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Photometric Phase Variations of Long-Period Eccentric Planets

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Abstract

The field of exoplanetary science has diversified rapidly over recent years as the field has progressed from exoplanet detection to exoplanet characterization. The refinement of orbital parameters allows precision targeting of transit windows and phase variations which constrain the dynamics of the orbit and the geometric albedo of the atmosphere. Here we describe the expected phase function variations at optical wavelengths for long-period planets, particularly those in the high-eccentricity regime and multiple systems in resonant and non-coplanar orbits. We apply this to the known exoplanets and discuss detection prospects and how observations of these signatures may be optimized by refining the orbital parameters.

1. Introduction

The currently known diversity of exoplanets is greatly attributable to the revolution of the transit detection method over the past 10 years. The measurement of radius and hence density were the first steps from the results of this technique, but soon to follow were atmospheric studies from both primary transit and secondary eclipse. However, the unknown inclination of the planetary orbits makes this technique only applicable to a relatively small fraction of the known exoplanets. For the non-transiting planets, reflected light and phase variations present an additional avenue through which to investigate planetary atmospheres. Phase variations of exoplanets in the IR and optical regimes have had success due to increased access to improved instrumentation and space-based observatories. This has primarily been investigated for transiting planets since the edge-on orbital plane produces the highest phase amplitude.

[1] and [2] showed that planets in eccentric orbits have inflated transit probabilities. These types of planets will produce relatively high phase amplitudes during a brief period (periaston passage) of the orbit. However, phase variations of non-transiting planets have been restricted to hot Jupiters. Exploring the atmospheric properties of longer-period planets requires taking advantage of highly-eccentric non-transiting systems. Thus we also constrain the inclination and hence the mass of such planets. This is described further by [3] and [4].

2. Exoplanet Phase Variations

Figure 1 shows a top-down view of an elliptical planetary orbit. The phase angle α is described by

$$\cos\alpha = \sin(\omega + f) \tag{1}$$

where ω is the argument of periastron and f is the true anomaly. The phase angle is defined to be $\alpha = 0$ degrees when the planet is at superior conjunction ("full" phase). In terms of orbital parameters, this location in the orbit occurs when $\omega + f = 270$ degrees.

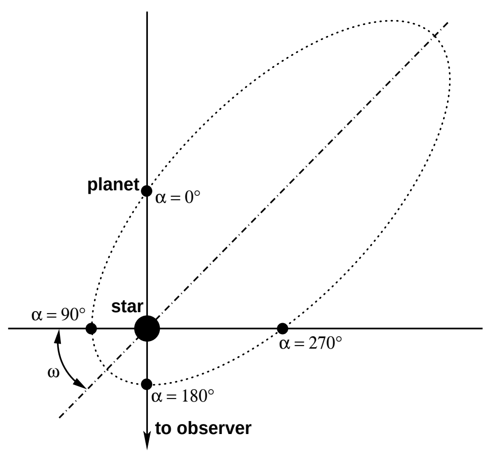

Figure 1: Orbit of eccentric planet, showing orbit phase angles corresponding to full, first quarter, new, and third quarter phases.

The flux ratio of the planet to the host star is defined as

$$\epsilon(\alpha,\lambda) \equiv \frac{f_p(\alpha,\lambda)}{f_\star(\lambda)} = A_g(\lambda) g(\alpha,\lambda) \frac{R_p^2}{r^2} \qquad (2)$$

and thus contains three major components; the geometric albedo, the phase function, and the inverse-square relation to the star–planet separation. Note that for a circular orbit, only the phase function is time dependent. For the analysis performed here, we adopt the empirically derived phase function of [5], based upon observations of Jupiter and Venus and incorporates substantially more back-scattering due to cloud-covering.

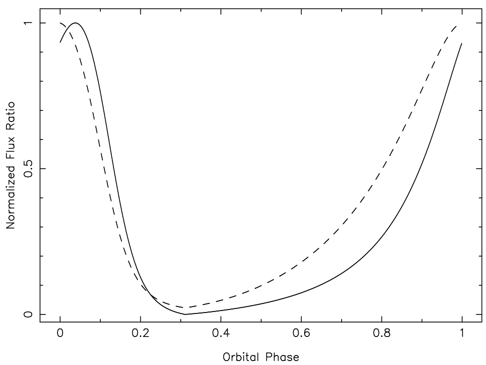

Figure 2: The phase function (dashed line) and normalized flux ratio (solid line) for an orbital configuration of $e = 0.3$ and $\omega = 0$ degrees.

Shown in Figure 2 is an example phase function for a planet in an eccentric orbit. Note that the maximum flux ratio does not necessarily occur at zero phase angle for a non-circular orbit. This is because the orbital distance is changing and thus the star–planet separation component of Equation 2 becomes dominant for highly eccentric orbits. This time-lag between maximum flux ratio and maximum phase was also noted by [6].

3. Multi-Planet Systems

Detection of multi-planet systems is becoming more frequent as we are increasingly able to probe into smaller mass and longer period regimes of parameter space. If indeed single planet systems are rare, then it is highly likely that the phase curve from a particular planet will be "contaminated" by the reflected light of other planets in the system. For planets which are similar in size, the effect of an outer planet to the combined phase curve will be small since (from Equation 2) $\epsilon(\alpha,\lambda) \propto r^{-2}$.

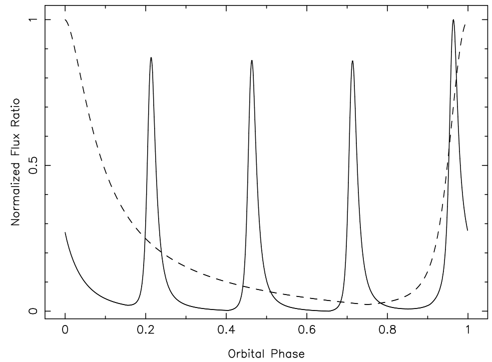

Figure 3: Normalized flux ratio (solid line) for a multi-planet system in which both planets are in 4:1 resonance with $e = 0.5$. The dashed line represents the phase function of the outer planet.

Shown in Figure 3 is an example multi-planet system with two Jupiter radii planets in 4:1 resonance with $e = 0.5$. This system presents a difficult problem in dis-entangling the separate planetary signatures, with the combination of high eccentricity and larger relative semi-major axis of the outer planet leading to a limited observation window, higher required cadence, and modest phase signature from the outer planet (seen close to an orbital phase of 0.95 in Figure 3). If one is unable to monitor this highest peak and also discern the difference in amplitude with the other three peaks then the presence of the outer planet will remain hidden to the observer. Thus the derived system architecture based purely upon the phase variations will be incorrect. Resonant systems such as this currently comprise a small fraction of the total number of exoplanet systems, but will increase in relevance as radial velocity surveys sample to longer periods and as Kepler discovers multi-planet systems.

4. Summary and Conclusions

Current generation space-missions are already detecting exoplanet phase variations in the optical (eg., Kepler) and the IR (eg., Spitzer). The steps these produce towards characterizing the atmospheres of these exoplanets are significant since they provide direct measurements of the atmospheric albedo and thermal properties. We have shown here how time and position dependent functions for the geometric albedo and phase can be used to describe expected phase variations for long-period eccentric giant planets. There is a clear degeneracy with orbital inclination and resonance when considering multi-planet systems and care must be taken to account for these possibilities. Most of the predicted flux ratios for the known planets push heavily against the boundaries of what is achievable with current ground and space-based instruments. A thorough search of all these planets will therefore likely need to await future generation telescopes, such as the European Extremely Large Telescope (E-ELT), the Thirty Meter Telescope (TMT), the Giant Magellan Telescope (GMT), and the James Webb Space Telescope (JWST).

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