Stars and their variability observed from space
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TOSC: AN ALGORITHM FOR THE TOMOGRAPHY OF SPOTTED TRANSIT CHORDS

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Abstract. Photometric observations of planetary transits may show localized bumps, called transit anomalies, due to the possible crossing of photospheric starspots. The aim of this work is to analyze the transit anomalies and derive the temperature profile inside the transit belt along the transit direction. We have developed the algorithm TOSC, a tomographic inverse-approach tool which, by means of simple algebra, reconstructs the flux distribution along the transit belt. Here we test TOSC against some simulated scenarios. We find that TOSC provides robust results for light curves with photometric accuracies better than 1 mmag, typical of current and future space photometers, returning the spot-photosphere temperature contrast with an accuracy better than 100 K. TOSC is also robust against the presence of unocculted spots, provided that the apparent planetary radius given by the fit of the transit light curve is used in place of the true radius. The analysis of space-borne and ground-based real data with TOSC returns results consistent with previous studies.

Keywords: methods: data analysis, methods: numerical, techniques: photometric, stars: activity, stars:atmospheres, stars: starspots

1 Introduction

During a planetary transit, the observed flux of the star decreases because part of the stellar disk is blocked by the planetary disk. It is possible to analyze the transit light-curve (LC), and to characterize the stellar surface. In particular, if the planet transits in front of starspots, an apparent rebrightening (called "transit anomaly") of the star is observed while the spot is being crossing: the brightening corresponds to an increase of the flux received from the unocculted stellar surface because a darker area is being occulted.

The analysis of transit anomalies has been approached using various methods. Some authors fit the transit anomaly with a given analytical model to retrieve the size of the spots and their contrast with respect to the photosphere (e.g., Sanchis-Ojeda & Winn 2011; Nascimbeni et al. 2015). Others have developed more sophisticated codes, which fit the LCs by means of Monte Carlo algorithms (e.g., Tregloan-Reed et al. 2013; Béky et al. 2014). In both cases, some assumptions about the shape and distribution of the spots over the stellar disk are needed.

Scandariato et al. (2017) presented the Tomography Of Spotted transit Chords (TOSC) code, a new and fast algorithm which reconstructs the flux distribution inside the area of the stellar surface crossed by the transiting planet, namely the "transit chord". The main advantage of our code is that it only needs a few assumptions about the geometry of the planetary system and the stellar spectrum. In other words, TOSC does not assume any *a priori* parameter of the photospheric starspots such as shape, size or temperature.

2 The model

The transit chord is divided into adjacent rectangular cells. For each photometric point recorded during the planetary transit at time t, the flux occulted by the planet $F_{occ}(t)$ corresponds to the sum of the fluxes radiated by the corresponding cells F, weighted by the fractional overlap area $w(t)$ between the cells and the planetary disk (see Fig. 1).

Each photometric point corresponds to the weighted sum of the unknown fluxes F_i. The sample of photometric points gives the system of linear equations in Eq. 2.1. TOSC inverts this system and returns the flux,

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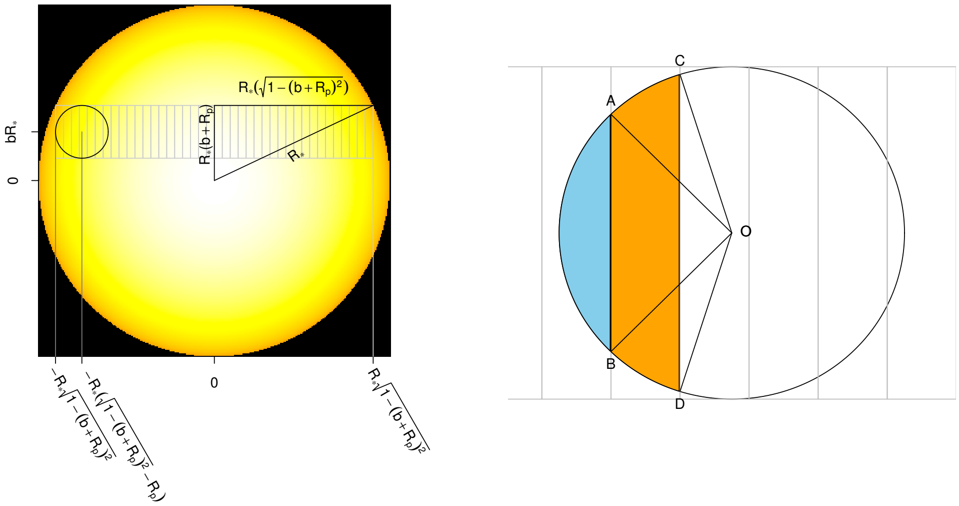

Fig. 1. Left: Schematic representation of the geometry discussed in the text. The circle represents the transiting planet, while the grid rectangles shows the cells used in the chord reconstruction.. **Right:** Graphical representation of the computation of the weights $w(t)$. The circle is the planetary disk centered at O, while the gray grid shows the cells drawn on the stellar disk partially covered by the planetary disk.

and thus the temperature, along the transit chord. Since the system inversion is an ill-posed problem from a mathematical point of view, TOSC uses Tikhonov's method to regularize the inversion algorithm.

$$\begin{bmatrix} w_1(t_1) & \cdots & w_N(t_1) \\ \vdots & \ddots & \vdots \\ w_1(t_M) & \cdots & w_N(t_M) \end{bmatrix} \cdot \begin{bmatrix} F_1 \\ \vdots \\ F_N \end{bmatrix} = \begin{bmatrix} F_{occ}(t_1) \\ \vdots \\ F_{occ}(t_M) \end{bmatrix} \tag{2.1}$$

3 Examples of applications

TOSC has been tested against different simulated scenarios, and it has proved to return the expected temperature profile of the chord within ∼100 K as long as the photometric precision of the LCs is better than 1 mmag.

We also tested TOSC against some actual datasets. HAT-P-11 is a V=9.6 K4 dwarf (T_{eff}=4780 K) in the Kepler field (Borucki et al. 2010), orbited by a hot Neptune every 4.9 days (Bakos et al. 2010). We analyzed the Kepler photometry of the transit occurring at BJD=2454967.6 (Fig. 2). The reconstructed chord (green line in the top panel) shows a cool spot centered at $\simeq$0.3 R_* and is $\simeq$0.15 R_* wide. The fitted spot-photosphere temperature contrast is $\Delta T \simeq$-900 K (bottom panel). These results are in line with previous results (Béky et al. 2014).

4 Conclusions

Extensive tests have shown that TOSC can reconstruct the crossed spots to give a photometric accuracy better than 1 mmag, and that the temperature contrast is returned with an uncertainty <100 K. TOSC is consistent with previous approaches available in literature, and also with more sophisticated algorithms. For a complete description of TOSC (e.g. Tychonov's regularization, treatment of unocculted spots and limb darkening, etc.), please see Scandariato et al. (2017).

TOSC is available as a web interface at `www.oact.inaf.it/tosc`, where the user can run the algorithm feeding a few input files and retrieving the output in table format complemented by quick-look plots. It is also possible to run multiple transit LCs in one go. The web page contains extensive instructions and some sample data. The source code is available for download too. For support, please contact the authors.

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I dedicate this work to my father, after whom TOSC is named.

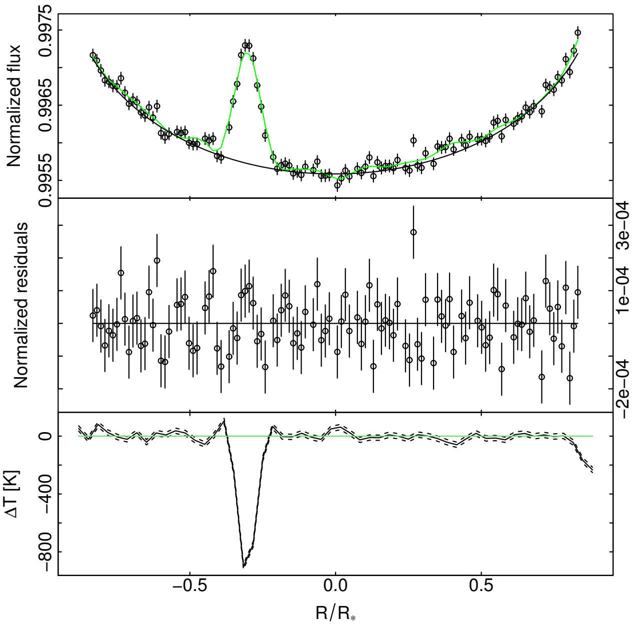

Fig. 2. *Top panel* - Kepler LC of HAT-P-11b. The "unspotted" transit model and the "spotted" transit fit are represented by the solid black line and the solid green line respectively. *Middle* - Residuals of the transit fit. *Bottom* - The reconstructed temperature profile of the transit chord with the uncertainty in the reconstruction shown by dashes.

References

Bakos, G. Á., Torres, G., Pál, A., et al. 2010, ApJ, 710, 1724
Béky, B., Kipping, D. M., & Holman, M. J. 2014, MNRAS, 442, 3686
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Science, 327, 977
Nascimbeni, V., Mallonn, M., Scandariato, G., et al. 2015, A&A, 579, A113
Sanchis-Ojeda, R. & Winn, J. N. 2011, ApJ, 743, 61
Scandariato, G., Nascimbeni, V., Lanza, A. F., et al. 2017, A&A, 606, A134
Tregloan-Reed, J., Southworth, J., & Tappert, C. 2013, MNRAS, 428, 3671