Light curve effects due to "exomoons" in exoplanetary transits

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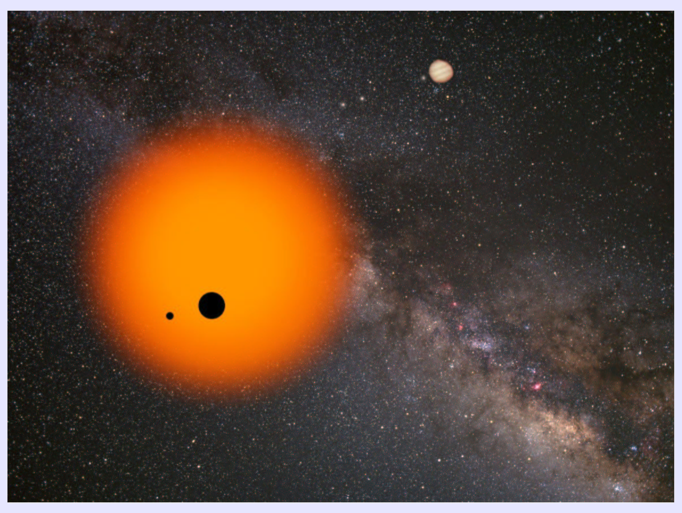
Introduction



The photometric transit detection of exoplanets has became an effective tool in about the past 5 years. In the future a few programs are planned to achieve as accurate measurements as about 0.1 mmag, allowing the detection of a large sample of Earth-like planets every year (e.g. COROT mission, Auvergne et al., 2003; Kepler mission, Borucki et al., 2003). The power of photometric detection is likely to keep increasing in the future. Sartoretti & Schneider (1999) argues that an "exomoon", a moon orbiting around an exoplanet, causes measurable photometric and timing effects. On the other hand, only negative observations are known by today (Brown et al, 2001, Charbonneau et al, 2005). Now we argue that the space missions may find a few dozen exomoons in the future. We illustrate the simulated observations, and discuss the direct photometric detections and the indirect detections via timing effects from the observational point of view, and characterize systems with detectable exomoons.

Light Curve Effects

The apparent stellar flux during the transit was evaluated from a simulated image of a real star model (Padova isochrones, Phoenix limb darkening) in which pixels are zeroed by the transiting objects. Stellar diameter was 1000 pixels, fluxes were normalized to out-of-transit stellar flux. Lightcurve calculation consisted of modelling stable planet-moon systems. We concluded the followings:

1, The direct detection would be the identification the separate transit of the moon (**photometric effect**). For a huge, Earth-sized moon these effects are characteristically 1 mmag for a 0.3 M_{Sun} star, 0.1 mmag for 1 M_{Sun} and 0.02 mmag for 2 M_{Sun}. For a Moon-sized moon, the effects are 0.1 mmag, 0.07 mmag and 0.001 mag, respectively. So few detections are likely for the forthcoming decade.
2, The detection of **timing effects** (the time shifts of the transit due to the orbital motion of the moon-planet system around its barycenter, e.g. Sartoretti & Schneider,1999, Szabó et al., in prep.) the most promising tool even in noisified and sampled model observations. This tool emphasizes the photometric distorsions even if they are smaller than the photometric error in the individual points.

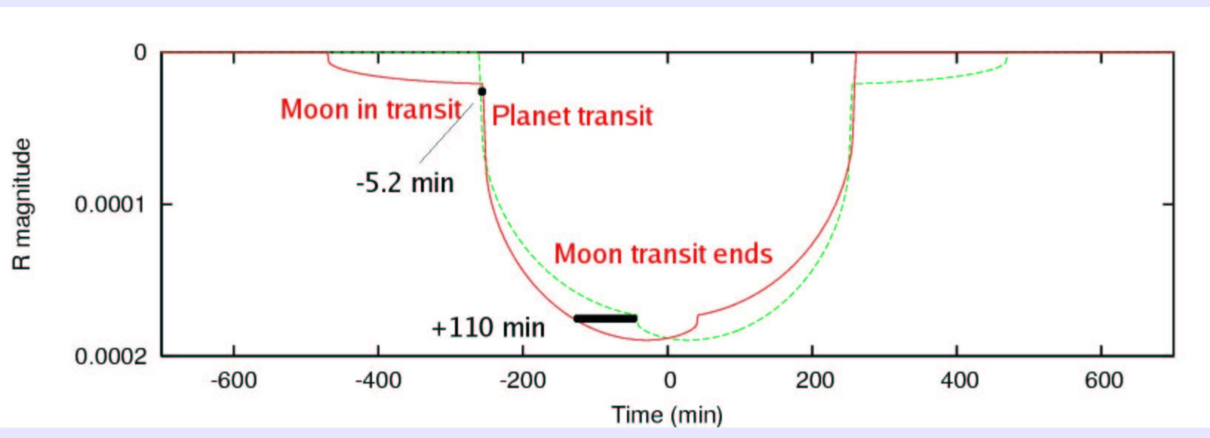


Figure 1. *Simulated light curves of our Earth-Moon system in transit. Red and green curves show two different transits with the Moon in leading and trailing position. The labels describe the event represented by the red curve. The transit of the planet occurs 5.2 min earlier with trailing moon, but the curve with leading moon starts decreasing rapidly, and reaches the signed magnitude 110 minutes earlier than with trailing moon. The averaged differences in each point result the timing effect of about 20 minutes.*

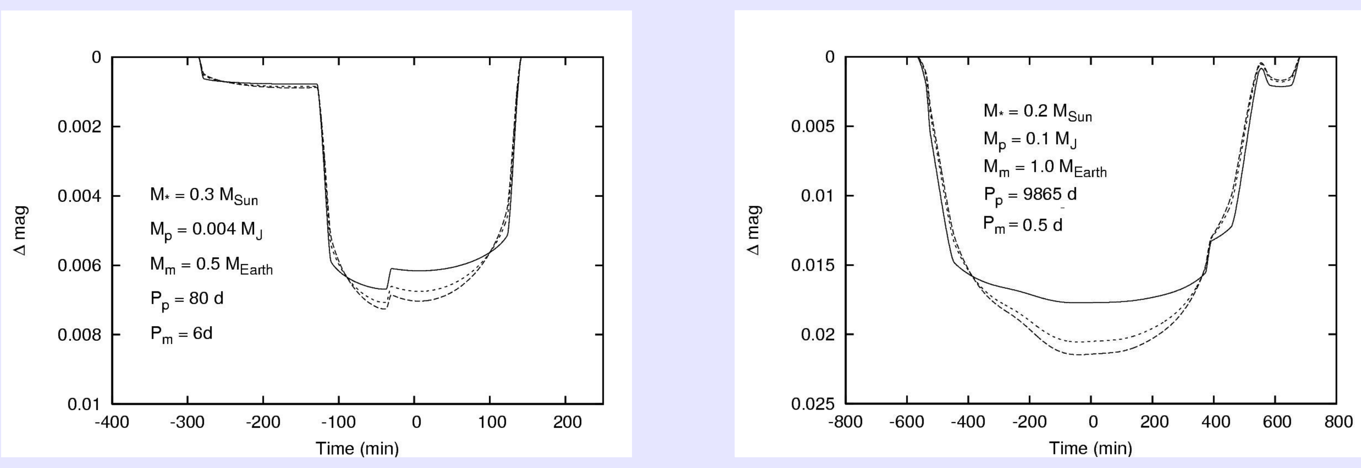


Figure 2. *Model calculations of the light curve effects in two different systems (M:mass, P:period, m:moon, p:planet) as appear in different photometric filters: K, I and R from the smallest to the largest amplitude, respectively.*

Detectable Systems

From the observational point of view, the interesting question is to characterize systems which contain observable moons. We applied a Monte-Carlo-like method for finding some appropriate systems: simulated transit observations were randomly set up, and we checked if the timing effect of the moon is observable with at least 3-σ confidence. 500 systems were designed containing both giant and Earth-like planets, different inclinations and orbital periods, where the period of the planet did not exceed 400 days in order to have at least 4 transits during the planned operation time of Kepler. Two subset of model measurements were calculated. One reflected the quality of Kepler and COROT (0.1 mmag accuracy, 1-minute sampling rate), and a "future observable" set was calculated with ten times better accuracy (0.01 mmag).
We found 51 "future observable" systems and 8 ones which could be observed with the present accuracy. Both giant and Earth-like planets can have observable moons; in the first case the S/N of the transit is high enough to allow accurate measurement, while the timing effect of an Earth-like planet exceeds a few (5-55) minutes. The present equipments allow the detection of moons of giant planets around red dwarf stars, but a positive detection suggests that there is some chance in case of Earth-like planets. The planet has to be at least 0.6 AU from the star for the presently available accuracy, and even not too closer, 0.4 AU for the ten-times accurate measurements. The moon orbiting further from the planet is more detectable. In the term of orbital period, the planet must have at least about 280 days orbital period for promising detections. This is not too favorable as one can expect only few transits during a 4-year mission, reducing the chance for somewhat detailed modeling of the moon itself.

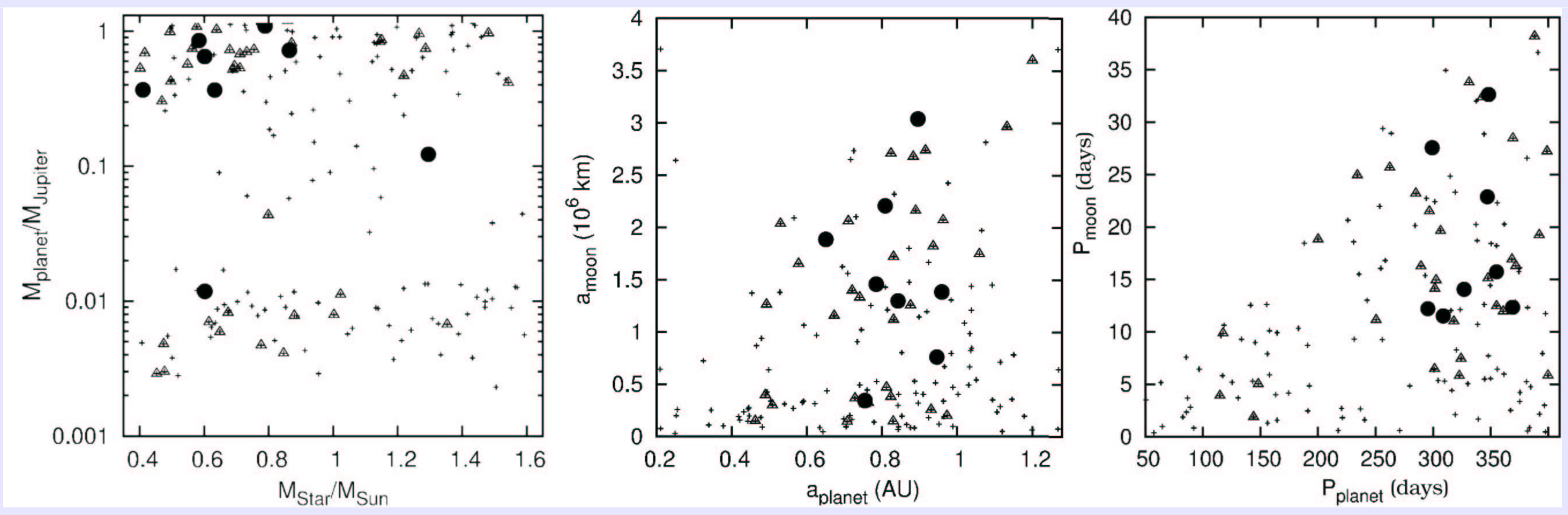


Figure 3. Modeled systems with moon detectable with photometric accuracy of 0.1 mmag (large dots) or 0.01 mmag (triangles); undetectable systems are marked by small crosses.

Could Kepler Detect Our Moon?

Although the photometric effect of our Moon is only 0.009 mmag, there is hope for such detection, due to the timing effect exceeding 20 minutes. Our calculation with Kepler-quality measurements showed that the detection is not too likely: we found 5 detections in 20 calculations, but the possibility cannot be excluded.
We defined a similar system so as to decide whether the photometric accuracy or the sampling rate is more dominant. There were a 0.7 M_{Sun} mass, 5 Gyr old, Z=0.019 central star selected, while the planet-moon masses, sizes and periods were the same as for the Earth-Moon. We conclude that the detection is primarily determined by the sampling rate. Even with the worst photometric accuracy, we got better detection than 3-σ if the sampling rate was 1 or 2 minutes. On the contrary, no positive detection was found with 20 or 30 minutes sampling rates, and the only positive detection with 10-minutes sampling rate is also rather ambiguous.

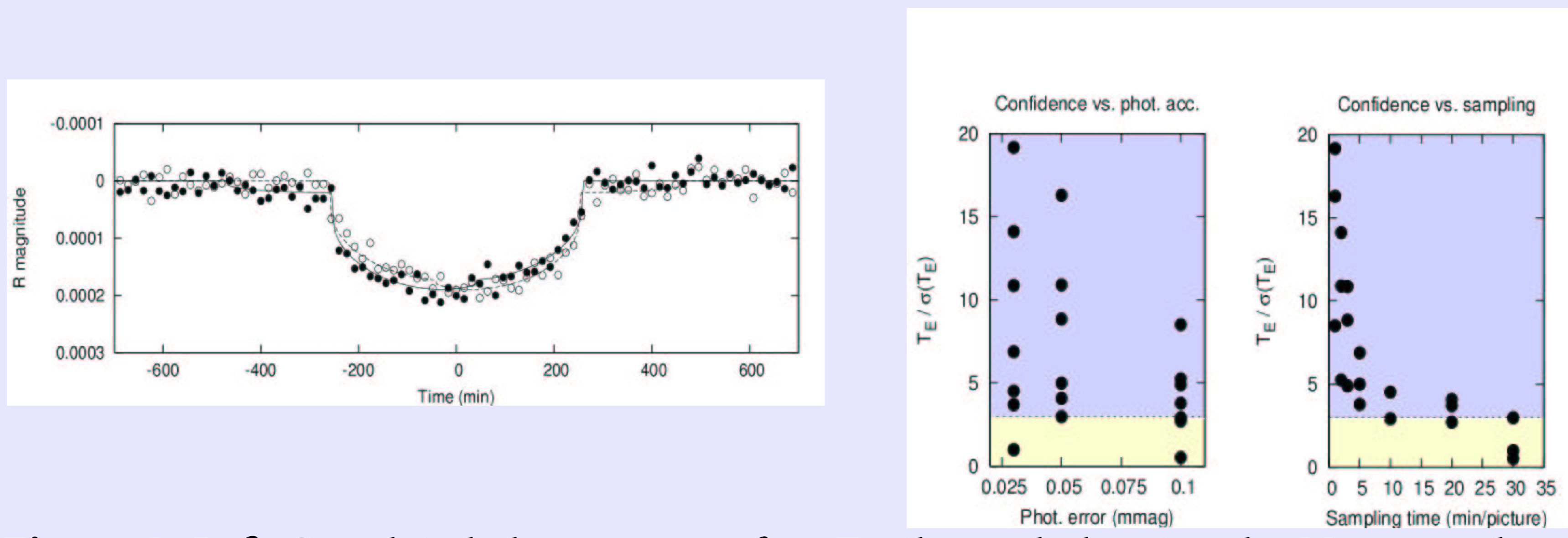


Figure 4. ***Left:*** Simulated observations of an Earth-sized planet and a Moon-sized moon before 0.7M_{Sun} star. The 5-minute average data points of expected Kepler-quality are shown; filled and open circles show observations with leading and trailing moon. The timing effect is even detectable with 3-σ. ***Right:*** The detectability of T_E timing effects vs accuracy (as 0.1, 0.05, 0.025 mmag) and sampling rate (as 1, 2, 5, 10, 20, 30 minutes). T_E /σ (T_E) is the confidence level (i.e. how-many-sigma detectability), positive detection is expected in blue areas.

Discussion

Are the fully modeled planets (Tres-1, TR10, TR56, TR111, TR113, TR132 and HD 209458) in Schneider's Extra-solar Planets Catalog (2005) likely to contain exomoons? They are hot Jupiters, orbiting very close to the central star, and their Hill-radius is only 1.2-2-times the planet radius. The possible position of dynamically stable moons does not seem to allow positive detections (expected timing effects are about 1 second), but considering the extended atmosphere, they are not too likely even to exist. One should rather concentrate on long-period planets.

What observational strategy is suggested in order to find exomoons? Although the required photometric accuracy (0.1-0.15 mmag) is about the best quality of nowadays, whenever it is possible, short sampling intervals should be used. This will help to increase the number of systems where the timing effect is less, e.g. as the moon is smaller, or is closer to the planet, or the mass ratio is smaller. The strategy of the planned missions is fits this. But also, the pipeline must be sensitive for timing effects potentially caused by moons, and has to avoid the automatic rejection of those transit candidates which are slightly discordant with a strictly monoperiodical orbit.

Based on the presented calculations, one may estimate the magnitude of the expected real detections with Kepler. The total number of the Earth-sized planets to be discovered is a few hundred, during the entire mission. If only 5 percent of them have a moon similar to our Moon, and only every fifth moon will be really found, we even should get a few positive detected exomoons. If we take into account the COROT mission, and the forthcoming missions, too, we may have a few dozen known exomoons by the end of the following decade.

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