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Exomoons around transiting exoplanets

PhD thesis

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Scientific Background

The study of extrasolar planets (exoplanets) has become a significant subject in astronomical research over the past twenty years.

The question of existence and detection of that kind of planets appeared first in the thoughts of the ancient Greeks. Later several philosophers (Giordano Bruno, Fontenelle, Goethe, Kant) were inspired by this topic. Huygens (1698) was the first who tried to detect planets around other stars, but he realized that such a planet detection is far beyond the capabilities of his telescopes. The attempts of W. S. Jacob in 1800s and that of van de Kamp in the first half of the 1900s were unsuccessful, too. The first confirmed detection was in 1992 by Wolszczan & Frail, with the discovery of a planet orbiting the pulsar PSR B1257+12. The next exoplanet discovery around a Sun-like star, 51 Pegasi, was published in 1995, when Mayor & Queloz detected a Jupiter-like exoplanet via radial velocity observations.

In 1999, Charbonneau and his colleagues were first to measure the change in starlight while an exoplanet is crossing in front of its parent star's disk. The number of known transiting exoplanets rapidly increased over the last decade because the transit method became efficient and simple due to technical and computational developments. As of October 2011 about 700 exoplanets have been confirmed and about 1200 candidates of Kepler and CoRoT space telescopes are waiting for confirmation from independent measurements.

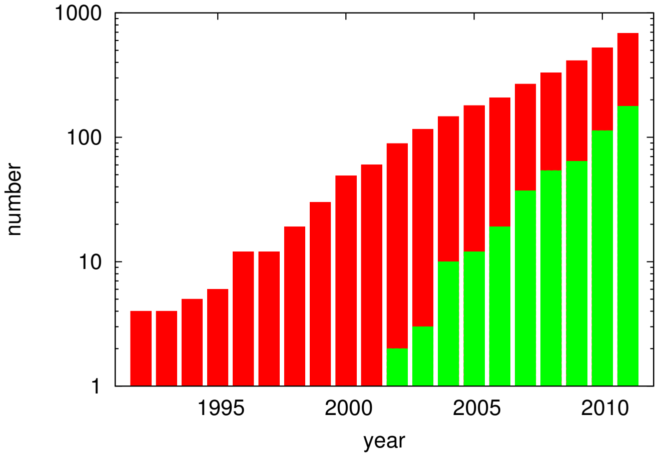

Figure 1: The number of discovered exoplanets. The red and green bars show the total number of all exoplanets and the transiting ones, respectively. The vertical axis is logarithmic. (Schneider, 2011)

The discovery of planets in other solar systems led to the question of how common they are or how similar they are to the planets of our solar system. The research into the distribution and physical characteristics of exoplanets is intimately linked to the question of finding life-hosting environments in the universe. In addition, Wagner (1936) & Asimov (1979) argued that our Moon played a key role in supporting life on Earth and it may be that the presence of a large exomoon is a *sine qua non* requirement for the development of intelligent civilization. Without a moon the rotation axis of an exoplanet could be varying significantly on a short time scale, so that in the case of a moonless Earth this process could have destroyed the life supporting environment.

My research was inspired by this idea, and I aimed at developing such kind of methods by which one can investigate the detectability of an exomoon orbiting planets of distant stars. The other reason I chose this fiels of research is that there has been no such example where the presence of an exomoon was proven.

Research methods

To study a light curve of an exomoon, the planet-moon system has to cross the parent star's disk. During the transit the planet and the moon are masking out a part of the stellar disk, hence the brightness of the star is decreased and the apparent radial velocity deviates from that of a Keplerian orbital motion. The latter is the Rossiter-McLaughlin (RM) effect: the average of the apparent radial velocity – taking the entire disk – of the rotating star is zero. This changes when the entire disk is not visible. Transits result in a typical light curve and Rossiter-McLaughlin curve that refer to the system. My research is based on the investigation of these kind of curves.

The individual light curve of the moon is similar to that of the planet, the differences are that the moon has smaller radius and the occulted light is less and so the depth of its light curve is smaller (Fig. 2). If the transit of the system occurs when the moon is not in the star-planet line directly then the central time of the individual transits of the planet and the moon will be different (Fig. 2 τ_b and τ_h).

For example in the case of a leading moon, the occultation starts with the moon followed by the planet. After that they moves together in front of the stellar disk. In the last phase the moon gets first over the edge of the star, and the planet follows it. Consequently, the first half of the combined transit light curve will be slightly deeper, and then shallower after the moon finished the transit (Figure 2 bottom left panel).

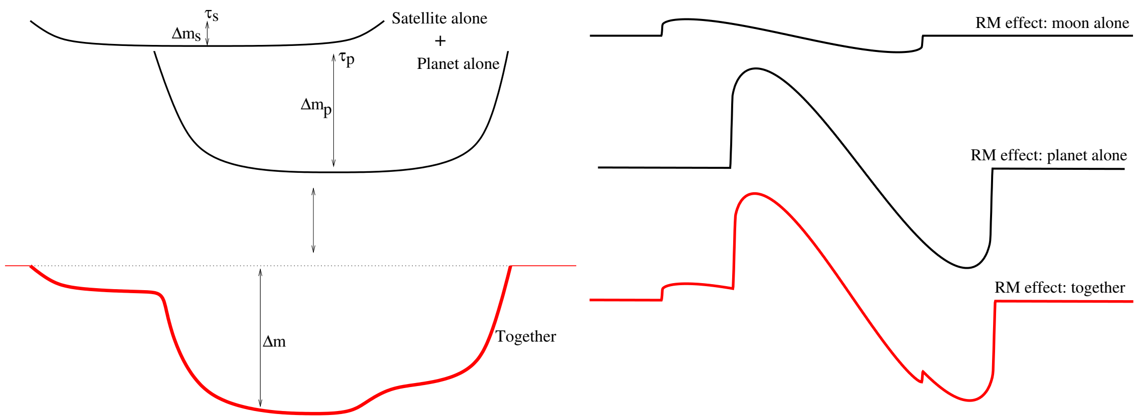

Figure 2: The light curves (left panel) and the RM effects (right panel) of the individual planet and moon and the combined curves and RM effect (red curves).

The modulation of the Rossiter-McLaughlin curve occurs in the same way in time, and the final curves will be the sum of the individual ones (Figure 2 top and bottom of the right panel).

The shape and the depth of the light curve are determined by several physical parameters of the star-planet-moon system. By increasing the radius of the planet and the moon relative to the star, the transit depth increases. By varying the temperature of the star, the value of the limb darkening differs and so are the shape and the depth of the light curve, too. The depth of the light curve also depends on the duration of the transit and the inclination of the orbit (due to the variation of local limb darkening). In addition, the Rossiter-McLaughlin curve is determined by the moving direction and the orbital angle parameters of the planet and the moon, and the rotational period of the star.

The effects mentioned above are observable only in that case when the orbital plane of the planet and the observer's plane is coplanar. This condition is especially true when the planet-moon system is orbiting far from the parent star.

I investigated the light and RM-curves via the numerical methods with a wide range of physical properties of individual systems.

Results

I. The simulator software and the characteristics of the light and RM-curve (Simon et al., 2009)

In my research it was necessary to develop a range of new algorithms to investigate the light curves caused by the planet-moon system that passes its star. I have written a new software, which is capable of creating simultaneously light curves and Rossiter-Mclaughlin (RM) curves. The numerical calculations are based on a bitmap of the star. The transit is calculated in such a way, that during the transit the value of the brightness and the local radial velocity of these pixels are set to zero in the given position of the planet and the moon. The software has a graphical user interface which allows us to adjust the physical parameters of the star-planet-moon system (e.g. radius, mass, orbital period, etc.), the sampling rate and the measurement error for different data quality.

The results of the investigation of several simulated systems are that the light and RM curves of the system are affected by moon in a special way. The curves of the moon are similar those of the planet, the differences are only the depth of the light curves and the time of the individual transit. The moon is smaller, so it can decrease the brightness of the star less than the planet, and its transit is shifted in time due to different position from the planet.

I examined the different shapes of the curves when the parameters of the system are changing. It was also found out how much is the light loss of the star caused by different sized moon and what are the differences between the curves of single planet and the planet-moon systems.

II. The photocentric model and the photocetric transit timing variation (Szabó et al., 2006)

In 1999, Sartoretti & Schneider suggested first that the moon around a transiting exoplanet may cause a measurable photometric effect. They found that there is a shift in the transit time of the planet due to the dinamical influence of the moon, and this is called barycentric transit timing variation ($\mathrm{TTV_b}$). They presented an analytical formula whit which one can get an upper estimate for the mass of the moon. Significant limitations of this method are that the tiny photometric signs of the moon in the light curve are ignored, and the shift of the transit of the planet is a hardly measurable effect.

In my work I presented a new approach for the photometric effect originated from the presence of the moon, and defined the transit timing variation as a shift in the median line of the light curve. In this photocentric model the transit time shifts in that direction where the tiny distortion of the light curve due to the moon appears relative to the planet. The transit of the moon occurs somewhat earlier or later than that of the planet and this variation in the transit time of the moon is much larger than that of the planet. This photometric effect makes the moon suitable to cause a significant shift in the transit time of the system even when the moon is too tiny to make observable light curve distortions.

The simulation in the Sun-Earth-Moon system showed that this photometric transit timing variation ($\mathrm{TTV_p}$) is more sensitive to the tiny variations of the moon in the light curves than the barycentric method of Sartoretti & Schneider.

III. The photocenter and the determination of the physical properties of exomoons (Simon et al., 2007)

With a detailed analysis of the photocentric model it turned out that the planet-moon system can be replaced by a artificial celestial body which is located in the photocenter on the planet-moon line and causes the same photometric effect than the planet and the moon together. The motion of this photometric point around the planet-moon barycenter leads to the photometric transit timing variation ($\mathrm{TTV_p}$).

Using the upper limit of $\mathrm{TTV_p}$ and the physical parameters of the planet-moon system I derived a new analytical formula with which one can estimate the radius, the mass and the density of an exomoon. Another results is that we can give more accurate estimation for the radius than the mass. The $\mathrm{TTV_p}$ has a maximum value for a given planet-moon system. If the values of $\mathrm{TTV_p}$ from the measurement are higher than that of the expected planet-moon system, we have to look for other explanations of this effect (e.g. perturbation of a second planet, exotrojan asteroids).

IV. Possibility of detection of exomoons via Rossiter-McLaughlin effect (Simon et al., 2010)

Measuring radial velocities is the main tool to confirm transiting exoplanet candidates. It has been suggested that the exoplanets can cause an observable signal via the Rossiter-McLaughlin effect (Gaudi & Winn, 2007). The shape of the RM-curve is determined by the shape of the orbits, so we can give an estimation not only for the radius but also the orbital angle parameters. This led to a question whether the moons around a planet can affect the shape of the RM-curve. This is a tiny modulation, but the $\sim$1 cm/s velocimetric accuracy, achieved by laser frequency combs in the laboratory, is promising in detecting the modulation due to an exomoon.

I made a detailed analysis of parameter reconstruction of an exomoon from the RM effect of a simulated observation. In the first step I determined the best fitted planet template to the observations data, then I fitted the residual (between the observations and the planet template) tuning the parameters of the moon.

The main conclusion is that the radius of the moon can be estimated the most accurately. In some cases, there is also meaningful information on its orbital period. When the transit time of the moon is exactly known (for example from transit photometry), the angle parameters of the moon's orbit can also be constrained from the RM effect. From transit light curves the mass can be determined, and combining this result with the radius from the RM effect, the experimental determination of the density of the moon is also possible.

The main limitation of this method is due to the stellar activity, so the best targets for exomoon exploration are the K and early M-dwarf stars, whose activity levels are lower. For an active star, there is reason for some optimism because the time-scales of the exoplanet-exomoon systems and those of the stellar signals are usually very different.

V. Signal of exomoons in averaged light curves of exoplanets (Simon et al., 2011)

Most of the methods in the literature utilize timing analysis of the raw light curves. I proposed a new approach for the direct detection of a moon in the transit light curves via the so-called "Scatter Peak". The essence of the method is the evaluation of the local scatter in the folded light curves of many transits.

The method requires $\approx$100 transit observations for a successful detection and each transits in the folded light curves must be overlaid very accurately, so the effects coming from other sources than moons must be removed. In the resulted "scatter curve" the different time-course effects of the moon are superimposed to each other and increase the value of the local scatter compared to that of the out-of transit phase. This leads to a simple wide peak around the transit time of the planet. It is an important step in the preprocessing phase of the data that the trend filtering of the light curves must be carried out in such a way that small deviations immediately before and after the transit of the planet shall remain unaffected.

I tested this method for four different sets of data quality (Kepler 'short cadence', Kepler 'long cadence', ground-based millimagnitude photometry with 3-min cadence and the expected data quality of the ESA planned mission of PLATO). The results of the simulation showed that the best result will be provided by the planned space telescope of PLATO with detection limit $0.5\ r_{Earth}$. Using the Kepler 'short cadence' data we have three times more chance of detection of Earth-sized moon than using ground-based data. The measurements with long exposure are suffered from the smearing effect that suppress the little light variations of the moon, so we do not expect successful detection of an exomoon.

Refereed publications associated with the dissertation

Publications in refereed journals

I. **Simon, A. E.**; Szabó, Gy. M.; Kiss, L. L. & Szatmáry, K.: *Signals of exomoons in averaged light curves of exoplanets* 2011, Monthly Notices of the Royal Astronomical Society, accepted

II. **Simon, A. E.**; Szabó, Gy. M.; Szatmáry, K. & Kiss, L. L.: *Methods for exomoon characterization: combining transit photometry and the Rossiter-McLaughlin effect*, 2010, Monthly Notices of the Royal Astronomical Society, **406**, 2038

III. **Simon, A. E.**; Szabó, Gy. M. & Szatmáry, K.: *Exomoon Simulations*, 2009, Earth, Moon and Planets, **105**, 385

IV. **Simon, A.**; Szatmáry, K. & Szabó, Gy. M.: *Determination of the size, mass, and density of "exomoons" from photometric transit timing variations*, 2007, Astronomy & Astrophysics, **470**, 727

V. Szabó, Gy. M.; Szatmáry, K.; Divéki, Zs. & **Simon, A.**: *Possibility of a photometric detection of "exomoons"*, 2006, Astronomy & Astrophysics, **450**, 395

Conference posters

I. Szabó, Gy. M., **Simon, A. E.**, Kiss, L. L., Regály, Zs., 2010, *Practical suggestions on detecting exomoons in exoplanet transit light curves*, "The Astrophysics of Planetary Systems: Formation, Structure, and Dynamical Evolution", Torino, Italy, 11-15 Oct, 2010

II. **Simon, A. E.**, Szabó, Gy. M., Szatmáry,K., 2008, *Exomoon simulations*, "Future Ground Based Solar System Research: Synergies with Space Probes and Space Telescope", Pertoferraio, Elba, Livorno, Italy, 8-12 Sept, 2008

III. Szabó, Gy. M., Szatmáry, K., **Simon, A.**, Divéki, Zs., 2007, *On the possible discovery of "exomoons" in exoplanetary transits*, "Extreme Solar Systems", Thira, Santorini, Greece, 25-29 July, 2007

IV. Szabó, Gy. M., Szatmáry, K., **Simon, A.**, Divéki, Zs., 2005, *Light curve effects due to "exomoons" in exoplanetary transits*, "Astrophysics of Variable Stars", Pécs, Hungary, 5-10 Sept, 2005