

On the orbital evolution of meteoroid 2020 CD₃, a temporarily captured orbiter of the Earth–Moon system

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ABSTRACT

Any near-Earth object (NEO) following an Earth-like orbit may eventually be captured by Earth’s gravity during low-velocity encounters. This theoretical possibility was first attested during the fly-by of 1991 VG in 1991–1992 with the confirmation of a brief capture episode—for about a month in 1992 February. Further evidence was obtained when 2006 RH₁₂₀ was temporarily captured into a geocentric orbit from July 2006 to July 2007. Here, we perform a numerical assessment of the orbital evolution of 2020 CD₃, a small NEO found recently that could be the third instance of a meteoroid temporarily captured by Earth’s gravity. We confirm that 2020 CD₃ is currently following a geocentric trajectory although it will escape into a heliocentric path by early May 2020. Our calculations indicate that it was captured by the Earth in 2016⁺²_{−4}, median and 16th and 84th percentiles. This episode is longer (4⁺⁴_{−2} yr) than that of 2006 RH₁₂₀. Prior to its capture as a minimoons, 2020 CD₃ was probably a NEO of the Aten type, but an Apollo type cannot be excluded; in both cases, the orbit was very Earth-like, with low eccentricity and low inclination, typical of an Arjuna-type meteoroid. A few clone orbits remained geocentric for nearly a century, opening the door to the existence of yet-to-be-detected minimoons that are relatively stable for time-scales comparable to those of unbound quasi-satellites such as (469219) Kamo’oalewa 2016 HO₃. In addition, nearly 10 per cent of the experiments led to brief moon-moon episodes in which the value of the selenocentric energy of 2020 CD₃ became negative.

Key words: methods: numerical – celestial mechanics – minor planets, asteroids: general – minor planets, asteroids: individual: 2020 CD₃ – planets and satellites: individual: Earth.

1 INTRODUCTION

If a minor body encounters a planet at very low relative velocity, a temporary capture may occur. This theoretical possibility has been confirmed multiple times in the case of the outer planets (see e.g. Carusi & Valsecchi 1981). The Earth is not strange to this dynamical situation. If the orbit of a minor body is somewhat Earth-like, low-velocity encounters (as low as 0.9 km s^{−1}) close or inside the Hill radius of the Earth, 0.0098 au, may lead to temporary capture episodes (Granvik, Vaubaillon & Jedicke 2012). This is particularly true for recurrent transient co-orbitals of the horseshoe type (see e.g. de la Fuente Marcos & de la Fuente Marcos 2018a,b). That there are circumstances under which this could occur was first confirmed during the fly-by of 1991 VG in 1991–1992, when this near-Earth object (NEO) experienced a temporary satellite capture by the Earth for about a month in 1992 February (Tancredi 1997; de la Fuente Marcos & de la Fuente Marcos 2018a). Further evidence was obtained when 2006 RH₁₂₀ was temporarily captured into a geocentric orbit from 2006 July to 2007 July (Bressi et al.

2008; Kwiatkowski et al. 2008, 2009). Small bodies 1991 VG and 2006 RH₁₂₀ have similar sizes of about 10 m and a few metres, respectively, and they could be secondary fragments of minor bodies that were originally part of the main belt and abandoned their formation region under the effect of Jupiter’s gravity (Rabinowitz et al. 1993; Gladman, Michel & Froeschlé 2000). While 2006 RH₁₂₀ was identified as a temporary capture while still bound to the Earth (Kwiatkowski et al. 2008), 1991 VG was not recognized as such until some time later (Tancredi 1997). The capture episodes experienced by 1991 VG and 2006 RH₁₂₀ were also rather different.

Following the terminology discussed by Fedorets, Granvik & Jedicke (2017), 1991 VG was subjected to a temporarily captured fly-by because it did not complete at least one revolution around the Earth when bound but 2006 RH₁₂₀ did, so it became a temporarily captured orbiter. Carusi & Valsecchi (1979) originally put forward that in order to be captured as a satellite of our planet, the geocentric energy of the object must be negative disregarding any constraint on the duration of the capture event; Rickman & Malin (1981) argued that a true satellite has to be able to complete at least one revolution around our planet while its geocentric energy is negative. Fedorets et al. (2017) have predicted that 40 per cent

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Table 1. Values of the Heliocentric Keplerian orbital elements of 2020 CD₃ and their associated 1σ uncertainties. The orbit determination has been computed by S. Naidu and it is referred to epoch JD 2458906.5 (2020-Feb-27.0) TDB (Barycentric Dynamical Time, J2000.0 ecliptic and equinox). Source: JPL’s SBDB (solution date, 2020-Mar-03 08:13:59).

Orbital parameter	value $\pm 1\sigma$ uncertainty
Eccentricity, e	= 0.041280 \pm 0.000002
Perihelion, q (au)	= 0.98566379 \pm 0.00000009
Inclination, i ($^\circ$)	= 0.92865 \pm 0.00007
Longitude of the ascending node, Ω ($^\circ$)	= 140.5181 \pm 0.0006
Argument of perihelion, ω ($^\circ$)	= 338.47199 \pm 0.00008
Time of perihelion passage, τ (TDB)	= 2458868.5067 \pm 0.0005
Absolute magnitude, H (mag)	= 31.7 \pm 0.3

of all captures should be temporarily captured orbiters. With only two recorded instances of temporary capture, numerical predictions cannot be tested; it is therefore important to identify additional examples to confirm and/or improve our current understanding of this phenomenon. A third example of a meteoroid following a geocentric trajectory has been found recently in 2020 CD₃ (Read et al. 2020). Here, we perform an assessment of the orbital evolution of 2020 CD₃ using the available data and N -body simulations. As its current orbit is rather chaotic and relatively uncertain, we adopt a statistical approach analysing the results of a large sample of orbits and focusing on how and when 2020 CD₃ arrived to its current dynamical state. This paper is organized as follows. In Section 2, we present data and methods. The orbital evolution of 2020 CD₃ is explored in Section 3. Our results are discussed in Section 4 and our conclusions are summarized in Section 5.

2 DATA AND METHODS

Meteoroid 2020 CD₃ was discovered as C26FED2 by T. Pruyne and K. Wierchoś on 2020 February 15 observing for the Mt. Lemmon Survey in Arizona with the 1.5-m reflector + 10K CCD and it was found to be temporarily bound to the Earth (Read et al. 2020). The discovery MPEC states that no evidence of perturbations due to solar radiation pressure has been observed in orbit integrations, and no link to a known artificial object has been found (Read et al. 2020). Therefore, it has to be assumed that, as in the case of 1991 VG and 2006 RH₁₂₀, 2020 CD₃ is a *bona fide* natural body, a very small asteroid or meteoroid with an absolute magnitude of 31.7 mag (assumed $G = 0.15$), which suggests a diameter in the range ~ 1 –6 m for an assumed albedo in the range 0.60–0.01. Meteoroid 2020 CD₃ is probably smaller than 1991 VG and 2006 RH₁₂₀; Arecibo Observatory pointed at 2020 CD₃ for about 2 hours on 2020 March 6 with negative results, probably because it is too small and it was too far away to detect with radar at that time (Taylor, private communication). Its most recent orbit determination is shown in Table 1 and it is based on 58 observations for a data-arc of 15 d. Its orbital elements are consistent with those of the Arjuna, a secondary asteroid belt located around the path of our planet and originally proposed by Rabinowitz et al. (1993). The Arjuna are a loosely resonant family of small NEOs, which form the near-Earth asteroid belt (see e.g. de la Fuente Marcos & de la Fuente Marcos 2013, 2015a).

The orbit determination in Table 1 is still uncertain and its associated evolution rather chaotic (see Section 3). Wiegert, Innanen & Mikkola (1998) have shown that the statistical analysis of

Table 2. Cartesian state vector of 2020 CD₃: components and associated 1σ uncertainties. Epoch as in Table 1. Source: JPL’s SBDB.

Component	value $\pm 1\sigma$ uncertainty
X (au)	= $-9.249461206824366 \times 10^{-1} \pm 2.23296462 \times 10^{-7}$
Y (au)	= $3.829494417698888 \times 10^{-1} \pm 8.27974473 \times 10^{-8}$
Z (au)	= $4.825464890142035 \times 10^{-3} \pm 2.00658446 \times 10^{-7}$
V_X (au d $^{-1}$)	= $-7.033807851735909 \times 10^{-3} \pm 2.16520750 \times 10^{-8}$
V_Y (au d $^{-1}$)	= $-1.606237689633747 \times 10^{-2} \pm 8.21345272 \times 10^{-9}$
V_Z (au d $^{-1}$)	= $2.735613730104734 \times 10^{-4} \pm 2.13010688 \times 10^{-8}$

an extensive set of numerical simulations accounting for the uncertainties associated with an orbit determination can produce reliable results. In order to obtain sufficiently robust conclusions, we apply the Monte Carlo using the Covariance Matrix (MCCM) method detailed in section 3 of de la Fuente Marcos & de la Fuente Marcos (2015b) to generate initial conditions for our N -body simulations that have been carried out using Aarseth’s implementation of the Hermite integrator (Aarseth 2003); the direct N -body code is publicly available.¹ The covariance matrix required to generate initial positions and velocities for 10^4 control or clone orbits has been obtained from Jet Propulsion Laboratory’s Solar System Dynamics Group Small-Body Database (JPL’s SSDG SBDB, Giorgini 2015).² This is also the source of the data in Table 1; JPL’s HORIZONS³ ephemeris system (Giorgini & Yeomans 1999) has been used to gather most input data used in our calculations (e.g. data in Table 2). Some data have been retrieved from JPL’s SBDB using the tools provided by the Python package Astroquery (Ginsburg et al. 2019; Mommert et al. 2019). Extensive details on our calculations and physical model can be found in de la Fuente Marcos & de la Fuente Marcos (2012, 2018a,b).

In order to analyse the results, we produced histograms using the Matplotlib library (Hunter 2007) with sets of bins of constant size computed using Astropy (Astropy Collaboration et al. 2013, 2018) by applying the Freedman and Diaconis rule (Freedman & Diaconis 1981). Instead of using frequency-based histograms, we considered counts to form a probability density so the area under the histogram will sum to one.

3 ORBITAL EVOLUTION

With our calculations we aimed at answering four main questions: (i) When did this capture take place? (ii) When is 2020 CD₃ leaving its current geocentric path? (iii) How was the pre-capture orbit of 2020 CD₃? (iv) How diverse is the evolution in the neighbourhood of the initial conditions in Table 2? Answering the first two questions, we can find out if 2020 CD₃ is experiencing a temporarily captured fly-by or a temporarily captured orbiter episode. The third question is directly related to the origin of 2020 CD₃ and the fourth question can inform us on the reliability of our results. In order to provide robust answers to all these questions, we first focus on the initial conditions in the form of Cartesian state vectors and then we use the MCCM method to study how the interlaced uncertainties propagate over time and how they impact our results.

Figure 1 provides an answer to the last question. It shows the

¹ <http://www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm>

² <https://ssd.jpl.nasa.gov/sbdb.cgi>

³ <https://ssd.jpl.nasa.gov/?horizons>

short-term evolution of two important parameters—the geocentric distance, Δ , and the geocentric energy—for a reduced but relevant set of control or clone orbits. Following Carusi & Valsecchi (1979), when the value of the geocentric energy is negative, a capture takes place. This is linked to being within the Hill radius of the Earth (in purple in Fig. 1). The current capture episode is clearly of the temporarily captured orbiter type as the value of the geocentric energy remains negative for an extended period of time, sufficient to complete multiple revolutions around the Earth–Moon system as argued for by Rickman & Malmort (1981). Just with the information in Fig. 1, we cannot confirm statistically this conclusion because we are using data from Table 2 and not taking into account how the uncertainty in the value of one orbital element affects all the others. Fig. 1 is therefore only suggestive of a temporarily captured orbiter.

On the other hand, we observe a variety of dynamical behaviours and although those centred about the 2008 epoch are consistent with a temporarily captured orbiter, temporarily captured fly-bys may have taken place in the past and they may repeat in the future (see Fig. 1, left-hand side set of panels). This indicates that the orbital evolution of 2020 CD₃ may lead to recurrent temporary captures and most episodes will be of the temporarily captured fly-by type. In addition, we observe that some initial conditions tend to produce longer captures. These are associated with control or clone orbits with Cartesian vectors separated -1σ (in green), $+2\sigma$ (in blue), and $+3\sigma$ (in red) from the nominal values in Table 2. In any case, the evolution is highly non-linear and a geocentric orbit of the $+2\sigma$ type lasts longer than those of the -1σ or $+3\sigma$ types. Gaussianly distributed initial conditions lead to rather different evolutionary outcomes due to the highly chaotic dynamical context.

Figures 2 and 3 show the results of 10^4 direct N -body simulations for which the MCCM method has been used to generate initial conditions (control or clone orbits). Figure 2 shows a trimodal distribution of the time of capture. From the data in the figure, 2020 CD₃ may have been captured by the Earth on $2015.9^{+2.0}_{-4.4}$, median and 16th and 84th percentiles. The outcome of the integrations backwards in time depends critically on crossing several gravitational keyholes (Chodas 1999) in sequence, the most important one took place late in 2017 (see Fig. 1, right-hand side set of panels). The outcome of integrations forward in time (not shown) is far more uniform with a departure date to follow a heliocentric trajectory on $2020.35109^{+0.00010}_{-0.00011}$ (see also Fig. 1, right-hand side set of panels). This confirms statistically that 2020 CD₃ is experiencing a temporarily captured orbiter episode, answering reliably the first two questions posed above.

Figure 3 provides the distributions of a , e , and i of the pre-capture orbits probably followed by 2020 CD₃. The results are fully consistent with the expectations for an Arjuna origin, which is often linked to recurrent transient co-orbitals of the horseshoe type (see e.g. de la Fuente Marcos & de la Fuente Marcos 2018a,b). The distribution in a is bimodal (Fig. 3, top panel) reflecting the fact that it may have been an Aten (slightly more likely) or an Apollo prior to capture—switching back and forth between dynamical classes is typical of co-orbitals of the horseshoe type. The distribution in e (Fig. 3, middle panel) gives a most probable value of 0.025 ± 0.014 and that of i (Fig. 3, bottom panel) has $0.65^{+0.2}_{-0.13}$. Meteoroid 2020 CD₃ is the only known object that may have crossed the volume of NEO orbital parameter space defined by $a \in (0.95, 1.07)$ au, $e \in (0.011, 0.039)$, and $i \in (0.51, 0.85)$. This suggests that hypothetical objects following similar orbits may have been removed from NEO space, either as a result of collisions with the Earth or the Moon (see e.g. Gladman et al. 1995; Brown

et al. 2002; Clark et al. 2016) or after being ejected dynamically following a close fly-by.

The most probable values of the orbital parameters of 2020 CD₃ after escaping capture will be $a = 1.019297^{+0.000003}_{-0.000004}$ au, $e = 0.020268^{+0.000012}_{-0.000013}$, and $i = 0.60900 \pm 0.00011$, corresponding to an Arjuna orbit of the Apollo type. Out of the known minor bodies, the one with the closest values to these orbital parameters is 2009 BD that has $H = 28.1$ mag with an area to mass ratio compatible with that of a very porous rock and for which direct detection of radiation pressure effects has been reported (Micheli, Tholen & Eliott 2012). This meteoroid may impact the Earth in the near future with impact solutions starting in 2071 (Micheli et al. 2012) and this supports our previous conclusion that objects moving along similar orbits may have been removed from NEO space via collisions with the Earth or the Moon.

4 DISCUSSION

After providing robust answers to the four questions posed at the beginning of Section 3, one may argue that other co-orbital objects such as quasi-satellites and horseshoe librators (Murray & Dermott 1999) have a greater intrinsic interest because they remain in regions relatively easy to access from the Earth during longer time-scales. For example, Earth’s quasi-satellite (469219) Kamo’oalewa 2016 HO₃ may remain as an unbound companion to the Earth for a few centuries (de la Fuente Marcos & de la Fuente Marcos 2016b). The fact is that some of the control or clone orbits studied in our numerical survey exhibit stability for comparable time-scales. Figure 4 shows an example in which the capture episode lasts longer than a century, opening the door to the existence of yet-to-be-detected minimoons that could be relatively stable for sufficiently long periods of time.

On the other hand, our calculations show that the role of the gravitational attraction of the Moon on the orbital evolution of 2020 CD₃ is far from negligible. We have found that nearly 10 per cent of the experiments carried out led to brief (a few hours to a few days) recurrent moon-moon episodes in which the value of the selenocentric energy of 2020 CD₃ became negative but failing to complete one full revolution around the Moon. Following Fedorets et al. (2017), 2020 CD₃ may have had temporarily captured fly-bys with the Moon. This dynamical situation was first mentioned by Kollmeier & Raymond (2019) and our analysis and results give some support to their conclusions.

Although the state-of-the-art orbit model⁴ developed by the Near-Earth Object Population Observation Program (NEOPOP) and described by Granvik et al. (2018) cannot make predictions regarding bodies as small as 2020 CD₃, the dynamical class to which it belongs, the Arjuna, cannot be fully explained within this orbit model. This is probably because fragmentation processes have not been included and some Arjuna may have been locally produced via sub-catastrophic impacts, tidal disruptions during very close encounters with the Earth and/or the Moon or, more likely, due to the action of the Yarkovsky–O’Keefe–Radzievskii–Paddack (YORP) mechanism (see e.g. de la Fuente Marcos & de la Fuente Marcos 2016a, 2018b; Jopek 2020). Meteoroid 2020 CD₃ may have its origin in one YORP-driven fragmentation event.

⁴ <http://neo.ssa.esa.int/neo-population>

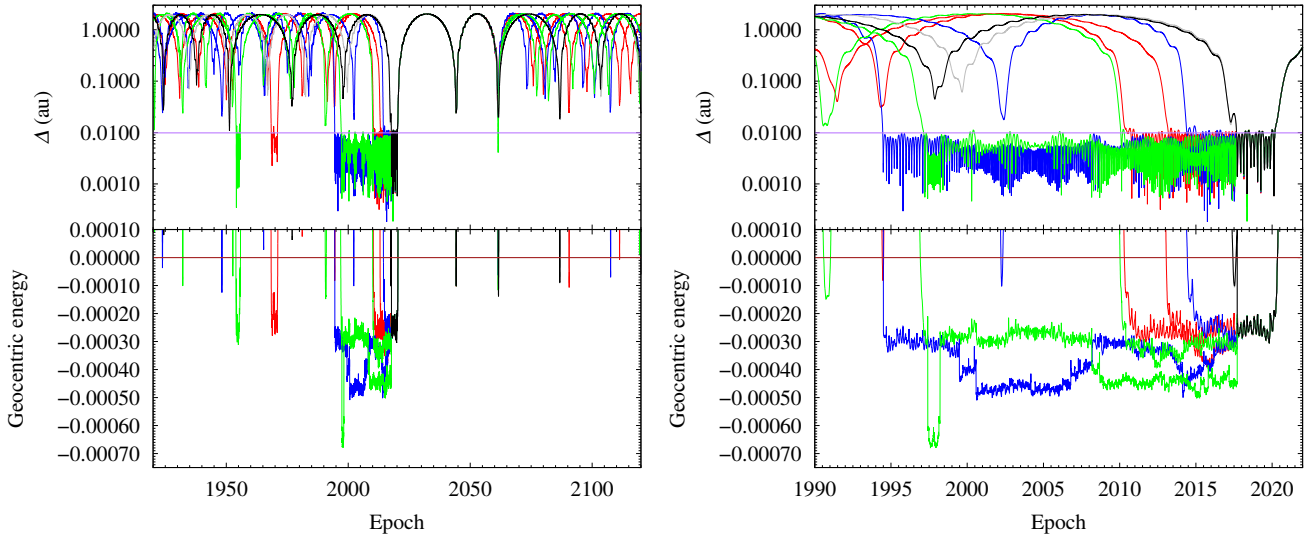


Figure 1. Evolution of the values of the geocentric distance (Δ , top panel) and the geocentric energy (bottom panel) of 2020 CD₃. As pointed out by [Carusi & Valsecchi \(1979\)](#), captures happen when the value of the geocentric energy becomes negative. The unit of energy is such that the unit of mass is $1 M_{\odot}$, the unit of distance is 1 au, and the unit of time is one sidereal year divided by 2π . The right-hand side set of panels is a magnified version of those on the left-hand side. The evolution according to the nominal orbit of 2020 CD₃ in Table 1 is shown in black, an arbitrarily close orbit appears in grey, and those of control or clone orbits with Cartesian vectors separated $\pm 1\sigma$ (in green), $\pm 2\sigma$ (in blue), and $\pm 3\sigma$ (in red) from the nominal values in Table 2. The Hill radius of the Earth, 0.0098 au, is shown in purple (top panels).

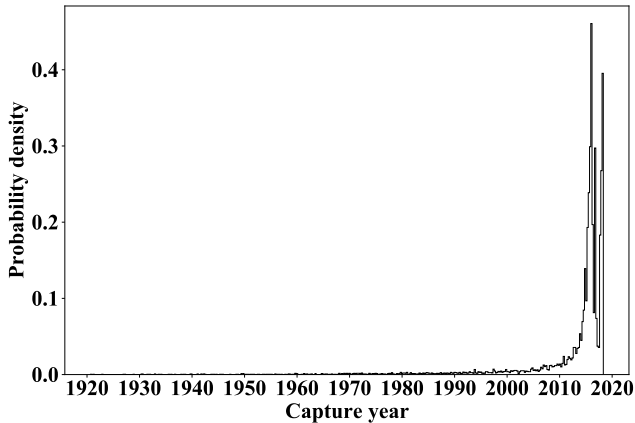


Figure 2. Distribution of the time of capture by Earth's gravity for 2020 CD₃ using initial conditions based on the orbit determination shown in Table 1 (see the text for details). The bins in the histogram have been computed using the Freedman and Diaconis rule.

5 CONCLUSIONS

In this paper, we have explored the sequence of events that led to the capture of 2020 CD₃ as a minimoon of the Earth. This is only the second time a minor body has been discovered while still engaged in geocentric motion—the first one was 2006 RH₁₂₀ ([Bressi et al. 2008](#); [Kwiatkowski et al. 2008, 2009](#)). Due to the chaotic path followed by 2020 CD₃, our exploration has been carried out in statistical terms using the results of 10^4 direct N -body simulations. Our conclusions can be summarized as follows.

- (i) All the control or clone orbits indicate that 2020 CD₃ is currently following a geocentric trajectory. This moonlet will end its current capture episode on 2020 May 6–7 and it has re-

- mained as a second moon to the Earth for several (4^{+4}_{-2} yr) years now. Future, shorter capture events cannot be discarded.
- (ii) During its orbital evolution as second satellite of the Earth, 2020 CD₃ may have experienced (with a probability of about 10 per cent) brief subsatellite episodes in which the value of its selenocentric energy became negative for a few hours or days (i.e. a temporarily captured fly-by with the Moon).
- (iii) Meteoroid 2020 CD₃ belongs to the population of NEOs that may experience recurrent transient co-orbital episodes of the horseshoe or even quasi-satellite type with the Earth. It was part of this population before its capture as a minimoon and it will return to it after its escape from its current geocentric path. This is consistent with the analysis carried out by [de la Fuente Marcos & de la Fuente Marcos \(2018a\)](#) for the case of 1991 VG.

Spectroscopic studies carried out before it leaves the neighbourhood of the Earth–Moon system may be able to confirm if 2020 CD₃ is indeed a natural object and provide its physical characterization.

Our results suggest that, in the case of the Earth, relatively long (for a century or more) capture events are possible (see Fig. 4). They also show that the answer to the question posed by [Kollmeier & Raymond \(2019\)](#) is probably in the affirmative, moons can have moons. However, in the case of the Moon its submoons may have an ephemeral existence due to their chaotic orbits. On the other hand, the fact is that 2020 CD₃ may have remained as a second moon of the Earth for several years, reaching values of the apparent magnitude close to or below 20 mag; however, it has only been identified as such a few months before leaving its geocentric path for a heliocentric one. This strongly suggests that other minimoon episodes may have been missed, neglected because their associated trajectories resembled, perhaps too closely, those followed by hardware with an Earth origin.

Minimoons are not mere dynamical curiosities, the scientific

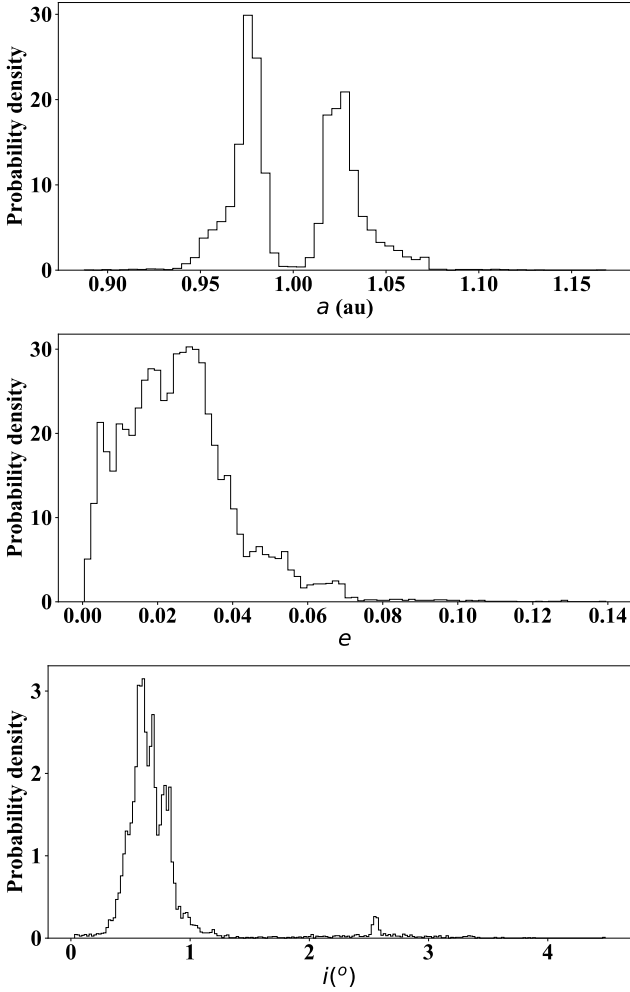


Figure 3. Distributions of semimajor axes, a (top panel), eccentricities, e (middle panel), and inclinations, i (bottom panel), of the pre-capture orbits probably followed by 2020 CD₃ and compatible with the orbit determination in Table 1. The bins in the histogram have been computed using the Freedman and Diaconis rule.

and commercial sides of minimoons have been reviewed by Jedicke et al. (2018) and its future discoverability from the Vera C. Rubin Observatory has been recently studied by Fedorets et al. (2020). Minimoons are also targets of the EURONEAR survey (Vaduvescu et al. 2018) from La Palma and their windows of visibility have been discussed by Bolin et al. (2014).

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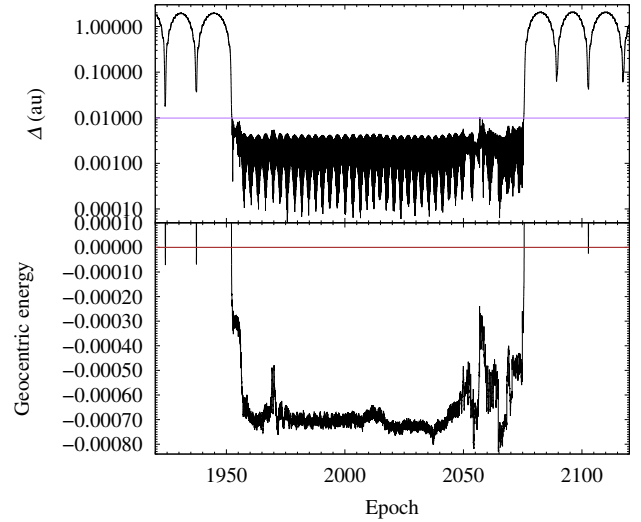


Figure 4. Similar to Fig. 1 but for a different control or clone orbit from one of the earliest orbit determinations of 2020 CD₃ available from JPL’s SBDB.

made use of Astropy,⁵ a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013, 2018).

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⁵ <http://www.astropy.org>

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