GLOBAL INSTABILITY OF THE EXO-MOON SYSTEM TRIGGERED BY PHOTO-EVAPORATION

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ABSTRACT

Many exoplanets have been found in orbits close to their host stars and thus they are subject to the effects of photo-evaporation. Previous studies have shown that a large portion of exoplanets detected by the Kepler mission have been significantly eroded by photo-evaporation. In this paper, we numerically study the effects of photo-evaporation on the orbital evolution of a hypothesized moon system around a planet. We find that photo-evaporation is crucial to the stability of the moon system. Photo-evaporation can erode the atmosphere of the planet thus leading to significant mass loss. As the planet loses mass, its Hill radius shrinks and its moons increase their orbital semimajor axes and eccentricities. When some moons approach their critical semimajor axes, global instability of the moon system would be triggered, which usually ends up with two, one or even zero surviving moons. Some lost moons could escape from the moon system to become a new planet orbiting the star or run away further to become a free-floating object in the Galaxy. Given the destructive role of photo-evaporation, we speculate that exomoons are less common for close-in planets (<0.1 au), especially those around M-type stars, because they are more X-ray luminous and thus enhancing photo-evaporation. The lessons we learn in this study may be helpful for the target selection of on-going/future exomoon searching programs.

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

1. INTRODUCTION

At the time of writing, the Kepler mission has detected more than 4600 planetary candidates, and over 1000 of them have been confirmed, boosting a total exoplanet number over 2000 (http://exoplanet.eu/). In contrast, the detection of an exomoon still remains elusive (Kipping 2014, and the references therein), though moons are much more frequent than planets in our solar system. The non-detection could be because, (1) technically, the signal of an exomoon is too weak to be captured (Kipping et al. 2012) and, (2) theoretically, few exomoons could exist around currently known exoplanets after a long formation and evolution process. Several effects which could affect the dynamical evolution of an exomoon have been studied in the literature.

First, from the view of dynamical stability, the orbit of a moon should be within the Hill radius of its host planet. Using detailed numerical simulations, Domingos et al. (2006) have shown that the critical semimajor axis of a moon can be expressed as

\[ a_{cr} = \alpha R_H, \]  

where

\[ R_H = a_p \left( \frac{M_p}{3M_*} \right)^{1/3} \]

is the Hill radius, \( M_p \) and \( M_* \) are the masses of the planet and the central star, respectively, and \( a_p \) is the orbital semimajor axis of the planet. According to Domingos et al. (2006):

\[ \alpha \approx 0.4895(1.0000 - 1.0305e_p - 0.2738e_m) \times \text{for prograde moons}, \]
\[ \approx 0.9309(1.0000 - 1.0764e_p - 0.9812e_m) \times \text{for retrograde moons}, \]

where \( e_p \) and \( e_m \) are the orbital eccentricities of planet and moon, respectively. Hereafter, subscript “p” and “m” denote properties of planet and moon, respectively. Note, orbital elements of planets are with respect to the central star, while those of moons are with respect to their host planets. Recently, using numerical integrations, Payne et al. (2013) found that \( \alpha \) would be slightly smaller for tightly packed inner planets.

Second, tidal effects could expand or shrink the orbit of a moon, depending on a few initial parameters, such as the moon’s orbital period and the planet’s rotation period. In certain circumstances, the moon could hit on the planet’s surface or escape from orbiting the planet (Barnes & O’Brien 2002). In some other circumstances, the moon could be evaporated or completely melted due to tidal heating ( Cassidy et al. 2009). However, one should note that the tidal effects have large uncertainty because of the poorly constrained tidal \( Q \) values of exoplanets and exomoons, which could vary in a range of several orders of magnitude.

Third, a close-in planet–moon system might not be formed in situ, namely it could be formed in the outer part of planetary disk and have migrated inward to the current orbit via certain mechanisms, e.g., type I or II migration (Papaloizou & Terquem 2006, and the references therein). The inward migration would affect the atmospheres of the moons (Heller et al. 2015; Heller & Pudritz 2015), shrink the Hill radius of the planet and sometimes could induce resonances between moons and the planet, causing orbital instability and ejection of the moons (Namouni 2010; Spalding et al. 2016). In addition, if planets underwent the planet–planet scattering process, they are likely to have lost their moons (Gong et al. 2013).

For the thousands of planet candidates detected by the Kepler mission, it has been suggested that the majority of them could be formed in situ without large scale migration (Chiang &Laughlin 2013; Hansen & Murray 2013), though an opposite scenario has also been proposed (Terquem & Papaloizou 2007; Raymond & Cossou 2014). Most of these candidates,
especially those in multiple transiting systems, are found to have low orbital eccentricities ($e_p < 0.1$) based on their transit durations (Van Eylen & Albrecht 2015; Xie et al. 2016) and timing variations (Wu & Lithwick 2013; Hadden & Lithwick 2014), suggesting that they are unlikely to have undergone planet–planet scattering, unless their orbits were subsequently damped via certain mechanisms, e.g., tidal effects (Fabrycky & Tremaine 2007). Nevertheless, a larger portion of these candidates are thought to have undergone the photo-evaporation process (Owen & Wu 2013) due to their proximity to the central stars. As photo-evaporation generally operates on a timescale of $10^7$–$10^8$ years, generally shorter than that (on order of $10^5$ year) of tidal effects, it thus plays a crucial role in determining the path of the dynamical evolution of planet–moon systems.

In this paper, we numerically investigate the effects of photo-evaporation on the dynamical evolution of planet–moon systems. In Section 2, we describe our numerical model and present the results. Discussions and summary are in Sections 3 and 4.

### 2. SIMULATIONS AND RESULTS

We use the N-body simulation package—MERCURY (Chambers 1999)—to numerically investigate the effects of photo-evaporation on the dynamical evolution of planet–satellite systems. We choose the Bulirsch–Stoer integration algorithm, which can handle close encounter accurately. It is important in the simulations, as we will see below, that many close encounters among moons and the planet are expected to happen. Collisions among moons, the planet, and the central star are also considered in simulations and treated simply as inelastic collisions without fragmentations. Each simulation consists of a central star, a planet, and some moons orbiting around the planet. The photo-evaporation is simply modeled as a slow (adiabatic) and isotropic mass-loss process of the planet. In reality, the photo-evaporation is a very slow process on a timescale of the order of $10^7$–$10^8$ year (Owen & Wu 2013). However, it is impractical and unnecessary to perform a simulation on such a long timescale. Instead, we model the mass-loss process on a timescale of $\tau_{\text{evap}}$, and each simulation typically lasts for several $\tau_{\text{evap}}$. As long as the adiabatic requirement is met, i.e., the mass-loss timescale is much longer than the dynamical timescale of the system ($\tau_{\text{evap}} \gg \tau_p$, where $\tau_p$ is the orbital period of the planet), one could study the dynamical effects of the mass-loss process equivalently. As we discussed in Section 3.3, the results converge if $\tau_{\text{evap}} > 10^2$–$10^3 \tau_p$, indicating the adiabatic condition is met. Therefore, in all other simulations, we set $\tau_{\text{evap}} = 10^4 \tau_p$. Other parameters are set to represent the typical values of Kepler planets. In particular, we consider a planet–satellite system orbiting a star of solar mass ($M_\star = M_{\odot}$) in a circular orbit ($e_p = 0.0$) with semimajor axis of $a_p = 0.1$ au. The orbit has a period of ~10 days (typical value of Kepler planets), and it is sufficiently close to the central star to be subject to significant photo-evaporation effect (Owen & Wu 2013), which removes massive hydrogen envelopes of the planet. The planet has an initial mass of $M_{\text{pi}}$ and a final mass of $M_{\text{pf}}$ after photo-evaporation.

In this paper, we adopt $M_{\text{pi}} = 20 M_{\oplus}$ and $M_{\text{pf}} = 10 M_{\oplus}$ nominally (close to the standard model adopted in Owen & Wu 2013). The mean density of the planet is set to the same as that of Neptune (1.66 g cm$^{-3}$). The effect of changing the planetary density is discussed in Section 3.3. We performed a number of sets of simulations by considering different planet–satellite configurations. Similar to the definition in MERCURY, hereafter, we define “small moons” as test particles (TPs) whose mutual gravity and corresponding effects on the planet and the star are ignored, while “big moons” are gravitationally important enough that their gravitational effects are fully considered. Table 1 lists the initial setups and parameters of various simulations, whose results are presented in the following subsections.

### 2.1. Simulation A: All Small Moons

We first consider the simplest case (Simulation A in Table 1), where a planet and its moons are initially in coplanar and circular orbits. The moons are treated as TPs, namely their mutual gravity and corresponding effects on the planet and the star are ignored. In this case, we aim to both analytically and numerically understand how the planet photo-evaporation (mass-loss equivalently) process affects the orbital evolutions of its moons.

Analytically, from the view of the planet–moon two-body problem, the adiabatic mass loss of the central body (i.e., the
its small moons. The black dashed lines in the middle and bottom (Equation evap) decrease with the planet mass. The X axis is the evolutionary time scaled by \( \tau_{\text{evap}} \), where \( \tau_{\text{evap}} \) is the photo-evaporation timescale setting to 10^4 times of the planet’s orbital period. Here we highlight three moons with semimajor axes starting respectively. As the moon’s orbit expands, it will be subject to stronger tidal perturbation from the third body, i.e., the star, and its mass by varying the mass in a large dynamical range, from \( 2 \times 10^{-10} M_\oplus \) to \( 2 M_\oplus \). 2.2. Simulations B–C: Small Moons Plus a Big Moon 2.2.1. A Stable Big Moon In this section, we consider an additional big moon added to Simulation A. As learned from Simulation A, the initial orbital semimajor axis of the moon plays a crucial role in determining the dynamical stability. Therefore, we study two cases in the following with the big moon starting from different semimajor axes. Furthermore, in each case, we also investigate the effect of the moon’s mass by varying the mass in a large dynamical range, from \( 2 \times 10^{-10} M_\oplus \) to \( 2 M_\oplus \). 2.2.2. Simulations B1–C6: Small Moons at the new semimajor axis, we give the statistics of test particles’ fates. For Simulations B1–B6, and C1–C6, we give the fraction of moons that finally collide with the planet (47%) or escape from the orbital system and become planet-like objects orbiting the star. Columns “Hit planet” and “Hit moon” give the fraction of moons that finally collide with the planet and other (big) moons, respectively.

Note. For Simulations A, B1–B6, and C1–C6, we give the statistics of test particles’ fates. For Simulations D and E, whose moons are all massive, we give the fraction of moons that finally escape from the planet–moon system and become planet-like objects orbiting the star. Columns “Hit planet” and “Hit moon” give the fraction of moons that finally collide with the planet and other (big) moons, respectively.
1.6% of the small moons can survive as satellites if the big moon’s mass is $2 \times 10^{-2} M_\oplus$. Once the big moon’s mass becomes even larger, no small moons can stay orbiting around the planet. Unstable small moons have one of the following three fates: (1) hit on the surface of the planet, (2) hit the big moon, or (3) escape from the planet–satellite system to become a planet-like object orbiting the star. We note that the escape fraction (column “Orbit star” in Table 2) first increases (from 9.7% to 24.8%) as the mass of the big moons increases (from $2 \times 10^{-10} M_\oplus$ to $2 \times 10^{-2} M_\oplus$), then it significantly decreases to 3.9% as the mass of the big moons continuously increase to $2 M_\oplus$. The turnover of the escape fraction is because the instability becomes dominated by the resonance overlap (Mudryk & Wu 2006) as the mass ratio of moon/planet increases to the level that is comparable to a binary (star) system. At the low moon/planet mass ratio end, resonances still affect the distribution of small moons. Figure 3 plots the final semimajor axis distributions of small moons in Simulations B1–B4 (Simulations B5 and B6 are not included because almost no small moons are left at the end of simulations). As can be seen, there are similar features (gap and pileup near resonance) as compared to the asteroid belt and the planets observed by Kepler mission (Fabrycky et al. 2012). These intriguing features may be associated with overlap and asymmetry of resonances (Petrovich et al. 2013; Xie 2014).

2.2.2. An Unstable Big Moon

In this case, we move the big moon outward with an initial semimajor axis of 0.25 $R_H(t_0)$ orbiting around the planet. All other initial parameters are the same to those in Simulations B1–B6. New simulations are identified as C1–C6 in Table 1 and Figure 4. The evolution of orbital semimajor axes of the
moons are shown in Figure 4. All moons’ orbits expand during the photo-evaporation process. The big moon becomes unstable at $t \sim 0.7 \tau_{\text{evap}}$ when approaching the critical semimajor axis, which triggers a global instability for all the small moons. The unstable big moon can have a very eccentric and chaotic orbit when approaching the stable boundary, thus crossing and destabilizing the orbits of small moons with a wide range of semimajor axes. A small fraction of small moons survive in Simulations C1–C3, but none can survive in Simulations C4–C6 due to the larger mass of the big moon. Compared to Simulations B, there are fewer small moons that become planet-like bodies orbiting the star. Most unstable small moons hit the planet or the big moon. The fraction of “hit moon” dominates (70.4%) in Simulation C1 and decrease to ~55.1% in Simulation C6. This is because the increase in the mass of the big moon (from C1 to C6) enhances the ability of the big moon to scatter more small moons toward the planet, leading to an increase in the fraction of “hit planet” as shown in Table 2.

2.3. Simulations D–E: All Big Moons

In this section, we consider the full gravitational effects of all the moons, namely to set all of them as big moons in the MERCURY simulations. We study two planet–moon configurations similar to the Neptune–moon system (Simulation D) and the Uranus–moon system (Simulation E) as follows.
2.3.1. Neptune–Moon System

For Simulation D, as in Simulations A, B, and C, the planet is still assumed orbiting the star at 0.1 au, except that, here, we set the planet–moon system as a clone of the Neptune with its seven regular moons. Similar to previous simulations, we hypothesize the planet would lose half of its mass during the photo-evaporation process and study the corresponding orbital evolution of the moons. We perform 100 simulations by randomly altering the angular orbital elements of the planet and moons, e.g., the orbital argument of periapsis, the longitude of the ascending node, and the mean anomaly.

Figure 5 plots the results of three typical cases. Note that here the Y axis is not the semimajor axes but $q$ (the periapsis: $q = a_m(1 - e_m)$) and $Q$ (the apoapsis: $Q = a_m(1 + e_m)$). The advantage of plotting $q$ and $Q$ here is that they show the radial extension of the Moon’s orbit. Panel (a) of Figure 5 shows a case with no surviving moon. The outermost and also the most massive moon gets its orbit excited as it moves outward due to the photo-evaporation of the host planet. Its orbit crosses the inner region and hits all the other lower-mass moons around $0.5 \tau_{\text{evap}}$ and then about $0.2 \tau_{\text{evap}}$ later, the moon finally collides with the planet. Panel (b) shows the result of one surviving moon. The outermost moon hits its four neighbor moons (except its closest neighbor—the second outermost one), then collides with the planet. The second outermost moon collides with the planet directly at $t \sim 0.6 \tau_{\text{evap}}$. The innermost moon is lucky to avoid all collisions and survives in the end. Panel (c) shows the result with two surviving moons. The outermost moon hits three
moons, then collides with the planet. The second innermost moon manages to survive, though hit by another lower-mass moon. The innermost moon also survives since it has no close encounter with other moons.

In all of the cases, the instability of the system is driven by the orbital excitation of the outermost moon, which contributes more than 80% of the total mass of all the moons. In most cases (87%), the outermost moon collides with other moons and ends up with a collision with the planet. In other cases (13%), it escapes from the planet system to become a planet-like object orbiting the star. In 100 simulations, we observe about 4% of simulations, which end up with no moons left, similar to case (a) in Figure 5. For surviving moons orbiting the planet, cases (b) and (c) are most common, accounting for 42% and 34%, respectively. There are also 13%, 6%, and 1% simulations with 3, 4, and 5 surviving moons. The innermost moon is the most-probable survivor. In our simulations, 23.4% of the moons still orbit the planet, 2.0% orbit the Sun, 21.2% hit the planet, and 53.4% hit other moons at the end of the simulation (Table 2).

2.3.2. Uranus–Moon System

Simulation E is similar to Simulation D, except that we adopt the clone of the Uranus–moon system as the configuration of the planet–moon system in simulations. Because Uranus has many more moons, we only consider the 14 regular moons with semimajor axes less than 0.5 \( R_{\text{H}}(t_0) \). The initial conditions are presented in Table 1. Similar to Figure 5, we plot in Figure 6 the results of three typical cases with 0, 1, and 2 surviving moons at the end of the simulation. The statistics of the final fates of these simulated moons are summarized in Table 2.

Compared to Simulation D, we find that the evolutions in Simulation E are generally more violent, leading to much fewer surviving moons. Of the simulations, 9% end up with zero moon (4% in Simulation D). Most simulations (78%) end up with only one moon, while 10% and 3% simulations end up with 2 and 3 moons. No system has more than 3 surviving moons. On the other hand, the fraction of surviving moons is 6.7% while most moons have mutual collisions among each other (72.9%). This is expected because Simulation E started.
with a much more dynamically compact configuration with twice the number of moons.

3. DISCUSSIONS

3.1. Fates of Escaping Moons

In the above simulations, we note that a certain fraction (see Table 2) of moons escape from the planet–moon system to become planet-like objects orbiting the star. Here we perform long-term simulations to follow their further orbital evolutions. In order to speed up the calculation, we reduce the number of small moons to 100. The results are plotted in Figure 7 for Simulations B5 and C5 with the evolution timescale extended to 1000 $\tau_{\text{evap}}$.

In Simulation B5, there are many escaping moons (24.8%). We follow two of them which are colored in red (a small moon) and blue (the big Moon). The big moon keeps orbiting the planet during the whole simulation. On the other hand, the small Moon escapes at the time $\sim 0.5 \tau_{\text{evap}}$ and becomes a planet-like object orbiting the star. Afterwards, the small moon keeps its orbital periastron near the planet, but gradually increases its orbital aphelion, though with large oscillations. Finally, at the time $\sim 700 \tau_{\text{evap}}$, the small moon boosts its aphelion to beyond the boundary (100 au) of our simulation. We speculate that the moon will be likely to escape from the star–planet system and finally to become a free-floating object in the Galaxy.

In Simulation C5, the escaping moons are fewer (8.4%). We also follow one small moon (red) and the big moon (blue). Unlike Simulation B5, the big Moon becomes a planet-like object orbiting the star at the time $\sim 0.7 \tau_{\text{evap}}$. Then it keeps its orbital aphelion near the planet but with its periastron oscillating between 0.05 and 0.1 au. The moon would have close encounters with the planet near its periastron and has the possibility to hit the planet. However, interactions with other planets or planetesimals (not included in our current simulations) may further change its orbit to let it become a stable planet. On the other hand, the small moon (red) finally collides with the planet at the time $\sim 500 \tau_{\text{evap}}$.

As learned from the above long-term simulations, we see that the fates of those escaping moons are diverse. They can further escape from the star–planet system to become rogue planets in the Galaxy or become stable planets orbiting the star or come back to collide with their parent planet after a certain time orbiting the star.

3.2. Effects of Other Model Parameters

In our simulations shown above, we simply adopt a linear photo-evaporation model with a timescale of $\tau_{\text{evap}} = 10^4 P_p$. In reality, the process of photo-evaporation is much longer...
and definitely nonlinear with time. In order to study the effects of these photo-evaporation model parameters, we performed more simulations with the linear/nonlinear mass-loss process of various timescales. The results are plotted in Figures 8 and 9. As can be seen, regardless of whether one is using the linear or nonlinear mode, the dynamical results are similar as long as the photo-evaporation timescale is much longer than the planet’s orbital period, i.e., $\tau_{\text{evap}}>1000 P_p$. This is expected because the evolution approaches an adiabatic progress for such a large $\tau_{\text{evap}}$.

Therefore, we choose $\tau_{\text{evap}}=10^4 P_p$ in our previous simulations to both meet the adiabatic condition and save the computation time.

In our nominal models, we simply fix the planet density ($1.66 \text{ g cm}^{-3}$, same as Neptune). In reality, as the planet loses mass due to photo-evaporation, its density and radius may change, which can modify the ability of the moon to hit the planet. In order to quantify these effects, we perform another two simulations. Both simulations have the same initial conditions as simulation A, except that the planetary densities are a factor of two larger and smaller, respectively. We find the results of these two simulations are comparable to that of simulation A. The fraction of surviving moons does not change at all (both are 26% same to simulation A). The only difference is the fraction of moons that hit the planet, which increases (decreases) from 47% to 55% (30%) for the simulation with smaller (larger) planet density. The results are expected as lower density leads to larger planetary radius for a given planetary mass and thus larger cross-section for the planet–moon collision. The stability of the moon is determined by the

Figure 8. Orbital evolutions with different $\tau_{\text{evap}}$. The timescale is shown in the top-right corner of each panel. The Y axis is $q$ (the pericenter: $q=a(1-e)$) and $Q$ (the apocenter: $Q=a(1+e)$) scaled by the initial Hill radius of the planet $R_H(t_0)$. Here we plot three moons with semimajor axes that started from 0.1 (green), 0.2 (blue), and 0.3 (red) $R_H(t_0)$, respectively. Each moon is associated with two lines ($q$ and $Q$ respectively). For better comparison, in each panel, we plot simulation results (black lines) with the longest timescale ($\tau_{\text{evap}}=10^6 P_p$). We see that the results are almost identical if the photo-evaporation timescale is sufficiently large, e.g., $\tau_{\text{evap}}>1000 P_p$. (10$^7$–10$^9$ year $\sim$ 10$^9$ $P_p$)
Hill radius of the planet (independent of planet radius), thus there is no change in surviving moons if only the planet radius (density) varies. Therefore, we conclude that changing the planetary density (thus radius) would not qualitatively change our major result, namely, photo-evaporation plays a destructive role in the orbital evolution of the moon system, generally leading to global instability of the exo-moon system.

3.3. Implications to Observations

The Kepler mission has detected more than 4600 exoplanets/candidates. A large portion (~40%) of them are in close-in orbits with orbital semimajor axes <0.1 au, for which photo-evaporation by the host star could be relevant. Indeed, Owen & Wu (2013) find that about 50% of Kepler planet candidates may have been significantly eroded by photo-evaporation. If those planets had moons, many of these moons would have been lost due to the instability triggered by the photo-evaporation as shown in the above simulations. As photo-evaporation depends on the proximity to the host star, we expect a gradient in observation: the occurrence rate of the exomoon significantly drops as it is approaching (<0.1 au) the center star. Furthermore, the X-ray exposure plays an important role in photo-evaporation and the X-ray flux varies greatly for different stars, with late-type stars being significantly more X-ray luminous (Güdel 2004; Jackson et al. 2012). Therefore, we expect that the instability induced by photo-evaporation also has a dependency on the spectrum type of the host star. From this aspect, we predict that exomoons are less likely to be found around M stars as compared to earlier type (F, G, and K) stars.

4. SUMMARY

Many planet candidates found by the Kepler mission are in close orbits around their host stars, whose photon radiation could evaporate the atmosphere of the close-in planets. In this paper, we model this photo-evaporation process as an adiabatic mass loss on the planet, and numerically investigate the corresponding effects on the dynamical evolution of the moons’ orbits around the planet.

We begin with the simplest case, where the moons are treated as TPs (small moons) without considering their mutual gravity (Section 2.1). Simulation A illustrates the direct effects of photo-evaporation on the moons, namely expanding ($q_\text{m}$) and exciting ($e_\text{m}$) the moons’ orbits (Figure 1), which triggers orbital instability as moons’ orbits cross the boundary of stability (Equation (1)). Next, we

![Figure 9. Orbital evolutions with different $\tau_{\text{evap}}$ and different planet mass-loss mode (linear: $M_p(t)/M_p(t_0) = 1 - \frac{1}{2}(t/\tau_{\text{evap}})^2$ (red, blue and green lines)). Note that the X axes are the mass of the planet (NOT time). The Y axes are the same to those in Figure 8.](image)
consider a set of new simulations (Simulations B and C) by adding a big moon with various masses and initial semimajor axes. These simulations help us understand the role of the moon’s gravity in developing the orbital instability. As expected, a moon with greater mass and larger initial semimajor axis (thus closer to the stability boundary) tends to make the system more unstable, with almost all moons being lost in the end (Figures 2–4). Finally, we perform two more realistic simulations (Simulations D and E) by cloning the moon systems of Neptune and Uranus (Figures 5 and 6). In these two set of simulations, mutual gravity of all moons have been fully considered, which leads to more chaotic evolution of the systems.

In any case, we learn that photo-evaporation plays a destructive role in the orbital evolution of the moon system, generally leading to moon loss. The fates of the lost moons are diverse. While the majority of them are likely to collide with other moons or with the planet, some of them could escape from the moon system to become a new planet orbiting the star or even a free-floating object in the Galaxy (Figure 7). Based on our simulations, we therefore speculate that exomoons are fewer around planets that are close (<0.1 au) to their host stars, especially M-type stars, because they are more X-ray luminous and thus enhancing photo-evaporation. On-going or future exomoon searching programs should consider the above effects for their target selection.

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