FORMATION OF IRREGULAR AND RUNAWAY MOONS/EXOMOONS
THROUGH MOON-MOON SCATTERING

HAGAI B. PERETS$^1$ AND MATTHEW J. PAYNE$^2$

ABSTRACT

Gas giant planets in the Solar system host large satellite systems with multiple regular and irregular moons. Regular moons revolve around their host planet in circular, low inclination short period orbits, and are thought to form in-situ through coagulation processes. In contrast, irregular moons have highly inclined (and even retrograde), typically eccentric and long period orbits around their host planet. Irregular moons are therefore often thought to have formed as unbound objects in heliocentric orbits that were later captured to their current orbits around the planet. However, such capture scenarios require fine tuned conditions and/or encounter difficulties in producing irregular moon populations around all gas giants. Here we study the possibility that regular moons form in-situ outside the currently observed regular-moon regime, and dynamically evolve through mutual moon-moon scattering (as well as by secular evolution due to perturbations by the Sun). We find that such evolution can excite the satellites into high eccentricities and inclinations. We find that moons are either ejected from the host planet to become runaway moons, or stay bound and become prograde orbiting irregular moons with inclined and eccentric orbits around their host planet. Ejected moons, unbound to the planet, can later be temporarily re-captured by the host planet even at retrograde orbits. Such moons are eventually re-ejected from the system or collide with the planet, at least in the absence of dissipative processes (e.g. collisions with existing bound moons, a debris disk or through tidal interactions with the host planet), not currently modeled. Uncaptured runaway moons may eventually be ejected from the Solar system, or be captured into stable heliocentric orbits and contribute to the populations of asteroidal or trans-Neptunian objects. Such scenarios are relevant both for the gas-giant satellites in the Solar system and for the dynamical evolution of exomoons.

1. INTRODUCTION

Satellites of the giant planets in the Solar system are typically categorized into regular and irregular moons. Regular moons orbit their host planet in circular, low inclination short period orbits; irregular moons have highly inclined (and even retrograde), typically eccentric and have longer period orbits. Similar to planet formation, the formation of satellite systems around giant planets in the Solar system (and in exoplanetary systems) is difficult to study theoretically. Regular satellites are thought to have formed through collisional growth of smaller planetesimals in the circum-planetary disk, very similar to planet formation in the coagulation model for the terrestrial planets. Irregular satellites are typically thought to have formed elsewhere in the Solar system (as asteroid/Kuiper-belt object like planetesimals), and only later be captured to become moons. The various models suggested have major difficulties in explaining the origin of the irregular moons (see Jewitt & Haghighipour[2007], for a review). More successful recent capture models have been suggested; these involve planet-planet interactions, and the existence of an additional third ice-giant planet in the Solar system that have been later ejected from it (Nesvorný et al.[2014]).

An oversimplified but useful approach used to study satellite formation is to divide it into two stages, based on the importance of the effects of gas and the circum-planetary disk on the growing satellites. The first stage lasts a few Myr, until the dissipation of the gaseous circum-planetary disk, following the dissipation of the gaseous protoplanetary disk which fuels it. At the end of this stage large moons should have formed (Canup & Ward[2006]) in addition to and (possibly many) smaller moonlets.

The second stage begins following the gas dissipation. At this stage the evolution is driven primarily by gravitational interactions and collisions between the moons. In comparison with the extensive study of the first stage of satellite-system formation in a gaseous disk, the dynamical relaxation through moon-moon scattering at the later stage have scarcely been explored. Here we study this dynamical evolution using analytic techniques and N-body simulations of moon-moon scattering around giant planets, and suggest that it can play a major role in the build-up and sculpting of the architecture of satellite systems, both in the Solar system as well as in (not yet detected) exomoon systems.

This paper is structured as follows. We first provide a brief overview of the various processes seen in our N-body moon-moon scattering simulations, which are later discussed in more detail. We introduce the N-body simulations used to study the satellite systems, and discuss the initial conditions following the dissipation of the gaseous circum-planetary disk, followed by a brief discussion of the stability of multi-moon systems. We then provide an analytic context to dynamical relaxation of multi-moon systems. We describe several examples of multi-moon systems studied through N-body simulations and present their evolution and outcomes, demonstrating the possi-
ble outcomes. Finally we discuss the evolution of multi-
moon system through scattering and their implications
for satellites systems as well as the populations of minor
bodies in the Solar system (asteroids, trans-Neptunian
objects, comets etc).

2. OVERVIEW

Dynamical evolution of a satellite system goes through
various stages. We will first review these stages, and
then discuss them in more detail both analytically and
through examples from N-body simulations.

Instability: Following the formation of the moons in
an extended circum-planetary disk, they mutually per-
turb each other gravitationally. As long as a gaseous
disk or a planetesimal disk exist, such disks might dis-
sipate the perturbation and stabilize the system. After
the disk is gone, the mutual perturbations may desta-
bilize the systems on short timescales, if their masses
are large and/or the separations between them are small
enough (similar to the well studied planet-planet scat-
tering case: e.g. [Rasio & Ford 1999]). The perturbations
can then grow and lead to orbit crossing between the vari-
ous moons. Here we study only the evolution of satellite
system at the onset of dynamical instability after the
gaseous disk has been gone.

Scattering, collisional growth and production of
prograde irregular satellites: In an unstable system
the moons will scatter each other gravitationally, leading
to orbital changes, exciting the eccentricity and inclina-
tions of the satellites. When the relative velocities be-
tween the moons become larger than the escape velocity
from their surface, physical collisions between moons will
occur, which might alleviate further growth of the moons
and/or their possible disruption. Moons excited to high
eccentricities may collide with the host planet. Alter-
natively, a moon can be scattered to a large distance
extending beyond the stable region around the planet
(typically \( \sim \frac{1}{3} R_H \) or even \( \sim \frac{2}{3} R_H \) for prograde and
retrograde orbits, respectively), and then be ejected from
the system to become a runaway moon. Through the
scattering process moons can migrate in the disk and ex-
change positions to produce a mixed order, i.e. erasing
the signature of the original moon ordering.

Secular evolution and the Kozai-Lidov “bar-
rier”: Moons excited to high inclinations with respect
to the orbital plane of the host planet around the Sun,
can become susceptible to large amplitude secular or-
bital evolution due to the tidal perturbations by the Sun
or by other moons (so called Kozai-Lidov oscillations).
Such secular evolution can drive the satellite orbits into
extremely eccentric orbits, and eventually lead to their
collision with another moon or the planet, or to their
ejection from the system. It is therefore difficult for moon
scattering processes to directly lead to excitation of ret-
rograde orbits from initially prograde orbits. A similar
limitation on eccentricities could also be seen in planet-
planet scattering simulations of exo-planetary systems
(e.g. [Nagasawa et al. 2008]). Scattering to stable high
inclination orbits is therefore limited by a Kozai-Lidov
“barrier”.

Temporary and permanent re-capture of run-
away moons and the origin of retrograde irregular
moons: Following their ejection, runaway moons, now
on helio-centric orbits, are likely to interact again with
the host planet. Some can interact with the other Solar
system planets and/or protoplanetary disk and may ob-
tain a stable helio-centric orbit. Others might strongly
interact with the planet and even be ejected from the
Solar system. Runaway moons can also be re-captured
temporarily into orbits around the planet even into ret-
rograde orbits with respect to the orbit of the planet
around the Sun. Such re-captured moons can potentially
dissipate some of their kinetic energy through scattering
and/or collisions with other moons orbiting the planet
and/or tidal interaction with the planet (i.e. some-
what similar to planet capture from wide eccentric or-
bits into close retrograde orbits in planet scattering sim-
ulations: [Nagasawa et al. 2008, Nagasawa & Ida 2011,
Beaugé & Nesvorný 2012]). and thereby be re-captured
into permanent orbits. We conjecture that such dissipa-
tive processes could produce retrograde irregular moons
(similar to the models envisioning capture of objects
formed independently in the protoplanetary disk). Here
we only model purely dynamical interactions and do not
include dissipative processes (beside direct collisions),
which will be explored elsewhere.

3. N-BODY SIMULATIONS

Throughout this paper we discuss the results of several
N-body simulations (using the mercury code [Chambers
1999]) of satellite systems. In following papers we will
describe the statistical results of a large sample of simu-
lations through the study of a wide range of initial con-
tions. The current paper focuses on presenting the basic
processes and outcomes of moon-moon scattering pro-
cess, and only presents results from a small number of
simulations to provide explicit examples. The results of
these specific simulations are corroborated by the much
larger set of simulations (see Payne & Perets; paper I),
for detailed discussion of the extended N-body simul-
ations). Table 1 provides the the initial conditions for
these simulations. We have used a single Neptune like
planet (Neptune mass and separation from the Sun), orbi-
ted by a large number of moons (10-50 massive moons,
and in some cases up to 1000 massless particles corre-
ponding to low mass moons). In all simulation the out-
nermost moon is placed at a distance \( R_{\text{out}} = \sim \frac{1}{6} R_H \)
(i.e. at stable orbits comparable to the outermost pro-
grade satellites in the Solar system; \( R_H \) is the planet Hill
radius) and subsequent moons are placed internal to this
moon at separations of 5 mutual Hill radii from each other.
In all simulations shown here the moons are put
on co-planar orbits coinciding with the orbital plane
of the planet orbit around the Sun; with only small random
inclinations, distributed randomly between \(-1^\circ \) and
0-0.01 eccentricities. Though we show results of moon-
moon scattering around a Neptune like planet, results of
similar satellite systems around other Solar system like
planets show similar results (Perets et al., in prep.).

4. CIRCUM-PLANETARY DISK

The first stage of moon formation has been explored by
several groups who provided a plausible explanation for
the origin of the regular moons in the a small (typically
\(< \text{few}\times0.01R_H \)) circum-planetary disk. Studies of the
formation of circum-planetary disks, however, suggest
that such disks should extend up to a large fraction of
the planetary Hill radius (up to approximately 0.33R_H; e.g.
Moon-moon scattering

Table 1
Simulation models

| #  | Planet | $N_{\text{moon}}$ | MF | $N_{\text{test}}$ | $R_{\text{out}}$ | $T_{\text{sim}}$ (yrs) |
|----|--------|-----------------|----|-----------------|-----------------|------------------|
| 1  | Neptune| 10              | equal mass; $m = 2 \times 10^{25}$ g | 0               | $0.17R_H$       | $10^5$           |
| 2  | Neptune| 50              | equal mass; $m = 5.5 \times 10^{25}$ g | 0               | $0.17R_H$       | $6.3 \times 10^5$ |
| 3  | Neptune| 20              | equal mass; $m = 9.3 \times 10^{24}$ g | 1000            | $0.17R_H$       | $10^5$           |
| 4  | Neptune| 3               | equal mass; $m = 2 \times 10^{24}$ g | 0               | $0.17R_H$       | $10^5$           |

Ayliffe & Bate 2008, Tanigawa et al 2012, and are not truncated at small separations, as was hitherto assumed (e.g. Canup & Ward 2008; Ogihara & Ida 2012); based on older non-resolved simulations of the gaseous disks; e.g. Lubow et al. 1999). Formation of regular moons can therefore potentially extend much beyond the region of the currently observed regular moons. Given these results, the likely initial conditions for a satellite system is the formation of a multi-moon system extending up to a large fraction of $R_H$. Consequently, the initial condition assumed throughout this study are the initial existence of a disk like population of moons extending up to 0.3 $R_H$ (the typical stability region for gas planet moons). A detailed study of the initial stages of regular moons formation in an extended circum-planetary disk is beyond the scope of this paper and will be discussed elsewhere. Here we focus on the dynamical evolution of moons in extended disks.

5. Stability

A general criteria for the stability of a multi-object Keplerian system has not been found yet. For a system with two low mass planets on circular, nearly co-planar orbits, a stability criteria was found by Marchal & Bozis (1982) and Gladman (1993), who showed that such systems do not have a close encounter (they are “Hill stable”) if their semi-major axes are separated by

\[
\Delta a = a_2 - a_1 = 2\sqrt{3}R_{H,\text{mutual}} = 2\sqrt{3}\left[\frac{a_1 + a_2}{2} \frac{(m_1 + m_2)}{3M_\odot}\right]^{1/3} \tag{1}
\]

We can now scale this criteria for a satellite system around a planet, and consider two moons (where the Solar mass is replaced by the planetary mass, and $m_1$, $m_2$ now refer to the satellite masses). For a system of two moons with $a_2 > a_1$ to be stable we then require from Eq. 1 that

\[
a_2 > \left[1 + \sqrt{3} \frac{(m_1 + m_2)}{3M_p}\right]^{1/3} a_1. \tag{2}
\]

From this relation one can find that some of the known pairs of neighboring regular moons in the Solar system could have been dynamically unstable, if they were located further away than their current orbit (e.g. in the irregular moons region), or if they were more massive than their current measured masses.

In higher multiplicity systems direct N-body simulations show that initially stable systems require a few mutual Hill radii separation between the planets in order not to destabilize on a short timescale (Chatterjee et al. 2008); however no general stability criteria is known for > 2 objects orbiting a central massive object. In all the simulations of moon scattering we initialized all moons to reside at 4-6 mutual Hill radii from their closest neighbor.

6. Scattering and prograde irregular moons

6.1. Single strong impulsive encounters

Let us first consider a single encounter between two moons, occurring at some distance $R$ from the planet, assuming a fast encounter at the impulse approximation limit. The kick velocity to a given moon (assumed to be smaller, for simplicity) through scattering by a moon of mass $M_s$ (and radius $r_s$) is of the order of

\[
\Delta v = \frac{GM_s}{br_v}\tag{3}
\]

where $b$ is the impact parameter, and $v_{rel}$ is the relative velocity between the moons, typically comparable to the velocity dispersion in the circum-planetary satellite disk. For a heated disk, the velocity dispersion is of the order of $\beta v_{\text{disp}}(R)$, where $\beta = H/R$ is the height ratio of the disk, and $v_{\text{Kep}}(R)$ is the Keplerian velocity at distance $R$ from the planet (cite), i.e. $v_{\text{rel}} = \beta \sqrt{GM_p/R}$. Comparing the kick velocity gained through a close approach (comparable to a few times the satellite radius, $r_s$, i.e. $b \geq 3r_s$, for which we can assume tidal effect are negligible) to the Keplerian velocity (for a circular orbit) around the planet at that position,

\[
v_{\text{Kep}} = \sqrt{\frac{GM_p}{R}} = \frac{GM_s}{3r_s\beta \sqrt{GM_p/R}}
\]

we get the radius at which a mutual kick could significantly change the satellite orbit (where we assume a constant disk height ratio, $\beta = 0.05$)

\[
R_{\text{sig}} = 3\beta \frac{M_p}{M_s} r_s. \tag{3}
\]

Replacing the Keplerian velocity with the escape velocity, we can similarly get the critical radius from which moons can be ejected from the system (though in practice, due to the tidal perturbation by the Sun moons ejected beyond $\sim 1/2R_H$ would already become unbound from the system).

For scattering by the most massive observed moons for each of the giant planets, we find that $R_{\text{sig}} = 3\beta \times 0.65, 0.16, 0.27 0.06 R_H$, taking the satellites Ganymede, Titan, Titania and Triton (for Jupiter, Saturn, Uranus and Neptune, respectively). It is therefore clear that even single strong encounters with such moons can significantly alter the orbits of companion moons and even eject them, if found beyond $R_{\text{sig}}$, which, for reasonable $H/R$ ratios includes most of the stable region around these planets.
As mentioned above, no analytic criteria for instability of multi-planets is currently known, but simulations of multi-planet systems show that such systems evolve into strong scatterings and orbit crossing when the mutual distance between planets are a few mutual Hill radii or less. In our simulations we typically separate each neighboring moon by 4 mutual Hill radii, but we find that even larger separations (5-6 mutual Hill radii) eventually lead to strong scatterings (see also Paper I).

6.2. Relaxation through viscous stirring, multiple encounters, and the origin of prograde irregular moons

The dynamical evolution of a disk of planetesimals has been extensively studied both numerically and analytically. Making use of similar tools we would expect viscous stirring to excite the eccentricities and inclinations of the moons in circum-planetary disk. For a disk composed of N equal mass moons, with mass m, the evolution of the velocity dispersion in the disk, σ, with time would then go like (following Alexander et al. 2007; see text, Eq. 4). Simulation results are smoothed with a window of 20K yrs for clarity. The multi-moon system shows similar evolution to that of a protoplanetary planetesimal disk. Note that at later evolutionary times (not shown here), the disk evolution differs since the tidal perturbation from sun become more significant for moons close to RH and/or at high inclinations, where significant secular evolution may occur.

\[
\frac{d\sigma}{dt} = \frac{G^2N m^2 \ln \Lambda}{CR_0\Delta R_{orb}\sigma^3} \quad (4)
\]

for a disk (or ring) centered at radius R_0, with a radial width ΔR; ln Λ is the Coulomb logarithm (≈ 9) and τ_{orb} is the Keplerian orbital period at R_0; C is a constant prefactor (Alexander et al. 2007) find 2 ≤ C ≤ 3 in their disk simulations. Effectively, as the disk evolves moons may be ejected or collide and therefore N and/or m should evolve with time. Nevertheless, this should serve as a good approximation at the earlier stages of the evolution, before a significant number of ejections/collisions of moons occur. The change in disk thickness would also affect the maximal effective distance between encounters, thereby affecting Λ; but the latter effect is logarithmically weak. We therefore expect the evolution of a circum-planetary disk to be similar to that of a protoplanetary disk, at least at the early stages and far from the instability region where moons can be easily ejected, i.e. σ(t) ∝ t^{1/3}. In fig. 1 we show the evolution of a single component disk in our N-body simulation (model 2 in table I), and compare it with the simplified analytic results (no fit; predictions for two extreme C values, C = 2, 3 are shown); we assume a disk size of R_0 = ΔR = 0.1 AU around a Neptune like (mass and distance from the Sun) planet. We show the evolution of the rms eccentricity and inclination (\( \epsilon_{\text{rms}} = \sqrt{\langle \epsilon^2 \rangle} \), \( \epsilon_{\text{rms}} \approx 2\epsilon_{\text{rms}} \)). At later times (> 10^6 yrs) the simple assumptions used in the model break down (due to ejections/collisions which change the number density and the mass of the moons) and the rms eccentricity of the moons evolve slightly slower than the analytic predictions (not shown),

6.3. Collisions and growth

As discussed above, moon-moon scattering dynamically heats the satellite system, leading to moon orbit crossing and potential physical collisions and the coagulation of smaller moons into big moons. Though collisions are included in our simulations (assuming sticking spheres model for the collision), we focus on the later stages of satellite systems after the main stage of the moon formation, where only a small number of massive moons reside in the disk. A more detailed study of satellite formation beyond the region of regular moons is beyond the scope of this study. We note, however, that collisions do play a role in the satellite system evolution, and a large fraction of the satellite mutually collide. Fig. 2 shows an example of the mass function evolution of a satellite system (initially with equal mass moons).
6.4. Satellite system evaporation: moon ejection and runaway moons

As illustrated in Fig. 4 (based on results from model 2), moon-scattering excites the eccentricities (and inclinations) of the satellites, as well as changes their semi-major axis. If the separation of a moon from its host planet (at apocenter) extends beyond the stability region around the planet, the tidal perturbations by the Sun start to dominate its dynamical evolution, leading to fast large amplitude fluctuations in its orbital elements. Typically such evolution would, eventually, lead to the ejection of the moon from the system as its orbit extends beyond the Hill radius. In some cases, however, scattering by other moons close to pericenter can decrease the apocenter distance of the moon from the planet and bring it back into a stable orbit. We find that satellites can migrate back and forth throughout the stability region, but, as can be seen clearly in Figs. 3 and 4, they can not survive for long beyond $\sim 0.4R_H$. The evolution of a satellite system is somewhat similar to that of an evaporating globular cluster in the tidal field of the galaxy. Relaxation processes lead to the contraction of the system into a tighter configuration accompanied by the ejection of moons either diffusively by slowly migrating beyond the stability region of the host planet, or through more rare strong encounters, which can scatter a moon from a stable inner orbit directly into a wide separation and unstable orbit. Our simulations clearly demonstrate both these evaporation channels (see Fig. 4).

Generally we find that, similar to multi-planet scattering results (e.g. Juric & Tremaine 2008), at the end of our simulations typically only 1-3 massive moons survive, irrespective of the initial number of massive moons in the simulations; this is corroborated by a large cohort of 3-10 massive moons simulations (using initial moon masses comparable to those of the most massive Solar system regular moons). The rest of the moons typically either collide with the planet or are ejected from the system into heliocentric orbits, thereby forming a population of “runaway” moons (see Fig. 4 for the evolution of such runaway moons). The results of these large phase-space studies are discussed in a companion paper (Payne et al., in prep.).

7. SECULAR EVOLUTION, MOON RECAPTURE AND RETROGRADE IRREGULAR MOONS

It is well established that irregular satellites can be strongly affected by secular Kozai-Lidov (KL) evolution due to perturbations by the Sun (see Jewitt & Haghighipour 2007 and references therein). Such evolution leads to periodical/quasi-periodical changes in the inclinations and eccentricities of the satellites. The amplitude of such oscillations can become large when the inclinations with respect to the orbit of the host planet around the Sun are larger than $\sim 40^\circ$ (somewhat smaller for non-zero eccentricity orbits). In particular, excitation of large eccentricities can lead to mutual orbit crossing of the various moons and eventually to strong scattering between them. The extremely high eccentricities potentially reached through this process also make the moons susceptible to physical collisions with the planet and/or to be affected by strong tidal interactions (at pericenter). At apocenter such moons might be ejection through a strong scattering from an inner stable orbit. Note that both ejected satellites were later temporarily captured. The first (red dots) is recaptured and even evolves into stable small separation orbit at very high and even retrograde inclinations (see bottom panel), before colliding with the planet. The (blue) rectangles show the evolution of a never ejected satellite. Middle: Evolution of the satellite eccentricity. Note the high eccentricities at the post-recapture stage of the satellite; eventually leading to the collision of the first (red dots) satellite with the planet. Top: Evolution of satellite inclinations. Note the retrograde orbit of the first recaptured (red dots) satellite.

FIG. 3.— Dynamical history of three different test-mass moons in model 3, two of which are eventually ejected from the system due to interactions with the massive satellites. Bottom: Evolution of apo-center. The (red) dots show the slow evolution of the satellite orbit into the unstable zone. The (green) pluses show a satellite ejection through a strong scattering from an inner stable orbit. Note that both ejected satellites were later temporarily captured. The first (red dots) is recaptured and even evolves into stable small separation orbit at very high and even retrograde inclinations (see bottom panel), before colliding with the planet. The (blue) rectangles show the evolution of a never ejected satellite. Middle: Evolution of the satellite eccentricity. Note the high eccentricities at the post-recapture stage of the satellite; eventually leading to the collision of the first (red dots) satellite with the planet. Top: Evolution of satellite inclinations. Note the retrograde orbit of the first recaptured (red dots) satellite.
ejected from the system if they approach the instability region at apocenter (approximately 0.3-0.4 of the planetary Hill radius). For these reasons, moons scattered into high (mutual) inclination (with respect to the planet orbit around the Sun) are not likely to survive long before they collide with the planet/other moon or are ejected from the system. Such evolution depletes moons at high inclinations; the lifetime of moons at such inclinations is short; they can not achieve high inclinations close to 90°, which would allow them, through additional scattering (or secular evolution) obtain retrograde orbits. Rather, they are either scattered into at most 50° – 60°, and are then scattered back to lower inclinations or they are destroyed (collision or ejection). We note, however, that KL evolution is very sensitive to other perturbations affecting the pericenter precession of the orbits, and can be easily quenched due to competing interactions (e.g. the combined perturbations of the other moons alter the pure KL evolution due to the Sun; tidal interaction and/or the oblateness of the planet can also alter such evolution, at least for moons achieving small pericenters; see also [Nagasawa & Ida 2011] for a similar discussion in the context of planet-planet scattering).

Though long term stability of high inclination orbit is difficult, we nevertheless find many moons do achieve retrograde orbits throughout their orbital evolution, sometimes even for long period of time (thousands of years). Moon-moon scattering can therefore produce not only prograde irregular satellites, but also retrograde irregular ones. Analysis of their dynamical history reveals that all moons showing this behavior have been, at earlier times, ejected from the system, and have later been temporarily recaptured into retrograde orbits (Fig. 3 show a typical example of such evolution).

Such a temporary capture, if followed by a dissipative process, could produce irregular moons; indeed this is the basic mechanism suggested to produce irregular moons in the moon-capture scenario. Our results therefore suggest that in-situ formation of moons followed by scattering can lead to similar outcomes as the capture scenarios, without allowing to capture of externally formed planetesimals, i.e. irregular moons might be recaptured moons, in addition to, or instead of being captured asteroids/KBOs.

In our simulations we do not account for any dissipation from e.g. interaction with gas or tidal friction during close encounters with the host planet. Scattering by other moons can also stabilize the orbit of such recaptured runaway moons to become permanently captured. Nevertheless, we find no satellites that survived in retrograde orbits more that few thousands years. In fact, we find that all the moons which eventually collided with the host planet in our simulations did so only after they have been ejected and had been temporarily recaptured. In Fig. 4 we show the inclination distribution of such satellites prior to their collision. This suggests that introducing tidal interaction with the planet can have a major part in potentially stabilizing the orbits of these moons, and potentially produce the retrograde satellites we see today. Indeed, it had been shown that the tidal effects are essential for producing retrograde planets in planet-scattering simulations (e.g. Payne et al., submitted). The potentially promising effects of adding such a dissipative process to the moon-scattering simulations is beyond the scope of this paper and will be discussed elsewhere.

8. DISCUSSION AND SUMMARY

The discovery of hundreds of exo-planetary systems in the last two decades have provided new perspectives on the possible architecture of planetary systems. In contrast to the Solar system with its co-planar configuration of planets in nearly circular orbits, many exo-planetary systems present planets on highly inclined (with respect to the spin of their host star) and/or on highly eccentric orbits. Planets are thought to form in a protoplanetary disk which could naturally account for the existence of planets on co-planar circular orbits. The new discoveries of eccentric/inclined planetary orbits gave rise to models in which following the formation of multiple planets, they mutually perturbed and scatter each other through gravitational interactions. Such dynamical excitation eventually leads to the ejection of most of the planets, and the survival of typically 1-3 planets on eccentric and inclined orbits, with orbital properties consistent with observations.

Regular moons of the Solar system gas giants have been suggested to form in a circum-planetary disk around their host planet, in an analogue process to the formation of the Solar system planets and exoplanets observed in co-planar, circular orbits. As demonstrated here, massive moons (comparable in mass to the regular moons) which formed on co-planar circular orbits beyond the region of the regular moons can scatter each other and/or scatter a population of low mass satellites (massless particles in our simulations) into eccentric and inclined configurations thereby producing irregular-like moons, serving as the satellite analogue for eccentric/inclined exo-planetary systems. Our main results can be summarized as follows.

![Fig. 5.— Distribution of inclinations for potentially tidally captured/dissipated moons (in model 3; that $R_H \sim 0.77$ AU), at the point they would have (strongly) tidally interacted with the planet (pericenter distance smaller than twice the planetary radius). The addition of tidal interactions could potentially dissipate sufficient energy as to recapture such moons, and quench any further excitation of the eccentricity which would have otherwise lead to their collision with the planet.
1. Most of the massive moons are ejected, typically leaving behind 1-4 surviving moons on stable configurations, irrespective of the initial number of moons, very similar to the results of planet-planet scattering experiments in multi-planet scattering studies (e.g. Jurić & Tremaine 2008). The rest of the moons are either ejected, collide with one each other (potentially leading to further satellite growth) or collide with the planet.

2. The surviving massive moons can obtain high eccentricities and inclinations, similar to those of prograde irregular moons observed in the Solar system. However, none of the massive moons obtain a stable retrograde orbit.

3. A non-negligible fraction of the small moons (massless particles) in our simulations (> 50%) are ejected from the system but are then temporarily recaptured, for times between a few years to a few thousand of years. Of these recaptured moons ~ 5 – 10 % have retrograde inclinations just before they collide with the planet.

We therefore conclude that multiple moon systems can behave very similarly to multiple planet systems, and can produce satellite systems with high eccentricity and high inclination prograde irregular satellites. We conjecture that moons observed to temporarily attain retrograde orbits during their evolution can potentially be stabilized through dissipative processes (such as strong interaction with a disk/other moons or the planet) and may also produce stable retrograde irregular moons, somewhat similar to the observed behavior of planet-scattering simulations which consider tidal interactions (e.g. Payne et al., submitted). Note that currently no massive irregular moons beside Triton are observed in the Solar system; though this may serve as an important constraint on the moon-moon scattering scenario ever happening in the Solar system, it is possible that massive irregular moons were later removed through dissipative processes not studied here (e.g. migration in the circum-planetary disk into close separations to the host planet, tidal interaction with the planet, or strong disrupting collisions). The introduction of dissipative processes in moon-moon scattering simulations will be studied in detail elsewhere.

Finally, we note that moon-moon scattering mechanism can produce large planetesimals in heliocentric orbits that were originally formed as moons, and were later ejected from their host planet. Such planetesimals might still be observed today as asteroids/Kuiper belt objects, and may have unique kinematic and/or peculiar properties in term of composition and/or structure compared to the background heliocentric formed planetesimal population, due to their different origin.

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