DEVETI PLANET

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Na podlagi Newtonovih zakonov gibanja so že v preteklosti astronomi uspešno matematično napovedali in kasneje z opazovanjem potrdili obstoj Neptuna. Možnost odkritja planeta na podlagi njegovega gravitacijskega vpliva na ostale objekte torej ni nič novega. Prispevek obravnava zaenkrat še nepojasnjene lastnosti orbit objektov Kuiperjevega pasu in možne razlagam zanje. Več pozornosti je namenjene razlagi, ki predvideva obstoj oddaljenega masivnega planeta v našem Osončju, in predvidenim lastnostim takega planeta, določenih s pomočjo numeričnih simulacij.

PLANET NINE

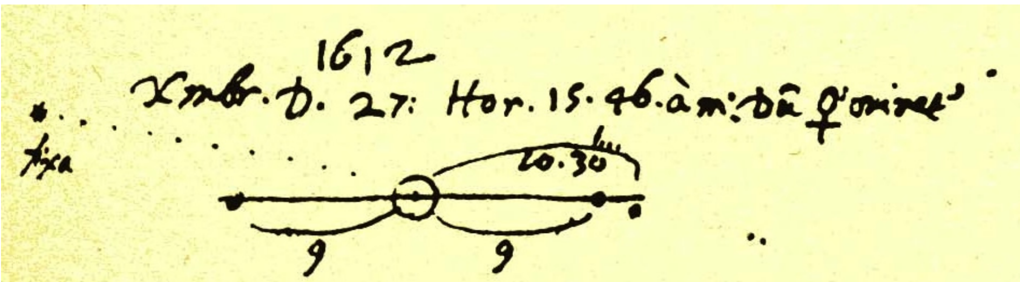
The beginning of the paper reviews how mathematical predictions have led to discoveries in our Solar System in the past, specifically in case of Neptune. The following sections then examine the clustering of orbit parameters for distant Kuiper Belt objects and how it might be explained, with main focus being on explanation involving an as of yet undiscovered massive planet in the outer Solar System. At the end possible origins of the planet and estimated parameters derived from numerical simulations are considered.

1. Introduction

Orbits of distant Kuiper Belt objects exhibit certain properties, that have so far not been properly explained. One of the hypothesized explanations suggests the observed properties are due to the effects of a distant eccentric planet with mass $\geqslant 10M_\oplus$ with its orbit lying in approximately the same plane as the orbits of distant Kuiper Belt objects and its perihelion 180°away from their perihelia (they are anti-aligned) [10].

2. Discovery of Neptune

The only planets that have been discovered are Uranus and Neptune, of which only Uranus has been discovered directly from observations. Neptune had first been predicted using mathematical arguments based on Newton's laws and later observed near its predicted locations [17].



Slika 1. Galileo's sketch of Jupiter's moons together with a star in the background. The star later turned out to be Neptune [14].

Neptune could have been discovered as early as 1613 by Galileo, who was the first person with the means to do so. He did in fact record it, but as an 8th magnitude star. He observed it the next night and noted the change in its position relative to another star, but did not pursue it further [17].

Before being discovered in 1846, Neptune had been observed and recorded on several occasions without being recognized as a planet. In September 1846, only days before its discovery, Neptune was observed by von Lamont, who should have recognized its motion over the four day period as that of a planet, but failed to do so [17].

In 1792 Delambre published computed tables of planetary positions for objects known at the time. However, Uranus deviated from its predicted path and taking perturbations of the other planets into account was not enough to make the observations fit [17].

In 1841 Adams began speculating that irregularities might be due to an undiscovered planet beyond Uranus. Another popular theory at the time was that the inverse square law of gravitation doesn't hold over large distances [17].

In 1845 Le Verrier, persuaded by Arago, also began working on the problem of Uranus' orbit. Neither he nor Adams knew the other was working on it. By September 1845 Adams had calculated the perturbing planet's orbit and mass and sent his predictions to the director of the Cambridge Observatory, Challis. This was the first time Newton's theory of gravity had been used to predict the position of an object based on its gravitational effects on other bodies [17].

In June 1846 Le Verrier published a paper in which he concluded that the only plausible explanation for Uranus' orbit was an undiscovered planet beyond Uranus. When the paper reached Airy, he asked Challis to begin a search for the planet at the Cambridge Observatory. He didn't tell Le Verrier about the search, nor did he tell either Le Verrier or Adams that they have both come to almost identical conclusions regarding new planet's position [17].

Challis began his search and in fact recorded the new planet on two separate nights, but never compared those results to each other [17].

In August 1846 Le Verrier published another paper, in which he noted that it should be possible to see the new planet using a good telescope and to distinguish it by the size of its disc [17].

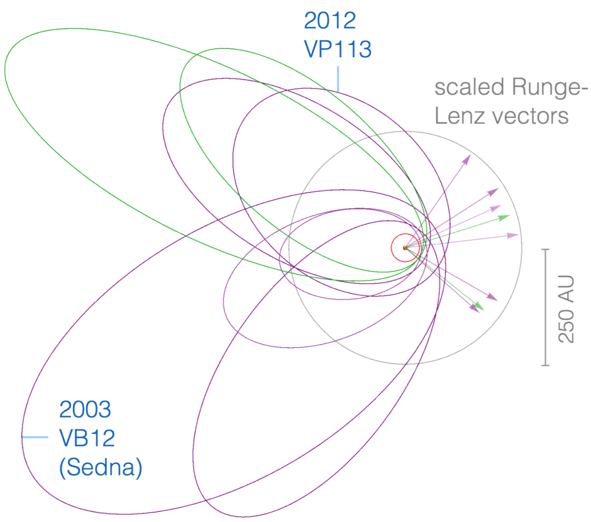
On 23 September Galle from the Royal Observatory in Berlin received Le Verrier's letter asking him to search for the new planet. He began that night with the help of his assistant d'Arrest, who suggested they use the latest star chart. In less than 30 minutes they located a star not on their map and confirmed it the following night by observing it had moved relative to the other stars. They have found the new planet [17].

It later turned out that both Adams and Le Verrier had been lucky, because while their predicted positions were quite close to the actual one, that was only true for the positions around 1840-1850. At other times their predicted orbits would put Neptune far from its actual position [17].

3. The Ninth Planet

Beyond the orbit of Neptune, at a distance of 30 AU we find a number of objects in a flattened, ring like volume called Kuiper Belt. These objects are relics from the accretion disc of the Sun. They are mostly small, about a dozen known objects have diameters of order 1000 km or more, including Pluto. Some of the Kupier Belt objects (or KBOs) have orbits that take them far from the Sun, but their perihelia are all at about 35-40 AU [11].

In 2014 Trujillo and Sheppard [18] noted in their paper that a set of KBOs exhibits clustering in their orbital elements (Fig. 2). Objects with perihelion further than 30 AU (beyond the orbit of Neptune) and semi-major axes greater than 150 AU have arguments of perihelia (ω, fig. 3)



Slika 2. Distant KBOs with perihelion further than 30 AU (beyond the orbit of Neptune) and semi-major axes greater than 150 AU exhibit clustering in their orbital elements [7].

clustered around zero ($\omega = 0$ means the object's perihelion lies precisely at the ecliptic). They also cross the ecliptic from south to north relative to the orientation of the Earth. Arguably there is an observational bias favouring objects with perihelion at the ecliptic, but there is none for south to north crossing (detection of objects crossing the ecliptic from north to south is just as likely) [7].

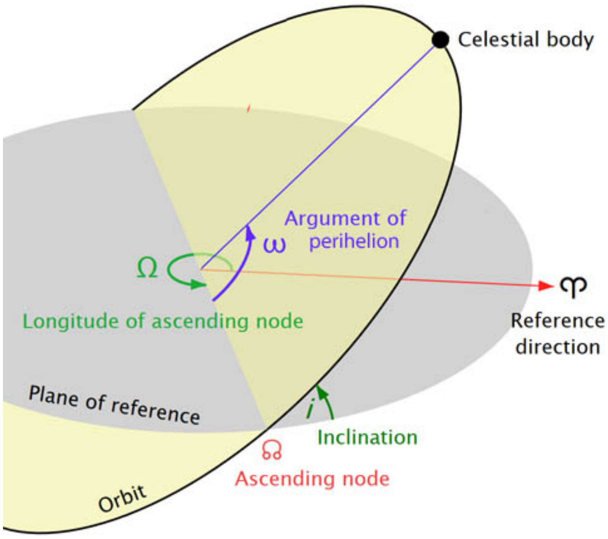
There have been several proposed explanations. The first, suggested by Trujillo and Sheppard in 2014 [18], was that the clustering of ω around zero could be the result of the Kozai mechanism - when an object is gravitationally influenced by other objects its orbit exhibits periodical oscillation in angle of inclination and eccentricity due to the conservation of angular momentum [21]. But for the alignment of all the observed objects within the known range of semi-major axes to be possible, there would likely need to exist several finely tuned planets [7].

In 2015 Madigan and McCourt proposed that the observed properties could be the result of an inclination instability. While additional calculations are needed to fully account for the effects of giant planets and scattering, their theory requires 1-10 $M_\oplus$ of material to exist between ~ 100 AU and $\sim 10,000$ AU which doesn't seem likely [7].

Third theory, put forward by Batygin and Brown in 2016[7], suggests that the observed properties of KBOs are caused by perturbations of a single long-period object. This could also explain other, seemingly unrelated dynamical features of the Kuiper Belt, such as the origin of Sedna and other distant detached objects [7].

In their paper Batygin and Brown focused on a carefully selected set of KBOs. Only objects with perihelia $q > 30$ AU and semi-major axes $a > 150$ AU were examined, because any object crossing Neptune's orbit would experience strong perturbation by recurring close encounters with Neptune. Furthermore, any objects experiencing large-scale semi-major axes variations, caused by strong encounters with Neptune, were excluded, leaving them with 6 out of 13 objects [7].

Observed objects cluster around $\omega = 318^{\circ} \pm 8\,^{\circ}$, which is inconsistent with the Kozai mechanism. They also exhibit strong clustering of longitude of ascending node (fig. 3) around $\Omega = 113^{\circ} \pm 13^{\circ}$and of longitude of perihelion $\tilde{\omega} = \omega + \Omega$ around $\tilde{\omega} = 71^{\circ} \pm 16^{\circ}$. All of this suggests that the orbits of these objects are physically aligned, something that cannot be maintained by either the Kozai effect or the inclination instability [7].



Slika 3. Orbital elements used to describe planetary orbits. [22]

Since each of the 6 objects was discovered in a separate survey, their biases are presumably uncorrelated. Batygin and Brown estimated the statistical significance of the observed clustering by assuming detection biases are similar for all objects with $q > 30$ AU and $a > 150$ AU and calculating RMS (root mean square) of the angular distance between perihelion position of each object and the average perihelion position of the 6 randomly selected bodies. Selection and calculation was repeated 100,000 times and the tight clustering of orbits in perihelion position occurred only 0,7% of the time [7].

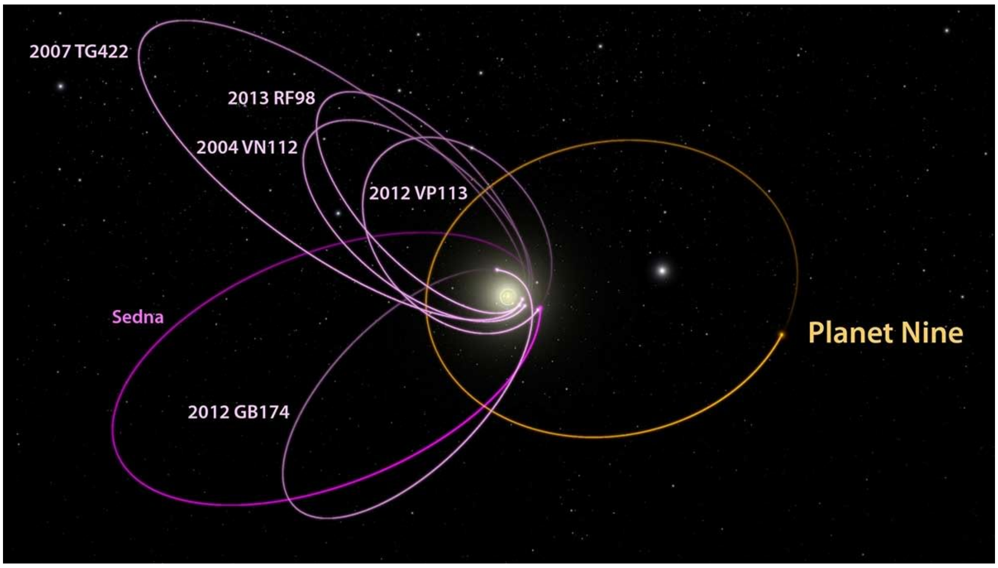
Similar calculations were made for clustering in orbital pole[1] position, which occurred 1% of the time. Since these two measurements are statistically uncorrelated, multiplying the probabilities is possible to find that the probability of observing clustering in both parameters simultaneously by chance is only 0.007%. It is therefore extremely unlikely that the clustering is due purely to chance [7].

Coherent dynamical structures (structures that are relatively consistent over long periods of time (compared to orbital periods) with minor perturbations) in particle discs are generally sustained by either self-gravity or gravitational effects of en extrinsic perturber (shepherding). Current mass of the Kuiper Belt is likely insufficient for the self-gravity to be the explanation. So far, calculations support the hypothesis that the observed structure of the distant Kuiper Belt is maintained by perturbations from an unseen planetary mass on an appreciably eccentric orbit. N-body simulations show there is a possibility of dynamically long-lived orbits, despite traversing the orbit of the perturber. That could be explained by the resonant coupling with the perturber. These results indicate, that a massive distant eccentric planet can sustain a population of clustered anti-aligned (its perihelion is 180°away from their perihelia) small bodies (Fig. 4) [7].

3.1 Origin

There are various explanations for how a massive planet might find itself on an orbit relatively far from its star: coagulation, gravitational instability, scattering, effects of passing stars or Galactic tides. Numerical simulations for each scenario give us predicted properties of the planet as a function

[1] Imaginary point on either side of the line running through the center of an orbit perpendicular to orbital plane. Similar to Earth's poles but based on an orbital plane instead of equatorial plane.



Slika 4. Orbits of distant KBOs with hypothesized Planet Nine. [3]

of initial conditions in the protoplanetary disc [8].

3.1.1 Scattering

During formation of a Solar System growing gas giants can gravitationally scatter super-Earths (planets with masses typically between mass of Earth and that of Uranus or Neptune) or more massive planets to large distances. Numerical simulations show these scattered planets are either eventually ejected or in case of a disc with larger surface density can settle into stable orbits further from the star due to dampening from dynamical friction [8].

In their paper from 2016, Bromley and Kenyon [8] analyse under what conditions a scattered planet can achieve an orbit with a semi-major axis beyond 300-400 AU as proposed by Batygin and Brown (2016) [10]. Their calculations support a scenario where a planet is scattered from $a \approx 10$ AU during the formation of a Solar System and settles on a more or less circular orbit at a much larger a through interactions with a protoplanetary gaseous disc [8].

3.1.2 Coagulation

For coagulation to be the mechanism for formation of a distant planet, there needs to exist a massive ring of solid debris produced during disc evolution at 100-750 AU. Timescales for formation of a super-Earth sized planet range from ~ 100 Myr to $\geqslant\sim 10$ Gyr. Such planet would typically have a fairly circular orbit with a between 250 AU and 750 AU [15].

Should Planet Nine be found at a large orbital distance on an orbit with low eccentricity and inclination, this could be the explanation [8].

3.1.3 Dynamical instability

Another possible explanation, similar to scattering is dynamical instability after the planets are formed and the inner gaseous cloud disc has dispersed (Nice model; [20]). This instability can scatter fully formed giant planets into the outer Solar System. While most of them are ejected, some might settle on stable orbits with high eccentricity and low inclination [8].

For a massive planet to settle beyond 100 AU, additional mechanisms are required, such as damping by an extended, static gas disc.

Other possibilities with broader range of outcomes include a stellar flyby, where a passing star, possibly a member of the Sun's birth cluster, could relocate a planet within our Solar System. Another possibility is the capturing of a planet from a passing star [8].

Galactic tidal effects are generally too weak inside a 10^4 AU range to have any significant effect. For this to be a likely explanation, the semi-major axis of Planet Nine should exceed 1000 AU and its perihelion distance should be at least 100 AU [8].

Observational data, gathered in the next 10-20 years together with numerical simulations should give us a more definitive answers regarding the origin of gas giants at large a [8].

3.2 Parameters

Batygin and Brown (2016) [7] estimated that best fit for the planet's orbit would be one with $a \sim 700$ AU, $e \sim 0.6$ and planet mass to be within the order of magnitude $m \sim 10M_{\oplus}$. This choice of parameters gave theoretical results that best matched the observational data on qualitative level.

Later studies and simulations showed similar results. Milholland and Laughlin (2017) [16] estimated unseen planet's position to be at ~ 654 AU. With a Monte-Carlo optimisation scheme they found that the planet is most consistently represented with a mass $m \sim 6 - 12M_{\oplus}$, semi-major axis $a \sim 654$ AU, eccentricity $e \sim 0.45$ and inclination $i \sim 30°$[16].

First studies aimed at determining Planet Nine's likely properties such as the atmosphere, emission, or cooling history, focused on blackbody approximations. While this is a valid starting point, we know that for instance spectra of our Solar System's gas giants differ strongly from blackbodies [13].

Fortney et al (2016) [13] used evolution models together with what we already know about Neptune and Uranus, such as the assumption that the planet has some H/He atmosphere, to estimate some of the new planet's properties. They found upper limits on T_{eff} to be ~ 35 to 50 K for masses $5 - 20M_{\oplus}$ and estimated the range of possible radii to be $2.7 - 6R_{\oplus}$. At these temperatures we could expect significant condensation of methane, which would have a strong effect on reflection and emission spectra, making them quite different from what we would expect based on Uranus and Neptune. Planet Nine would then likely appear to be rather blue [13].

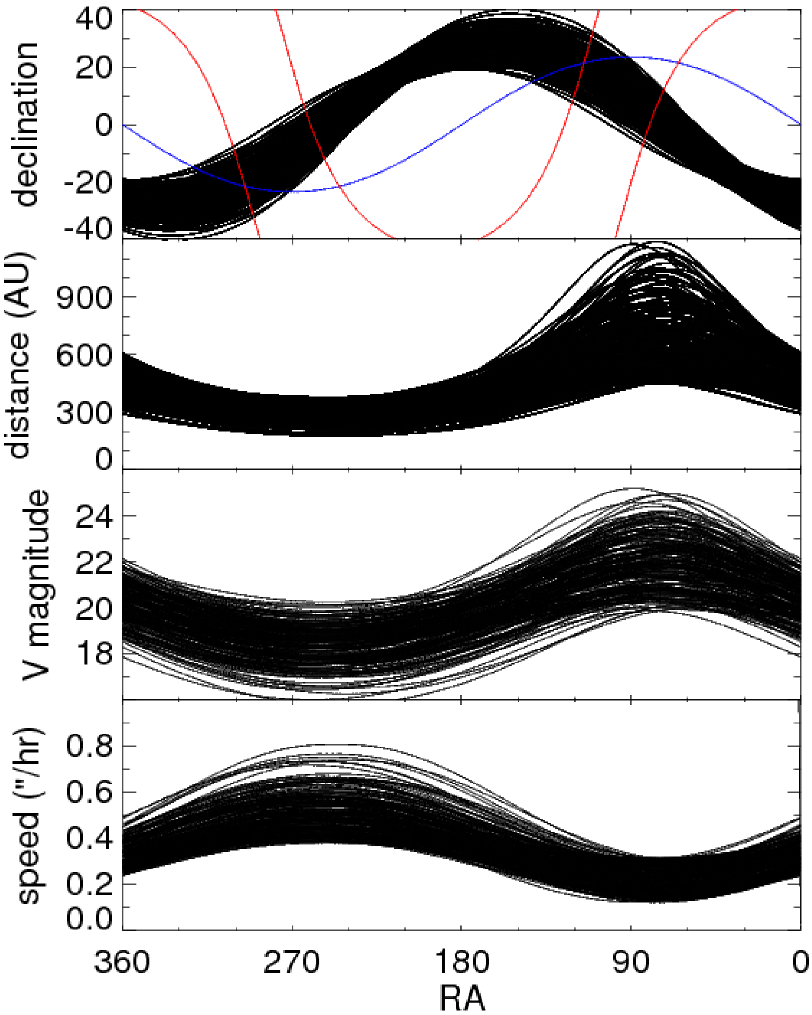
In the event that Planet Nine is detected, the study of its properties could help us speculate about properties of distant exoplanets, since many of them are in the same mass range, although not many are found at such large a [13].

3.3 Observation

When the theory of the new planet was announced, the hunt began to find it. Fortney et al (2016) [13] suggested a good place to start the search would be in the region $30° \leqslant RA \leqslant 50°$, $-20° \leqslant \delta \leqslant 20°$.

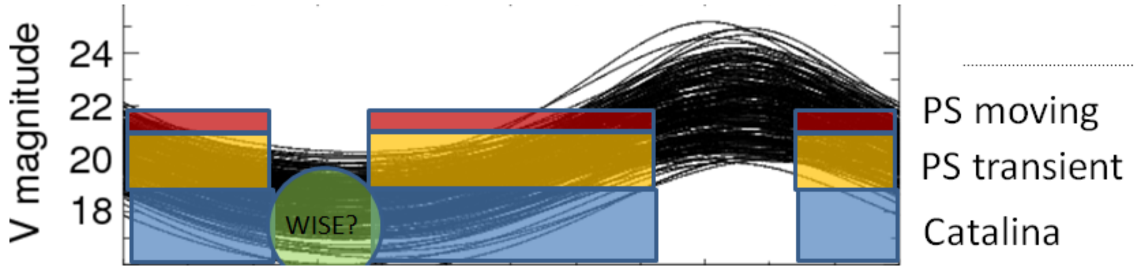
The perihelion distance has been estimated to be approximately 200 AU, but could be larger, up to ~ 350 AU. The aphelion distance is harder to estimate and is thought to be between 500 AU and 1200 AU. We assume the planet looks similar to Neptune with similar albedo [9].

If the planet was near perihelion, we would have most likely already detected it. While surveys over the last few years failed to find it, they have ruled out much of the sky up to the 22nd magnitude except parts of the galactic plane (Fig. 5 and 6). We can now estimate that the planet is near the aphelion, possibly in the area of the sky where it has the band of the Milky Way galaxy as a background and probably fainter than 22nd magnitude [9].



Slika 5. Modeled properties of Planet Nine. Red lines mark the borders of the Milky Way Galaxy, while the blue line represents the ecliptic. [9]

In the near future, Planet Nine could possibly be detected by the ongoing Gaia-ESO survey [2], which will systematically cover all major components of the Milky Way galaxy. While Gaia should detect objects as dark as 20.7th magnitude, the undiscovered planet might very well be fainter. Our next hope for discovery (or refutation of theory) of Planet Nine then lies with the LSST project [19], currently under construction and set to begin fully operational survey in early 2022. The LSST is expected to detect objects as faint as 24th (single image) or even 27th (stacked images) magnitude.



Slika 6. Parts of Planet Nine's likely orbit already covered by the Catalina [1], PanSTARRS transient [4] and moving [12] object surveys, as well as WISE [6] survey. Other properties are shown on figure 5. Horizontal axis shows RA. [9]

4. Conclusion

Objects of distant Kuiper Belt exhibit a strong clustering in their orbital elements, namely in their arguments of perihelion, as well as clustering of orbits in physical space. The probability of both confinements occurring due to chance is less than 0.007 %. While several explanations have been proposed, among them Kozai mechanism and inclination instability, the best fit to the observational data was obtained by considering a distant perturbing planet of mass $m \sim 6 - 12 M_{\oplus}$ on an orbit that is anti-aligned to the orbits of distant KBOs (its perihelion is 180°away from their perihelia) and has a semi-major axis $a \sim 654$ AU, eccentricity $e \sim 0.45$ and inclination $i \sim 30°$[7].

Several theories have been discussed regarding the possible origin of Planet Nine, from coagulation, gravitational instability and scattering to capturing a planet from a passing star and Galactic tides. Each explanation gives us a slightly different constraints on planet's properties, so once the planet is found, the observational data could show which of the theories is most likely to be the correct explanation [8].

So far the surveys have not uncovered a new planet lurking in the outer Solar System, but have eliminated the possibly of it being in a large portion of the sky, assuming it is not fainter than 22nd magnitude. If it is currently near its aphelion, this would put it in a position on the sky where it has the band Milky Way galaxy as background. This makes detection harder because of the bright background [9]. Since the perturbing planet seems to allow for the existence of additional population of high perihelion KBOs that do not exhibit the same type of clustering as those first used to suggest Planet Nine's existence, another viable way of testing the hypothesis of its existence would be to discover such objects [7].

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