Starspots and spin orientation of HAT-P-11

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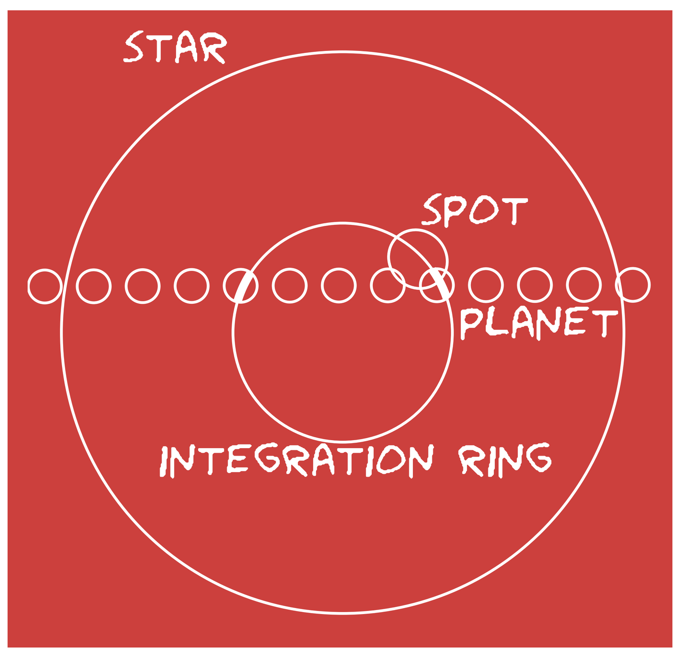
Abstract

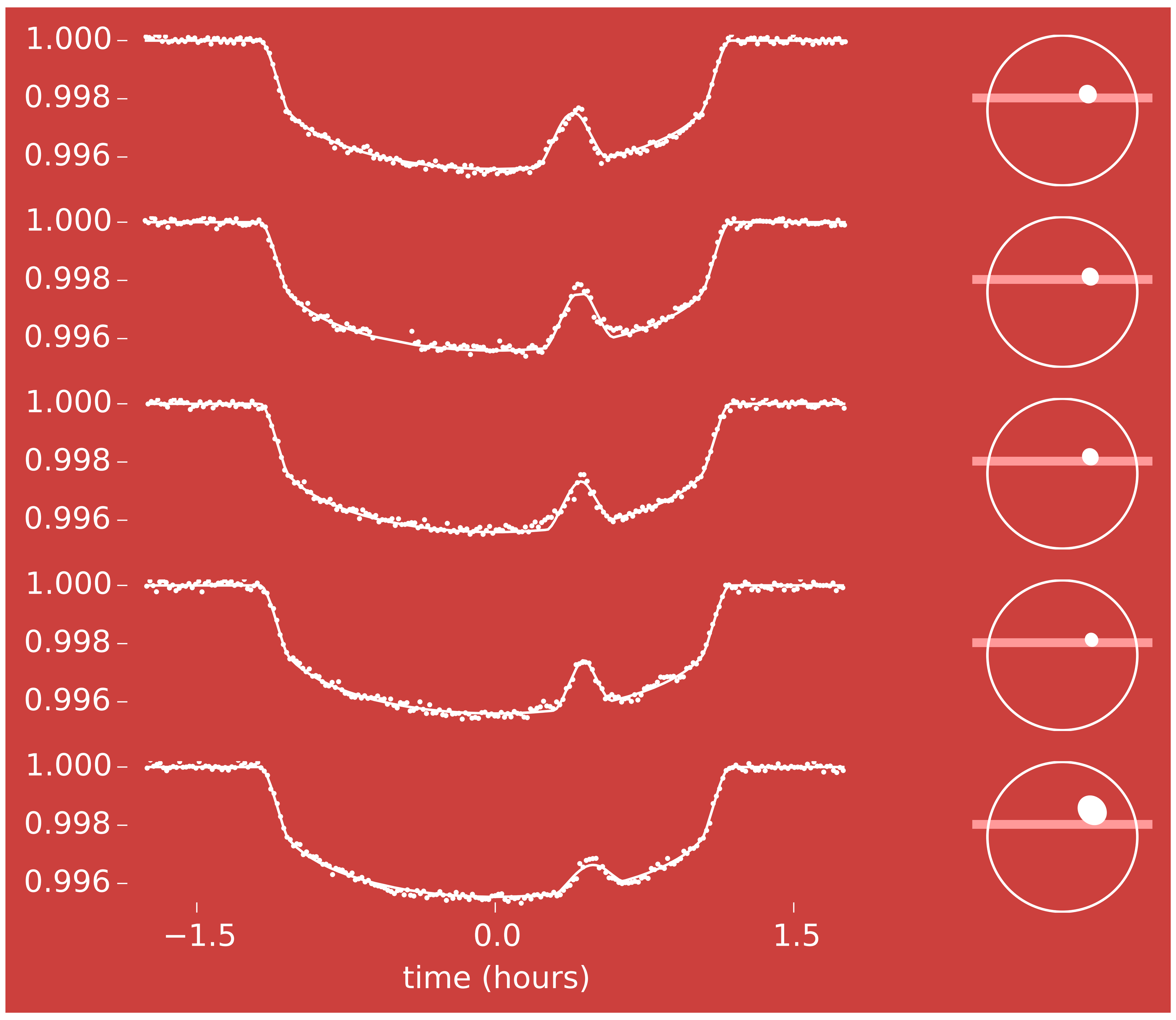
HAT-P-11 is a bright ($V = 9.5$) K dwarf in the Kepler field, with thirteen quarters of short cadence observations. It hosts HAT-P-11b, a hot Neptune on a 4.9 day orbit (Bakos et al. 2010). The rotational period of the star is approximately 29.2 days, close to six times the orbital period of its planet. The transit lightcurves exhibit frequent anomalies, which are commonly attributed to the planet transiting spots on the stellar surface. The spots also influence the out-of-transit lightcurve through another phenomenon: they cause rotational modulation as they appear and disappear from the visible hemisphere of the star during its rotation. Both phenomena are sensitive to the spin vector orientation of the star, therefore they allow us to put constraints on the obliquity and spin inclination of the system. Ultimately, a joint analysis of the two phenomena should make it possible to confine the spin orientation based on photometric data only.
On this poster, we introduce a new numerical model for transit anomalies caused by spots, we present statistical proof for long-lived spots and planetary orbit–stellar rotation resonance, and show preliminary results on stellar spin distribution.

Transit model with spots

To model transit lightcurves with starspots, we divide the projected stellar surface into concentric annulii. For the ring at the center of each annulus, we calculate the length of the arc that overlaps with the projection of the planet and of each spot. (The spots are assumed to be circular, therefore they become elliptical in projection.) This way, we can calculate how much light the planet obscures in the annulus, taking into account the effect of spots. We multiply this value by the limb darkening coefficient corresponding to the radius, then sum the results up over all annulii. This method assumes the same limb darkening law for the spots as the rest of the star. However, the model does not rely on any particular limb darkening law, instead it takes the limb darkening values at the radii of each ring as input parameters. Also, the intersection arc length of each ring and the planet at the time of the observations can be precalculated, and reused for each re-evaluation of the model with different spots. This speeds up fitting and MCMC tremendously.



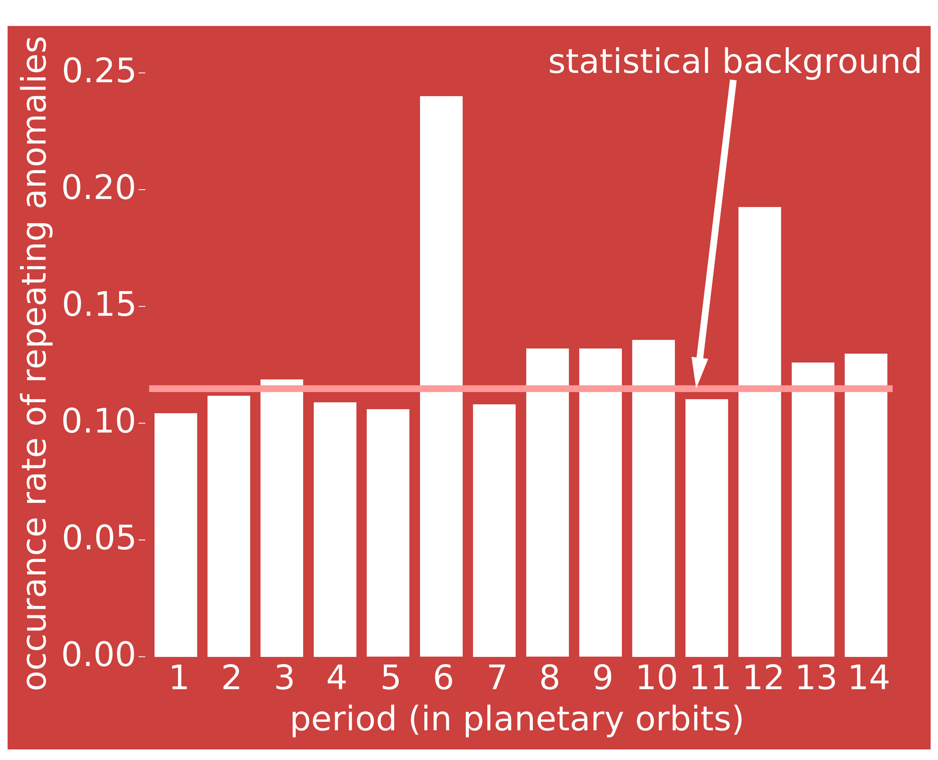
A long-lived spot



The stellar rotational period reported by Bakos et al. (2010) is close to six times the planetary orbital period. If it was an exact resonance, and spots lived long enough, then we would expect to see some transit anomalies repeat every six transits. Indeed, the spot displayed above has been observed five times, in every sixth transit, during Q09 and Q10. The left column shows the transit observations along with our best fit, whereas the right column displays the projected configuration of the planetary transit chord (pink strip) and the best fit spot (white filled ellipse) on the star (white circle). This is compelling evidence of that the stellar rotation and planetary orbit are in 6:1 resonance, and that some spots live for many months.

Resonance

In this section, we investigate the repetition rate of transit anomalies with different periods. We use an automated transit anomaly detection algorithm to identify 62 anomalies out of 183 good quality transits in total, an occurance rate of 0.34. We then count pairs of transits six orbits apart, and identify the fraction of them where both exhibit anomalies. If there was no correlation, we would expect this fraction to be 0.34^2. However, the actual rate is more than twice as large, proving that the spot recurrance pattern presented in the previous section is not just coincidence. We repeat this procedure with other potential periods: subsequent transits, every second transit, etc. The barchart reveals another strong signal with the period of twelve orbits, an alias due to long lived spots. For other periods, we do not see significant deviation from the statistical background, confirming that the actual resonance ratio is indeed 6:1.



References

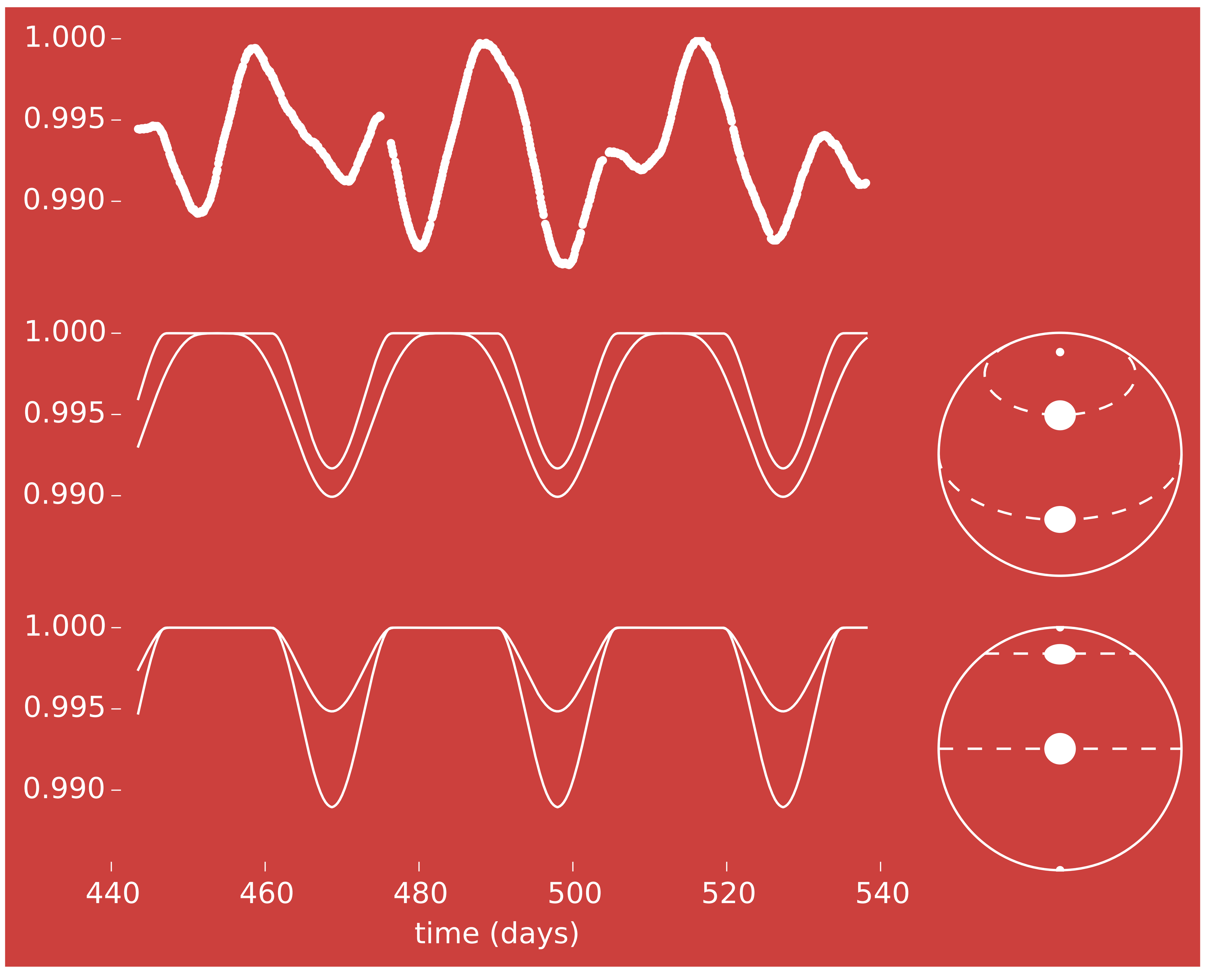
Bakos et al. 2010, ApJ, 710, 1724
Sanchis-Ojeda et al. 2011, ApJ, 743, 61
Kipping 2012, MNRAS, 427, 2487

Animations

For an animation of HAT-P-11b transiting spots, visit `youtu.be/XSNQtyOcTcQ`, or scan the QR code:

For an animation of the posterior spin vector distribution of HAT-P-11, visit `youtu.be/gkj7FSut0Vs`, or scan the QR code:

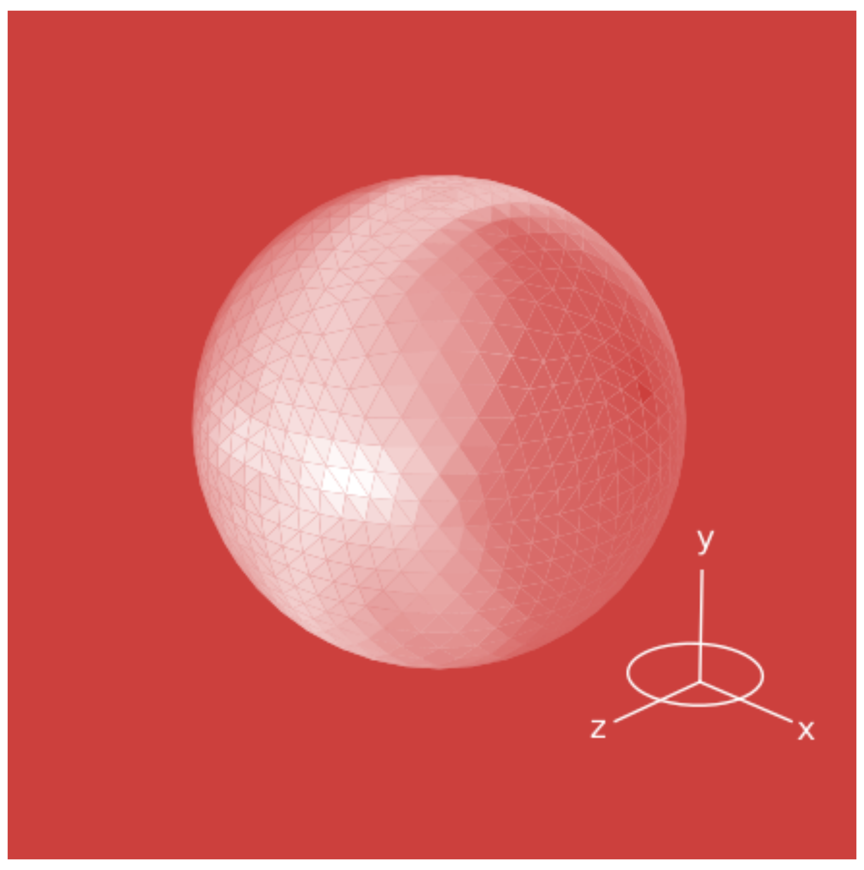
`macula`



The code `macula` by Kipping (2012) provides an efficient way to model rotational modulations of a star due to starspots. The above figure presents Kepler data from Q05, which shows a strong frequency component with six times the planetary orbital period, the proposed stellar rotation rate. The lightcurve hints the presence of two spots, with an evolution on the timescale of months. In this section, we demonstrate some basic features of `macula`, presenting model lightcurves on the left due to a hypothetical spot that does not change in contrast and size throughout the quarter. The right panels show the trajectory of the spot on the rotating star with a dashed curve, also indicating the stellar poles. Each panel presents two scenarios: an equatorial spot, and one at a higher latitude. We see that at a general inclination, the duration of the spot being visible depends on the latitude. This provides a variety of lightcurves to be used for fitting. However, as the bottom panels demonstrate, in case the spin axis is in the sky plane, the duration of the dip in the lightcurve does not depend on the spot latitude. In this case, the model lightcurves are close to being linearly dependent, therefore the subspace they span in the space of all lightcurve vectors has much fewer dimensions. In other words, the family of lightcurves that a star with this inclination can exhibit is very restricted.

Posterior distribution of stellar spin orientation based on transit data

We map all spots discovered by transit anomalies on the longitude-latitude map of the star, and calculate their position for preceding and succeeding transits for different directions of stellar spin. The better the resulting model transit lightcurve matches observations, the larger the posterior probability for that spin orientation is. The figure on the right presents a sphere in spin space color-coded based on this posterior probability: lighter color means less likely, darker means more likely. The axes in the bottom right corner show the orientation of our coordinate system: the planet is moving in the positive x direction at the time of transit, the planetary orbit vector points close to the positive y direction, and the positive z direction points towards the observer. The actual inclined eccentric orbit is also displayed. The whitish forbidden belt in the yz plane corresponds to zero projected obliquity. In this case, each transited spot would reappear at an earlier or later transit, but the observations exclude this. Sanchis-Ojeda et al. (2011) introduced this idea, and hereby we extend and quantify this argument.



Posterior distribution of stellar spin orientation based on rotational modulation

In this section, we also start from spots revealed through transit anomalies, but this time we explore how compatible they are with the observed rotational modulation. To do so, we generate a model `macula` lightcurve using the known spots. We also calculate the contributions due to a set of single spots on a mash on the stellar surface. We then apply a non-negative coefficient least square fit on these lightcurves, and focus on the residual of this fit. A large residual means the proposed spin orientation is not likely, and it is again denoted with lighter color on the diagram. Now there are two forbidden regions: first, the spin axis cannot point directly towards or directly away from the observer. Indeed, in this case, we would always see the same hemisphere of the star, and there would be no rotational modulation. Second, the spin axis is unlikely to lie in the sky plane. This is a consequence of the phenomenon explained in the section about `macula`: the family of possible lightcurves in this configuration is very restricted, and our analysis shows that the HAT-P-11 lightcurve does not fall into this family.