Special cases: moons, rings, comets, trojans

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Abstract  Non-planetary bodies provide valuable insight into our current understanding of planetary formation and evolution. Although these objects are challenging to detect and characterize, the potential information to be drawn from them has motivated various searches through a number of techniques. Here, we briefly review the current status in the search of moons, rings, comets, and trojans in exoplanet systems and suggest what future discoveries may occur in the near future.

Introduction

It is not original admitting that it is complicated to make accurate predictions about the future. There is a quote, attributed to Napoleon Bonaparte, warning against insisting too much in having the full control of the present status of a problem and a detailed plan for the future developments before starting to do the work (Celui qui, au départ, insiste pour savoir où il va, quand il part et par où il passe n'ira pas loin). However, considering the importance of the investment required to answer certain scientific questions, it is mandatory to have a realistic idea of the likelihood
of success of the research. These considerations apply to the topic of this chapter: the search and characterization of moons, rings, comets, and trojans in exoplanetary systems.

We know from the solar system that satellites and ring systems, minor planets, and comets provide meaningful insights into the processes of planetary formation and evolution (de Pater and Lissauer 2015). Many of them are interesting objects of research on their own, in particular considering their prospects of habitability. However, in view of the difficulty of categorically proving, or ruling out, the existence of life on other worlds in our solar system (i.e. Waite et al. 2017), one can rightfully wonder about the possibilities of actually finding life in extrasolar systems (for a summary of the technical difficulties, see Schneider et al. 2010; for a recent review on habitability, see Cockell et al. 2016).

In the following Sections we briefly discuss what to expect from near future researches about extrasolar systems of moons, rings, comets, and trojan minor planets.

Exomoons

In this volume there is an excellent review on exomoons and ring detections by R. Heller, therefore we have orientated this chapter towards complementary aspects. Additionally, we refer the reader to some recent reviews on the topic by Barr (2016); Kipping et al. (2014a); Schneider et al. (2015); Sinukoff et al. (2013). In order not to dwell long on topics already addressed by previous reviews, we will only briefly discuss processes of exomoon formation and evolution before addressing the present status of discoveries and our expectations for the future.

The research on the processes leading to the formation of exomoons has benefited from studies applied to the solar system (see Heller and Pudritz 2015; Miguel and Ida 2016; Ogihara and Ida 2012; Crida and Charnoz 2012). However, exomoons are expected to be found in different environments depending on the details of their evolution in the disk (Fujii et al. 2017), the outcome of scattering processes (Gong et al. 2013), capture (Ochiai et al. 2014) or collisions (Barr and Bruck Syal 2017), to name a few. Exotic situations where planets are ejected from the planetary system conserving their moons have been mentioned, though their detection is extremely challenging in this configuration (Laughlin and Adams 2000).

Moons exist between the Roche lobe and the Hill radius of their host planets (Murray and Dermott 2000). There are numerous studies researching the dynamical stability and the tidal evolution of moons (Adams and Bloch 2016; Barnes and O’Brien 2002; Debes and Sigurdsson 2007; Domingos et al. 2006; Donnison 2010; Hong et al. 2015; Namouni 2010; Payne et al. 2013; Sasaki et al. 2012; Sasaki and Barnes 2014). Consequently, their final configuration will depend on planetary processes like migration (Spalding et al. 2016), photoevaporation (Yang et al. 2016), or tidal interactions (Cassidy et al. 2009), all of them open to a certain degree of interpretation today. Rather than a disadvantage this is an encouragement to study moons, as they could provide useful measurable constraints. However, the expected
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diversity requires observational support to understand the relative impact of the different processes proposed.

Habitability is another important reason to look for exomoons (Kaltenegger 2010; Lammer et al. 2014). There are interesting processes that are exclusive of these systems and that deserve specific attention. They include tidal interactions (Dobos et al. 2017; Forgan and Kipping 2013; Heller 2012; Scharf 2006), planetary illumination (Forgan and Yotov 2014), amount of volatiles depending on the formation and migration mechanisms (Heller and Pudritz 2015; Heller and Barnes 2015). Finally, the possible presence of moons might impact the interpretation of biosignatures (Rein et al. 2014; Li et al. 2016).

Current status of detections

There is no known reason preventing exomoons from existing and we expect them to be present in many different configurations. Therefore, all detection methods applied to exoplanets (Wright and Gaudi 2013) have also been extended to detect exomoons with a varying degree of predicted success rate. The different detection methods are excellently described in Heller’s review in this volume and we will refer the reader to that text for an overview.

Almost twenty years ago there were high expectations on the detection possibilities of exomoons with space-borne facilities like Hubble (Brown et al. 2001), CoRoT (Sartoretti and Schneider 1999), or Kepler (Szabó et al. 2006); but also with microlensing (Gaudi et al. 2003) or direct imaging (Cabrera and Schneider 2007).

However, there is no uncontroversial detection of an exomoon as we write this lines in August 2017. The situation might change soon, as we will see in the next section. Which have been the difficulties encountered?

Photometric detections during transit and occultation are challenging, even with the latest instrumentation (e.g. see Dobos et al. 2016), and have two main practical limitations: stellar activity and instrumental systematics. A paradigmatic example is the transit of TrEs-1b (Rabus et al. 2009), whose Hubble light curve can be interpreted as a two planet system or as the passage of the transiting planet over an active region on the stellar surface. The same difficulty has been encountered by other systematic studies (Lewis et al. 2015). More challenging is the occurrence of instrumental systematics mimicking the effects of moons, like the case of Kepler-90g (Kipping et al. 2015a). Instrumental systematics can be very difficult to eliminate, even in presence of large amounts of data with high photometric quality (see, for example, Gaidos et al. 2016).

Therefore, the problem is not necessarily the detection but rather the unique interpretation of the measurement as being caused by an exomoon. There is indeed a number of processes that can lead to comparable observational effects but do not involve exomoons. In this respect, the transit timing variation (TTV) method is considered promising, as it can solve part of the degeneracies intrinsic to photometric detections (see Lewis and Fujii 2014 and references therein). However, the transit
timing variations (TTVs) of Kepler-46b (KOI-872b) can be interpreted as an additional planet in the system or as a moon (Nesvorný et al. 2012). TTVs are also strongly affected by stellar activity (Barros et al. 2013; Lewis 2013) and systematics (Szabó et al. 2013). As a result of these limitations, there are presently many systems studied (Weidner and Horne 2010; Kipping et al. 2013a,b, 2014, 2015; Hippke 2015; Kane 2017), but no claimed detection of exomoon.

Microlensing surveys have suffered from similar difficulties in the interpretation of the observations with the added challenge of the reproducibility of the measurements (Bennett et al. 2014; Skowron et al. 2014).

Ten years ago, we estimated the possibility of detecting moons around direct imaged planets measuring the reflex motion of the moon around the planet considering photon noise (Cabrera and Schneider 2007). The required precision of the astrometric measurement of the position of the planet was in the range from microarcsec to few milliarcsec. Unfortunately, it is more likely that these observations are actually limited by speckle noise and systematic uncertainties in the astrometric position of the host star rather than photon noise. However, precisions of milliarcseconds are
Special cases: moons, rings, comets, trojans currently within reach (Wertz et al. 2017), though no moon has been claimed yet (see Fig. [1]).

**Expectations for the future**

![Diagram of Planet/moon events](image)

**Fig. 2** Planet/moon events. As a satellite orbits its host planet, there are different events that can be observed in the system, depending on the relative configuration of the planet, satellite, and observer.

The photometric detection of moons is theoretically possible with space-borne photometry delivered by missions such as CoRoT and Kepler or with microlensing surveys, but so far no detection has been secured. Soon the next generation of exoplanet space-borne facilities, including CHEOPS (Simon et al. 2015), TESS (Ricker et al. 2015), and PLATO (Rauer et al. 2014), will expand on the CoRoT and Kepler legacy. The difficulty in the detection of exomoons will be the same, but these missions will observe brighter stars, easier to characterize, and will benefit from the experience of the previous surveys. For example, one wonders about the follow-up of the TTVs of Kepler candidates with PLATO, collecting a baseline of observations longer than ten years. PLATO has a smaller collecting area than Kepler, but a higher cadence, so the TTV accuracy will be close enough to make meaningful compar-
issons. These new missions might be able to definitely settle the nature of some of the candidates proposed today.

An important limitation of transit photometry arises from the fact that a system is in transit only a very small fraction of its orbit (0.15% of the time for the Earth around the Sun). The relative scarcity of the data and the difficulty of reproducing the observations, as the moon changes its relative phase from transit to transit, will not improve for the new missions. A possibility that might still have a chance are binary planets, which have a very distinct transit signature of larger amplitude. Though we know they are not common, they are known to exist in certain configurations (Nielsen et al. 2013; Best et al. 2017; Han et al. 2017).

Despite all the mentioned difficulties, in July 2017 Teachey et al. (2018) announced the presence of a possible exomoon around the planet Kepler-1625b. If confirmed, it would be a sensational discovery culminating the efforts of the HEK (Hunt for Exomoons with Kepler) team (Kipping et al. 2012). However, the authors remain cautious about the nature of the candidate and warn the community about the limited amount of existing observational evidence on this target. There are additional observations scheduled of October 2017 with the potential to confirm the presence of the candidate. Unfortunately, this text will have to go into publication before the results of these observations are known, but we keep our fingers crossed.

In the near future, another breakthrough might come though from directly imaged planets (see the review by Bowler 2016). As mentioned earlier, current facilities can reach the milliarcsecond precision required to start sampling the existence of massive moons (see Fig. 1). There are important synergies with missions like Gaia (Gaia Collaboration et al. 2016), which will probe the parameter space for giant planets beyond the snow-line, potentially observable with current high-contrast adaptive optics facilities. Gaia planet yield is expected to outnumber the current sample known (Casertano et al. 2008). The reflex motion of planets, which allows to measure the moon’s mass, and the next step, studying planet-moon occultation events (see Schneider et al. 2015), are promising methods to characterize exomoons. The reflex motion is observable during the whole orbit and the planet-moon events occur up to 5 times per moon orbit (see Fig. 2), which is in the order of up to a few tenths of days, giving considerable advantage in comparison to photometric transits. Observing the 5 types of events shown in Fig. 2 is only possible if the relative orientation of orbit of the satellite is favorable to the observer. However, two of the events, when the satellite casts its shadow on the planet and when the satellite is occulted by the shadow of the planet, only depend on the relative orientation of the satellite orbit with the orbital plane of the planet. If the orbital plane of the satellites has a low inclination with respect to the ecliptic, these events will be visible, regardless of the orientation towards the observer.

Though elusive, exomoons are fundamental in the study of the processes of planetary formation and evolution and, furthermore, provide a rich ground for studies constraining the processes of planetary formation and evolution and provide a great opportunity to study habitable systems. Given the new facilities that will become available in the coming years and the expertise accumulated, there are good reasons
to remain optimistic and hope that the next 10 years will be more fruitful than the last two decades.

Rings

All the giant planets in the solar system are surrounded by systems of rings, though they have very different properties. The processes that affect the stability and evolution of rings involve tidal forces, dynamical interactions with moons, resonances, spiral waves, radiation pressure, and interactions with charged particles (de Pater and Lissauer 2015), making them a very rich field for research.

We bring up in this section rings and disks around planets, but there are ring-structures everywhere in the Universe within an unimaginable range of sizes (see, for example, the review by Latter et al. 2017).

For the detection methods of rings around extrasolar planets, we will refer to the review in this very same volume by R. Heller. Regarding formation mechanisms, see Zanazzi and Lai (2017) and references therein.

Current status of detections

In contrast to exomoons, there are several detections claimed in the literature, though not all of them completely undisputed.

One example is the indirect detection of a ring system around the brown dwarf G 196-3 B (Zakhozhay et al. 2017). A ring system with properties resembling those around Jupiter or Neptune, but with a very different age and on different environment, can satisfactorily reproduce the colors of this target.

A hypothetical ring system that can make its première in 2017 would be the one around β Pictoris b (Lagrange et al. 2010), a giant planet orbiting a 10 million year old star with an orbital period of about 35 years. The large semi-major axis makes the transit probability meager, but it might actually be transiting (Lecavelier des Etangs and Vidal-Madjar 2016; Wang et al. 2016) and a campaign has been orchestrated to characterize the Hill sphere of the planet as it crosses the stellar disk from Earth (Kenworthy 2017).

And there is the unusual, from our solar system perspective, system of rings proposed around J1407 (1SWASP J140747.93-394542.6; Mamajek et al. 2012; Rieder and Kenworthy 2016), which is described in Heller’s chapter in this volume. We will mention it again in the next section.

Despite the wealth of giant planets at large orbital periods, including several Jupiter-analogs, found by different surveys (Bedell et al. 2015; Díaz et al. 2016; Esposito et al. 2013; Foreman-Mackey et al. 2016; Kipping et al. 2014b; 2016; Uehara et al. 2016), space missions like CoRoT and Kepler have not yielded any report...
of exorings so far (see Heising et al. 2015, Lecavelier des Etangs et al. 2017, Turner et al. 2016).

The paper by Aizawa et al. (2017) deserves special attention as it carefully shows that the limitations of the photometric method with current surveys are not dictated by the photon noise, but by the residuals of systematic noise sources and the interpretation of the results, as it was the case for exomoons previously described.

Overcoming the limitations of photometric searches, there are alternative techniques like high resolution spectroscopy (Santos et al. 2015) and direct imaging.

**Characterization of rings with direct imaging**

WFIRST-AFTA (Spergel et al. 2015) is an observatory of NASA devoted to the study of dark matter, infrared astrophysics, and extrasolar planets. It is currently in its Phase A, undergoing the study of mission requirements. The mission concept is based on a 2.4 m telescope with a large field-of-view and is equipped with a wide field instrument and a coronograph. The on-board spectrograph will foreseeably provide a contrast of $10^{-9}$ and an inner working angle of $3\lambda/D$ at 430 nm. Such a performance will enable the characterization of the atmospheres of directly imaged exoplanets (Greco and Burrows 2015).

We have used a numerical model based on previous work by Arnold and Schneider (2004) to simulate the integrated light curve of ringed planets that could be observed with WFIRST. The exercise intends to elucidate the effects that exorings would have in the phase curve and spectra of an exoplanet observed via direct imaging, thereby drawing conclusions on the planet atmosphere and the planet size. The planets are assumed at orbital distances of 1-10 AU from their star and 10 pc away from the solar system.

The numerical model considers mutual shadow of the planet on the ring and the ring on the planet. The shadow of the planet on the ring and the occultation are also taken into account. However, mutual reflection and shadow of the ring on the planet are neglected. The code accepts elliptical orbits and rings with fixed inner and outer radius. The planet is assumed to scatter starlight as a Lambertian sphere (Lester et al. 1979), and the rings are assumed to be planar. At the ring, only single scattering is considered.

There are nine parameters that define the planet-ring system geometry of the model: the planetary radius $R_p$, the inclination of the orbital plane $i$, the wavelength dependent planetary albedo $A_p$, the rings optical thickness $\tau_R$, the ring’s inner and outer radius $R_{in}$ and $R_{out}$, the single scattering albedo of the ring $\omega_o$, the ring’s plane inclination $i_R$, and the ring’s plane intersection with the orbital plane $\lambda_R$ (Arnold and Schneider 2004).

As a reference for the capabilities of WFIRST we have made simulations of a ring system like J1407. To facilitate the study of this system with the planned specifications of WFIRST’s inner working angle, we assumed that the system is located
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at 10 pc from Earth, rather than the actual 128 pc. The values of the parameters used in the simulation are shown in Table 1 and the results are shown in Figs. 3 and 4.

A system of rings as that proposed for J1407 reflects a significant amount of the stellar light and produces a signal several orders of magnitude larger than the planet itself. This unique case therefore opens the possibility of spectroscopically investigating exorings without the interfering effect of the planet. Less extreme situations such as enabled by Saturn-like exoplanets will show signals that blend the ring and planet contributions. This blending will dilute the main absorption features in the planet atmosphere, thereby complicating its analysis.

Table 1 Parameters used in the simulation of the ring system.

| Element | Parameter | Value       |
|---------|-----------|-------------|
| Star    | mass      | 0.9M_Sun    |
|         | distance  | 10 pc       |
| Planet  | R_p       | 1.46 R_Jupiter |
|         | semi-major axis | 5 au |
|         | eccentricity | 0.65 |
|         | i         | 89°         |
|         | A_p       | Jupiter     |
| Ring    | τ_R       | 0.5         |
|         | R_{in}    | 0.25 R_{Hill} |
|         | R_{out}   | R_{Hill}    |
|         | i_R       | 13°         |
|         | λ_R       | 70°         |

The albedo values of Jupiter as a function of the wavelength are taken from Karkoschka (1994).

Comets

Comets are some of the largest structures in the solar system, if one accounts for the extension of their tails (i.e. Neugebauer et al. 2007). However, the very low density of the extended tails makes their detection and characterization challenging outside the solar system. Nevertheless, this difficulty didn’t stop observers from trying to observe the extended, low density, exospheres of extrasolar planets soon after their discovery (Rauer et al. 2000, Vidal-Madjar et al. 2003, Lecavelier Des Etangs et al. 2010, Haswell et al. 2012, Ehrenreich et al. 2012, 2015, Poppenhaeger et al. 2013). The evaporation of giant planets has been followed by the detection of disintegrating small planets which display tails similar to comets (Rappaport et al. 2012, 2014, Sanchis-Ojeda et al. 2015, Vanderburg et al. 2015), which in some cases has allowed the characterization of the properties of the particles in the tail (van Lieshout et al. 2014, 2016, Zhou et al. 2016, Alonso et al. 2016, Rappaport et al. 2016). Of interest
Fig. 3 Contrast vs. inner working angle for a J1407-like system compared to the WFIRST detection limits for a planet without rings (dark blue) and with rings (orange). The detectability improves moving from left to right and from bottom to top. The red horizontal line represents the planned $10^{-9}$ contrast limit of WFIRST. Correspondingly, the red vertical line represents a tentative limit of the inner working angle possibilities.

Fig. 4 Phase curves for a J1407-like system. Left: for a system without rings. Right: for a system with rings, note the change in the vertical scale. In the latter, the shape of the phase curve is dominated by the size of the rings and their relative orientation to the observer.
are also the transient signatures recently discovered around the young star RIK-210, though their interpretation is not so straightforward (David et al. 2017).

The discovery of comets with photometric transit surveys has been more difficult that what was originally expected (Lecavelier Des Etangs et al. 1999) for possibly the same reasons that have been already described above. There have been clear detections in the circumstellar disk of young stars (Kiefer et al. 2014b; Eiroa et al. 2016; Marino et al. 2017). But the first evidence for exocomets transiting in front of a star in visible light had to wait until August 2017. It comes from the discovery of possibly several comets around the star KIC 3542116 (Rappaport et al. 2018). This pioneering paper further analyses the possible properties of the comets based on the shape of the observed light curves, which are book examples of the expectations in (Lecavelier Des Etangs et al. 1999). The authors of the paper are optimist that new examples will be found in future analyses of the Kepler data.

One disputed case is KIC 8462852 (Boyajian et al. 2016), a target observed by the Kepler mission that show irregular flux drops that account for up to 20% of the stellar flux lasting several days. Some teams have invoked the possibility of comets (Bodman and Quillen 2016) to explain the observations, but the hypothesis has been recently challenged (Wright and Sigurdsson 2016). However, new observations in May 2017 (triggered by a tweet by T. Boyajian, @tsboyajian) suggest that the phenomenon has a characteristic time-scale of 700 days and its origin, whatever its nature, is indeed gravitationally linked to the star. It has been proposed that ringed planet and a large swarm of trojan bodies could explain the features observed in the light curve and predict its future behaviour (Ballesteros et al. 2018). The semi-major axis of the system would be around 6 au and the orbital period 12 years, a large observational span, but certainly within reach in the near future.

Trojans

In the solar system the term Trojans refer to a family of minor bodies that share the orbits of the giant planets like Jupiter and Neptune. They represent a special case of the co-orbital dynamics of the N-body problem (see, for example, Veras et al. 2016).

The stability of such configurations is not simple, nor their dynamical evolution as planets migrate (Nesvorny et al. 2013), but there is no known reason preventing their existence in extrasolar systems. Only that, if they have similar sizes to those in the solar system, their direct detectability with photometry is beyond reach for current and near future facilities.

Therefore, researchers have tried to infer the presence of trojans studying the perturbations introduce in the orbit of their larger, companion planet, both with radial velocity, transit timing variations, or both (Ford and Holman 2007; Dobrovolskis 2013; Haghighipour et al. 2013; Leleu et al. 2015, 2017; Nesvorny and Vokrouhlicky 2016; Vokrouhlicky and Nesvorny 2014). There have been several systematic searches that have not found any reliable candidate so far (Madhusudhan and Winn 2009; Janson 2013).
There have been claims in the literature with detections, but so far none of these claims has been confirmed by subsequent independent analysis, like the cases of HD 82943 and HD 128311 (Goździewski and Konacki 2006), but see McArthur et al. (2014) and Rein (2015), or the Kepler candidates by Hippke and Angerhausen (2015), which at least in the case of Kepler-91 b have not been confirmed by later studies (Placek et al. 2015). A recent claim on WASP-12 and HD 18733 by Kissyakova et al. (2016) remains to be confirmed.

In this case, the direct confirmation of the presence of a trojan suffers from the same limitations of reproducibility, credibility in presence of correlated noise, and degeneracy of interpretation as in the previous examples of moons and rings, with the detriment of the smaller size and mass of the researched object.

**Summary**

We would like to close with a quote attributed to Napoleon Bonaparte dissuading from taking predictions too seriously (Il faut toujours se réserver le droit de rire le lendemain de ses idées de la veille). Or in the words of a famous astronomer, you should listen to theorists but never take them too seriously. The discovery and characterization of moons, rings, comets, and trojans has proven more challenging than expected, but the interest of the community has not decreased in the last 20 years. It is rather the opposite. And there are also new ideas coming out, like synestias (Lock and Stewart 2017). These are transient structures predicted by theoretical models produced during planetary formation processes. They have not been observed, or confirmed independently yet, but they are certainly welcome because of their interest.

The wealth of data from transit photometry has been carefully studied and most of the systematics are well understood, yet no undisputed detection has been definitely accepted by the community. However, the situation is quickly changing in a very positive way. TESS and PLATO will have their chance in the next decade, but it is time to think about different methods, in particular direct imaging and probably high resolution spectroscopy (for example, the serendipitous discovery of a moon or ring system via Rossiter-McLaughlin during planet characterization). With instruments like Gaia, ALMA, and E-ELT class telescopes it is difficult not to end with the conclusion that moons, rings, comets, and trojans will not only be detected in large numbers in the next decades, but also will contribute to our knowledge about planets and planetary systems, in our galaxy and in the solar system.

**Cross-References**

- On the Detection of Extrasolar Moons and Rings
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