Is there an exoplanet in the Solar System?

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ABSTRACT

We investigate the prospects for the capture of the proposed Planet 9 from other stars in the Sun’s birth cluster. Any capture scenario must satisfy three conditions: the encounter must be more distant than \( \sim 150 \) au to avoid perturbing the Kuiper belt; the other star must have a wide-orbit planet \( (a \gtrsim 100 \text{ au}) \); the planet must be captured onto an appropriate orbit to sculpt the orbital distribution of wide-orbit Solar System bodies. Here we use N-body simulations to show that these criteria may be simultaneously satisfied. In a few percent of slow close encounters in a cluster, bodies are captured onto heliocentric, Planet 9-like orbits. During the \( \sim 100 \text{ Myr} \) cluster phase, many stars are likely to host planets on highly-eccentric orbits with apastron distances beyond 100 au if Neptune-sized planets are common and susceptible to planet–planet scattering. While the existence of Planet 9 remains unproven, we consider capture from one of the Sun’s young brethren a plausible route to explain such an object’s orbit. Capture appears to predict a large population of Trans-Neptunian Objects (TNOs) whose orbits are aligned with the captured planet, and we propose that different formation mechanisms will be distinguishable based on their imprint on the distribution of TNOs.

Key words: Kuiper Belt: general — planets and satellites: dynamical evolution and stability — planets and satellites: individual: Planet 9 — planetary systems — open clusters and associations: general

1 INTRODUCTION

Recent speculation suggests that the outer Solar System hosts a “Planet 9” of several Earth masses or greater. Trujillo & Sheppard (2014), in announcing the discovery of an unusual trans-Neptunian object (TNO) of high perihelion (2012 VP113), noticed a clustering of the argument of perihelion of bodies lying beyond \( \sim 150 \) au, and attributed this to a hypothetical super-Earth body lying at several hundred au whose gravity dominates over the perihelion precession induced by the known planets that would cause an orbital de-phasing over 100s of Myr. This argument has been developed by de la Fuente Marcos & de la Fuente Marcos (2014), who proposed two distant planets to explain further patterns in the distributions of orbital elements. Malhotra et al. (2016) point out mean-motion commensurabilities between the distant TNOs, which they trace back to a hypothetical body at \( \sim 665 \) au whose resonant perturbations on the TNOs would lead to their apsidal confinement. Earlier work was summarized and extensively developed by Lykawka & Mukai (2008), who favoured a sub-Earth mass embryo at \( 100 - 200 \) au.

Current interest has been fomented by Batygin & Brown (2016), who show numerically and analytically how the apsidal and nodal clustering of the distant TNOs arises as a result of resonant and secular dynamical effects from a distant perturber. They identify a range of semi-major axes \( (400 - 1500 \text{ au}) \) and eccentricities \( (0.5 - 0.8) \) for which a distant planet can explain the orbital elements of the distant TNOs, refined to a roughly triangular region in \( a - e \) space in a follow-up study, with \( a \in [300, 900] \) au and \( e \in [0.1, 0.8] \) (Brown & Batygin 2016, and see Figure 1). This range of semi-major axes is more distant than proposed by Trujillo & Sheppard (2014) and de la Fuente Marcos & de la Fuente Marcos (2014), but brackets the resonant perturber of Malhotra et al. (2016). The latter authors favour a lower eccentricity for Planet 9, but as the range proposed by Brown & Batygin (2016) is backed up by multi-Gyr numerical simulations, we adopt their ranges of \( a \) and \( e \) as orbital elements of Planet 9 in this paper. Unfortunately, observations currently do not constrain the possible orbit very strongly. Sub-Neptune mass bodies can exist undetected in electromagnetic emission at several hundred au (Luhman 2014;
Linder & Mordasini 2016; Ginzburg et al. 2016), and Fienga et al. (2016) show that a dynamical analysis of Cassini ranging data may rule out some ranges of orbital phase for a Planet 9, although they restricted their analysis to only a single choice of a and e. Henceforth, we consider the whole of the parameter space identified by Brown & Batygin (2016) to be viable.

In this paper we investigate how the Solar System might have come to host a wide-orbit eccentric body such as Planet 9, a class of object we refer to as ‘Novenitos’. A number of lines of evidence suggest that the Sun formed in a sizeable cluster of a few thousand stars (see Adams 2010; Pfalzner et al. 2015, for reviews), and previous dynamical studies have shown that orbiting bodies at large radii can be transferred between stars in the low (∼1 km s$^{-1}$) close encounters typical in open clusters (Clarke & Pringle 1993; Kenyon & Bromley 2004; Morbidelli & Levison 2004; Pfalzner et al. 2005; Levison et al. 2010; Malmberg et al. 2011; Belbruno et al. 2012; Jilková et al. 2015), and we show that it is indeed possible for the Sun to have captured such a planet from another star in a close encounter in its birth cluster. Our study is complementary to the recent work of Li & Adams (2016), who also identify capture in a cluster as a possible source for Planet 9. Whereas these authors consider the capture of planets initially on circular or moderately-eccentric orbits, we focus on a scenario in which the Sun captures a highly-eccentric planet with a semi-major axis of several hundred au but a pericentre of ∼10 au. In Section 2 we present our simulations for the capture of eccentric planets by the Sun; we show how suitable source planets may exist on highly eccentric orbits around their parent star for many Myr during eras of planet–planet scattering in Section 3; and we discuss our results in Section 4.

2 CAPTURE OF NOVENITOS IN A FLYBY

We first consider the likelihood of the capture of a wide-orbit planet by the Sun in a close encounter with another star. Capture can occur when the initial orbital velocity of the planet around its original host and the velocity of the encounter are comparable, which leaves the planet with a similar orbital velocity around its new star. For the postulated orbit of Planet 9 of ∼500 au, this suggests a similarly wide orbit around the original host (unless the host is low mass, in which case smaller orbits become favoured) and an encounter velocity of ∼1 km s$^{-1}$. Given this velocity, we constrain the impact parameter by requiring that the cold classical Kuiper Belt not be disrupted during the flyby. This requires a perihelion separation greater than ∼150 au (Kobayashi & Ida 2001; Breslau et al. 2014), or an impact parameter greater than 500 au, depending on the mass of the original host. For transfer of material between stars, the minimum separation must also be at most roughly three times the semi-major axis of the orbiting bodies (Pfalzner et al. 2005), meaning a perihelion separation ≤ 1500 au for the close encounter. Fortunately for the capture hypothesis, these encounters occur remarkably frequently in clusters of a few hundred stars or more: Malmberg et al. (2007, 2011) found that only ∼20% of Solar-mass stars in a cluster of $N = 700$ avoid a close encounter within 1000 au, and the mean minimum perihelion distance is ∼250 au; similarly, Adams et al. (2006) found an encounter rate of 0.01 encounters within ∼300 au per star per Myr in an $N = 1000$ subvirial cluster.

The above considerations thus define a broad parameter space for capture with $v_{\text{inf}}$ ∼1 km s$^{-1}$ ∼5 × 10$^{-4}$ au d$^{-1}$, and initial orbits of $a = 100$ au, $q = 10$ au around the star. The orbits of captured planets around the Sun are shown in black, while the blue box marks the range for Novenitos, following Brown & Batygin (2016). In red, at the lower left corner, are the post-flyby orbits of the barely-perturbed Kuiper Belt Objects, initially on circular orbits at 50 au from the Sun.

Figure 1. Semi-major axes and eccentricities of particles after a flyby with $M = 0.1 M_\odot$, $b = 1250$ au, $v_{\text{inf}} = 5 \times 10^{-4}$ au d$^{-1}$, and initial orbits of $a = 100$ au, $q = 10$ au around the star. The orbits of captured particles around the Sun are shown in black, while the blue box marks the range for Novenitos, following Brown & Batygin (2016). In red, at the lower left corner, are the post-flyby orbits of the barely-perturbed Kuiper Belt Objects, initially on circular orbits at 50 au from the Sun.

Table 1. Parameter choices for our flyby simulations.

| Parameter | Values |
|-----------|--------|
| Mass of intruder $M$ | $\{0.1, 0.2, 0.5, 1.0, 1.5\}$ $M_\odot$ |
| Encounter velocity $v_{\text{inf}}$ | $\{500, 750, 1000, 1250\}$ au |
| Initial planet semimajor axis $a$ | $\{50, 100, 200, 400, 800\}$ au |
| Initial planet pericentre $q$ | $\{1, 10\}$ au |
posing a cut-off of $a = 5000$ au to reject particles which spuriously remain bound after removal of the original host), as well as the number captured onto Novenito orbits of Brown & Batygin (2016).

We find that the Sun can capture bodies from the intruding star for many combinations of parameters. Examples of the final orbital elements of captured bodies are shown in Figure 1. Our highest capture rate is 44%, attained for $M_* = 0.5 M_\odot$, $b = 750$ au, $a = 800$ au, $v_{\text{inf}} = 5 \times 10^{-4}$ au d$^{-1}$. However, of these captured particles, only 2% (1% of the total) have orbital elements suitable for a Novenito. Other parameter combinations give higher rates of capture into Novenito orbits, reaching almost 4% for $M_* = 0.1 M_\odot$, $b = 1250$ au, $a = 100$ au, $v_{\text{inf}} = 5 \times 10^{-4}$ au d$^{-1}$. While this is our most successful simulation, capture rates of a few percent are attained for a much wider range of parameters. Cuts through the parameter space are shown in Figure 2. Our full results are given in Table A1 of the online version of this paper.

We also ran simulations to check that the Sun’s Kuiper Belt would not be disrupted in such an encounter. For these we distributed around the Sun 750 particles at $a = 50$ au, $e = 0$, with isotropic inclinations, and verified that eccentricities remained low ($\lesssim 0.1$) after the flyby. These simulations ruled out impact parameters of $b = 1000$ au and below for a 1.5 $M_\odot$ intruder, down to $b = 500$ au and below for a 0.1 $M_\odot$ intruder, with $v_{\text{inf}} = 5 \times 10^{-4}$ au d$^{-1}$.

### 3 SOURCE POPULATIONS OF NOVENITOS

Our flyby simulations show that capture of Novenitos can occur, without disrupting the cold classical KBOs, so long as such planets exist on orbits with apasia greater than 100 au around their parent star. How common are such low-mass, wide-orbit planets? While direct imaging surveys have revealed a handful of massive super-Jovian planets on very wide orbits around young stars (e.g., Marois et al. 2010), the occurrence rate of lower-mass planets on wide orbits is unknown. However, in regions closer to the star the planet occurrence rate is observed to rise strongly with decreasing planet mass (Cumming et al. 2008; Howard et al. 2010; Fressin et al. 2013), while microlensing surveys probing the snow line find that ~50% of low-mass stars host a snowline planet (Gould et al. 2010; Shvartzvald et al. 2016), and we might therefore expect suitable planets to be fairly common. How might such planets attain very wide orbits? While in situ formation of super-Jovian planets may be possible via gravitational instability (Boss 1997; Kratter & Lodato 2016), this could not lead to the formation of Neptune- or super Earth-mass planets. One possibility would be pebble accretion onto an existing core (Lambrechts & Johansen 2012), although at distances of 10s or 100s of au this may require massive discs or high dust:gas ratios (Lambrechts & Johansen 2014). Coagulation of small rocks may be possible at several hundreds of au (Kenyon & Bromley 2015).

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**Figure 2.** Fractions of particles captured into Novenito orbits for objects on orbits of different initial semi-major axes around stars of different masses. Other parameters are fixed at bodies’ initial pericentre $q = 10$ au, impact parameter $b = 1000$ au, $v_{\text{inf}} = 5 \times 10^{-4}$ au d$^{-1}$. Note that a 1.5 $M_\odot$ star with these encounter parameters would disrupt the Kuiper Belt. Error bars show the 1σ range of the posterior distribution from inverting the binomial sampling distribution. Symbols offset for clarity.

**Figure 3.** Evolution of the apocentre of the most distant bound planet in example 6-planet scattering simulations with the inner-most planet at 10 au around a 0.2 $M_\odot$ star. Each line (10 per panel) shows the evolution in one simulation.
although this process takes several Gyr, far longer than the expected time for which the Sun resided in its birth cluster.

More promising may be the the ejection of planets from regions closer to the star. Previous studies have shown that planets in the process of being ejected from unstable multiple systems may persist on wide orbits for extended periods of time (Scharf & Menou 2009; Veras et al. 2009; Raymond et al. 2010; Malmberg et al. 2011, Götberg et al., A&A, submitted). We run scattering simulations with the hybrid integrator of the MERCURY package to quantify more carefully the timescales on which such planets are retained on orbits that we showed above are suitable for capture by the Sun in a flyby. We take a 0.2 M⊕ primary and study 4- and 6-planet systems of a range of masses. The inner two planets’ masses range from 10 M⊕ to 300 M⊕, while the outer planets are always assigned 10 M⊕ (the mass identified by Batygin & Brown 2016). Planets are initially started in unstable configurations on near-circular, near-coplanar orbits (e < 0.02, i < 1°) separated by 3.5–5 mutual Hill radii, and we conduct two sets of simulations: one “pessimistic” with the innermost planet at 3 au and four planets in total and one “optimistic” with the innermost planet at 10 au and 6 planets in total. For each set of planet masses and inner orbit, we run 10 simulations. The systems are integrated for 100 Myr. Planets are considered “ejected” once their distance from the star exceeds 10000 au (In a cluster environment, the tidal field of the cluster or perturbations from passing stars would make themselves felt at these distances, Tremaine 1993.). For each system, we record the fraction of time for which a 10 M⊕ planet exists with an apocentre Q beyond 100 au. Energy is always conserved to better than 2 parts in 10−4.

Sample orbital evolution is shown in Figure 3, for the simulations with the innermost planet at 10 au. Systems with very massive planets (Saturn–Jupiter mass) swiftly eject the lower-mass planets. In contrast, systems comprising only ~ Neptune-mass planets (10 and 30 M⊕) can retain their unstable planets for many 10s of Myr. The mean durations for which systems retain planets with apocentres beyond 100 au are indicated in Figure 3, and are tabulated in Table A2 of the online version of this paper. When starting with planets on wider orbits (innermost at 10 au), we find that planets can be retained on Q > 100 au orbits for most of the first 100 Myr (our best case being 75%), while with the planets starting at 3au the planets can be retained for at most a few 10s of Myr. This can be attributed partly to the longer dynamical timescales for the wider systems, and partly to the larger number of orbits required for ejection with lower-mass planets (see e.g., Raymond et al. 2010). The wide-orbit scattered planets typically have pericentres of ≥ 10 au.

4 DISCUSSION

How likely is the Sun to have picked up Planet 9 in a flyby, following scattering of the planet to a wide orbit around its original host? We can estimate the probability of a successful capture as $P_{\text{capture}} = P_{\text{flyby}} P_{\text{multi}} P_{\text{stable}} f_{\text{wide}} P_{\text{capture}}$, where $P_{\text{flyby}}$ is the probability of the Sun experiencing a suitable flyby, $P_{\text{multi}}$ is the probability of having a multiple planetary system, $P_{\text{stable}}$ is the probability of said system being unstable, $f_{\text{wide}}$ is the fraction of the cluster lifetime that such an unstable system retains a wide-orbit planet, and $P_{\text{capture}}$ is the probability of capturing a wide-orbit planet into a suitable orbit around the Sun. We show in Section 2 that $P_{\text{capture}} \lesssim 4\%$, and in Section 3 $f_{\text{wide}} \lesssim 75\%$. Previous studies of cluster dynamics show that $P_{\text{flyby}} \sim 1$ (Malmberg et al. 2007, 2011). The most difficult numbers to estimate are $P_{\text{stable}}$ and $P_{\text{multi}}$. An optimistic estimate draws a parallel with Jovian planets where a very high incidence of instability is required to explain the eccentricity distribution: Juric & Tremaine (2008) find $P_{\text{stable}} \sim 75\%$, while Raymond et al. (2011) find 83%. We may then combine this with the microlensing estimate of 50% of stars having a wide-orbit Neptune (Shvartzvald et al. 2016), and assume that all such systems are or were multiple. This gives an optimistic $P_{\text{Planet9}} = 1\%$. Pessimistically, we may assume that all multiple-Neptune systems are intrinsically stable (as appears to be the case for Kepler systems, Johansen et al. 2012); in a cluster environment however, otherwise stable systems can be destabilised by encounters with other stars, and Malmberg et al. (2011) find that $P_{\text{stable}} \sim 10\%$ of Solar System clones (otherwise stable) in a cluster will eject a planet within 100 Myr as a result of a close encounter. We then take $P_{\text{multi}} = 16\%$ from Gould et al. (2010), which was based on a single detection of a two-planet system. Taking a pessimistic $P_{\text{capture}} = 1\%$, we then find a pessimistic $P_{\text{Planet9}} \sim 0.01\%$. Thus, the probability for our Planet 9 capture scenario is $P_{\text{Planet9}} \sim 0.01 – 1\%$, although if the additional constraint on Planet 9’s inclination is demanded, the probabilities would shrink by a factor of 10. These numbers compare favourably to the probability of a random alignment of 7 × 10−5 estimated by Batygin & Brown (2016). We caution that we are calculating the conditional probability that Planet 9 ends up on a suitable orbit given the capture hypothesis, and as Planet 9’s possible orbit gets refined this probability will become arbitrarily small. Calculation of the more interesting (Bayesian) probability that the capture occurred, given Planet 9’s orbit, will have to await further studies that calculate the probability of Planet 9’s orbit given different formation scenarios. We also note that the study of Li & Adams (2016) found a probability of ≲ 2% for the capture of Planet 9, assuming the existence of such a body on a wide circular orbit around another star, and sampling the mass of the original host from the stellar IMF. This number corresponds to our $P_{\text{flyby}} P_{\text{capture}}$; thus our studies are broadly in agreement. A better knowledge of the occurrence rate of low-mass wide-orbit planets will be needed to refine the probabilities for capture.

How might the capture scenario be confirmed or refuted? Different histories for Planet 9 may affect the distributions of orbital elements of distant TNOs in different ways. As an example, we ran a capture simulation in which a 10 M⊕ planet was captured from a 0.2 M⊕ star onto an orbit of 283 au. In this simulation, the Sun already possesses a scattered disc of 750 test particles with pericentres of 40 au and eccentricities of 0 to 0.9, and all bodies are co-planar. Following the flyby, the system was integrated for over 800 Myr. The time evolution of the longitudes of pericentres of particles, relative to that of the planet, is shown in Figure 4. Only particles with semi-major axes between 70 and 1000 au are shown. Batygin & Brown (2016) show that families of aligned and anti-aligned particles can exist under the influence of Planet 9, and in our integration a strong
concentration of particles in orbits aligned with the planet is evident, together with a small number in an anti-aligned configuration. Furthermore, Jilková et al. (2016) show that if multiple bodies are captured in an encounter then they typically have similar arguments of periapsis, so if the Sun picked up planetesimals along with Planet 9 (perhaps from the “mini Oort clouds” that can accompany planet–planet scattering, Raymond & Armitage 2013), these would add to the aligned population. If Planet 9 should truly exist, the capture scenario would thus seem to predict a much larger population of bodies with periapsides opposite those of Sedna and similar TNOs. Clouds of points represent highly chaotic trajectories.

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Table A1: Numbers of particles (out of 750) captured in our flyby simulations. First three columns give the flyby parameters. Fourth column gives the particles’ initial semi-major axes. Fifth and sixth columns show \( n_{\text{capt}} \), the number of particles captured by the Sun, and \( n_{\text{Novenito}} \), the number captured onto orbits suitable for Planet 9, for our simulations where particles had initial pericentres of 1 au. Seventh and eighth columns show the same for initial particle pericentres of 10 au. A “-” indicates that the simulation was not run with these parameters.

| \( M_r \) [M\(_{\odot}\)] | \( b \) [au] | \( v_{\text{inf}} \) [au d\(^{-1}\)] | \( a \) [au] | \( n_{\text{capt}} \) | \( n_{\text{Novenito}} \) | \( n_{\text{capt}} \) | \( n_{\text{Novenito}} \) |
|----------------|----------|----------------|---------|--------------|---------------|--------------|---------------|
| 0.1            | 500      | \( 1 \times 10^{-3} \) | 50      | 46           | 0             | 44           | 0             |
| 0.1            | 500      | \( 1 \times 10^{-3} \) | 100     | 51           | 3             | 58           | 3             |
| 0.1            | 500      | \( 1 \times 10^{-3} \) | 200     | 32           | 5             | 26           | 2             |
| 0.1            | 500      | \( 1 \times 10^{-3} \) | 400     | 11           | 0             | 11           | 3             |
| 0.1            | 500      | \( 1 \times 10^{-3} \) | 800     | 4            | 1             | 3            | 2             |
| 0.1            | 750      | \( 1 \times 10^{-3} \) | 50      | 0            | 0             | 0            | 0             |
| 0.1            | 750      | \( 1 \times 10^{-3} \) | 100     | 1            | 0             | 6            | 0             |
| 0.1            | 750      | \( 1 \times 10^{-3} \) | 200     | 81           | 7             | 83           | 3             |
| 0.1            | 750      | \( 1 \times 10^{-3} \) | 400     | 30           | 5             | 37           | 2             |
| 0.1            | 750      | \( 1 \times 10^{-3} \) | 800     | 20           | 1             | 25           | 3             |
| 0.1            | 750      | \( 5 \times 10^{-4} \) | 50      | 301          | 0             | 182          | 0             |
| 0.1            | 750      | \( 5 \times 10^{-4} \) | 100     | 178          | 3             | 150          | 5             |
| 0.1            | 750      | \( 5 \times 10^{-4} \) | 200     | 68           | 2             | 96           | 8             |
| 0.1            | 750      | \( 5 \times 10^{-4} \) | 400     | 51           | 3             | 40           | 2             |
| 0.1            | 750      | \( 5 \times 10^{-4} \) | 800     | 14           | 0             | 14           | 0             |
| 0.1            | 1000     | \( 1 \times 10^{-3} \) | 400     | -            | -             | 2            | 0             |
| 0.1            | 1000     | \( 1 \times 10^{-3} \) | 800     | -            | -             | 1            | 0             |
| 0.1            | 1000     | \( 5 \times 10^{-4} \) | 50      | 20           | 0             | 25           | 0             |
| 0.1            | 1000     | \( 5 \times 10^{-4} \) | 100     | 205          | 17            | 192          | 20            |
| 0.1            | 1000     | \( 5 \times 10^{-4} \) | 200     | 96           | 21            | 131          | 25            |
| 0.1            | 1000     | \( 5 \times 10^{-4} \) | 400     | 50           | 5             | 50           | 11            |
| 0.1            | 1000     | \( 5 \times 10^{-4} \) | 800     | 19           | 1             | 17           | 1             |
| 0.1            | 1250     | \( 1 \times 10^{-3} \) | 400     | -            | -             | 1            | 0             |
| 0.1            | 1250     | \( 1 \times 10^{-3} \) | 800     | -            | -             | 3            | 0             |
| 0.1            | 1250     | \( 5 \times 10^{-4} \) | 50      | 0            | 0             | 0            | 0             |
| 0.1            | 1250     | \( 5 \times 10^{-4} \) | 100     | 183          | 21            | 195          | 28            |
| 0.1            | 1250     | \( 5 \times 10^{-4} \) | 200     | 111          | 23            | 121          | 17            |
| 0.1            | 1250     | \( 5 \times 10^{-4} \) | 400     | 65           | 10            | 46           | 6             |
| 0.1            | 1250     | \( 5 \times 10^{-4} \) | 800     | 17           | 3             | 14           | 0             |
| 0.2            | 500      | \( 1 \times 10^{-3} \) | 50      | 22           | 0             | 34           | 0             |
| 0.2            | 500      | \( 1 \times 10^{-3} \) | 100     | 72           | 0             | 54           | 2             |
| 0.2            | 500      | \( 1 \times 10^{-3} \) | 200     | 39           | 5             | 35           | 1             |
| 0.2            | 500      | \( 1 \times 10^{-3} \) | 400     | 14           | 3             | 20           | 3             |
| 0.2            | 500      | \( 1 \times 10^{-3} \) | 800     | -            | -             | 6            | 0             |
| 0.2            | 750      | \( 1 \times 10^{-3} \) | 50      | 0            | 0             | 0            | 0             |
| 0.2            | 750      | \( 1 \times 10^{-3} \) | 100     | 0            | 0             | 6            | 0             |
| 0.2            | 750      | \( 1 \times 10^{-3} \) | 200     | 18           | 1             | 16           | 1             |
| 0.2            | 750      | \( 1 \times 10^{-3} \) | 400     | 16           | 6             | 20           | 3             |
| 0.2            | 750      | \( 1 \times 10^{-3} \) | 800     | 12           | 0             | 3            | 1             |
| 0.2            | 750      | \( 5 \times 10^{-4} \) | 50      | 191          | 0             | 129          | 0             |
| 0.2            | 750      | \( 5 \times 10^{-4} \) | 100     | 128          | 1             | 135          | 4             |
| 0.2            | 750      | \( 5 \times 10^{-4} \) | 200     | 75           | 6             | 75           | 3             |
| 0.2            | 750      | \( 5 \times 10^{-4} \) | 400     | 99           | 6             | 88           | 1             |
| 0.2            | 750      | \( 5 \times 10^{-4} \) | 800     | 54           | 1             | 74           | 2             |
| 0.2            | 1000     | \( 1 \times 10^{-3} \) | 800     | -            | -             | 7            | 1             |
| 0.2            | 1000     | \( 5 \times 10^{-4} \) | 50      | 0            | 0             | 1            | 0             |
| 0.2            | 1000     | \( 5 \times 10^{-4} \) | 100     | 153          | 8             | 149          | 16            |
| 0.2            | 1000     | \( 5 \times 10^{-4} \) | 200     | 104          | 22            | 115          | 10            |
| 0.2            | 1000     | \( 5 \times 10^{-4} \) | 400     | 54           | 8             | 53           | 2             |

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### Table A1 — continued

| $M_\star$ [M$_\odot$] | $b$ [au] | $v_{\text{inf}}$ [au d$^{-1}$] | $q = 1$ au | $q = 10$ au |
|----------------------|---------|-----------------|-----------|-----------|
| 0.2                  | 1000    | $5 \times 10^{-4}$ | 800 | 39 | 3 | 39 | 2 |
| 0.2                  | 1250    | $1 \times 10^{-4}$ | 800 | - | - | 1 | 0 |
| 0.2                  | 1250    | $5 \times 10^{-4}$ | 100 | 67 | 14 | 70 | 15 |
| 0.2                  | 1250    | $5 \times 10^{-4}$ | 200 | 130 | 19 | 115 | 13 |
| 0.2                  | 1250    | $5 \times 10^{-4}$ | 400 | 72 | 5 | 54 | 7 |
| 0.2                  | 1250    | $5 \times 10^{-4}$ | 800 | 29 | 1 | 28 | 4 |
| 0.5                  | 750     | $5 \times 10^{-4}$ | 50 | 139 | 1 | 108 | 3 |
| 0.5                  | 750     | $5 \times 10^{-4}$ | 100 | 84 | 2 | 86 | 3 |
| 0.5                  | 750     | $5 \times 10^{-4}$ | 200 | 105 | 1 | 101 | 8 |
| 0.5                  | 750     | $5 \times 10^{-4}$ | 400 | 258 | 15 | 242 | 18 |
| 0.5                  | 750     | $5 \times 10^{-4}$ | 800 | 331 | 7 | 328 | 3 |
| 0.5                  | 1000    | $1 \times 10^{-3}$ | 800 | - | - | 21 | 0 |
| 0.5                  | 1000    | $5 \times 10^{-4}$ | 50 | 0 | 0 | 0 | 0 |
| 0.5                  | 1000    | $5 \times 10^{-4}$ | 100 | 132 | 9 | 113 | 9 |
| 0.5                  | 1000    | $5 \times 10^{-4}$ | 200 | 80 | 15 | 91 | 17 |
| 0.5                  | 1000    | $5 \times 10^{-4}$ | 400 | 107 | 14 | 99 | 13 |
| 0.5                  | 1000    | $5 \times 10^{-4}$ | 800 | 157 | 5 | 164 | 5 |
| 0.5                  | 1250    | $1 \times 10^{-3}$ | 800 | - | - | 4 | 1 |
| 0.5                  | 1250    | $5 \times 10^{-4}$ | 100 | 45 | 4 | 34 | 3 |
| 0.5                  | 1250    | $5 \times 10^{-4}$ | 200 | 94 | 14 | 79 | 8 |
| 0.5                  | 1250    | $5 \times 10^{-4}$ | 400 | 63 | 11 | 69 | 12 |
| 0.5                  | 1250    | $5 \times 10^{-4}$ | 800 | 73 | 5 | 86 | 5 |
| 1.0                  | 1000    | $1 \times 10^{-3}$ | 800 | - | - | 28 | 2 |
| 1.0                  | 1000    | $5 \times 10^{-4}$ | 50 | 1 | 0 | 6 | 0 |
| 1.0                  | 1000    | $5 \times 10^{-4}$ | 100 | 79 | 2 | 52 | 1 |
| 1.0                  | 1000    | $5 \times 10^{-4}$ | 200 | 54 | 10 | 57 | 5 |
| 1.0                  | 1000    | $5 \times 10^{-4}$ | 400 | 83 | 3 | 92 | 8 |
| 1.0                  | 1000    | $5 \times 10^{-4}$ | 800 | 191 | 9 | 193 | 6 |
| 1.0                  | 1250    | $1 \times 10^{-3}$ | 800 | - | - | 15 | 0 |
| 1.0                  | 1250    | $5 \times 10^{-4}$ | 100 | 64 | 5 | 43 | 3 |
| 1.0                  | 1250    | $5 \times 10^{-4}$ | 200 | 64 | 2 | 58 | 12 |
| 1.0                  | 1250    | $5 \times 10^{-4}$ | 400 | 60 | 9 | 54 | 7 |
| 1.0                  | 1250    | $5 \times 10^{-4}$ | 800 | 105 | 1 | 92 | 2 |
| 1.5                  | 1250    | $1 \times 10^{-3}$ | 800 | - | - | 15 | 0 |
| 1.5                  | 1250    | $5 \times 10^{-4}$ | 100 | 33 | 3 | 40 | 3 |
| 1.5                  | 1250    | $5 \times 10^{-4}$ | 200 | 56 | 6 | 48 | 11 |
| 1.5                  | 1250    | $5 \times 10^{-4}$ | 400 | 26 | 3 | 23 | 2 |
| 1.5                  | 1250    | $5 \times 10^{-4}$ | 800 | 65 | 5 | 82 | 4 |
Table A2. Mean durations for which systems retain planets with apastron distances > 100 au. First column: masses of inner two planets. Second column: mean duration in our pessimistic case (4 planets total; innermost at 3 au). Third column: mean duration in our optimistic case (6 planets total; innermost at 10 au).

| Planet mass [M_⊕] | Pessimistic duration [Myr] | Optimistic duration [Myr] |
|-------------------|---------------------------|---------------------------|
| 10, 10            | 3.7                       | 68.0                      |
| 30, 10            | 12.0                      | 75.1                      |
| 30, 30            | 21.9                      | 69.8                      |
| 100, 10           | 6.7                       | 44.2                      |
| 100, 30           | 1.6                       | 31.9                      |
| 100, 100          | 1.6                       | 16.8                      |
| 300, 10           | 0.04                      | 0.86                      |
| 300, 30           | 0.04                      | 0.83                      |
| 300, 100          | 0.09                      | 11.6                      |
| 300, 300          | 2.97                      | 21.6                      |