Further support and a candidate location for Planet 9

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ABSTRACT

The existence of a hypothetical Planet 9 lurking in the outer solar system has been invoked as a plausible explanation for the anomalous clustering in the orbits of trans-Neptunian objects. Here we propose to use meteors arriving at Earth as messengers with the potential of revealing the presence of a hitherto undiscovered massive object. The peculiar meteor CNEOS 2014-01-08, recently put forward as the first interstellar meteor, might be one such messenger. Its origin in the sky overlaps with the predicted band of possible Planet 9 orbits and it is actually compatible with the highest probability region. The odds of this coincidence being due to chance are of \textasciitilde 1%. Furthermore, some statistical anomalies about CNEOS 2014-01-08 are resolved under the hypothesis that it was flung at Earth by a gravitational encounter with Planet 9. Based on the available data, we propose the region at coordinates R.A. 48.2\textdegree\textpm 1.8\textdegree, declination 10.3\textdegree\textpm 1.8\textdegree, in the constellation Aries, as the first candidate location for Planet 9.

Key words. planets and satellites: detection – Kuiper belt: general – minor planets, asteroids: general – meteorites, meteors, meteoroids

1. Introduction

The peculiar clustering of orbital parameters observed in very eccentric extreme trans-Neptunian objects (ETNOs) has prompted the suggestion that there might be a large planetary mass object still undiscovered in the outer solar system (Trujillo & Sheppard 2014; de la Fuente Marcos & de la Fuente Marcos 2014; Batygin & Brown 2016; Brown & Batygin 2016; Millholland & Laughlin 2017). These ETNOs are too far away from Neptune to feel its gravitational influence. However, they all reach their perihelion in the ecliptic and have their elliptical orbits aligned, with an ascending node (Ω) and orbital plane inclination (i) that are tightly clustered. This coincidence could be explained by the presence of a large, very distant planet with a mass between 5 and 8.4 times that of the Earth and a semimajor axis between 300 and 520 AU (Brown & Batygin 2021) hereafter BB21, see also de la Fuente Marcos & de la Fuente Marcos 2016). It has even been suggested that the unseen perturber might not be a planet at all but a primordial black hole (Scholtz & Unwin 2020), a hypothetical class of black holes formed in the early Universe.

It should be noted that the evidence for ETNO clustering is not undisputed. Some controversy exists on whether it is a real effect or a statistical artifact caused by observational biases (Shankman et al. 2017; Bernardinelli et al. 2020; Napper et al. 2021; Brown 2021). If Planet 9 indeed exists, it would be extremely difficult to detect and identify. First, it would be a very faint object (probably around magnitude 20\pm 2 in the R band). Furthermore, its orbital velocity would be extremely slow, completing an orbit every 7,000 to 15,000 years (see BB21).

Every planet that we know of has been found by observing its light. Planet 9 might be the first exception, given its faintness and slow proper motion. Multi-messenger astronomy has been gaining importance very rapidly during the last decade and is often recognized as a high priority for funding agencies (see, e.g., Astro2020, National Academies 2021). The term messenger here means particles or waves, other than photons, sent in our direction by celestial bodies. Normally, this refers to neutrinos, gravitational waves and cosmic rays. We note that small asteroids or meteoroids, accelerated by massive bodies and eventually hitting Earth as meteors or meteorites, behave as particles that bring us information from distant astrophysical objects. Thus, they may be considered as cosmic messengers, as well. In this paper we argue that the first detection of such meteoroid messenger could be CNEOS 2014-01-08 (hereafter CNEOS14), perhaps unveiling to us the location of Planet 9.

In an attempt to discover new interstellar objects, Siraj & Loeb (2019) (hereafter SL19) searched the CNEOS fireball database for meteors with a hyperbolic trajectory. CNEOS is the Center for Near-Earth Object Studies of NASA’s Jet Propulsion Laboratory. The database compiles information on impact events reported since 1988, including data from the U.S. Department of Defense network of satellite sensors (hereafter USG), and makes this information publicly available for scientific studies. Amongst all recorded events, SL19 found one meteor with an unmistakably hyperbolic trajectory, CNEOS14, which impacted at 17:05:34 (UT) near Papua New Guinea (impact coordinates 1.3S, 147.6E). The hyperbolic nature of this meteoroid has been confirmed independently by the U.S. Space Force\textsuperscript{1} and by Peña-Asensio et al. (2022). The meteoroid had a radius of \textasciitilde 1.3 cm and carried a pre-impact velocity of \textasciitilde 44.8 km s\textsuperscript{-1}. Its heliocentric velocity at that moment was \textasciitilde 60 km s\textsuperscript{-1}, according to SL19, or \textasciitilde 61\pm 5.8 km s\textsuperscript{-1}, according to Peña-Asensio et al.

\textsuperscript{1}https://twitter.com/US_SpaceCom/status/1511856370756177921
These values are well beyond the Sun’s escape velocity at 1 AU (42.12 km s\(^{-1}\)) and therefore imply that CNEOS14 was not gravitationally bound to the solar system.

2. The meteoroid

2.1. Interstellar origin

The USG sensors that recorded the CNEOS14 information constitute a defense infrastructure and not all of the information is made publicly available. An agreement between NASA and the U.S. Space Force authorizes the release of vector velocities and light curves of bolides recorded by the USG network. The data are compiled by NASA’s JPL in the CNEOS database. Uncertainties in the velocity vectors are generally not published. However, some information has been released in this case. The U.S. Space Force made a public statement to the effect that they were able to confirm the interstellar origin of the meteoroid using additional data available to them. In a popular article, Siraj (2022) provides upper bounds to the uncertainties of this event, stating that they are no larger than 10%.

Some authors have criticized the lack of reliability in the USG data. Devillepoix et al. (2019) (see also Borovička et al. 2017) made a comparison of bolides observed by the USG network with their own instruments and found that, while some events are accurately reported, others exhibit significant discrepancies. A relevant question in this context is to what extent one can be certain about the interstellar origin of CNEOS14. To address this question, let us keep in mind that the heliocentric speed determined for the meteoroid at 1 AU was 60 km s\(^{-1}\). In order to negate the interstellar nature of CNEOS14, the error would need to be almost 20 km s\(^{-1}\) or, given that the observed geocentric velocity was of 44 km s\(^{-1}\), about 50% of the measurement. The largest discrepancies found by the aforementioned authors were of 5 km s\(^{-1}\) for 2008-11-21-00:26:40 and 8 km s\(^{-1}\) for 2015-01-07-01:05:59. Therefore, even if we take the highest discrepancies reported in the literature, the meteoroid would still be, by a large margin, an interstellar object.

In a more recent comparison by Peña-Asensio et al. (2022), the authors state that “the data provided by CNEOS are generally in good agreement with independent ground-based records in location and time. However, for some cases, important differences in velocity have been reported.” They also arrived at the same conclusion that CNEOS14 was an interstellar meteoroid. In fact, according to their analysis, hyperbolic meteors are more common than previously thought, accounting for about 1% of all large bolides.

Given these independent verifications (the velocity data are the same in all cases but the uncertainties have been independently estimated by different groups), we can consider the interstellar origin of CNEOS14 as a rather robust result.

2.2. Anomalies

There are some intriguing statistical anomalies about CNEOS14 if we consider it as an interstellar object with an unperturbed inbound trajectory from the interstellar medium.

1. Its approach trajectory was very close to the plane of the ecliptic, with only a 10° inclination. An interstellar object would be expected to come in from any random direction.

For instance, 1I/‘Oumuamua had an inclination of 123° (i.e., 33° from the ecliptic plane but moving in a retrograde motion), while 2I/Borisov had 44°. The probability for an interstellar CNEOS14 to follow a trajectory that close to the plane of the ecliptic is only 5%.

2. Its velocity with respect to the local standard of rest (LSR, the mean motion of matter around the galactic center) was oddly large at \(v_{LSR} = 58\ \text{km s}^{-1}\) (SL19). For comparison with the other two known interstellar interlopers, the speeds of 1I/‘Oumuamua and 2I/Borisov with respect to the LSR were 11 and 35 km s\(^{-1}\), respectively. Majek et al. (2017) reported that only 6% of stars move at 58 km s\(^{-1}\) or faster (as a reference, the Sun moves with respect to the LSR at 13 km s\(^{-1}\)). The LSR speed of CNEOS14 is then peculiarly high. If we consider that it was ejected from a “normal” star moving slower than 38 km s\(^{-1}\), it must have received a kick strong enough to eject it with a relative velocity at infinity \(v_{\infty}\) of at least 20 km s\(^{-1}\) with respect to its parent star. To put this into context, the Voyager spacecraft, after two gravity assist maneuvers with Jupiter and Saturn, are leaving the solar system at \(v_{\infty} = 17\ \text{km s}^{-1}\). Not only the kick would need to be extremely strong but also aligned with the direction of the star motion in order to eject CNEOS14 into the interstellar medium at a speed of 58 km s\(^{-1}\) with respect to the LSR. Such alignment would be extremely unlikely. SL19 suggest that perhaps the parent star is from the Milky Way thick disk, which have a larger velocity dispersion of \(\sim 50\ \text{km s}^{-1}\). This is possible but again unlikely since the thick disk population constitutes only about \(\sim 10\%\) of the stars. In summary, CNEOS14 had a peculiarly high velocity with respect to the LSR, compatible with only 6% to 10% of stars.

3. SL19 claim that, in order to detect one interstellar object in a period of \(\sim 10\) years, the number density of such objects in our environment should be \(n = 10^{6.15} \text{AU}^{-3}\) (at 95% confidence, assuming Poisson statistics) and such amount of objects would be at tension with the mass of available material inside the 60 km s\(^{-1}\) orbit expected in a solar nebula. This means that, with our current knowledge, it is unlikely that we would have an interstellar object like CNEOS14 in the database.

When considered together, the probability that these three anomalies are due to chance is less than 1%. In the remainder of this paper, we discuss a hypothetical scenario that resolves these anomalies by postulating that CNEOS14 was deflected by a gravitational encounter with a massive body in the outer solar system.

3. Interstellar meteor or messenger

There are two possibilities regarding the origin of CNEOS14. The first one is that it was an interstellar meteoroid that entered the solar system in a direct collision course with Earth and hit us without the mediation of any other intervention (the interstellar meteor hypothesis). The other possibility, that we put forward in this paper, is that it experienced a gravitational encounter with a massive body and was slingshotted in our direction (the messenger hypothesis). This requires the presence of a hitherto undiscovered planetary-mass object along its path.

BB21 performed a very exhaustive exploration of the parameter space with the goal of constraining the possible masses and
orbits of Planet 9 that would reproduce the observed ETNO clustering. Thanks to this and other previous works, we now have some idea of the projected location on the sky of all the possible Planet 9 orbits. The region of interest defines a band of about 15° thickness around the entire sky (see Figure 9 in BB21). Unfortunately, there is no way to tell from the simulations what is the current position of the planet in its orbit around us. However, not all the possible locations have the same probability. Near the aphelion, the planet has a slower motion. Moreover, a given distance on the sky is compressed into a smaller angular distance. This means that the planet spends more time at a given angular element during its passage through the aphelion and, conversely, less in the perihelion. This information is also provided by BB21 in their figure.

Plotting together the results of BB21 with the meteoroid radiant reveals a remarkable coincidence, as we can see in Figure 1. The horizontal ellipse is the meteoroid asymptotic radiant calculated by SL19 (R.A. 49.4±4.1, declination 11.2±1.8), whereas the vertical ellipse is the corrected geocentric radiant of Peña-Asensio et al. (2022) (R.A. 62.8±1.1, declination 14.0±2.8) transformed to the heliocentric ecliptic frame. Note that these two sets of coordinates are not exactly the same because they have a slightly different meaning. In any case, we can see that the trajectory of CNEOS14 originates in the higher probability contour of the Planet 9 prediction.

In the undeflected interstellar meteor hypothesis, there is no particular reason for this coincidence and it is very unlikely to occur by chance. If the meteoroid enters the solar system from any random incoming direction, it would have equal probability of originating anywhere in the figure (the Mollweide projection preserves areas). The probability of coincidence by chance with the high-probability contour is 1% (the ratio of areas in the contour to the entire sky). If we consider the entire Planet 9 band around the sky calculated by BB21, then the probability of a chance coincidence would increase to 9%.

The probabilities quoted above are upper bounds because they assume, for simplicity, an isotropic distribution of velocities for interstellar objects in the heliocentric frame. The solar system is moving at 13 km s\(^{-1}\) with respect to the LSR in the direction of the solar apex, marked by a green dot in the figure. This means that the probability of interstellar asteroids entering from that side of the sky will be relatively higher and, conversely, lower from the other side. The solar apex and the origin of CNEOS14 are separated in RA by 133° and therefore the number of objects entering the solar system from that direction should be lower, thus lowering the probability of chance coincidence quoted in the previous paragraph.

The messenger hypothesis, on the other hand, explains the coincidence of the CNEOS14 asymptotic radiant with the Planet 9 high probability contour. Furthermore, this scenario also resolves the CNEOS14 anomalies discussed in Section 2.2 above. There would be nothing particularly peculiar about CNEOS14. A significant part of its large impact velocity of 60 km s\(^{-1}\) in the heliocentric frame is provided by the solar gravitational acceleration (up to 42 km s\(^{-1}\)). The remaining kinetic energy, corresponding to another 42 km s\(^{-1}\), would be the combination of its inbound velocity from the interstellar medium plus the delta-v supplied by the Planet 9 slingshot. In the limiting case of zero delta-v (i.e., the slingshot would have only caused a deflection but no velocity increase), the required 42 km s\(^{-1}\) is very close to the typical rms velocity of objects with respect to the LSR (38 km s\(^{-1}\)). For other delta-v values, the meteoroid velocity in the LSR would be even lower.

### Table 1. Coordinates of outer planets on the date when CNEOS14 crossed their orbits. None of them was close in the sky to the meteoroid (RA: 49.4, dec: 11.2)

| Planet  | Orbit crossing | R.A.  | dec  |
|---------|----------------|------|------|
| Mars    | 2013-12-21     | 187.24° | 0.88° |
| Jupiter | 2013-08-12     | 101.33° | 22.88° |
| Saturn  | 2013-03-01     | 219.80° | -11.19° |
| Uranus  | 2012-02-19     | 2.71°   | 0.41° |
| Neptune | 2010-12-13     | 328.70° | -12.79° |

Thus far we have discussed CNEOS14 in the context of previous Planet 9 clues. One might also consider what this meteor tells us independently of all previous work. CNEOS14 was found in a search for a meteor with high heliocentric speed, returning a match with ~60 km s\(^{-1}\). At such a high speed, CNEOS14 was not bound to the solar gravity and therefore it must be either an interstellar (undeflected) meteor or a messenger accelerated into our direction by a gravitational encounter.

In the first case (undeflected), the meteor would be expected to arrive from any direction in space with a random inclination with respect to the plane of the ecliptic. However, the trajectory followed by CNEOS14 was very close to the ecliptic, with only a 10° inclination. There is only a 5% probability for a chance alignment, which strongly disfavors this first scenario.

Furthermore, if CNEOS14 were an undeflected meteor, its speed with respect to the LSR would be of 58 km s\(^{-1}\) which, as discussed in Section 2.2, is peculiarly high. Only about 6% of stars move that fast. This anomaly further decreases the probability of the undeflected hypothesis by an unknown factor.

The odds that CNEOS14 had a gravitational encounter during its passage through the solar system before hitting Earth may be estimated conservatively to be of at least 95% (and almost certainly higher than that), based on the considerations discussed above. However, it did not come close to any of the known planets. Table 1 lists the approximate dates at which the projected trajectory of CNEOS14 crossed each one of the outer planet orbits and the coordinates of the planets at that time.

Therefore, even if one disregards all previous evidence for Planet 9 based on the ETNO clustering, this meteor is most likely a messenger sent to us by some object in the outer solar system. It is additional evidence for the existence of Planet 9 independent of the ETNOS.

### 4. Simulations

If we assume the messenger scenario and wish to find the location where CNEOS14 encountered Planet 9, we need to trace back its path out to a distance roughly between 300 and 600 AU, which is the range of distances predicted for Planet 9.

The coordinates published by Peña-Asensio et al. (2022) (vertical ellipse in Figure 1) mark their corrected geocentric radiant. This represents the true incoming direction of the object when it hit the Earth. However, since the meteoroid trajectory was curved by the gravitation of the Sun and other solar system bodies, this location on the sky is not necessarily where the Planet 9 encounter would have occurred. SL19 published the asymptotic radiant, which marks the origin of the trajectory taking into account all the relevant gravitational influences. Their coordinates (horizontal ellipse in Figure 1) mark the position of the meteoroid at infinity. These two sets of coordinates (one at 1 AU and the other and infinity) are close to the location we seek but, strictly speaking, neither of them is the correct one. The en-
counter would have occurred somewhere in between these two radiants (at 300 to 600 AU).

In order to determine the encounter location, we conducted a set of numerical simulations. We explored the trajectory of CNEOS14 by tracing the meteoroid motion backwards from its impact location throughout the solar system. A newtonian N-body simulation code was employed, accounting for the gravi-
tation of the Sun, the planets and the Moon. This code is publicly available and has been described elsewhere (Socas-Navarro 2019).

The simulation is initialized with the meteoroid at the im-
pact location and observed velocity. A total of 5,000 clones are generated with random perturbations applied to the initial ve-
locity in order to account for the observational uncertainties. In the first 500 clones, the initial velocity modulus is multiplied by a random perturbation factor following a Gaussian distribution centered at $\mu = 1$ and having a standard deviation $\sigma = 0.1$. The R.A. and declination angles are perturbed by adding a random value with a Gaussian distribution of width $\sigma = 2^\circ$, which corresponds to perturbations in the velocity components of $\pm 15\%$.

In a recent research note, Siraj & Loeb (2022) argue that CNEOS14 must have experienced a strong deceleration during its atmospheric entry, which means that its pre-impact speed would have been even higher than the 60 km s$^{-1}$ (heliocentric) that we have considered here. Their results imply that the initial velocity would have been 40% higher. To explore this possibility, we employed a range of velocity modulus multiplicative perturbations between 1 and 1.45 (uniform distribution) for the remaining 4,500 simulation clones.

The simulation is divided in two stages. In the first stage, the meteoroid is very close to Earth and the Moon, and we need a higher temporal resolution to obtain an accurate trajectory reconstruction. For this step we use a time resolution of 1 s and compute one million frames. The simulation time spanned in this phase is 11.57 days and ends with the meteoroid in interplane-
tary space at 0.3 AU from Earth and the Moon. The second phase starts at the end of phase 1, has a coarser time resolution and a much longer span of simulation time to cover the meteoroid trip into the outer solar system. For this phase we used a time reso-
lution of 1 hour and again one million frames, spanning a total of 110 years of simulation time.

According to the simulations, the meteoroid crossed the 300 and 600 AU heliocentric distances 30.12 and 60.48 years before the impact. The celestial coordinates do not vary significantly between 300 and 600 AU but they do vary among clones. These are plotted in Figure 2 with orange dots representing the first 500 clones and blue dots representing the clones with the large atmospheric deceleration proposed by Siraj & Loeb (2022). The coordinates are R.A. $47\pm 4^\circ$, declination $9.7\pm 1.8^\circ$ for the first 500 clones and R.A. $52.4\pm 5^\circ$, declination $10.7\pm 1.8^\circ$ when the entire sample is considered. Since the second set is based on data that have not been formally published and independently verified, we consider here the first coordinates (orange dots in the figure) as the most reliable. Note that the errors on these co-
ordinates are not uncorrelated. On average, clones with higher values of R.A. will have higher declinations, as well. This is be-
cause faster clones are less affected by the solar system gravity and their trajectories will have less curvature in both directions.

The current position of Planet 9 has changed in the 30 to 60 years elapsed since the hypothetical encounter with the me-
teoroid because of the planet’s proper motion. Given the orbital parameters estimated for Planet 9 (e.g. BB21), the proper motion must be between 1.3° and 1.7°. Taking this into account, we end up with coordinates R.A. $48.2\pm 4^\circ$, declination $10.3\pm 1.8^\circ$ as the predicted current position for Planet 9.

5. Conclusions

We propose the first plausible candidate location for Planet 9 at
coordinates R.A. $48.2\pm 4^\circ$, declination $10.3\pm 1.8^\circ$ in the trijunc-
tion of Aries, Taurus and Cetus. This is also the first supporting evidence in favor of Planet 9 that is completely independent of the distant ETNOs orbital clustering. It should be emphasized that the proposed location is only a candidate, there is no cer-
tainty about this prediction, which could be just a curious cosmic coincidence. However, it is a plausible, easily testable and well motivated proposal. The odds of a chance coincidence between Planet 9’s orbit and the CNEOS14 origin is lower than 9% or

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Fig1.png}
\caption{Map of the entire sky in a Mollweide projection. The colored band marks the range of possible Planet 9 orbits, as obtained by BB21 (greater probability in red colors). Vertical blue ellipse: Corrected geocentric radiant of CNEOS14 calculated by Peña-Asensio et al. (2022) and translated into ecliptic coordinates. Horizontal blue ellipse: Asymptotic radiant of CNEOS14 published by SL19. The green dot marks de solar apex, i.e. the direction of motion of the solar system.}
\end{figure}
At the predicted distances, a parallax between 12′ and 23′ is expected. Unfortunately, the BB21 calculations suggest that Planet 9 is just beyond the magnitude limit for GAIA. However, given the exploratory nature of the calculation and the marginal difference with the limit, it is probably worth some search efforts.

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