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Terrestrial Exoplanet Light Curves

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Abstract. The phase or orbital light curves of extrasolar terrestrial planets in reflected or emitted light will contain information about their atmospheres and surfaces complementary to data obtained by other techniques such as spectrosopy. We show calculated light curves at optical and thermal infrared wavelengths for a variety of Earth-like and Earth-unlike planets. We also show that large satellites of Earth-sized planets are detectable, but may cause aliasing effects if the lightcurve is insufficiently sampled.

Keywords. stars: planetary systems, techniques: photometric, planets and sateliites: general, Earth, scattering.

1. Introduction

The variation in the reflected or emitted light from a planet as it orbits its parent star contains unique information about that body. In 1610, Galileo Galilei used his telescope to discover that the changing brightness of Venus was partly a consequence of its phases (and also overthrowing the Ptolmeic theory of the Cosmos). His anagram to the Tuscan ambassador of Prague (the forerunner to the IAU telegram?) read *Haec immatura a me iam frustra leguntur o.y.* [This immature female has already been read in vain by me] but unscrambled to *Cynthiae figuras aemulatur mater amorum* [The mother of love (Venus) resembles Cynthia (the Moon)] (van Helden 1989).

The first direct detection of an Earth-sized planet around another star would be a scientific triumph of equal significance, yet the ultimate goal is to obtain information about its atmospheres and surfaces, especially those properties related to its ability to support life, or even evidence for life itself. Spectroscopy is a powerful technique to obtain such information (Des Marais *et al.* 2002, Seager *et al.* 2005), however high signal-to-noise is required. Regardless of whether spectroscopy is succesful, direct detection of a planet, confirmation of its companion status, and determination of its orbit require observations at multiple epochs. Photometry at these epochs will produce a partial or complete phase light curve of the planet. Such a light curve is distinct from photometric variability in the planet induced by its rotation and surface features (Ford, Seager & Turner 2001). The latter may be diffiult to observe, but easy to remove by sufficiently long integration times.

A theoretical model of an orbital light curve must include a full description of the star-planet-observer geometry, including 5 orbital parameters plus the obliquity (Figure 1). The light curve will also depend on the scattering and emission properties of the atmosphere and surface modulated by any seasonal effects induced by finite obliquity or eccentricity. The presence of Saturn-like rings around a giant planet may also manifest itself by specific photometric features (Arnold & Schneider 2004). The reflected and emitted light from extrasolar giant planets has been modeled, including effects induced by changes in effective temperature on highly eccentric orbits (Burrows, Hubeny & Sudarsky 2005,Fortney *et al.* 2005, Dyudina *et al.* 2005, Sudarsky *et al.* 2005, Barman, Hauschildt & Allard 2005). Although the complete light curve of a giant planet has not been measured, there are useful upper limits for the reflected light of close-in and transiting planets (Charbonneau *et al.* 1999, Leigh *et al.* 2003, Green *et al.* 2003, Deming *et al.* 2005, Snellen 2005) and detections of secondary eclipses at thermal infrared wavelengths (Charbonneau *et al.* 2005, Deming *et al.* 2005).

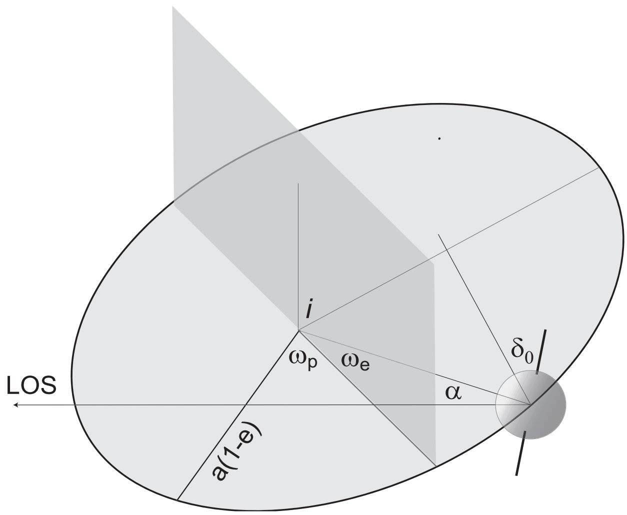

Figure 1. The geometry of the star-planet-observer system for light curve calculations is specified by the inclination of the normal of the planetary orbit plane to the line of sight (i), semi-major axis (a) and orbital eccentricity (e), the longitude of the periastron relative to the ascending node (ω_p), the longitude of the spring equinox of the hemisphere most in view relative to the ascending node (ω_e), and the obliquity (δ_0). α is the phase angle.

2. Reflected Light from Terrestrial Planets

The reflected light from an Earth-like planet will depend on the scattering properties (phase function) of the principle reflectors, i.e., clouds, the atmosphere, ice, and land. Superposed on these effects will be seasonal variation in reflectivity, which for the Earth is as much as 10% (Woolf *et al.* 2002). However, it seems likely that many Earth-sized planets will be non Earth-like, and it is therefore useful to ask whether orbital light curves can distinguish between hypothetical, broad classes of objects characterized by a uniform reflecting surface and a simple scattering law. The simplest case is isotropic (Lambertian) scattering, however Solar System surfaces are better represented by Hapke single-scattering models (Hapke 1993).The phase curves of Mercury and Mars have been successfully reproduced using a representation of the double Henyey-Greenstein function

$$p(\alpha) = \frac{(1+c)(1-b^2)}{2\,(1-2b\cos\alpha+b^2)^{3/2}} + \frac{(1-c)(1-b^2)}{2\,(1+2b\cos\alpha+b^2)^{3/2}}, \tag{2.1}$$

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and parameter values $b = 0.21, c = 0.7$, and $b = 0.18, c = 1.1$, respectively (Warell 2004). The reflected light from a planet with a deep, transparant atmosphere and a dark surface, e.g. a global ocean, will be dominatd by Rayleight scattering (RS). Single RS has the phase function

$$p(\alpha) = \frac{3}{4}\left(1 + \cos^2 \alpha\right). \tag{2.2}$$

Can Hapke- and Rayleigh-scattering planets be distinguished solely on the shape of their reflected light curves (absolute albedos require observations in the infrared)? Figure 2a shows the light curves of hypothetical Lambertian-, single Rayleigh-, and Hapke-scattering planets with uniform surfaces as seen at an orbital inclination angle of 60 deg. The opposition effect is clearly discernable, but the small difference between the Hapke- and Rayleigh-scattering models are unlikely to be distinguishable at observable phase angles. The signal from planets with smooth surfaces, e.g., a cloud-free ocean world Léger *et al.* 2004) with a thin atmosphere, or an ice-covered planet, will include significant specular reflection as well as diffuse scattering. The light curves of such objects can be clearly distinguished (Figure 2b) from those of the previous cases, although increasing cloud cover and Rayleigh scattering by an atmosphere will moderate these effects (Williams *et al.*, in prep).

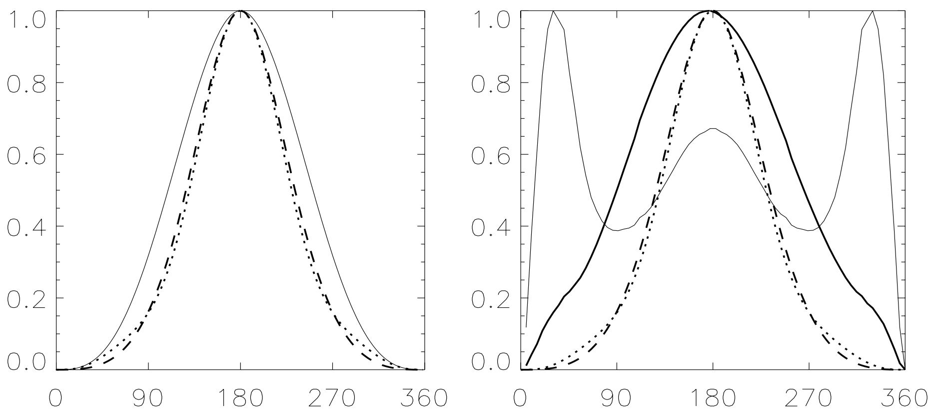

Figure 2. (a) Orbital reflected light curves of three uniform planets observed at $i = 90$ deg. with and different scattering laws; Lambertian (solid line), single RS (dotted line) and a model of Mercury (dashed line) (Warell 2004). (b) Light curves of "smooth" (ocean) planets (solid lines) with 0% (thin) and 38% (thick) cloud cover compared to RS and Mercury models. All curves have been normalized.

3. Emitted Light from Terrestrial Planets

The simplest terrestrial planet case is that of a rotating rocky planet lacking oceans or atmosphere, having a uniform albedo and blackbody emissivity, e.g., Mercury. The thermal inertia j of a solid surface subject to diurnal heating with frequency Ω is $\sqrt{k\rho c}$, where k is the thermal conductivity, ρ the density, and c is the specific heat capacity of the material. Solid basalt ($k = 2$ W m^{-1}K^{-1}, $\rho = 2900$ kg m^{-3}, $c = 1$ kJ kg^{-1} K^{-1}) has $J \approx 2400$ J m^{-2}K^{-1} sec$^{-1/2}$. Dust-covered surfaces on Mars have J values as low as 30 W m^{-2}K^{-1} sec$^{-1/2}$ (Mellon *et al.* 2000). The thermal inertia of the lunar regolith is ~45 W m^{-2}K^{-1} sec$^{-1/2}$, and the large main-belt asteroids have still lower J values

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(Müller & Lagerros 1998). The thermal response of a planet can be divided into two regimes, $t_{day} \ll t_{thermal}$ and $t_{day} \gg t_{thermal}$, where the thermal response time is

$$t_{thermal} = \frac{\pi J^2}{4\sigma^2 \bar{T}^6}, \tag{3.1}$$

and σ and $\bar{T}$ are the Stefan-Boltzmann constant and the mean temperature, respectively. For a bare rock surface at 255 K (the emission temperature of the Earth), t_d is 2 months (note the extreme sensitivity to $\bar{T}$). A planet with the thermal properties of the lunar surface has $t_{thermal} = 30$ minutes!

A planets with a fine-grained regoliths and no atmospheres will experience large diurnal temperature variation, and, depending on i, will exhibit significant orbital variation in disk-averaged flux. In contrast, a planets covered with bare rock, e.g. one on which geologic resurfacing continues, will have a relatively small day-night surface temperature difference and orbital variation in its emitted flux would occur only if it had a significant obliquity and seasonality. The modest average obliquity of the Earth ($\delta_0 = 23.45$ deg. may not be typical of terrestrial planets (Laskar, Joutel & Robutel 1993): The obliquities of Mars and Venus are thought to have undergone large excursions over Solar System history and numerical simulations of the final stage of terrestrial planet formation produce planets with an isotropic distribution of primordial obliquities due to the final stochastic accretion of a few large embryos (Agnor, Canup & Levison 1999). Large δ_0 leads to large seasonal and hemispherical differences in incident stellar radiation and a high amplitude light curve (Gaidos & Williams 2004) (Figure 3a).

An ocean and/or an appreciable atmosphere will profoundly affect the emitted flux from a terrestrial planet. The relation between outgoing infrared flux and temperature $I(T)$ for a greenhouse atmosphere deviates significantly from that of a blackbody. Oceans and atmospheres transport heat along thermal gradients and have large thermal inerties. The energy-balance equation governing the surface temperature T of a planet as a function of time t and latitude θ can be modeled using the heat transport equation

$$C\frac{\partial T}{\partial t} = S(1-A) - I(T) + \frac{1}{\cos\theta}\frac{\partial}{\partial\theta}\left(D\cos\theta\frac{\partial T}{\partial\theta}\right), \tag{3.2}$$

where S is the incident stellar flux, A is the top-of-the atmosphere albedo, and C and D parameterize the effective heat capacity of the atmosphere and surface, and meridional heat transport, respectively. The net effect is to obviate diurnal variation and attenuate seasonal variations (Gaidos & Williams 2004) (Figure 3b). Even planets with extremely high obliquities experience habitable temperature ranges over much of their surfaces as a consequence of the modering effect of an ocean and atmosphere (Williams & Kasting 1997, Williams & Pollard 2003). Thus, observation of marked infrared variability alone suggests properties of a planet relating to habitability; lack of an atmosphere or oceans and either a geologically old surface or a high obliquity. On the other hand, *absence* of variability cannot be uniquely interpreted as suggesting habitable conditions. The planet might resemble Earth; it might also be a barren planet with a very low obliquity, or have a thick runaway greenhouse atmosphere like Venus.

4. Terrestrial Planet Satellites

The Earth's Moon is thought to have formed by a low-velocity glancing impact with a Mars-sized body early in its history (Canup 2004). The Moon (or the angular momentum of the Earth-Moon system) stabilizes the Earth's obliquity against chaotic excursions and may be important for habitability (Laskar, Joutel & Robutel 1993). Numerical

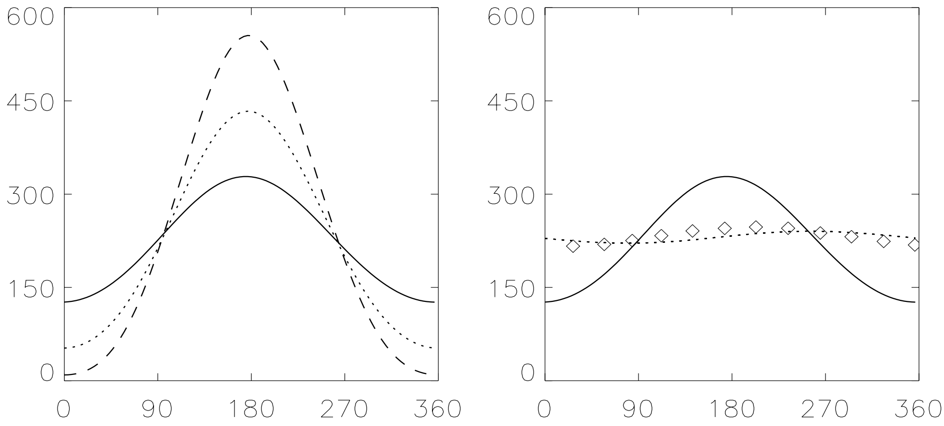

Figure 3. (a) Disk-averaged emitted light curves of planets W m^{-2}) seen at $i = 60$ deg. and with negligible thermal inertia over the orbital period, large thermal inertia over the rotation period, and $\delta_0 = 23.45$ (solid line), 40, and 60 deg. (b) Earth's emitted light curve modeled by a 2-D energy balance model (dotted line) and a 3-D global circulation model (points) (Gaidos & Williams 2004) compared to that of a simlar body with negligible thermal inertia (solid line).

simulations of planet formation show that potentially satellite-forming collisions are common (Ida, Canup & Stewart) and it is dynamically plausible that Mercury and Venus also had satellites but then lost them (Burns 1973, Ward & Reid 1973, Yokoyama 1999). Extrasolar satellites will be unresolved from their parent planet (the Earth-Moon distance subtends 0.25 mas at 10 pc) and only the total signal of the system will be observable.

The theory of impact origin explains the Moon's lack of volatiles by invoking high temperatures in the post-impact circumterrestrial disk; this may be a common property of satellites formed in this manner. There are two consequences of a lack of atmospheres or oceans: First, the satellite will be darker and essentially undectable in reflected light (the Moon-Earth flux ratio is 1.7%). Second, the lower thermal inertia of the satellite (see §3) means that the surface of the satellite experiences larger diurnal temperature variation, and consequently exhibit larger flux variation at thermal infrared wavelengths. Despite the satellite being smaller than the parent planet, the satellite's variation in IR flux may be larger (Figure 4). Satellites of planets may be detectable by sufficiently time-resolved measurements in the infrared. On the other hand, insufficiently time-resolved measurements may suffer from confusion of the two signals and aliasing. Satellites represent another opportunity and a new challenge for the direct detection and characterize terrestrial exoplanets.

Acknowledgements

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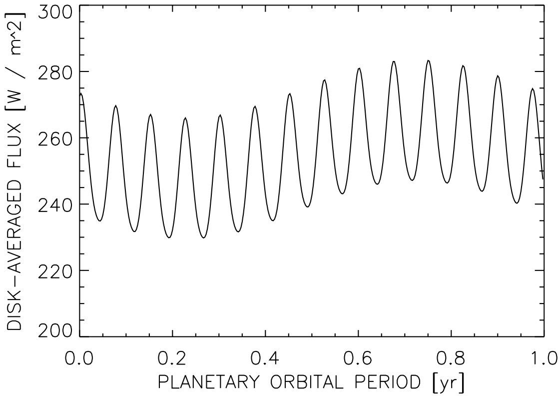

Figure 4. Disk-averaged emitted light curve of the Earth-Moon system (W m^{-2}) seen at $i = 60$ deg. The variation induced by the Moon's phases is larger than that of the Earth.

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