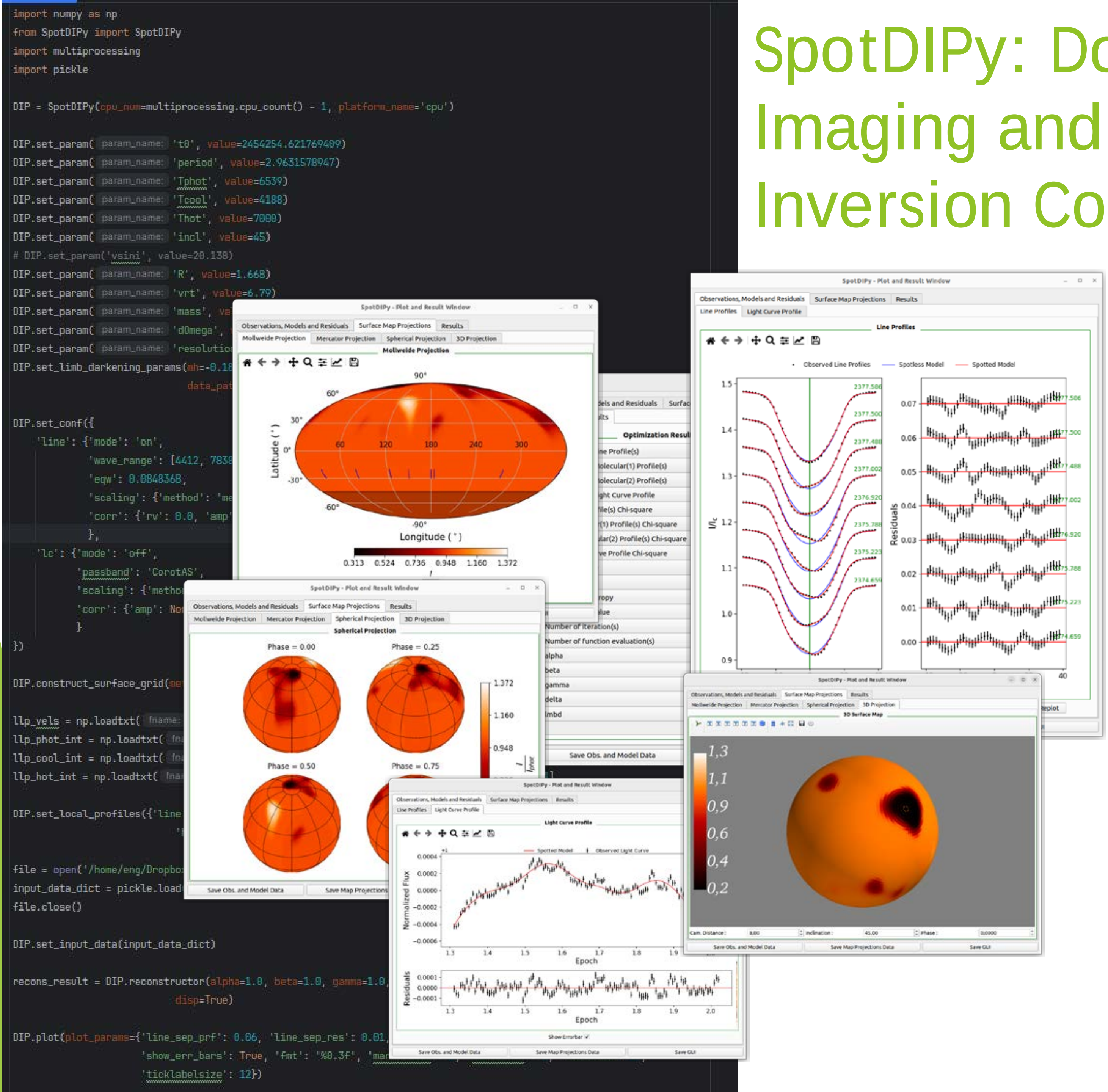


Figure 9. Projected disc images of EK Dra obtained from DI inversions at different rotational phases ϕ=0.0, 0.25, 0.50, and 0.75.

Surface brightness distribution of
a solar analog EK Dra
(Şenavcı et al. 2021)

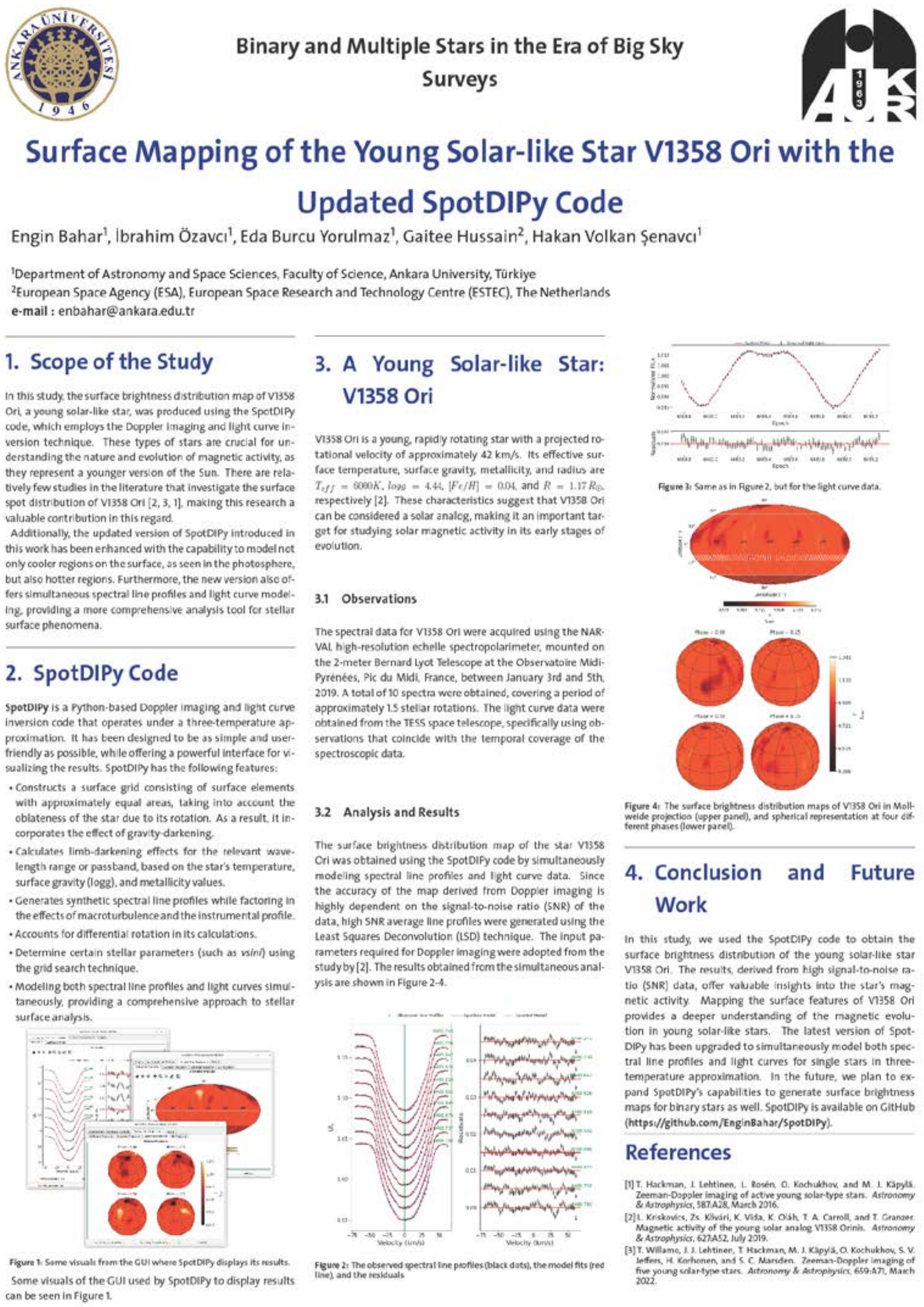
The spot distributions on this map are similar to those of another solar analog, EK Dra.



SpotDIPy: Doppler Imaging and Light Curve Inversion Code

- Performs Doppler imaging and light curve inversion either separately or simultaneously
- User-friendly and easy to use
- Provides robust graphical outputs

Available on GitHub:



Binary and Multiple Stars in the Era of Big Sky Surveys

Surface Mapping of the Young Solar-like Star V1358 Ori with the Updated SpotDIPy Code

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1. Scope of the Study

In this study, the surface brightness distribution map of V1358 Ori, a young solar-like star, was produced using the SpotDIPy code, which employs the Doppler imaging and light curve inversion technique. These types of stars are crucial for understanding the nature and evolution of magnetic activity, as they represent a younger version of the Sun. There are relatively few studies in the literature that investigate the surface spot distribution of V1358 Ori [2, 3, 1], making this research a valuable contribution in this regard.

Additionally, the updated version of SpotDIPy introduced in this work has been enhanced with the capability to model not only cooler regions on the surface, as seen in the photosphere, but also hotter regions. Furthermore, the new version also offers simultaneous spectral line profiles and light curve modeling, providing a more comprehensive analysis tool for stellar surface phenomena.

2. SpotDIPy Code

SpotDIPy is a Python-based Doppler imaging and light curve inversion code that operates under 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. SpotDIPy has the following features:

- Constructs a surface grid consisting of surface elements with approximately equal areas, taking into account the oblateness of the star due to its rotation. As a result, it incorporates the effect of gravity-darkening.
- Calculates limb-darkening effects for the relevant wavelength range or passband, based on the star's temperature, surface gravity (logg), and metallicity values.
- Generates synthetic spectral line profiles while factoring in the effects of macroturbulence and the instrumental profile.
- Accounts for differential rotation in its calculations.
- Determine certain stellar parameters (such as *vsini*) using the grid search technique.
- Modeling both spectral line profiles and light curves simultaneously, providing a comprehensive approach to stellar surface analysis.

Figure 1: Some visuals from the GUI where SpotDIPy displays its results.

Some visuals of the GUI used by SpotDIPy to display results can be seen in Figure 1.

3. A Young Solar-like Star: V1358 Ori

V1358 Ori is a young, rapidly rotating star with a projected rotational velocity of approximately 42 km/s. Its effective surface temperature, surface gravity, metallicity, and radius are $T_{eff} = 6000K$, $logg = 4.44$, $[Fe/H] = 0.04$, and $R = 1.17 R_{\odot}$, respectively [2]. These characteristics suggest that V1358 Ori can be considered a solar analog, making it an important target for studying solar magnetic activity in its early stages of evolution.

3.1 Observations

The spectral data for V1358 Ori were acquired using the NARVAL high-resolution echelle spectropolarimeter, mounted on the 2-meter Bernard Lyot Telescope at the Observatoire Midi-Pyrénées, Pic du Midi, France, between January 3rd and 5th, 2019. A total of 10 spectra were obtained, covering a period of approximately 1.5 stellar rotations. The light curve data were obtained from the TESS space telescope, specifically using observations that coincide with the temporal coverage of the spectroscopic data.

3.2 Analysis and Results

The surface brightness distribution map 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 map 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 (LSD) technique. The input parameters required for Doppler imaging were adopted from the study by [2]. The results obtained from the simultaneous analysis are shown in Figure 2-4.

Figure 2: The observed spectral line profiles (black dots), the model fits (red line), and the residuals

Figure 3: Same as in Figure 2, but for the light curve data.

Figure 4: The surface brightness distribution maps of V1358 Ori in Mollweide projection (upper panel), and spherical representation at four different phases (lower panel).

4. Conclusion and Future Work

In this study, we used the SpotDIPy code to obtain the surface brightness distribution of the young solar-like star V1358 Ori. The results, derived from high signal-to-noise ratio (SNR) data, offer valuable insights into the star's magnetic activity. Mapping the surface features of V1358 Ori provides a deeper understanding of the magnetic evolution in young solar-like stars. The latest version of SpotDIPy has been upgraded to simultaneously model both spectral line profiles and light curves for single stars in three-temperature approximation. In the future, we plan to expand SpotDIPy's capabilities to generate surface brightness maps for binary stars as well. SpotDIPy is available on GitHub (**https://github.com/EnginBahar/SpotDIPy**).

References

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