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A pilot investigation to constrain the presence of ring systems around transiting exoplanets

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ABSTRACT

We demonstrate a process by which to evaluate the presence of large, Saturn-like ring systems around transiting extrasolar giant planets. We use extrasolar planet candidate KOI-422.01 as an example around which to establish limits on the presence of ring systems. We find that the spherical-planet (no-rings) fit matches the lightcurve of KOI-422.01 better than a lightcurve with a planet having obliquity angles 90°, 60°, 45°, or 20°. Hence we find no evidence for rings around KOI-422.01, but the methods that we have developed can be used for more comprehensive ring searches in the future. If the Hedman (2015) low-temperature rings hypothesis is correct, then the first positive detection of exorings might require transits of very long period ($\gtrsim$ 10 yr) giant planets outside their stars' ice lines.

1. Introduction

Rings surround all of the giant planets in our Solar System, and so it is reasonable to expect that at least some of the planets around distant stars might also have rings. Furthermore, the known rings exhibit a wide range of properties, and it is still not clear why the different planets possess such different ring systems. Jupiter, for example, is the largest planet in our Solar System and has the most massive satellite system, but strangely its rings are the most tenuous of all the giant planets, probably consisting primarily of debris knocked off of its various small moons (Burns et al., 2004). Similarly, both the ice giants Neptune and Uranus have ring systems dominated by narrow ringlets that consist of very dark material, but Neptune's rings are far more tenuous than Uranus'. Why does Uranus have several complete rings with sufficient optical depth to be detectable in occultations (French et al., 1991), while the only parts of Neptune's rings that are detectable in this way are a few arcs in one ring (Cruikshank and Matthews, 1995)?

Saturn, of course, has the most extensive ring system. Indeed, Saturn's rings are so large and bright that they could be seen by the earliest telescopes (Galilei, 1989). However, even after 400 years of study no one can say for certain why Saturn has such an exceptional set of rings. Observations of rings around 'exoplanets', or 'exorings', could therefore help us to better understand what sorts of rings a planet is likely to have.

Additional examples of ringed planets would also help answer the still-contentious question of how dense, extensive ring systems are formed. While various scenarios have been proposed for Saturn's rings (Charnoz et al., 2009a) including disruption of a passing centaur (Charnoz et al., 2009b), tidal breakup of a Kuiper Belt Object (Hyodo et al., 2016), or a moon that migrated too close to the planet (Canup, 2010), each of these scenarios have potentially significant issues. For example, if Saturn's rings formed early from something like a migrating moon, it is not obvious how the rings would remain so bright after being polluted by 4.5 billion years' worth of dark cometary debris (Cuzzi and Estrada, 1998). On the other hand, if the rings formed more recently from the disruption of a large comet or centaur, then it is surprising that similar rings do not exist around the other giant planets, which are much more likely to capture such objects (Charnoz et al., 2009b).

The recent discovery of rings around the centaur 10,199 Chariklo (Braga-Ribas et al., 2014) and possibly 2060 Chiron (Ortiz et al., 2015; Ruprecht et al., 2015; Thiessenhusen et al., 2002) reveals that rings can be found around small bodies and thus has forced scientists to reconsider the question of how rings form. On the one hand, this finding suggests that rings could be found under a wider variety of conditions than previously considered. On the other hand, it is not clear why these objects possess dense rings while objects like Ceres and Pluto, for instance, do not, and so the conditions for ring formation remain obscured.

Thus far, no-one has found evidence for dense rings around any planets outside our Solar System. While a 'ring-like' system was recently

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found around the companion to the star 1SWASP J140747.93–394542.6 (Mamajek et al., 2012), this ‘J1407b’ system is very large, with a radius on the order of 0.6 AU (Kenworthy and Mamajek, 2015). Since 0.6 AU is much larger than the Roche limit for J1407b, this ring-like system might be better described as a proto-satellite disk than as a conventional planetary ring. The rings of Saturn and Uranus lie close enough to their host planets for tidal forces to prevent material from aggregating into isolated objects like moons, but the J1407b disk extends far enough that its constituent particles should coalesce into moons in astronomically short timescales. Still, this discovery bodes well for current efforts to find Saturn-like rings around extra-solar planets.

Several different methods have been proposed to detect exorings, including detailed modeling of transit lightcurves (Barnes and Fortney, 2004), phase functions (Arnold and Schneider, 2004; Dyudina et al., 2005), and Rossiter–McLaughlin-like radial velocity data (Ohta et al., 2009). Recently, Santos et al. (2015) determined that the anomalously strong reflected light signature from 51 Peg b (Martins et al., 2015) does not represent a ring system.

In this paper we describe a pilot investigation of a handful of *Kepler* giant planets to explore the feasibility of constraining the presence of exorings with the transit lightcurve technique. In Section 2 we explain our process for choosing which candidates to investigate. Section 3 describes the *Kepler* data and their reduction. How we model and analyze these systems to determine the presence of rings is explained in Section 4. Section 5 discusses the results from lightcurve fitting, particularly its application to KOI-422. Finally, Section 6 discusses some conclusions and possible implications of finding exorings.

2. Methods

Based on Barnes and Fortney (2004), we explore the constraints on the nature of potential rings around exoplanets that detailed analysis of transit lightcurve s might provide. To do so we use the transit fitting algorithm `transitfitter` (Barnes and Fortney, 2004), which produces synthetic light curves by integrating the total stellar flux blocked by the planet and ring at each timestep.[1] The algorithm uses a Levenberg–Marquardt system to arrive at best-fit quantities for fitted parameters.

We assume that planetary ring systems have zero thickness and lie in their parent planet's Laplace plane. As shown in Burns et al. (1979), close to a planet (as is the case within the Roche limit for particle breakup) the Laplace plane is essentially identical to the equatorial plane, thus placing rings around the equator of the exoplanet.

2.1. Model parameters

While Barnes and Fortney (2004) forward-calculated theoretical transit lightcurve s of ringed planets, it did not allow for a lightcurve fit using the ringed planet model. Here we update `transitfitter` to explicitly allow for fitting of ringed planet parameters in addition to the standard parameters.

The biggest challenge to fitting using ringed planets comes from geometry. Generalized orientations of rings and their lack of spherical symmetry require that the model fully account for the rings' opening angle and projected orientation. Our fitting algorithm allows the adjustment of the five following ring parameters, also shown in Fig. 1:

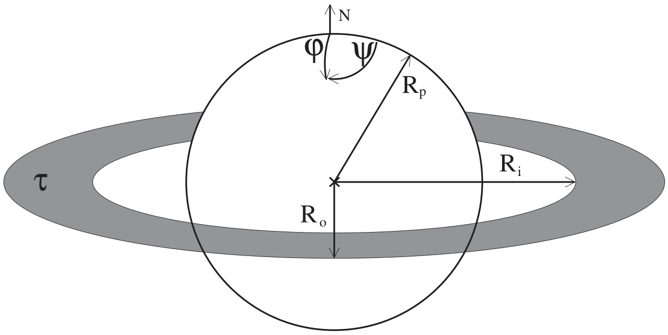

Fig. 1. Fit parameters: obliquity (ϕ), azimuth (ψ), outer radius of rings (R_o), inner radius of rings (R_i), and radius of the planet (R_p).

1. Inner ring radius (R_i)
2. Outer ring radius (R_o)
3. Normal optical depth (τ)
4. Obliquity (ϕ)
5. Azimuth angle (ψ)

Assuming a single, uniform ring, the inner radius (R_i) is the distance from the center of the planet to the inner edge of the ring. The outer radius (R_o), likewise, is the distance from the center of the planet to the outer edge of the ring. The area between these two radii within the planet's equatorial plane represents the extent of the rings as determined by the fit.

The normal optical depth τ controls the attenuation ($e^{-\tau}$) through the rings when they are viewed face-on. Solar System rings show a broad range of normal optical depth values, τ, with tenuous systems like Jupiter's main rings and the various tenuous components of the other planet's ring systems having $\tau < 10^{-3}$ (Tyler et al., 1981; Horányi et al., 2009), while some portions of Saturn's B rings have $\tau > 5$ (Colwell et al., 2009). The effective slant optical depth of the rings as viewed in transit will always be equal to or higher than the normal optical depth as a function of the rings' opening angle α.

The opening angle α measures whether the rings present to us edge on ($\alpha = 0^\circ$), face-on ($\alpha = 90^\circ$), or in-between ($0^\circ < \alpha < 90^\circ$). The actual, observed optical depth τ_{slant} of a planar ring system then becomes $\tau_{\text{slant}} = \frac{\tau}{\sin\alpha}$. Note that at $\alpha = 0^\circ$ the observed optical depth is infinite, however its projected area is zero thus this mathematically problematic condition never affects any real fit.

While the opening angle α of the rings is the more direct observable, we instead fit for the more physically relevant planetary obliquity ϕ, the angle between the planet's rotational angular momentum vector and its orbital angular momentum vector (which lies close to orthogonal to the earth's line of sight to the star since the planet transits). Hence when the north pole is pointed towards Earth, the rings are face-on with $\alpha = 90^\circ$ and $\phi \sim \pm 90^\circ$. In this face-on case the lightcurve will be symmetric about the mid-transit point, as shown in Fig. 2.

The rings' observed outline depends not just on how much the planet is tilted, but also on whether it is tilted straight toward you, within the plane of the sky, or somewhere in between. The azimuth angle, ψ, represents the orientation of the planet's rotational angular momentum vector in space, measured clockwise from the plane of the sky as viewed from over the stellar north pole. The ring opening angle α relates to the obliquity ϕ and the azimuth ψ as

$$\alpha = |\sin^{-1}(\sin\phi\ \sin\psi)|. \tag{1}$$

A rotation in ψ will therefore have no effect on the lightcurve if $\phi = 0^\circ$ (edge-on) because the position of the north pole is unaffected; however, the ingress and egress of the lightcurve will typically change as a function of ψ at any other obliquity. Note that, even with a nonzero planetary obliquity ϕ, if the azimuth is $\psi = 0^\circ$ or $\psi = 180^\circ$, then the rings will still appear edge-on.

2.2. Algorithm improvement

The problem of calculating theoretical lightcurves for transiting

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[1] Please email JWB at `jwbarnes@uidaho.edu` for a copy of the source code for the `transitfitter` program.