

The Case for an Early Solar Binary Companion

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ABSTRACT

We show that an equal-mass, temporary binary companion to the Sun in the solar birth cluster at a separation of $\sim 10^3$ AU would have increased the likelihood of forming the observed population of outer Oort cloud objects and of capturing Planet Nine. In particular, the discovery of a captured origin for Planet Nine would favor our binary model by an order of magnitude relative to a lone stellar history. Our model predicts an overabundance of dwarf planets, discoverable by LSST, with similar orbits to Planet Nine, which would result from capture by the stellar binary.

Keywords: Binary stars – Oort cloud – Planet Nine

1. INTRODUCTION

Simulations of outer Oort cloud (OOC)¹ formation in the Solar system (Dones et al. 2004; Kaib & Quinn 2008; Brasser et al. 2010) have difficulties reproducing the observed ratio between scattered disk (SD)² and OOC objects (Duncan & Levison 1997; Levison et al. 2008). As a result, the origin of the OOC is an unsolved puzzle. Scenarios positing that the formation of the OOC occurred in the stellar birth cluster of the Sun tend to rely on drag from dense cluster gas (Fernández & Brunini 2000; Brasser et al. 2006; Kaib & Quinn 2008; Levison et al. 2010; Brasser et al. 2012), a factor that hinders the scattering of comets to large distances, reducing the plausibility of the explanations (Brasser et al. 2007; Brasser & Morbidelli 2013). There are $N_{OC} \sim 7.6 \pm 3.3 \times 10^{10}$ OOC bodies and $N_{SD} \sim 1.7_{-0.9}^{+3.0} \times 10^9$ SD bodies with diameters of $D > 2.3$ km (Brasser & Morbidelli 2013; Rickman et al. 2017). Simulations of OOC formation due to a dynamical instability in the solar system result in an OOC/SD ratio of $N_{OC}/N_{SD} \sim 12 \pm 1$, which is in tension, but not incompatible with, the observed ratio (Brasser & Morbidelli 2013).

Separately, clustering of extreme trans-Neptunian objects (ETNOs) in the outer solar system suggest the possible existence of a planet, labeled Planet Nine, at

a distance of ~ 500 AU from the Sun (Brown & Batygin 2016; Batygin et al. 2019). Zderic & Madigan (2020) argued that Planet Nine may not exist, and its observed gravitational effects could potentially be caused by an unobserved ring of small bodies in the outer solar system. There also exists the possibility that the clustering is a statistical fluke (Clement & Kaib 2020). The origin of Planet Nine, if it exists, is a second unsolved puzzle in the outskirts of the Solar system. Possible solutions include (Batygin et al. 2019) formation amongst the giant planets followed by scattering and orbital circularization (Brasser et al. 2006, 2012; Li & Adams 2016), and capture in the solar birth cluster (Li & Adams 2016; Mustill et al. 2016; Parker et al. 2017).

Interestingly, stellar binary systems are capable of capturing background objects via three-body processes (Heggie 1975; Valtonen 1983), leading to capture rates that are enhanced relative to lone stars (Ginsburg et al. 2018; Siraj & Loeb 2020). Current binary companions to the Sun were previously considered (Matese et al. 2005; Melott & Bambach 2010), and subsequently ruled out (Luhman 2014). Here, we consider a temporary binary companion to the Sun that could have existed only in the solar birth cluster, and explore the plausibility and implications of such a possibility for both the formation of the OOC and the capture of Planet Nine.

Our discussion is structured as follows. In Section 2, we explore the plausibility of a binary companion to the Sun in the solar birth cluster. In Section 3, we investigate the effects of an early binary on the formation of the OOC. In Section 4, we consider the implications of the binary model for the Planet Nine capture cross-section and use the likelihood of the binary configuration con-

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¹ Defined here as the collection of solar system bodies with semimajor axes of $\sim 10^4 - 10^5$ AU, and with orbits decoupled from Neptune.

² Defined here as the collection of solar system bodies with semimajor axes of $\lesssim 10^3$ AU, and with orbits controlled by Neptune.

sidered to estimate the overall merits of binary model if a captured origin for Planet Nine is verified. Finally, Section 5 summarizes the key implications of our model.

2. PLAUSIBILITY

The orbit of Planet Nine would be stable in an equal-mass binary if the binary separation were a factor of ~ 3 larger than that of Planet Nine (Fig. 4, Quarles et al. 2020). Since the semi-major axis of Planet Nine is likely ~ 500 AU, we consider an equal-mass binary with a separation of $a \sim 1500$ AU, at which a solar binary could have plausibly been born and survived the protostellar phase (Connelley et al. 2008), although more research may be necessary (Sadavoy & Stahler 2017). Figure 1 shows a sketch of the scenario considered here. Separations of $\gtrsim 1500$ AU are possible, but they would reduce both the capture cross-section, which scales as a^{-1} , and the lifetime in the birth cluster, which scales as $a^{-1/2}$.

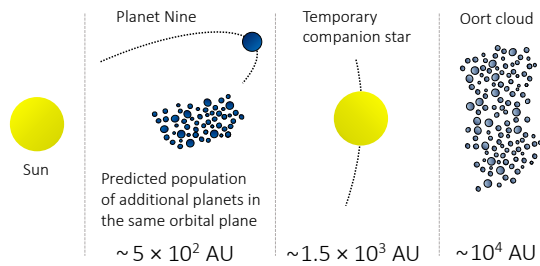


Figure 1. Sketch of scenario considered here (not to scale).

The orbits of the planets in the Solar system would be unaffected by Kozai-Lidov oscillations from such a binary partner (see Table 1 in Innanen et al. 1997; extrapolated using the b_*^3/m_*^3 relation).

Since the ejection probability for a body at a separation of ~ 500 AU over the lifetime of the solar birth cluster is ~ 0.3 (Batygin et al. 2019), and orbital speed scales as $a^{-1/2}$ while the distribution of Δv impulses is the same at any point in space where gravitational focusing is not significant, the probability of ejection for an object with a separation of $a \sim 1500$ AU is $f_e \sim 0.5$ ($f_e \sim 1$ for $a \sim 6000$ AU), which is consistent with the fact that no solar-mass binary companion is presently observed.

Additionally, since tidal force scales as the cube of distance, Planet Nine with a perihelion of ~ 250 AU and mass $\sim 5-10 M_\oplus$ acting over a timescale comparable to the age of the solar system ~ 4.5 Gyr, would have a comparable effect on solar obliquity as a binary stellar companion (Batygin 2012) with a perihelion of $\gtrsim 1500$ AU, and a mass of $\sim M_\odot$, acting over the lifetime of the solar

birth cluster ~ 0.1 Gyr (Bailey et al. 2016). Furthermore, a binary stellar companion could potentially produce the observed (Batygin & Brown 2016; Chen et al. 2016) high-inclination Centaurs.

Furthermore, the evidence in the distribution of long-period comets for a Jupiter-mass solar companion at a distance of $\sim 10^4$ AU (Matese & Whitmire 2011), which was ruled out (Luhman 2014), could be consistent with the effects of an equal-mass binary companion at ~ 1500 AU acting over a timescale of ~ 0.1 Gyr. The impulse delivered by a binary companion to objects in the OOC scales inversely with the square of the distance between the companion and the OOC objects (Babich & Loeb 2009). While the impulse also scales inversely with the orbital speed of the binary companion, this effect is compensated for by the orbital period scaling with the orbital speed. The total magnitude impulses delivered by the hypothetical Jupiter-mass companion at $\sim 10^4$ AU to OOC objects at similar separations from the Sun would be comparable to those provided equal-mass binary companion at a separation of ~ 1500 AU in the solar birth cluster. The overall structure of the OOC, however, is in a steady-state with little dependence on initial conditions (Fouchard et al. 2017), which is encouraging for the binary capture model of OOC objects.

Finally, we note that the product of velocity dispersion, stellar density, and lifetime, for the solar birth cluster and field, respectively, are comparable to order unity, implying that the minimum impact parameter of a stellar encounter relative to the Sun is similar between the birth cluster and the field. Since the impulse approximation dictates that the velocity shift, Δv , imparted to an orbiting body by a perturber is inversely proportional to the relative encounter speed, the dissociation of the stellar companion from the Sun is more likely to have taken place in the birth cluster than the field by more than an order of magnitude, due to the difference in velocity dispersion between the birth cluster and the field.

3. OUTER OORT CLOUD FORMATION

Next, we quantify the expected abundance of OOC objects for the model considered here, in order to compare to both observations and other models. 2I/Borisov is the only confirmed interstellar comet (Guzik et al. 2020).³ The number density of Borisov-like objects is $n_B \sim 8.8 \times 10^{-3} \text{ AU}^{-3}$ (Jewitt & Luu 2019). Since

³ We do not consider 1I/'Oumuamua to be a traditional comet given the lack of observed outgassing (Micheli et al. 2018; Trilling et al. 2018).

the local number density of stars is $n_f \sim 0.14 \text{ pc}^{-3}$, we estimate that each star produces $\sim 5.5 \times 10^{14}$ Borisov-like objects. The nucleus of Borisov had a diameter of $0.4 - 1 \text{ km}$ (Jewitt et al. 2020), so we adopt the central value of $D \sim 0.7 \text{ km}$, and a cumulative size distribution with a power-law index -3 , corresponding to equal mass per logarithmic bin, as justified by the size distribution of interstellar objects (Siraj & Loeb 2019). The number of $D \gtrsim 2.3 \text{ km}$ interstellar comets produced per star is thereby estimated to be, $\sim 1.6 \times 10^{13}$. The total capture cross-section⁴ for a solar-mass binary with separation $\sim 1500 \text{ AU}$ for objects with a velocity dispersion of $v \sim 1 \text{ km s}^{-1}$ is $\sigma \sim 1.6 \times 10^6 \text{ AU}$ (Heggie 1975; Valtonen 1983), and we adopt a cluster stellar density of $n_c \sim 100 \text{ pc}^{-3}$ and lifetime of $\tau \sim 10^8 \text{ yr}$ (Adams 2010), which is consistent with the limit set by the observed inclination of the cold classical Kuiper belt (Batygin et al. 2020). The fraction of the interstellar comets produced per star captured by such a binary over the lifetime of the solar birth cluster is $(\sigma v \tau n_c) \sim 40\%$. As a result, the number of captured objects over the lifetime of the birth cluster is expected to be $\sim 6.4 \times 10^{12}$.

The closest stellar encounters have the greatest effects on erosion of OOCs (Hanse et al. 2018), so here we focus on the closest stellar encounter to the solar system over the cluster lifetime, and assume that this encounter unbound the stellar binary. Ignoring the gas-rich initial period lasting $\sim 1 \text{ Myr}$, the impact parameter of the closest stellar encounter over the cluster lifetime is estimated to be $b \sim (n_c \tau v)^{-1/2} \sim 2 \times 10^3 \text{ AU}$. We adopt a distance an order of magnitude larger than this impact parameter as the fiducial separation between the Sun and the outer OOC, $r \sim 2 \times 10^4 \text{ AU}$. The mass of the perturbing star is assumed to be, $M_p \sim 0.1 M_\odot$.

The impulse approximation, which holds since $v_p \gg \sqrt{2GM_\odot/r}$, for the velocity kick of an OOC object relative to the Sun as a result of a stellar perturbation (Babich & Loeb 2009) gives,

$$\Delta \mathbf{v} = \frac{2GM_p r}{b^2 v} [\hat{\mathbf{r}} - 3\hat{\mathbf{b}}(\hat{\mathbf{r}} \cdot \hat{\mathbf{b}}) - \hat{\mathbf{v}}^p(\hat{\mathbf{r}} \cdot \hat{\mathbf{v}}^p)] , \quad (1)$$

where $\hat{\mathbf{r}}$ is the vector from the Sun to the OOC object, $\hat{\mathbf{b}}$ is the impact parameter vector from the Sun to the closest approach of the perturber, and $\hat{\mathbf{v}}^p$ is the velocity vector of the perturber.

For simplicity, we consider a model in which the trajectory of the perturber is normal to the orbital plane of the binary, in which case OOC objects with posi-

tion vectors aligned or anti-aligned with the perturber trajectory would receive no velocity kick relative to the Sun, meaning that they remain bound. In particular, the condition for remaining bound post-perturbation is $\Delta v \lesssim \sqrt{GM_\odot/r}$. For the conventions described above, any OOC object within $\sim 14^\circ$ of the perturber's trajectory should remain bound to the Sun. The infinitesimal element of solid angle is $d[\sin \theta]$, and since the average value of $\sin \theta$ over the range of possible perturber trajectory angles is $(2/\pi)$, we use the small angle approximation to apply a correction factor of $(2/\pi)$ to the range of angular separations for which OOC objects survive, resulting in a value of $\sim 9^\circ$ for a typical perturber trajectory. The area covered by points within $\lesssim 9^\circ$ of a diameter vector of a sphere is $\sim 1\%$ of the surface area. We thereby estimate that $\sim 99\%$ of OOC objects are lost due to the stellar encounter that unbinds the binary, resulting in $\sim 8 \times 10^{10}$ surviving objects at the end of the birth cluster lifetime.

The disruptions of OOC orbits by additional passing stars from the birth cluster are relatively insignificant since, as a result of the only the closest stellar encounter, the ejection fraction for OOC objects is $f_e \sim 1$. If we considered the next logarithmic bin of impact parameters, reasoning that the combination of the impulse approximation giving $\Delta \mathbf{v} \propto b^2$ and the fact that $P(b) \propto b^2$ would yield a comparable cumulative Δv , the impulse approximation would break down since $v_p \sim \sqrt{2GM_\odot/r}$, necessitating that we rely on the results of direct simulations like those of Hanse et al. (2018), which show that the closest encounters dominate the loss of comets. We note that the survival of $\sim 1\%$ of the objects captured during the lifetime of the birth cluster the outer OOC is consistent with the finding that $35\% - 75\%$ of objects survive over the lifetime of the solar system excluding the birth cluster (Hanse et al. 2018), since the total numbers of stellar encounters inside and outside of the birth cluster are comparable, and the velocity kick per encounter in the cluster is ~ 20 times larger than in the field.

Propagating the aforementioned uncertainty on the size of Borisov, we estimate that a binary would result in an OOC with $N_{OC} \sim 8 \pm 3.4 \times 10^{10}$ comets with $D > 2.3 \text{ km}$, which is in excellent agreement with the observed value of $N_{OC} \sim 7.6 \pm 3.3 \times 10^{10}$. Based on these calculations, we used a Monte Carlo simulation, the results of which are shown in Figure 2, to quantify the goodness-of-fit of our model versus that of Brassier & Morbidelli (2013) relative to the observations, and found that the overlapping coefficient for the former is ~ 5 times greater than the latter, implying that based upon the current understanding of the OOC, our binary model

⁴ For marginally bound objects with $E \sim 0$, where E is defined after the companion and most objects leave the system.

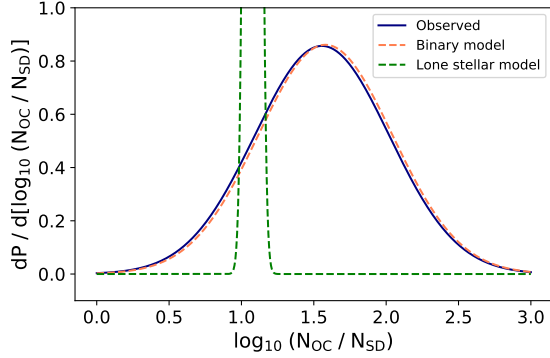


Figure 2. The normalized probability distributions of the ratio between OOC and SD objects for the binary model described here and for the lone stellar model (Brasser & Morbidelli 2013), with the observed ratio (Brasser & Morbidelli 2013) shown for reference.

increases the chances of forming the observed number of OOC objects by a factor of ~ 5 relative to the lone stellar model.

4. PLANET NINE & OVERALL LIKELIHOOD

We now consider the implications of the binary model for the Planet Nine capture cross-section and evaluate the binary model conditional upon a captured origin for Planet Nine being verified. The Planet Nine capture-cross-section for a binary stellar system is (Heggie 1975; Valtonen 1983),

$$\sigma \sim 2 \times 10^5 \text{ AU}^2 \left(\frac{a}{1500 \text{ AU}} \right)^{-1} \left(\frac{m}{M_\odot} \right)^2 \left(\frac{m + M_\odot}{2M_\odot} \right)^{-1} \left(\frac{v}{1 \text{ km s}^{-1}} \right)^{-1} \left(\frac{\sqrt{v^2 + v_c^2}}{\sqrt{2} \text{ km s}^{-1}} \right)^{-6}, \quad (2)$$

where a is the semi-major axis of the binary, m is the mass of the Sun’s binary companion, v is the typical encounter velocity in the solar birth cluster, and v_c is the orbital speed of the captured orbit of Planet Nine. This cross-section is a factor of ~ 20 times greater than the Planet Nine capture-cross section for a lone solar-type star (Table 1, Li & Adams 2016). The binary and lone capture cross-sections would undergo the same enhancements when considering the capture of a planet bound to another star.

We now consider the likelihood of the binary configuration considered here and how this forms the overall statistical argument. The fraction of solar-type stars with roughly equal-mass binary companions is $f_m \sim 0.25$, since there is an overabundance of observed equal-mass binary companions relative to lower masses (Fig.

16, Raghavan et al. 2010; El-Badry et al. 2019). As explained in Section 2, we only consider binary companions at separations $a \gtrsim 1500$ AU. The probability for a binary partner with a separation of $\gtrsim 1500$ AU relative to one with a separation of $\gtrsim 500$ AU is $f_a \sim 0.6$ (Fig. 16, Raghavan et al. 2010). Since $\gtrsim 50\%$ of solar-type stars are members of binaries (Raghavan et al. 2010; Duchêne & Kraus 2013), the likelihood of the binary configuration described here is $f_m f_a f_e \sim 10\%$. We note that these values are primarily based upon observations of binaries in the field and therefore may be conservative for binaries in clusters.

Since the binary model improves the likelihood of the observed OOC population by a factor of ~ 5 and the capture of a putative Planet Nine by a factor of ~ 20 , whereas the binary configuration considered here applies to $\sim 10\%$ of solar-type stars, we find that the discovery of a captured Planet Nine would result in the binary model being favored by an order of magnitude relative to the conventional lone stellar model.

5. DISCUSSION

We propose that an equal-mass binary companion to the Sun in the solar birth cluster at a separation of $\sim 10^3$ AU would explain the formation of the observed population of OOC objects and the putative existence of Planet Nine. Separations greater than the fiducial example given here, $a \sim 1500$ AU, are entirely plausible; the capture cross-section would simply scale as a^{-1} and the likelihood of ejection in the birth cluster as $a^{1/2}$, up to a maximum of $a \sim 6000$ AU since the chance of ejection in the birth cluster would then be of order unity. If Planet Nine is discovered, evidence of a captured origin, as opposed to formation within the Solar system, could potentially come from a cloud of objects with associated orbits (Mustill et al. 2016). Accounting for the likelihood of the binary configuration considered here, the discovery of a captured Planet Nine would favor our binary model by a factor of ~ 10 , when the increased likelihoods of both forming the OOC and capturing Planet Nine are considered.

The specific smoking gun for our binary model will be a significant overabundance of dwarf planets with similar orbits to Planet Nine, since the the capture cross-section for such objects would have been a factor of ~ 20 larger than implied by the conventional lone stellar model, and given that orbits situated closer to the proposed binary than Planet Nine would be unstable (Quarles et al. 2020). These objects could potentially be detected by the Legacy Survey of Space and Time

(LSST)⁵ on the Vera C. Rubin Observatory. In addition, since the binary model would bring the likelihood of Planet Nine capture in the solar birth cluster near unity, the existence of a captured planet in addition to Planet Nine would be probable. Detailed modeling of the effects of a binary on long-period comets, the solar obliquity, and ETNOs will allow for the development of additional tests.

ACKNOWLEDGEMENTS

We thank Fred Adams, Gongjie Li, and Konstantin Batygin for helpful comments on the manuscript. This work was supported in part by the Origins of Life Summer Undergraduate Research Prize Award and a grant from the Breakthrough Prize Foundation.

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⁵ <https://www.lsst.org/>