Model of Transit Simulation of Planets with Moons and Rings

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Introduction

Currently, 543 exoplanets are known (**www.exoplanet.eu**, in April 18). Most of these are gas giants, very close to their parent stars. Because of this, they are called Hot Jupiters. In the last few years, the possibility of these planets having moons has been studied. One of the reasons for this supposition is because all the gas planets in the Solar System have moons. If the gas planet is on he habitable zone (the region around the star where a planet with adequate atmospheric conditions can hold water in liquid state) of the star, then the exomoons may be habitable.

A few detection techniques have been suggested. Timing variations caused by the planet movement around the planet-moon barycenter (**Kipping 2009a**, **Kipping 2009b**) are the most studied.

In this work, we present a model to study the exomoons detection using photometry (**Sartoretti & Schneider, 1999**). Due to the small size of the moon, the direct detection is very difficult, but indirect detection is possible from small deformation caused by them on the transit light curve.

We developed a model to simulate the planet+moon transit in front of the host star, producing the light curve. With that, we study the detectability of moons using photometry, and stablish detection limits. We also consider the possibility of planetary rings. Effects of surface spots on the star are also considered.

The Model

Our model is made in IDL, based on Silva (2003) and Silva-Valio (2008). It considers the star as a limb-darkened disk. Planet and moon are opaque discs, and planetary rings are modelled as disks with user-defined transparency.

In each step, the program computes the planet position in front of the star. The luminosity is estimated by summing over all uncovered pixels. At the end of the transit, luminosity is normalized, yielding the transit light curve.

Noise and Detectability

The model has the feature to add gaussian noise and adjust the time resolution. Doing that, we can simulate light curves as would be observed by the CoRoT and Kepler space telescopes. After that, a fitting process using Pikaia and Amoeba algorithms is used to recover the original parameters.

To simulate the CoRoT light curves, we used noise level of 6×10^{-4} and time resolution of 32 seconds. For Kepler simulations, we used noise level of 2×10^{-5} and time resolution of 60 seconds.

Planet Detection

Our first example is the detection of a planet similar to HD 209458b. Below are shown the transit and the light curve, in a CoRoT transit simulation. The table compares the original and the fitted parameters, in simulations for CoRoT and Kepler.

The Q value is the *goodness of fit*, an indication of the fit quality, defined in **Press et. al., 1992**. . If Q is greater than 0.001, then the fit is acceptable.

Simulation	Parameter	Original Value	Fitted Value	Q
CoRoT	Planet radius (R_J)	1.38	1.37	0.188
	Inclination Angle (^{o})	86.677	86.694	
Kepler	Planet radius (R_J)	1.38	1.38	0.501
	Inclination Angle (^{o})	86.677	86.677	

Exomoons Detection

The signatures left by exomoons in the light curve depend on the moon physical and orbital parameters, but consist basically in steps in the ingress or egress region of the light curve and asymmetries in the bottom part, caused by the moon eclipse by the planet. Below we see an example of a moon with 3 Earth radius and 5 d period around a Jupiter-like planet with 45 d period.

Simulation	Parameter	Original Value	Fitted Value	Q
CoRoT	Planet radius (R_J)	1	1	0.533
	Moon Period (days)	5	5	
	Moon Radius (R_E)	3	2.9	
	Angular Position (^{o})	0	0.6	
Kepler	Planet radius (R_J)	1	1	0.807
	Moon Period (days)	5	5	
	Moon Radius (R_E)	3	3	
	Angular Position (^{o})	0	-0.4	

Rings Detection

The rings signal consists of small deformations in the ingress and egress regions of the light curve. Besides, the transit becomes deeper because the covered region of the star increases. To detect the planet rings, we have to differentiate between transits of planets and transits of planets+rings. So, we first fit the light curve considering just the presence of the planet. If the fit is not satisfactory, then the rings are detectable, and we redo the fit, considering the planet and the rings. The example below is a planet identical to Saturn with a 5 d period as detected by Kepler.

Simulation	Parameter	Original Value	Fitted Value	Q
Kepler	Planet Radius (R_J)	0.84	0.84	0.036
	Ring Internal Radius (R_p)	1.11	1.52	
	Ring External Radius (R_p)	2.32	2.12	
	Angle with sky plane (^{o})	78	78.35	
	Angle with sight line (days)	20	20.35	
	Transparency (R_E)	0.5	0.10	

Detection Limits

Our simulations indicate that CoRoT is capable of detecting exomoons of at least 1.3 R_E, and Kepler, 0.3 R_E. In the case of planetary rings, CoRoT would detect them only if they are 50% larger then Saturn's. Kepler would detected the rings even if they were 50% smaller than Saturn's rings.

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