THE EFFECT OF PLANET–PLANET SCATTERING ON THE SURVIVAL OF EXOMOONS

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ABSTRACT

Compared to the giant planets in the solar system, exoplanets have many remarkable properties, such as the prevalence of giant planets on eccentric orbits and the presence of hot Jupiters. Planet–planet scattering (PPS) between giant planets is a possible mechanism to interpret the above and other observed properties. If the observed giant planet architectures are indeed outcomes of PPS, such a drastic dynamical process must affect their primordial moon systems. In this Letter, we discuss the effect of PPS on the survival of exoplanets’ regular moons. From an observational viewpoint, some preliminary conclusions are drawn from the simulations. (1) PPS is a destructive process to the moon systems; single planets on eccentric orbits are not ideal moon-search targets. (2) If hot Jupiters formed through PPS, their original moons have little chance of survival. (3) Planets in multiple systems with small eccentricities are more likely to hold their primordial moons. (4) Compared with lower-mass planets, massive planets in multiple systems may not be the preferred moon-search targets if the system underwent a PPS history.

Key words: methods: numerical – planets and satellites: dynamical evolution and stability

Online-only material: color figures

1. INTRODUCTION

Are there moons around exoplanets? This topic has greatly interested scientists since the discovery of extrasolar giant planets in the 1990s (Williams et al. 1997; Barnes & O’Brien 2002; Domingos et al. 2006; Cassidy et al. 2009; Donnison Gaidos 2013), but they support neither solid nor liquid surfaces been found in the habitable zone (HZ; Porter & Grundy 2011; Namouni 2010; Kaltenegger 2010; Zhuang et al. 2012). In our solar system, all giant planets have many moons. Natural satellites of the giant planets are divided into two categories: regular satellites and irregular satellites. Regular satellites with little eccentricities and orbital inclinations most likely formed in circumplanetary disks during the formation of the planet itself. However, irregular satellites with significant inclinations and eccentricities were most likely captured at a much later stage in the evolution of the planet. Another difference is that regular satellites are close to their host planets, while irregular satellites are smaller bodies moving on distant orbits. The prevalence of moons in the solar system implies that extrasolar giant planets may also harbor moon systems.

Searching for exomoons also has significance in exploring extrasolar lives. To date, many extrasolar giant planets have been found in the habitable zone (HZ; Porter & Grundy 2011; Gaidos 2013), but they support neither solid nor liquid surfaces near which organisms might dwell. Exomoons of these giant planets, if they exist, may be alternative hosts for extrasolar life (Williams et al. 1997; Heller 2012). Based on the Kepler mission, exomoon-search methods and projects have been proposed by several authors (Kipping 2009; Simon et al. 2012; Kipping et al. 2012; Lewis 2013). Lately, several viable moon-hosting planet candidates have been analyzed, although no compelling evidence for exomoons has yet been found (Kipping et al. 2013).

However, extrasolar giant planets have very different properties compared to the giant planets in the solar system. A prominent feature is that extrasolar giant planets have significant eccentricities, whereas four giant planets in the solar system are on nearly circular orbits. Currently, one possible mechanism that can explain this is planet–planet scattering (PPS) between giant planets (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Lin & Ida 1997; Marzari et al. 2005; Zhou et al. 2007; Ford & Rasio 2008; Chatterjee et al. 2008; Jurić & Tremaine 2008; Raymond et al. 2013, etc.). Some other phenomena of exoplanet systems can also be explained by involving PPS, such as the formation of hot Jupiters (HJs; Nagasawa et al. 2008; Nagasawa & Ida 2011; Hirano et al. 2012; Beauge & Nesvorný 2012) and mutual inclinations between planets in multiple-planet systems (Lissauer et al. 2011).

Strong evidence of PPS in multiple-planet systems such as the $\upsilon$ And (Ford et al. 2005) implies that PPS may be a natural dynamical process. Actually, even in the solar system, studies by Morbidelli et al. (2009) have shown that PPS between Saturn and one of the ice giants (Uranus or Neptune) must have occurred to reproduce the current secular properties of the giant planets, whereas other mechanisms such as the smooth migration of giant planets through a planetesimal disk (Malhotra 1995) cannot reproduce them.

If PPS indeed took place in the formation process of exoplanets, it is natural to ask whether and how such a strong dynamical process affects the survival of their primordial (regular) moons. In this Letter, some preliminary studies are carried out on this topic.

2. INITIAL CONDITIONS

According to the core accretion theory, giant planets can only form outside the snow line. However, the diversity of the protoplanetary disk, the disk-driven migration, and the presence of secular resonances such as the Lidov–Kozai effects make the configuration of exoplanet systems diverse (Zhou et al. 2012). As for the disk migration, the speed and direction depend intricately on disk physics (Kley & Nelson 2012), so the observed orbital architectures of exoplanet systems cannot be reproduced well even if we consider the normal migration and planet-growth models. Here, we use the giant-planet formation model in Kokubo & Ida (2002) and similar initial conditions as
proposed by Chatterjee et al. (2008):

\[
M_p = 16\pi \left( \frac{1}{3} \frac{M_{\text{core}}}{M_\odot} \right)^{1/3} f_i \Sigma_i a^{1/2} + M_{\text{core}},
\]

(1)

\[
a_{i+1} = a_i + K R_{H,i},
\]

(2)

where \(R_{H,i}\) is the Hill radius of the \(i\)th planet and \(K = 4.5\), \(f_i = 240\), \(\Sigma_i = 10\ g\ \text{cm}^{-2}\), \(a_i = 3\ \text{AU}\) (the innermost planet is near the snow line). We also assume that \(M_{\text{core}}\) satisfies a uniform distribution between 1 and 15 \(M_\oplus\). The initial masses of the planets obtained with this procedure are between 0.25 and 1.7 \(M_J\), where \(M_J\) is the mass of Jupiter. Such initial configurations can reproduce at least two observed properties of exoplanets: (1) the observed eccentricity distribution of exoplanets and (2) the proportion of the potential HJs (\(~\sim\%\) planets with periapsis distances < 0.03 AU; Chatterjee et al. 2008).

For moons, researchers are generally concerned about Earth-like moons (Barnes & O’Brien 2002; Kaltenegger 2010; Heller 2012; Canup & Ward 2006) indicate that Earth-like moons should not form for Jupiter-mass planets. Whether this also holds in the extrasolar systems is unclear. According to Williams et al. (1997), moons satisfying two criteria are also present in the extrasolar systems: (1) the observed eccentricity distribution of exoplanets and (2) proportion of the potential HJs (\(~\sim\%\) planets with periapsis distances < 0.03 AU; Chatterjee et al. 2008). For moons, researchers are generally concerned about Earth-like moons (Barnes & O’Brien 2002; Kaltenegger 2010; Heller 2012)

Donnison (2010) derived the critical semimajor axis (SMA), \(a_m\), of a stable moon based on the Hill stability criteria:

\[
\frac{a_p}{a_c} = \frac{3}{x} + \frac{(1 + \lambda)^2}{\lambda} + \frac{2\lambda(\lambda - 1) - 3(1 + \lambda)^3}{3\lambda(1 + \lambda)} + \left[ \frac{\lambda(2 + 5\lambda) + \frac{2\lambda^2}{1 + \lambda} + \frac{9(1 + \lambda)^5}{(1 + \lambda)^5}}{3\lambda(1 + \lambda)} \right] x,
\]

(3)

where \(\lambda = M_m/M_p\) and \(x = [(M_m + M_p)/3M_*]^{1/3}\), \(a_p\) is the SMA of the planet, \(M_*\) is the mass of the central star, and we take \(M_* = M_\odot\) in this work. We define the initial SMA of the moon as

\[
a_m = f \cdot a_c \quad (f \leq 1).
\]

(4)

The purpose of doing so is to guarantee that the escape of the moon is caused by the scattering between giant planets rather than the planet–moon system itself. The lower limit of SMA of the moon is the Roche radius (Weidner & Horne 2010),

\[
R_{\text{roche}} = 2.44 \left( \frac{4\pi}{3} \right)^{-1/3} \left( \frac{M_p}{\rho_m} \right)^{1/3} M_\odot,
\]

where \(\rho_m\) is the mean densities of the moon. \(f = [0.2, 0.4, 0.6, 0.8, 1.0]\) are explored (to ensure that the moon is outside the Roche limit).

We perform few approximations here as done by other studies on exomoons. (1) Tidal effects can be ignored if the dynamical timescale concerned is much shorter than the tidal evolution timescale (Namouni 2010). The typical tidal evolution timescale of the moons is in Gyr, which is much longer than the PPS timescales (\(~\sim\times 10^3\) in this work). Thus no significant tidal evolution of the moon occurs during PPS. (2) The interactions between the moons (around the same giant planet) are ignored (Barnes & O’Brien 2002). Though the interactions between moons may cause additional instabilities, other factors, such as resonance (mean motion resonance, spin–orbit resonance, or Laplace resonance) between them, may guarantee stability. The above-mentioned complex issues are beyond the scope of this Letter. Our model contains three planets, and each bears an identical moon. Because irregular moons are thought to most likely have been captured at a much later stage in the evolution of the planet, we do not consider the effects of PPS on the survival of irregular moons. Both the planets and moons are on initial coplanar and circular orbits.

We use the Bulirsch–Stoer integrator in the MERCURY package (Chambers 1999); the accuracy requirement is \(10^{-12}\). For every combination of \([f, M_m]\), we perform 100 runs; thus a total of 1500 runs of numerical simulations are performed in this work. The integral time is \(10^8\) yr; we find it long enough to obtain credible results. If the moon’s planetocentric energy became positive, we consider it to have escaped from the planet (Domingos et al. 2006).

3. SIMULATION RESULTS AND ANALYSIS

Figure 1 shows a randomly selected, representative example of dynamical evolution of planets with moon systems, showing both the chaotic phases and the stable final configurations. In Table 1, we present an overview of the results. Evidently, the PPSs between giant planets have violent impacts on their moons. Even if the moons are initially located at the inner stable region of giant planets (\(f = 0.2\), nearly two-thirds of the systems lost their moons completely. For three moons of different masses, the simulation results are similar; this is understandable because the mass of the moon is involved in the critical SMA (Equation (3)). In order to provide some clues for future observations, we give a detailed analysis based on the architectures of extrasolar giant planet systems. After the scattering process, the resulting systems can be classified into two categories based on the final configuration of the giant planets: (1) two-planet

| Table 1 |
|----------|
| \(M_m\) (\(M_\oplus\)) | \(f\) | 0 Moon | 1 Moon | 2 Moons | 1 Planet | 2 Planets |
| 1 | 1.0 | 88% | 10% | 2% | 24% | 76% |
| 0.8 | 83% | 17% | 0% | 31% | 69% |
| 0.6 | 77% | 20% | 3% | 30% | 70% |
| 0.4 | 71% | 28% | 1% | 35% | 65% |
| 0.2 | 65% | 32% | 3% | 39% | 61% |

| 0.1 | 1.0 | 88% | 10% | 2% | 31% | 69% |
| 0.8 | 82% | 16% | 2% | 26% | 74% |
| 0.6 | 74% | 23% | 3% | 25% | 75% |
| 0.4 | 69% | 28% | 3% | 31% | 69% |
| 0.2 | 65% | 26% | 9% | 33% | 67% |

| 0.01 | 1.0 | 84% | 14% | 2% | 39% | 61% |
| 0.8 | 82% | 17% | 1% | 28% | 72% |
| 0.6 | 79% | 20% | 1% | 34% | 66% |
| 0.4 | 76% | 21% | 3% | 35% | 65% |
| 0.2 | 72% | 24% | 4% | 27% | 73% |

Note. The fraction is to 100 planetary systems.
systems and (2) one-planet systems. We discuss the survival of exomoons in detail according to the above categories.

One-planet systems. For a total of 500 systems with the same masses of moons, the average fractions resulting in one-planet systems (with or without moons) are 31.8% (1 M⊕), 29.2% (0.1 M⊕), and 32.6% (0.01 M⊕). But the fractions of the remaining one-planet systems with a moon are only 2.2%, 1.2%, and 2.8%, respectively. This implies that if a single planet on an eccentric orbit comes from a primordial multiple system through PPS, the probability of harboring their primordial moons is very low.

Two-planet systems. If two giant planets survived the scattering process, they must be on well-separated orbits to ensure long-term stability. The total fractions of two-planet systems for three types of moons are 68.2% (1 M⊕), 70.8% (0.1 M⊕), and 67.4% (0.01 M⊕), respectively. In these cases, the fractions of each planet having a moon (2p + 2m) are 1.6% (1 M⊕), 3.6% (0.1 M⊕), and 2.2% (0.01 M⊕). The fractions of systems with only one moon remaining (2p + 1m) are 19.2% (1 M⊕), 19.4% (0.1 M⊕), and 16.4% (0.01 M⊕). In a significant number of cases, there are only two planets left in the system (2p + 0m); the fractions are 47.4%, 47.8%, and 48.8%. In this way, we found eight systems where moon exchanges take place, the fraction of which is only 0.5% of the total 1500 systems. In the above eight systems, five are “2p + 1m” systems, two are “2p + 2m” systems, and one belongs to the “1p + 1m” system. Compared to other systems, the number of moon exchange systems is insignificant. We do not discuss the details of them in this Letter.

Evidently, the ability of moons to survive in two-planet systems is higher than in one-planet systems. Since the “2p + 1m” systems are the dominant outcomes where at least one stable moon survived in two-planet systems, we focus on these cases. In Figure 2, we give the SMA versus eccentricity map for all of the surviving planets (Mm = 0.1 M⊕). As we can see in Figure 2, moon-bearing planets generally have small or moderate eccentricities.

1. Mass dependencies. It can be seen from Figure 3 that of the two planets the lower-mass one has a larger chance of bearing moons. In all “2p + 1m” systems (275; see Table 2), 87.6% of the systems (241) have a moon encircling the lower-mass planet. From the viewpoint of dynamical stability, this conclusion is somewhat counterintuitive because the massive planet seems to be better suited to hold a moon. Actually, in significant cases, the bigger planets resulted from the merging of two planets (the total fraction is 84.4% in all “2p + 1m” cases; see Table 2), which means that their moons have been destroyed in the process of close encounters between two merged planets.

Table 2

| Systems Containing Two Giant Planets and a Moon |
|------------------------------------------------|
| Total 2p + 1m (275) | Smaller 84.4% (232) |
| Mergers 92.4% (254) | Bigger 8.0% (22) |
| Ejections 7.6% (21) | Smaller 3.3% (9) |
| Stable 4.4% (12) | Bigger 4.4% (12) |

Notes. “Smaller” and “bigger” mean that the moon-bearing planet is the smaller one and the bigger one, respectively.
Figure 2. Final semimajor axis vs. eccentricity plot for all the remaining planets (500 systems, $M_{\text{moon}} = 0.1 \, M_\oplus$). The open stars and triangles represent the final inner and outer planets in two-planet systems, respectively. The open squares show the distribution of planets in one-planet systems. The red circles are plotted on all moon-bearing planets. Some moons turn into planets after the scattering process; they are denoted as open blue circles. The green lines show the habitable zone of the star (Mischna et al. 2000). The planar initial configuration we adopt means that the Lidov–Kozai mechanism does not operate, which will reduce the amount of hot Jupiters (Nagasawa & Ida 2011). Here, we define the planet with pericentric distance $q < 0.3 \, \text{AU}$ (blue line) as a potential hot Jupiter.

(A color version of this figure is available in the online journal.)

Figure 3. Distribution of $M_{\text{phm}} - M_{\text{pnm}}$ in two-planet systems harboring a moon. $M_{\text{phm}}$ denotes the mass of moon-bearing planet and $M_{\text{pnm}}$ denotes the mass of moon-lost planet. If $|M_{\text{phm}} - M_{\text{pnm}}| > 1$, the bigger one mainly comes from the collisional merger.

(A color version of this figure is available in the online journal.)

2. Collisions versus ejections. Two-planet systems formed through two channels: by collisional merging of two planets or the ejection of one planet. In all 1032 two-planet systems (including no-moon systems), $\sim 80\%$ (826) are derived from merger and $\sim 20\%$ (206) come from ejections. One may argue that collisional mergers are the dominant outcomes, which makes dominant the “2p + 1m” systems that result from mergers. However, detailed analysis provides us with other information. In the above 206 systems, $\sim 90\%$ (185) are no-moon systems; ejection systems account for only $7.0\%$ (21) of all “2p + 1m” systems.\(^3\) It means that the survival rate of moons in two-planet systems formed due to ejections is very low. The ejection of one planet in a system needs more frequent close encounters than a collisional merger (Ford & Rasio 2008), so the low survival rate of the moon is understandable.

Even in all “2p + 1m” systems that formed due to ejections, only about half of them (12/21) have moons encircling the bigger planets. This demonstrates the chaotic nature of PPS. For example, if the smallest planet (in the initial three-planet system) is ejected from the system due to close encounters mainly between it and the largest planet, their moons are destroyed, whereas the moon of a moderate-mass planet survives, so the moon-bearing planet is the smaller one of the two surviving planets.

3. Inner versus outer. We also find that the outer planets have a larger chance of harboring moons than the inner planets. The ratios of outer planets harboring moons to the inner ones are 65/31 (1 $M_\oplus$), 56/41 (0.1 $M_\oplus$), and 55/27 (0.01 $M_\oplus$). This preference seems to be independent of the initial mass distribution of giant planets. Our procedure (Equation (1)) produces significant systems with $m_1 < m_2 < m_3$, where $m_1, m_2,$ and $m_3$ are the mass of initial inner, middle, and outer planets, respectively. We perform 200 additional simulations to check whether SMA dependencies are related to the initial mass distribution of giant planets. We randomly selected planets’ masses according to the observed distribution of exoplanet masses: $dN/dM \propto \ldots$\(^3\) The other 8.0% of “2p + 1m” systems may be unphysical—one moon of the two merged planets survived the merging process and encircles the merged body. They are discarded in Figure 3.
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M$^{-1.1}$ (Marcy et al. 2008); the masses are limited in the range of 0.3–1.7 $M_J$. We make all the systems satisfy $m_1 > m_2 > m_3$ and $M_m = 1 M_\oplus$. Other initial conditions are similar to those given in Section 2. We found that the ratio of outer planets harboring moons to the inner ones is 39/17 in all 56 “2p + 1m” systems. This implies that collisional mergers take place mainly in the inner region during PPS. Interestingly, within Kepler multiple-candidate systems, the larger planet is most often the one with the longer period for planet pairs for which one or both objects are approximately Neptune-sized or larger (Ciardi et al. 2013). Besides, many planet pairs are found near low-order mean-motion resonances (Lissauer et al. 2011), it accords with resonant capture (Snellgrove et al. 2001) of planets followed by turbulent removal from resonance (Adams et al. 2008). This scenario is thought of as an origin of PPS (Ford & Rasio 2008). Consequently, SMA dependencies of exomoons in multiple planet system can give us clues about the evolution of planet systems.

4. HJs and giant planets in the HZ. If HJs formed by the scattering mechanism (Nagasawa et al. 2008; Nagasawa & Ida 2011; Beaugé & Nesvorný 2012), their primordial moons may be completely destroyed; this can be seen clearly in Figure 2. In this mechanism, planets need to achieve great eccentricities to form a potential HJ, which means they must undergo strong dynamical process, so the survivability of their moons is very low. We also find that some giant planets in the HZ can hold their moons after strong PPS. In this work, the main aim is to see the impact of PPS on the survival rate of moons rather than to reproduce the observed amount of HJs or HZ giant planets. The probability of forming HJs and giant planets in the HZ is closely related to the initial locations of giant planets. Additional simulations are performed using similar initial conditions (giant planets to those suggested by Beaugé & Nesvorný (2012) or Raymond et al. (2013); we find similar conclusions besides the number of HJs and giant planets in the HZ.

Finally, we found that some moons are stripped from their parent planets in the scattering process and thus become planets encircling the star on stable orbits (see Figure 2). In some cases, the remaining small planets (original moon) and giant planets constitute a solar-like system (terrestrial planets in the inner region and gas giant planets in the outer orbits). Though the formation of Earth-like planets through this mechanism is infrequent, it has enlightening meanings. The origin and amount of water on Earth is an unresolved problem. Many attempts have been made to explain the source of water (Izidoro et al. 2013). If the inner planets themselves or some embryos were originally the moons of giant planets (such as Ganymede), then significant water content is understandable. This mechanism may be unlikely in our solar system, but a dramatic dynamical process in exoplanet systems cannot exclude this possibility.

4. SUMMARY

In this Letter, we focus on the impact of PPS on the survival of exomoons. Although there are some uncertainties in the model, some preliminary conclusions can be drawn from our simulations. (1) PPS is a destructive process to moon systems; planets in single-planet systems, if they have large eccentricities, are not the ideal moon-search targets. (2) If HJs formed through the PPS mechanism, as suggested by many authors, their original moons have little chance of surviving. (3) Exoplanets with small eccentricities in multiple systems are more likely to retain their primordial moons. (4) Massive planets in multiple systems may not be the preferred moon-search targets if they formed via the collision–merger mechanism, as suggested by Lin & Ida (1997). We expect exomoon-search projects such as the “Hunt for Exomoons with Kepler” (Kipping et al. 2012) to present interesting discoveries in the near future. The properties of exomoons can provide us with clues about the evolution of planet systems and deepen our understanding about planet formation. In particular, exomoons are good pieces of evidence to check the PPS hypothesis.

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