The Dynamical Viability of an Extended Jupiter Ring System

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ABSTRACT

Planetary rings are often speculated as being a relatively common attribute of giant planets, partly based on their prevalence within the Solar System. However, their formation and sustainability remain a topic of open discussion, and the most massive planet within our planetary system harbors a very modest ring system. Here, we present the results of a N-body simulation that explores dynamical constraints on the presence of substantial ring material for Jupiter. Our simulations extend from within the rigid satellite Roche limit to 10% of the Jupiter Hill radius, and include outcomes from 10^6 and 10^7 year integrations. The results show possible regions of a sustained dense ring material presence around Jupiter that may comprise the foundation for moon formation. The results largely demonstrate the truncation of stable orbits imposed by the Galilean satellites, and dynamical desiccation of dense ring material within the range \( \sim 3 - 29 \) Jupiter radii. We discuss the implications of these results for exoplanets, and the complex relationship between the simultaneous presence of rings and massive moon systems.

Keywords: planetary systems – planets and satellites: dynamical evolution and stability – planets and satellites: individual (Jupiter)

1. INTRODUCTION

A distinctive common feature of the giant planets within the Solar System is the presence of ring systems orbiting the planet. Rings systems have been detected and studied extensively for each of Jupiter (Showalter et al. 1987; Porco et al. 2003), Saturn (Pollack 1975; Porco et al. 2005), Uranus (Elliot et al. 1977; Tyler et al. 1986), and Neptune (Lane et al. 1989; Showalter 2020). In particular, the prominent rings of Saturn have been the source of numerous investigations with regards to their formation (Goldreich & Tremaine 1978a; Charnoz et al. 2009) and dynamics (Goldreich & Tremaine 1978b; Bridges et al. 1984). For example, density waves detected within Saturn’s rings have been utilized as an effective means to infer oscillations within the planetary interior (Hedman & Nicholson 2013) and determine differential rotation of the outer envelope (Mankovich et al. 2019) and a diffuse core (Mankovich & Fuller 2021). Additionally, the age of Saturn’s rings has a range of estimated values, from several hundred Myrs (Zhang et al. 2017; Dubinski 2019; Iess et al. 2019) to as old as the Solar System (Crida et al. 2019). Age determinations depend on many factors, such as the velocity dispersion and interaction between ring particles (Salo 1995). Rings also stand as a possible record of past collision events, and indeed the formation of Saturn’s rings has been suggested as the result of a substantial moon being desiccated by tidal forces as it spiraled into the planet (Canup 2010).

By comparison, the Jupiter system contains a substantially more modest ring system that has been extensively studied via data from such missions as Voyager and Galileo, as well as ground-based observations (Smith et al. 1979; Ockert-Bell et al. 1999). Theories regarding the origin and evolution of the Jovian rings vary, such as their possible formation along with the Galilean satellites (Prentice & ter Haar 1979), and the contributions of collisional ejecta lost from inclined satellites (Burns et al. 1999) and escaping ejecta from the Galilean satellites and/or the inner small moons (Burns et al. 1999; Esposito 2002; Krivov et al. 2002). Further possible sources of potential ring material originate from impact debris (Ahrens et al. 1994; Hueso et al. 2013; Sankar et al. 2020) and the tidal disruption of satellites (Hyodo & Charnoz 2017) or large passing Kuiper belt objects (Hyodo et al. 2017). Such events are likely stochastic in nature whose frequency is an age-dependent phenomenon (Horner & Jones 2008).
Moreover, the dynamical evolution of Jupiter’s rings can have complicated explanations, partially with interactions between ions and the Jovian magnetosphere (Horányi & Cravens 1996) and the incorporation of dissipation effects (Greenberg 1983). The formation and dynamical evolution of Jupiter’s rings have important consequences regarding the prevalence of rings of giant exoplanets. Exoplanetary rings can be a source of confusion when evaluating the true nature of the planet and its properties (Piro 2018; Piro & Vissapragada 2020) and their successful detection may reveal important information regarding the formation of the planet and its local environment (Arnold & Schneider 2004; Zuluaga et al. 2015; Sucerquia et al. 2020). The Jupiter and Saturn systems demonstrate that the presence and sustainability of rings may be an intricate function of the architecture of planetary moons, as well as the intrinsic properties of the planet itself. The discoveries and/or limits on exoplanet rings and moons will provide crucial statistical data to further understand how rings may have formed and evolved in our Solar System (Kenworthy & Mamajek 2015).

In this work, we provide the results of an extensive dynamical simulation that tests regions of long-term dynamical stability for ring systems near the plane of the Jovian equator, and in the presence of the Galilean moons. In Section 2, we describe the architectures of the Jupiter and Saturn systems, specifically the structure of their rings with respect to the orbits of their respective moons. Section 3 provides the methodology and results for our dynamical simulation of stable orbits at locations that extend from within the rigid satellite Roche limit to 10% of the Jupiter Hill radius. The implications of our simulation results are discussed in Section 4, both in terms of the potential for past/future Jovian ring systems and within the context of giant exoplanets. Concluding remarks and suggestions for observational tests are provided in Section 5.

2. ARCHITECTURE OF JUPITER AND SATURN SYSTEMS

At the time of writing, the Solar System is known to contain over 200 moons, with Jupiter and Saturn harboring at least 79 and 82 moons, respectively\(^1\). The prevalence of moons within the Solar System has been a primary motivator behind the study of and search for exomoons (e.g., Hinkel & Kane 2013; Kipping et al. 2013; Heller et al. 2014; Hill et al. 2018). It has further been suggested that Solar System regular moons may serve as analogs of compact exoplanetary systems in terms of their formation and architectures (Kane et al. 2013; Makarov et al. 2018; Dobos et al. 2019; Batygin & Morbidelli 2020). Regular moons are particularly notable in that they likely formed with the planet, as evidenced by their equatorial prograde orbits, and are often large enough to exhibit hydrostatic equilibrium, resulting in a near-round morphology. For example, the four Galilean moons likely formed from the protoplanetary disk surrounding Jupiter (Ogihara & Ida 2012; Heller et al. 2015), possibly catalyzed by migration of Saturn (Ronnet et al. 2018), and now contain \(~99.997\)% of the total mass orbiting the planet. The mass contained within the regular moons will therefore have a significant influence on the dynamics of ring formation and sustainability.

Figure 1 provides a scaled view of the Jupiter and Saturn systems, where the separation from the planetary centers, located at zero, are provided in units of the respective host planet radius. The regular moons are shown as blue circles, where their sizes are relative to each other rather than in units of planetary radii, and the names of the major moons are provided. It is worth noting that all of Jupiter’s regular moons, including the Galilean moons, have semi-major axes that are within 1/25 of the Jupiter Hill radius, possibly a result of the mass distribution of the circumplanetary disk and moon migration processes that may have occurred. The extent of the rings in units of the planetary radii are shown as gray regions, and the vertical red dashed lines indicate the location of the fluid satellite Roche limit for each planet. The depiction of Jupiter’s rings include the Halo to Thebe gossamer rings, which span a distance of 1.29–3.16 Jupiter radii. Similarly, the depiction of Saturn’s rings include rings D–E, which extend a distance of 1.11–7.96 Saturn radii. The fluid satellite Roche limits are 2.76 and 2.22 planet radii for Jupiter and Saturn, respectively. Note that the rings depicted in Figure 1 contain both “dense” and “tenuous” rings, both of which have different sources of material and physical processes acting upon them (Daisaka et al. 2001). For example, Saturn’s E ring originates mainly from the cryovolcanic plumes of Enceladus, and is considerably more tenuous than the main ring (Horányi et al. 2009; Cuzzi et al. 2010).

Figure 1 highlights the differences in the distribution of moon mass with respect to the rings for each of the planets. In particular, the rings of Saturn contain numerous small moons, whose presence can both feed the rings with new material, and also “shepherd” the rings through their gravitational influence (Petit & Henon 1988; Charnoz et al. 2011; Cuzzi et al. 2014; Nakajima et al. 2020). Indeed, moons can ac-

\(^1\) https://solarsystem.nasa.gov/moons/in-depth/
cretes relatively rapidly from ring material beyond the Roche limit, and such rings are thought to have been a source of numerous moons within the present Saturn architecture (Charnoz et al. 2010; Crida & Charnoz 2012; Salmon & Canup 2017). Gaps in Saturn’s rings form through several processes, among them orbital resonances with moons, such as the relationship between the Cassini Division and Mimas (Goldreich & Tremaine 1978a; Iess et al. 2019; Noyelles et al. 2019). Titan is relatively far from the main ring structure, but its presence does result in a ringlet within the inner C ring through the effect of orbital resonance (Porco et al. 1984). However, there is evidence to suggest that Titan has experienced an outward migration through tidal dissipation (Lainey et al. 2020). This is somewhat in contrast to the effects of the more massive Galilean moons on the dynamical environment around Jupiter, particularly as Io, Europa, and Ganymede are located in a 4:2:1 Laplace resonance (Malhotra 1991; Peale & Lee 2002). Their orbital configuration is interpreted as strong evidence that the moons migrated inward either during formation or soon thereafter (Greenberg 1987; Peale & Lee 2002; Sasaki et al. 2010; Ogihara & Ida 2012). This may have resulted in a significant gravitational truncation of a potential massive ring system for Jupiter, such as that seen for Saturn, depending on the formation and migration timescales of the Galilean moons. Overall, there are significant differences between the ways in which dense and tenuous rings interact with the planet and satellite system, partially depending on the location of the rings relative to the Roche limits. The simulations described in this paper consider only dense rings for a range of semi-major axes. The physical processes acting upon the rings are described further in Section 4.1.

3. DYNAMICAL SIMULATIONS

This section describes the dynamical simulations, including their configuration, results for the Galilean moons, and injection of ring particles.

3.1. Dynamics of the Galilean Moons

As discussed in Section 2, an important factor in the formation and evolution of planetary rings is the moons present in the system. In this context, the Galilean moons are by far the largest gravitational influence on the presence of rings within the inner part of the Jupiter system. Thus, the dynamical evolution of the Galilean moons is a crucial component of evaluating potential ring sustainability. There are substantial data that contribute toward accurate ephemerides of the moons, and their dynamics have previously been studied in detail (Lieske 1980; Greenberg 1987; Lainey et al. 2004; Lari 2018). However, the vast majority of these studies focus on the short-term (∼100 year) dynamics of the moons, whereas this study is concentrated on timescales related to the sustainability of planetary rings (1–10 million years).

The simulations carried out for this work were conducted within the dynamical simulation package RE-
Figure 2. Eccentricity as a function of time for the Galilean satellites: Io, Europa, Ganymede, and Callisto. The eccentricity variations were recorded every 100 years during a $10^6$ year simulation, as described in Section 3.

BOUND (Rein & Liu 2012) with the symplectic integrator WHFast (Rein & Tamayo 2015). The initial conditions of the system were constructed to reproduce the configuration of the Galilean moon system, incorporating the current orbital elements extracted from the Horizons DE431 ephemerides (Folkner et al. 2014), and including the effects of Jupiter’s oblateness (Tamayo et al. 2020). The dynamical simulation presented in this work provides an independent assessment for the eccentricity evolution of the Galilean moons, the results of which are shown in Figure 2 for a duration of $10^6$ years. The combination of the resonance configuration and tidal dissipation present in the Galilean system ensures that the moons have exceptionally stable orbits through time and that they remain largely circular. Note that tidal dissipation was not included in our dynamical simulation. Figure 2 shows that the eccentricities remain below 2%, 3%, 1%, and 1% for Io, Europa, Ganymede, and Callisto, respectively. The short-term analyses of the Galilean moon eccentricities, such as the semi-analytical model provided by Lari (2018), reveal a transfer of angular momentum within the Laplace resonance of the three inner
moons with a period in the range 400-500 days. The long-term eccentricity evolution represented in Figure 2 does not reveal periodic behavior at significantly longer timescales, but does demonstrate that angular momentum transfer results in higher eccentricity variations for the less massive inner two moons than the more massive outer two moons. The slightly higher eccentricity variations for Io and Europa increase regions of dynamical instability in their vicinity, and thus has consequences for long-term ring stability close to Jupiter.

3.2. Particle Injection and Ring Stability

To explore the gravitational constraints that the Galilean moons impose upon potential ring particles orbiting Jupiter, we conducted a suite of dynamical simulations for the system based upon the architecture framework described in Section 3.1. The stability of an extensive ring system and possible moon forming material around Jupiter was tested by introducing a series of test particles to the Galilean moon system and evaluating their survivability at different locations within the system. The test particles were assumed to have a density of water ice (0.917 g/cm$^3$), the value for which is representative of most of the materials in Saturn’s ring system, and a spherical shape with radius of ∼1 meter, yielding a total particle mass of ∼3841 kg. Thus, we are considering only dense ring material and the gravitational perturbations acting upon them (see Section 4.1). The particle orbits were set to be circular with an inclination of ∼0° with respect to the Jupiter equator (coplanar with the Galilean moons). The test particles were placed at different locations from Jupiter, extending from inside the rigid satellite Roche limit (see Figure 1) to 1/10 of the Jupiter Hill radius. This region was sampled with 1000 evenly spaced locations, resulting in a location step size of ∼4963 km. The simulations were carried out with both 10$^6$ year and 10$^7$ year integration times for each of the separation cases, which translates to $4.6 \times 10^6$ and $4.6 \times 10^7$ orbits at the outer edge of our sample space, respectively. For each simulation, the time step was set to be 0.05 of Io’s orbital period (2.1 hours), except for cases where the test particle locations were inside Io’s orbit, where the time step was adjusted to 0.05 of the orbital period at each particle location. This ensured an adequate time resolution to properly sample the dynamical interactions between test particles and the Galilean moons. The orbital properties of the particles and Galilean moons were output every 100 years during the simulation and the survival rates of the test particle were calculated at each orbital separation. Test particle survival was based upon the elapsed time to be either ejected from the system or suffering a collision with one of the large system bodies during the entire simulation.

The primary results of our simulations that include particle injections are shown in the top two panels of Figure 3, and are represented as the percentage of the total simulation survived by particles for each separation location. The simulation durations of 10$^6$ years and 10$^7$ years are shown in the top and bottom panels, respectively, and the location of the Galilean moons are indicated by vertical dotted lines. The vertical dashed lines indicate the location of both the rigid and fluid body Roche limits. The top panel shows that, even for 10$^6$ years, the region surrounding the Laplace resonance of Io, Europa, and Ganymede is rendered unstable, exacerbated by the slight eccentricity variations of Io and Europa described in Section 3.1. The inner limits of dynamical stability are located at ∼3.55 Jupiter radii and ∼3.12 Jupiter radii for the 10$^6$ year and 10$^7$ year simulations, respectively. The current Jupiter ring system, depicted in Figure 1, extends to ∼3.16 Jupiter radii, indicating that the ring is young (< 10$^7$ years) and/or is being sustained with additional material to the Thebe extension (Borisov & Krüger 2021). The structure of the dynamical stability beyond the orbit of Callisto is a complicated result of Ganymede and Callisto resonance locations. For example, the dynamical instability located at ∼31.2 Jupiter radii, partially present at 10$^6$ years and significantly more pronounced at 10$^7$ years, is the 1:3 resonance location with Ganymede. Furthermore, there is an island of stability located at ∼41.8 Jupiter radii, which is not evident in the 10$^6$ year results but becomes apparent at 10$^7$ years, which is a result of a 1:2 resonance with Callisto. The effect of resonances is further emphasized in the bottom panel of Figure 3, which shows the change in eccentricity, δ$e$, that occurs during the course of the 10$^7$ year simulations. It is worth noting that, although the bottom panel of Figure 3 implies that particles close to the Roche limits are predominantly scattered into high eccentricity orbits, stable low-eccentricity orbits can exist within that region. For example, the inner Jovian moons of Metis, Adrastea, Amalthea, and Thebe have semimajor axes that lie within the range 1.8–3.2 Jupiter radii and are known to have eccentricities that are below 0.02 (Cooper et al. 2006; Borisov & Krüger 2020), although dynamical interactions with Io have inflated the eccentricity of Thebe (Burns et al. 2004). We conducted additional simulations for the specific cases of those four inner moons where, as for the Galilean moons, current orbital elements were extracted from the Horizons DE431 ephemerides. The results of these simulations show that their mean eccentricities remained small.
Figure 3. Results of particle injection and survival for the $10^6$ year (top panel) and $10^7$ year (middle panel) dynamical simulations. The horizontal axis is the separation from Jupiter in planetary radii, and the vertical axis shows the percentage of the total dynamical simulation that particles survived at that location, represented by the green line. The vertical dotted lines represent the semi-major axes of the Galilean moons, and the vertical dashed lines represent the locations of the rigid and fluid Roche limits. The bottom panel shows the change in eccentricity that occurs for each particle as a function of their initial semi-major axis during the course of the $10^7$ year simulations.
throughout the entire simulation, with mean eccentricities of 0.008, 0.008, 0.005, and 0.016 for Metis, Adrastea, Amalthea, and Thebe, respectively. As noted in Section 3.1, tidal dissipation was not included in our simulations, and so these dynamically induced eccentricities may be considered upper limits to their expected values.

The rate at which particles are lost from within the investigated semi-major axis region around Jupiter, shown as a function of time (fractions of 10^7 years) and the percentage of particles that survive to that time.

![Figure 4](image_url)  
**Figure 4.** The loss rate for all particles within the investigated semi-major axis region around Jupiter, shown as a function of time (fractions of 10^7 years) and the percentage of particles that survive to that time.

As the dominant planetary mass in the Solar System, Jupiter has undoubtedly had a complex and eventful dynamical history. Such a history includes significant impacts and other events that have resulted in raw material for substantial ring formation. The major question regarding these ring structures pertain to their long-term viability within the architecture of the system. The results of our simulations described in Section 3.2 demonstrate that ring structures within the separation range ∼3–29 Jupiter radii are mostly removed within 10^6 years. What remains are a system of ringlets between Ganymede and Callisto (∼20–24 Jupiter radii), and rings that coincide with the orbit of Callisto. Rings beyond 29 Jupiter radii are viable for 10^6 years, but such rings would likely consist of remaining material from planet and moon formation processes when the Solar System was relatively young. After 10^7 years, the dynamical influence of the Galilean moons further desiccates the material in the region of ∼3–29 Jupiter radii, including the ringlet structure between Ganymede and Callisto. As discussed in Section 3.2, orbital resonances with Ganymede and Callisto also compromise the region beyond 29 Jupiter radii, ensuring that the primordial material would not have remained beyond a few tens of millions of years.

The results presented in this work are based primarily on dynamical interactions within the Jupiter system. However, there are numerous other factors that have not been taken into account. Events that may increase the lifetime of ring structures, such as impacts and outgassing of moons that release solid particles, have not been considered. Jupiter is well known to suffer relatively frequent impacts (Zahnle et al. 2003; Horner & Jones 2008; Hueso et al. 2013, 2018), such as the Comet Shoemaker-Levy-9 event (Zahnle & Mac Low 1994; Asphaug & Benz 1996), with observations of recent impact events helping to place constraints on ejection material that achieves escape velocity (Ahrens et al. 1994; Sankar et al. 2020), and thus may contribute to ring material. It is worth noting that contributions from isotropic impactors (compared with ecliptic impactors) may result in a stochastic distribution of ring material, whereas our simulations specifically investigate rings coplanar with Jupiter’s equator. Furthermore, orbital precession and collisions will naturally cause any orbiting debris to collapse into the planet’s equatorial plane. Additional sources of ring material are the grinding down of small moons and outgassing from the Galilean moons (Burns et al. 1999; Esposito 2002).

On the other hand, there are numerous processes that serve to decrease the ring lifetime, such as Poynting-Robertson drag, the Yarkovsky effect, and the electromagnetic influence of the Jovian magnetosphere (Burns et al. 1999; Rubincam 2006; Kobayashi et al. 2009). Such non-gravitational forces primarily govern particles that are significantly smaller (µm–mm) than those used in our simulations (Burns et al. 1979), and...
so are unlikely to substantially impact the results presented here. For dense rings, such as those that are considered in our simulations, a major source of ring material loss beyond the Roche limit is the accretion into small moons \cite{Crida2012}. Such accretion can happen on relatively small timescales, such that the loss of ring material in this manner may occur well within the periods of time considered by our simulations. In fact, our results provided in Section 3.2 demonstrate that the excitation of particles into eccentric orbits may further promote collision scenarios. However, moonlets that form in the investigated region of semi-major axes will likely remain subject to the instability caused by the Galilean moons, resulting in possible ejection from the system. Migration of moons have also played a role in shaping the dynamical environment around Jupiter. Resonances between moons can promote inward and outward migration and is thought to have occurred for both the Jupiter and Saturn moon systems \cite{Fuller2016}. The mechanics of resonance trapping for moons is the same process that takes place for planetary migration \cite{Wyatt2003} and can greatly affect their composition, such as the case of the TRAPPIST-1 planets \cite{Unterborn2018}. Indeed, interaction with the rings themselves can result in the migration of small moons \cite{Bromley2013}, which may in turn result in their contribution to the rings near the Roche limit. Furthermore, given the relatively small mass of the test particles used in our simulations, the calculated life expectancy of those particles may be considered an upper limit in many cases.

With the various above described competing factors in ring contributions, the sustainability of planetary rings may be sensitive to the architecture of the local environment. Based on our simulations, it is possible that the Galilean moons may be a significant reason that, integrated over time, Jupiter is unable to harbor substantial rings. However, there may also have been periods of Jupiter history during which impact and small moon collision rates exceeded dynamical disruption by the Galilean moons, allowing sustained rings significantly more massive than those observed at the present epoch. Although the sustainability of an extended ring system beyond the Roche limit may be dominated by the combination of dynamical effects and moon coalescence, the lifetime of rings within the Roche limit is substantially more complicated. For example, in the case of Saturn, an examination of the Pallene dusty ring found that non-gravitational forces dominate over the dynamical effects with regards to the sustainability of the ring, although the moon mass within the Saturnian system is significantly less than that of the Galilean moons

![Figure 5. Planet masses (Jupiter masses) and Hill radii (planetary radii) for the known exoplanets with measured masses and radii. The locations of Earth, Jupiter, and Saturn are marked by E, J, and S, respectively. The gray region indicates where formation of massive moons may be limited by disk migration, whilst a larger Hill radius maximizes primordial and new material to contribute to ring formation.](image-url)
suggested by Canup & Ward (2006) that disk migration may limit the maximum size of moons, beyond which the moons may migrate through the circumplanetary disk and into the planet. The implication is that Saturn may possibly represent a “sweet spot” of ring formation in terms of mass, Hill radius, and moon-forming capacity, although this is quite difficult to gauge fully without more complete knowledge of the Jupiter and Saturn architecture evolutions. Moreover, careful consideration must be given to the various processes acting upon ring formation and dessication, described in Section 4.1. In particular, there are numerous non-gravitational forces acting upon ring material within or close to the Roche limit that can have a dominating effect on ring evolution (see Section 4.1). It is also worth noting that these implied correlations between planet mass and ring/moon prevalence are based upon the limited inventory of giant planets present in the Solar System, for which exoplanet studies will provide a much needed statistical validation.

However, if indeed the presence of relatively massive moon systems is correlated with planet mass and Hill radius, then the prevalence of ring systems may be likewise rare amongst many of the discovered giant exoplanets. Shown in Figure 5 are planetary masses (Jupiter masses) and calculated Hill radii (planetary radii) for known exoplanets with relevant data available. The data were extracted from the NASA Exoplanet Archive (Akeson et al. 2013) and are current as of 2021 December 18 (NASA Exoplanet Archive 2021). For comparison, the locations of Earth, Jupiter, and Saturn are also marked on the diagram. The gray box provides a rough guide for what may be considered an optimization region where the harboring of substantial planetary rings could be favorable. The planet mass range of the gray box is 10 Earth masses to 1 Jupiter mass to approximately capture planets within the ice/gas giant regime (Weiss et al. 2013; Lammer et al. 2014; Lopez & Fortney 2014; Rogers 2015; Chen & Kipping 2017) whilst limiting the potential for substantial moon formation. The Hill radius range is for all Hill radii beyond 50 planetary radii since small Hill radii truncates both the extent of the circumplanetary disk (Shabram & Boley 2013) and the dynamical viability of moons (Barnes & O’Brien 2002; Hinkel & Kane 2013; Kane 2017). Saturn is deeply embedded within the gray region, whilst Uranus and Neptune (also fulfilling the planet mass criteria) are located at Hill radii of 2631 and 4644 planetary radii, respectively. As described above, planets more massive than Jupiter, with larger mass proto-satellite disks and a larger Hill radius in which to engage in moon formation, may experience significantly reduced timescale of ring sustainability. Such a timescale reduction would result from the rapid formation of large moons, whose gravitational presence would, in turn, either eject the remaining ring material or excite their eccentricities resulting in further enhancement of moon formation (see Section 3.2). The size of the box shown in Figure 5 is empirical in nature and requires further investigation of the various competing factors toward ring formation and sustainability, but may serve as a useful guide for testing models regarding how the presence of substantial moons could potentially influence the long-term presence of rings around giant planets.

5. CONCLUSIONS

Planetary rings and moons are very important features of our Solar System, both in their intrinsic geo-logic and dynamical properties, and as crucial signposts of planetary formation and evolution. Understanding the complex interactions between moons and rings, and how these vary with planetary mass, composition, Hill radius, and time, remains one of the most intricate research topics in planetary science. The dynamical evolution of giant planet systems is one of the primary ways in which tracing of rings systems and their ages may be undertaken.

The results of our dynamical simulations demonstrate that the presence of massive moons, especially systems that have migrated into resonance traps as for the Galilean moons, can create significant dynamical constraints on ring systems comprised of dense material. This indicates that, although Jupiter may have had intermittent periods of substantial rings systems, their long-term sustainability may be severely truncated by the presence of the Galilean moons and associated resonances. Ring material beyond the Roche limit that remain in stable orbits may also experience eccentricity excitation that enhances moonlet coalescence. Furthermore, we have shown that the outer edge of the present ring system must be relatively young (< 10^7 years) in order to have survived dynamical scattering processes. The balance between planet mass, the formation of massive moons, and the sustainability of significant ring mass, means that Saturn may be near the optimal region for the formation and long-term survival of substantial rings. A useful extension to this work could thus include longer timescale simulations combined with migration effects that fully explore the interaction between moons and rings during periods of formation, as well as moon formation from ring material and the inclusion of non-gravitational forces near the Roche limit.

Although the inventory of Solar System giant planets and their associated rings and moons is limited, they yet provide the best clues to the formation and evo-
ution of such systems (Horner et al. 2020; Kane et al. 2021), as well as a guide toward detecting their exoplanet analogs (Dalba et al. 2015; Mayorga et al. 2016, 2020; Wakeford & Dalba 2020). The detailed data available for local giant planet systems must necessarily be balanced by the statistical knowledge that will be gained through the discovery of exomoons and exorings. Such discoveries will provide the means to fully explore the above described potential correlation of moons and ring properties with those of their host planet.

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Software: REBOUND (Rein & Liu 2012)

REFERENCES

Ahrens, T. J., Takata, T., O’Keefe, J. D., & Orton, G. S. 1994, Geophys. Res. Lett., 21, 1087, doi: 10.1029/94GL01325

Akeson, R. L., Chen, X., Ciardi, D., et al. 2013, PASP, 125, 989, doi: 10.1086/672273

Arnold, L., & Schneider, J. 2004, A&A, 420, 1153, doi: 10.1051/0004-6361:20035720

Asphaug, E., & Benz, W. 1996, Icarus, 121, 225, doi: 10.1006/icar.1996.0083

Barnes, J. W., & O’Brien, D. P. 2002, ApJ, 575, 1087, doi: 10.1086/341477

Batygin, K., & Morbidelli, A. 2020, ApJ, 894, 143, doi: 10.3847/1538-4357/ab8937

Bridges, F. G., Hatzes, A., & Lin, D. N. C. 1984, Nature, 309, 333, doi: 10.1038/309333a0

Bromley, B. C., & Kenyon, S. J. 2013, ApJ, 764, 192, doi: 10.1088/0004-637X/764/2/192

Burns, J. A., Lamy, P. L., & Soter, S. 1979, Icarus, 40, 1, doi: 10.1016/0019-1035(79)90050-2

Burns, J. A., Showalter, M. R., Hamilton, D. P., et al. 1999, Science, 284, 1146, doi: 10.1126/science.284.5417.1146

Burns, J. A., Simonelli, D. P., Showalter, M. R., et al. 2004, in Jupiter. The Planet, Satellites and Magnetosphere, ed. F. Bagenal, T. E. Dowling, & W. B. McKinnon, Vol. 1 (Cambridge University Press), 241–262

Canup, R. M. 2010, Nature, 468, 943, doi: 10.1038/nature09661

Canup, R. M., & Ward, W. R. 2006, Nature, 441, 834, doi: 10.1038/nature04860

Charnoz, S., Morbidelli, A., Dones, L., & Salmon, J. 2009, Icarus, 199, 413, doi: 10.1016/j.icarus.2008.10.019

Charnoz, S., Salmon, J., & Crida, A. 2010, Nature, 465, 752, doi: 10.1038/nature09096

Charnoz, S., Crida, A., Castillo-Rogez, J. C., et al. 2011, Icarus, 216, 535, doi: 10.1016/j.icarus.2011.09.017

Chen, J., & Kipping, D. 2017, ApJ, 834, 17, doi: 10.3847/1538-4357/834/1/17

Cooper, N. J., Murray, C. D., Porco, C. C., & Spitele, J. N. 2006, Icarus, 181, 223, doi: 10.1016/j.icarus.2005.11.007

Crida, A., & Charnoz, S. 2012, Science, 338, 1196, doi: 10.1126/science.1226477

Crida, A., Criddle, S., Hsu, H.-W., & Dones, L. 2019, Nature Astronomy, 3, 967, doi: 10.1038/s41550-019-0876-y

Cuzzi, J. N., Whizin, A. D., Hogan, R. C., et al. 2014, Icarus, 232, 157, doi: 10.1016/j.icarus.2013.12.027

Cuzzi, J. N., Burns, J. A., Charnoz, S., et al. 2010, Science, 327, 1470, doi: 10.1126/science.1179118

Daisaka, H., Tanaka, H., & Ida, S. 2001, Icarus, 154, 296, doi: 10.1006/icar.2001.6716

Dalba, P. A., Muirhead, P. S., Fortney, J. J., et al. 2015, ApJ, 814, 154, doi: 10.1088/0004-637X/814/2/154

Dobos, V., Barr, A. C., & Kiss, L. L. 2019, A&A, 624, A2, doi: 10.1051/0004-6361/201834254

Dubinski, J. 2019, Icarus, 321, 291, doi: 10.1016/j.icarus.2018.11.034

Elliot, J. L., Dunham, E., & Mink, D. 1977, Nature, 267, 328, doi: 10.1038/267328a0

Esposito, L. W. 2002, Reports on Progress in Physics, 65, 1741, doi: 10.1088/0034-4885/65/12/201

Folkner, W. M., Williams, J. G., Boggs, D. H., Park, R. S., & Kuchynka, P. 2014, Interplanetary Network Progress Report, 42-196, 1

Fujii, Y. I., Kobayashi, H., Takahashi, S. Z., & Gressel, O. 2017, AJ, 153, 194, doi: 10.3847/1538-3881/aa647d
The Dynamical Viability of an Extended Jupiter Ring System

Fuller, J., Luan, J., & Quataert, E. 2016, MNRAS, 458, 3867, doi: 10.1093/mnras/stw609

Goldreich, P., & Tremaine, S. D. 1978a, Icarus, 34, 240, doi: 10.1016/0019-1035(78)90165-3
—. 1978b, Icarus, 34, 227, doi: 10.1016/0019-1035(78)90164-1

Greenberg, R. 1983, Icarus, 53, 207, doi: 10.1016/0019-1035(83)90142-2
—. 1987, Icarus, 70, 334, doi: 10.1016/0019-1035(87)90139-4

Hedman, M. M., & Nicholson, P. D. 2013, AJ, 146, 12, doi: 10.1088/0004-6256/146/1/12

Heller, R., Marleau, G. D., & Pudritz, R. E. 2015, A&A, 579, L4, doi: 10.1051/0004-6361/201526348

Heller, R., Williams, D., Kipping, D., et al. 2014, Astrobiology, 14, 798, doi: 10.1089/ast.2014.1147

Hill, M. L., Kane, S. R., Seperuelo Duarte, E., et al. 2018, ApJ, 860, 67, doi: 10.3847/1538-4357/aac384

Hinkel, N. R., & Kane, S. R. 2013, ApJ, 774, 27, doi: 10.1088/0004-637X/774/1/27

Horányi, M., Burns, J. A., Hedman, M. M., Jones, G. H., & Kempf, S. 2009, in Saturn from Cassini-Huygens, ed. M. K. Dougherty, L. W. Esposito, & S. M. Krimigis (Springer Science+Business Media), 511, doi: 10.1007/978-1-4020-9217-6

Horányi, M., & Cravens, T. E. 1996, Nature, 381, 293, doi: 10.1038/381293a0

Horner, J., & Jones, B. W. 2008, International Journal of Astrobiology, 7, 251, doi: 10.1017/S1473550408004187

Horner, J., Kane, S. R., Marshall, J. P., et al. 2020, PASP, 132, 102001, doi: 10.1088/1538-3873/132/4/102001

Hueso, R., Pérez-Hoyos, S., Sánchez-Lavega, A., et al. 2013, A&A, 560, A55, doi: 10.1051/0004-6361/201322216

Hueso, R., Delcroix, M., Sánchez-Lavega, A., et al. 2018, A&A, 617, A68, doi: 10.1051/0004-6361/201832689

Hyodo, R., & Charnoz, S. 2017, AJ, 154, 34, doi: 10.3847/1538-3881/aa74c9

Hyodo, R., Charnoz, S., Ohtsuki, K., & Genda, H. 2017, Icarus, 282, 195, doi: 10.1016/j.icarus.2016.09.012

Iess, L., Militzer, B., Kaspi, Y., et al. 2019, Science, 364, aat2965, doi: 10.1126/science.aat2965

Kane, S. R. 2017, ApJL, 839, L19, doi: 10.3847/2041-8213/aa6bf2

Kane, S. R., Hinkel, N. R., & Raymond, S. N. 2013, AJ, 146, 122, doi: 10.1088/0004-6256/146/5/122

Kenworthy, M. A., & Mamajek, E. E. 2015, ApJ, 800, 126, doi: 10.1088/0004-637X/800/2/126

Kipping, D. M., Forgan, D., Hartman, J., et al. 2013, ApJ, 777, 134, doi: 10.1088/0004-637X/777/2/134

Kobayashi, H., Watanabe, S.-i., Kimura, H., & Yamamoto, T. 2009, Icarus, 201, 395, doi: 10.1016/j.icarus.2009.01.002

Krivov, A. V., Krüger, H., Griin, E., Thiessenhusen, K.-U., & Hamilton, D. P. 2002, Journal of Geophysical Research (Planets), 107, 5002, doi: 10.1029/2000JE001434

Laine, V., Duriez, L., & Vienne, A. 2004, A&A, 420, 1171, doi: 10.1051/0004-6361:20034565

Laine, V., Casajus, L. G., Fuller, J., et al. 2020, Nature Astronomy, 4, 1053, doi: 10.1038/s41550-020-1120-5

Lammer, H., Stökl, A., Erkaev, N. V., et al. 2014, MNRAS, 439, 3225, doi: 10.1093/mnras/stu085

Lane, A. L., West, R. A., Hord, C. W., et al. 1989, Science, 246, 1450, doi: 10.1126/science.246.4936.1450

Lari, G. 2018, Celestial Mechanics and Dynamical Astronomy, 130, 50, doi: 10.1007/s10569-018-9846-4

Lieske, J. H. 1980, A&A, 82, 340

Lopez, E. D., & Fortney, J. J. 2014, ApJ, 792, 1, doi: 10.1088/0004-637X/792/1/1

Makarov, V. V., Berghea, C. T., & Efroimsky, M. 2018, ApJ, 857, 142, doi: 10.3847/1538-4357/aab845

Malhotra, R. 1991, Icarus, 94, 399, doi: 10.1016/0019-1035(91)90237-N

Mankovich, C., Marley, M. S., Fortney, J. J., & Movshovitz, N. 2019, ApJ, 871, 1, doi: 10.3847/1538-4357/aaf798

Mankovich, C. R., & Fuller, J. 2021, Nature Astronomy, 5, 1103, doi: 10.1038/s41550-021-01448-3

Mayorga, L. C., Charbonneau, D., & Thorngren, D. P. 2020, AJ, 160, 233, doi: 10.3847/1538-3881/abb8df

Mayorga, L. C., Jackiewicz, J., Rages, K., et al. 2016, AJ, 152, 209, doi: 10.3847/0004-6256/152/6/209

Muñoz-Gutiérrez, M. A., Granados Contreras, A. P., Madeira, G., A’Hearn, J. A., & Giuliatti Winter, S. 2022, MNRAS, 511, 4202, doi: 10.1093/mnras/stab3627

Nakajima, A., Ida, S., & Ishigaki, Y. 2020, A&A, 640, L15, doi: 10.1051/0004-6361/202038743

NASA Exoplanet Archive. 2021, Planetary Systems, Version: 2021-12-18, NExScI-Caltech/IPAC, doi: 10.26133/NEA12

Noyelles, B., Baillié, K., Charnoz, S., Lainey, V., & Tobie, G. 2019, MNRAS, 486, 2947, doi: 10.1093/mnras/stz445

Ockert-Bell, M. E., Burns, J. A., Daubar, I. J., et al. 1999, Icarus, 138, 188, doi: 10.1016/S0019-1035(98)87040-X

Ogilvie, M., & Ida, S. 2012, ApJ, 753, 60, doi: 10.1088/0004-637X/753/1/60
Peale, S. J., & Lee, M. H. 2002, Science, 298, 593, doi: 10.1126/science.1076557
Petit, J. M., & Henon, M. 1988, A&A, 199, 343
Piro, A. L. 2018, AJ, 156, 80, doi: 10.3847/1538-3881/aa039e
Piro, A. L., & Vissapragada, S. 2020, AJ, 159, 131, doi: 10.3847/1538-3881/ab7192
Pollack, J. B. 1975, SSRv, 18, 3, doi: 10.1007/BF00350197
Porco, C., Nicholson, P. D., Borderies, N., et al. 1984, Icarus, 60, 1, doi: 10.1016/0019-1035(84)90134-9
Porco, C. C., West, R. A., McEwen, A., et al. 2003, Science, 299, 1541, doi: 10.1126/science.1079462
Porco, C. C., Baker, E., Barbara, J., et al. 2005, Science, 307, 1226, doi: 10.1126/science.1108056
Prentice, A. J. R., & ter Haar, D. 1979, Nature, 280, 300, doi: 10.1038/280300a0
Rein, H., & Liu, S. F. 2012, A&A, 537, A128, doi: 10.1051/0004-6361/201118085
Rein, H., & Tamayo, D. 2015, MNRAS, 452, 376, doi: 10.1093/mnras/stv1257
Rogers, L. A. 2015, ApJ, 801, 41, doi: 10.1088/0004-637X/801/1/41
Ronnet, T., Mousis, O., Vernazza, P., Lunine, J. I., & Crida, A. 2018, AJ, 155, 224, doi: 10.3847/1538-3881/aabcc7
Rubincam, D. P. 2006, Icarus, 184, 532, doi: 10.1016/j.icarus.2006.05.017
Salmon, J., & Canup, R. M. 2017, ApJ, 836, 109, doi: 10.3847/1538-4357/836/1/109
Salo, H. 1995, Icarus, 117, 287, doi: 10.1006/icar.1995.1157
Sankar, R., Palotai, C., Hueso, R., et al. 2020, MNRAS, 493, 4622, doi: 10.1093/mnras/staa563
Sasaki, T., Stewart, G. R., & Ida, S. 2010, ApJ, 714, 1052, doi: 10.1088/0004-637X/714/2/1052
Shabram, M., & Boley, A. C. 2013, ApJ, 767, 63, doi: 10.1088/0004-637X/767/1/63
Showalter, M. R. 2020, Philosophical Transactions of the Royal Society of London Series A, 378, 20190482, doi: 10.1098/rstaa.2019.0482
Showalter, M. R., Burns, J. A., Cuzzi, J. N., & Pollack, J. B. 1987, Icarus, 69, 458, doi: 10.1016/0019-1035(87)90018-2
Smith, B. A., Soderblom, L. A., Johnson, T. V., et al. 1979, Science, 204, 951, doi: 10.1126/science.204.4396.951
Sucerquia, M., Alvarado-Montes, J. A., Zuluaga, J. I., Montesinos, M., & Bayo, A. 2020, MNRAS, 496, L85, doi: 10.1093/mnrasl/slaa080
Sucerquia, M., Alvarado-Montes, J. A., Bayo, A., et al. 2021, MNRAS, doi: 10.1093/mnras/stab3531
Tamayo, D., Rein, H., Shi, P., & Hernandez, D. M. 2020, MNRAS, 491, 2885, doi: 10.1093/mnras/stz2870
Tyler, G. L., Sweetnam, D. N., Anderson, J. D., et al. 1986, Science, 233, 79, doi: 10.1126/science.233.4759.79
Unterborn, C. T., Desch, S. J., Hinkel, N. R., & Lorenzo, A. 2018, Nature Astronomy, 2, 297, doi: 10.1038/s41550-018-0411-6
Wakeford, H. R., & Dalba, P. A. 2020, Philosophical Transactions of the Royal Society of London Series A, 378, 20200054, doi: 10.1098/rsta.2020.0054
Weiss, L. M., Marcy, G. W., Rowe, J. F., et al. 2013, ApJ, 768, 14, doi: 10.1088/0004-637X/768/1/14
Wyatt, M. C. 2003, ApJ, 598, 1321, doi: 10.1086/379064
Zahnle, K., & Mac Low, M.-M. 1994, Icarus, 108, 1, doi: 10.1006/icar.1994.1038
Zahnle, K., Schenk, P., Levison, H., & Dones, L. 2003, Icarus, 163, 263, doi: 10.1016/S0019-1035(03)00484-4
Zhang, Z., Hayes, A. G., Janssen, M. A., et al. 2017, Icarus, 294, 14, doi: 10.1016/j.icarus.2017.04.008
Zuluaga, J. I., Kipping, D. M., Sucerquia, M., & Alvarado, J. A. 2015, ApJL, 803, L14, doi: 10.1088/2041-8205/803/1/L14