FORMATION AND EVOLUTION OF PLUTO’S SMALL SATELLITES

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Received 2014 July 2; accepted 2015 May 2; published 2015 June 18

ABSTRACT

Pluto’s system of five known satellites is in a puzzling orbital configuration. Each of the four small satellites are on low-eccentricity and low-inclination orbits situated near a mean motion resonance with the largest satellite Charon. The Pluto–Charon binary likely formed as a result of a giant impact, and so the simplest explanation for the small satellites is that they accreted from the debris of that collision. The Pluto–Charon binary has evolved outward since its formation due to tidal forces, which drove them into their current doubly synchronous state. Meanwhile, leftover debris from the formation of Charon was not initially distant enough from Pluto–Charon to explain the orbits of the current small satellites. The outstanding problems of the system are the movement of debris outward and the small satellites’ location near mean motion resonances with Charon. This work explores the dynamical behavior of the collisionally interacting debris orbiting the Pluto–Charon system. While this work specifically tests initial disk and ring configurations designed to mimic the aftermath of the disruption of satellites by heliocentric impactors, we generally find that collisional interactions can help move material outward and keep otherwise unstable material dynamically bound to the Pluto–Charon system. These processes can produce rings of debris whose orbits evolve rapidly due to collisional processes, with increasing pericenters and decreasing semimajor axes. While these rings and disks of debris eventually build satellites that are significantly farther out than the initial locations of a disrupted satellite, they do not show a strong preference for building satellites in or near mean motion resonances with Charon under a wide array of tested conditions.

Key words: Kuiper belt: general – minor planets, asteroids: general – planets and satellites: dynamical evolution and stability

1. INTRODUCTION

Charon is the most massive satellite in the Solar System relative to it is primary’s mass, with $M_{\text{Charon}} = 0.1126 M_{\text{Pluto}}$ (Beauvalet et al. 2013). It is a doubly synchronous system, with rotational and orbital periods of 6.38 days, orbiting on a near-zero eccentricity orbit with semimajor axis $a_{\text{Charon}} = 19,596$ km, which is $\sim 17 R_{\text{Pluto}}$ (Stern et al. 2003; Buie et al. 2012a, 2012b; Brozović et al. 2015). Pluto has at least four smaller satellites, each orbiting with a period that is near an integer ratio of Charon’s period and at distances between 30 and 60 $R_{\text{Pluto}}$ (Buie et al. 2006; Weaver et al. 2006; Stern et al. 2007; Showalter et al. 2011; Showalter et al. 2012; Buie et al. 2013; Brozović et al. 2015). Their orbits are estimated to be nearly circular ($e < 0.01$) and co-planar ($i < 1^\circ$; Brozović et al. 2015).

While there are doubly synchronous binary asteroid systems with even higher mass ratios (where satellite mass divided by primary mass is closer to 1; Main Belt Asteroid (90) Antiope and Trojan Asteroid (617) Patroclus are both nearly similarly sized; Richardson & Walsh 2006), the seemingly delicate dynamics of the system of small satellites are not found to be duplicated among asteroid satellite systems. Meanwhile the extreme size of Charon relative to Pluto makes it unique in the Solar System relative to planetary satellites, but the system has some similarity, at least in complexity, to Saturn’s system. Some works, including this one, envision the small satellites forming from a disk or ring of debris. This disk would differ from Saturn’s rings, or the recently discovered rings around the Centaur (10199) Chariklo (Braga-Ribas et al. 2014), because it would be entirely outside the Roche Limit of Pluto, where Styx, the innermost small satellite, is more than 10 times farther from Pluto than its nominal Roche Limit. Therefore particles could accrete into large satellites once relative velocities became low on timescales that are fast compared to viscous stirring timescales.

1.1. Physical and Orbital Properties

Brozović et al. (2015) reported the best fits for the orbital properties of Nix, Kerberos, and Hydra, based on multiple Hubble Space Telescope observing campaigns (Table 1; see also Buie et al. 2013). Of particular importance to this study are the period ratios between each satellite and Charon: 3.1565, 3.8913, 5.0363, 5.9810 for Kerberos, Nix, Kerberos, and Hydra, respectively (Brozović et al. 2015). From these data it appears that none of the satellites are currently in resonance with Charon or one another, and they are not systematically on the inside or outside of resonance, nor do their distances from resonance correlate with size.

The physical properties of the small satellites are difficult to estimate because imaging is limited to optical wavelengths, and photometric measurements can determine size only with an estimate for each bodies’ albedo, and mass only with an estimate for density and size. Orbital stability has been used to place limits on masses of both hypothetical satellites (pre-discovery) and also for subsets of the current system. Stern et al. (1994) studied the stability of hypothetical satellites in the Pluto–Charon system, primarily placing an upper limit on satellite mass, $3 \times 10^{-4}(M_{\text{Pluto}} + M_{\text{Charon}})$, that would create observable perturbations in Charon’s orbit. Following the discovery of Nix and Hydra, Pires dos Santos et al. (2011) tested for stable regions where more satellites could reside, assuming masses of $5.8 \times 10^{17}$ kg and $3.2 \times 10^{17}$ kg for Nix and Hydra, respectively (using masses from Tholen...
et al. 2008). With these masses the stable region between those satellites is quite narrow and centered around the 5:1 MMR— the location where Kerberos was eventually found.

Youdin et al. (2012) presented a series of numerical experiments attempting to constrain the mass of the larger satellites (Nix and Hydra) by considering the long-term survival of Kerberos orbiting between them. This work suggested that period ratios for Kerberos relative to Charon were more stable below 4.98 and above 5.01, which agrees with the recent period ratios estimate (5.0363) from Brozović et al. (2015). Upper limits for mass found in that work, $M_{\text{Nix}} \lesssim 5 \times 10^{16}$ kg and $M_{\text{Hyd}} \lesssim 9 \times 10^{16}$ kg, required that the satellites have an albedo above 0.30 for the assumption of an internal density of 1 g cm$^{-3}$.

The orbital fits by Brozović et al. (2015) also constrained the masses of individual satellites. The larger satellites were found to have masses $M_{\text{Nix}} = 4.5 \times 10^{16}$ kg and $M_{\text{Hyd}} = 4.7 \times 10^{16}$ kg, which are both similar and within a factor of two, respectively, from that found in Youdin et al. (2012). The estimated mass for Kerberos is $M_{\text{Kerberos}} = 1.6 \times 10^{16}$ kg. Using a range of possible visible albedo (35%–4%), this work estimated radii ranges for all four satellites: 4–14, 23–70, 7–22, and 29–86 km for Styx, Nix, Kerberos, and Hydra, respectively.

### 1.2. Formation of Charon and Debris

Charon is thought to have formed in a giant impact (McKinnon 1989; Canup 2005, 2011). Smoothed particle hydrodynamics (SPH) simulations show that it likely remained intact following the collision, making it a prototype for an “intact capture” type of a high impact-parameter collision event (Canup 2005). Formation from a disk following the impact appears to still be dynamically possible (Canup 2005), but the intact capture is preferred due to the fact that Charon has a similar density to Pluto. More violent events that result in the accretion of Charon from a circum-Pluto disk (similar to the Earth–Moon scenarios) lead to the loss of rocky material to Pluto and create larger density disparity between Pluto and Charon (see Desch 2015 for a model to preserve density similarities during the formation of Charon from a disk).

The high angular momentum of the system, and its doubly synchronous state, point to past tidal evolution from a closer orbit of Charon around a more rapidly rotating Pluto (Farinella et al. 1979; Dobrovolskis 1989; McKinnon 1989; Cheng 2011). The SPH models of the Charon-forming event that satisfy these angular momentum constraints typically find that its orbit would initially have been eccentric (Canup 2005, 2011). The possible post-collision orbits for Charon are discussed in detail in Canup (2005, 2011), where the initial orbits range between semimajor axes of 4–10 $R_{\text{Pluto}}$, with eccentricities between 0.1 and 0.8 (see Figure 5, Canup 2011). There are also simulations that produce $e \sim 0.9$ with $a/R_{\text{Pluto}} \sim 25$.

Peale et al. (2011), Cheng (2011), and Cheng et al. (2014a), show that the tidal evolution of Charon required a few million years to reach its current semimajor axis with variations in the orbit evolution dominated by the choice of tidal models. These recent works consider an initially eccentric orbit for Charon as predicted in the “intact capture” formation models and find similar evolution timescales as in previous estimates for Charon evolving on a circular orbit (Farinella et al. 1979; Dobrovolskis 1989; Peale 1999). Solutions where the eccentricity of Charon remained moderate were desirable outcomes to test the viability of the resonant transport of the satellites in the corotation resonance with Charon (Ward & Canup 2006; Lithwick & Wu 2008; Cheng 2011; Cheng et al. 2014a, 2014b). Cheng et al. (2014a) find that for Charon to remain moderately eccentric during its tidal evolution, the ratio of dissipation between Pluto and Charon has different values depending on the tidal model used. However, for a range of these parameters, both tidal models tested by Cheng et al. (2014a) find evolutions where Charon has $e \sim 0.1–0.5$ for the entire outward evolution, only damping to 0 when Charon has reached its current semimajor axis.

There are alternative orbital evolutions due to different initial conditions or tidal parameters. For example, Canup (2011) finds some collision simulation outcomes where Charon has a semimajor axis close to where it is found today, but with a much larger eccentricity (see Figure 5 of Canup 2011). Similarly, if the tidal dissipation parameters were substantially different than those used in the calculations, the timescale for the evolution could change. While these extremes are not essential for the work presented here and therefore not discussed in depth, it is possible that other mechanisms for explaining the small satellites may require them.

Canup (2011) characterized the debris created in the “intact capture” models in terms of the mass and maximum equivalent circular orbit of disk material ($a_{\text{eq,max}}$), where $a_{\text{eq}}$ is the circular orbit containing the same amount of angular momentum, and $a_{\text{eq,max}}$ is the maximum value for all debris in the simulation (see Figure 6). The total mass of debris was typically between $10^{17}$ and $10^{18}$ kg on orbits between $a_{\text{eq}} = 2$ and 30 $R_{\text{Pluto}}$, with no clear correlation between the two. Typical orbits of post-impact Charon are eccentric with $a \sim 4–10 R_{\text{Pluto}}$. Holman & Wiegert (1999) studied the stability around binary systems and found that in a best-case scenario of zero eccentricity for both Charon and the debris, the closest stable orbit is at $a = 1.974 a_{\text{charon}}$. For a nominal formation outcome of $a_{\text{charon}} \sim 4–10 R_{\text{Pluto}}$, debris closer than $a_{\text{charon}} \sim 8–20 R_{\text{Pluto}}$ would be immediately unstable. If Charon had an initially eccentric orbit,

| Satellite | $a$ (km) | $a$ ($R_{\text{Pluto}}$) | $e$ | $i$ (degree) | $P$ (days) | $P_{\text{sat}}/P_{\text{Charon}}$ | $R$ (km) |
|-----------|---------|----------------|-----|-----------|-----------|----------------|---------|
| Charon    | 19,596  | 16.59         | 0.00005 | 0.0      | 6.3872    | 1              | 603.6 ± 1.4 |
| Styx      | 42,413  | 35.91         | 0.00001 | 0.0      | 20.1617   | 3.165         | 4–14    |
| Nix       | 48,690  | 41.22         | 0.00000 | 0.0      | 25.8548   | 3.8913        | 23–70   |
| Kerberos  | 57,750  | 48.89         | 0.00000 | 0.4      | 32.1679   | 5.0363        | 7–22    |
| Hydra     | 64,721  | 54.80         | 0.00554 | 0.3      | 38.2021   | 5.9810        | 29–86   |

Note: Charon’s diameter is from occultation measurements (Sicardy et al. 2006). Pluto’s radius, 1181 km, for all $R_{\text{Pluto}}$ estimates from Lellouch et al. (2009). Charon’s orbital elements are plutocentric, while the small satellites’ orbital elements are relative to the Pluto–Charon barycenter.
then the nearest stable orbit is further away with less debris being stable.

The current orbits of the small satellites (∼30–60 \( R_{\text{Pluto}} \)), are much further from Pluto than any of the debris in the simulations of Canup (2011), and thus it is unlikely that today’s satellites formed directly on today’s orbits during the formation of Charon. Any satellites formed during the formation of Charon would later witness its outward tidal evolution. As Charon moved outward, the locations of its mean motion resonances would also move and would sweep over the orbits of any existing satellites. Mean motion resonances with Charon would perturb or capture satellites resulting in rapid and destabilizing eccentricity excitation (Ward & Canup 2006). Because tidal forces are far too weak to damp the current satellites’ eccentricities (Stern et al. 2006), their near-zero eccentricity orbits also suggest that they did not witness the tidal evolution of Charon in their present configuration.

A corotation resonance capture has been proposed as a means to transport satellites without exciting their eccentricities (Ward & Canup 2006). This resonance capture requires a moderate eccentricity for Charon during its outward migration. However, the restriction on the corotation resonance is that transport in resonance requires a narrow range of eccentricity for Charon for each different resonance, and for multiple satellites these requirements are probably mutually exclusive (Lithwick & Wu 2008; Cheng 2011; Cheng et al. 2014b). With a moderate or large eccentricity for Charon it is also possible to capture a satellite in multiple resonances at once and keep a relatively low eccentricity for the satellite. However, this was found to be an extremely low probability event and also ineffective for the inner resonances where Styx and Nix are found (Cheng 2011; Cheng et al. 2014b).

Kenyon & Bromley (2014) estimate that primordial debris from the Pluto–Charon forming collision would, by way of a collisional cascade, reach stable orbits just outside the region of orbital instability caused by Charon’s orbit. This ring would then spread on timescales of 5–10 years due to the tidal input of angular momentum into an optically thick disk. These short timescales, if less than accretion timescales, could permit the spreading of the ring into a disk before the accretion begins. An essential aspect of the analytical estimate of the spreading time is that angular momentum transfer among ring particles slows their precession, which helps maintain low-velocity collisions. This avoids collisional fragmentation on timescales that is short compared to that for spreading. However, Kenyon & Bromley (2014) do not account for the fact that low-velocity collisions will simply result in accretion and growth. Rather, accretion will likely happen before spreading and a disk will not form, which is something that is found in the simulations presented in Section 4. The timescales for this disk spreading and satellite growth proposed by Kenyon & Bromley (2014) are faster than the tidal evolution of Charon. Any satellite system formed in this manner, immediately following the formation of Charon, would then be subjected to the sweeping resonances caused by Charon’s outward tidal evolution, which would induce significant eccentricities into the small satellites.

Material can also be captured from heliocentric orbit. Two passing objects colliding within the Hill Sphere of the Pluto–Charon system can result in the capture of some of the collisional debris (Pires dos Santos et al. 2012). The total amount of captured material depends on the orbital and size distributions of the passing material. Pires dos Santos et al. (2012) explored this mechanism, finding that large objects that would carry significant mass have collision timescales that are too long, resulting in a very small total amount of captured mass.

How the present satellites or their building blocks got to where they are today is still an open question. The capture of material from outside the Pluto–Charon system is inefficient, and moving the present day satellites in various arrangements of orbital resonances has not been demonstrated. Moving a single satellite outward may be possible (Lithwick & Wu 2008; see also Cheng 2011; Cheng et al. 2014b), and some eccentricity excitement would be irrelevant if the transported satellite simply served as the source material for the entire suite of today’s satellites (of course too much eccentricity excitement can lead to dynamical ejection or accretion by Pluto or Charon). A satellite disrupted after the tidal evolution of Charon could form a collisionally active disk as envisioned by Kenyon & Bromley (2014). But growth of satellites from a collisionally damped disk does not imply growth near mean motion resonances, as Kenyon & Bromley (2014) found no strong preference for growth in those locations.

The breakup of a satellite may also form an eccentric ring, which could have strong dynamical interactions with Charon at the same time that it is collisionally evolving. Similarly, the disruption of a primordial satellite during the tidal evolution of Charon could have interactions with Charon while it is still on an eccentric orbit. If a satellite is disrupted it will be important if the dynamical environment forces it to reaccrete in a new location. If the timescale for the disruption and reaccretion of a satellite is short compared to the tidal evolution of Charon, then it is a process that could be repeated multiple times. This could be a way to avoid the dynamical ejection of a satellite because repeated disruption and reaccretion events could help it avoid interacting with the strongest resonances that sweep outward as Charon’s orbit expands. What happens during its disruption, its evolution as a ring or disk of debris, and its reaccumulation into a new satellite could then be important. Here we endeavor to study the evolution of debris following the disruption of a satellite.

1.3. The Role of Collisional Evolution

The state of the Kuiper Belt at the time of the Charon-forming collision is important for determining the collisional environment of the Pluto–Charon system during and after its formation. The giant impact that formed Charon was the last giant impact on Pluto, but it must characterize a substantially different collisional environment in the Kuiper Belt than is found today. Today the chance of such a collision is essentially zero (Brown & Schaller 2007). Meanwhile the tidal evolution of Charon was relatively short compared to the timescales for dynamical mixing and depletion of the Kuiper Belt (Levison & et al. 2008), and thus an enhanced collisional environment may have persisted throughout the entire tidal evolution. In this study we repeatedly refer to this idea and consider the possibility that small satellites \((D < 100 \text{ km})\) in the Pluto–Charon system may have had a very short collisional disruption timescale in the epoch immediately following the Charon-forming event and during the tidal evolution of Charon.

Collisional interactions between particles in the system will change their dynamical evolution by damping excess energy and changing particles’ orbits. A satellite experiencing
This work focuses on the role that collisional evolution could play in both the transport of material outward during the tidal evolution of Charon, and also during the accretion of satellites following the conclusion of tidal evolution. Unlike previous works, we examine the outcome of satellite disruption around a tidally evolving Charon and the formation and evolution of the eccentric ring of debris. For collisional processes to be important, there must have been collisions, and material or debris in enough quantity to affect the evolution of the system. Specifically, we assume and then explore the idea that the current satellites we see today were built from pieces of previously disrupted satellites.

In Section 2, we explore stable orbits in \( a - e \) space around Pluto–Charon systems with different eccentricity for Charon's orbit because tidal evolution models allow for a range of eccentricities. In Section 3, we explore the collisional evolution of a few simple idealized disks of particles. Finally, in Section 4, we model the evolution of the debris of a disrupted satellite, and compare this evolution among systems with different eccentricities for Charon's orbit, as well as around a system with a single central body.

2. STABILITY OF ORBITS IN THE PLUTO/CHARON SYSTEM

The long-term stability of a particle around the Pluto–Charon pair depends on the particle semimajor axis and the eccentricity of both its orbit and that of Charon. The innermost stable orbit, often cited as a critical semimajor axis \( a_{\text{crit}} \), is a value that has been explored in detail in previous numerical and analytical works. Holman & Wiegert (1999) produced an empirical fit for the \( a_{\text{crit}} \) as a function of orbital eccentricity \( e \) and reduced mass \( \mu = M_2/(M_1 + M_2) \). Using the Pluto–Charon reduced mass \( \mu = 0.104 \), this simplifies to \( a_{\text{crit}} = 1.974 + 4.65e - 2.17e^2 \).

Of particular interest for the origin of the small satellites of Pluto are regions of stability while Charon is tidally evolving, during which Charon could have a range of non-zero eccentricities. We explored stability limits for the Pluto–Charon mass ratios, seeking not just the innermost stable orbit, but also the envelope of allowable eccentricities as a function of distance from Pluto–Charon for a range of Charon eccentricities.

We include tests for Charon eccentricity between 0.0 and 0.3, in steps of 0.1, and consider initial test particle semimajor axes that ranged from 1.35 to 5.1 \( a_{\text{Charon}} \) with randomized orbital angles (see Figure 1). The tests were simulated for 1000 years using the \textit{swift_symba5} numerical integrator (Duncan et al. 1998) with a timestep of \( 2 \times 10^{-4} \) years (1.75 hr, which is \( \sim 1/87 \)th Charon's orbital period). We consider co-planar or nearly co-planar cases because the observed system of small satellites appears to be very close to co-planar (see also Pires dos Santos et al. 2011, who considered some small inclination variations in similar tests).

For each of the tested eccentricity values of Charon, \( e = 0.0 \)–0.3, the formulation of Holman & Wiegert (1999) yields \( a_{\text{crit}} = 1.97, 2.41, 2.81, 3.17 a_{\text{Charon}} \). These values were found to agree with those found by Dvorak et al. (1989). The simulations performed here find similar innermost stable orbits. For Charon on a circular orbit we find virtually no stable orbits inside the 3:1 MMR \(( \sim 2.08 a_{\text{Charon}}, \text{see Figure 1}) \), near 1.97 \( a_{\text{Charon}} \) as found in the Holman and Weigert work. Meanwhile, at the location of the furthest known satellite, Hydra, near the 6:1 MMR, particles are unstable with \( e > 0.35 \).

We have made an empirical fit to the stable region when \( e_{\text{Charon}} = 0 \) with a curve described by \( e < (1 - (1.7 a_{\text{Charon}})/a)^{5/3} \). We use this curve throughout the
later sections as a guide for when the regions of an eccentric disk are on unstable orbits.

In cases where Charon has an eccentricity of 0.3, the stability region is truncated near the 5:1 MMR (at 2.9 $a_{\text{Charon}}$, which is similar to the Holman & Wiegert (1999) value of 3.17 $a_{\text{Charon}}$). Lower eccentricities are generally required for stability, with a particle near the 6:1 MMR requiring $e < 0.25$ for this case. We estimate the boundary of this stable region with the following empirical curve, $e < (1 - (2.2a_{\text{Charon}}/a)^{5/3})$ and $a > 2.9a_{\text{Charon}}$.

An important aspect of this result is that particles with an eccentricity above the established $a-e$ curve are unstable on short timescales. However, if their collisional timescale is shorter, then a series of collisions need only to decrease their orbital eccentricity below these stability limits to keep them in the system for long times. Another implication of this experiment is that while Charon has a high eccentricity, at times as high as 0.3 as suggested by Peale et al. (2011), the current orbits of Nix, P4, and P5 would not be stable. Thus, we could expect that these bodies formed after the eccentricity damping of Charon or were in a stable resonant state that increased their stability. We did not find such stable resonant states in this work, but we did not design experiments specifically for that purpose. Cheng (2011) and Cheng et al. (2014b) explored the behavior of particles in multiple resonances and struggled particularly to find stable cases in the 4:1 resonance.

3. EVOLUTION OF COLLISIONALLY EVOLVING DISKS

In this section we model a series of eccentric rings of debris and track their different dynamical evolution as a function of different collisional environments. The role of Charon in changing the evolution of the disk is explored by alternatively placing some disks around single bodies with the combined mass of Pluto and Charon. We model the collisional interactions of the ring particles and their effects on the ring’s eccentricity and semimajor axis.

Required for these tests are the calculations of interparticle collision outcomes. The frequency and outcome of collisions are strongly dependent on relative particle sizes, total system mass, and orbital distributions, all of which can change readily owing to accretion, fragmentation, and gravitational interactions with Charon. Statistical calculations must be made in order to model the high collisional frequencies possible for populations of small particles. If each particle were included directly in a simulation, the total number of particles ($N$) of any calculation would be overwhelmingly large. However, the dynamics of capture in MMR and interactions with Charon demand that the simulation also accurately model the gravitational dynamics, where timescales are controlled by the orbital period of Charon.

The primary code we employ is LIPAD, which stands for Lagrangian Integrator for Planetary Accretion and Dynamics (Levison et al. 2012). It is based on the efficient integration techniques known as the Wisdom–Holman Mapping (Wisdom & Holman 1991), and specifically SyMBA, which has the added property of treating close encounters between bodies (Duncan et al. 1998).

In order to represent the extremely large number of particles required, LIPAD relies on “tracer” particles. Each tracer particle represents a large number of comparably sized particles on very similar orbits. Each tracer is defined by three quantities: the physical radius $s$, the bulk density $\rho$, and the total mass of particles that the tracer represents $m_p$. Throughout the simulation $m_p$ and $\rho$ do not change. When fragmentation and accretion are included the radius $s$ can change and thus the number of particles that the tracer represents will change as a function of $s$, with $N_s = m_p/(4/3)\pi s^3$. For all of the work presented here, the density of each tracer is set at 1 g cm$^{-3}$.

Collisional probabilities for tracers are calculated for each tracer as a function of its size $s$ and the total mass, sizes, and orbits of its neighbors using particle-in-a-box algorithms. The outcome of the collision then affects the tracer particle itself, as though it were a planetesimal of radius $s$, so that each tracer is tracing the behavior of the system (see Section 2.1.1 of Levison et al. 2012 for more details on the tracer–tracer interactions). Meanwhile, the dynamics of each tracer are modeled with gravity calculations and other effects that are handled statistically (dynamical friction, viscous–tracer interactions), some of which depend on the particle’s radius $s$ and the masses, sizes, and orbits of its neighbors.

A particular advantage for this problem is that the Lagrangian nature of the code enables it to model eccentric rings (see Levison & Morbidelli 2007; Levison et al. 2012). When a tracer is determined to have collided with another particle, it is necessary to determine the properties of the impactor. The orbit that the impactor would have had prior to impact is determined by tracking particles that have most recently inhabited the correct regime of the semimajor axis $a$ and radius $s$. From this list of possible impactors, the one with the closest true anomaly is selected, which was shown by Levison & Morbidelli (2007) to be critical to support asymmetries and eccentric rings.

When collisions occur, LIPAD uses a fragmentation law based on Benz & Asphaug (1999) to determine the outcomes. This fragmentation law determines the expected size distribution of fragments, but the entire distribution is not assigned to either tracer—rather, a radius $s$ is chosen for each from the distribution. The system’s size distribution is built from a number of tracer particles with different sizes $s$, and matches standard collisional evolution codes owing to the statistical nature of the radius selection from a large number of collisions (see Levison et al. 2012).

For the cases presented in this section, the collisional fragmentation and growth of particles is not used, rather we simply explore the role of collisional damping.

The first test case, dubbed a “simple eccentric disk,” is designed to examine how the perturbations of Charon change the evolution of a collisionally active disk at distances similar to the current small satellites. This test begins with a co-planar disk of particles with the same semimajor axis $a = 3.05 a_{\text{Charon}}$ and eccentricity $e = 0.2$, and randomized orbital angles (see Figure 2(a)). The semimajor axis is just beyond the 5:1 MMR, which is located at $\sim 2.9 a_{\text{Charon}}$. The equivalent circular orbit of disk material ($a_{\text{eq}}$) is inside the 5:1 MMR at $\sim 2.85 a_{\text{Charon}}$ meaning that the removal of orbital energy by collisional damping, while conserving angular momentum, would result in a ring at this lower semimajor axis orbit. All the particles are initially within the stability boundaries defined in Section 1, and are therefore stable for long timescales. The simulations used 10,000 particles, where each has a mass of $1.02 \times 10^{14}$ kg (totalling $\sim M_{\text{Nix}} + M_{\text{Hydra}}$). Three simulations were run where the tracer particles’ representative radii were varied to be $R = 0.3, 0.1$, or 0.01 km (i.e., $N_s = 8 \times 10^6, 2.4 \times 10^6, 2.4 \times 10^5$).
Charon’s eccentricity was ∼0.2 throughout and it was at its current semimajor axis. For the case of \( R = 0.1 \) km (illustrated in Figure 2) the ring experiences rapid gravitational evolution due to interactions with Charon. The eccentricity distribution is spread out with values reaching as high as 0.4 in just a few Charon orbits. Collisional damping is also dramatic for these conditions and is on similar timescales. After a few Charon periods many particles experience damping, with their eccentricities decreasing to near 0. For these conditions the damping effects are powerful enough to decrease all particle eccentricities on year timescales. After this time, nearly all particles have eccentricities below their initial value of 0.2 and the disk reaches a coherent ring-like structure (see Figure 2(d)).

The evolution to a ring, an eccentric ring at first, is important for the results of this study. The ring does not immediately spread into a disk because each of the particles is very small and gravitational interactions can only supply extremely small changes to eccentricities (collisional damping timescales are much shorter than viscous stirring timescales). Collisions between particles will damp energy and conserve angular momentum, resulting in decreased eccentricities. In Section 4, when accretion is included the ring-like structures start to spread when particles have grown to km-sized bodies and larger. Note that the eccentricity of the particles do not damp to zero because of the presence of the resonance. Also, due to the collisions, no particles are lost from the system despite the fact that many were above the stability curve at times.

The evolution of each disk’s angular momentum is correlated with the collisional damping in each. Initially, the averaged \( a_{eq} \) is at ∼2.87 \( a_{Charon} \), which is just inside the 5:1 MMR with Charon at ∼2.92 \( a_{Charon} \). This value rapidly increases, reaching ∼2.91 \( a_{Charon} \) on year-long timescales for the \( R = 0.1 \) km case plotted in Figure 2 (red triangles in Figure 3). The amount of the increase depends strongly on the collisional evolution, which varies depending on the representative particle radii (ranging from 0.3 to 0.01 km). We also ran a simple test case without collisions, which provides an upper bound to the outcomes shown here. The case with no collisions experienced the most dramatic outward movement of the ring’s angular momentum owing to the absence of collisions to damp particles’ eccentricities (“No collisions” in Figure 3). There is a clear trend in outcomes as a function of the particle radii, as the systems with fewer collisions have the most extreme outward evolution of system angular momentum. The system with particles \( R = 0.3 \) km experienced on average 0.17 collisions per particle per orbit of Charon, which was roughly an order of magnitude less than that for the \( R = 0.1 \) km system, with 1.7, and roughly three orders of magnitude less than the \( R = 0.01 \) km system, which had 218 collisions per particle per Charon orbit.

A separate test removed the perturbations of Charon by examining the same disks of debris orbiting around a single central mass of mass equal to the combined mass of Pluto and Charon (see straight lines at ∼2.84 \( a_{Charon} \) in Figure 3). The
results are plotted with those described above, and are distinct because they all show unchanging angular momentum as a function of time for each of the same three tested radii. This validates that, in the absence of external perturbation, the code conserves angular momentum as a population collisionally damps. It also shows that Charon is the cause of the angular momentum increase in our simulations.

We interpret that the dominating physical effect is that the timescale for interparticle collisions is on order or shorter than the timescale for dynamical loss. In the collisionless system we find that more than half of the particles are ejected from the system due to Charon. As the collision rates increase from zero for this case to a few tenths (0.17 per particle per orbit for $R = 0.3\, \text{km}$) and up to hundreds (for $R = 0.01\, \text{km}$) not only are all particles kept in the system, but the outward evolution of the ring decreases. The longer that ring particles stay highly eccentric, the more these interactions they have with Charon, and the more chances they have to receive kicks to expand their orbits. Thus the lower collision rates are able to keep particles in the system, but they are still kicked substantially by Charon and the ring expands. By moving to higher collision rates (decreasing $R$) the ring damps faster, allowing less time for kicks from Charon and minimal expansion of the rings. We will find in more complex simulations in Section 4 that this outward movement of the ring works for eccentricities of Charon ranging from 0 to 0.3 and for a wide range of distances from Charon in terms of Charon’s orbital separation from Pluto.

What about the resonances? In Figure 4 we present results of similar disks of debris starting at a different semimajor axis relative to the barycenter of the Pluto–Charon system. Here the systems are evolving between the 4:1 or the 5:1 MMR. The results are slightly different. These disks start closer to Charon, and the increased perturbations are evident with more extreme movement of the system’s angular momentum for a given particle size. However, the $R = 0.1\, \text{km}$ case moves more than the $R = 0.01\, \text{km}$ case, as would be expected given the two order of magnitude increase in collision frequency in the latter case. For the test cases further from Charon (starting between 2.8 and 2.9 $a_{\text{eq}}$), the $R = 0.1\, \text{km}$ case and the $R = 0.01\, \text{km}$ case evolve to the same spot—near the 5:1 MMR. While the evolution of the $R = 0.3\, \text{km}$ case rapidly moved past the resonance, both of the more collisionally active cases show signs of resonant interactions with Charon. The smaller radii case had much more eccentricity damping and therefore a decreased semimajor axes. As the semimajor axes decreased, the particles were converging with Charon, allowing for resonant interactions (see Cheng 2011).

A similar series of test cases was created to provide a simplistic representation of a disrupted satellite (dubbed “simple disrupted satellite”). Here debris shares a similar point of origin on the orbit, but has a range of $a$ and $e$ due to different initial ejection velocities away from the disrupted bodies orbit. Particles were distributed on orbits with a range of $a = 2.6–4.0$ $a_{\text{Charon}}$ and $e = 0.5–0.65$, but with similar pericenter values ($q \sim 1.35$ $a_{\text{Charon}}$) and a similar longitude of pericenter value. In this test all the particles were initially on unstable orbits, therefore without collisional interactions they would all be ejected from the system on very short timescales ($<10\, \text{years}$) despite Charon being on a zero eccentricity orbit. The particles had similar collisional properties described above ($R = 0.1\, \text{km}$, with no growth or fragmentation).

The behavior of this disk is similar to the first test case, with the system rapidly ($<3\, \text{years}$) damping into a ring-like structure, this time near the 4:1 MMR. This system also experienced a large increase in angular momentum, circularizing near $\sim 2.5$ $a_{\text{Charon}}$, which is a substantial increase from the initial value of $\sim 2.25$ $a_{\text{Charon}}$.

As before, this same disk of debris was also modeled without collisions. The resulting evolution resulted in the ejection or accretion by Charon of more than 60% of all the particles over the course of the simulation and no coherent ring-like structure (see small, cyan, particles in upper panes of Figure 5).

These two simplistic test cases explored the powerful effects of collisional damping on the dynamical evolution of an eccentric ring. The tests showed that the combined effects of dynamic perturbations from Charon and the collisional damping of an eccentric ring can lead to outward movement of material in the system. This was one of the main problems in understanding the suite of small satellites in the Pluto–Charon system and this is a viable solution. While these tests only considered one value of disk semimajor axes and only one orbit for Charon (with different eccentricities in each test), the outcome of the outward movement of material would scale to an epoch where Charon was closer to Pluto and still tidally evolving outward. In the case where a satellite was disrupted during the tidal evolution, this outward movement would be very useful in helping to push the satellite outward without relying on any resonances to move material long distances in the system.

However, these simulations are missing the important physics of fragmentation and accretion that are necessary to understand where the disrupted satellite will rebuild after it damps and moves out. High velocity collisions could create swarms of small debris that would dramatically change the collisional damping timescales of the large particles, while accretion during low relative velocity collisions could grow a few or many large bodies from the entire system. Where these bodies grow will show whether this mechanism can answer the second open question about the system, as to why the small satellites are located near resonances.
4. DISRUPTION OF A PRIMORDIAL SATELLITE—INCLUDING FRAGMENTATION AND GROWTH

As shown in Section 3, collisional interaction between debris orbiting Pluto/Charon can radically change the collective dynamical behavior of an eccentric ring. Here we test similar scenarios with growth and accretion aiming to see if the collisionally evolving rings will preferentially grow near resonances, and we expand the study to investigate a wider range of initial ring locations relative to the orbit of Charon. There are a few sources of such debris that could have played a role in the history of the Pluto–Charon system. Specifically, the simulations of Canup (2005, 2011) find significant amounts of debris orbiting the Pluto–Charon system following their giant impact. Any debris that avoids accretion by Charon, survives dynamical ejection, and accretes into satellites is then at risk of later dynamical ejection from the system during the outward tidal evolution of Charon (Lithwick & Wu 2008; Cheng 2011). The mechanism explored in the preceding section can help to move material outward and avoid ejection, but depends on the disruptions of satellites on similar timescales to the tidal evolution.

Mutual collisions between satellites are a possible means to disrupt bodies. Any satellites could have their eccentricities excited by entering or crossing MMRs, leading to crossing orbits and collisions (Cheng 2011; Cheng et al. 2014b). Collision velocities would be on order of a few 10 m s$^{-1}$ and approaching 100 m s$^{-1}$ as eccentricities get very high (Nix’s orbital velocity is $\sim$140 m s$^{-1}$). However, lower velocity collisions may simply lead to accretion rather than disruption (an $R = 50$ km target needs to be hit by a $R \sim 43$ km projectile at 100 m s$^{-1}$ to disrupt, using the $Q_0$ calculation from Benz & Asphaug 1999).

Heliocentric impactors are another method for disrupting any existing satellites and producing a significant amount of debris. In the environment where the collision probability for Charon’s formation was unity (and nearly every large KBO appears to have suffered similar impacts), then the lifetime of the smaller satellites ($R \sim 10–100$ km) could be much shorter than the time to dynamically deplete the Kuiper Belt (Levison et al. 2008) and possibly shorter than Charon’s tidal evolution timescale. The distribution of relative velocities for a heliocentric impactor depends on the dynamical state of the Kuiper Belt, and could range from $\sim$100 to 500 m s$^{-1}$ (Pires dos Santos et al. 2012).

We start this series of calculations by generating the debris from the disruption of a satellite impacted by an object from a heliocentric orbit for use as the initial conditions for our LIPAD simulations. We relied on an approximation by way of an N-body simulation of a 39 km radius object striking a 89 km radius body at 500 m s$^{-1}$ with an impact angle of approximately 45°. The target body was made of 9965 discrete, spherical, and unbreakable particles, and the impactor of 717 particles. The disruption event was modeled with the gravitational and granular mechanics code pkdgrav, which is commonly used for low-velocity impact modeling (see Leinhardt et al. 2000 and Richardson et al. 2000). This collision was done in a frame centered on the target-impactor center of mass. It was then translated into a frame relative to that of a satellite on different orbits around Pluto/Charon and with different orientations of the impact direction. This allowed for the exploration of collisions with a wide range of geometry relative to the velocity vector of the satellite. The specific collision modeled here is not derived from a collisional model, rather it was designed to be very general and have a high enough resolution and violent enough disruption to model the relevant physics in a wide range of cases.

The nature of the debris field causes a thin “tail” of debris that generally shares a very similar pericenter ($q$) at the breakup location with a range of distributed, but correlated, $a$ and $e$ (this is a similar configuration to the second of our simple disrupted satellite tests, demonstrated above; Figure 6(a) shows the collision outcome translated to the frame orbiting Pluto–Charon). The geometry tested most frequently in this work was when the impactor’s velocity vector was aligned with the target’s (satellite) velocity vector around Pluto–Charon. With this geometry some of the mass was immediately on orbits.
escaping the Pluto–Charon system, but most of the mass was on moderate eccentricity orbits ($e < 0.4$) within the semimajor axis $\sim 4\ a_{\text{Charon}}$. In the opposite geometry, when the impact velocity was anti-aligned with the satellite velocity, most mass was rapidly ejected from the system due to decreased pericenter distances and subsequent close encounters with Pluto or Charon.

In our main simulations we employed the complete fragmentation and growth capabilities of Lipad. The simulations were started with 4096 tracer particles, each of mass $1.86 \times 10^{14}\text{kg}$, totaling $7.6 \times 10^{17}\text{kg}$ in the system (Tholen et al. 2008 estimated a mass for Nix of $6 \times 10^{17}\text{kg}$). The smallest radius that a fragment could attain during a collision was $5 \times 10^{-4}\text{km}$, and the collisional routines used the Benz & Asphaug (1999) $Q^*$ law for ice (line 4 in their Table III). The simulation used timesteps of $4 \times 10^{-5}\text{years}$, or about 21 minutes, which is $\sim 437$ timesteps per orbit of Charon.

This formula of taking the debris from a collision and placing it on a satellite’s orbit was repeated for different eccentricities of Charon, 0.0–0.3, and for different satellite semimajor axes $a = 2.2–2.8\ a_{\text{Ch}}$. This grid of simulations was designed to test for the preferential growth of satellites in or near MMRs for a wide range of Charon orbital properties. Computational limitations did not allow for simulations to extend for the $\gg 1000\text{years}$ that might be necessary to allow each simulation to evolve to a single or stable system of satellites. Instead, we consider the location of the angular momentum of the system of debris at the end of each run (typically at 200 years), as each run is typically collisionally damped to a ring on the order of a few years allowed for the growth of large bodies in tens of years.

In all, 24 simulations were run to cover this parameter space, with significantly more test runs to examine the sensitivity of each to the various simulation parameters. The typical behavior is shown in Figure 6, where the particles inititally have a radius of 0.01 km (some tests were run over an order of magnitude range of initial sizes and also using an initial size distribution with minimal differences in outcomes). The first few years were dominated by fragmentation, where many particles grind down to the minimum allowable size. This is followed by a period of accretion due to increased collisional damping leading to lower impact velocities (see the column forming in Figure 6(b)).

The location of the first collisions resulting in growth was important for the simulation outcomes (Figure 6(c)). The growth always started with the smallest particles because they have damped to very low eccentricity, and experience low-velocity collisions with each other. After the first accretion events there is rapid growth at the same location, building a “tower” structure in radius versus semimajor axis space. The growth occurs in a very limited space, the “tower,” from this point forward where eventually the largest bodies in the system are built and most of the mass is in this structure. These structures are essentially ring structures where the fragmentation and collisional damping have limited much of the simulation mass to a narrow range of semimajor axis, and subsequent growth at this spot is inevitable and then quite fast.

In Figure 6(c) the growth has reached $\sim 10\text{km}$ sized particles and most of the mass of the system resides in the larger ($>1\text{km}$) particles with only a tail of smaller debris. The high eccentricity tail of debris is largely gone, and nearly all material is on low-eccentricity ($e < 0.2$) orbits in a narrow range of semimajor axis. It has damped to a narrow ring. There are a few particles that appear to hug the 6:1 MMR at slightly higher eccentricity, suggesting that they are possibly being excited due to resonant interactions.

Finally in Figure 6(d) the ring has built enough large particles that it is now diffusing in semimajor axis. There are still a few particles seemingly excited by the 6:1 MMR, and also some particles that appear to have diffused inward and started interacting with the 5:1 MMR. The state of this simulation shows the complication in determining the endstate of these simulations. The angular momentum of this system is very near the 6:1 MMR, but the disk is clearly diffusing and not simply accreting into one or a few satellites. The build up at the 5:1 MMR may be an important process, but computational limits have frustrated further investigation.

The collisional environment that produces the evolution in Figure 6 produces fragmentation early when eccentricities are high, and accretion later after the disk has dynamically cooled into a ring. In a similar simulation the collisions suffered by one object were tracked, and the impact velocities as a function of time are plotted in Figure 7. During the first $\sim 10\text{years}$ of the
While some simulations result in rings of material near MMRs, it does not appear to be a systematic outcome when the smaller ones, with some particles reaching higher eccentricities. A disk due to the presence of the larger bodies dynamically kicked outward and built rings at much more distant orbits than the initial ring distribution was on unstable orbits. Meanwhile the combination of perturbations by Charon or particles reaching resonant orbits combine to increase the angular momentum of a collisionally evolving disk of debris, moving the entire system outward.

While there is no preference for growth near MMR, the movement outward of material is clearly seen here, as it was in the simple collision-only cases demonstrated previously. The tail of debris extends into regions of the $a-e$ space that are unstable and thus there are substantial perturbations from Charon that drive the whole system outward. Meanwhile the collisions between disk particles are energetic enough to fragment particles, which leads to substantial populations of small particles and enhances collisional damping of the system. This drives each system to damp on orbits further than the initial location of the disrupted satellite and a net movement outward of the system.

While this clearly shows the outward movement of material in the system for all Charon eccentricities examined, including $e_{\text{Ch}} = 0.0$, the suite of simulations were only run for one specific semimajor axis of Charon, that of today’s separation. Given that the stability region in the $a-e$ space will scale with Charon’s orbit, the dynamical lifetimes should also scale with Charon’s orbit. The collisional timescales may change somewhat for closer orbits of Charon as the disrupted satellite at the same distance in terms of Charon’s orbit $a_{\text{Ch}}$ will fill less volume and have an increased collision rate. Our earlier tests explored three orders of magnitude of collision rates and all found outward movement of material, so we expect that these results will apply throughout the tidal evolution of Charon.

5. CONCLUSIONS AND DISCUSSION

This work reports on a series of numerical experiments designed to understand the origin and evolution of the small satellites of Pluto. This work found the following.

1. There are regions of stability in $a-e$ space, outside of which particles have very short survival timescales in the Pluto–Charon system if only gravitational interactions are considered. Collisions between particles can stabilize particles initially in the unstable region.

2. The combination of perturbations by Charon or particles reaching resonant orbits combine to increase the angular momentum of a collisionally evolving disk of debris, moving the entire system outward.

3. Satellite disruption, and the subsequent collisional damping and reaccretion, does not lead to preferential formation in MMRs in the range of parameters tested in this work.

The satellite system of Pluto remains mysterious. As stated earlier, there are two major problems with the small satellites of Pluto, and we can report progress on one of the two. The first problem is that the satellites today are much more distant than can be explained by the Charon-formation impact models. Here, by including collisional evolution in dynamical models, we found that debris can experience substantial kicks from Charon while on unstable orbits, but then return to stable orbits due to collisions with other orbiting debris. This effect can result in the movement of material outward in the system.
The likelihood of this being an important process during the history of the Pluto–Charon system is not calculated, nor is it a trivial calculation because it requires a detailed understanding of the excitation, depletion, and collisional evolution of the Kuiper Belt. The tidal evolution timescale of Charon is on the order of a few million years, and so collisional lifetimes must have been shorter than this for it to be important. However, it is expected that the Charon-forming collision happened in a different collision environment than found today in the Kuiper Belt, and collisional timescales for ~100 km bodies must have been very short. Understanding the collisional history of both bodies by investigations with the New Horizons spacecraft mission may help to better understand these issues. This, in effect, suggests that today’s small satellites are essentially the last in multiple generations of previous satellites.

The second problem is the curious configuration of the small satellites, with each near an MMR with Charon. There were indications in some simulations that collisionally active disks of debris would damp into a ring structure and could be caught in some simulations that collisionally active disks of debris would damp into a ring structure and could be caught in. However, a larger parameter space of simulations using a full fragmentation and accretion model failed to show a strong preferential at any eccentricity of Charon. A large number of the simulation parameters were varied, with none clearly indicating importance in an MMR. The importance of this effect could not be investigated here due to computational limitations, but could potentially be responsible for building small satellites one MMR inward of a larger satellite.

Can success be claimed in the first problem and not the second? If collisional damping of an eccentric ring is necessary to move material outward should it not also explain the orbital configuration? It is certainly possible that collisional evolution as tested here is not important or that there was another more dominant mechanism that could both move the satellites or their building blocks and result in their organized accretion near resonance. It is also possible that we have uncovered the means to move material outward in the system, and that there are more or different effects that will ultimately be responsible for the final orbital configuration.

Is it possible that we are simply being fooled by the system and that the orbital configuration is just luck? While four satellites near resonance is hard to explain, both Kerberos and Styx reside in relatively narrow regions of orbital stability (Pires dos Santos et al. 2012; Youdin et al. 2012). Nix and Hydra are near a resonant configuration with each other, so it is conceivable that Kerberos and Styx simply formed in the only places they could in a system with two more massive satellites that were somehow pushed into or near a resonance with each other.

Another question that this work can address with the tools developed here relates to the very first step of this entire process — the survival of any debris immediately following the formation of Charon. In the preceeding sections, we assumed that the post-impact debris measured by Canup (2011) would survive and remain in the Pluto–Charon system, despite the typically close orbits (~10 $a_{\text{pluto}}$) and the potentially high eccentricity of Charon. Using the same simulation configuration described above we performed a series of tests to estimate the collision rates necessary to stabilize debris at the formation distances found in Canup (2011). For a Charon eccentricity of 0.3, we considered disk masses of $6.75 \times 10^{17}$, $3.2 \times 10^{17}$ and $1.2 \times 10^{17}$ kg (Brozović et al. 2015 estimated $M_{\text{Nix}} + M_{\text{Hyd}} = 9.2 \times 10^{16}$ kg), placed on orbits at approximately $2 \times a_{\text{charon}}$. This configuration is similar to the $a \sim 10 R_{\text{pluto}}$ typically found for the debris relative to $a = 4–6 R_{\text{pluto}}$ for Charon in Canup (2011). The simulations used the same collisional debris setup as explored in the previous sections.

Only in the most massive case did significant amounts of debris survive. For $1.2 \times 10^{17}$ kg only five particles were left at 500 years, and no coherent ring structure ever formed. Increasing to $3.2 \times 10^{17}$ kg, a very tenuous ring structure formed from the 70 particles that survived for 500 years. For the $6.75 \times 10^{17}$ kg case, more than 800 particles remained, formed a ring, and experienced significant growth. The largest particle reached 4.8 km, and the recognizable “tower” structure grew between the 6:1 and 7:1 MMR.

These tests spanned the critical regime where the collision rate became high enough to keep debris in the system. The collision rates of 0.006, 0.039, and 0.102 collisions per particle per Charon orbit were found for the lowest to highest mass cases, respectively, and thus a rate between the latter two values can be considered the critical limit for survival of debris in this scenario. The Canup (2011) simulations found total masses of debris ranging from $10^{17}$ to $10^{21}$ kg (only three of 19 simulations were below $10^{18}$ kg). While the masses are typically above what was used in this test (with many simulations with 2–3 orders of magnitude higher mass), the collision rate will be the important quantity and will depend on the size distribution of debris in the system.

Looking beyond the Pluto–Charon system, some of the dynamical interactions between a massive perturber and a disk or ring of debris could be relevant on planetary scales. In our own Solar System, the scattered disk of Kuiper Belt Objects shows the characteristic orbital features of having been excited by Neptune. In the context of this work, the dynamically excited scattered disk would have collisionally damped if the characteristic collisional timescales were shorter than the dynamical lifetimes.

Beyond our Solar System, there are circumbinary planets orbiting stellar systems with mass ratios similar to Pluto–Charon (see Kepler-16b reported in Doyle et al. 2011 and Kepler-34b and Kepler-35b reported in Welsh et al. 2012). Many of the effects driving planet formation in these systems will be different, particularly the effects of the gaseous stellar nebula (see Meschiari 2014), but some of the orbital perturbations on the planetary building blocks will be of similar magnitude as those on satellite building blocks around Pluto and Charon.

In summary, this work has made progress on part of the confounding problems of the small satellites of Pluto. Hopefully this and other recent works, when combined with a very detailed study of the system by way of the New Horizons spacecraft mission (Stern 2008), will help to solve some of these outstanding mysteries.

K.J.W. and H.F.L. acknowledge support from NASAs NLSI (NNA09DB32A) and SSERVI (NNA14AB03A) programs that supported code development and H.F.L. acknowledges support from NASA’s OPR and OSS programs. This work used the Extreme Science and Engineering Discovery
Environment (XSEDE), which is supported by National Science Foundation grant number ACI-1053575.

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