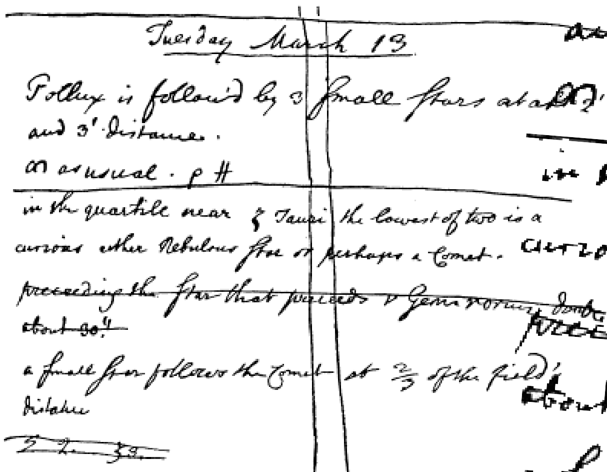
Planets beyond Pluto?

R. de la Fuente Marcos

(Research made in collaboration with C. de la Fuente Marcos, S. J. Aarseth, J. de León, G. Carraro and E. Costa)

the remarks which Herschel entered in his Journal and reproduce a facsimile of the original record of the "comet" on March 13, 1781. The authors of this volume have also given a valuable discussion of the identification of the comet as a new planet.

The original entry in Herschel's Journal is as follows:— (the two vertical lines down the middle mean that the observations have been copied into separate books for fixed stars, planets, etc.)



Tuesday March 13

Pollux is followed by 3 small stars at abt 2' and 3' distance.

♂ as usual. p H

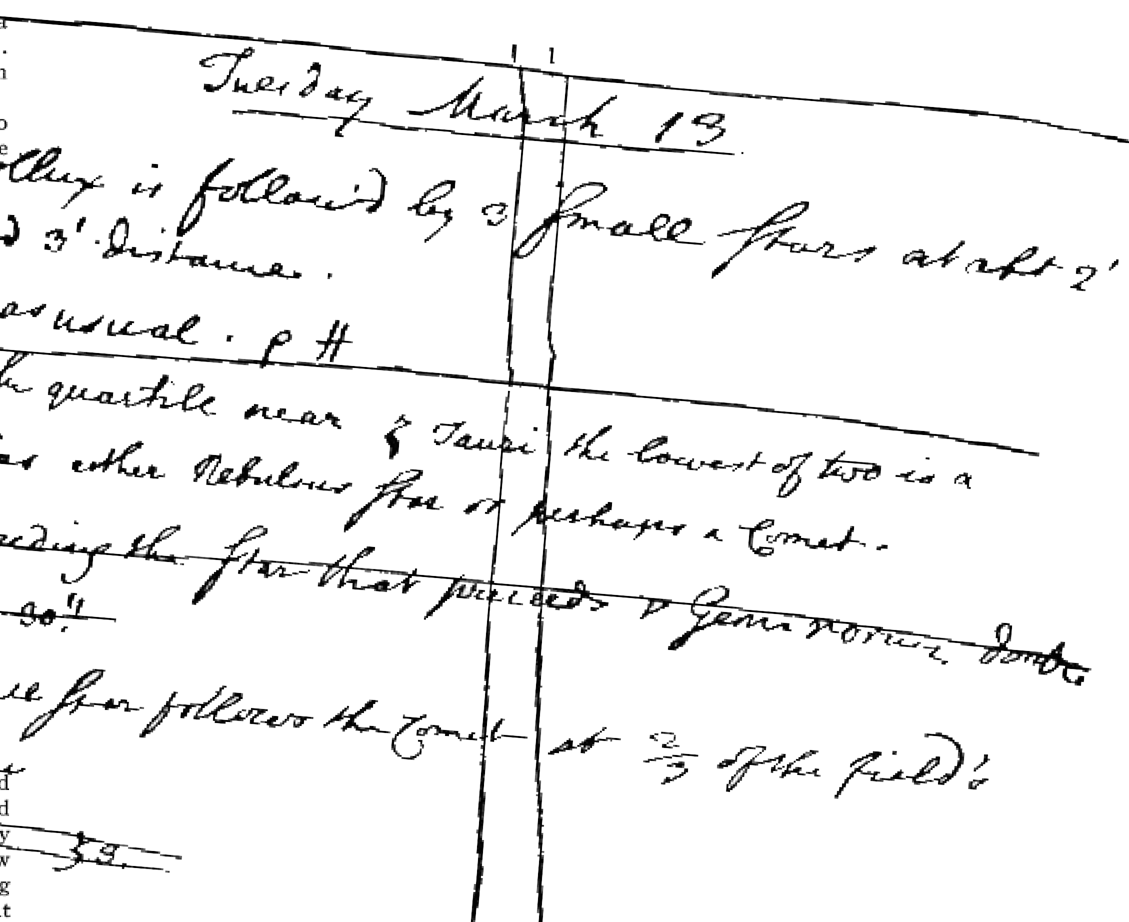
in the quartile near ζ Tauri the lowest of two is a curious either Nebulous star or perhaps a Comet.

~~preceding the star that precedes ν Geminorum double about 30'~~

a small star follows the Comet at 2/3 of the field's distance

~~2. 2. 33~~

FROM HERSCHEL'S JOURNAL.
Slightly reduced in size.



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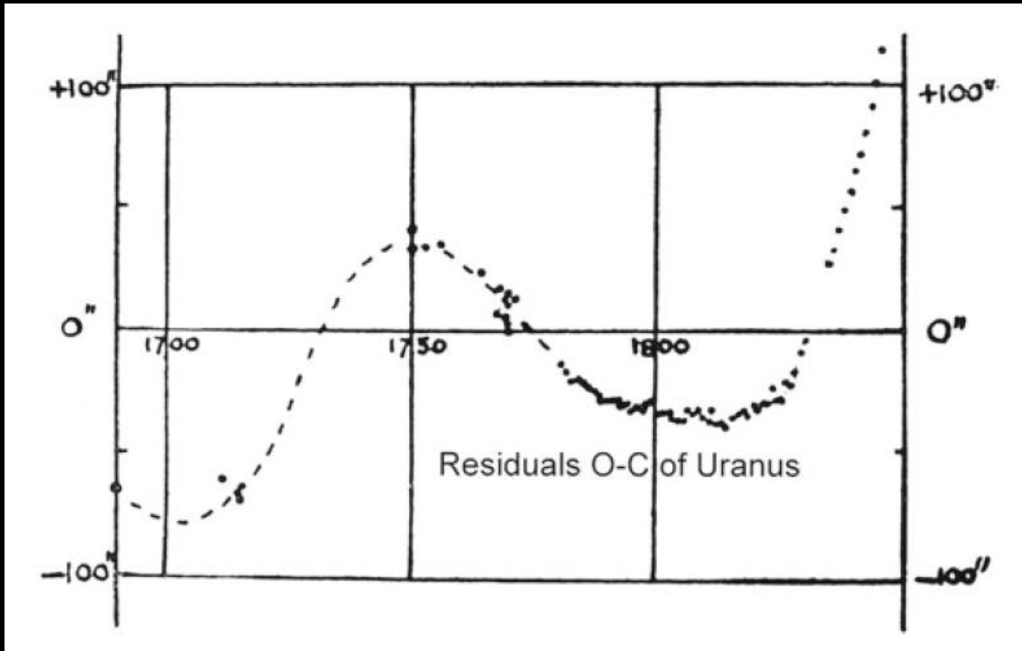
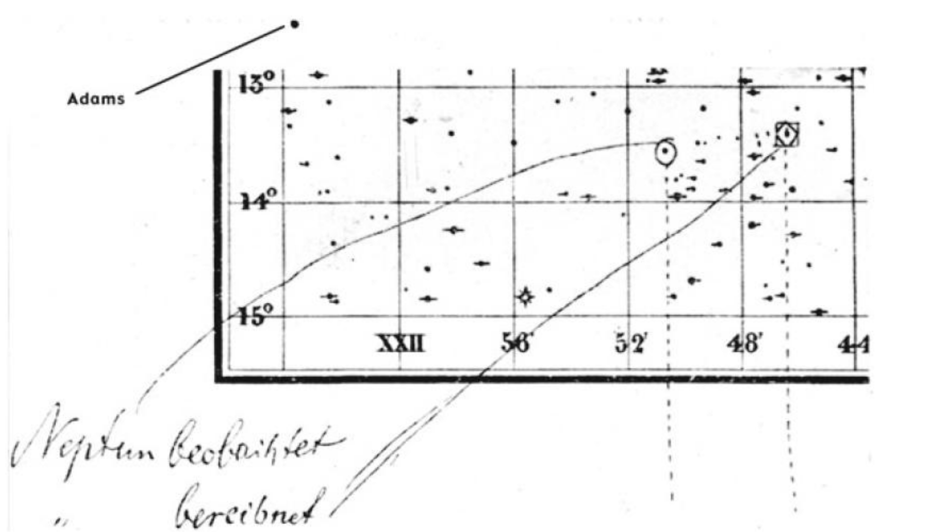
~~33~~

After this original entry it was some days before Herschel could observe his comet again. On Thursday morning between five and six o'clock he observed Mars and Saturn, but apparently the sky was not clear enough for him to hunt for the comet. He first saw it again on Saturday, March 17th, and we quote the following account from "Collected Scientific Papers," p. xxx. It shows that not only did Herschel fail to realize that he had found a new planet, but also, because of inaccuracy in his micrometers, he mistakenly thought the object was much nearer to us than it proved to be.





A fragment of Bremiker's celestial map on which a German hand (Galle's?) has plotted the position of Neptune predicted by Le Verrier (*Neptun bereibnet*) and the actual position (*Neptun beobachtet*). The position predicted by Adams is also indicated

THE NEW PLANET.

The discovery by M. Leverrier of a new planet beyond the boundaries of our solar system (as hitherto known), must rank as one of the most wonderful scientific achievements of our time. From an extensive examination of the movements of Uranus, it had been for some time certain that it was affected by some unknown influence, and a conjecture was formed that a planet existed beyond it, disturbing its motions.

To M. Leverrier belongs the honour of the discovery. On the 31st of August he made public the elements of the orbit of the supposed planet, deduced by most laborious calculation from the observed disturbances. He also announced that the planet would probably present a disc of about 3 sec. in magnitude. This announcement reached Dr Galle, at Berlin, on the 23d of September, and on the same evening Dr Galle, on comparing the stars in Dr Bremiker's chart with the heavens, found a star of the eighth magnitude which was not marked upon the map, and this star eventually proved to be the expected new planet. M. Leverrier and M. Galle are both to receive from the King of the French crosses of the Legion of Honour for their grand discovery.

The present distance of the new planet, expressed in common measure, is about 3,200,000,000 English miles from the sun, and about 3,100,000,000 from the earth. Its distance from Uranus—whose motions it disturbs—is about 150,000,000 of miles. Its diameter is estimated at 50,000 miles. That of Uranus is about 35,000; of Jupiter, 86,000; of Saturn, 79,000; of the Earth, 8000. Its cubic bulk is to that of the earth as 250 to 1. The new planet is the largest in our system except Jupiter and Saturn; and since these two planets, as well as Uranus, are each attended by a train of satellites, it is extremely probable that the new planet will have a similar accompaniment. The planet comes to the meridian a few minutes before nine, and is within a short distance of Saturn. With a power under 200, it is not distinguishable from a fixed star.

Mr Lassell, of Starfield, Liverpool, has written to state that he believes he can discern a ring surrounding the planet, and a star having every appearance of a satellite. The discovery of the ring and satellite is interesting, as completing that chain of uniformity and order we find pervading the whole creation. Thus the system of the universe, the work of Almighty intelligence, assists man in his researches, and enables him to proceed almost with certainty, from one discovery to another.

FRIDAY, MARCH 14, 1930.

Role

HINDENBURG.

A NINTH PLANET, GREATER THAN EARTH, FOUND

New Discovery Bears Out Calculations of Lowell and is Most Important Since That of Neptune.

SAVANTS THINK IT MAY BE BIGGER THAN JUPITER

Orb Sighted Jan. 1 by Delicate Lens, Observatory at Flagstaff Reports.

FLAGSTAFF, Ariz., March 13 (AP).—In that little cluster of orbs which scampers across the sidereal

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G SIGNS
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SPACE WATCH

Houston, do we have a new planet?

An artistic rendering of Planet Nine, with the Sun seen at the back. The 'planet' is thought to be gaseous, similar to Uranus and Neptune. — PHOTO: CALTECH

Earlier this week, astronomers Konstantin Batygin and Mike Brown of the California Institute of Technology (Caltech) in Pasadena, U.S., reported in the peer-reviewed *Astronomical Journal* that a body as big as Neptune — but as yet unseen — orbits the Sun every 15,000 years. Mr. Brown was among those who played a pivotal role in downgrading Pluto from 'planet' to a mere 'dwarf planet' and so his championing for Planet Nine is being taken quite seriously by the astronomer community. Then again, unless there's visual confirmation, we don't have a new planet.

How big is it?

The object, which the researchers have nicknamed Planet Nine, has a mass about 10 times that of Earth and orbits about 20 times farther from the Sun on average than does Neptune (which orbits the Sun at an average distance of 2.8 billion miles). In fact, it would take this new planet between 10,000 and 20,000 years to make just one full orbit around the Sun.

How long has the search for such planets been on?

The search for planets beyond Uranus has an over 150-year-old history. Based on the peculiar movements in the orbit of that planet, astronomers felt there had to be a heavy body that was causing these skewed movements and presto, Neptune was found in the mid 19th century. But that still wasn't enough. Among the several objects found beyond Neptune — in a region that is now known as the Kuiper belt — the most prominent was Pluto, discovered by Clyde Tombaugh, in 1928. But decades of data later suggested that Pluto was too small to be a proper planet and there were bigger objects that could be better contenders.

Why is the Batygin-Brown duo so confident about their potential discovery?

According to a news report in *Science*, the duo inferred Planet Nine's presence from the way six Kuiper objects orbit. They say there's only a 0.007 per cent chance, or about one in 15,000, that the clustering could be a coincidence. Instead, they say, a planet with the mass of 10 Earths has forced the six objects into their strange elliptical orbits, tilted out of the plane of the solar system.

The orbit of the inferred planet is similarly tilted, as well as stretched to distances that will explode previous conceptions of the solar system. Its closest approach to the Sun is seven times farther than Neptune, or 200 astronomical units (AUs). (An AU is the distance between Earth and the Sun, about 150 million kilometres.)

Can we ever see Planet Nine?

Icy and cold definitely but over at *Wired*, Rhett Allain has made some back-of-the-envelope calculations to suggest that if Nine were to be at its closest to our Sun, it would take 63 years for a spacecraft like New Horizons (that flew past Pluto last year) to fly past it. That's the best shot and at worst, it could be around 300 years.

Compiled by Jacob Koshy

THE ASTRONOMICAL JOURNAL VOLUME 76, NUMBER 8 OCTOBER 1971

A Dynamical Search for a Transplutonian Planet

P. K. SEIDELMANN
U. S. Naval Observatory, Washington, D. C.
(Received 22 June 1971)

A dynamical search for three hypothetical planets having representative characteristics of transplutonian planets, but within certain magnitude limits, was made by numerical integration of the orbits of the outer planets with, and without, a hypothetical planet. Careful comparison of these orbits with observations indicates that, although there may be undiscovered planets beyond Neptune, their dynamical effect on the known planets is so small that their presence, or absence, cannot be clearly discerned from the observation residuals.

Pub. Astron. Soc. Pacific, Volume 84, April 1972

THE EFFECT OF A TRANS-PLUTONIAN PLANET ON HALLEY'S COMET

JOSEPH L. BRADY
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Received 17 January 1972

An orbit and mass for a hypothetical trans-Plutonian planet is determined which reduces the residuals in the time of perihelion passage of Halley's comet at the seven apparitions from 1910 to 1456 by 93%. The effect of this hypothetical planet on the major planets is briefly discussed, and it is shown that the residuals of two similar periodic comets, Olbers and Pons-Brooks, are also improved.

Key words: comet — Halley's comet — planet — trans-Plutonian

Mon. Not. R. astr. Soc. (1973) **162**, 261–270.

MASS AND POSITION LIMITS FOR AN HYPOTHETICAL TENTH PLANET OF THE SOLAR SYSTEM

D. Rawlins and M. Hammerton

(Received 1972 December 20)

SUMMARY

This paper describes an analysis of the residuals of Neptune, conducted in order to delimit the possible range of mass and position for an hypothetical tenth planet of the solar system. Classical perturbation theory was employed, using a least-squares fit to residual normals, the problem being simplified by assuming a circular orbit for any hypothetical body. Results are presented which offer a restricted range of possible values; and their possible significance is discussed.

THE ASTRONOMICAL JOURNAL VOLUME 101, NUMBER 6 JUNE 1991

DYNAMICAL LIMITS ON DARK MASS IN THE OUTER SOLAR SYSTEM

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Received 26 December 1990; revised 12 February 1991

ABSTRACT

Dark matter in the outer solar system, such as a hypothetical Planet X or a Kuiper belt of material outside Neptune's orbit, may be detected by its dynamical influence on the orbits of the outer planets and comets. The study of simplified model solar systems with known observational errors offers insights into the best strategies to use in dynamical searches for dark mass, the significance of apparent anomalies, and the minimum detectable amounts of dark mass. We use this approach to establish the following results. (i) The inability of modern ephemerides to predict the longitude of Neptune accurately is a consequence of Neptune's long orbital period, and provides no evidence for the existence of dark mass. (ii) Searching for anomalous residuals when fitting observational data to models of the solar system that do not include dark mass is an inefficient way to detect dark mass; a more powerful test (by about a factor of 3–4) is to examine the improvement in fit when the observations are fitted to models that include dark mass. (iii) It is much harder to locate Planet X than to detect its existence: in order to predict the location of Planet X to within 1° its mass must exceed about 10 times the minimum detectable mass. (iv) If Planet X is massive and close enough to exert a detectable dynamical influence on the outer planets, then it is more likely than not that it would have been detected already in the *IRAS* survey. (v) Residuals in the orbits of comets such as Halley's are far more powerful probes for the Kuiper belt than are residuals in the orbits of the outer planets.

Mon. Not. R. Astron. Soc. **318**, 101–108 (2000)

The effect on the Edgeworth–Kuiper Belt of a large distant tenth planet

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Accepted 2000 April 26. Received 2000 April 26; in original form 1999 December 10

ABSTRACT
We investigate the orbital evolution of both real and hypothetical Edgeworth–Kuiper Objects in order to determine whether any conclusions can be drawn regarding the existence, or otherwise, of the tenth planet postulated by Murray. We find no qualitative difference in the orbital evolution, and so conclude that the hypothetical planet has been placed on an orbit at such a large heliocentric distance that no evidence for the existence, or non-existence, can be found from a study of the known Edgeworth–Kuiper Objects.

Key words: celestial mechanics, stellar dynamics – minor planets, asteroids – Solar system: general.

Mon. Not. R. Astron. Soc. **335,** 641–654 (2002)

Biases in cometary catalogues and Planet X

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Accepted 2002 May 2. Received 2002 May 2; in original form 2001 January 31

ABSTRACT
Two sets of investigators – Murray and Matese et al. – have recently claimed evidence for an undiscovered Solar System planet from possible great circle alignments in the aphelia directions of the long-period comets. However, comet discoveries are bedevilled by selection effects. These include anomalies caused by the excess of observers in the Northern as against the Southern hemisphere, seasonal and diurnal biases, directional effects which make it harder to discover comets in certain regions of the sky, as well as sociological biases. A simple mathematical model is developed to illustrate the geometrical selection effects controlling comet discoveries. The stream proposed by Murray is shown on an equal-area Hammer–Aitoff projection. The addition of newer data weakens the case for the alignment. There is also evidence that the subsample in the stream is affected by seasonal and north–south biases. The stream proposed by Matese et al. is most obvious in the sample of dynamically new comets, and especially in those whose orbits are best known. The most recent data continue to maintain the overpopulation in the great circle. This pattern in the data occurs with a probability of only $\sim 1.5 \times 10^{-3}$ by chance. None of the known biases is able to provide such an alignment. Numerical integrations are used to demonstrate that a planet by itself can reduce the perihelia of comets in its orbital plane to sufficiently small values so that they could be discovered from the Earth. To maintain the observed flux of comets in the stream requires a parent population of $\sim 3 \times 10^9$ objects on orbits close to the planet's orbital plane. There is a need for a sample of long-period comets that is free from unknown or hard-to-model selection effects. Such will be provided by the European Space Agency satellite *GAIA*, which will discover ~1000 long-period comets during its 5-yr mission. This may finally bring to fruition the long tradition of looking for the effects of perturbers in cometary catalogues.

Key words: stellar dynamics – celestial mechanics – comets: general – Kuiper Belt – Oort Cloud – planets and satellites: general.

THE ASTROPHYSICAL JOURNAL, 781:4 (7pp), 2014 January 20 doi:10.1088/0004-637X/781/1/4

A SEARCH FOR A DISTANT COMPANION TO THE SUN WITH THE *WIDE-FIELD INFRARED SURVEY EXPLORER*[*]

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Received 2013 September 12; accepted 2013 November 14; published 2013 December 24

ABSTRACT

I have used multi-epoch astrometry from the *Wide-field Infrared Survey Explorer* to perform a search for a distant companion to the Sun via its parallactic motion. I have not found an object of this kind down to $W2 = 14.5$. This limit corresponds to analogs of Saturn and Jupiter at 28,000 and 82,000 AU, respectively, according to models of the Jovian planets by Fortney and coworkers. Models of brown dwarfs by Burrows and coworkers predict fainter fluxes at a given mass for the age of the solar system, producing a closer distance limit of 26,000 AU for a Jupiter-mass brown dwarf. These constraints exclude most combinations of mass and separation at which a solar companion has been suggested to exist by various studies over the years.

Key words: brown dwarfs – infrared: planetary systems – planets and satellites: detection – proper motions – solar neighborhood

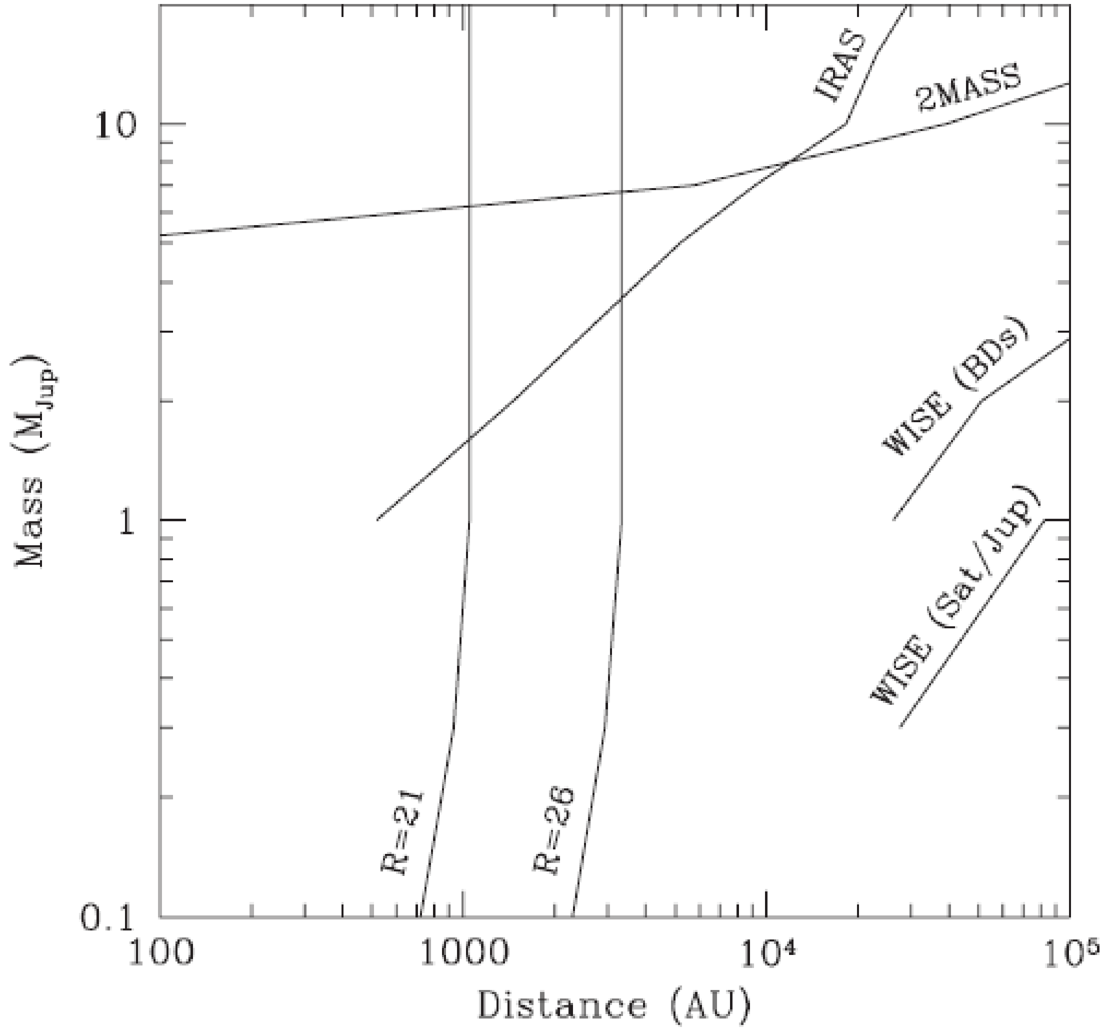


Figure 3. Detection limits for a companion to the Sun produced by current ($R = 21$) and future ($R = 26$) optical surveys and IR images from *IRAS* ($F_{12} = 0.4$ mJy), 2MASS ($J = 16.6$), and *WISE* ($W2 = 14.5$). For the optical limits, objects with masses of $\geqslant 1\ M_{Jup}$ are assumed to have the same fluxes of reflected light because of their similar radii. The IR limits have been derived with fluxes predicted by models of brown dwarfs at an age of 5 Gyr (Burrows et al. 1997, 2003) and (for *WISE* only) models of Saturn and Jupiter in the absence of solar irradiation (Fortney et al. 2011).

Orbits in the Solar System

In general, celestial bodies do not follow Keplerian orbits. Their current orbital states are described by osculating orbits or heliocentric (or barycentric) orbits in the absence of external perturbations.

Orbits in the Solar System

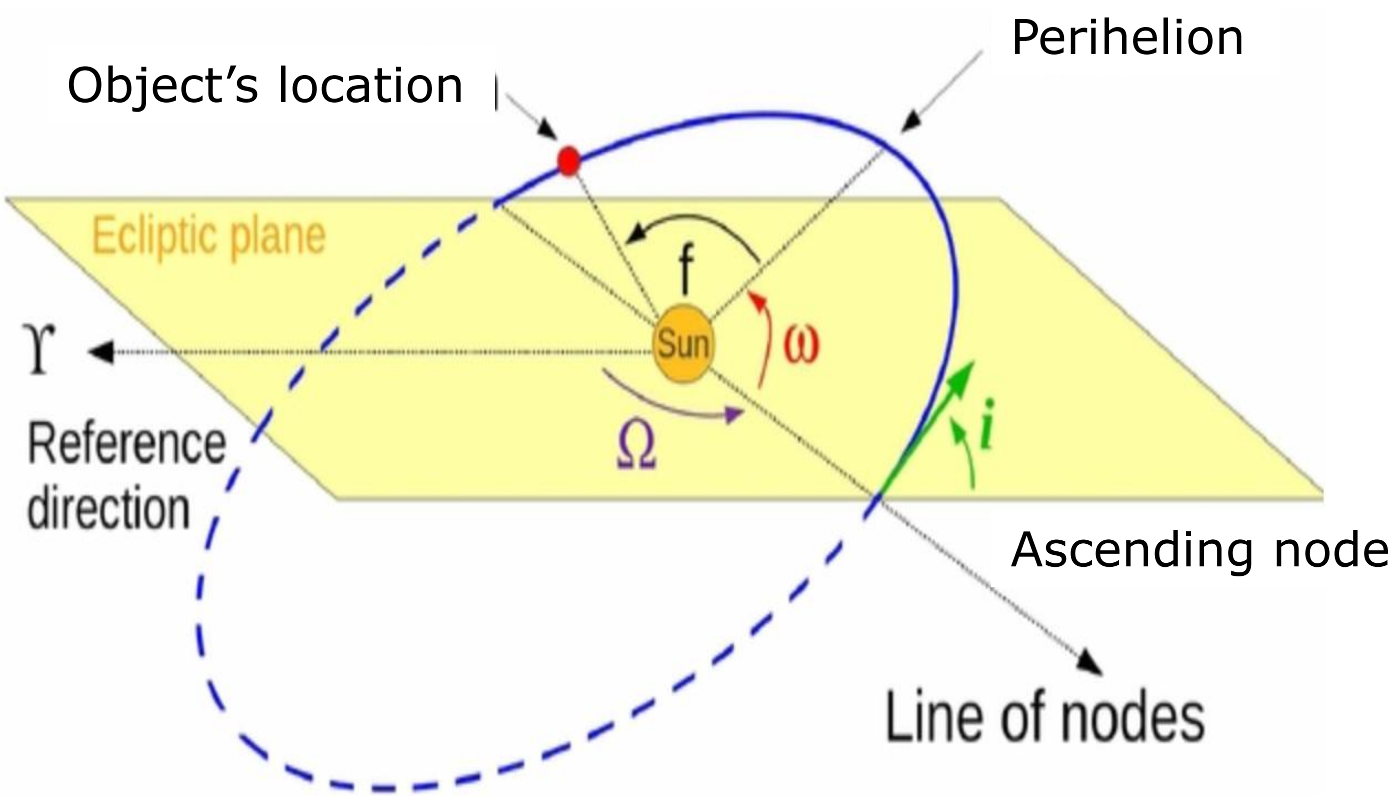
Osculating orbits are characterized by:

- Size — semi-major axis (a)
- Shape — eccentricity (e)
- Orientation in space —
  inclination (i) 0°-90°, direct — 90°-180°, retrograde
  longitude of the ascending node (Ω)
  argument of perihelion (ω)

perihelion distance
$q = a\,(1 - e)$
aphelion distance
$Q = a\,(1 + e)$

longitude of perihelion parameter, $\varpi = \Omega + \omega$.

Orbits in the Solar System



Orbits in the Solar System

- The value of the semi-major axis defines the specific orbital energy and angular momentum (with e) of the object.
- The value of the eccentricity defines the specific orbital angular momentum (with a) of the object.
- The value of the inclination defines the angle between the orbital plane of the object and that of the ecliptic (Earth's orbit).
- In absence of external perturbations their values remain constant.

Orbits in the Solar System

- For an unperturbed population of asteroids or comets, the values of the angular parameters (longitude of the ascending node, argument of perihelion and true anomaly, f) must be uniformly distributed, i.e. all the values are equally probable.
- External perturbations in the form of close encounters, and/or mean motion (and/or secular) resonances can transform a uniform distribution into any other.
- In absence of resonances the angular parameters circulate (can take any value); however, if resonances are at work, they may librate or oscillate (e.g. ω can librate about 0º or 180º).

Orbits in the Solar System

itationally with a planet. The ecliptic coordinates of the pole of a prograde orbit, longitude and latitude, are given by the expressions:

$$(l_{\rm p}, b_{\rm p}) = (\Omega - 90^\circ, 90^\circ - i)\,. \tag{1}$$

In other words, objects with comparable values of the orbital inclination, i, and longitude of the ascending node, Ω, have similar orbital planes. In Öpik (1971), objects with similar orbital planes

perihelion, q, and aphelion, Q, for these objects. The coordinates of the perihelion, (l_q, b_q), are given by the expressions (see e.g. Murray & Dermott 1999):

$$\tan(l_q - \Omega) = \tan\omega\,\cos i\,, \quad \sin b_q = \sin\omega\,\sin i\,. \tag{2}$$

And the longitude and latitude of the aphelion are:

$$(l_Q, b_Q) = (l_q + 180^\circ, -b_q)\,. \tag{3}$$

In other words, objects with comparable values of i, Ω and ω have also very similar coordinates of both perihelion and aphelion. The three angular elements —i, Ω and ω— specify the spatial orientation of the orbit. The analysis in Öpik (1971) using cometary

Tomanov's Law. If the perihelia of a population of minor bodies are concentrated around a set of values, (l_q, b_q), then a relation of the form:

$$\tan i = \tan b_q / \sin(l_q - \Omega)\,, \tag{4}$$

must exist between inclination and longitude of the ascending node.

THE ASTRONOMICAL JOURNAL VOLUME 87, NUMBER 6 JUNE 1982

ON THE DISTRIBUTION OF ORBITS AMONG LONG-PERIOD COMETS

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Received 10 December 1981; revised 8 February 1982

ABSTRACT

The distribution of the axes defining the planes and orientations of the orbits of 542 long-period comets are analyzed. The directions of the perihelia and of the oriented plane normals show significant nonuniformity in their distributions. The preferred direction of perihelia near the apex of solar motion is refined to an (1σ) error circle of 20°.6, and possible concentrations of the plane normals and the directions of perihelion velocity along roughly orthogonal directions are noted, although the error circles extend to nearly full hemispheres. Planes of preference (and avoidance) are found from the distribution ellipsoids of the three orbital axes, with the perihelion directions lying preferentially along the galactic plane. The distribution ellipsoids of all three sets of orbital axes exhibit anisotropies roughly twice those expected for random distributions.

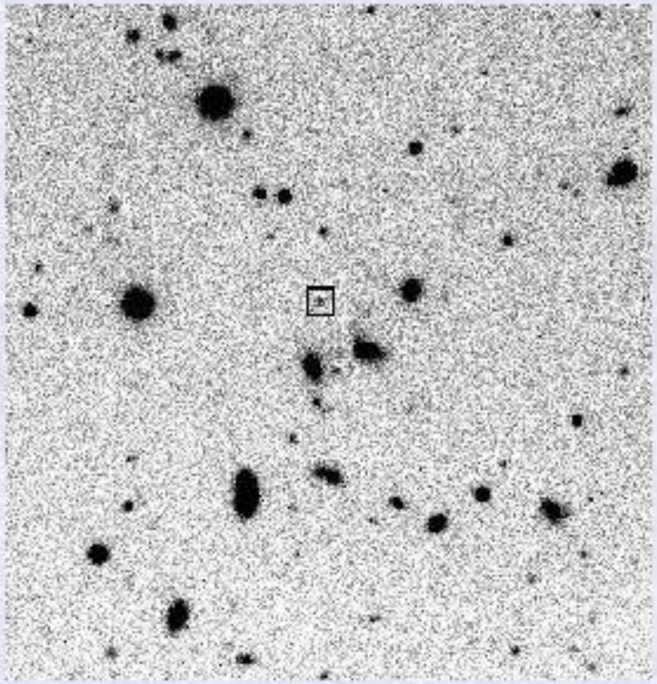
certain distances of one another are not, of course, independent. For N random orbits, the mean number of pairs expected with plane normals differing by an angle less than X and with perihelion directions differing by an angle less than Y may be approximated, however, by

$$n_2 \approx N(N-1)Y(1-\cos X)/4\pi \tag{1b}$$

for small X.

anomalous as the distribution of major axes and may be as instructive. The perihelion velocity direction, in particular, may reflect impulses received by the comet at aphelion, and it is surprising that it has been neglected in the statistical studies of the past.

Evidence for an Extended Scattered Disk?



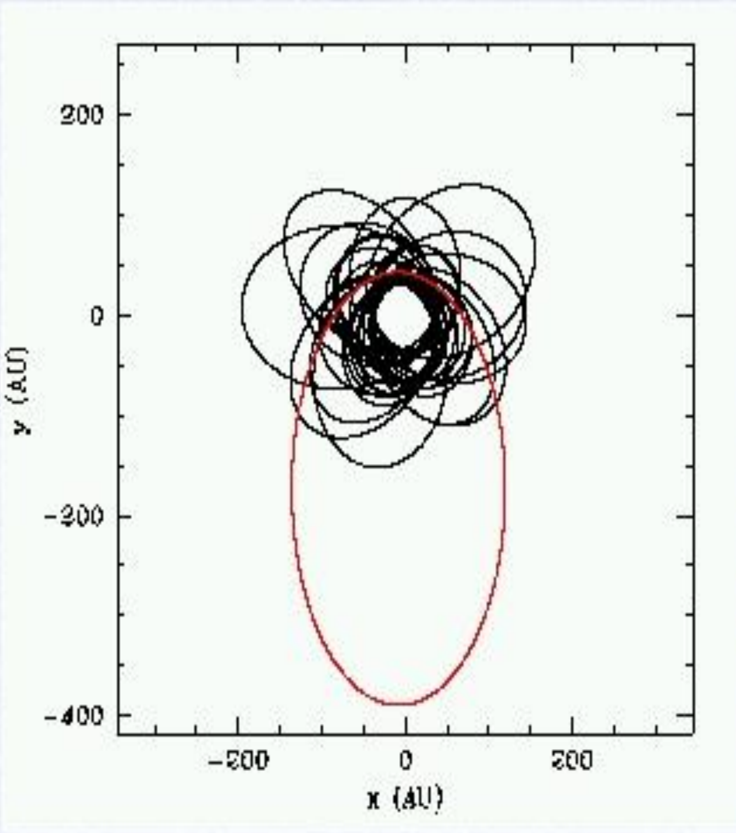
Orbit Determination of 2000 CR105

2000 CR105 is a transneptunain object (in our Solar System's Kuiper Belt beyond Neptune), discovered in Febuary 2000 during a Kuiper Belt survey by a team at Lowell Observatory. We tracked the object in March 2000 from the Canada-France-Hawaii telescope and showed that the object's orbit was larger than any other known Kuiper Belt object, and in particular the fact that it's pericenter was farther from Neptune than any other highly-eccentric object. Since then we have continued to follow the object and have proven that its orbit is only weakly affected by the giant planets. A paper has been submitted to the journal Icarus describing the implications of this fact.

Evidence for an extended scattered disk
by
B. Gladman, M. Holman, T. Grav, J. Kavelaars, P. Nicholson, K. Aksnes, and J-M. Petit.

Images

JPG images of 2000 CR105 in Normal black and white and Negative formats.



ORBIT OF SCATTERED DISK OBJECTS AND 2000 CR105

This figure compares the orbits of the other scattered disk objects
with that we have estimated for 2000 CR105.

This figure shows the orbits of all the known scattered disk objects (SDOs)
as well as the much larger orbit of 2000 CR105 (in red).
The SDOs are objects which are on large looping orbits; the most developed theories for the creation of the scattered disk produce these orbits by gravitational scattering due to Neptune, which hurls them out to external orbits which take hundreds of year to circulate around the Sun.
Numerical calculations have shown that some of the objects can rest in this state for the 4.5-billion year lifetime of the Solar System.
The first recognized SDO was 1996 TL66, discovered by Luu et al. in 1996 (reprint in pdf format available on the www).
About two dozen such SDOs are now known, many of them have been discovered and tracked by C. Trujillo et al.

The figure shows that 2000 CR105 journeys far from the Sun, several times further than the other SDOs.
There are long-period comets that journey much farther away towards the Oort cloud.
The interesting facet of CR105's orbit is NOT its large size, but rather the fact that its perihelion (distance of closest approach to the Sun) is larger than any other known Solar System object.

Icy Bodies of the Solar System
Proceedings IAU Symposium No. 263, 2009
J.A. Fernández, D. Lazzaro, D. Prialnik & R. Schulz, eds.

doi:10.1017/S1743921310001511

Sedna, 2004 VN112 and 2000 CR105: the tip of an iceberg

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Abstract. We review two main scenarios that may have implanted Sedna, 2004 VN112 and 2000 CR105 on their current peculiar orbits. These scenarios are based on perihelion lifting mechanisms that acted upon primordial scattered icy bodies. Supposing that the Sun was formed in a dense star cluster and that the gas giants were also forming while the cluster was still dense, an inner Oort cloud that includes Sedna at its inner edge could have been formed by the circularization of icy leftovers orbits scattered by the gas giants. A putative planetary mass solar companion can also produce a similar population of icy bodies through a perihelion lifting mechanism induced by secular resonances from the companion. A third scenario also dependent on a primordial dense cluster may contribute to adding a significant number of extrasolar icy bodies to the main solar component of the population created by the cluster model. These extrasolar objects are transferred to Sun orbits from the scattered disk of passing stars that were numerous in the dense primordial environment. We compare the scenarios as to the orbital distribution of the induced populations as well as their total mass. We conclude that both the cluster model and the solar companion model can produce icy body populations consistent with Sedna's orbit. It is also quite possible that this inner Oort cloud may be composed of roughly one tenth of extrasolar objects.

Keywords. Sedna, Oort cloud, star cluster, solar companion

There is no compelling reason to believe that there are no planets beyond Pluto

- Observational data accumulated during the last decade do not explicitly rule out the presence of one or more super-Earth-sized planets at hundreds or thousands of AU from the Sun (see e.g. Luhman 2014; Batygin & Brown 2016; Brown & Batygin 2016; Fienga et al. 2016).

- The study of exo-planetary systems shows that planets moving in wide orbits do indeed exist (see e.g. Luhman et al. 2012; Bailey et al. 2014; Naud et al. 2014).

- Most exo-planets have masses below those of Uranus and Neptune but above that of the Earth (see e.g. Howard et al. 2010; Malhotra 2015; Silburt et al. 2015).

LETTER

doi:10.1038/nature13156

A Sedna-like body with a perihelion of 80 astronomical units

Chadwick A. Trujillo[1]* & Scott S. Sheppard[2]*

The observable Solar System can be divided into three distinct regions: the rocky terrestrial planets including the asteroids at 0.39 to 4.2 astronomical units (AU) from the Sun (where 1 AU is the mean distance between Earth and the Sun), the gas giant planets at 5 to 30 AU from the Sun, and the icy Kuiper belt objects at 30 to 50 AU from the Sun. The 1,000-kilometre-diameter dwarf planet Sedna was discovered ten years ago and was unique in that its closest approach to the Sun (perihelion) is 76 AU, far greater than that of any other Solar System body[1]. Formation models indicate that Sedna could be a link between the Kuiper belt objects and the hypothesized outer Oort cloud at around 10,000 AU from the Sun[2–6]. Here we report the presence of a second Sedna-like object, 2012 VP_{113}, whose perihelion is 80 AU. The detection of 2012 VP_{113} confirms that Sedna is not an isolated object; instead, both bodies may be members of the inner Oort cloud, whose objects could outnumber all other dynamically stable populations in the Solar System.

The inner Oort cloud objects probably formed on nearly circular orbits, allowing them to accumulate mass efficiently[6–9], and were later perturbed into the eccentric orbits we see today. We define an inner Oort cloud object as a body whose orbit is not readily formed with the known mass in the Solar System. This typically means a perihelion greater than 50 AU (beyond the range of significant Neptune interaction) and a semi-major axis in the range 150 AU $< a <$ 1,500 AU. At above 1,500 AU objects may be considered to be in the outer Oort cloud, as galactic tides start to become important in the formation process[10].

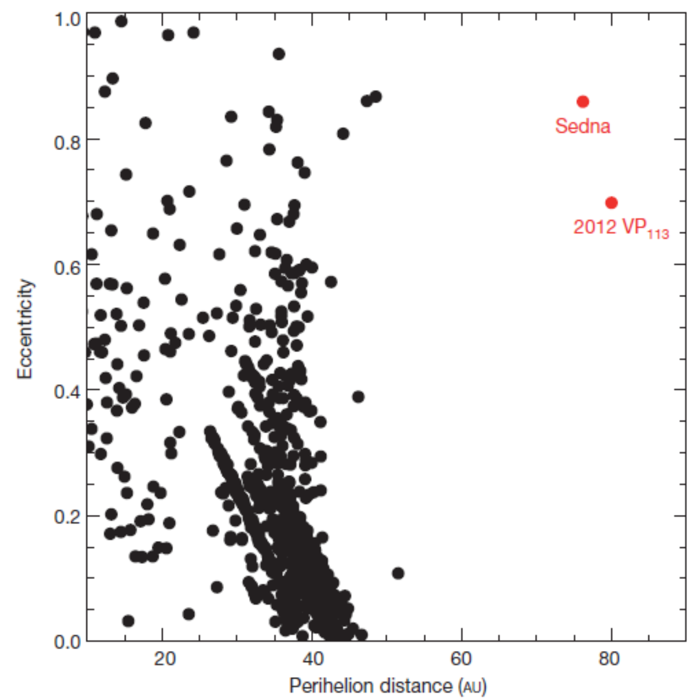

Figure 1 | Sedna and 2012 VP_{113} are clear dynamical outliers in the Solar

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Extreme trans-Neptunian objects and the Kozai mechanism: signalling the presence of trans-Plutonian planets

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ABSTRACT

The existence of an outer planet beyond Pluto has been a matter of debate for decades and the recent discovery of 2012 VP_{113} has just revived the interest for this controversial topic. This Sedna-like object has the most distant perihelion of any known minor planet and the value of its argument of perihelion is close to 0°. This property appears to be shared by almost all known asteroids with semimajor axis greater than 150 au and perihelion greater than 30 au (the extreme trans-Neptunian objects or ETNOs), and this fact has been interpreted as evidence for the existence of a super-Earth at 250 au. In this scenario, a population of stable asteroids may be shepherded by a distant, undiscovered planet larger than the Earth that keeps the value of their argument of perihelion librating around 0° as a result of the Kozai mechanism. Here, we study the visibility of these ETNOs and confirm that the observed excess of objects reaching perihelion near the ascending node cannot be explained in terms of any observational biases. This excess must be a true feature of this population and its possible origin is explored in the framework of the Kozai effect. The analysis of several possible scenarios strongly suggest that at least two trans-Plutonian planets must exist.

Key words: celestial mechanics – minor planets, asteroids: general – minor planets, asteroids: individual: 2012 VP_{113} – planets and satellites: individual: Neptune.

Table 1. Equatorial coordinates, apparent magnitudes (with filter if known) at discovery time, absolute magnitude, and ω for the 13 objects discussed in this Letter. (J2000.0 ecliptic and equinox. Source: MPC data base.)

Object	α (^{h}:^{m}:^{s})	δ ($^{\circ}$:$'$:$''$)	m (mag)	H (mag)	ω ($^{\circ}$)
82158	11:57:50.69	+00:21:42.7	22.2 (R)	6.0	6.77
Sedna	03:15:10.09	+05:38:16.5	20.8 (R)	1.5	311.19
148209	09:14:02.39	+19:05:58.7	22.5 (R)	6.3	317.09
2002 GB_{32}	12:28:25.94	−00:17:28.4	21.9 (R)	7.7	36.89
2003 HB_{57}	13:00:30.58	−06:43:05.4	23.1 (R)	7.4	10.64
2003 SS_{422}	23:27:48.15	−09:28:43.4	22.9 (R)	7.1	209.98
2004 VN_{112}	02:08:41.12	−04:33:02.1	22.7 (R)	6.4	327.23
2005 RH_{52}	22:31:51.90	+04:08:06.1	23.8 (g)	7.8	32.59
2007 TG_{422}	03:11:29.90	−00:40:26.9	22.2	6.2	285.84
2007 VJ_{305}	00:29:31.74	−00:45:45.0	22.4	6.6	338.53
2010 GB_{174}	12:38:29.365	+15:02:45.54	25.09 (g)	6.5	347.53
2010 VZ_{98}	02:08:43.575	+08:06:50.90	20.3 (R)	5.0	313.80
2012 VP_{113}	03:23:47.159	+01:12:01.65	23.1 (r)	4.1	293.97

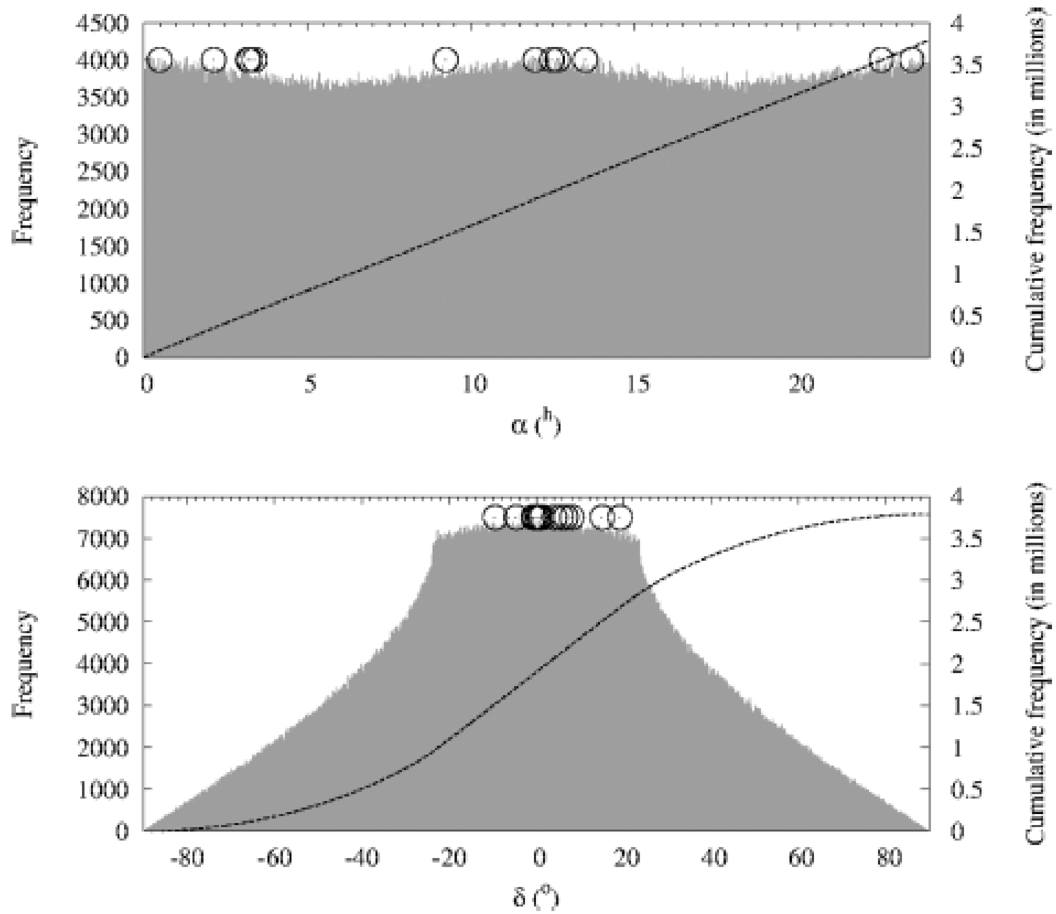

Figure 2. Frequency distribution in equatorial coordinates (right ascension, top panel, and declination, bottom panel) of the studied test orbits at perigee. The distribution is rather uniform in right ascension and shows a maximum for declinations in the range $-24°$ to $24°$. The bin sizes are 0.024 h in right ascension and $0\overset{\circ}{.}18$ in declination, error bars are too small to be seen. The black circles correspond to objects in Table 1.

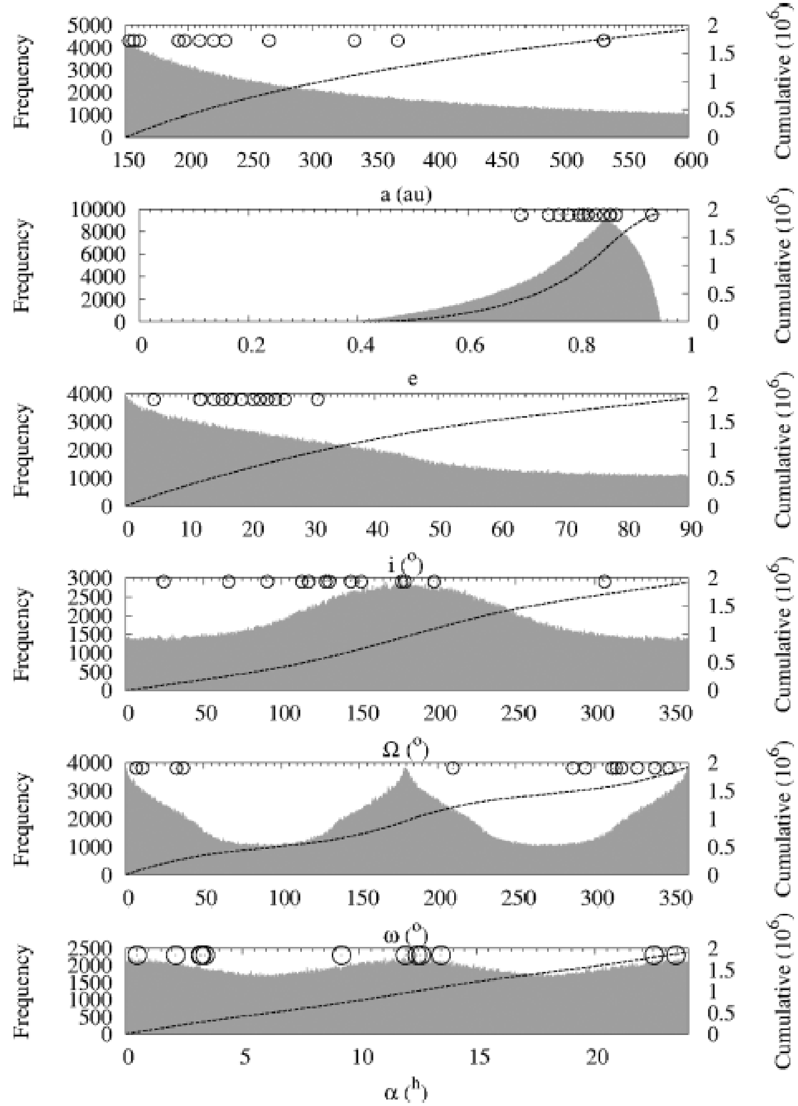

Figure 3. Frequency distribution in right ascension (bottom panel) and the orbital elements of test orbits with $|\delta| < 24°$. The bin sizes are 0.45 au in semimajor axis, 0.001 in eccentricity, 0°.09 in inclination, 0°.36 in longitude of the node, 0°.36 in argument of perihelion and 0.024 h in right ascension, error bars are too small to be seen. The black circles correspond to objects in Table 1. Data from Table A1 have been used, this table is only available online.

$$\sqrt{1-e^2}\cos i = \text{constant}$$

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Flipping minor bodies: what comet 96P/Machholz 1 can tell us about the orbital evolution of extreme trans-Neptunian objects and the production of near-Earth objects on retrograde orbits

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ABSTRACT
Nearly all known extreme trans-Neptunian objects (ETNOs) have argument of perihelion close to 0°. An existing observational bias strongly favours the detection of ETNOs with arguments of perihelion close to 0° and 180° yet no objects have been found at 180°. No plausible explanation has been offered so far to account for this unusual pattern. Here, we study the dynamical evolution of comet 96P/Machholz 1, a bizarre near-Earth object (NEO) that may provide the key to explain the puzzling clustering of orbits around argument of perihelion close to 0° recently found for the population of ETNOs. Comet 96P/Machholz 1 is currently locked in a Kozai resonance with Jupiter such that the value of its argument of perihelion is always close to 0° at its shortest possible perihelion (highest eccentricity and lowest inclination) and about 180° near its shortest aphelion (longest perihelion distance, lowest eccentricity and highest inclination). If this object is a dynamical analogue (albeit limited) of the known ETNOs, this implies that massive perturbers must keep them confined in orbital parameter space. Besides, its future dynamical evolution displays orbital flips when its eccentricity is excited to a high value and its orbit turns over by nearly 180°, rolling over its major axis. This unusual behaviour, that is preserved when post-Newtonian terms are included in the numerical integrations, may also help understand the production of NEOs on retrograde orbits.

Key words: relativistic processes – celestial mechanics – comets: individual: 96P/Machholz 1 – minor planets, asteroids: individual: 2012 VP_{113} – planets and satellites: individual: Earth – planets and satellites: individual: Jupiter.

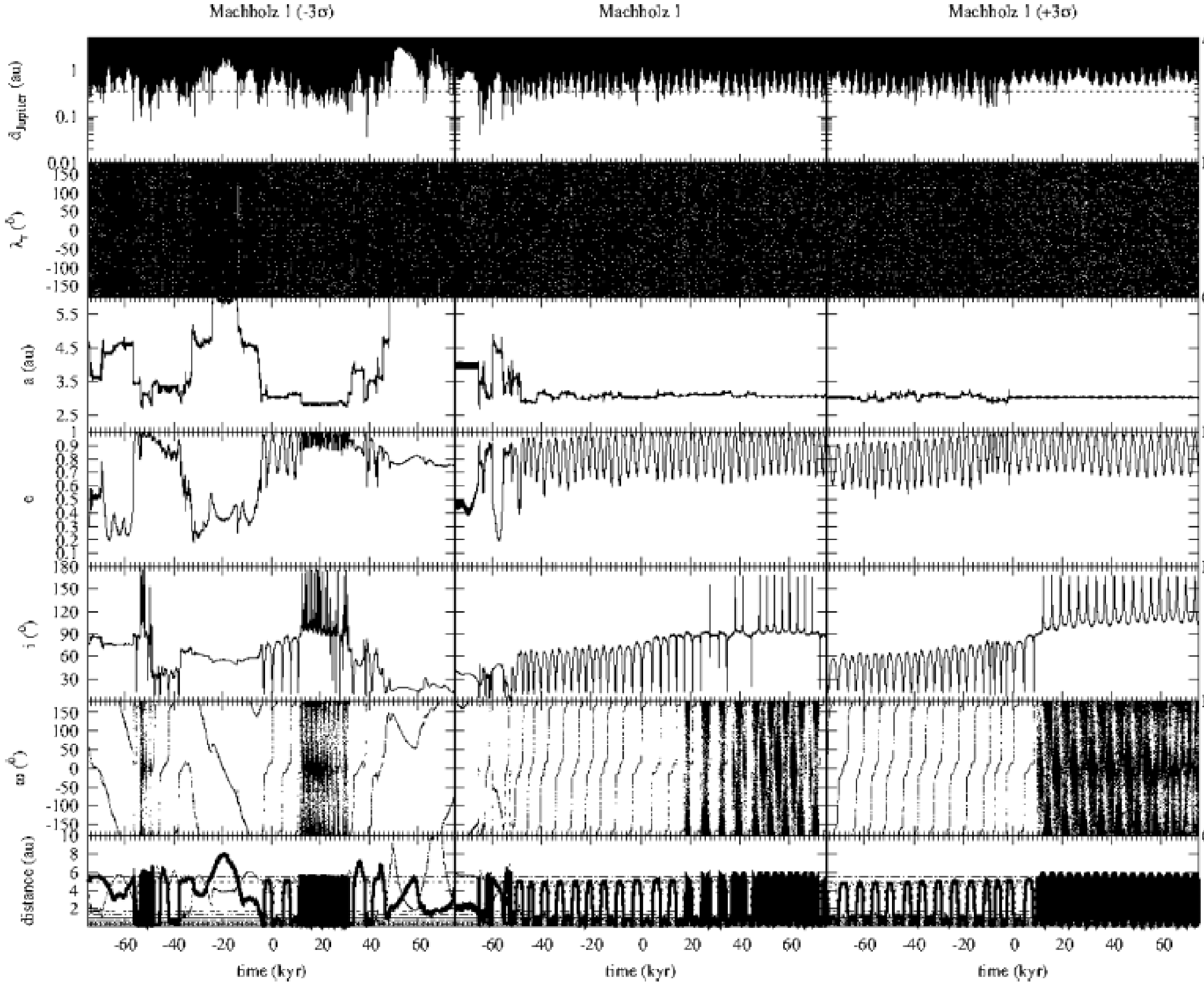

Figure 2. Comparative short-term dynamical evolution of various parameters for the nominal orbit of comet 96P/Machholz 1 as presented in Table 2 (central panels) and two representative examples of orbits that are most different from the nominal one (see the text for details). The distance from Jupiter (A-panels); the value of the Hill sphere radius of Jupiter, 0.35 au, is displayed. The resonant angle, λ_r (B-panels). The orbital elements a (C-panels), e (D-panels), i (E-panels) and ω (F-panels). The distances to the descending (thick line) and ascending nodes (dotted line) appear in the G-panels. Planetary aphelion and perihelion distances are also shown. The orbit labelled as 'nominal' is arbitrarily close to the nominal one but not that of Fig. 1.

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EVIDENCE FOR A DISTANT GIANT PLANET IN THE SOLAR SYSTEM

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ABSTRACT

Recent analyses have shown that distant orbits within the scattered disk population of the Kuiper Belt exhibit an unexpected clustering in their respective arguments of perihelion. While several hypotheses have been put forward to explain this alignment, to date, a theoretical model that can successfully account for the observations remains elusive. In this work we show that the orbits of distant Kuiper Belt objects (KBOs) cluster not only in argument of perihelion, but also in physical space. We demonstrate that the perihelion positions and orbital planes of the objects are tightly confined and that such a clustering has only a probability of 0.007% to be due to chance, thus requiring a dynamical origin. We find that the observed orbital alignment can be maintained by a distant eccentric planet with mass $\gtrsim 10\, m_{\oplus}$ whose orbit lies in approximately the same plane as those of the distant KBOs, but whose perihelion is 180° away from the perihelia of the minor bodies. In addition to accounting for the observed orbital alignment, the existence of such a planet naturally explains the presence of high-perihelion Sedna-like objects, as well as the known collection of high semimajor axis objects with inclinations between 60° and 150° whose origin was previously unclear. Continued analysis of both distant and highly inclined outer solar system objects provides the opportunity for testing our hypothesis as well as further constraining the orbital elements and mass of the distant planet.

Key words: Kuiper Belt: general – planets and satellites: dynamical evolution and stability

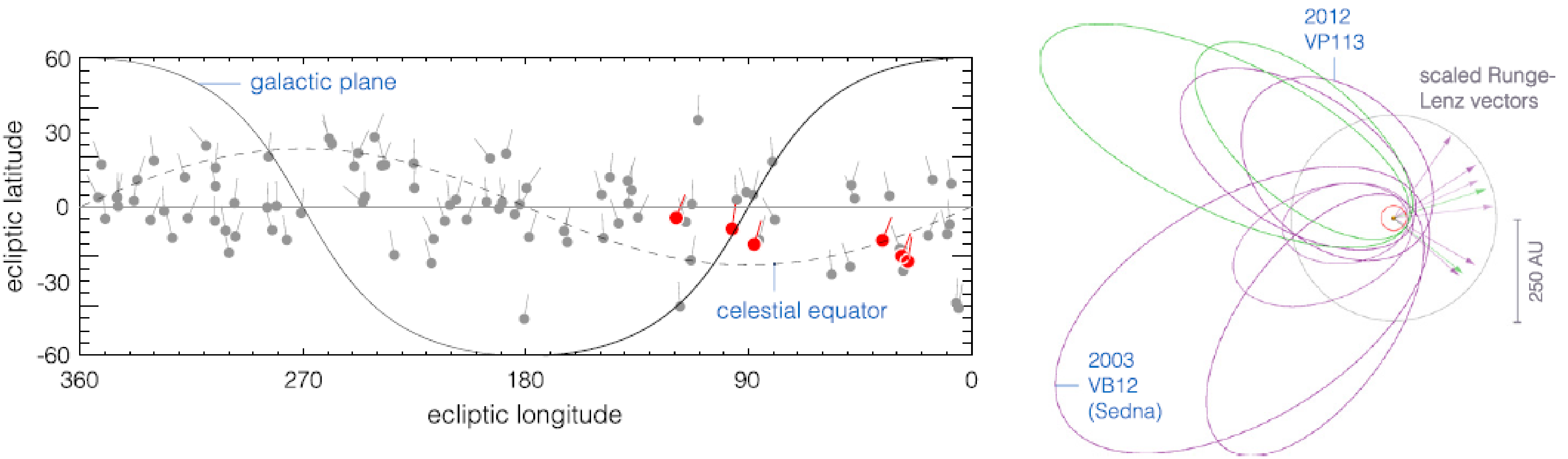

Figure 2. Orbital clustering in physical space. The right panels depicts the side and top views of the Keplerian trajectories of all bodies with $a > 250$ AU as well as dynamically stable objects with $a > 150$ AU. The adopted color scheme is identical to that employed in Figure 1, and the two thin purple orbits correspond to stable bodies within the $150 < a < 250$ AU range. For each object, the directions of the angular momentum and Runge–Lenz (eccentricity) vectors are additionally shown. The left panel shows the location of perihelia of the minor bodies with $q > 30$ AU and $a > 50$ AU on the celestial sphere as points, along with the projection of their orbit poles with adjacent lines. The orbits with $a > 250$ AU are emphasized in red. The physical confinement of the orbits is clearly evident in both panels.

We estimate the statistical significance of the observed clustering by assuming that the detection biases for our clustered objects are similar to the detection biases for the collection of all objects with $q > 30$ AU and $a > 50$ AU. We then randomly select six objects from the sample 100,000 times and calculate the root mean square (rms) of the angular distance between the perihelion position of each object and the average perihelion position of the selected bodies. Orbits as tightly clustered in perihelion position as the six observed KBOs occur only 0.7% of the time. Moreover, the objects with clustered perihelia also exhibit clustering in orbital pole position, as can be seen by the nearly identical direction of their projected pole orientations. We similarly calculated the rms spread of the polar angles, and find that a cluster as tight as that observed in the data occurs only 1% of the time. The two measurements are statistically uncorrelated, and we can safely multiply the probabilities together to find that the joint probability of observing both the clustering in perihelion position and in pole orientation simultaneously is only 0.007%. Even with only six objects currently in the group, the significance level is about 3.8σ. It is extremely unlikely that the objects are so tightly confined purely due to chance.

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OBSERVATIONAL CONSTRAINTS ON THE ORBIT AND LOCATION OF PLANET NINE IN THE OUTER SOLAR SYSTEM

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ABSTRACT

We use an extensive suite of numerical simulations to constrain the mass and orbit of Planet Nine, the recently proposed perturber in a distant eccentric orbit in the outer solar system. We compare our simulations to the observed population of aligned eccentric high semimajor axis Kuiper belt objects (KBOs) and determine which simulation parameters are statistically compatible with the observations. We find that only a narrow range of orbital elements can reproduce the observations. In particular, the combination of semimajor axis, eccentricity, and mass of Planet Nine strongly dictates the semimajor axis range of the orbital confinement of the distant eccentric KBOs. Allowed orbits, which confine KBOs with semimajor axis beyond 380 au, have perihelia roughly between 150 and 350 au, semimajor axes between 380 and 980 au, and masses between 5 and 20 Earth masses. Orbitally confined objects also generally have orbital planes similar to that of the planet, suggesting that the planet is inclined approximately 30°to the ecliptic. We compare the allowed orbital positions and estimated brightness of Planet Nine to previous and ongoing surveys which would be sensitive to the planet's detection and use these surveys to rule out approximately two-thirds of the planet's orbit. Planet Nine is likely near aphelion with an approximate brightness of $22 < V < 25$. At opposition, its motion, mainly due to parallax, can easily be detected within 24 hours.

Key words: celestial mechanics – Kuiper belt: general – planets and satellites: detection

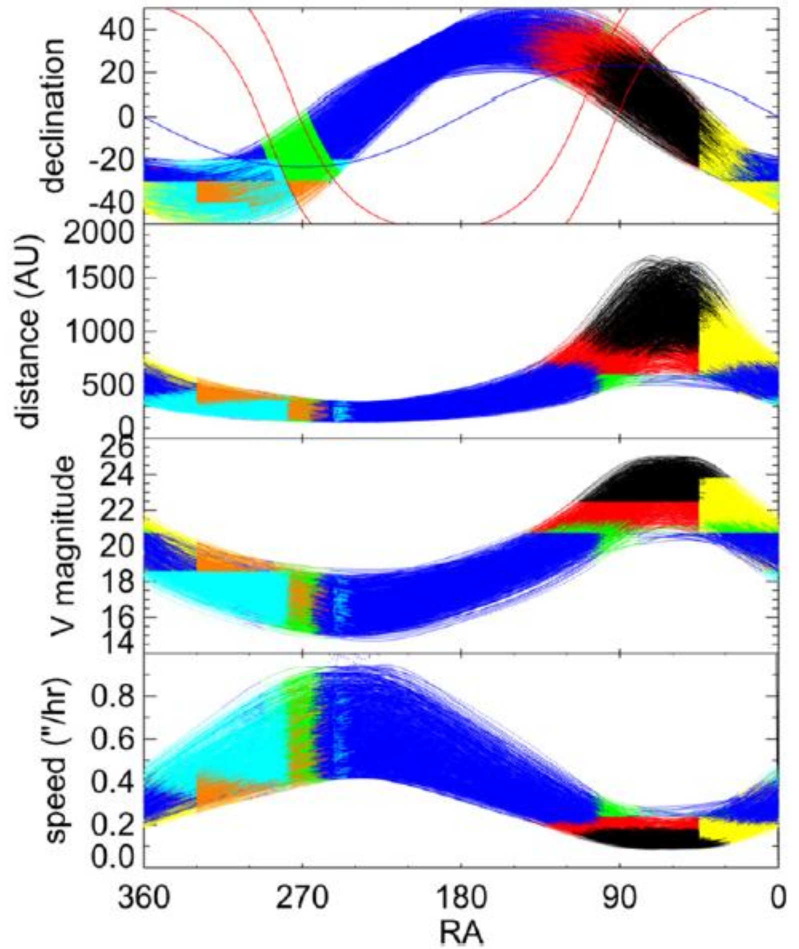


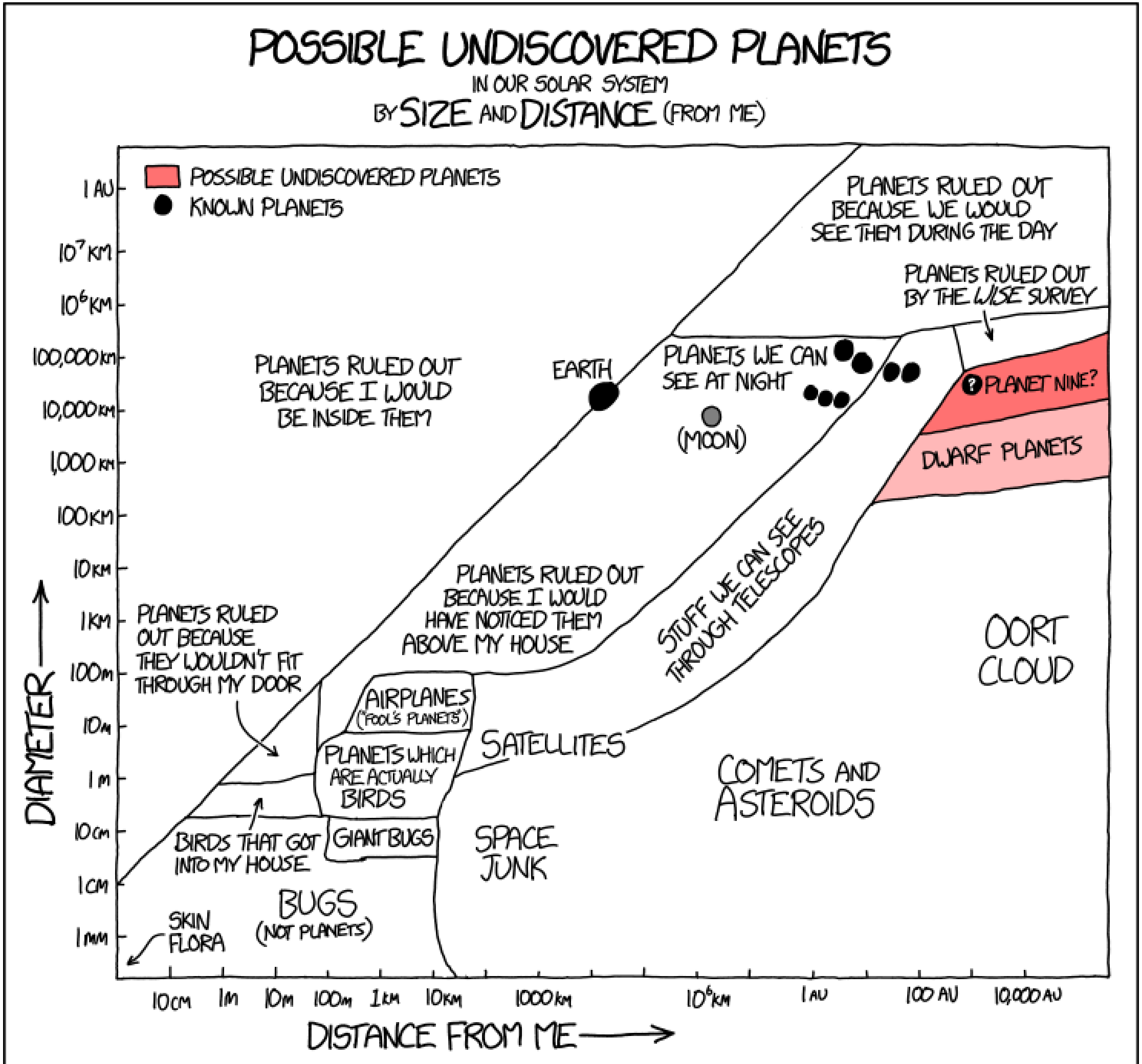
Figure 10. Using all constraints on the orbital and physical parameters of Planet Nine, we can predict the location, distance, brightness, and speed of the planet throughout its orbit. Regions within 10° of the galactic plane are outlined in red, and the ecliptic plane is shown in blue. The colored portions show regions where Planet Nine would have been or should be detected by previous or ongoing surveys. Light blue shows limits from the CRTS reanalysis, yellow shows Dark Energy Survey limits and coverage, dark blue shows Pan-STARRS transient analysis limits, green shows Pan-STARRS moving object analysis current limits, and red shows eventual Pan-STARRS expected limits. Orange shows the region exclusively ruled out by lack of observed perturbation to Saturn (Fienga et al. 2016; Holman & Payne 2016). The black regions show regions of phase space where Planet Nine could not have been or will not be detected in previous or currently planned surveys.

As important as continued simulation, continued detection of distant solar system objects is the key to refining the orbital parameters of Planet Nine. Each addition KBO (or Centaur) with $a > 100$ au tightens the observational constraints on the location of Planet Nine (or, alternatively, if significant numbers of objects are found outside of the expected cluster location, the objects can refute the presence of a Planet Nine).

Planet Nine hypothesis

Assuming a mass, *m*, in terms of the mass of the Earth:

- Semi-major axis (200 AU + 30 m, 600 AU + 20 m)
  if m = 10 Earth masses ➔ (500 AU, 800 AU)
- Eccentricity = 0.75 – ((250 AU + 20 m)/a)^8
  if m = 10 Earth masses ➔ (0.32, 0.74)
- Inclination (22^o, 40^o)
- Longitude of the ascending node (72^o, 121^o)
- Argument of perihelion (120^o, 160^o)


POSSIBLE UNDISCOVERED PLANETS
IN OUR SOLAR SYSTEM
BY SIZE AND DISTANCE (FROM ME)
POSSIBLE UNDISCOVERED PLANETS
KNOWN PLANETS
PLANETS RULED OUT BECAUSE WE WOULD SEE THEM DURING THE DAY
PLANETS RULED OUT BY THE WISE SURVEY
PLANETS RULED OUT BECAUSE I WOULD BE INSIDE THEM
EARTH
PLANETS WE CAN SEE AT NIGHT
(MOON)
PLANET NINE?
DWARF PLANETS
STUFF WE CAN SEE THROUGH TELESCOPES
PLANETS RULED OUT BECAUSE I WOULD HAVE NOTICED THEM ABOVE MY HOUSE
OORT CLOUD
PLANETS RULED OUT BECAUSE THEY WOULDN'T FIT THROUGH MY DOOR
AIRPLANES ("FOOL'S PLANETS")
SATELLITES
PLANETS WHICH ARE ACTUALLY BIRDS
COMETS AND ASTEROIDS
BIRDS THAT GOT INTO MY HOUSE
GIANT BUGS
SPACE JUNK
SKIN FLORA
BUGS (NOT PLANETS)
DIAMETER
1 AU
10^7 KM
10^6 KM
100,000 KM
10,000 KM
1,000 KM
100 KM
10 KM
1 KM
100 m
10 m
1 m
10 cm
1 CM
1 MM
DISTANCE FROM ME
10 CM
1 m
10 m
100 m
1 km
10 KM
1000 km
10^6 km
1 AU
100 AU
10,000 AU

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Dynamical impact of the Planet Nine scenario: *N*-body experiments

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ABSTRACT

The Planet Nine hypothesis has now enough constraints to deserve further attention in the form of detailed numerical experiments. The results of such studies can help us improve our understanding of the dynamical effects of such a hypothetical object on the extreme trans-Neptunian objects or ETNOs and perhaps provide additional constraints on the orbit of Planet Nine itself. Here, we present the results of direct *N*-body calculations including the latest data available on the Planet Nine conjecture. The present-day orbits of the six ETNOs originally linked to the hypothesis are evolved backwards in time and into the future under some plausible incarnations of the hypothesis to investigate if the values of several orbital elements, including the argument of perihelion, remain confined to relatively narrow ranges. We find that a nominal Planet Nine can keep the orbits of (90377) Sedna and 2012 VP_{113} relatively well confined in orbital parameter space for hundreds of Myr, but it may make the orbits of 2004 VN_{112}, 2007 TG_{422} and 2013 RF_{98} very unstable on time-scales of dozens of Myr, turning them retrograde and eventually triggering their ejection from the Solar system. Far more stable orbital evolution is found with slightly modified orbits for Planet Nine.

Key words: methods: numerical – celestial mechanics – Kuiper belt: general – minor planets, asteroids: general – Oort Cloud – planets and satellites: general.

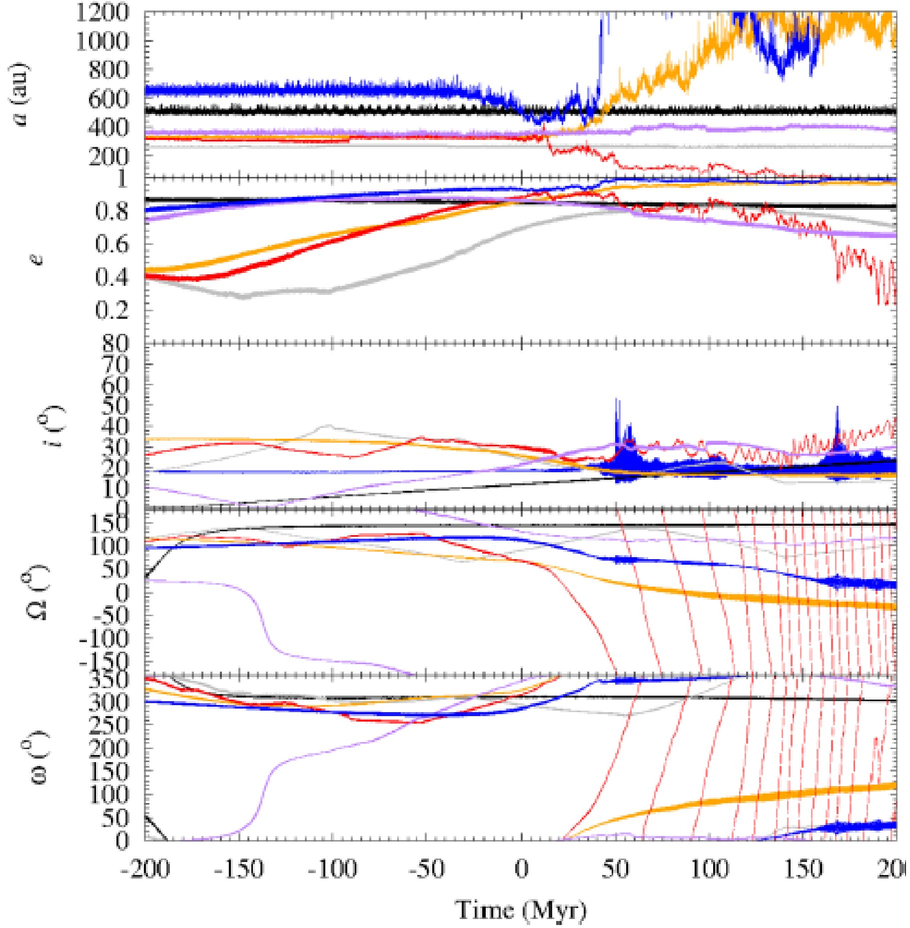

Figure 2. Orbital evolution of the six ETNOs in Table 1 subjected to th nominal Planet Nine perturbation (see the text for details): (90377) Sedn (black), 2004 VN_{112} (orange), 2007 TG_{422} (blue), 2010 GB_{174} (purple), 2012 VP_{113} (grey) and 2013 RF_{98} (red).

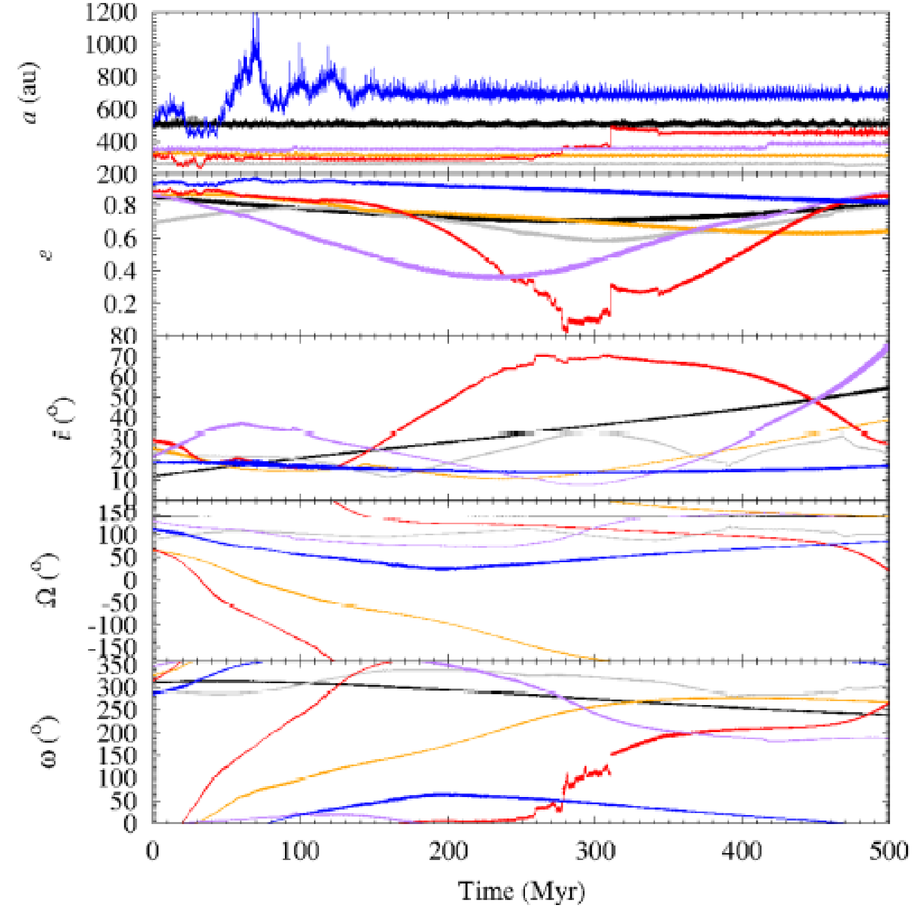

Figure 5. Orbital evolution into the future for a representative solution with $\Delta\Omega = 0°$ and $\Delta\varpi = 180°$ (see the text for details). Colours as in Fig. 2.

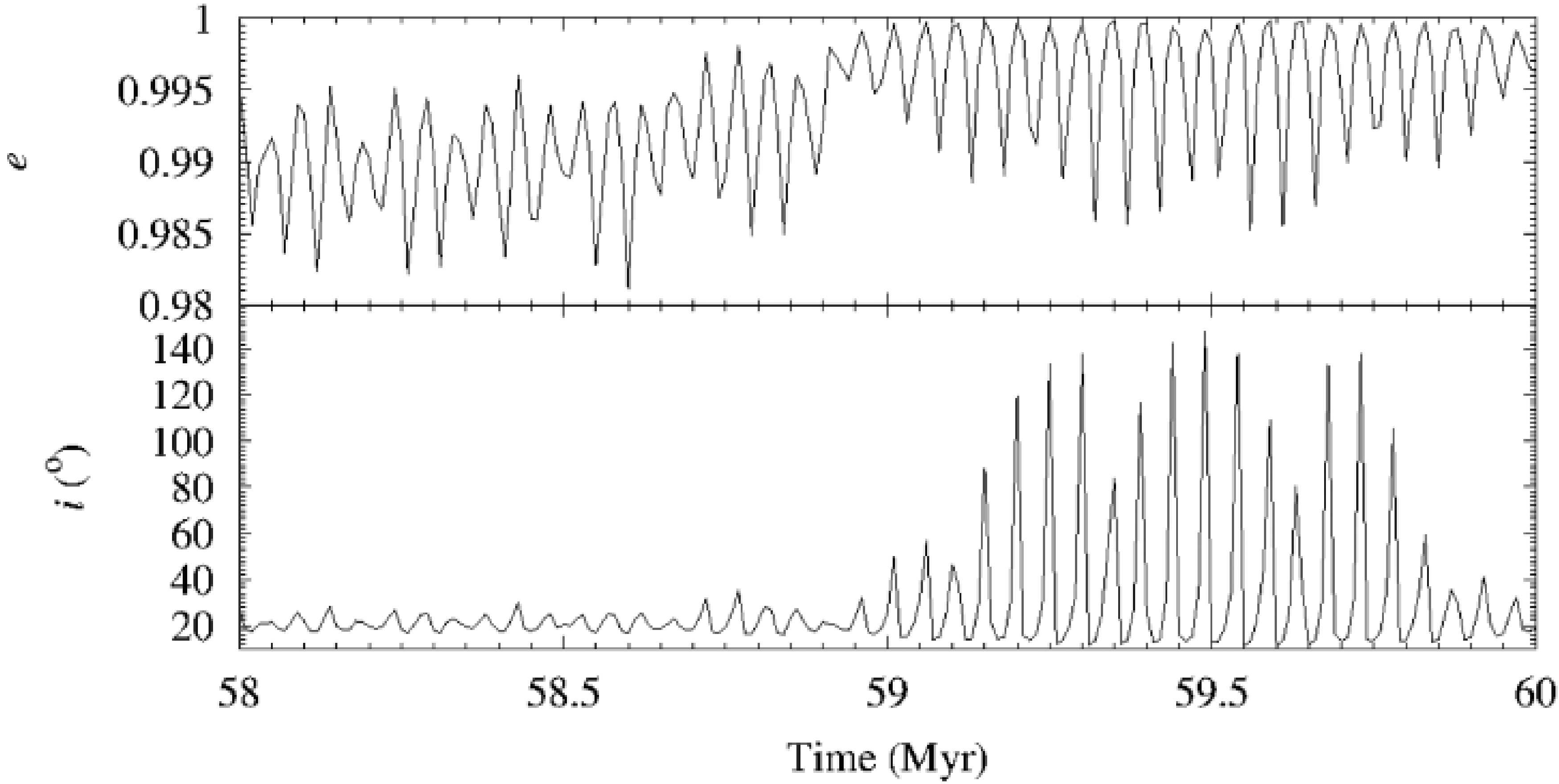

Figure 3. Detail of the pre-ejection evolution of 2007 TG_{422} for a simulation different from the one displayed in Fig. 2.

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Finding Planet Nine: apsidal anti-alignment Monte Carlo results

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ABSTRACT

The distribution of the orbital elements of the known extreme trans-Neptunian objects or ETNOs has been found to be statistically incompatible with that of an unperturbed asteroid population following heliocentric or, better, barycentric orbits. Such trends, if confirmed by future discoveries of ETNOs, strongly suggest that one or more massive perturbers could be located well beyond Pluto. Within the trans-Plutonian planets paradigm, the Planet Nine hypothesis has received much attention as a robust scenario to explain the observed clustering in physical space of the perihelia of seven ETNOs which also exhibit clustering in orbital pole position. Here, we revisit the subject of clustering in perihelia and poles of the known ETNOs using barycentric orbits, and study the visibility of the latest incarnation of the orbit of Planet Nine applying Monte Carlo techniques and focusing on the effects of the apsidal anti-alignment constraint. We provide visibility maps indicating the most likely location of this putative planet if it is near aphelion. We also show that the available data suggest that at least two massive perturbers are present beyond Pluto.

Key words: methods: statistical – celestial mechanics – minor planets, asteroids: general – Oort Cloud – planets and satellites: detection – planets and satellites: general.

The resonant coupling mechanism described in Batygin & Brown (2016) emphasizes the existence of simultaneous apsidal anti-alignment and nodal alignment, i.e. $\Delta\varpi$ librates about 180°and $\Delta\Omega$ librates about 0°. The relative values of ϖ and Ω of the ETNO with respect to those of the perturber must oscillate in order to maintain orbital confinement but see Beust (2016) for a detailed analysis. In Batygin & Brown (2016), the value of ω of the putative

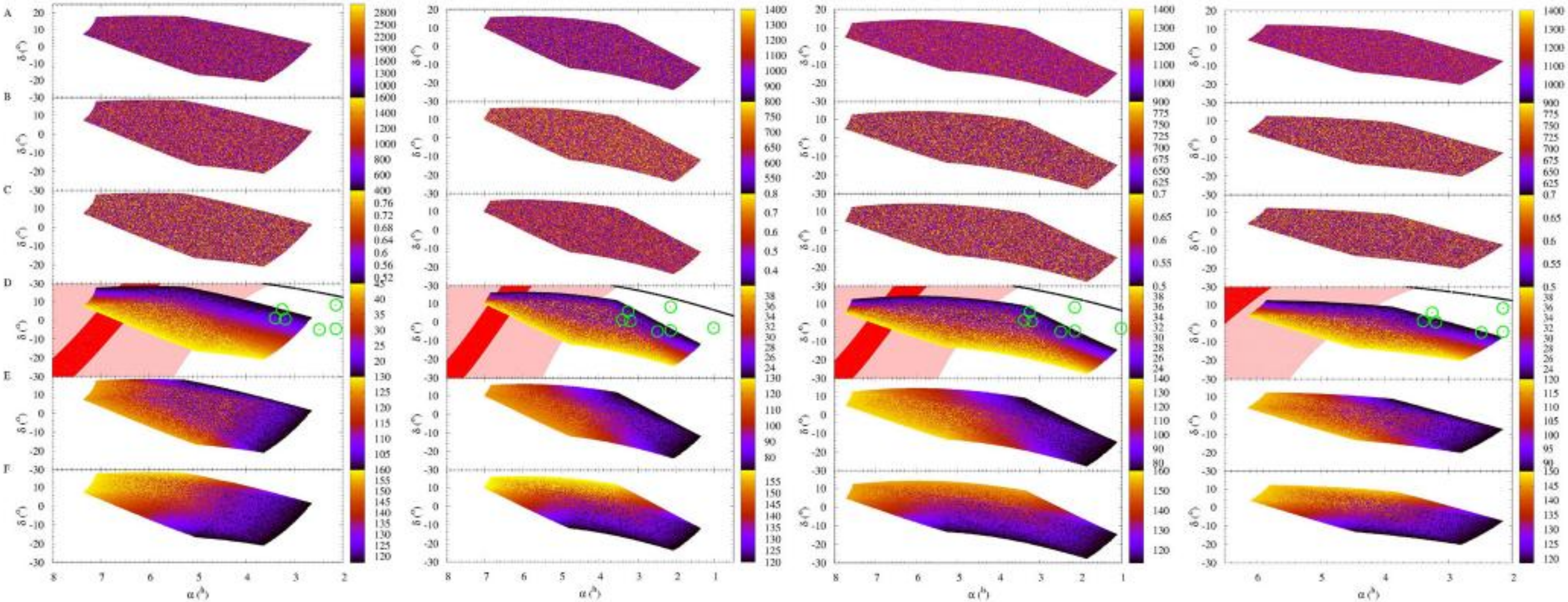

Figure 3. Distribution in equatorial coordinates of the aphelia of the studied orbits as a function of various orbital parameters: Q (panel A), a (panel B), e (panel C), i (panel D), Ω (panel E), and ω (panel F). The left-hand panels show results using the sets of orbits in Batygin & Brown (2016), those of orbits from Brown & Batygin (2016) are displayed in the second to left-hand panels; the second to right-hand panels and the right-hand panels focus on the set of orbits described in Section 3.3, imposing $\Delta\varpi \sim 180°$ and $\Delta\Omega \sim 0°$ using the data in Tables 2 and A1, respectively. In panel D, the green circles give the location at discovery of known ETNOs (see table 2 in de la Fuente Marcos & de la Fuente Marcos 2016a), in red we have the Galactic disc that is arbitrarily defined as the region confined between galactic latitude $-5°$ and $5°$, in pink the region enclosed between galactic latitude $-30°$ and $30°$, and in black the ecliptic.

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CONSEQUENCES OF A DISTANT MASSIVE PLANET ON THE LARGE SEMIMAJOR AXIS TRANS-NEPTUNIAN OBJECTS

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ABSTRACT

We explore the distant giant planet hypothesis by integrating the large-semimajor-axis, large-pericenter trans-Neptunian objects (TNOs) in the presence of the giant planets and an external perturber whose orbit is consistent with the proposed distant, eccentric, and inclined giant planet, so-called planet 9. We find that TNOs with semimajor axes greater than 250 au experience some longitude of perihelion shepherding, but that a generic outcome of such evolutions is that the TNOs evolve to larger pericenter orbits and commonly get raised to retrograde inclinations. This pericenter and inclination evolution requires a massive disk of TNOs (tens of $M_{\oplus}$) in order to explain the detection of the known sample today. Some of the highly inclined orbits produced by the examined perturbers will be inside of the orbital parameter space probed by prior surveys, implying a missing signature of the ninth-planet scenario. The distant giant planet scenarios explored in this work do not reproduce the observed signal of simultaneous clustering in argument of pericenter, longitude of the ascending node, and longitude of perihelion in the region of the known TNOs.

Key words: Kuiper belt: general – planet–disk interactions

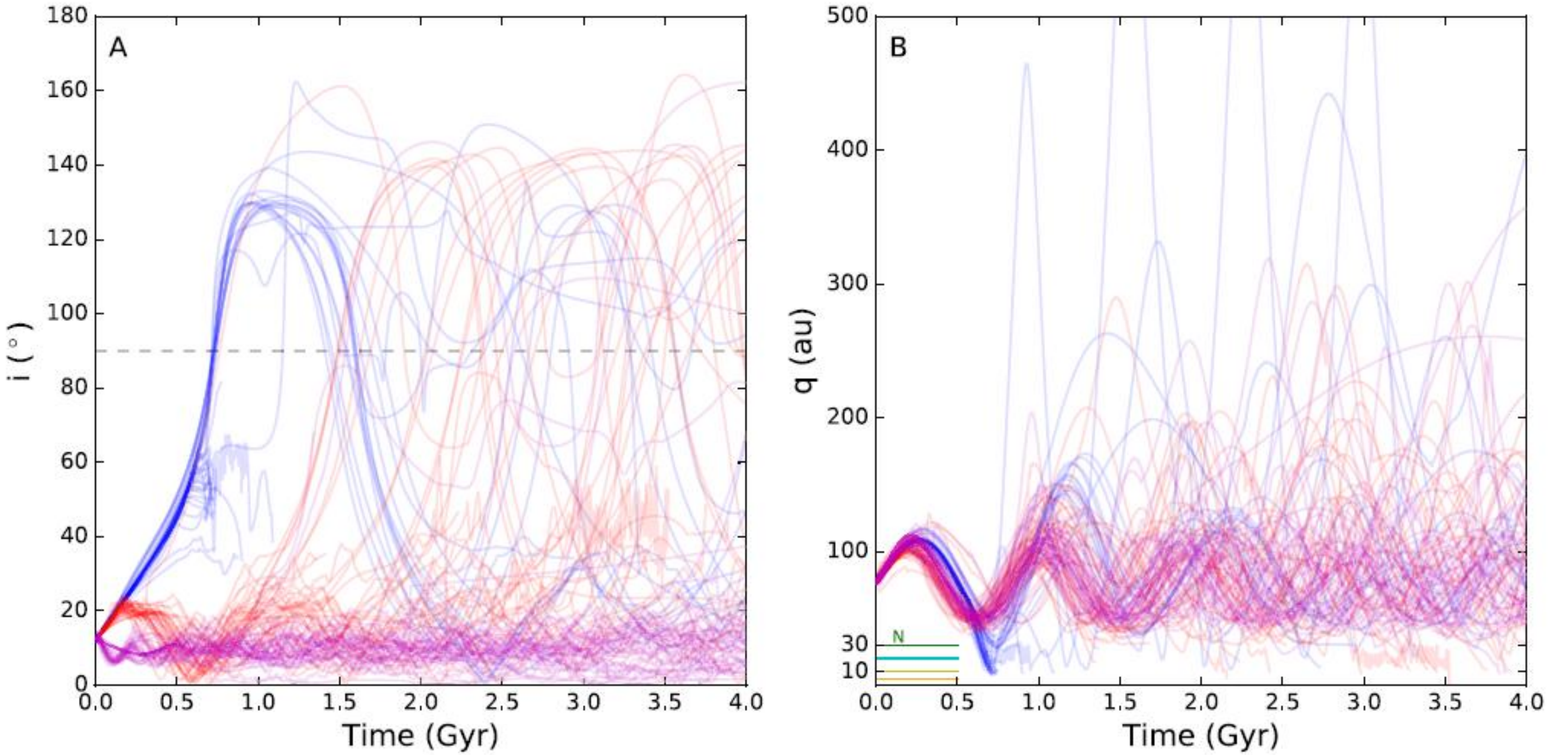

Figure 7. The i, q evolution of the Sedna clones for the various P9 configurations. Clones from the simulation with $i = 30^{\circ}$ are shown in blue, P9 $i = 15^{\circ}$ in red, and P9 $i = 0^{\circ}$ in magenta. A dashed gray line marks $i = 90^{\circ}$ in panel (a). Panel (a) shows that the same i raising and flipping is induced for ϖ-shepherded clones in both the P9 $i = 30^{\circ}$ and P9 $i = 15^{\circ}$ cases. Panel (b) shows that large-q oscillations occur for ϖ-shepherded clones in all simulations. The cycling of q is a generic feature of a massive external perturber, regardless of the perturber's inclination. Inclination raising occurs generically for ϖ shepherded clones in the simulations with high (30°) and more moderate (15°) perturber inclinations.

TNOs with shepherded ω values, suggesting that there is a currently missing or unseen signature of P9. The P9 scenario does not produce the observed simultaneous clustering in the angles ω, Ω, and ϖ that is seen in the detected sample. Taken

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Commensurabilities between ETNOs: a Monte Carlo survey

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ABSTRACT

Many asteroids in the main and trans-Neptunian belts are trapped in mean motion resonances with Jupiter and Neptune, respectively. As a side effect, they experience accidental commensurabilities among themselves. These commensurabilities define characteristic patterns that can be used to trace the source of the observed resonant behaviour. Here, we explore systematically the existence of commensurabilities between the known ETNOs using their heliocentric and barycentric semimajor axes, their uncertainties, and Monte Carlo techniques. We find that the commensurability patterns present in the known ETNO population resemble those found in the main and trans-Neptunian belts. Although based on small number statistics, such patterns can only be properly explained if most, if not all, of the known ETNOs are subjected to the resonant gravitational perturbations of yet undetected trans-Plutonian planets. We show explicitly that some of the statistically significant commensurabilities are compatible with the Planet Nine hypothesis; in particular, a number of objects may be trapped in the 5:3 and 3:1 mean motion resonances with a putative Planet Nine with semimajor axis ∼700 au.

Key words: methods: statistical – celestial mechanics – Kuiper belt: general – minor planets, asteroids: general – Oort Cloud – planets and satellites: general.

Ignoring the mass of the object, expressing distances in astronomical units, times in sidereal years, and masses in Solar masses, Kepler's Third Law applied to an object orbiting the Sun states that $P^2 = a^3$, where P is the period and a is the semimajor axis of the orbit of the object. Given two objects – the first one with a_i and P_i, and the second one with a_j and P_j, $i \neq j$ – Kepler's Third Law is given by $(P_j/P_i)^2 = (a_j/a_i)^3$. If P_j/P_i can be written in the form of a ratio of small integers then we have a mean motion resonance. In order to investigate the distribution of ratios of orbital periods, P_j/P_i, for the ETNOs the values of the semimajor axes are needed.

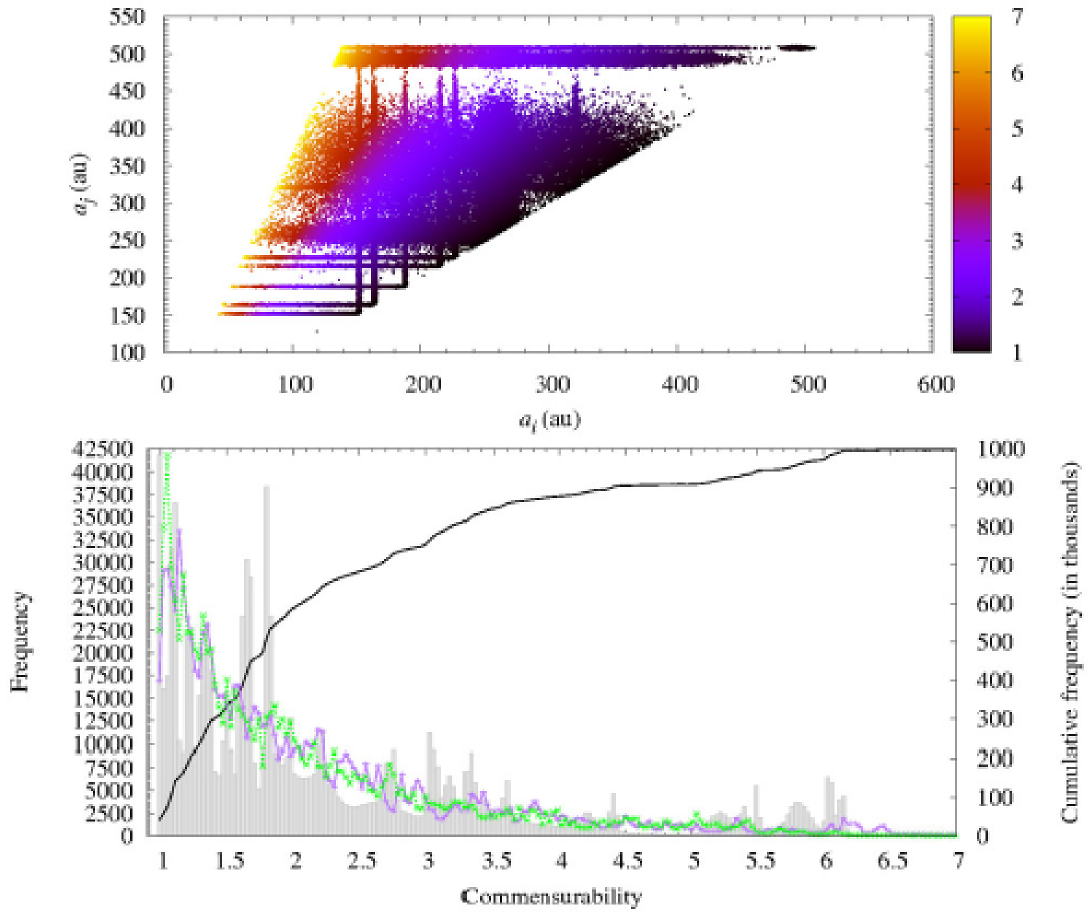

Figure 1. Commensurability map (top panel) for the values of the heliocentric semimajor axes and their uncertainties in Table 1. Frequency distribution (bottom panel) in $(a_j/a_i)^{3/2}$ from the commensurability map. The results from a uniform spread in semimajor axis are plotted in purple and those from a biased uniform sample in green. The number of bins in the frequency distribution plot is $2\,n^{1/3}$, where n is the number of pairs of virtual ETNOs tested, $n = 10^6$. The black curve shows the cumulative distribution.

If the mechanisms responsible for inducing dynamical structure in the main and trans-Neptunian belts are also at work in the region occupied by the ETNOs then we should expect that for two given ETNOs in near commensurability:

$$\left(\frac{a_{\rm p}}{a_j}\right)^{3/2} \left(\frac{a_i}{a_{\rm p}}\right)^{3/2} = \left(\frac{m}{n}\right) \left(\frac{k}{l}\right), \tag{1}$$

where $a_{\rm p}$ is the semimajor axis of the orbit of the perturber and k, l, m, n are all small integers. This expression can be applied to two of the most clear clusterings in semimajor axis in Table 2. The average value of the barycentric semimajor axis of (90377) Sedna and 2007 TG_{422} is 504 au. On the other hand, the equivalent mean value for 2004 VN_{112}, 2010 GB_{174} and 2013 RF_{98} is 332 au. These five objects are part of the set of six singled out by Batygin & Brown (2016). The associated period ratio for these two sets of ETNOs is 1.87. In the main asteroid belt, this ratio is obtained for objects trapped in the 5:3 mean motion resonance with Jupiter and those in the 3:1, that is one of the main resonances in the outer belt (Holman & Murray 1996). Making a dynamical analogy between the two situations and decomposing equation (1) in two we have: $(a_{\rm p}/504)^{3/2} = 5/3$ and $(332/a_{\rm p})^{3/2} = 1/3$. The average of the two values of $a_{\rm p}$ is $\sim$700 au which is the favoured value for the semimajor axis of Planet Nine in Batygin & Brown (2016). The 1.8 commensurability has a statistical significance of 239σ for heliocentric orbits, the 1.89 commensurability has 51σ for barycentric orbits (see Fig. 3). This is unlikely to be mere coincidence.

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NEW EXTREME TRANS-NEPTUNIAN OBJECTS: TOWARD A SUPER-EARTH IN THE OUTER SOLAR SYSTEM

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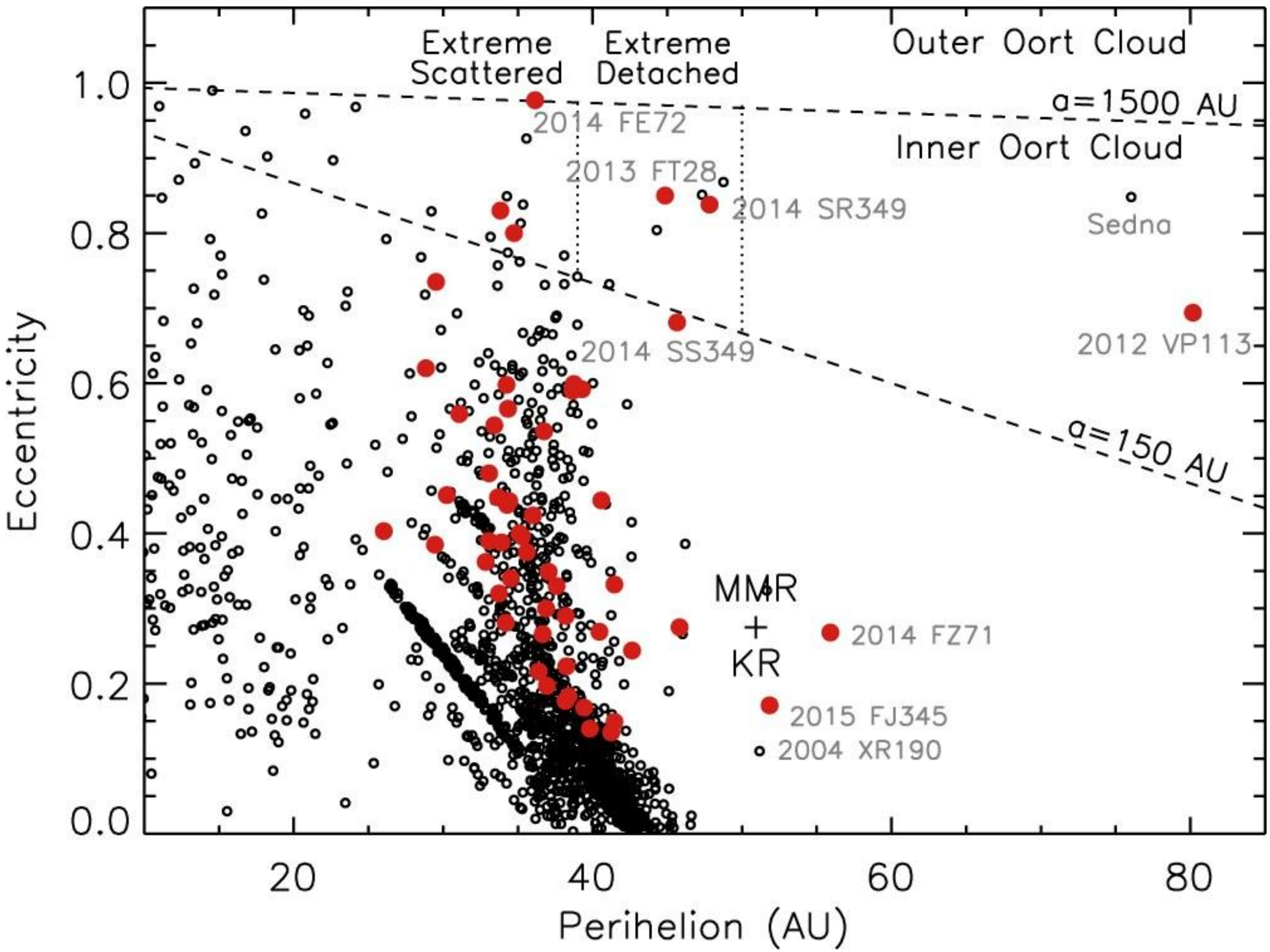
ABSTRACT

We are performing a wide and deep survey for extreme distant solar system objects. Our goal is to understand the high-perihelion objects Sedna and 2012 VP113 and determine if an unknown massive planet exists in the outer solar system. The discovery of new extreme objects from our survey of some 1080 square degrees of sky to over 24th magnitude in the *r*-band are reported. Two of the new objects, 2014 SR349 and 2013 FT28, are extreme detached trans-Neptunian objects, which have semimajor axes greater than 150 au and perihelia well beyond Neptune ($q > 40$ au). Both new objects have orbits with arguments of perihelia within the range of the clustering of this angle seen in the other known extreme objects. One of these objects, 2014 SR349, has a longitude of perihelion similar to the other extreme objects, but 2013 FT28 is about 180° away or anti-aligned in its longitude of perihelion. We also discovered the first outer Oort Cloud object with a perihelion beyond Neptune, 2014 FE72. We discuss these and other interesting objects discovered in our ongoing survey. All the high semimajor axis ($a > 150$ au) and high-perihelion ($q > 35$ au) bodies follow the previously identified argument of perihelion clustering as first reported and explained as being from an unknown massive planet in 2014 by Trujillo & Sheppard, which some have called Planet X or Planet Nine. With the discovery of 2013 FT28 on the opposite side of the sky, we now report that the argument of perihelion is significantly correlated with the longitude of perihelion and orbit pole angles for extreme objects and find there are two distinct extreme clusterings anti-aligned with each other. This previously unnoticed correlation is further evidence of an unknown massive planet on a distant eccentric inclined orbit, as extreme eccentric objects with perihelia on opposite sides of the sky (180° longitude of perihelion differences) would approach the inclined planet at opposite points in their orbits, thus making the extreme objects prefer to stay away from opposite ecliptic latitudes to avoid the planet (i.e., opposite argument of perihelia or orbit pole angles).

Key words: comets: general – Kuiper belt: general – minor planets, asteroids: general – Oort Cloud – planets and satellites: individual (Sedna, 2012 VP113)



Extreme Scattered
Extreme Detached
Outer Oort Cloud
a=1500 AU
Inner Oort Cloud
a=150 AU
2014 FE72
2013 FT28
2014 SR349
Sedna
2014 SS349
2012 VP113
MMR + KR
2014 FZ71
2015 FJ345
2004 XR190
Eccentricity
Perihelion (AU)
0.0
0.2
0.4
0.6
0.8
1.0
20
40
60
80

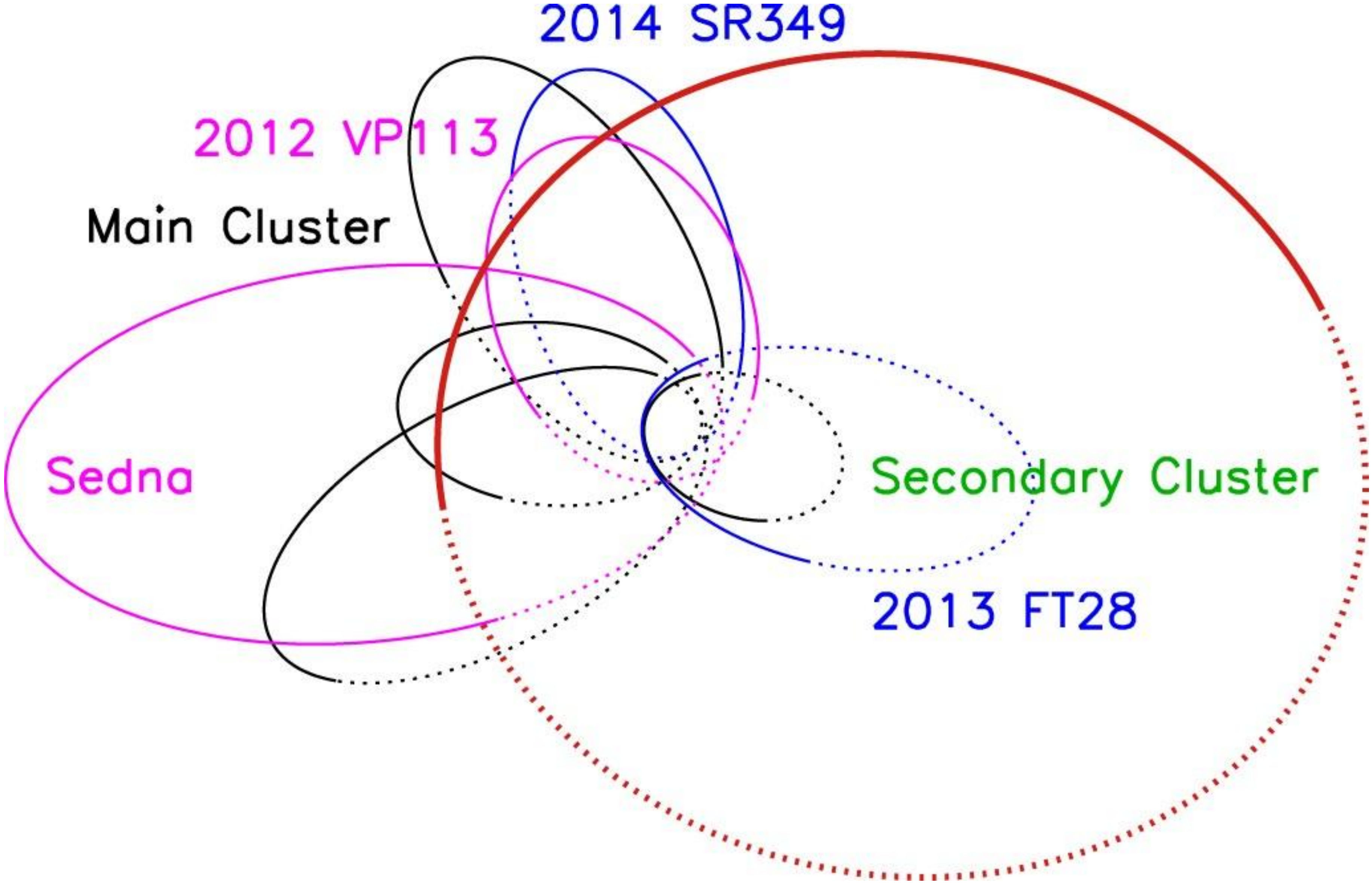

2014 SR349
2012 VP113
Main Cluster
Sedna
Secondary Cluster
2013 FT28

Table 1. Equatorial coordinates (α, δ, J2000.0 ecliptic and equinox), apparent magnitudes (m, with filter if known) at discovery time, and absolute magnitude, H, for the 21 known ETNOs. Source: MPC Database.

Object	α ($^{h}:^{m}:^{s}$)	δ ($^{\circ}:':''$)	m (mag)	H (mag)
(82158) 2001 FP_{185}	11:57:50.69	+00:21:42.7	22.2 (R)	6.0
(90377) Sedna	03:15:10.09	+05:38:16.5	20.8 (R)	1.5
(148209) 2000 CR_{105}	09:14:02.39	+19:05:58.7	22.5 (R)	6.3
(445473) 2010 VZ_{98}	02:08:43.575	+08:06:50.90	20.3 (R)	5.0
(474640) 2004 VN_{112}	02:08:41.12	−04:33:02.1	22.7 (R)	6.4
2002 GB_{32}	12:28:25.94	−00:17:28.4	21.9 (R)	7.7
2003 HB_{57}	13:00:30.58	−06:43:05.4	23.1 (R)	7.4
2003 SS_{422}	23:27:48.15	−09:28:43.4	22.9 (R)	7.1
2005 RH_{52}	22:31:51.90	+04:08:06.1	23.8 (g)	7.8
2007 TG_{422}	03:11:29.90	−00:40:26.9	22.2	6.2
2007 VJ_{305}	00:29:31.74	−00:45:45.0	22.4	6.6
2010 GB_{174}	12:38:29.365	+15:02:45.54	25.09 (g)	6.5
2012 VP_{113}	03:23:47.159	+01:12:01.65	23.1 (r)	4.1
2013 FS_{28}	12:58:03.652	−08:18:12.61	24.4 (r)	4.9
2013 FT_{28}	12:44:55.262	−12:28:17.85	24.4 (r)	6.7
2013 GP_{136}	14:07:32.880	−11:09:38.81	22.9 (r)	6.6
2013 RF_{98}	02:29:07.61	−04:56:34.6	23.5 (z)	8.6
2013 UH_{15}	01:38:30.772	−02:46:20.79	24.8 (r)	7.7
2014 FE_{72}	12:09:10.566	−12:59:00.28	23.9 (r)	6.1
2014 SR_{349}	22:17:39.955	−28:55:52.76	24.1 (r)	6.6
2015 SO_{20}	01:01:17.301	−03:11:00.81	21.4 (R)	6.5

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Visible spectra of (474640) 2004 VN_{112}–2013 RF_{98} with OSIRIS at the 10.4 m GTC: evidence for binary dissociation near aphelion among the extreme trans-Neptunian objects

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ABSTRACT

The existence of significant anisotropies in the distributions of the directions of perihelia and orbital poles of the known extreme trans-Neptunian objects (ETNOs) has been used to claim that trans-Plutonian planets may exist. Among the known ETNOs, the pair (474640) 2004 VN_{112}–2013 RF_{98} stands out. Their orbital poles and the directions of their perihelia and their velocities at perihelion/aphelion are separated by a few degrees, but orbital similarity does not necessarily imply common physical origin. In an attempt to unravel their physical nature, visible spectroscopy of both targets was obtained using the OSIRIS camera-spectrograph at the 10.4 m Gran Telescopio Canarias (GTC). From the spectral analysis, we find that 474640–2013 RF_{98} have similar spectral slopes (12 versus 15 per cent/0.1 μm), very different from Sedna's but compatible with those of (148209) 2000 CR_{105} and 2012 VP_{113}. These five ETNOs belong to the group of seven linked to the Planet Nine hypothesis. A dynamical pathway consistent with these findings is dissociation of a binary asteroid during a close encounter with a planet and we confirm its plausibility using *N*-body simulations. We thus conclude that both the dynamical and spectroscopic properties of 474640–2013 RF_{98} favour a genetic link and their current orbits suggest that the pair was kicked by a perturber near aphelion.

Key words: techniques: photometric – techniques: spectroscopic – astrometry – celestial mechanics – minor planets, asteroids: individual: (474640) 2004 VN_{112} – minor planets, asteroids: individual: 2013 RF_{98}.

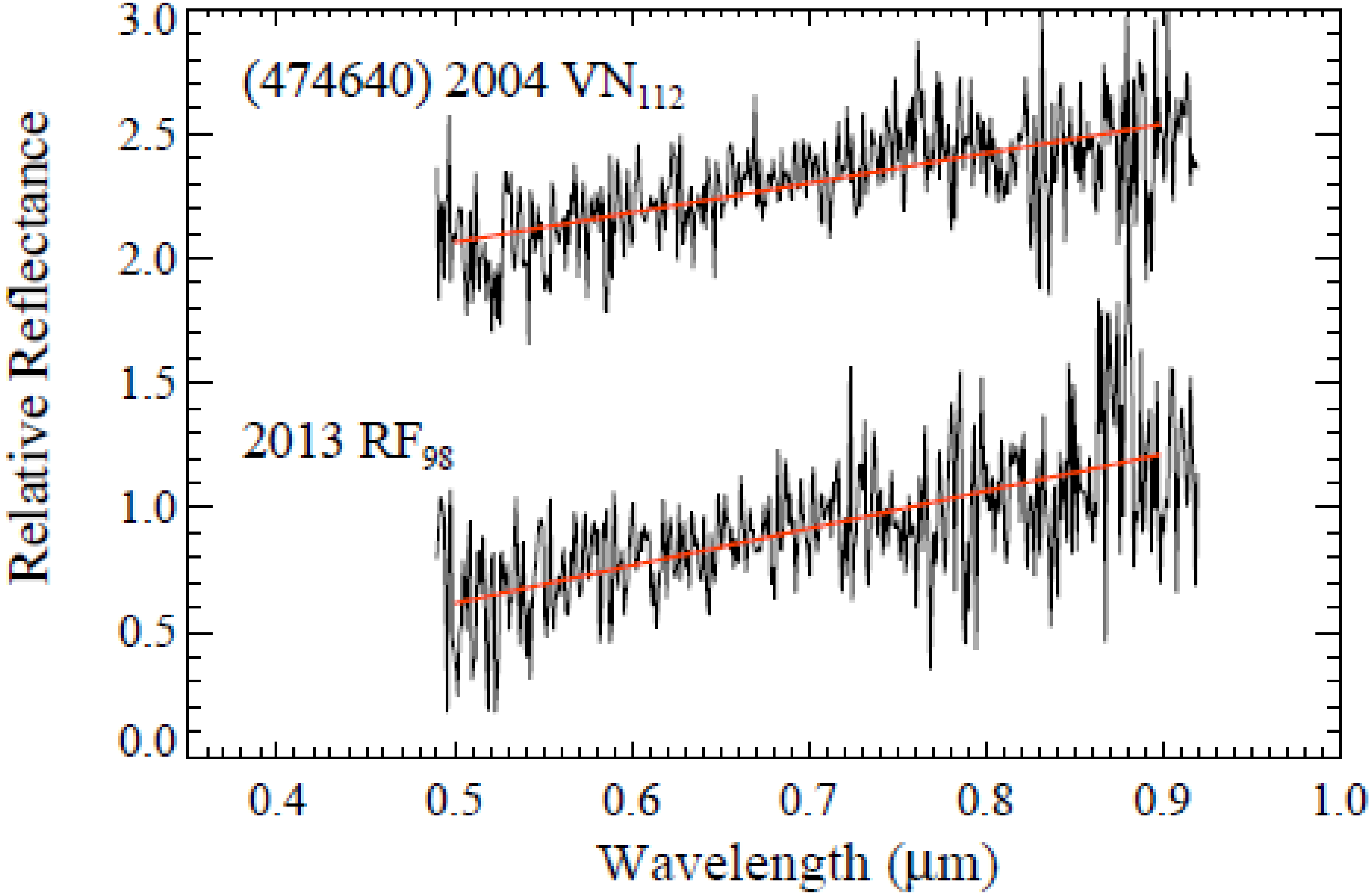

Figure 2. Final visible spectra of the pair of ETNOs (see the text for details).

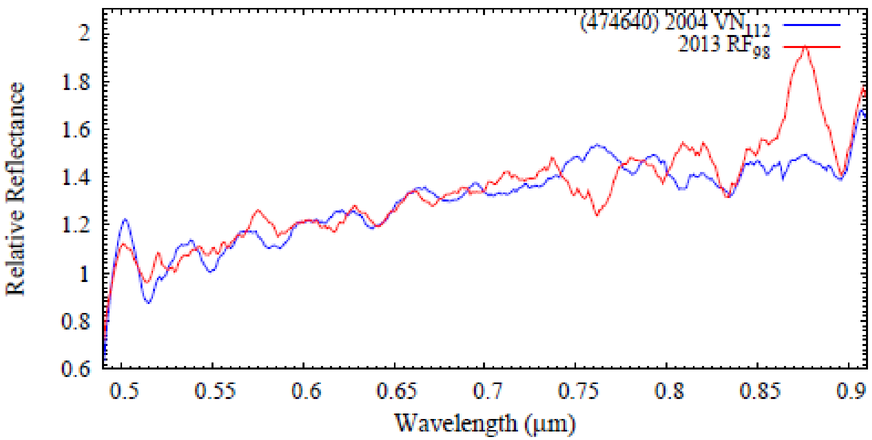

Figure 3. Comparison between the spectra of (474640) 2004 VN_{112} and 2013 RF_{98} smoothed by a Savitzky-Golay filter (see the text) and scaled to match at 0.60 μm. The most prominent absorption band of pure methane ice at 0.73 μm is not seen on either spectra.

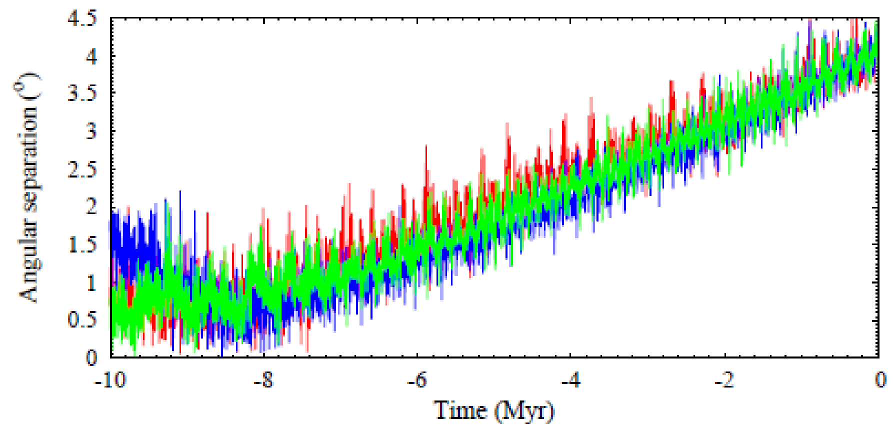

Figure 4. Evolution of the angular separation between the orbital poles of the pair (474640) 2004 VN_{112}–2013 RF_{98} for three representative test calculations with different perturbers. Red: a = 549 au, e = 0.21, i = 47°and m = 16 $M_{\oplus}$. Blue: a = 448 au, e = 0.16, i = 33°and m = 12 $M_{\oplus}$. Green: a = 421 au, e = 0.10, i = 33°and m = 12 $M_{\oplus}$.

with varying orbital and physical parameters (per numerical exper-
iment). Our preliminary results indicate that a planet with mass, m, in the range 10–20 $M_\oplus$ moving in an eccentric (0.1–0.4) and inclined (20–50°) orbit with semimajor axis of 300–600 au, may be able to induce the observed tilt on a time-scale of 5–10 Myr. Per-

Consistent with the Planet Nine hypothesis?

Assuming a mass, *m*, in terms of the mass of the Earth:

if *m* is in the range 10 to 20 Earth masses

- Semi-major axis (200 AU + 30 *m*, 600 AU + 20 *m*)
  (300 AU, 600 AU)
- Eccentricity = 0.75 – ((250 AU + 20 *m*)/*a*)^8
  (0.1, 0.4)
- Inclination (22^o, 40^o)
  (20^o, 50^o)
- Longitude of the ascending node (72^o, 121^o)

- Argument of perihelion (120^o, 160^o)

Kreutz Sungrazers: The ultimate case of cometary fragmentation and disintegration?

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Table 6
Overview of Perturbations of Orbital Elements of Fragments
Due to Separation Velocity of ~5 m/s

Fragments that are products of a breakup ...	... Reach next perihelion ...	... In orbits that are ...
at or shortly after perihelion	at vastly different times (up to 2 millennia apart)	identical in ω, Ω, i, and q, but very different in P
near 1 AU after perihelion	less than 1 century apart	slightly different in ω, Ω, i ($\ll 1^\circ$), and q ($<0.01\ R_\odot$), but moderately different in P
at a heliocentric distance of tens of AU after perihelion	tens of years apart	somewhat different in ω, Ω (both up to a few deg), i (up to $\sim 1^\circ$), q (up to $\sim 0.1\ R_\odot$), but fairly similar in P
at a very large heliocentric distance preaphelion	several years apart	significantly different in ω, Ω (both $\sim 10^\circ$), i (a few deg), and q (up to $\sim 0.5\ R_\odot$), but only slightly different in P
in the general proximity of aphelion	1 year or less apart	very different in ω, Ω, i, and q, but nearly identical in P
after aphelion	nearly simultaneously, not more than some weeks apart	determined by approximate symmetry of perturbations relative to aphelion, except for those in perihelion time

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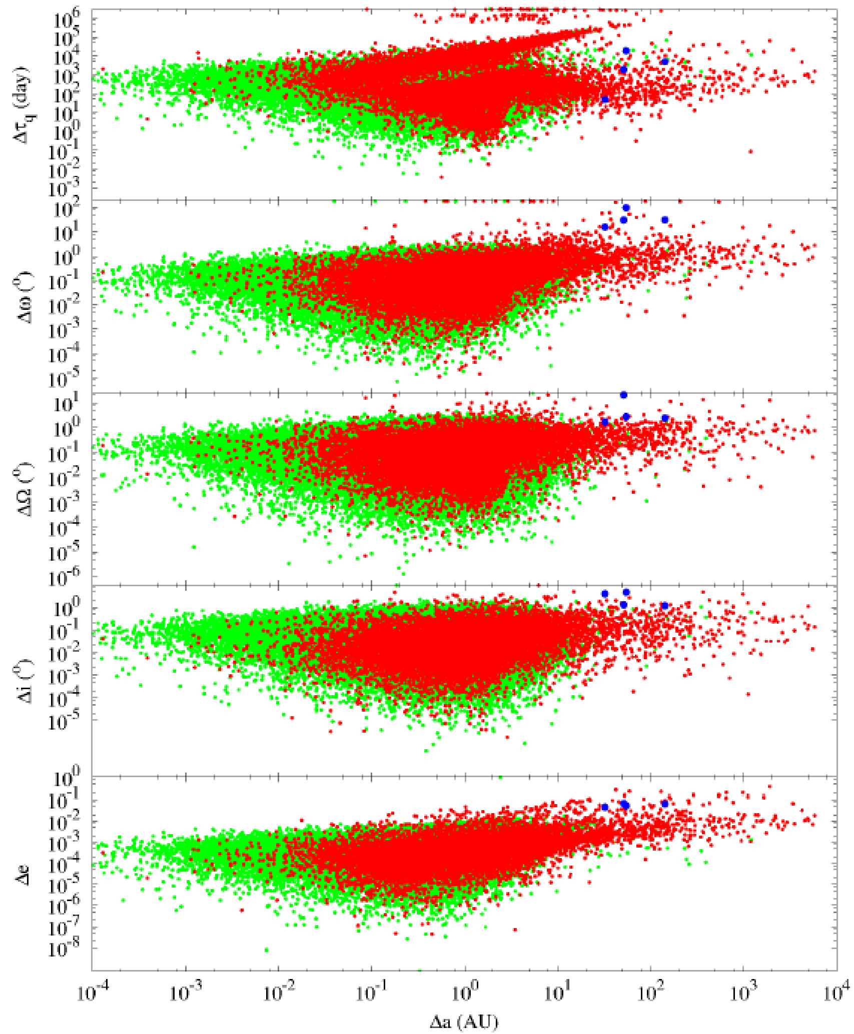

Figure 3: Differences between the values of the heliocentric orbital elements of the members of the initially bound binary at the end of the simulation. Bound pairs are plotted in green, unbound couples in red; the blue points show the actual values for the pairs of ETNOs (474640) 2004 VN_{112}–2013 RF_{98} ($\Delta a = 32.6$ AU), 2002 GB_{32}–2003 HB_{57} ($\Delta a = 51.9$ AU), (82158) 2001 FP_{185}–2013 UH_{15} ($\Delta a = 54.8$ AU), and (148209) 2000 CR_{105}–2010 GB_{174} ($\Delta a = 143.1$ AU). The results of 200 000 experiments are plotted.

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PAIRS AND GROUPS OF GENETICALLY RELATED LONG-PERIOD COMETS AND PROPOSED IDENTITY OF THE MYSTERIOUS LICK OBJECT OF 1921

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ABSTRACT

We present the history of investigation of the dynamical properties of pairs and groups of genetically related long-period comets (other than the Kreutz sungrazing system). Members of a comet pair or group move in nearly identical orbits, and their origin as fragments of a common parent comet is unquestionable. The only variable is the time of perihelion passage, which differs considerably from member to member owing primarily to an orbital-momentum increment acquired during breakup. Meter-per-second separation velocities account for gaps of years or tens of years, thanks to the orbital periods of many millennia. The physical properties of individual members may not at all be alike, as illustrated by the trio of C/1988 A1, C/1996 Q1, and C/2015 F3. We exploit orbital similarity to examine whether the enigmatic and as-yet-unidentified object discovered from the Lick Observatory near the Sun at sunset on 1921 August 7 happened to be a member of such a pair and to track down the long-period comet to which it might be genetically related. Our search shows that the Lick object, which could not be a Kreutz sungrazer, was likely a companion to comet C/1847 C1 (Hind), whose perihelion distance was ~9 $R_{\odot}$ and true orbital period was approximately 8300 yr. The gap of 74.4 yr between their perihelion times is consistent with a separation velocity of ~1 m s^{-1} which sets the fragments apart following the parent's breakup in a general proximity of perihelion during the previous return to the Sun in the seventh millennium BCE.

Key words: comets: general – methods: data analysis

Table 1
Orbital Elements of Comets C/1988 F1 (Levy) and C/1988 J1 (Shoemaker–Holt) (Equinox J2000.0)

Orbital Element/Quantity		Comet C/1988 F1	Comet C/1988 J1
Osculation epoch (TT)		1987 Nov 21.0	1988 Feb 9.0
Time of perihelion passage t_π (TT)		1987 Nov 29.94718	1988 Feb 14.22162
Argument of perihelion ω (deg)		326.51491	326.51498
Longitude of ascending node Ω (deg)		288.76505	288.76487
Orbit inclination i (deg)		62.80744	62.80658
Perihelion distance q (au)		1.1741762	1.1744657
Orbital eccentricity e		0.9978157	0.9978301
Orbital period P (yr)	osculation	12,460 ± 460	12,590 ± 230
	original[a]	13,960	13,840
Orbital arc covered by observations		1988 Mar 22–1988 Jul 18	1988 May 13–1988 Oct 20
Number of observations employed		30	60
rms residual (arcsec)		±0.7	±0.9
Orbit-quality code[b]		2A	2A
Reference		Marsden (1989b)	Marsden (1989b)

Notes.
[a] Referring to the barycenter of the solar system.
[b] Following the classification system introduced by Marsden et al. (1978); the errors of the elements other than the orbital period are unavailable.

06 30 00.13 +47 10 47.5
(nearly 400 years ago they were at minimum separation)

Planets beyond Pluto?

In brief, the existence of significant anisotropies in the distributions of the directions of perihelia and poles of the ETNOs is the main observational fact used to argue in favour of the presence of trans-Plutonian planets. The very same argument, but making use of comet data, has been proposed multiple times during the last ten decades or so to claim new planetary discoveries. Each and every one of these propositions was eventually dismissed as induced by strong observational bias. These historical precedents may lead us to ask, why is this time going to be any different? The answer is in the data.

Planets beyond Pluto?

AND THE

DATA

SAY, YES!

Planets beyond Pluto?

Neptune was predicted using pen and paper; computers are leading the way to the trans-Plutonian Planets.

Updates

https://www.researchgate.net/project/Trans-Plutonian-Planets