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Letter to the Editor

Polar stellar-spots and grazing planetary transits

Possible explanation for the low number of discovered grazing planets

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ABSTRACT

We assess whether there is a physically feasible explanation for the few discovered (nearly) grazing planetary transits through all ground- and space-based transit surveys. We performed simulations to generate a synthetic distribution of detectable planets based on their impact parameter, and found that more (nearly) grazing planets should have been detected than have been detected. Our explanation for the insufficient number of (nearly) grazing planets is based on the simple assumption that many (nearly) grazing planets transit host stars that harbor a dark giant polar spot, and thus the transit light-curve vanishes due to the occultation of the grazing planet and the polar spot. We conclude by evaluating the properties required of polar spots to cause the grazing transit light-curve to disappear and find that the spot properties are compatible with the expected properties from observations.

Key words. planetary systems – planets and satellites: detection – stars: activity – starspots – methods: numerical

1. Introduction

The impact parameter (b) of a transiting planet on a circular orbit is defined as $a\cos(i)/R_\star$, in which a is the orbital semi-major axis, i is the orbital inclination, and $R_\star$ is the stellar radius. If $(1 - R_{\rm planet}/R_\star) < b \leq (1 + R_{\rm planet}/R_\star)$, where $R_{\rm planet}$ is the planet radius, the planet does not fully cover the stellar disk during its transit, and therefore the planetary transit is said to be grazing. So far, only a handful of (nearly) grazing exoplanets have been detected and confirmed through all ground- and space-based transit surveys. To be more accurate, only eight such systems have been discovered: WASP-34b (Smalley et al. 2011), WASP-67b (Hellier et al. 2012; Mancini et al. 2014), HAT-P-27/WASP-40 (Béky et al. 2011; Anderson et al. 2011), WASP-45b (Anderson et al. 2012), CoRoT-25b (Almenara et al. 2013), Kepler-434b (Almenara et al. 2015), Kepler-447b (Lillo-Box et al. 2015), and CoRoT-33b (Csizmadia et al. 2015). The (nearly) grazing planets are interesting targets because they can be used to detect the gravitational perturbation of small bodies in the systems, such as exomoons and Trojans (Lillo-Box et al. 2015). In this way, they provide important information on planetary formation and evolution. To date, there has been no study to explore why only so few (nearly) grazing planets have been discovered.

Large, cool (dark), and long-lived stellar spots located near the stellar rotational axis (either at high latitude or covering the pole) are common features on stars independent of the stellar rotational velocity or spectral type (e.g., Strassmeier et al. 1991; Schuessler & Solanki 1992; Piskunov & Wehlau 1994; Strassmeier & Rice 1998; Hatzes 1998; Strassmeier 2002; Jeffers et al. 2002; Berdyugina 2005). Observations have revealed that polar spots can reach a filling factor (f)[1] of up to 50% and have a lifetime of about a decade. These two properties suggest that the polar spots might be formed by a different physical mechanism than the low- to mid-latitude spots (Holzwarth et al. 2006; Strassmeier 2009; Berdyugina 2005). Different techniques have been used to rule out different biases in various techniques and to thereby independently confirm and characterize polar spots (Unruh & Collier Cameron 1995; Bruls et al. 1998; Berdyugina 2002; Sanchis-Ojeda et al. 2013). Moreover, several theoretical and numerical studies have been carried out to define the proper mechanism that is responsible for the polar spot formation and persistence (e.g., Schrijver & Title 2001; Holzwarth et al. 2006; Brown et al. 2010; Yadav et al. 2015).

It has been shown in several studies that the occultation of spots by a transiting planet can generate anomalies in the transit light-curve and may lead to an incorrect estimate of the planetary parameters (e.g., Sanchis-Ojeda & Winn 2011; Oshagh et al. 2013b; Sanchis-Ojeda et al. 2013; Barros et al. 2013). In this work we first examine if there are fewer (nearly) grazing planets detected so far than are physically predicted. To do this, we try to explain the low number of detected (nearly) grazing planets based on the assumption that many (nearly) grazing planets occult large polar spots during their transit. If a (nearly) grazing planet crosses a large polar spot, then the transit depth decreases significantly (considering that the limb-darkening also causes a decrease in the transit depth when compared to a central transit), and this leads to a lower signal-to-noise ratio and may cause the

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[1] The filling factor is defined as $f = (R_{\rm spot}/R_\star)^2$, where $R_{\rm spot}$ is the spot radius.

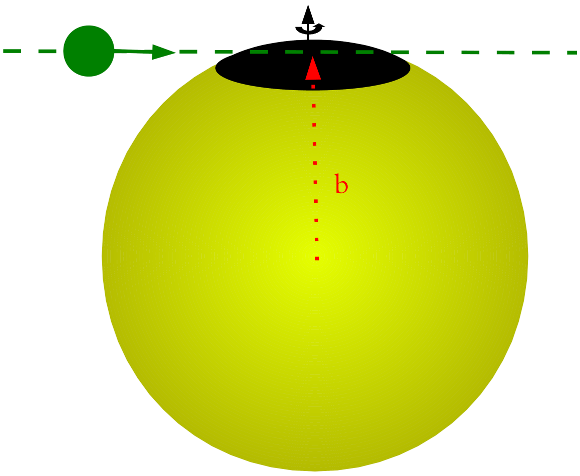

Fig. 1. Schematic view of a grazing planet occulting a polar spot.

transit signal to be below the detection threshold and be completely missed (see Fig. 3 for a schematic illustration of the our basic assumption). In Sect. 2 we describe the simulation that allows us to compare the number of expected grazing planets with actually discovered planets. In Sect. 3 we interpret the results obtained in Sect. 2 to evaluate our hypothesis that grazing planets may be missed because they occult the polar spots. In Sect. 4 we conclude.

2. Simulation

In this section we generate a synthetic distribution of the transiting planets impact parameter. To do this, we perform a Monte Carlo simulation by simulating 50 000 transiting planets. The planet radius (R_{planet}), orbital period (P), semi-major axis (a), and stellar radius ($R_\star$) were drawn from the observed distributions of all confirmed transiting planets[2]. We would like to note that since the observation distribution suffers from observational biases and it is our objective to reproduce the observations even with these (uncharacterized) biases, we chose to draw the parameter(s) for the distribution of observed parameter(s). The orbital inclination (i) was drawn from a linear distribution in $\cos i$ in the range of 75–90 degree. We note that the range of 75–90 degree was chosen because for an inclination smaller than 75 degrees the transit probability decreases to zero based on the orbital distribution used in this study. The orbital eccentricity and misalignment angle of planets were fixed to zero. From the semi-major axis, stellar radius, and inclination, the impact parameter can be calculated through $a\cos(i)/R_\star$. The stellar limb-darkening coefficients were fixed to the value of the Sun $u1 = 0.29$ and $u2 = 0.34$ (Claret & Bloemen 2011). The stellar inclination was fixed to 90 degrees, which means that it is seen edge-on. We also considered that the star does not have any spots.

We assigned the transiting planet and host star parameters of each system in the SOAP-T tool[3]. SOAP-T requires both the orbital period and semi-major axis, thus it does not require the stellar mass. Then SOAP-T generates the transit light-curve of the each system. If the transit light-curve shows a transit depth higher than 225 ppm (which means a transit depth higher than 3σ when we consider the σ around 75 ppm that is due to the granulation noise for solar-type stars Gilliland et al. 2011) and also has a duration longer than an hour (in other words, the transit light-curve at least shows more than or equal to three points in the transit by assuming *Kepler*'s long-cadence 30 min). If this is the case, we consider the transiting planet detectable; if not, we consider it not detected. As a consequence, we can depict the impact parameter distribution of detectable planets.

We would like to note that the granulation noise level strongly depends on the spectral type of the host star (Gilliland et al. 2011). For different stars the detection limit on the transit depth can therefore be lower than the threshold value used (225 ppm). Furthermore, the transit duration limit that we considered (at least three points in one transit) can be a strict limit because in reality by phase-folding several transits and thus increasing the signal-to-noise ratio, observers are able to detect planets even with a shorter transit duration than this limit. Thus the proper transit duration limit should be defined as $3\sigma/\sqrt{n}$, which n is the number of observed transits. However, since we are interested in the minimum number of planets to be detected, then by assuming these strict limits (on the transit depth and also duration) we obtain a conservative estimate of the minimum number of grazing planets. As we show in Sect. 3, this expected number is still higher than observed. As we noted, planets can be detected well below the 225 ppm transit depth limit by observing more transits, down to 99 ppm (e.g., Kepler-90b, Cabrera et al. 2014) or down to ~20 ppm (e.g., Kepler-37b, Barclay et al. 2013). This means that the discrepancy between the observed and expected numbers of grazing transits can be even higher than we present in Sect. 3, but we did not study this problem in detail. We also note that our simulation is based on some simplistic assumptions, such as fixing the stellar limb-darkening coefficient, stellar inclination, and orbital eccentricity. However, it can still deliver some insightful and quite realistic approximation about the estimated number of grazing planets. In the presence of polar spots the limb-darkening also changes (because it is temperature dependent), which can affect the transit depth as a second-order effect. Exploring this effect is beyond the scope of this paper.

Comparing the distribution of the impact parameters of the known transiting exoplanets and the synthetic planets delivered by our simulation can provide insight into the significance of missing (nearly) grazing planets.

3. Results and interpretation

Figure 2 presents the synthetic impact parameter distribution obtained from our simulation in Sect. 2 and the confirmed transiting planet impact parameter distribution. As the results show, in the roughly estimated region of (nearly) grazing planets we would expect to detect more (nearly) grazing planets than have been detected. To quantify the significance of the discrepancies between the simulation and confirmed transiting planets, we performed the two-sample Kolmogorov-Smirnoff (K-S) and the Anderson–Darling(A-D)[4] statistical tests in the region of (nearly) grazing planets ($0.9 \leq b \leq 1.1$). The K-S and A-D statistics yield $P_{\text{KS}} = 0.005$, and $P_{\text{AD}} = 0.00031$, respectively. These results present strong evidence that two samples are expected from completely different underlying distribution.

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[2] The data were obtained through `exoplanets.org`

[3] The SOAP-T tool can generate the light curves and radial velocity variations for systems consisting of a rotating spotted star with a transiting planet. More details about the tool can be obtained in Oshagh et al. (2013a) or `http://www.astro.up.pt/resources/soap-t/`

[4] A-D test is similar to K-S, but more sensitive because it give more weight to the tails of distribution (`https://asaip.psu.edu/Articles/beware-the-kolmogorov-smirnov-test`).

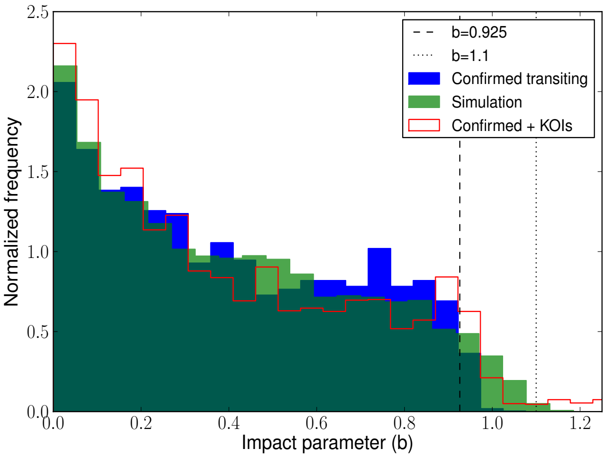

Fig. 2. Impact parameter distribution of all confirmed transiting planets (blue histogram). The synthetic impact parameter distribution from our simulation (green histogram). The impact parameter distribution of *Kepler* planet candidates (KOI)(red histogram). The roughly estimated region of (nearly) grazing planets is shown in the region between the dashed and dotted lines.

The K-S and A-D tests for ($b \leq 0.9$) deliver $P_{\mathrm{KS}} = 0.30$, and $P_{\mathrm{AD}} = 0.22$, respectively, which suggests that we cannot reject the hypothesis that they come from the same distribution. Therefore, this disagreement supports our hypothesis that there should be more grazing planets whose signals have been missed as a result of occultation by the giant polar spots. The red histogram in Fig. 3 displays the impact parameter distribution of *Kepler* planet candidates, known as the *Kepler* Object of Interest (KOI), which shows many grazing planet candidates, but they have yet to be confirmed. As a speculative interpretation from comparing KOIs and the synthetic distribution, at least some of the grazing planet candidates should be real, and if confirmed, they will partially fill the observed gap of (nearly) grazing transiting planets.

To determine whether the polar spot property required to cause a grazing transit light-curve to disappear has physically feasible values or not, we performed a simple test. We again used the SOAP-T tool (Oshagh et al. 2013a) to generate transit light-curves of four (nearly) grazing transiting planets, with $b = 0.90, 0.95, 1.00$, and 1.05. The transiting planets were Jupiter-size planets with a radius of $R_{\mathrm{planet}} = 0.1R_{\star}$ on a three-day orbit with a semi-major axis of $a = 10\ R_{\odot}$. The stellar radius was fixed to one solar radius ($R_{\odot}$), and its limb-darkening coefficients were fixed to the value of the Sun $u1 = 0.29$ and $u2 = 0.34$ (Claret & Bloemen 2011). The stellar effective temperature ($T_{\star}$) was fixed to the solar value, 5778 K. The stellar inclination was fixed to 90 degrees, which means that it is seen edge-on. Figure 3 shows the (nearly) grazing transit light-curves of all four systems in the lines. In the next step we added a giant exactly polar spot (centered on the rotational axis) on the surface of the host star[5]. Then for each (nearly) grazing planet we varied the filling factor and temperature of the polar spots until the grazing transit light-curve vanished (as shown in Fig. 3). The criterion for considering a transit light-curve to have vanished is that the transit depth is lower than 75 ppm (Gilliland et al. 2011). The spot temperature contrast with the stellar temperature ($\Delta T = T_{\star} - T_{\mathrm{spot}}$) required to cause the grazing transit to vanish was estimated to be around 2500 K. The filling factor required for the planet on the lower impact parameters is higher than for the higher impact parameter. For instance, a grazing planet with $b = 1.05$ required a polar spot with a filling factor of $f = 12\%$, and a nearly grazing planet with $b = 0.90$ needed a polar spot with a filling factor of $f = 42\%$. It is also important to note that the highest spot filling factor and temperature contrast required in our test are lower than the highest observed polar spot filling factor and temperature contrast. Therefore, our hypothesis does not require an unphysical property for the polar spot to be valid.

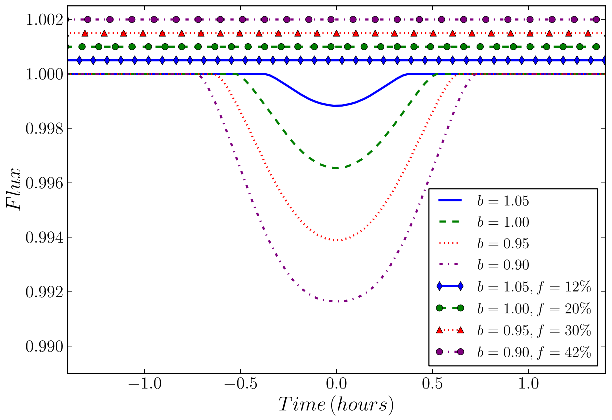

Fig. 3. Transit light-curve disappears because of occultation of the grazing transiting planet with polar spots. The transit light-curves are generated with the SOAP-T tool. The lines show that the grazing planet transit light-curves correspond to different impact parameters ($b = 0.90, 0.95, 1.00, 1.05$) over a star without any spot. The line markers indicate the grazing planets that occult polar spots (centered on the stellar pole) with different filling factors (f). All the spots have a temperature contrast with respect to the stellar temperature of $\Delta T = 2500$ K. The line markers are offset vertically for clarity.

4. Conclusions

We assessed the possible cause for the few discovered (nearly) grazing planetary transits. We compared the synthetic impact parameter distribution of detectable planets (through our simulation) with the observed impact parameter distribution. We found that more (nearly) grazing planets should have been detected than have been detected. Our hypothesis to explain the insufficient number of (nearly) grazing planets is based on the assumption that many (nearly) grazing planets transit host stars with a dark giant polar spot. As a consequence, the transit light-curves disappear due to the occultation of the grazing planet and the polar spot. Because the (nearly) grazing transit light-curves are shorter, shallower, and are often V-shaped (similar to the light curve of an eclipsing binary), they can introduce an observational bias that leads to fewer (nearly) grazing planets detected. We would like to encourage transit hunters to perform more careful analyses on V-shaped transit candidates.

Finally, we evaluated the filling factor and temperature contrast of the required polar spots and conclude that their filling factors and temperature contrasts are within a reasonable and physically feasible range.

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[5] Note that the exactly polar spot does not generate any out of transit modulation also, which may be mis-interpreted as an non-active star.

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