

## DISCOVERY AND DYNAMICAL ANALYSIS OF AN EXTREME TRANS-NEPTUNIAN OBJECT WITH A HIGH ORBITAL INCLINATION

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## ABSTRACT

We report the discovery and dynamical analysis of 2015 BP<sub>519</sub>, an extreme Trans-Neptunian Object detected by the Dark Energy Survey at a heliocentric distance of 55 AU, perihelion of  $\sim$ 36 AU, and absolute magnitude  $H_r = 4.3$ . The current orbit, determined from an 1110-day observational arc, has semi-major axis  $a \approx 450$  AU, eccentricity  $e \approx 0.92$ , and inclination  $i \approx 54$  degrees. With these orbital elements, 2015 BP<sub>519</sub> is the most extreme TNO discovered to date, as quantified by the reduced Kozai action,  $\eta_0 = (1 - e^2)^{1/2} \cos i$ , which is a conserved quantity at fixed semi-major axis  $a$  for axisymmetric perturbations. We discuss the orbital stability and evolution of this object, and find that under the influence of the four known giant planets 2015 BP<sub>519</sub> displays rich dynamical behavior, including rapid diffusion in semi-major axis and more constrained variations in eccentricity and inclination. We also consider the long term orbital stability and evolutionary behavior within the context of the Planet Nine hypothesis, and find that 2015 BP<sub>519</sub> adds to the circumstantial evidence for the existence of this proposed new member of the solar system, as it would represent the first member of the population of high- $i$ ,  $\varpi$ -shepherded TNOs.

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## 1. INTRODUCTION

The most extreme members of any dynamical class of solar system objects serve as particularly acute test cases for theories of our solar system’s formation and evolution. In particular, Trans-Neptunian Objects (TNOs) with very large semi-major axes probe the most distant observable regions of the solar system, aiding to reveal the migration histories of the giant planets. Very high inclination TNOs and centaurs mostly remain puzzling. Both classes of objects may also be dynamically influenced by distant, yet-unseen perturbers. Indeed, the apparent clustering in orbital and physical space of the so-called “extreme TNOs” with  $a > 250$  AU and perihelion distances  $q > 30$  AU was used by Batygin & Brown (2016a) to argue for the existence of a distant super-Earth known as Planet Nine.

The 13 currently known extreme TNOs have an average orbital inclination of  $17.3^\circ$ . The most highly-inclined of these objects, 2013 RF<sub>98</sub>, was discovered in our earlier work (Dark Energy Survey Collaboration et al. 2016a) and has an inclination of  $29.6^\circ$ , consistent with other members of the scattered disk population. In this work, we report the discovery by the Dark Energy Survey of 2015 BP<sub>519</sub>, a TNO with a semi-major axis of 450 AU (the sixth-largest among known TNOs), an eccentricity of 0.92, and a remarkable inclination of 54 degrees. The orbital elements of this object make it the “most extreme” of the extreme TNOs, in a sense that we make precise in Section 3.2. With a perihelion distance of  $q = 35.249 \pm 0.078$  AU, it may also be the first purely trans-Neptunian member of the Planet-Nine-induced high-inclination population first predicted in Batygin & Morbidelli (2017).

Objects in the outer solar system populate several distinct dynamical categories (Gladman et al. 2008). Cold classical Kuiper Belt Objects (CKBOs) are dynamically cool, with perihelion distances greater than 40 AU, low orbital eccentricities, and low orbital inclinations (Tegler & Romanishin 2000; Elliot et al. 2005). The orbits of these objects are not controlled by dynamical interactions with Neptune, and they may originate from material left over from the formation of the solar system. On the contrary, hot classical KBOs as well as resonant KBOs are believed to have been placed in the trans-Neptunian region from smaller original heliocentric distances. Another class of objects have orbits that are perturbed significantly through scattering interactions with Neptune (Duncan & Levison 1997; Gladman et al. 2002). Yet another set of objects have high eccentricities, but also have sufficiently large perihelia that they are not influenced by either scattering or resonant interactions with Neptune.

Recently, a new subset of objects has attracted considerable attention. The TNOs with semi-major axes  $a > 150$  AU and perihelia distances beyond 30 AU were found in Trujillo & Sheppard (2014) to exhibit a clustering in their argument of perihelion,  $\omega$ . Batygin & Brown (2016a) subsequently noted that this clustering persists in physical space (as measured by the longitude of perihelion  $\varpi$ , where  $\varpi = \omega + \Omega$ , where  $\Omega$  is the longitude of ascending node). Trujillo & Sheppard (2014) noted that one explanation for the clustering might be a ninth planet, and Batygin & Brown (2016a) suggested that the existence of a ninth planet of about 10 Earth masses in the outer solar system could explain the apparent alignment of large-semi-major axis objects (Batygin & Brown 2016a). The motions of objects with  $a > 250$  AU would in this case be dominated by Planet Nine, while TNOs falling in the intermediate regime, with  $a = 150 - 250$  AU, may experience differing degrees of influence from Planet Nine. The TNOs with  $a > 250$  AU constitute the “extreme” TNOs, or ETNOs. The evidence and consequences of the Planet Nine hypothesis have been explored in previous literature from both dynamical and observational perspectives (Batygin & Brown 2016b; Li & Adams 2016; Malhotra et al. 2016; Mustill et al. 2016; Kenyon & Bromley 2016; Bromley & Kenyon 2016; Chen et al. 2016; Holman & Payne 2016a,b; de la Fuente Marcos & de la Fuente Marcos 2016; Sheppard & Trujillo 2016; Shankman et al. 2017a; Millholland & Laughlin 2017; Sallennfest et al. 2017; Becker et al. 2017; Batygin & Morbidelli 2017; Hadden et al. 2017; Parker et al. 2017; Eriksson et al. 2018; Khain et al. 2018). The Planet Nine hypothesis has been invoked to explain the detachment of perihelia distance for the most distant class of TNOs (Khain et al. 2018), the 6 degree solar obliquity (Bailey et al. 2016; Gomes et al. 2017), and the existence of highly inclined objects in the outer solar system (Batygin & Brown 2016b). The subset of objects discovered so far to have semi-major axis greater than 250 AU and perihelion distances greater than 30 AU (the extreme TNOs) includes 2003 VB<sub>12</sub> (known as Sedna, Brown et al. 2004), 2004 VN<sub>112</sub> (MPC), 2007 TG<sub>422</sub> (MPC), 2010 GB<sub>174</sub> (Chen et al. 2013), 2012 VP<sub>113</sub> (Trujillo & Sheppard 2014), 2013 FT<sub>28</sub> (Sheppard & Trujillo 2016), 2013 RF<sub>98</sub> (MPC), 2013 SY<sub>99</sub> (Bannister et al. 2017), 2014 FE<sub>72</sub> (Sheppard & Trujillo 2016), 2014 SR<sub>349</sub> (Sheppard & Trujillo 2016), 2015 GT<sub>50</sub> (Shankman et al. 2017b), 2015 KG<sub>163</sub> (Shankman et al. 2017b), and 2015 RX<sub>245</sub> (Shankman et al. 2017b). The orbital elements of these objects are listed in the Appendix for reference. These objects have inclinations ranging from nearly zero up to a maximum of about 30 degrees.

The orbital inclinations of these high- $a$  objects are of particular interest dynamically. Gladman et al. (2009) discovered 2008 KV<sub>42</sub> (Drac), the first retrograde Centaur (where a Centaur is an object with a semi-major axis between 5 AU and 30 AU, placing its orbit in the region of the solar system containing the gas giants). This object does not appear to be primordial and could imply the existence of a reservoir of high inclination TNOs. The discovery of the retrograde centaur 2011 KT<sub>19</sub> (Niku) (Chen et al. 2016) added to the small collection of such objects, and suggested that they may cluster in a common orbital plane.

Batygin & Brown (2016a) predicted that Planet Nine could create such a supply of objects by sourcing them from a more distant population of high-inclination orbits, which are in turn generated by Planet Nine. Batygin & Morbidelli (2017) presented a dynamical model for the orbital evolution of high-inclination, long period ( $a > 250$  AU) objects and compared the model to the existing high- $a$ , high- $i$  objects. However, the objects then known to reside in that population have perihelia  $q < 30$  AU, and thus experience orbit crossing with the giant planets, complicating their ability to test the Planet Nine hypothesis. To better test this particular prediction of the Planet Nine model, high- $a$ , high- $i$  objects with perihelion  $q > 30$  AU are needed.

Apart from the Planet Nine debate, the continued discovery of new objects in the outer solar system enables a better understanding of how the solar system arrived at its present state. For this reason, many groups have conducted surveys to increase the census of objects known in the outer solar system and better understand their properties (including Millis et al. 2002; Elliot et al. 2005; Müller et al. 2010; Lellouch et al. 2010; Lim et al. 2010; Fornasier et al. 2013; Bannister et al. 2016; Lin et al. 2016). Data from other surveys or archival data sets have also been utilized to enable solar system science (Fuentes & Holman 2008; Solontoi et al. 2012; Ahn et al. 2014). The Dark Energy Survey (DES, Dark Energy Survey Collaboration et al. 2016b) follows in these footsteps, enabling study of new populations including high-inclination objects like 2015 BP<sub>519</sub>.

This paper is organized as follows. We start with a description of the discovery of 2015 BP<sub>519</sub> by DES in Section 2. Given the extreme status of this object, Section 3 considers its dynamical status using a secular approach, starting with an analytic treatment of the problem. The dynamics of this object are rich and complicated, so that a complete characterization requires full N-body numerical simulations to include interactions with Neptune and the other giant planets, as well as other complexities. These numerical simulations are presented in Section 4

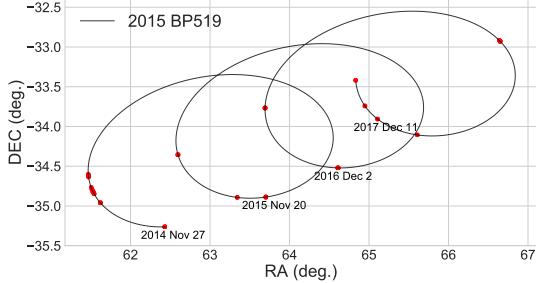
for the dynamics of 2015 BP<sub>519</sub> in the context of the currently known solar system. Section 5 then considers the dynamics of this new object in the presence of the proposed Planet Nine. The paper concludes with a discussion of the implications (Section 6) and a summary of the results (Section 7).

## 2. DISCOVERY OF 2015 BP<sub>519</sub>

DES Dark Energy Survey Collaboration et al. 2016b is an optical survey targeting nearly 5000 square degrees of sky. It uses the Dark Energy Camera (DECam, Flaugher et al. 2015) on the 4-meter Blanco telescope at the Cerro Tololo Inter-American Observatory in Chile. DECam is a prime-focus imager on Blanco with a 3 square degree field of view and a focal plane consisting of 62 2K × 4K red-sensitive science CCDs. DES saw first light in 2012, and the nominal survey period of 520 nights over five years ran from August 2013 through February 2018. During this time, DES has operated in two survey modes. The Wide Survey observes the full of the survey area roughly twice per year in each of the *grizY* bands. The Supernova Survey (Bernstein et al. 2012) consists of ten 3 square degree regions that are observed roughly every 6 days in the *griz* bands. Due to the large survey area, high repetition, and deep limiting magnitude for single-epoch exposures ( $r \sim 23.8$  magnitude), DES has many applications in addition to its main cosmological objectives (Dark Energy Survey Collaboration et al. 2016a). It is well-suited for solar-system science, and in particular to the study of high-inclination populations.

In this paper, we report the discovery of 2015 BP<sub>519</sub>, which has the largest semi-major axis of any object yet found by DES, and the highest inclination of any known extreme TNO. 2015 BP<sub>519</sub> was first detected at a heliocentric distance of 55 AU in the same set of observations from 2013-16 that were used to discover the dwarf planet candidate 2014 UZ<sub>224</sub> (Gerdes et al. 2017). The original detection of 2015 BP<sub>519</sub> came from a difference-imaging analysis of the wide field images (using software from Kessler et al. 2015). Transient objects are found by image subtraction. Artifacts and low-quality detections are rejected using the techniques described in Goldstein et al. (2015). The surviving sources are compiled into a catalog of measurements, each of which corresponds to a transient at one epoch. From those, TNOs are extracted by identifying pairs of detections within 60 nights of each other whose angular separation is consistent with what would be expected for an object with perihelion  $q > 30$  AU given Earth's motion. These pairs are linked into chains of observations that correspond to the same object by testing the goodness of fit of the best-fit orbit for

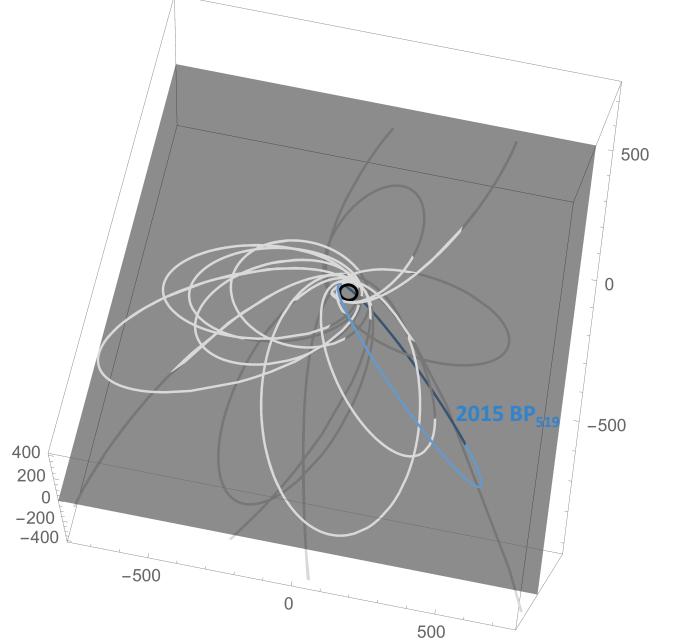
each chain. A reduced chi-squared  $\chi^2/N < 2$  (Bernstein & Khushalani 2000) is considered a detection of a TNO.



**Figure 1.** Trajectory of 2015 BP<sub>519</sub> over its measured four-opposition arc. Larger, red dots along the trajectory indicate points at which it was observed by DES.

Although 2015 BP<sub>519</sub> was originally identified using data from observing campaigns 2-4, we have obtained additional observations in two ways: first, some of the subsequent planned DES exposures provided additional serendipitous observations of this object. Second, we performed three targeted observations on 2 Feb. 2017 and 6-7 August 2017. The result is a series of 30 observations over four oppositions between 27 Nov. 2014 and 15 Feb. 2018, shown in Figure 1. We computed astrometric positions using the WCSFIT software described in Bernstein et al. (2017), which provides astrometric solutions referenced to the Gaia DR1 catalog (Gaia Collaboration et al. 2016). This includes corrections for the effects of tree-ring and edge distortions on the DECam CCDs, as well as for chromatic terms from lateral color and differential atmospheric refraction. We obtain barycentric osculating orbital elements using the method of Bernstein & Khushalani (2000). For consistency with the orbital elements and uncertainties used in the simulation results presented below, our fit uses the 27 observations available through 11 Dec. 2017. The resulting fit has a  $\chi^2$  of 48.2 for 48 degrees of freedom, and a mean residual of 29 mas. These orbital elements are shown in Table 1. 2015 BP<sub>519</sub>'s inclination and orbital orientation relative to the other extreme TNOs is also visualized in Fig. 2 (where the orbital elements used for the other plotted extreme TNOs are given in the Appendix, Table 3).

These 27 observations of 2015 BP519 include 8 measurements in the *g*-band, 9 in *r*-band, 6 in *i*-band, and 4 in *z*-band. Few of these observations were taken in close temporal proximity. To compute the colors of this object, we therefore compute the corresponding absolute magnitude  $H$  of each measurement to correct for the varying object-sun and object-earth distances as well as differences in observational phase. The *g-r* color, for ex-



**Figure 2.** A visual representation of the orbit of 2015 BP<sub>519</sub>, plotted with the other ETNOs as comparisons. For each orbit, the darker regions on the curve denote where an object falls below the plane of the solar system. 2015 BP<sub>519</sub> has the highest inclination of any extreme TNO discovered to date. The full, interactive 3D orbit visualization can be found at <https://smillholland.github.io/BP519/>.

ample, is then computed as  $\langle H_g \rangle - \langle H_r \rangle$ , and its uncertainty is  $(\langle H_g^2 \rangle + \langle H_r^2 \rangle)^{1/2}$ . The moderately red *g-r* and *r-z* colors are consistent with the values measured in (Pike et al. 2017) for objects identified as dynamically excited.

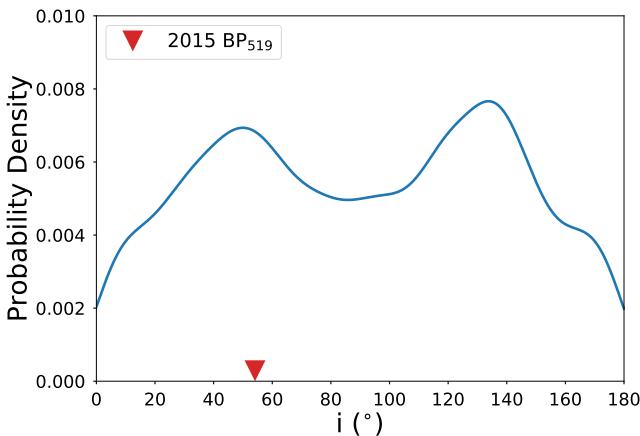
For TNOs with magnitudes in the range  $H \sim 2 - 4$ , measured visual albedos have been found to range between 0.07 and 0.21 (Brucker et al. 2009; Lellouch et al. 2013; Fraser et al. 2014; Gerdes et al. 2016; Holman et al. 2018). With  $H_r = 4.3$ , the diameter of 2015 BP<sub>519</sub> could range from 400-700 km, depending on whether the albedo falls near the high or low end of this range.

Because the DES survey area lies predominantly out of the ecliptic, the status of 2015 BP<sub>519</sub> as the highest inclination TNO of those with semi-major axis  $a > 250$  AU and perihelion  $q > 30$  AU must be considered in the context of possible bias of the DES selection function. To explore this issue, we simulate an ensemble of clones of 2015 BP<sub>519</sub> and test their recoverability in the DES TNO search pipeline. The orbital elements of these clones are drawn from the observed posteriors provided in Table 1, but with the inclination angle  $i$  drawn from a uniform distribution between 0 and 180 degrees. We

then compute the orbits of these objects and where the clones would fall on the nights DES observed.

Using these synthetic orbital elements, we first remove any object that is not detectable by DES because it is either too faint or outside the survey area. We then compute the position of each remaining clone at the time of every DES exposure belonging to the data set in which 2015 BP<sub>519</sub> was discovered, and determine which clones could be linked together into an orbit. The clones that could be identified as candidates are those with at least three observations on three different nights separated by less than 60 nights, and with observations on at least five different nights in total.

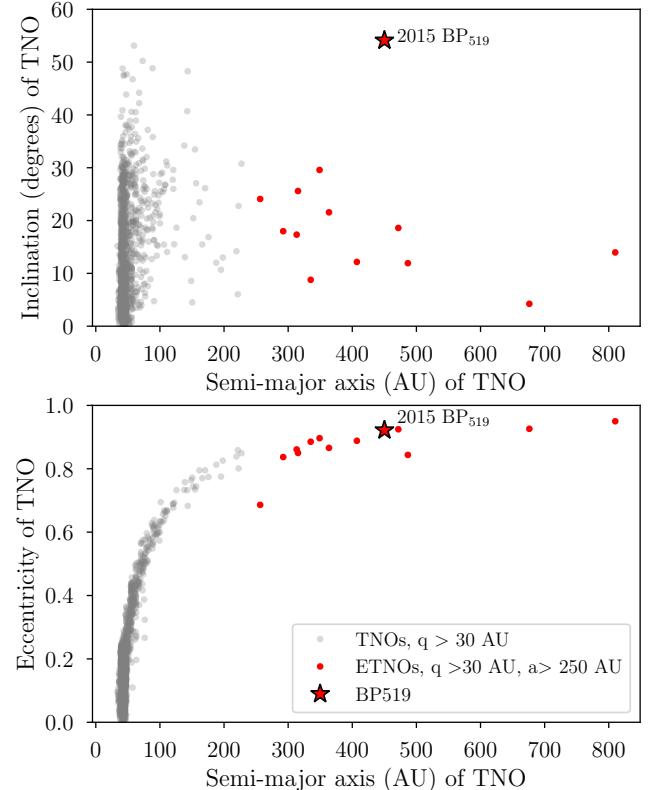
The distribution of clones that survives this process, and hence is potentially detectable, is presented in Fig. 3. This plot thus shows the sensitivity function for objects with the orbital parameters ( $a, e, \omega, \Omega$ ) of 2015 BP<sub>519</sub>, but with varying orbital inclinations and mean anomalies. The resulting sensitivity function shows some structure, but is not heavily biased toward the observed inclination angle of 2015 BP<sub>519</sub>.



**Figure 3.** The DES selection function for the discovery of objects with the orbital elements of 2015 BP<sub>519</sub>, but with varying inclination angles. The value for 2015 BP<sub>519</sub> is shown as the red triangle. The probability distribution is normalized so that the area under the curve is unity.

2015 BP<sub>519</sub> has the highest inclination of any known TNO (defined as objects with  $q > 30$  AU). 2015 BP<sub>519</sub> also has an extreme eccentricity (0.92). Figure 4 compares the inclination and eccentricity occurrences by semi-major axis of the regular and extreme ( $a > 250$  AU) TNO populations. Compared to the other known TNOs, 2015 BP<sub>519</sub> has the largest orbital inclination. Since the number of known ETNOs is small, however, is it unclear where 2015 BP<sub>519</sub>'s inclination places it in the true distribution of ETNO inclinations. For regular

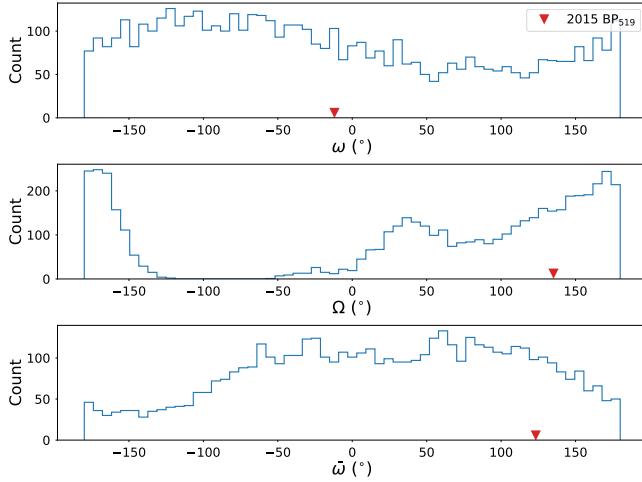
TNOs (objects with perihelion distance  $q > 30$  AU but any semi-major axis), for which nearly 1500 have been discovered, 2015 BP<sub>519</sub> is the most extreme and seems to lie at the upper tail of the inclination distribution of known objects; among TNOs, 2015 BP<sub>519</sub> has the highest currently measured value, but this population is by no means complete.



**Figure 4.** The distributions of inclinations (top panel) and eccentricities (bottom panel) for the two populations of TNOs considered in this work: all objects with perihelia distances greater than 30 AU, and then the subset of those with semi-major axes greater than 250 AU. Orbits of known objects are fit from observations posted to the Minor Planet Center database. 2015 BP<sub>519</sub> represents the tail of the inclination distribution of the known TNOs, as well as the upper limit of eccentricities populated by TNOs.

In Fig. 5, we plot a sensitivity histogram computed in the method described above, but for objects with the orbital parameters ( $a, e, i$ ) of 2015 BP<sub>519</sub>, and varying  $\omega$  and  $\Omega$ . As was true for the previous sensitivity function, the final sensitivity histogram shows some structure in each orbital angle of interest, but is not heavily biased towards the measured angles of 2015 BP<sub>519</sub> (which happen to be consistent with the region of clustering that was used to predict Planet Nine, as will be discussed fur-

ther in later sections of this paper; Trujillo & Sheppard 2014; Batygin & Brown 2016a).



**Figure 5.** The DES selection function for the discovery of objects with the orbital elements ( $a, e, i$ ) of 2015 BP<sub>519</sub>, but with varying angles  $\omega$ ,  $\Omega$ . The observed values for 2015 BP<sub>519</sub> are shown as red triangles on each panel. For objects with the orbital elements ( $a, e, i$ ) of 2015 BP<sub>519</sub>, the DES observation bias allows discovery of  $\omega$  and  $\Omega$  subtending most of the allowable ranges.

### 3. CHARACTERIZATION OF 2015 BP<sub>519</sub>

As a starting point, we consider the dynamical behavior of 2015 BP<sub>519</sub> using a secular treatment. The basic approach is outlined and compared with numerical N-body experiments in subsection 3.1, and this formalism is used to elucidate the extreme nature of this object in subsection 3.2.

#### 3.1. Secular Dynamics

A secular approach averages over the mean motion of solar system objects and thus allows for a simplified treatment of the long-term dynamics. Kozai (1962) provided secular equations for the orbital evolution of small bodies with high inclinations and eccentricities in the presence of an inner perturber. Here we want to describe the behavior of 2015 BP<sub>519</sub>, which orbits outside a system of four interior perturbers (namely, the known giant planets). The contribution from the terrestrial planets is negligible in this context. We can write the mean perturbing function  $R_m$  for a test particle evolving in the

**Table 1.** Orbital Elements of 2015 BP<sub>519</sub>

Parameter	Value
$a$	$448.99 \pm 0.49$ AU
$e$	$0.92149 \pm 0.00009$
$i$	$54.1107 \pm 0.00001$ deg
$\omega$	$348.058 \pm 0.00136$ deg
$\Omega$	$135.2131 \pm 0.00010$ deg
Time of Perihelion (JD)	$2473015.55 \pm 0.56$
Perihelion	$35.249 \pm 0.078$ AU
Aphelion	$862.733 \pm 0.972$ AU
Orbital Period	$9513.84 \pm 15.42$ years
Absolute magnitude	$H_r = 4.3$
$g-r$ (mag)	$0.79 \pm 0.17$
$r-i$ (mag)	$0.19 \pm 0.12$
$r-z$ (mag)	$0.42 \pm 0.15$
$i-z$ (mag)	$0.23 \pm 0.15$

NOTE—2015 BP<sub>519</sub> barycentric osculating elements at epoch 2456988.83, based on 27 observations over a 1110-day arc from 27 Nov. 2014 to 12 Dec. 2017. 2015 BP<sub>519</sub> has a mean anomaly 358.34 degrees and will reach perihelion on 14 Oct. 2058.

presence of a set of inner planets in the form

$$R_m = \frac{G}{16a^3(1-e^2)^{3/2}} \left[ \sum_j^N (m_j a_j^2) (1 + 3 \cos 2i) \right. \\ \left. + \frac{9 \sum_j^N (m_j a_j^4) (2 + 3e^2) (9 + 20 \cos 2i + 35 \cos 4i)}{512a^2(1-e^2)^2} \right. \\ \left. + \frac{9 \sum_j^N (m_j a_j^4) 40e^2(5 + 7 \cos 2i) \cos 2\omega \sin^2 i}{512a^2(1-e^2)^2} \right], \quad (1)$$

where the effects of the inner planets are included here as a mean moment of inertia (Gallardo et al. 2012). In this expression,  $G$  is the gravitational constant ( $G = 4\pi^2$ ; we work in units of solar mass, AU, and year),  $(a, e, i)$  are the orbital elements of the test particle,  $\sum_j^N (m_j a_j^2)$  is the moment of inertia in the direction out of the plane containing the giant planets, and the label  $j$  denotes each giant planet under consideration.

From this secular Hamiltonian, we can derive an expression for the time evolution of the inclination angle using Lagrange's planetary equations, which takes the

form

$$\frac{di}{dt} = -\tan(i/2)(na^2\sqrt{1-e^2})^{-1} \left( \frac{dR_m}{d\epsilon} + \frac{dR_m}{d\omega} \right) - (na^2\sqrt{1-e^2}\sin i)^{-1} \frac{dR_m}{d\Omega}. \quad (2)$$

where  $n = (GM/a^3)^{1/2}$  is the mean motion,  $M$  is the mass of the central body, and  $\epsilon$  is the mean longitude at epoch. Combining the previous two expressions yields the equation of motion for  $i$ :

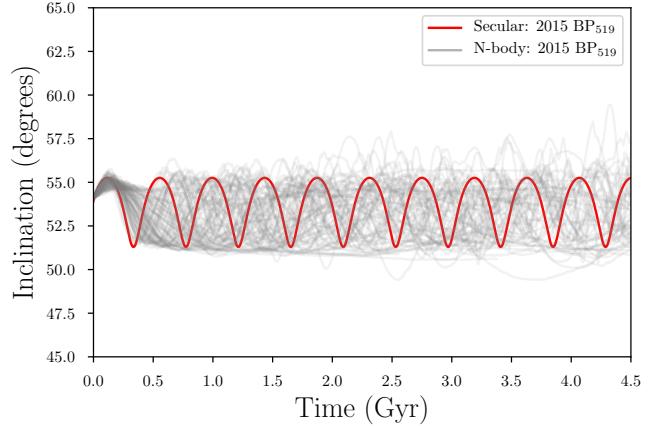
$$\frac{di}{dt} = \frac{45e^2G^{1/2}\sum_j^N(m_ja_j^4)}{1024M^{1/2}a^{11/2}(1-e^2)^4}(5+7\cos 2i)\sin 2i\sin 2\omega. \quad (3)$$

Analogous equations can also be constructed using the other Lagrange planetary equations, resulting in equations of motion for  $de/dt$ ,  $d\omega/dt$ ,  $d\Omega/dt$  (see Equations 7-11 of Gallardo et al. 2012), and  $da/dt = 0$ . Using the known (estimated) orbital elements for 2015 BP<sub>519</sub> (see Table 1) as initial conditions, we simultaneously solved these five equations of motion, resulting in predicted secular evolution for 2015 BP<sub>519</sub>'s orbital evolution. This result is shown in Fig. 6 as the solid curve. The figure shows additional curves in thinner grey lines corresponding to the orbital evolution computed for the same initial conditions, but using full N-body integrations instead of secular theory. These simulations are described in full in the following section, and their parameters are also summarized as Set 1 in Table 2. As a quick summary, these integrations are computed using the *Mercury6* integration package (Chambers 1999), using the hybrid symplectic and Bulirsch-Stoer (B-S) integrator and a time-step of 20 days. In these simulations, all four of the known giant planets are treated as active bodies (rather than being modeled using the  $J_2$  approximation that is often used).

Figure 6 shows that the secular approximation provides a good order of magnitude description of the time evolution of the inclination angle, even through the secular approximation does not include the scattering interactions that lead to slight divergence in the N-body simulations. Both the secular and N-body treatments predict that, in the known solar system, the inclination of 2015 BP<sub>519</sub> will remain fairly well constrained around its presently observed value.

### 3.2. The Extreme Nature of 2015 BP<sub>519</sub>

Although the orbit of 2015 BP<sub>519</sub> is highly unusual among known TNOs, we need a quantitative assessment of its properties relative to other TNOs of its dynamical class. Toward that end, we consider the Kozai Hamilton-



**Figure 6.** The future evolution of 2015 BP<sub>519</sub> (using its current day best-fit orbital parameters as initial conditions) in the presence of the known solar system. The secular curve plotted as a solid dark line was solved from the disturbing function (Equation 1) and the best-fit orbital elements of 2015 BP<sub>519</sub>. The numerical results, plotted as grey lines, are drawn from simulation Set 1, where the orbit of 2015 BP<sub>519</sub> is evolved in the presence of the known solar system for 4.5 Gyr. See Table 2 for more details on the simulation parameters.

nian written in Delaunay coordinates (Thomas & Morbidelli 1996), for which the action  $H$  is defined as:

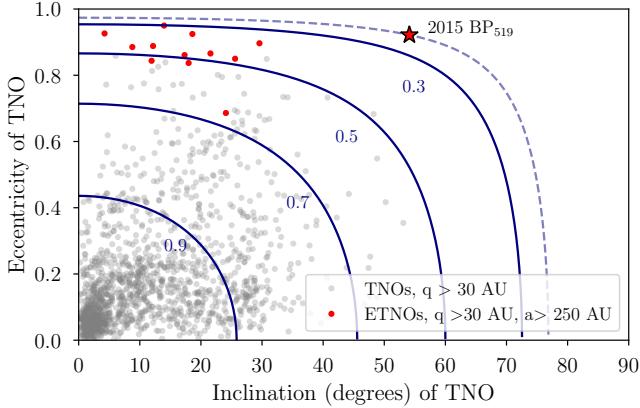
$$H = \sqrt{a(1-e^2)}\cos i. \quad (4)$$

Note that this action is equivalent to the standard ' $\mathcal{H}$ ' variable in Delaunay coordinates (Murray & Dermott 1999) and is a constant of the motion in the quadrupolar approximation. The action  $L = \sqrt{a}$  will also be constant, as the Kozai Hamiltonian averaged over the mean anomaly and thus rotationally invariant and thus depends only on action  $G = \sqrt{a(1-e^2)}$  and coordinate  $g = \omega$ , with actions  $L$  and  $H$  being conserved. Next, we define a reduced Kozai action  $\eta_0$ , which has the form

$$\eta_0 = \sqrt{(1-e^2)}\cos i. \quad (5)$$

As action  $L$  is conserved for the Kozai Hamiltonian, this reduced form of action  $H$  should also be conserved. Note that  $\eta_0$  is the specific angular momentum vector in the direction out of the plane of the solar system (Kinoshita & Nakai 1999; we follow the notation in Saillenfest et al. 2016). For sufficiently distant TNOs, the potential of the solar system is effectively axially symmetric (but not spherically symmetric), so that the  $z$ -component of angular momentum (but not total angular momentum) is conserved. In the known solar system, TNOs with constant semi-major axis are thus expected to evolve in  $(i, e)$  space along contours of constant  $\eta_0$ . In Fig. 7, we overlay curves of constant  $\eta_0$  on a plot comparing the  $i, e$  of all TNOs and ETNOs discovered so far. Compared to

previously discovered objects, 2015 BP<sub>519</sub> has the lowest  $\eta_0$  value which signifies its relative extremeness.



**Figure 7.** We plot curves of constant  $\eta_0$  in  $(i, e)$  space (see Equation 5). Also plotted are (in grey) the orbital elements of all objects with perihelion distances outside of Neptune and data quality flags of 6 or better, as reported to the Minor Planet Center database (files downloaded 10/25/2017) and (in red) the subset of those objects that also have a semi-major axis measured to be  $a > 250$  AU. With  $\eta_0 = 0.2274$ , 2015 BP<sub>519</sub> has the lowest value of  $\eta_0$  out of any TNO with  $q > 30$  AU that has been discovered thus far. This metric, which measures the extremeness of the  $(i, e)$  of each object, characterizes 2015 BP<sub>519</sub> as the most extreme of the extreme TNOs.

#### 4. FULL DYNAMICS OF 2015 BP<sub>519</sub> IN THE KNOWN SOLAR SYSTEM

The analytic formulation presented in Section 3 classifies 2015 BP<sub>519</sub> as the most extreme TNO discovered in the outer solar system to date, due to its high inclination, high eccentricity, and large semi-major axis. However, the secular approximation used in the previous section neglects the importance of interactions with Neptune, which will occur when 2015 BP<sub>519</sub> reaches its perihelion. 2015 BP<sub>519</sub>'s relatively small perihelion distance ( $\approx 35$  AU) suggests that it will be subject to repeated strong interactions with Neptune, which will change the energy of 2015 BP<sub>519</sub>'s orbit by a factor of roughly  $6 \times 10^{-6}$  per perihelion crossing (when this process can be modeled as a random walk; see Fig. 1 of Duncan et al. 1987). The change in orbital energy will also lead to change in the semi-major axis of the orbit, and as a result, the level curves presented in Fig. 7 may not truly represent the evolution of 2015 BP<sub>519</sub> over extended spans of time. Instead, quantities which appear as constants of motion in the previous section

( $\eta_0$ ) will no longer be conserved as 2015 BP<sub>519</sub> changes its orbital elements, in particular its semi major axis, due to interactions with Neptune. The true orbital evolution, being the result of a chaotic process, will also vary widely between trials in numerical integrations. As shown in Fig. 6, the numerically computed orbital evolution does not perfectly match the secular expectation, and multiple integrations of the same object will give slightly different periods and amplitudes of evolution.

To fully test the effect of additional dynamics not encapsulated by the secular analysis of the previous section, we perform a suite of numerical N-body simulations using computing resources provided by Open Science Grid (Pordes et al. 2007; Sfiligoi 2008; Sfiligoi et al. 2009) through the Extreme Science and Engineering Discovery Environment (XSEDE) portal (Towns et al. 2014). These simulations include the new body 2015 BP<sub>519</sub> and all of the relevant known solar system objects (the case of Planet Nine is considered in the following section, but is excluded from this initial set of simulations).

#### 4.1. Numerical Evolution of 2015 BP<sub>519</sub> in the Known Solar System

The precession time scales and orbital evolution of 2015 BP<sub>519</sub> can be tested more directly with numerical N-body simulations. To examine the complete evolution of 2015 BP<sub>519</sub> in the known solar system, we perform a suite of numerical integrations using the *Mercury6* integration package (Chambers 1999). We exclude the terrestrial planets from the simulations, but include the gas giants (Jupiter, Saturn, Uranus, and Neptune) as active, massive particles with their currently measured masses and orbital elements. We start with a time-step of 20 days, which is roughly 0.5% of Jupiter's orbital period. We use the hybrid symplectic and Bulirsch-Stoer (B-S) integrator built into *Mercury6* and conserve energy to better than 1 part in  $10^9$  over the course of the 4.5 Gyr integrations. The orbital elements for 2015 BP<sub>519</sub> are drawn from the covariance matrix derived from the fit to the DES data. Fifty-two simulations are run of the solar system, each with five clones of 2015 BP<sub>519</sub>. Half of these simulations are integrated forward in time from the current day, and the other half evolve back in time for 4.5 Gyr. Other parameters used for this set of simulations (which we call Set 1 in this work) are given in Table 2.

The results of these integrations are presented in Fig. 8, and demonstrate that the semi-major axis of 2015 BP<sub>519</sub> diffuses widely in the presence of the known giant planets. The perihelion distance tends to remain fairly well-confined near the initial value of even as the

**Table 2.** Simulation Sets used in this work

Set	Initial Timestep	Active Planets	$J_2$	Abs. Radius	Backwards Clones	Forward Clones	Details
Set 1	20 days	4 (JSUN)	$2 \times 10^{-7}$	$4.65 \times 10^{-3}$ AU	130	130	No P9
Set 2	3000 days	1 (P9)	0.00015244	20 AU	0	1000	low $i^1$ , P9 $^2$
Set 3	3000 days	1 (P9)	0.00015244	20 AU	0	1000	P9 $^2$
Set 4	200 days	2 (N,P9)	0.00036247	9.8 AU	0	600	P9 $^2$
Set 5	20 days	5 (JSUN, P9)	$2 \times 10^{-7}$	$4.65 \times 10^{-3}$ AU	0	130	P9 $^2$

NOTE—A list of the sets of simulations used in this work, with their relevant parameters listed. When included as active particles in a simulation, gas giant planets are denoted by their first initials (J for Jupiter, S for Saturn, U for Uranus, N for Neptune) and when Planet Nine is included, it is denoted by P9. The absorbing radius is the radius of the central body in the simulations. The ejection radius is set to 10000 AU for all simulation sets, and all integrations are run for 4.5 Gyr. Except when denoted otherwise, the orbital elements of 2015 BP<sub>519</sub> are drawn from the covariance matrix describing the best-fit values and errors in Table 1. Simulations were run in batches; for simulation Sets 1 and 5, 5 clones of 2015 BP<sub>519</sub> were included as test particles in each individual integration. For simulation Sets 2, 3, and 4, 10 clones were included in each integration.

<sup>1</sup> Inclination of 2015 BP<sub>519</sub> was drawn from a half-normal distribution around 0 degrees with a width of 5 degrees. <sup>2</sup> The best-fit version of Planet Nine from Batygin & Morbidelli (2017) was used (700 AU, 0.6 eccentricity, 20 degrees inclination). The solar quadrupole moment  $J_2$  is defined by Eq. 6 when any giant planets are absorbed, and set to the solar value otherwise (Pireaux & Rozelot 2003).

orbital energy changes due to repeated kicks from Neptune.

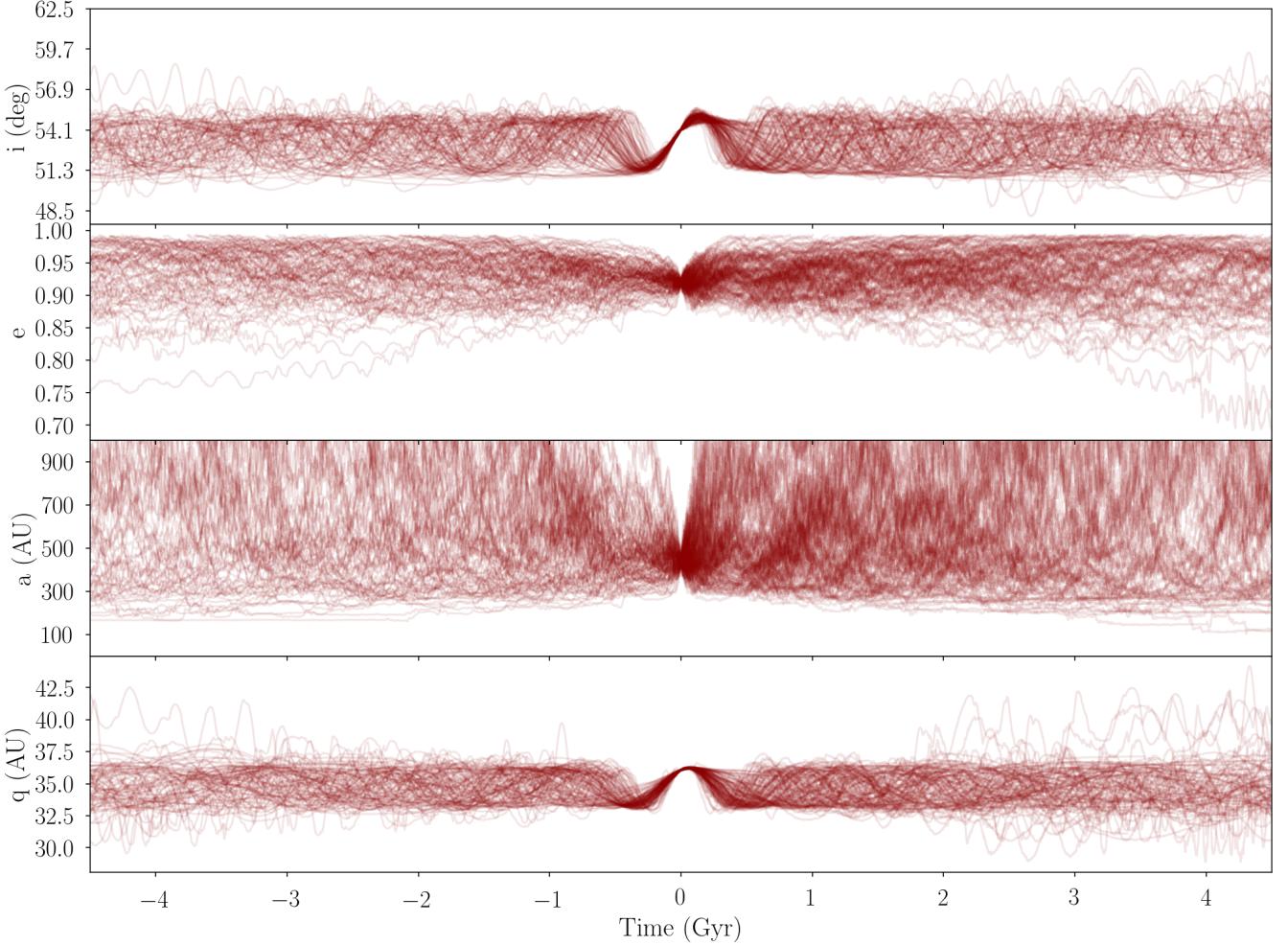
The Hamiltonian used in Section 3.2 requires that the semi-major axis of the particle remain roughly constant. From these simulations, it is clear that the semi-major axis of 2015 BP<sub>519</sub> tends to change significantly over relatively rapid ( $\sim 10^6 - 10^7$  year) timescales. As such, Equation 5 is a good model for 2015 BP<sub>519</sub>'s short-term dynamical behavior, but not its long-term orbital evolution.

#### 4.2. Generating Highly Inclined Objects in the Known Solar System

In the previous section, we used numerical simulations to determine the expected evolution of 2015 BP<sub>519</sub> in the presence of the four known gas giants. The results show that the inclination of 2015 BP<sub>519</sub> tends to be confined to within a range of roughly 5 degrees. Although the semi-major axis diffuses over a wide range of values, the corresponding evolution in eccentricity is constrained by the behavior of the perihelion: to leading order, the perihelion distance of 2015 BP<sub>519</sub> remains well confined. Specifically,  $q$  is constant to within  $\sim 5$  AU over the entire envelope of all dynamically stable clones. The eccentricity evolution of 2015 BP<sub>519</sub> is thus explained by the requirement that the perihelion remains nearly constant as the semi-major axis varies. Moreover, this behavior is mediated by Neptune. The orbital evolution

is consistent with that expected for a member of the scattered disk.

The high present-day inclination of 2015 BP<sub>519</sub> is more difficult to explain. In the numerical simulations shown in Figure 8 in the context of the currently-observed solar system, the orbital inclination of 2015 BP<sub>519</sub> is found to remain roughly constant. This trend holds for simulations running both backwards and forwards in time. Since the solar system formed from a disk, we expect the orbital inclination of 2015 BP<sub>519</sub> to be low at birth. The transition from an initially low inclination orbit to the present-day (high) value must be explained by some mechanism that is not included in our simulations. Some possible explanations include the following: a passing star could excite objects to highly inclined and eccentric orbits; a particularly favorable impact parameter during a close encounter with Neptune could excite an object out of the plane of the solar system; the high inclination could be a fossil from violent migration processes in the early solar system; the self-gravity of a large disk of planetesimals in the scattered disk; and finally, the existence of proposed solar system member Planet Nine, which could lead to secular evolution in eccentricity and inclination for long-period TNOs, thereby producing the current-day orbit of 2015 BP<sub>519</sub>. In this section, we briefly consider the first three possibilities, and then examine the Planet Nine hypothesis in detail in Section 5.



**Figure 8.** The results of numerical simulations where 2015 BP<sub>519</sub> is evolved forward and backward in time in the presence of the four giant planets (Set 1; see Table 2). All trials are plotted here; curves that end prematurely before 4.5 Gyr correspond to the integrations where a clone becomes dynamically unstable (collision into the central body, ejection from the system, physical collision with a planet, or a scattering event resulting in an unbound orbit). For trials that remain dynamically stable, the inclination and eccentricity are relatively well constrained to values near their initial conditions. The semi-major axis of 2015 BP<sub>519</sub> diffuses rapidly.

#### 4.2.1. Scattering interactions with other stars

As most planetary systems form in clusters (Lada & Lada 2003; Porras et al. 2003), the solar system is likely to have formed in such an environment (Adams 2010). Dynamical interactions between cluster members can shape the dynamics of the constituent planetary systems (Brasser et al. 2012a). The interactions tend to have a moderate effect (Adams et al. 2006), but can nonetheless sculpt the outer portions of the planetary system or the original disk, which are of interest here. Interactions in the birth cluster are expected to dominate over those that occur later on in the field, but the latter can still be significant. If the trajectory of a binary or single star brings it sufficiently close to a star hosting a planetary system, the geometry of the plane-

tary system can be altered (Jiménez-Torres et al. 2011). For example, Kenyon & Bromley (2004) discuss the possibility that Sedna's orbit is the result of a passing star perturbing the orbit of objects in the Kuiper Belt. They find that if such a star had its own disk of planets and planetesimals, then some objects could be captured into our solar system onto high-inclination orbits. It is thus possible that 2015 BP<sub>519</sub> is the result of interactions between our solar system and another external, perturbing body. The interaction cross sections for such events are much larger at the low fly-by speed realized in young embedded clusters (Li & Adams 2015), so that the required event is more likely to occur in the birth cluster (compared to the field).

#### 4.2.2. Scattering interactions with Neptune

As discussed in [Duncan et al. \(1987\)](#), TNOs will experience a perturbation in orbital energy at each periapsis, when the TNO passes closest to the orbit of Neptune. Although Fig. 8 demonstrates that in our set of backwards integrations 2015 BP<sub>519</sub> has retained *roughly* the same inclination for the past 4.5 Gyr, there is some variation among the individual trials. More specifically, one particular integration in the backwards time direction attained (at one point) an orbital inclination of 60 degrees, although such a large value was not attained in any of the other integrations in either direction. With a large enough set of simulations, one could find the probability that 2015 BP<sub>519</sub> could originate in an orbit closer to the plane of the solar system, and subsequently evolve into its present orbit. In this scenario, 2015 BP<sub>519</sub> could have reached its high inclination from a series of extreme scattering events with Neptune. Our current set of numerical simulations shows that this scenario is possible, but unlikely.

#### 4.2.3. Remnant of planetary migration

The Nice model ([Tsiganis et al. 2005](#); [Morbidelli et al. 2005](#); [Gomes et al. 2005](#)) suggests that even if the solar system starts as a roughly co-planar disk, the planets attain their small eccentricities and inclinations through scattering events with the large reservoir of planetesimals in the outer solar system. Some of these bodies will be forced to high eccentricities and inclinations, while others will be able to maintain their lower ( $e, i$ ) distributions ([Levison et al. 2008](#)). This scenario is characterized by a short period of extreme instability, which corresponds to the Late Heavy Bombardment inferred in the history of our solar system (at an age of  $\sim$ 600 Myr). As a result of this violent period, high-inclination objects can be created from objects originating at the outer edge of the planetesimal disk. Although it is unclear how an object with a semi-major axis as high as that of 2015 BP<sub>519</sub> would be generated in this process, we cannot exclude the idea that 2015 BP<sub>519</sub>'s currently observed orbital inclination may come from a period of violent instability in the early history of the solar system.

Another explanation for high semi-major axis, high eccentricity orbits could be the diffusion hypothesis proposed in [Bannister et al. \(2017\)](#) for the generation of 2013 SY<sub>99</sub>'s orbit. Objects with the longest orbital periods may sequentially scatter outwards, detach their perihelia through galactic tides, and then diffuse inwards into orbits with long periods and detached perihelia. Galactic tides start to dominate once an object attains a semi-major axis of roughly 3000 AU or more ([Duncan et al. 1987](#)), meaning that the currently-observed

TNOs are not generally susceptible to these effects. This mechanism does appear to describe 2013 SY<sub>99</sub>, an object with a semi-major axis  $a \approx 730$  AU and an eccentricity of 0.93, which fits into the dynamical class of objects that would be produced by this mechanism. However, 2015 BP<sub>519</sub>'s perihelion is not sufficiently detached (35 AU vs. 50 AU for 2013 SY<sub>99</sub>) for this mechanism to operate.

Another explanation for this object's extreme orbit could be galactic tides acting on remnants of the inner Oort cloud. It has been suggested ([Brasser et al. 2012b](#)) that centaurs may come from the inner Oort cloud rather than the scattered disk. [Brasser et al. \(2012a\)](#) shows that the median inclination of the inner Oort cloud should be around 50 degrees. As mentioned in [Brasser et al. \(2012a\)](#), the number and orbital parameters of objects with large semi-major axis can be used to constrain birth cluster properties. An object at 450 AU would be near the inner 2-5% of the cloud, depending on the density profile used. However, objects formed via this mechanism (such as SY99, [Bannister et al. 2017](#)) would be expected to have detached perihelia distances, which 2015 BP<sub>519</sub> does not.

[Silsbee & Tremaine \(2018\)](#) discuss the possibility that a potentially planetary-mass object (sub-earth mass) could have formed among the giant planets, and its influence during Neptune's migration could have excited TNOs to present-day high inclinations. This object is distinct from the Planet Nine discussed in the next section.

#### 4.2.4. Self-gravity of the scattered disk

A sufficiently large (1-10 Earth masses in total mass), eccentric disk would experience an instability due to the self-gravity of the disk ([Madigan & McCourt 2016](#)). This proposed instability could cause clustering in  $\omega$  (as observed) for the objects experiencing the instability, and a subsequent pumping of inclination for objects that find their apocenter above the orbital plane ([Madigan et al. 2018](#)). This would result in the population of high inclinations for eccentric objects. 2015 BP<sub>519</sub> could undergo this mechanism if the scattered disk contains enough mass to cause the instability: for this explanation to be feasible, a large number of additional objects in the scattered disk will need to be found, as the early mass of the scattered disk must have been high for this instability to occur.

## 5. DYNAMICS IN THE PRESENCE OF PLANET NINE

Many recent papers have considered the existence of a possible ninth planet. In this section, we consider how the existence of Planet Nine would alter the orbital

behavior and evolution of 2015 BP<sub>519</sub>. In considering possible dynamical interactions between 2015 BP<sub>519</sub> and Planet Nine, there are two main classes of effects that may be relevant:

- Constant- $a$  evolution (while in or near resonance with another body). Due to 2015 BP<sub>519</sub>'s large semi-major axis, we do not expect Neptune resonances to be relevant. The longest period objects known to be in resonance with Neptune have semi-major axis of  $\sim 130$  AU (Volk et al. 2018). 2015 BP<sub>519</sub>'s semi-major axis of  $\sim 450$  AU is likely too large for these processes to be relevant. However, resonances with Planet Nine may be important.
- Diffusion and scattering in  $a$  due to close encounters with Neptune or Planet Nine. These encounters may be very close ( $< 3$  AU) and lead to significant changes in the orbit of 2015 BP<sub>519</sub>, or may be more distant (5-15 AU) and act more as a series of perturbations than an abrupt change.

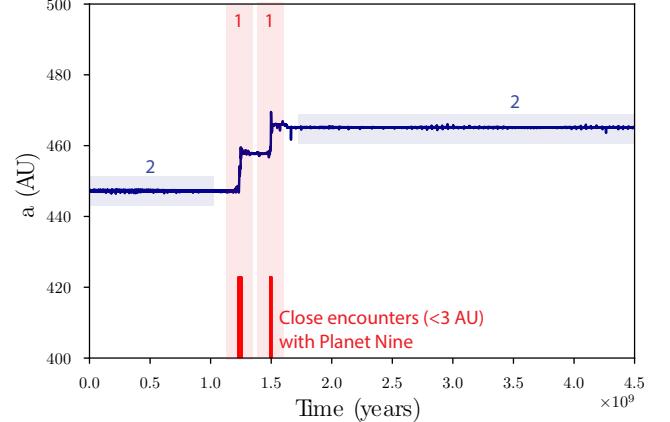
Both of these modes of evolution can occur over the entire history of the solar system. For example, Fig. 9 shows one sample numerical realization of the orbital evolution of 2015 BP<sub>519</sub>, which demonstrates these two evolutionary modes within a single 4.5 Gyr integration.

### 5.1. Evolution with Constant Semi-major Axis

The existence of Planet Nine can lead to a behavior in which TNOs “hop” between resonances (Becker et al. 2017; Hadden et al. 2017). This is differentiated from ‘resonance sticking’ (Duncan & Levison 1997; Robutel & Laskar 2001; Lykawka & Mukai 2006), where scattered disk objects are temporarily captured into resonances with Neptune. In the Planet Nine paradigm, TNOs generally spend more time living in resonances than not, with relatively short periods between the attainment of resonances.

An example of what resonance hopping looks like is given in Fig. 9, where the semi-major axis makes sudden transitions between relatively long periods at nearly constant values (note that further examples can be found in Figures 8 and 9 of Becker et al. 2017). The transitions in the resonance hopping paradigm are generally caused by close encounters with either Neptune or Planet Nine.

Batygin & Morbidelli (2017) conducted a thorough analytic and numerical exploration of the evolution of TNOs in the case where the TNOs remain at a nearly constant semi-major axis. Fig. 9 demonstrates the typical behavior of 2015 BP<sub>519</sub> in the presence of Planet Nine – for extended periods of time, it orbits with



**Figure 9.** A single clone of 2015 BP<sub>519</sub> in the presence of Planet Nine drawn from Set 3 of our simulations. There are two modes of evolution, both shown and labeled in this panel. The first (1) occurs when 2015 BP<sub>519</sub> passes physically close to Planet Nine (a close encounter), and the orbit of the TNO may be slightly jostled. Times when 2015 BP<sub>519</sub> passes within 3 AU of Planet Nine are denoted with red vertical lines. When close encounters occur, the orbit of 2015 BP<sub>519</sub> is altered and appears to migrate for some time before settling into a new equilibrium semi-major axis. These jumps are the same ‘resonance hopping’ discussed in previous work (Becker et al. 2017). The second mode of evolution shown here (2) occurs when the semi-major axis remains constant, but the inclination and eccentricity of 2015 BP<sub>519</sub> may still evolve. The work in Batygin & Morbidelli (2017) describes what happens during these (2) regions of constant semi-major axis.

a roughly constant semi-major axis, until a close encounter (denoted by red vertical bars in the figure) perturbs the semi-major axis into a different value. A new equilibrium is quickly attained, and the object returns to evolution with nearly constant semi-major axis  $a$ . During the long periods of constant- $a$  orbital motion, the dynamics described in Batygin & Morbidelli (2017) will apply, as described below.

To study the evolution of 2015 BP<sub>519</sub> under the same conditions starting in the early solar system and integrating to the current day, we conduct another set of simulations (Set 2; see Table 2). In contrast to the earlier Set 1 integrations, where the giant planets were considered as active bodies, these simulations absorb all four gas giants into the quadrupole moment of the central body. The corresponding contribution of the planets to the value of  $J_2$  is given by

$$J_2 = \frac{1}{2} \sum_{j=1}^4 \frac{m_j a_j^2}{M R_{abs}^2}, \quad (6)$$

where  $R_{abs}$  is the absorbing radius, within which objects are removed from the simulation, the index  $j$

counts through the four gas giants,  $m_j$  and  $a_j$  denote planetary masses and semi-major axes, and  $M$  denotes the mass of the central body. This approximation minimizes perturbations in  $a$ -space, allowing for an easier study of the orbital evolution at constant- $a$ . As was done in [Batygin & Morbidelli \(2017\)](#), we initialize the inclination of 2015 BP<sub>519</sub> to be drawn from a half-normal distribution with mean 0 degrees and width 5 degrees, which simulates the expected initial conditions in the early solar system. We also include Planet Nine, using the best-fit values of its orbital elements ( $a = 700$  AU,  $e = 0.6$ ,  $i = 20$ ,  $\omega = 150$ ,  $\Omega = 90$ ), which come from [Millholland & Laughlin \(2017\)](#) and [Batygin & Morbidelli \(2017\)](#). We also run an additional set of simulations (Set 3) with identical parameters, but using the observed inclination of 2015 BP<sub>519</sub> as drawn from the observationally-derived covariance matrix. Simulation Set 2 is intended to study the behavior of an object like 2015 BP<sub>519</sub>, but starting from early in solar system history, before the inclination of 2015 BP<sub>519</sub> is perturbed to its current-day value. Simulation Set 2 is intended to answer the following question: assuming that 2015 BP<sub>519</sub> started in the same plane as the outer solar system objects that were present in the early solar system, can secular interactions with Planet Nine excite 2015 BP<sub>519</sub>'s inclination to its current day value? For comparison, simulation Set 3 studies the behavior of 2015 BP<sub>519</sub> from the current day forwards (but using the same approximations that are used in Set 2; namely, neglecting perturbations caused by scattering interactions with the giant planets and treating evolution as occurring at constant- $a$ ).

In Fig. 10, we plot the action-angle evolution of the results of Set 2, using angle

$$\theta = \Delta\varpi = 2\Omega - \varpi - \varpi_9 \quad (7)$$

and coordinate action

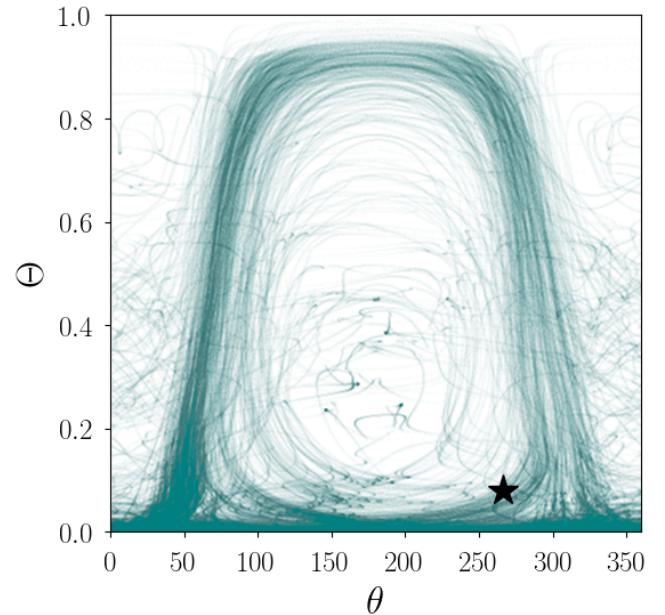
$$\Theta = \frac{\sqrt{1-e^2}}{2}(1-\cos i) \quad (8)$$

as done in [Batygin & Morbidelli \(2017\)](#).

The resulting evolution of 2015 BP<sub>519</sub> in this action-angle phase space is plotted in Fig. 10. The lines trace the 4.5 Gyr evolution of the realizations of 2015 BP<sub>519</sub> from simulation Set 2. The star symbol marks the present-day location of 2015 BP<sub>519</sub> in this parameter space, using its observed inclination, eccentricity, and (expected)  $\Delta\varpi$ . It is important to note that the remarkably high observed inclination of 2015 BP<sub>519</sub> is not a guaranteed outcome of these simulations. Nonetheless, the star symbol lies along the teal contours, which describe regions of the phase space to which an initially-coplanar 2015 BP<sub>519</sub> could evolve. These simulations

demonstrate that in the case where 2015 BP<sub>519</sub> starts its life close to the plane containing the solar system planets, 2015 BP<sub>519</sub> is able to attain its current day inclination, eccentricity, and orbital orientation through secular interactions with Planet Nine alone.

As a result, Set 2 of our simulations shows that orbital evolution with constant semi-major axis ( $a$ ) evolution can explain how 2015 BP<sub>519</sub> achieves its observed inclination in the presence of Planet Nine. In other words, the existence of Planet Nine is sufficient to explain the currently observed orbit of 2015 BP<sub>519</sub>.



**Figure 10.** Orbital evolution of 2015 BP<sub>519</sub> in action-angle space. This figure shows results from simulations where the initial inclination of 2015 BP<sub>519</sub> was drawn from a half-normal distribution centered at 0 degrees, with a width of 5 degrees (Set 2; see Table 2). This plot should be compared to the bottom panel of Fig. 11 in [Batygin & Morbidelli \(2017\)](#). The currently observed action-angle coordinates  $\theta$  and  $\Theta$  (computed using the simulated version of Planet Nine) is marked by the star symbol. The current-day orbital elements of 2015 BP<sub>519</sub> are easily reproduced in the scenario with Planet Nine and with 2015 BP<sub>519</sub> starting in the plane with the other solar system objects.

## 5.2. Orbital Evolution with Planet Nine and Neptune

The constant- $a$  evolution is relevant for the majority of the lifetimes of the TNOs in the presence of Planet Nine, and the behavior of the TNOs will generally behave as described in the previous section during those times. Close encounters with Planet Nine do occur even in the idealized simulation Set 2, but they are rare and tend to lead to only small hops between nearby reso-

nances with Planet Nine. However, as the current perihelion distance of 2015 BP<sub>519</sub> brings it fairly close to the orbit of Neptune during each perihelion passage, the true evolution of 2015 BP<sub>519</sub> will be affected heavily by those Neptune–2015 BP<sub>519</sub> interactions. In Fig. 9, we show a sample orbital evolution of 2015 BP<sub>519</sub> without Neptune. During a close encounter with Planet Nine, 2015 BP<sub>519</sub>’s orbit is rapidly altered, where the average distance of its orbit diffuses until it is trapped into or near a new resonance. The inclusion of Neptune as an active body increases the number of close encounters experienced by 2015 BP<sub>519</sub>, as it will interact with both Planet Nine and Neptune. This increase in interactions, in turn, allows for the orbit of 2015 BP<sub>519</sub> to become more heavily perturbed over time.

To test the effect of these kicks from Neptune, we set up another set of simulations (Set 4; see Table 2). In this case, we replace Jupiter, Saturn, and Uranus with an effective  $J_2$  term to represent the potential of those three planets. However, this time we include Neptune as an active body, which allows Neptune scattering events to be resolved. As before, the energy is conserved to one part in  $10^9$  and the hybrid symplectic-Bulirsch-Stoer integrator is used. The other parameters of this set of simulations are summarized in Table 2, and the results are plotted in Fig. 11. As expected, in this new set of simulations, 2015 BP<sub>519</sub> appears to be significantly less dynamically stable than in the previous sets (which do not include an active Neptune). However, part of this apparent dynamical instability is due to the nonphysical absorbing radius used in the simulations: specifically, we remove particles from the simulation when they reach orbital radii within the absorbing radius. This inner boundary is set to be 9.8 AU in this case, since we are replacing the Sun and inner three giant planets with an oblate central body with a larger radius, to represent the effective quadrupole term of the entire system.

As a result of the complication outlined above, ensembles of simulations that use effective  $J_2$  terms (like Set 4) to represent time-averaged planetary orbits cannot be used to study the final outcomes of these objects. For example, if the orbit of a realization of 2015 BP<sub>519</sub> was to evolve to the point where the clone becomes a Jupiter-family comet, simulation Set 4 would not resolve this end state, and would instead classify the clone as dynamically unstable. On the other hand, this approximation can be used to describe the expected secular evolution for objects that remain a part of the same dynamical population.

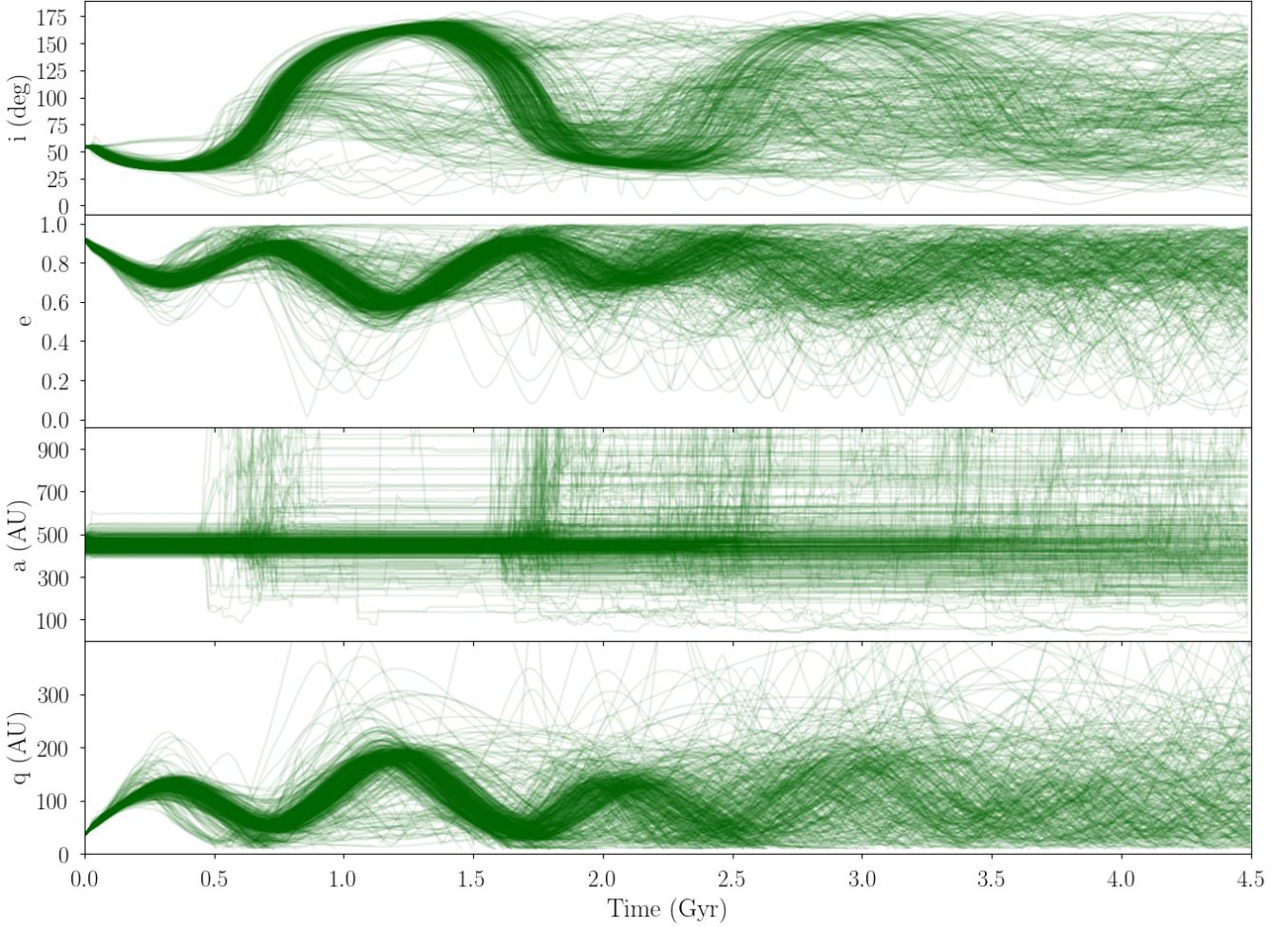
### 5.3. Orbital Evolution with Planet Nine and the Four Giant Planets

Both of the previous sections discussing the orbital evolution of 2015 BP<sub>519</sub> in the presence of Planet Nine replaced some (or all) of the gas giants with an effective  $J_2$  term. This time-saving integration strategy has been used extensively in the Planet Nine literature (Batygin & Brown 2016a; Brown & Batygin 2016; Millholland & Laughlin 2017; Hadden et al. 2017). In Section 5.2, we showed that the physical presence of Neptune leads to a greater number of transitions (‘hops’) between Planet Nine (true or near) resonances. Next, our final set of simulations (Set 5) investigates the effect of including all four gas giants as active bodies. The details of Set 5 are given in Table 2. One important detail about this set of simulations is that since all the gas giants are included as active particles (and terrestrial planets ignored), no planets need be modeled as perturbations on the solar  $J_2$ . As such, the absorbing radius of the central body is set equal to the Solar radius. This aspect of the simulations allows for the resolution of outcomes where 2015 BP<sub>519</sub> settles into a stable orbit with a perihelion distance that passes into the inner solar system; the results of this set of simulations is shown in Fig. 12. This figure appears very similar to 11, but describes the full motion of 2015 BP<sub>519</sub>. The striking similarity between the two figures can be used as justification for using the  $J_2$  approximation when secular evolution is being studied.

## 6. DISCUSSION

In this work, we present the discovery and dynamical analysis of a new extreme TNO, a population defined as those objects with  $a > 250$  AU and  $q > 30$  AU. Because 2015 BP<sub>519</sub> has the largest eccentricity and inclination of any of the extreme TNOs, it allows us to probe the behavior of a new regime in the solar system. Ideally, DES and other surveys will find more of these high-inclination, large semi-major axis objects. Once such a population is found and grows to a sufficient size, it will inform a variety of hypotheses about the structure of the outer solar system and the migration of the giant planets. For now, while the number of such known objects is small, we have performed an in-depth study of the dynamical evolution of 2015 BP<sub>519</sub> in various scenarios with two goals: first, we would like to make whatever insights are possible with a single object to improve our understanding of the outer solar system; second, we would like to determine which hypotheses and analyses will be most fruitful for future study once more of these objects are found.

Our analysis of the orbital evolution of 2015 BP<sub>519</sub> using forward and backwards integrations has revealed that it is difficult to reproduce 2015 BP<sub>519</sub>’s high

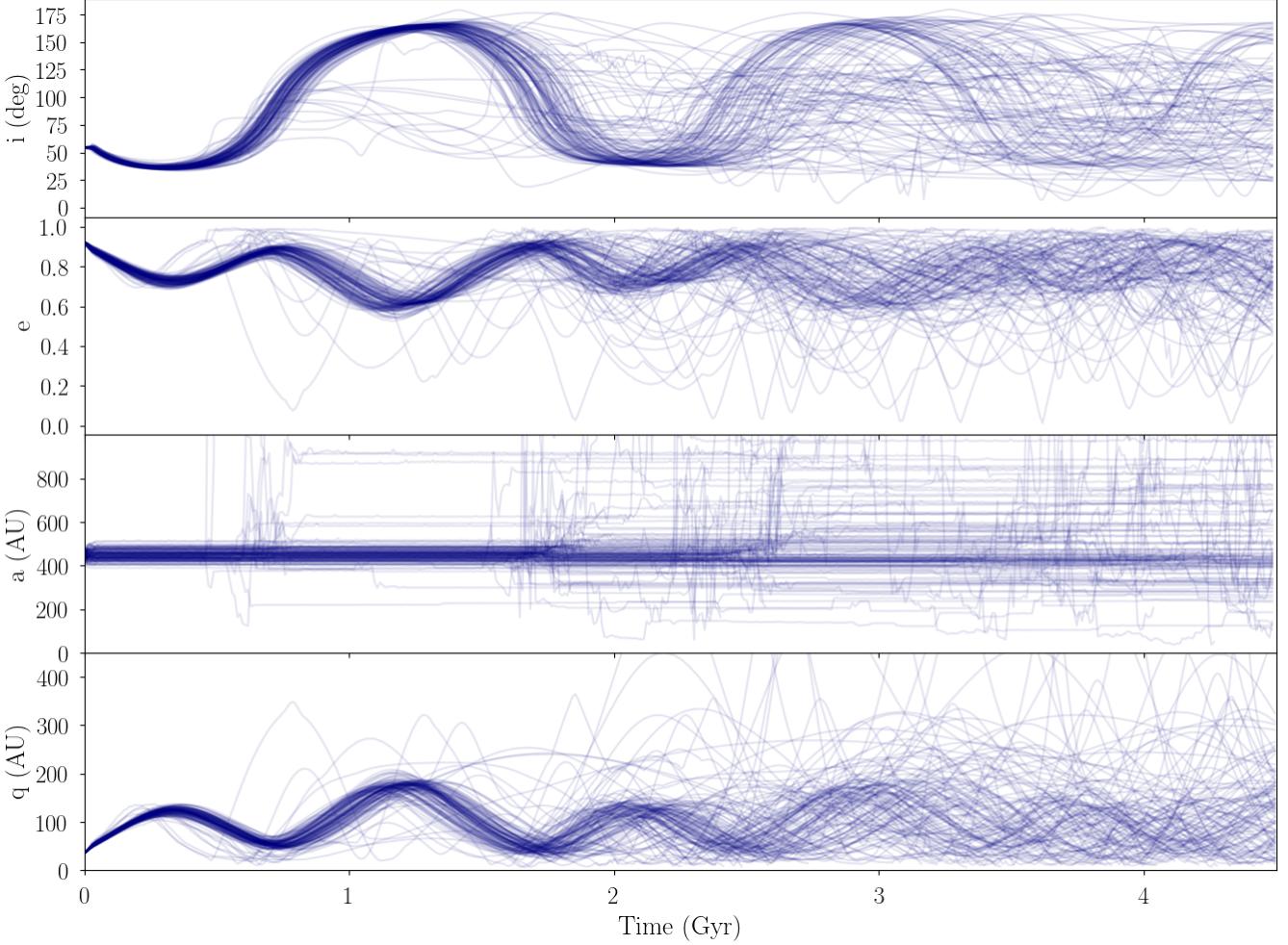


**Figure 11.** The orbital evolution of 2015 BP<sub>519</sub> as computed using N-body simulations for Simulation Set 4, which includes Neptune as an active particle, replaces the other three gas giants with an effective  $J_2$ , and includes Planet Nine. These integrations do describe well the secular dynamics of *surviving* particles. The evolution of semi-major axis also shows the horizontal banding structure in semi-major axis, which is characteristic of resonance hopping.

current-day inclination in the known solar system without considering some other mechanism. In Simulation Set 1, which studied the evolution of this object in the known solar system, 0 out of the 260 simulated clones of 2015 BP<sub>519</sub> attained inclinations less than 48 degrees or greater than 60 degrees, when integrations were initialized with 2015 BP<sub>519</sub>'s measured inclination of  $\sim 54$  degrees. This strong confinement in inclination space that is evident in the numerical simulations requires us to consider other mechanisms to excite the inclination of this object. Some potential explanations (discussed in Section 4.2) include a stellar fly-by, a remnant excitation from the early migration of the giant planets, a particularly serendipitous outcome not captured by our 260 N-body simulations, or an inclination instability caused by the self-gravity of a massive scattered disk.

One additional explanation to those listed above is the existence of a ninth planet in our solar system, as

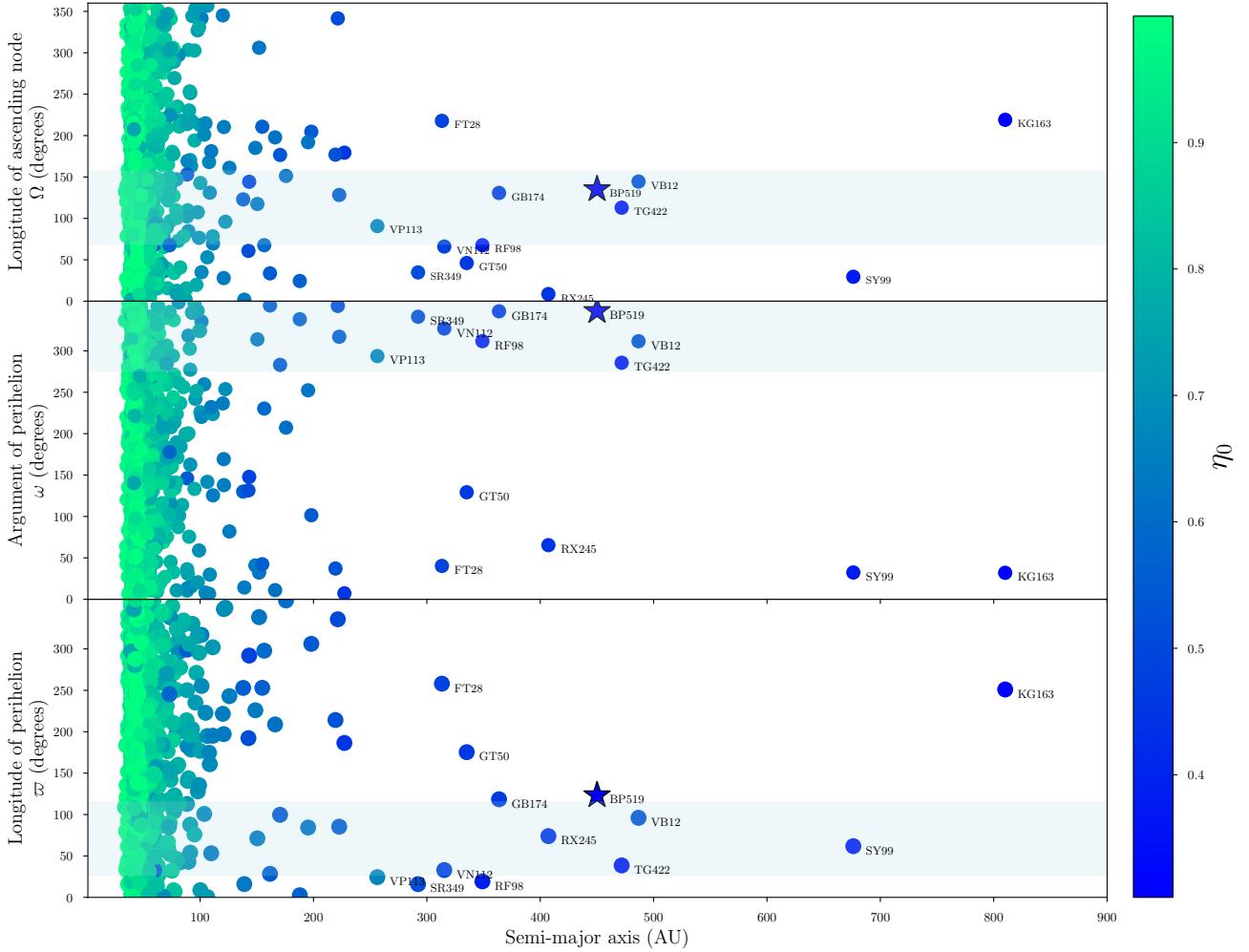
proposed by Trujillo & Sheppard (2014) and Batygin & Brown (2016a). As shown in Fig. 10, in the presence of Planet Nine 2015 BP<sub>519</sub> can start out with a relatively low inclination and easily attain its current-day inclination. Additionally, as shown in Fig. 13, 2015 BP<sub>519</sub>'s orbital angles  $\omega$ ,  $\Omega$ , and  $\varpi$  appear to be consistent with the clustering first noted in Trujillo & Sheppard (2014). This clustering in physical space has been proposed to be caused by the  $\sim 10$  Earth-mass Planet Nine at 700 AU (Batygin & Brown 2016a) and is the line of evidence most commonly used to support the existence of Planet Nine. Although 2015 BP<sub>519</sub> does appear to fit into this paradigm, the physicality of the clustering remains a contentious piece of evidence for Planet Nine (Shankman et al. 2017b; Brown 2017). In Fig. 5, we showed the bias in DES detections of objects with varying orbital angles  $\omega$ ,  $\Omega$ , but the same  $(a, e, i)$  as 2015 BP<sub>519</sub> has. For 2015 BP<sub>519</sub>, at least, the biases are sufficiently mild



**Figure 12.** The orbital evolution of 2015 BP<sub>519</sub> as computed using N-body simulations for Simulation Set 5, which includes all four gas giants as active particles and also includes Planet Nine. The integrations show the same horizontal banding structure in semi-major axis characteristic of resonance hopping. The evolution computed here is very similar in secular trajectory to that of Set 4 (Fig. 11).

that it seems that 2015 BP<sub>519</sub> can be used as evidence towards the existence of the clustering. However, the observational biases we determine for 2015 BP<sub>519</sub> do not tell us anything about other objects that may be found by DES or other surveys: without fully accounting for the observational biases for each individual survey that has discovered these ETNOs, it cannot fully be determined how much of the clustering is physical and how much is due to observational bias. Past surveys have been able to quantify this: the Deep Ecliptic Survey had well-documented pointings, and as a result was able to construct a model of its detection biases (Adams et al. 2014). Similarly, the Outer Solar Systems Origin Survey has quantified its own biases (Lawler et al. 2018). Future work (Hamilton et al., in prep) will do the same for the Dark Energy Survey, and enable a better understanding of whether the clustering suggesting Planet Nine’s existence is real or a sampling bias.

However, 2015 BP<sub>519</sub> does provide additional diagnostics unrelated to angular clustering which inform the Planet Nine debate. Batygin & Brown (2016a) predicted that high inclination KBOs would serve as an important constraint on Planet Nine’s properties. Subsequently, dynamical analysis presented in Batygin & Morbidelli (2017) suggests that the population of highly inclined centaurs can be explained by the presence of Planet Nine. Shankman et al. (2017a) predicted that if there is a ninth planet in the solar system, there should also be a reservoir of high- $i$  TNOs that exhibit clustering of their orbits with the existing population. Finally, Batygin & Morbidelli (2017) provided a model of the secular evolution expected for high- $i$ , high- $a$  objects, but was only able to test it on objects with  $q < 30$  AU. 2015 BP<sub>519</sub> is the first known high- $a$  ( $a > 250$  AU), high- $i$  ( $i > 40$  degrees), high- $q$  ( $q > 30$  AU) object, a class of objects whose existence is predicted by Batygin & Morbidelli



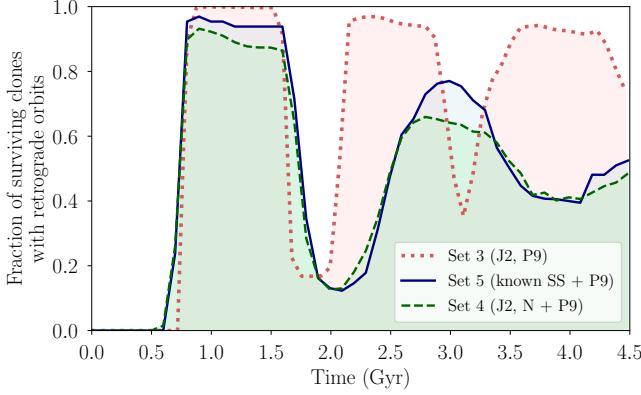
**Figure 13.** A visualization of the two orbital angles  $\Omega$  (longitude of ascending node, top panel) and  $\omega$  (argument of perihelion, middle panel), along with their sum longitude of perihelion  $\varpi = \omega + \Omega$  (top panel). The points are color coded by the specific angular momentum of the orbit  $\eta_0 = \sqrt{1 - e^2} \cos i$ . The plot includes all objects with  $q > 30$  AU and data quality  $U < 6$  from the MPC database (Marsden et al. 1978), with 2015 BP<sub>519</sub> denoted as a star. Horizontal bars denote the approximate regions of clustering in each angle, as identified in Batygin & Brown (2016a).

(2017). 2015 BP<sub>519</sub> is the first discovered high- $i$  object, and it fits into the Planet Nine paradigm as predicted by this previous work.

In Fig. 14, we show the fraction of surviving objects that have retrograde orbits for three of the different simulations sets used in this work. A sizable fraction of 2015 BP<sub>519</sub>'s potential future orbits attain retrograde orientations, an outcome predicted in Batygin & Brown (2016b) and Batygin & Morbidelli (2017). A subset of these also evolve to lower semi-major axes, potentially resulting in 2015 BP<sub>519</sub> eventually becoming a retrograde centaur; however, our simulations show that it is more likely that 2015 BP<sub>519</sub> retains a large semi-major axis and retrograde configuration than that it migrates inwards and becomes a centaur. In the presence of Planet Nine, TNOs with orbits as extreme as

2015 BP<sub>519</sub> would appear to cycle through populations, changing their orbital inclinations and perihelion distances rather than living at roughly constant perihelion distances (as they would in the known solar system without Planet Nine; see Fig. 8). Finally, the presence of Planet Nine in the solar system naturally produces objects with orbits like that of 2015 BP<sub>519</sub>, a feature which cannot be reproduced in the solar system without Planet Nine without invoking some other mechanism (such as interaction with a passing star, or a 1-10 Earth mass scattered disk that can cause an inclination instability, Madigan & McCourt 2016; Madigan et al. 2018).

Although 2015 BP<sub>519</sub> appears to fit well into the Planet Nine paradigm and aid in a better differentiation between these two potential scenarios – a solar system with or without Planet Nine – more objects of this



**Figure 14.** A measure of the fraction of 2015 BP<sub>519</sub> clones that attain retrograde orbits as a function of time in the numerical simulations that include Planet Nine. The coherence between all sets of simulations is due to a single realization of Planet Nine’s orbital elements being used for all simulations. The good agreement between the simulations that used a  $J_2$  approximation (Set 4) and those that included all gas giants as active particles (Set 5) suggests that the  $J_2$  approximation (while keeping Neptune an active particle) is appropriate for studying the orbital evolution of surviving particles, even if it does not work well on its own for studying the dynamical stability. The integrations in Set 1 (which included the known solar system and no Planet Nine) never attain retrograde geometries.

type need to be found. Future work using the Dark Energy Survey will both identify additional high-semimajor axis, high-inclination objects which will help us better understand the high-inclination structure of the outermost regions of the solar system, and make a more definitive statement on the existence of Planet Nine.

## 7. CONCLUSION

This paper reports the detection and initial dynamical analysis of the extreme Trans-Neptunian Object 2015 BP<sub>519</sub>. This object was discovered as part of the Dark Energy Survey and adds to the growing inventory of unusual bodies in the outer solar system. Our main results can be summarized as follows:

[1] The estimated orbital elements for this new (minor) member of the solar system include semi-major axis  $a \approx 450$  AU, eccentricity  $e \approx 0.92$ , and inclination  $i \approx 54$  degrees. With these orbital properties, 2015 BP<sub>519</sub> resides well outside the classical Kuiper Belt. On the other hand, the perihelion distance is only  $q \sim 36$  AU, close enough to be influenced by Neptune.

[2] The newly discovered body 2015 BP<sub>519</sub> is the most extreme TNO found to date. This claim can be quantified using the reduced Kozai action  $\eta_0$  (see Equation 5), which is equivalent to the  $z$ -component of the specific orbital angular momentum. Among all known solar sys-

tem objects, 2015 BP<sub>519</sub> has the most extreme value of this parameter, as shown in Fig. 7.

[3] 2015 BP<sub>519</sub> provides support for the Planet Nine hypothesis. If the object is formed in the plane of the solar system, as expected, then there is a low probability that its orbit can attain the observed high inclination through dynamical processes involving only the known planets. In contrast, the observed orbital elements of 2015 BP<sub>519</sub> are readily produced through dynamical interactions if the solar system also contains Planet Nine (see Fig. 10).

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**Software:** WCSfit (Bernstein et al. 2017), mp\_ephem (<https://github.com/OSSOS/liborbfit>), pandas (McKinney 2010), IPython (Pérez & Granger 2007), matplotlib (Hunter 2007), scipy (Jones et al. 2001), numpy (Oliphant 2006), Jupyter (Kluyver et al. 2016)

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## A. APPENDIX: EXTREME TNO DATA TABLE

**Table 3.** Orbital Elements of Extreme TNOs

Object	a (AU)	e	i	$\omega$	$\Omega$	H (abs. mag)
2003 VB <sub>12</sub>	507 ± 10	0.8496 ± 0.003	11.9 ± 0.1	311.3 ± 0.1	144.4 ± 0.1	1.5
2007 TG <sub>422</sub>	503 ± 0.35	0.93 ± 0.001	18.6 ± 0.1	285.7 ± 0.1	112.9 ± 0.1	6.2
2010 GB <sub>174</sub>	351 ± 9	0.862 ± 0.004	21.6 ± 0.1	347.2 ± 0.1	130.7 ± 0.1	6.6
2012 VP <sub>113</sub>	266 <sup>+26</sup> <sub>-17</sub>	0.69 ± 0.03	24.1 ± 0.1	292.7 ± 0.1	90.8 ± 0.1	4
2013 FT <sub>28</sub>	295 ± 7	0.853 ± 0.004	17.4 ± 0.1	40.7 ± 0.1	217.7 ± 0.1	6.7
2013 RF <sub>98</sub>	363 ± 5	0.9 ± 0.001	29.6 ± 0.1	311.8 ± 0.1	67.6 ± 0.1	8.7
2013 SY <sub>99</sub>	735 ± 15	0.932 ± 0.007	4.2 ± 0.1	32.2 ± 0.1	29.5 ± 0.1	6.8
2014 SR <sub>349</sub>	299 ± 12	0.841 ± 0.007	18 ± 0.1	341.2 ± 0.1	34.9 ± 0.1	6.6
2015 GT <sub>50</sub>	312 ± 2	0.877 ± 0.001	8.8 ± 0.1	129 ± 0.1	46.1 ± 0.1	8.3
2015 KG <sub>163</sub>	680 ± 2	0.94 ± 0.001	14 ± 0.1	32.1 ± 0.1	219.1 ± 0.1	8.1
2015 RX <sub>245</sub>	430 ± 20	0.894 ± 0.001	12.1 ± 0.1	65.2 ± 0.1	8.6 ± 0.1	6.1
2004 VN <sub>112</sub>	316 ± 1	0.8505 ± 0.0005	25.6 ± 0.1	327.1 ± 0.1	66 ± 0.1	6.5
2014 FE <sub>72</sub>	1655 ± 336	0.98 ± 0.02	20.64 ± 0.1	133.89 ± 0.04	336.84 ± 0.1	6.1

NOTE—Barycentric osculating elements for the currently known set of TNOs with  $a > 250$  AU and  $q > 30$  AU. Excluding our new object 2015 BP519, solutions were drawn from [Shankman et al. \(2017b\)](#) and [Bannister et al. \(2017\)](#) for all objects except 2013 RF98, 2007 TG422, and 2014 FE72. The barycentric orbital solutions for these three objects were fit using the OSSOS ([Bannister et al. 2016](#)) implementation<sup>a</sup> of the [Bernstein & Khushalani \(2000\)](#) orbit fitter, using the observations of each object available<sup>b</sup> at the Minor Planet Center.

<sup>a</sup>Available at <https://github.com/OSSOS/liborbfit>, and from the Python Package Index via `pip install mp_ephem`

<sup>b</sup>[https://www.minorplanetcenter.net/db\\_search/](https://www.minorplanetcenter.net/db_search/) as of 2/1/2018