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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$ au); the planet must be captured on to 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 per cent of slow close encounters in a cluster, bodies are captured on to heliocentric, Planet 9-like orbits. During the $\sim$100 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 VP_{113}), 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, Volk & Wang (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 semimajor axes (400–1500 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 Fig. 1). This range of semimajor 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 Letter. 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; Ginzburg, Sari & Loeb 2016; Linder & Mordasini 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

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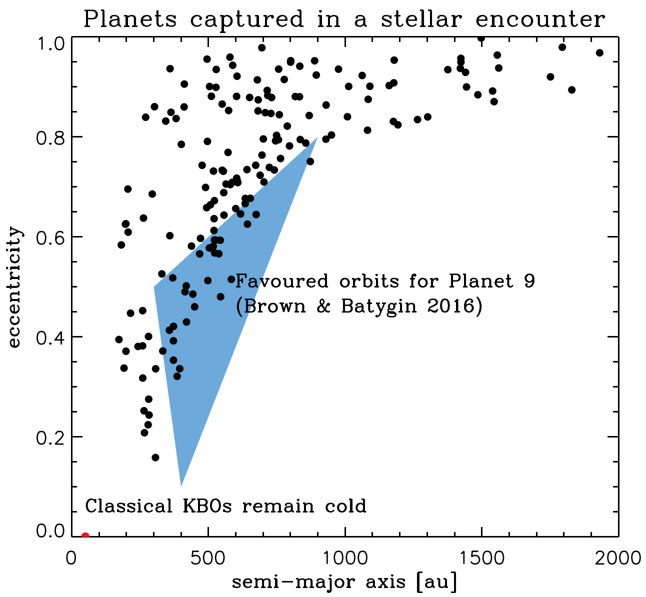

Figure 1. Semimajor axes and eccentricities of particles after a flyby with $M_\star = 0.1\,\mathrm{M}_\odot$, $b = 1250$ au, $v_\mathrm{inf} = 5 \times 10^{-4}$ au d^{-1}, and initial orbits of $a = 100$ au, $q = 10$ au around the star. The orbits of captured particles around the Sun are shown in black, 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.

the parameter space identified by Brown & Batygin (2016) to be viable.

In this Letter 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 slow ($\sim$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, Davies & Heggie 2011; Belbruno et al. 2012; Jílková 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 semimajor axis of several hundred au but a pericentre of $\sim$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

Table 1. Parameter choices for our flyby simulations.

Parameter	Values
Mass of intruder $M_\star$	$\{0.1, 0.2, 0.5, 1.0, 1.5\}\,\mathrm{M}_\odot$
Impact parameter b	$\{500, 750, 1000, 1250\}$ au
Encounter velocity v_inf	$\{0.5, 1.0\} \times 10^{-3}$ au d^{-1}
Initial planet semimajor axis a	$\{50, 100, 200, 400, 800\}$ au
Initial planet pericentre q	$\{1, 10\}$ au

postulated orbit of Planet 9 of $\sim$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 $\sim$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 $\sim$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 semimajor axis of the orbiting bodies (Pfalzner et al. 2005), meaning a perihelion separation $\lesssim$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 $\sim$20 per cent of Solar-mass stars in a cluster of $N = 700$ avoid a close encounter within 1000 au, and the mean minimum perihelion distance is $\sim$250 au; similarly, Adams et al. (2006) found an encounter rate of 0.01 encounters within $\sim$300 au per star per Myr in an $N = 1000$ subvirial cluster.

The above considerations thus define a broad parameter space for capture with $v_\mathrm{inf} \sim 1$ km s$^{-1} \approx 5.8 \times 10^{-4}$ au d^{-1}, impact parameter $b \sim 1000$ au, semimajor axis $a \sim 500$ au. For the mass of the original host $M_\star$ we consider a range from 0.1 to 1.5 $\mathrm{M}_\odot$, covering a wide range of known planet hosts. For the eccentricity of Planet 9's original orbit, we focus on very high values corresponding to pericentres of 1–10 au, consistent with the aftermath of a phase of strong planet–planet scattering as we describe in Section 3. Our parameter choices are listed in Table 1. We explore this parameter space with *N*-body integrations using the Mercury package (Chambers 1999). We use the conservative BS algorithm to integrate the trajectories of the Sun and an intruder; the latter is surrounded by an isotropic swarm of massless test particles (750 per integration). The intruder begins at 10 000 au with a velocity v_inf, and the system is integrated until the intruder attains a heliocentric distance of 20 000 au, at which distance bodies are removed from the integration. For each integration, we count the number of particles captured on to bound orbits around the Sun (imposing 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 on to 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 Fig. 1. Our highest capture rate is 44 per cent, attained for $M_\star = 0.5\,\mathrm{M}_\odot$, $b = 750$ au, $a = 800$ au, $v_\mathrm{inf} = 5 \times 10^{-4}$ au d^{-1}. However, of these captured particles, only 2 per cent (1 per cent of the total) have orbital elements suitable for a Novenito. Other parameter combinations give higher rates of capture into Novenito orbits, reaching almost 4 per cent for $M_\star = 0.1\,\mathrm{M}_\odot$, $b = 1250$ au, $a = 100$ au, $v_\mathrm{inf} = 5 \times 10^{-4}$ au d^{-1}. While this is our most successful simulation, capture rates of a few per cent are attained for a much wider range of parameters. Cuts

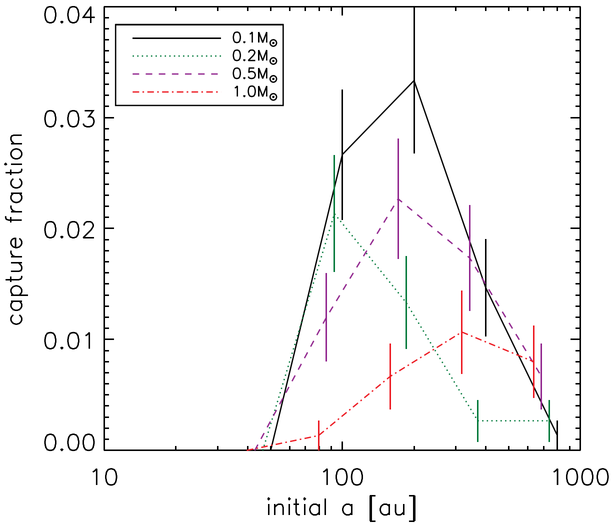

Figure 2. Fractions of particles captured into Novenito orbits for objects on orbits of different initial semimajor axes around stars of different masses. Other parameters are fixed at bodies' initial pericentre $q = 10$ au, impact parameter $b = 1000$ au, $v_{\rm inf} = 5 \times 10^{-4}$ au d^{-1}. 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.

through the parameter space are shown in Fig. 2. Our full results are given in Table A1 of the online version of this Letter.

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 $v_{\rm inf} = 5 \times 10^{-4}$ 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 apastra 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 per cent of low-mass stars host a snow-line 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 on to 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), 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 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, Crepp & Ford 2009; Raymond, Armitage & Gorelick 2010; Malmberg, Davies & Heggie 2011, Götberg et al. 2016). We run scattering simulations with the hybrid integrator of the Mercury package to quantify more carefully the time-scales 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$_\odot$ primary and study four- and six-planet systems of a range of masses: The inner two planets' masses range from 10 M$_\oplus$; to 300 M$_\oplus$;, while the outer planets are always assigned 10 M$_\oplus$; (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 10 000 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$_\oplus$; planet exists with an apocentre Q beyond 100 au. Energy is always conserved to better than two parts in 10^{-4}.

Sample orbital evolution is shown in Fig. 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$_\oplus$;) 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 Fig. 3, and are tabulated in Table A2 of the online version of this Letter. 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 per cent), while with the planets starting at 3 au the planets can be retained for at most a few 10s of Myr. This can be attributed partly to the longer dynamical time-scales 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 $\gtrsim$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 $P_{\rm Planet9} = P_{\rm flyby} P_{\rm multi} P_{\rm unstable} f_{\rm wide} P_{\rm capture}$, where $P_{\rm flyby}$ is the probability of the Sun experiencing a suitable flyby, $P_{\rm multi}$ is the probability of having a multiple planetary system, $P_{\rm unstable}$ is the probability of said system being unstable, $f_{\rm wide}$ is the fraction of the cluster lifetime that such an unstable system retains a wide-orbit planet, and $P_{\rm capture}$ is the probability of capturing a wide-orbit planet into a suitable orbit around the Sun. We show in Section 2 that $P_{\rm capture} \lesssim 4$ per cent, and in Section 3 $f_{\rm wide} \lesssim 75$ per cent. Previous studies of cluster dynamics show that $P_{\rm flyby} \sim 1$ (Malmberg et al. 2007, 2011). The most difficult numbers to estimate are $P_{\rm unstable}$ and $P_{\rm multi}$. An optimistic estimate draws a parallel with Jovian planets where a very

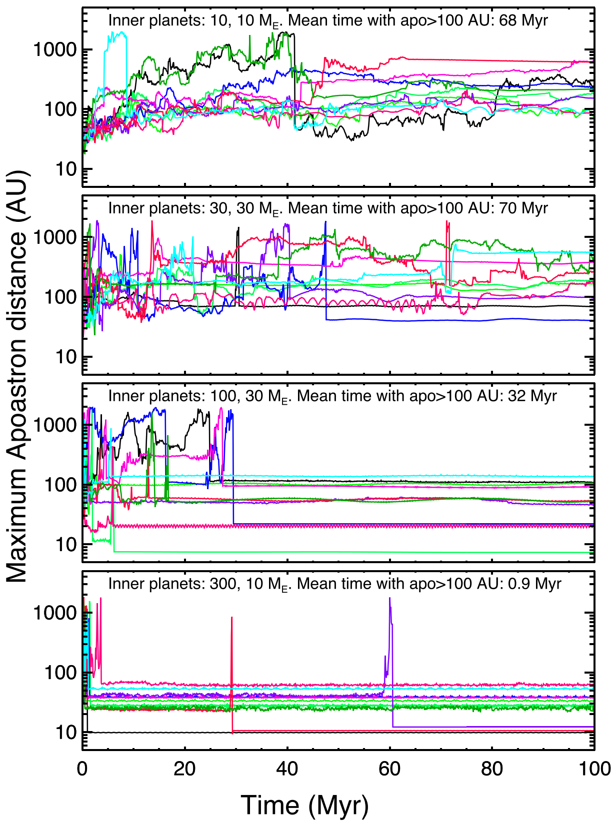

Figure 3. Evolution of the apocentre of the most distant bound planet in example six-planet scattering simulations with the innermost planet at 10 au around a 0.2 $M_{\odot}$ star. Each line (10 per panel) shows the evolution in one simulation.

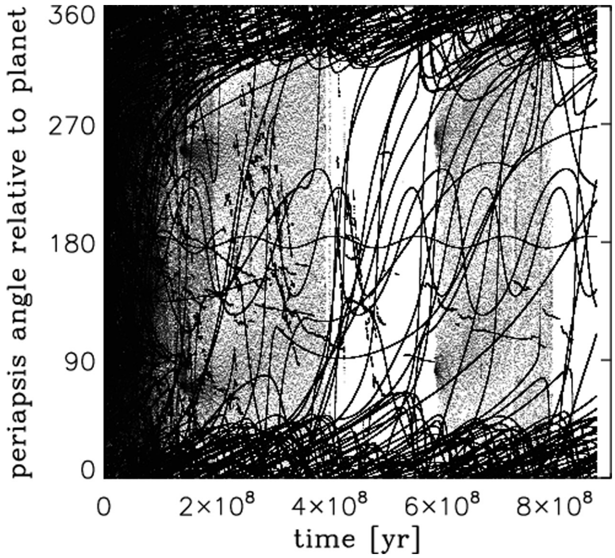

Figure 4. Orbital evolution of outer Solar system bodies sculpted by a captured Planet 9. We plot every 100 yr the longitude of periapsis of scattered disc particles between 70 and 1000 au, relative to that of the planet at 283 au. After removal of unstable particles after ~100 Myr, a concentration of particles at $\Delta\varpi \approx 0°$ is evident, together with a smaller number in the anti-aligned configuration ($\Delta\varpi \approx 180°$) postulated by Batygin & Brown (2016) for the orientation of Sedna and similar TNOs. Clouds of points represent highly chaotic trajectories.

high incidence of instability is required to explain the eccentricity distribution: Jurić & Tremaine (2008) find $P_{\mathrm{unstable}} = 75$ per cent, while Raymond et al. (2011) find 83 per cent. We may then combine this with the microlensing estimate of 50 per cent 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 $P_{\mathrm{Planet9}} = 1$ per cent. 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 $P_{\mathrm{unstable}} \sim 10$ per cent 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 $P_{\mathrm{multi}} = 16$ per cent from Gould et al. (2010), which was based on a single detection of a two-planet system. Taking a pessimistic $P_{\mathrm{capture}} = 1$ per cent, we then find a pessimistic $P_{\mathrm{Planet9}} \sim 0.01$ per cent. Thus, the probability for our Planet 9 capture scenario is $P_{\mathrm{Planet9}} \sim 0.01$–1 per cent, although if the additional constraint on Planet 9's inclination is demanded (Brown & Batygin 2016), these 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 $\lesssim 2$ per cent 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 $P_{\mathrm{flyby}} P_{\mathrm{capture}}$; 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 $M_{\oplus}$; planet was captured from a 0.2 $M_{\odot}$ star on to 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 0–0.9, and all bodies are coplanar. Following the flyby, the system was integrated for over 800 Myr. The time evolution of the longitudes of periapsis of particles, relative to that of the planet, is shown in Fig. 4. Only particles with semimajor 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, Jílková 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 its ilk. While we caution that this is based on one single example of a coplanar capture, and we have neglected the effects of the known planets, it is likely that the distribution of orbital elements of distant TNOs will in the future prove a powerful discriminant between different scenarios for emplacing Planet 9 on its orbit, such as capture, *in situ* formation, and scattering by the Solar system's known giant planets, and we encourage further dynamical studies to explore these possibilities.

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REFERENCES

Adams F. C., 2010, ARA&A, 48, 47
Adams F. C., Proszkow E. M., Fatuzzo M., Myers P. C., 2006, ApJ, 641, 504
Batygin K., Brown M. E., 2016, AJ, 151, 22
Belbruno E., Moro-Martín A., Malhotra R., Savransky D., 2012, Astrobiology, 12, 754
Boss A. P., 1997, Science, 276, 1836
Breslau A., Steinhausen M., Vincke K., Pfalzner S., 2014, A&A, 565, A130
Brown M. E., Batygin K., 2016, preprint (arXiv:1603.05712)
Chambers J. E., 1999, MNRAS, 304, 793
Clarke C. J., Pringle J. E., 1993, MNRAS, 261, 190
Cumming A., Butler R. P., Marcy G. W., Vogt S. S., Wright J. T., Fischer D. A., 2008, PASP, 120, 531
de la Fuente Marcos C., de la Fuente Marcos R., 2014, MNRAS, 443, L59
Fienga A., Laskar J., Manche H., Gastineau M., 2016, A&A, 587, L8
Fressin F. et al., 2013, ApJ, 766, 81
Ginzburg S., Sari R., Loeb A., 2016, ApJ, 822, L11
Götberg Y., Davies M. B., Mustill A. J., Johansen A., Church R. P., 2016, A&A, submitted
Gould A. et al., 2010, ApJ, 720, 1073
Howard A. W. et al., 2010, Science, 330, 653
Jílková L., Portegies Zwart S., Pijloo T., Hammer M., 2015, MNRAS, 453, 3157
Jílková L., Hamers A. S., Hammer M., Portegies Zwart S., 2016, MNRAS, 457, 4218
Johansen A., Davies M. B., Church R. P., Holmelin V., 2012, ApJ, 758, 39
Jurić M., Tremaine S., 2008, ApJ, 686, 603
Kenyon S. J., Bromley B. C., 2004, Nature, 432, 598
Kenyon S. J., Bromley B. C., 2015, ApJ, 806, 42
Kobayashi H., Ida S., 2001, Icarus, 153, 416
Kratter K. M., Lodato G., 2016, preprint (arXiv:1603.01280)
Lambrechts M., Johansen A., 2012, A&A, 544, A32
Lambrechts M., Johansen A., 2014, A&A, 572, A107
Levison H. F., Duncan M. J., Brasser R., Kaufmann D. E. Kaufmann D. E., 2010, Science, 329, 187
Li G., Adams F. C., 2016, preprint (arXiv:1602.08496)
Linder E. F., Mordasini C., 2016, A&A, 589, A134
Luhman K. L., 2014, ApJ, 781, 4
Lykawka P. S., Mukai T., 2008, AJ, 135, 1161
Malhotra R., Volk K., Wang X., 2016, preprint (arXiv:1603.02196)
Malmberg D., de Angeli F., Davies M. B., Church R. P., Mackey D., Wilkinson M. I., 2007, MNRAS, 378, 1207
Malmberg D., Davies M. B., Heggie D. C., 2011, MNRAS, 411, 859
Marois C., Zuckerman B., Konopacky Q. M., Macintosh B., Barman T., 2010, Nature, 468, 1080
Morbidelli A., Levison H. F., 2004, AJ, 128, 2564
Pfalzner S., Vogel P., Scharwächter J., Olczak C., 2005, A&A, 437, 967
Pfalzner S. et al., 2015, Phys. Scr., 90, 068001
Raymond S. N., Armitage P. J., 2013, MNRAS, 429, L99
Raymond S. N., Armitage P. J., Gorelick N., 2010, ApJ, 711, 772
Raymond S. N. et al., 2011, A&A, 530, A62
Scharf C., Menou K., 2009, ApJ, 693, L113
Shvartzvald Y. et al., 2016, MNRAS, 457, 4089
Tremaine S., 1993, in Phillips J. A., Thorsett S. E., Kulkarni S. R., eds, ASP Conf. Ser. Vol. 36, Planets Around Pulsars. Astron. Soc. Pac., San Francisco, p. 335
Trujillo C. A., Sheppard S. S., 2014, Nature, 507, 471
Veras D., Crepp J. R., Ford E. B., 2009, ApJ, 696, 1600

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix
(http://www.mnrasl.oxfordjournals.org/lookup/suppl/doi:10.1093/mnrasl/slw075/-/DC1).

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