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Encounter Circumstances of Asteroid 99942 Apophis with the Catalog of Known Asteroids

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Abstract

Asteroid 99942 Apophis will pass near Earth in 2029 April. Expected to miss our planet by a safe margin, that could change if Apophis's path were perturbed by a collision with another asteroid in the interim. Though the statistical chance of such a collision is minuscule, the high risk associated with Apophis motivates us to examine even this very unlikely scenario. In this work, we identify encounters between known asteroids and Apophis up to 2029 April. Here we show that Apophis will encounter the 1300 m diameter asteroid 4544 Xanthus in 2026 December. Their minimum orbit intersection distance is less than 10,000 km, with Apophis passing that closest point just 4 hr before Xanthus. Though a direct collision is ruled out, the encounter is close enough that material accompanying Xanthus (if any) could strike Apophis. We also identify other asteroid encounters that deserve monitoring.

Unified Astronomy Thesaurus concepts: Asteroid dynamics (2210); Near-Earth objects (1092)

Supporting material: animation

1. Introduction

Asteroid 99942 Apophis is one of the most-studied near-Earth asteroids (NEAs), stemming in large part from its close passages to Earth. Initially thought to pose an impact danger, careful observations of its trajectory and properties have shown that the risk of a collision with our planet during any of its upcoming close approaches in 2029 and 2036 is nil.[4] However, these assessments, e.g., Farnocchia et al. (2013), Vokrouhlický et al. (2015), among many others, have assumed that the motion of the asteroid will continue uninterrupted by any impulsive perturbations such as might arise from Apophis's collision with another asteroid.

The a priori probability of an asteroid colliding with Apophis during the period of a few years between now and that asteroid's close approach to Earth in 2029 is extremely low. Nevertheless, asteroid collisions are believed to occur. Asteroid families are thought to originate from a disruptive collision between asteroids (Michel et al. 2001). In addition, the probable collision of smaller asteroids with larger ones has been observed at least twice in the recent past: P/2010 A2 is thought to have been struck in 2009 by an object a few meters in size (Jewitt et al. 2010; Snodgrass et al. 2010), and asteroid 596 Scheila in 2011 by a body 35 m in size (Ishiguro et al. 2011; Jewitt et al. 2011).

Even if a particular asteroid might not directly collide with Apophis, material accompanying that asteroid (whether gravitationally bound or not) could also pose some risk. Binary and multiple asteroids are seen among all asteroid populations, including the NEAs (Margot et al. 2015). Solar system bodies may also shed material from their surface through processes driven by water-ice sublimation. A comet is the classic example, usually having a meteoroid stream composed of material shed from its surface traveling along its orbit. So-called "active asteroids" may also release material through a wide array of mechanisms: impact disruption, rotational destabilization (Hsieh 2017), thermal fracturing (Knight et al. 2016), radiation pressure sweeping, and electrostatic levitation (Jewitt et al. 2015). Active asteroids may release substantial amounts of mass. For example, active asteroid 3200 Phaethon shows no or only very weak cometary activity (Tabeshian et al. 2019) and yet is accompanied by a substantial debris stream (total mass 10^{13}–10^{14} kg; Hughes & McBride 1989; Blaauw 2017) that produces one of the strongest meteor showers at Earth, the Geminids meteor shower.

For completeness, we note that, even in the absence of a collision, there is a change in Apophis's velocity Δv due to the gravitational attraction of a passing asteroid. The magnitude of this change can be estimated through the impulse approximation (Aguilar & White 1985)

$$\Delta v \approx \frac{2Gm}{v_{\rm rel}\, d}, \tag{1}$$

where m is the mass of the passing body, G is the gravitational constant, d is the minimum distance between the body and Apophis, and $v_{\rm rel}$ is the relative velocity at the time of their closest approach. Such changes will invariably turn out to be negligibly small for the cases examined here.

Though the chances of Apophis undergoing an interaction with another asteroid that could affect its impact risk with Earth are minimal, the high stakes involved motivate us to extend the study of this asteroid even to these unlikely eventualities. In this work we identify close encounters between Apophis and members of the catalog of known asteroids and comets, with the purpose of

[4] https://www.jpl.nasa.gov/news/nasa-analysis-earth-is-safe-from-asteroid-apophis-for-100-plus-years

1. examining the probability of a direct collision;
2. assessing the possibility of collisions with asteroidal satellites or other accompanying debris;
3. planning for telescopic observation of Apophis−asteroid encounter events to verify the absence of a collision and maintain situational awareness; and
4. identifying those asteroids for which additional observations or analysis are needed to better assess their collision probability with Apophis.

2. Methods

The primary goal of this analysis is to assess the risk of a known small body in the solar system impacting Apophis prior to its close approach to Earth in 2029 April. Here we examine the time frame beginning 2023 February 25 (JD 2460000.5) and ending 2029 April 13 (JD 2462239.5), which is the time of Apophis's next close approach to Earth. Though an examination of possible impacts with Apophis after the 2029 close approach is also of interest, it will be more appropriate once the deflection of Apophis from its current orbit by that encounter has been measured precisely.

Two catalogs of asteroid and comet orbital information are used and the results compared. The Small-Body Database, maintained by NASA's Jet Propulsion Laboratory (JPL) on their Solar System Dynamics (SSD) web page,[5] contains the orbital elements for over 1.2 million asteroids and comets. The data retrieved from the JPL Small-Body Database for the present study are current as of 2023 May 1. The NEODyS-2 database sponsored by ESA contained information on 31,886 NEAs when retrieved on 2023 May 1.[6]

The orbital determinations of both the JPL and NeoDys teams are based on the same database of observations maintained by the IAU's Minor Planet Center and employ similar techniques, yet their results differ slightly. Each of these two teams of global experts accommodates the inherent measurement uncertainties in asteroid and comet observations via different approaches, informed by their collective expertise. This independence serves as an effective mechanism for cross-validation and enhances the reliability of NEA catalogs. This will also turn out to have some importance in the interpretation of our results in rare cases where they disagree substantially, which we will return to in Section 3.2.

2.1. Initial Subsample Selection

To properly assess the impact probability of a particular asteroid with Apophis requires a full-scale simulation of its orbit through time, including planetary and other perturbations. Though we will perform such an analysis for the most interesting objects, we first filter the JPL catalog to remove the many objects that cannot approach Apophis. At this filtering stage, we will assume that the orbital elements provided by the catalog are approximately constant over the time interval considered, though we will see that this is not always the case, and we will assess this further in Section 2.2.

We ignore objects in the JPL catalog whose probability of impacting Apophis cannot be effectively assessed, because of missing orbital elements and/or no uncertainties provided. We do not at this stage exclude objects because they have large orbital uncertainties. We will address their uncertainties carefully at later stages when we will use their orbital covariance matrices to determine the effect of uncertainty on our understanding of their trajectories. We do at this stage, however, eliminate those objects that cannot reach Apophis because their perihelia and/or aphelia do not overlap. An object is eliminated if its perihelion q is not at least as small as Apophis's aphelion Q_A, or its aphelion Q is not at least as large as Apophis's perihelion q_A within 5σ, or specifically, if either of the conditions below is met:

$$q - 5\sigma_q > Q_A + 5\sigma_{Q_A} \tag{2}$$

$$Q + 5\sigma_Q < q_A - 5\sigma_{q_A}, \tag{3}$$

where σ_q and σ_Q represent the uncertainties in the perihelia and aphelia of the asteroids in question. This reduces the JPL sample to about 30,000 objects. These, together with the entire NeoDys catalog, are passed to the next step.

In our second filtering step, we examine the minimum orbit intersection distance (MOID) of these objects with respect to Apophis. The MOIDs are computed using a simple 2D minimization of the distance between two orbits as a function of their true anomalies using Powell's method (Press et al. 1986), with a tolerance of 10^{-6}. This is a general-purpose minimization routine, widely used and considered robust against pathological cases. Though much slower than purpose-built MOID routines such as that of Baluev & Mikryukov (2019), we have compared our routine extensively against the BM2019 implementation, and ours gives answers identical to within the tolerance.

At this stage, we continue to take the orbital elements of the asteroids to be constant. Apophis's orbit is so well-known that we will model it as a single particle on its nominal orbit. For all other asteroids, a set of 100 clones are generated from the covariance matrices. The MOID is computed between each of the 100 orbit clones and the nominal orbit of Apophis. The standard deviation σ_{MOID} of this set of 100 MOID values is taken as representative of the dispersion of the object's nominal MOID with respect to Apophis. The accurate calculation of the uncertainty in the MOID is certainly more involved than simply taking the standard deviation, e.g., advanced methods for doing so are presented by Gronchi & Tommei (2007). However, we did not adopt a more detailed calculation here because we do not require a precise uncertainty but a simple dispersion, as it is used here only to determine the outer envelope for our sample.

We will include objects in our next subsample if they meet one of the two criteria below. These criteria are chosen iteratively, by examining the results of our simulations (discussed further below) and in particular by determining by how much the MOIDs of the NEAs change over the course of a few years. We found that the typical variation in the MOIDs of the asteroids in this study was $\lesssim 0.001$ au. These changes result from planetary perturbations, with a handful of cases (involving encounters with Jupiter) reaching changes in the MOID of nearly 0.01 au. Based on these values, we choose our selection criteria to be as follows:

1. Any object with a nominal MOID less than 0.001 au is included regardless of its orbital uncertainty.
2. Any objects that have a $\mathrm{MOID} < 5\sigma_{\mathrm{MOID}}$ and $\mathrm{MOID} < 0.01$ au will also be included in our sample. This condition ensures that the MOID is small and

[5] https://ssd.jpl.nasa.gov/tools/sbdb_query.html (retrieved 2023 May 1)
[6] https://newton.spacedys.com/neodys/index.php?pc=5 (retrieved on 2023 May 1)

consistent within 5 standard deviations with zero. We note that, for a true Gaussian distribution, only one part in 3.5 million of the integrated probability is beyond 5 standard deviations. The distribution of the MOIDs is not strictly Gaussian, but our choice of 5 standard deviations means that we exclude objects whose orbits are so uncertain that they have less than of order 10^{-6} chance of intersecting the orbit of Apophis.

Because of the possibility of the MOIDs changing as a result of planetary perturbations, our sample may not include all asteroids that could approach Apophis. A full numerical simulation of all NEAs, or at least the approximately 30,000 objects identified by our earlier filtering, would be necessary to categorize such a sample exhaustively. This study discusses the most straightforward cases, but a full examination of possible encounters will be presented in a future work.

Our final filtering reduces the sample to 376 objects from the JPL catalog and 396 objects from the NeoDys catalog, many of the same objects appearing on both lists. Most are asteroids; seven are known comets. There are 322 objects that appear on both lists, while 54 objects appear only on the JPL list and 74 objects only on the NeoDys list. The nonoverlapping objects all lie near the threshold boundaries, appearing just inside in one sample and just outside in the other. Such differences are to be expected and are precisely why we considered both catalogs independently. Each of the objects on our final JPL and NeoDys lists will undergo more rigorous further analysis discussed in the next section.

2.2. Full Simulation of Objects in the Subsample

For the objects in our filtered subsample, a full-scale numerical integration of their motion within the solar system is performed. Apophis is represented by a single particle on its nominal JPL orbit. Each of the other asteroids is represented by 2000 clones, 1000 clones each generated from the JPL CNEOS covariance matrices and NeoDys covariance matrices for that object.

The clones are integrated with the RADAU (Everhart 1979) algorithm within a solar system that includes the eight planets, with Earth and the Moon combined into a single body at their barycenter. Initial conditions are from the JPL DE405 ephemeris (Standish 1998). The integration runs from JDE 2460000.5 to JDE 2462239.5 with an external time step of 10 days. The candidate asteroid clones and Apophis are treated as massless test particles, and nongravitational forces such as Yarkovsky are ignored. We recognize that our model does not include the full suite of perturbations as are, for example, included in the JPL Horizons model. We will nonetheless find that our results are highly compatible with theirs where we can compare them, which we will do later in this section.

To determine the possibility of a collision, we examine (1) the MOID between Apophis's orbit and that of a known asteroid and (2) the difference in time of flight to the MOID ΔToF. Here the MOID will always refer to the mutual MOID between Apophis and some other asteroid, unless otherwise specified. The time of flight (ToF) to the MOID is the time needed for an asteroid to travel from its current position to the MOID. The difference in the ToF to the MOID of two asteroids ΔToF represents the interval of time by which they miss both being at their mutual MOID at the same time. For example, if Apophis will reach its MOID with asteroid X in ToF $= 4$ days and X will reach its mutual MOID with Apophis in $\mathrm{ToF}_X = 7$ days, then $\Delta\mathrm{ToF}_X = -3$ days. We adopt the convention that ΔToF is negative if Apophis reaches the MOID first. The condition of MOID $= \Delta$ToF $= 0$ corresponds to a collision with Apophis.

We select our sample based on the MOID – ΔToF values for two reasons:

1. Material released at low velocity from a small solar system body tends to disperse along its orbit, even if released with an isotropic velocity distribution relative to its parent. This is the well-known mechanism by which a comet creates a meteoroid stream that may stretch for hundreds of au along its entire orbit. As a result, if any material is released by an object examined in this study, it is reasonable to assume that that material will have an overall orbit shaped much like its parent's and have a similar MOID but with a larger spread in ΔToF. This simplifies our interpretation of scenarios involving possible collisions with asteroidal debris. Consider two asteroids, each of which passes the same minimum physical distance R from Apophis, but where one has a large MOID and the other a small one. Any material released from the first one cannot approach Apophis to small distances, while material (if any) released from the asteroid with a small MOID may. Thus, asteroids with small MOIDs naturally entail a higher risk of collision with any material that may have been shed by it.
2. A useful property of the MOID and ΔToF is that both are approximately constant during the days and weeks around a particular close approach between two asteroids. Using these quantities avoids difficulties associated with selecting close approaches between Apophis and another asteroid based on their mutual distance (which is rapidly changing) within a numerical simulation. Such a simulation, which inevitably produces output at some discrete set of time steps, could inadvertently step over a close encounter without careful interpolation, but our choice of quantities avoids this difficulty entirely.

Our approach is similar to the use of the Opik target plane, e.g., as described in Farnocchia et al. (2019). The Opik target plane offers the helpful properties that the minimum absolute value of the x-axis is the MOID and the y-axis is related to the timing offset, with $y = 0$ indicating that both bodies arrive at their mutual MOID at the same time. However, the Opik plane assumes that the closest point of approach is near enough to the MOID that the motions of the bodies can be taken to be linear during the encounter. This is not the case for many of the encounters we examine, where an object with a small MOID with Apophis may have a ΔToF of months or years. In our formulation, both the MOID and the difference in the ToF to the MOID always remain well-defined and intuitive, while the Opik target plane does not.

We verified the details of the close approaches discussed below with JPL's Horizon's integrator. We queried the SSD/CNEOS Horizons API service for the nominal Cartesian positions and velocities of Apophis and the asteroid in question during the time of the close encounter and used our own codes to determine the MOID and ΔToF. We found differences in the MOID typically of less than 10^{-6} au ($\sim$100 km) and in ΔToF of less than 10 minutes. These results are consistent across the cases discussed in this work, perhaps not surprising since the encounters are all between orbits of modest eccentricity and inclinations. We will discuss additional differences further in cases (e.g., Xanthus in Section 3.1.1) where they arise. The JPL integrator likely outperforms our own in precision, but the overall consistency of JPL computations with ours reinforces our confidence in our results.

To determine appropriate conditions under which material accompanying a cataloged asteroid might pose some hazard of collision with Apophis, we use the fact that material released at low speed (which includes most of the mass-shedding mechanisms listed earlier in Section 1) will follow its parent's orbit, with some motion away from it but dispersing primarily forward or backward along the orbit owing to Keplerian shear. The orbital periods of the bodies in our sample are about 1 yr, and material released at a few meters per second will, to an order of magnitude, move $\sim 10^5$ km before its orbit closes on itself. During a single orbit, the material will acquire a time offset $\sim$1 hr from its parent, and this offset accumulates over time. The chaotic *e*-folding time for these types of Earth-crossing orbits is typically 100 yr (Whipple 1995), and so we might expect any material released by an asteroid to have been scattered from its orbit on that timescale. From this, we determine that any material released by an asteroid might be expected very roughly to have a MOID $\lesssim 10^5$ km with Apophis and a ΔToF $\lesssim 100$ hr.

We note that a ΔToF $\lesssim 100$ hr corresponds to a much larger distance than the MOID $\lesssim 10^5$ km criteria: an asteroid traveling at 30 km s^{-1} will travel about 10 million km in 100 hr. However, a larger along-track distance is reasonable because the uncertainties in the asteroid positions are primarily along the orbit owing to Keplerian shear. As a result, material released from an asteroid may end up dispersed over a very large volume, much larger than the volume of Apophis itself. Thus, the chances of a collision with asteroid-released material remain very low, though not always negligible. Comets release material that disperses over an even larger volume, but that may still create substantial flux, for example, as seen at Earth during a meteor shower. Nonetheless, the risk of collision between Apophis and any of the asteroids discussed in this work (or with material released from them) remains exceptionally low.

We tighten the criteria slightly to reduce our list to the most interesting objects. From our simulations of the 376 JPL objects and 396 NeoDys objects, we extract all those for which at least one clone, at some point during the simulation, meets the condition

$$\text{MOID} < 10^4\,\text{km} \quad \text{and} \quad |\Delta\text{ToF}| < 12\,\text{hr}, \tag{4}$$

which we will term an "encounter." Since each of our 1000 clones at this stage corresponds to an equally likely case within the formal error distribution of the asteroid's orbital solution, this corresponds to a 0.1% chance of the asteroid in question passing within 10,000 km of Apophis within ±12 hr of Apophis doing the same. Fifteen asteroids meet this criterion, and they will be discussed in more detail below.

3. Results and Discussion

We will group our results into the following categories:

1. Both JPL and NeoDys agree that there is a substantial (2%–100%) probability of an asteroid passing Apophis at a MOID $< 10^4$ km and a ΔToF < 0.5 days
2. At least one of JPL or NeoDys indicates a marginal (0.1%–2%) probability of an asteroid passing Apophis at a MOID $< 10^4$ km and a ΔToF < 0.5 days
3. JPL and NeoDys disagree substantially. This is of some concern, as it indicates that we do not have a consensus as to exactly how close Apophis will pass to the asteroid in question.
4. Other cases not strictly falling within our threshold but that are otherwise unusual.

Where orbital or physical parameters are discussed in the sections below, they will be derived from those reported by the JPL Small Bodies Database unless otherwise specified. The cases of interest are summarized in Table 1.

3.1. Substantial Probability of a Close Approach

3.1.1. 4544 Xanthus

Unique among our results is a close approach between Apophis and asteroid 4544 Xanthus on 2026 December 25. All of the 1000 clones of the JPL and NeoDys solutions meet our threshold of MOID $< 10^4$ km and ΔToF < 12 hr, indicating that an encounter between these two asteroids is certain.

4544 Xanthus has an absolute magnitude of $H = 17.4$ (Minor Planet Center 2023) and a 1.3 km diameter. This is considerably larger than Apophis, about 25 times more massive, assuming a similar density and an albedo of 0.15 (Chapman et al. 1994). Its JPL orbit is based on over 1800 observations over 34 yr, together with a single Doppler radar observation taken from Arecibo soon after its discovery in 1990 (Ostro et al. 1991). As a result, it has an orbit code of 0, indicating that its orbit is very well determined.

In late 2026, Xanthus has a mean MOID with Apophis of 9604 ± 6 km and a mean ΔToF of -4.1121 ± 0.0006 hr (JPL). From the NeoDys data, Xanthus has a mean MOID with Apophis of 9607 ± 6 km and a mean ΔToF of -4.1117 ± 0.0004 hr (Figure 1). Xanthus will pass its mutual MOID with Apophis just over 4 hr after Apophis itself passes that point; see Figure 2 for an animated illustration of the solar system context and encounter circumstances.

The fact that the JPL and NeoDys distributions are not identical in Figure 1 is a result of their independent operations. The JPL and NeoDys orbits are each computed by a group of expert astronomers on the basis of the same data using similar techniques. However, the data invariably contain some measurement uncertainty. Each group compensates for this using their own weightings and corrections, based on their respective extensive collective experience, so the final results may differ. This independence of one group from the other allows extensive cross-checking and verification and increases the robustness of our NEA catalogs.

Because of the close agreement between JPL and NeoDys in Figure 1, with each heavily overlapping within the other's formal errors, we conclude with high confidence that Xanthus has a MOID with Apophis of less than 10,000 km and will arrive at that point just over 4 hr after it in 2026 December. Despite their relatively small MOID, the 4 hr delay means that they are in no danger of collision. In terms of physical distance, Xanthus reaches a minimum distance of about 528,000 km with Apophis on JD 2461400.1 (2026 December 25) as they pass each other at a relative velocity of 11 km s^{-1}.

The encounter of Xanthus with Apophis is one where our results differ more than usual with JPL Horizons, though only

Table 1
Summary of Encounter Circumstances of Known Asteroids with 99942 Apophis during the Time Frame of This Study

Encounter Probability	Name	a (au)	e	i (deg)	$T_{\rm Jup}$	H	Diam. (m)	$v_{\rm rel}$ (km s^{-1})	Orbit Code	Encounter Date
	99942 Apophis	0.923	0.191	3.34	6.464	19.1	340	⋯	0	⋯
High to moderate	4544 Xanthus	1.041	0.250	14.1	5.834	17.4	1300	11	0	25 Dec 2026
	2009 JG2	2.032	0.659	2.73	3.500	22.6	100	10	8	6 Dec 2026
	2016 FB12	1.332	0.264	7.73	4.872	26.0	20	11	8	1 Dec 2023
	2022 KN3	2.069	0.617	3.69	3.505	24.8	40	20	8	1 Feb 2028
Conflicting	2016 CL18	1.366	0.434	0.41	4.733	24.0	50	9	9	20 Dec 2026
Low	2001 FB90	2.455	0.782	1.92	2.976	19.8	380	19	9	8 Sep 2028
	2001 VE76	1.744	0.515	4.17	3.974	23.6	70	16	9	5 Feb 2027
	2004 JP12	1.908	0.778	8.26	3.480	23.4	70	32	9	28 Nov 2024
	2012 TQ231	1.195	0.465	3.36	5.200	27.6	10	20	9	12 May 2024
	2015 FA345	2.363	0.581	4.70	3.295	24.1	50	15	9	10 Sep 2025
	2017 FA159	1.548	0.400	0.53	4.362	28.5	7	8	8	7 Jan 2024
	2020 BO9	2.116	0.619	5.44	3.456	23.5	70	19	8	9 May 2026
	2020 HX2	0.860	0.313	9.55	6.810	21.9	140	8	7	9 Oct 2026
	2020 US7	1.078	0.189	7.28	5.714	25.8	20	6	9	9 Nov 2024
Other	373135	1.652	0.497	4.39	4.124	19.5	1050	9	0	15 Dec 2023
	2014 AD16	1.401	0.368	0.35	4.677	27.4	10	14	4	13 Jul 2027
	25143 Itokawa	1.324	0.280	1.62	4.898	19.3	330	7	0	12 Oct 2025

Note. Orbital and physical data are from the JPL Small-Body Database. The relative velocity $v_{\rm rel}$ is measured at the MOID. "Encounter date" is the date that Apophis is at its MOID with the nominal asteroid orbit. The actual time of any encounter with material on the asteroid orbit will depend on the orbital uncertainty; see text for more details. For diameter estimates, the albedo is assumed to be 0.15 unless it is otherwise available.

slightly. We find differences in the MOID of ≈300 km between our and JPL's propagation of the orbits and a difference in the ΔToF of 1.3 minutes. This is larger than the spread in the MOID and ΔToF seen in Figure 1 , which are only ≈10 km and a few seconds, respectively. Though we differ in detail with the JPL results, we do so only at the few-parts-per-million level in overall position ($300\,{\rm km} \approx 2 \times 10^{-6}$ au), and our MOIDs and ΔToF differ only at the $(300\,{\rm km}/9600\,{\rm km}) \approx 3\%$ and $1.3\,{\rm minutes}/(4.1\,{\rm hr} \times 60\,{\rm minutes}) = 0.5\%$ levels. The difference likely stems from the frequent encounters between Xanthus and Earth: the JPL Small-Body Database records three of them in 2021–2022 and four of them in 2023–2024. These encounters occur at modest distances (typically 0.2 au) and at low relative speed ($10\,{\rm km\,s^{-1}}$) and tax attempts to model Xanthus's motion accurately. Nonetheless, our results are consistent with those of JPL Horizons, and the slight discrepancies arise in this case from an asteroid that is particularly difficult to model.

It is extremely unlikely that the orbital parameters as computed by JPL or NeoDys could harbor uncertainties large enough to permit a collision. Even if one or more of the observations upon which those orbital parameters are based are of poor quality or even outright wrong, the overall computation is tightly constrained by the many other observations and the laws of motion. The one observation that perhaps deserves a second look is the radar Doppler observation (Ostro et al. 1991), which provides a single data point that strongly affects the final orbit determination. Though there is no reason to expect that reviewing the radar data will improve its precision or accuracy, we recommend that this object, along with some more problematic cases we discuss later, have its orbit computations revisited on a purely precautionary basis.

Of more concern than direct collision is the question of whether Apophis could collide with material accompanying Xanthus. This could result in a perturbation of its future path that could affect its impact probability with Earth. There are a number of possibilities:

1. *Satellite asteroids.* There is no evidence to suggest that Xanthus is a multiple asteroid, but it may be. Stable satellites of Xanthus could only reside within its Hill sphere. For a 1.3 km diameter asteroid with a density of $2000\,{\rm kg\,m^3}$ this translates to about 200 km, and in practice most NEA multiples remain at much smaller distances from each other. For example, for the 87 NEAs and Mars-crossing asteroids with satellites listed in Johnston (2019), the median separation was 3.3 km and the largest was 378 km. Given that Apophis and Xanthus will pass each other at a much larger distance (>500,000 km), it is unlikely that Apophis could collide with satellites of Xanthus, if any exist.

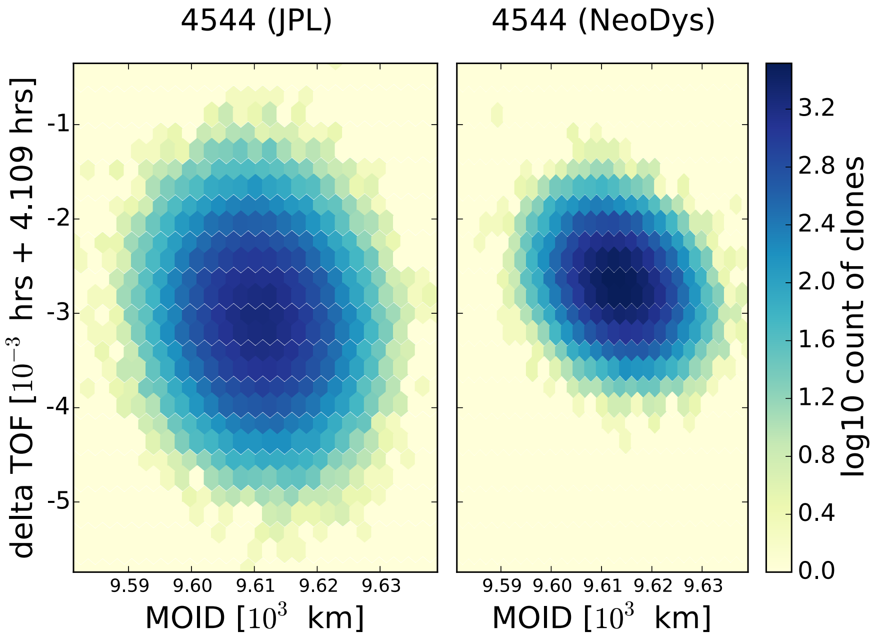

Figure 1. The left panel shows the MOID − ΔToF for asteroid 4544 Xanthus with 99942 Apophis for 10^5 clones. The density indicates the relative probability under the observational uncertainty, as determined by JPL (left) and NeoDys (right).

2. *Cometary activity.* We are not aware of any reports of cometary activity from this asteroid, and its Tisserand parameter with respect to Jupiter is 5.834, more typical of asteroids than comets. It is unlikely that it has produced a traditional cometary meteoroid stream.
3. *Active asteroid.* Xanthus could have low-level undetected mass loss, which would make it an "active asteroid." There are a handful of active asteroids known (Jewitt et al. 2015) that may release material through a wide array of mechanisms. Material traveling with Xanthus will be particularly difficult to detect with telescopes on Earth if it is low in dust production, dust having a large optical cross section for its mass. For example, the OSIRIS-Rex spacecraft revealed that asteroid 101955 Bennu was surrounded by 1–10 cm particles ejected from its surface at speeds of a few meters per second (Hergenrother et al. 2019; Lauretta et al. 2019). These particles are thought to be ejecta due to meteor impacts, but no dust was reported. Particles were seen to persist for several days in some cases, and some were on trajectories that would allow them to escape Bennu's gravity entirely. It is possible that Xanthus is producing material in this way. The material discovered near Bennu was a surprise, and other mechanisms could also produce unexpected material traveling with almost any asteroid.
4. *Gravitational impulse.* To be of concern, any change in Apophis's velocity would have to be able to move Apophis's trajectory substantially relative to the locations of various "keyholes" (Valsecchi et al. 2003; Farnocchia et al. 2013), which could lead to future impacts with our planet. This would require moving Apophis at least tens of kilometers over the course of several years, or an impulse of order 10^{-3} m s^{-1}.

   Assuming a density $\rho = 2000$ kg m^{-3} for Xanthus, the expected Δv to Apophis for the 2026 December encounter is (from Equation (1))

$$\Delta v \approx 10^{-10}\left(\frac{\rho}{2000\ \mathrm{kg\ m^{-3}}}\right)\left(\frac{11\ \mathrm{km\ s^{-1}}}{v_{\mathrm{rel}}}\right) \times \left(\frac{5.3\times 10^5\ \mathrm{km}}{d}\right)\mathrm{m\ s^{-1}} \tag{5}$$

   and is entirely negligible. To provide some context, the largest gravitational impulse that Xanthus could exert on Apophis without a collision—that is, assuming that they passed each other as closely as possible ($d \approx 1$ km)—is $\sim 10^{-4}$ m s^{-1}. So even a very close pass by a kilometer-class asteroid could perturb Apophis's orbit only marginally via purely gravitational effects.

If particles were being ejected from Xanthus by any mechanism, it is possible that Apophis could collide with this debris as the asteroids pass each other. Debris from Xanthus (if any) could pass closer to Apophis than Xanthus itself and could strike it. The impact of dust particles in the submillimeter range is unlikely to have a substantial effect (Wiegert 2015) on Apophis's path, but the impact on Apophis of even a single 10 cm particle such as seen at Bennu at a relative speed of 11 km s^{-1} and a typical asteroid density of 2000 kg m^{-3} (Britt et al. 2002) would release about 20 MJ of kinetic energy, the equivalent of 20 sticks of dynamite. Such an event could have a nonnegligible effect on the impact probability of Apophis with Earth at a later date.

The presence or absence of macroscopic material accompanying Xanthus cannot easily be determined by current telescopes, particularly if the mass-shedding mechanism does not produce much dust, as was the case for particles seen by OSIRIS-Rex at Bennu. Not all asteroids visited by spacecraft have had such particles reported, and even if such material exists, the probability of a collision with Apophis is low. However, we suggest telescopic monitoring of the encounter

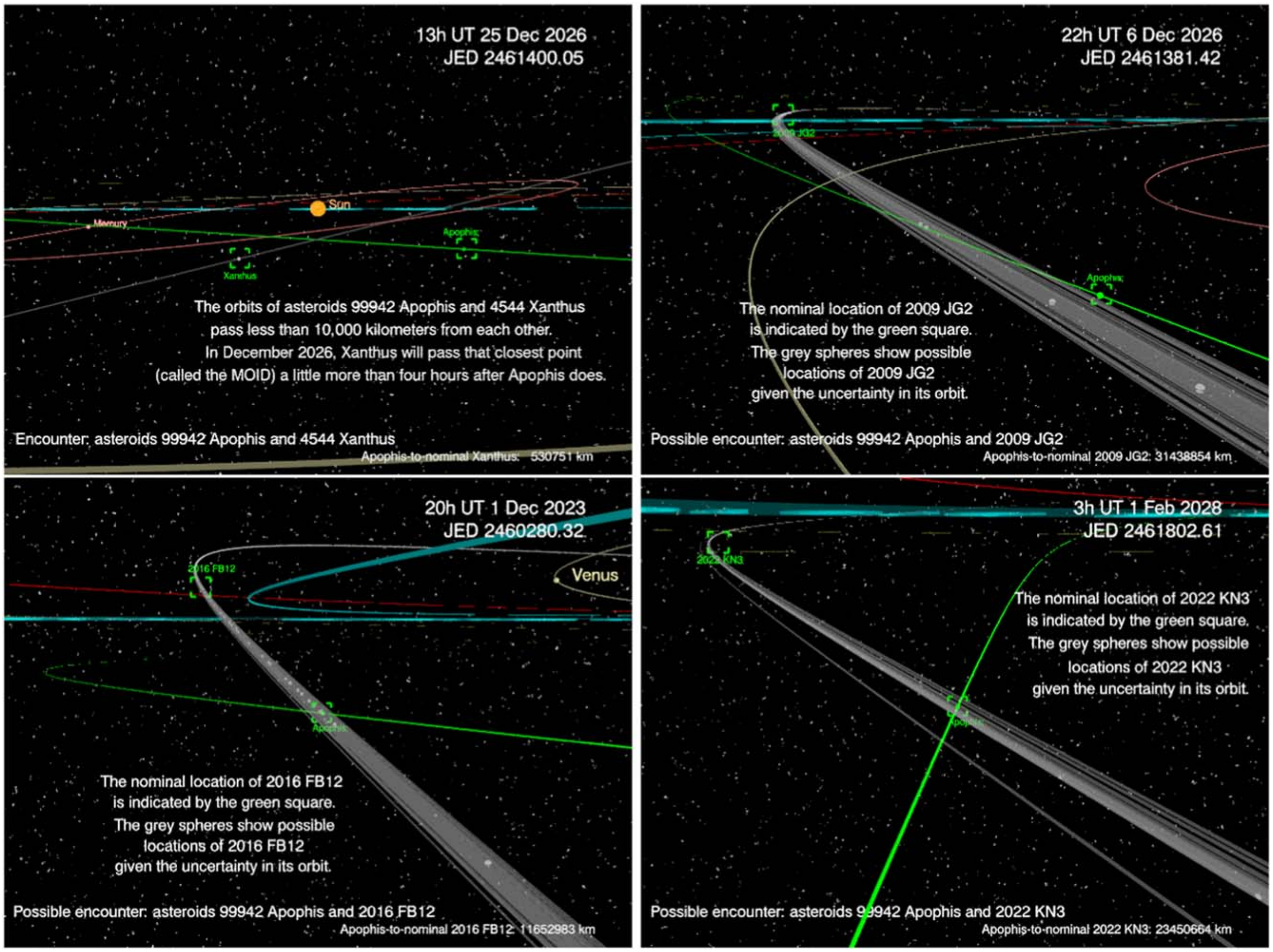

Figure 2. Illustrations of the solar system context and encounter circumstances for 4544 Xanthus, 2009 JG2, 2016 FB12, and 2022 KN3. An animation is available in the HTML version of the paper for each panel. Each first shows a broad view of the solar system and then zooms in to illustrate the encounter geometry. The time and nominal asteroid–Apophis distance are also indicated. Duration of each animation is approximately 30 s.

(An animation of this figure is available.)

between Apophis and Xanthus to assess whether such an impact occurs, for example, by looking for the dust production that could be expected from a hypervelocity impact.

As seen from Earth in late 2026 December, the two asteroids will approach each other closely on the sky (an "appulse"). According to JPL Horizons,[7] the event will be difficult to observe from Earth, as it occurs at a solar elongation of only 47° in the evening sky, in the constellation Capricorn. Apophis will be at $m_v = 20.7$ and Xanthus at $m_v = 19.2$, accessible in principle with professional-caliber telescopes, but interference by scattered sunlight could be an issue for ground-based observers. An animated illustration of the event is in Figure 2.

Out of curiosity, we note that the two asteroids will not reach naked-eye visibility to each other during this close approach, though each would be easily visible from the other through binoculars. Xanthus will reach a peak visual magnitude $m_v = 8.1$ as seen from Apophis, while an observer on Xanthus will see Apophis brighten to $m_v = 9.2$. For reference, Apophis would reach naked-eye visibility ($m_v = 6$) from any particular asteroid (assuming a heliocentric distance of 1 au and zero phase) at a mutual distance of 0.0024 au or 358,800 km. Asteroid 2014 AD16 is the only object in this study for which it can be confidently said that it will approach Apophis this closely, though phase effects keep the apparent magnitude of Apophis as seen by an observer on that asteroid below naked-eye visibility (see Section 3.5).

The encounter between Apophis and Xanthus is unique over the next few years, but there are other cases of modest probability of close encounters between Apophis and other asteroids. We will first discuss the chance of a direct collision in each case (which will turn out to be nil) and then discuss the possibility of collision with material accompanying these asteroids in aggregate at the end.

3.1.2. Asteroid 2009 JG2

Asteroid 2009 JG2 is a 100 m diameter asteroid that was only observed briefly (for 23 days) in 2009 and has an orbit code of 8 (poor). Its MOID − ΔToF plot is presented for the encounter that occurs in late 2026 in Figure 3. The uncertainty in its orbit determination is reflected primarily in its time of arrival at the MOID with Apophis, which is uncertain by several weeks in either direction. Both JPL and NeoDys orbital solutions yield a 2% chance of having an encounter (as defined by Equation (4)) with Apophis.

The distribution of the NeoDys clones in Figure 3 is rather linear (in fact, they trace out an elongated ellipse, reflected

[7] https://ssd.jpl.nasa.gov/horizons/app.html#/

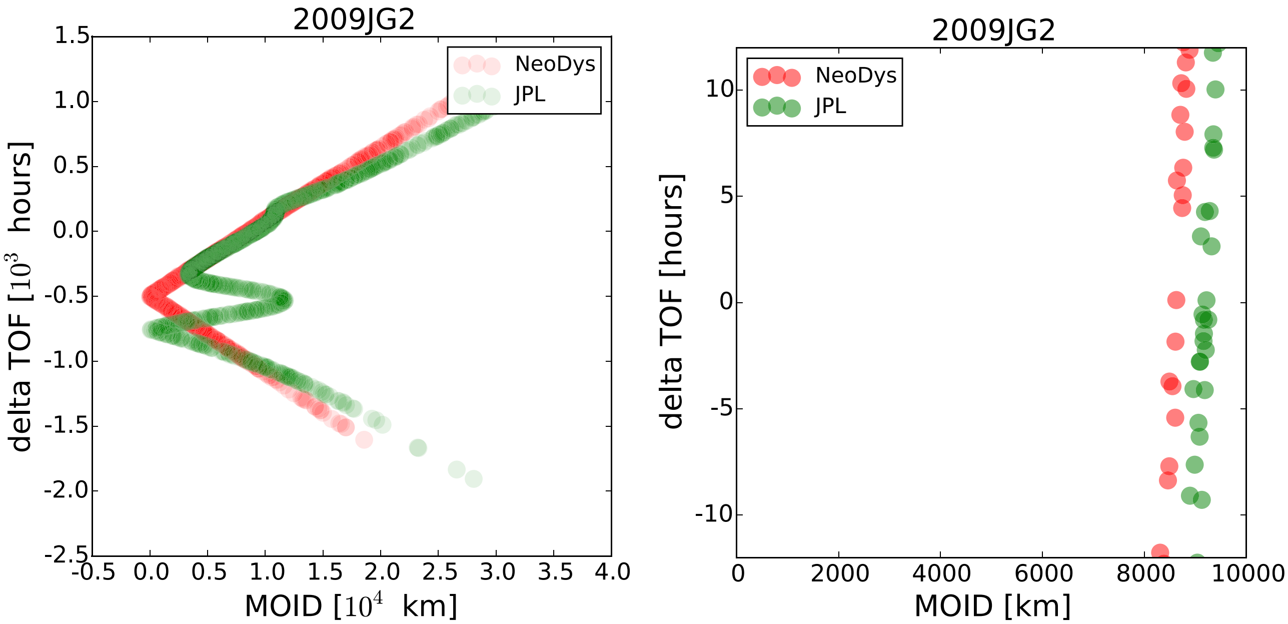

Figure 3. The MOID − ΔToF for the 2026 December approach of asteroid 2009 JG2 to 99942 Apophis (10^3 clones). The right panel is zoomed in on a region near the origin.

across the y-axis at its crossing), while the JPL clones have their basic elliptical shape distorted. The distortion of the JPL clone cloud arises as a result of a moderately close encounter of 2009 JG2 with Venus in early 2021. Despite the differences between the JPL and NeoDys solutions, by examining the region nearest the origin in Figure 3, we can see that both agree that this asteroid will not collide with Apophis. Even if the two asteroids do both happen to be at the MOID at the same time (ΔToF = 0), they will still remain 8000–9000 km apart. It is also possible that Apophis and 2009 JG2 have intersecting orbits (MOID = 0), but in this case, 2009 JG2 will pass that intersection point 20–30 days after Apophis. An illustration of the event is presented in Figure 2.

While the uncertainty in the currently known orbit of 2009 JG2 allows the possibility of a zero MOID or of a zero ΔToF, the case where both MOID and ΔToF are zero is excluded. Both JPL and NeoDys solutions agree that the asteroids will not collide.

To monitor whether Apophis collides with any material on the orbit of 2009 JG2, observations should be taken around the time when Apophis is crossing the orbit of the asteroid, but the time of the possible closest approach is spread over tens of days. Apophis is at its MOID with the nominal orbit of 2009 JG2 on 2026 December 6 at a solar elongation of only 41°, in the constellation Sagittarius. Apophis will be at $m_v = 20.7$; the nominal location of 2009 JG2 will be several degrees away and closer to the Sun.

3.1.3. Asteroid 2016 FB12

Both JPL and NeoDys predict a ≈2% chance that 2016 FB12 will have an encounter with Apophis in early December of 2023. Figure 4 shows the distribution of MOID and ΔToF. The distributions are similar for the JPL and NeoDys solutions, though not identical.

2016 FB12 was only observed briefly (for 4 days) in 2016 and has an orbit code of 8, indicating that its path is rather poorly known, as a direct result of the shortage of observations. Its absolute magnitude of 22.6 means that its diameter is roughly 20 m.

For 2016 FB12, Figure 4 also shows (on the right) the region nearest the origin. We can see that, despite the uncertainty in the precise position of this asteroid, both the JPL and NeoDys solutions indicate that the asteroid will not collide with Apophis, because the MOIDs are well constrained away from zero. Though these solutions do allow that both asteroids could be at the MOID at the same time, both would still be 6000–7000 km apart should this occur. And the orbital solution allows that the MOID could be zero, but in that case 2016 FB12 will arrive at the MOID days before Apophis. The MOID = ΔToF = 0 (collision) case is not consistent with the observations of the asteroid's orbit to date. The chance of a direct collision is nil.

If one wished to observe Apophis at its 2023 December encounter to monitor for possible collisions with accompanying material, the time of close approach is uncertain by tens of days and the circumstances unfavorable. Apophis will be at a solar elongation of only 33° at $m_v = 21.6$ in Virgo. The nominal location of 2016 FB12 is nearby in the same constellation, but its small size means that its apparent magnitude will be fainter than 28. The encounter circumstances are illustrated in Figure 2.

3.1.4. Asteroid 2022 KN3

Asteroid 2022 KN3 was observed for 12 days only and has an orbit code of 8 (poor). Its absolute magnitude of 24.8 indicates an approximate diameter of 40 m. The MOID − ΔToF plot of asteroid 2022 KN3 is shown in Figure 5 for its encounter with Apophis in early 2028.

The distribution shows some distortion, in this case due to close approaches with Earth in 2025 May and in 2028 May (the asteroid has a semimajor axis near the 3:1 mean motion resonance with Earth). But by examining the plot's inner region more closely, both JPL and NeoDys predict that Apophis and 2022 KN32 will pass each other at a distance of 4000 km at most, even if both are at the MOID at the same time. Both JPL

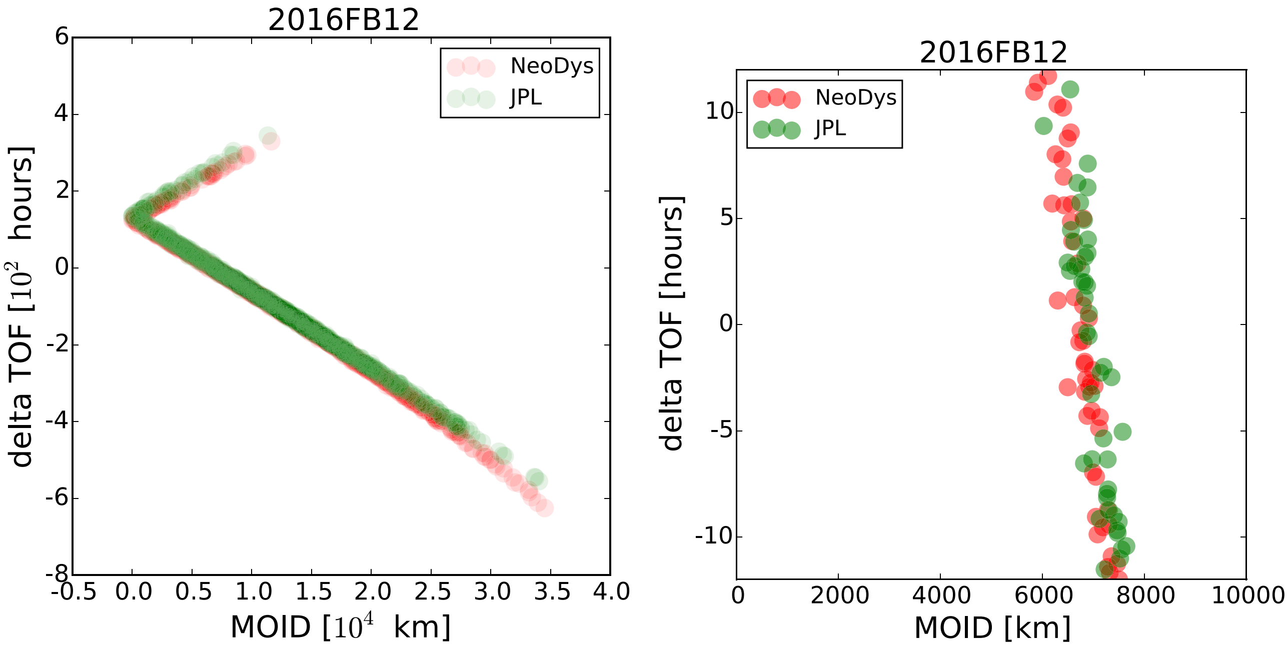

Figure 4. The MOID – ΔToF for the 2023 December approach of asteroid 2016 FB12 to 99942 Apophis (10^3 clones). The right panel is zoomed in on a region near the origin.

and NeoDys agree that there is no chance of a direct collision, and any impacts associated with this encounter would be due to material (if any) following the orbit of 2022 KN3.

If any collision with debris will occur, it is most likely as Apophis passes its MOID with 2022 KN3. Apophis crosses its MOID with the nominal orbits of this asteroid in 2028 at a solar elongation of 89° in the constellation Cetus. These relatively favorable circumstances have Apophis at $m_v = 19.3$, though 2022 KN3 will be very faint at 25.8 and nominally a few degrees away on the sky. An illustration of the encounter circumstances is in Figure 2.

3.1.5. Collision with Material Associated with These Asteroids

The possibility of collision with material accompanying any of the last three asteroids discussed is comparable in many ways to that of Xanthus. However, the last three are all much smaller (20–100 m vs. 1300 m for Xanthus), reducing the likelihood of stable satellites and the amount of debris that might be in their neighborhood. Nevertheless, we would encourage observations of Apophis near their times of close approach to confirm or deny the occurrence of impacts by debris. We suggest that observers monitor Apophis, who's on-sky position is well-known, rather than attempting to recover the asteroids themselves, as their ephemeris uncertainties are much larger. If a collision occurs, the resulting dust will be revealed by the ejection of dust from Apophis, even if the colliding asteroid itself goes unseen.

Even before the times of encounter, additional observations of these asteroids would be useful in further constraining their orbits; however, ephemeris uncertainties make this difficult. Regardless, these objects' orbits could be improved by (1) remeasurement or reanalysis of existing observations and/or (2) the identification of additional precovery observations in image archives.

Though JPL and NeoDys agree that collisions will not occur, we will see in the next section that discrepancies between the JPL and NeoDys predictions can occur for poorly known orbits, and there remains an element of unreported uncertainty that is associated with these cases, which we turn to now.

3.2. Conflicting Case: 2016 CL18

We discuss here the one asteroid we examined whose orbital encounter circumstances with Apophis differ significantly between JPL and NeoDys solutions. Despite both sources confidently predicting noncollision, the divergence between their results undermines our ability to assert this outcome with absolute certainty. This is an object that would benefit from additional observations and analysis.

Asteroid 2016 CL18 is a 50 m Apollo class asteroid that was only observed for 7 days near its time of discovery. Its orbit is very imperfectly known (orbit code 9). Its MOID – ΔToF plot is shown in Figure 6 for late 2026.

This asteroid passes our threshold criterion for an encounter (Equation (4)) for many of the clones in its JPL sample but none in the NeoDys sample. Though it is perhaps not surprising that JPL and NeoDys should differ markedly given the sparseness of the data, the technical point of concern is that both groups put the object with high confidence into regions of space that hardly overlap. In this case, we are forced to assume that the real uncertainty in the asteroid's position is of order the difference between the distributions predicted by these two groups, tens of thousands of kilometers in the MOID and days in ΔToF.

The solution to this problem is additional observations of these objects, as we find that the JPL and NeoDys solutions almost always agree when there is good data coverage. Additional data could come from new telescopic recovery observations and archival precovery observations. Extending the observational arc of these objects will allow a more refined and confident statement to be made about the chances of collision, and observations of Apophis near the time of orbit crossing with 2016 CL18 can also determine whether or not a collision has occurred. The observing circumstances for the 2016 CL18 encounter with Apophis are similar to those of

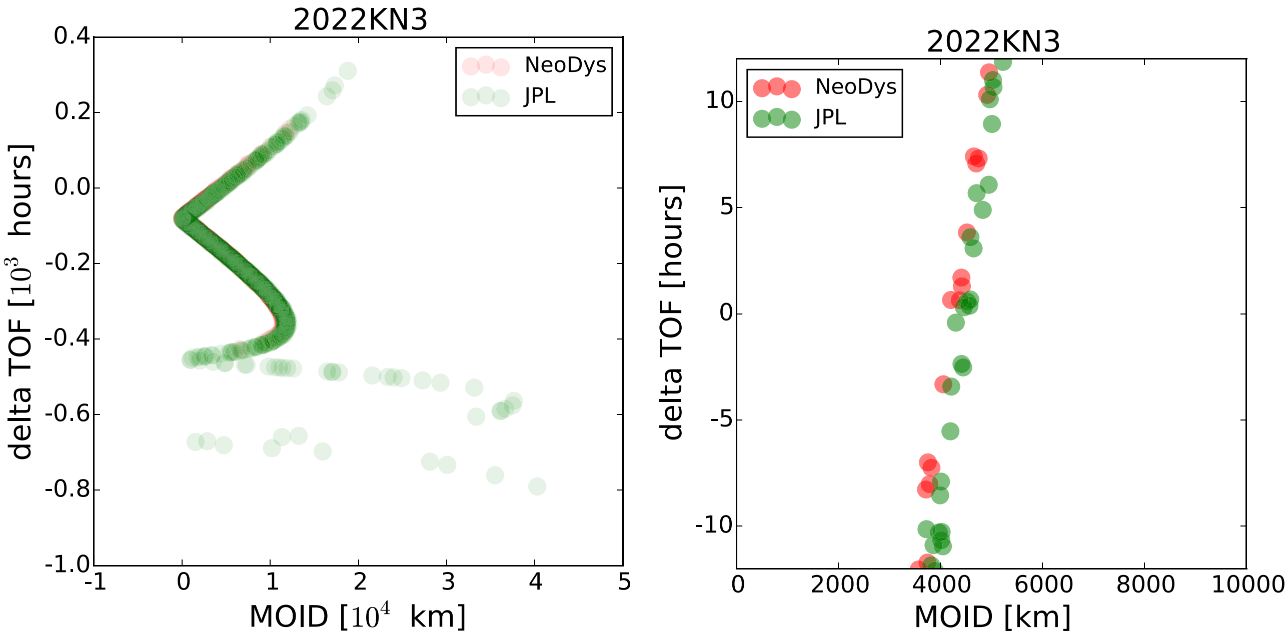

Figure 5. The MOID − ΔToF for the 2028 February approach of asteroid 2022 KN3 to 99942 Apophis (10^3 clones). The right panel is zoomed in on a region near the origin.

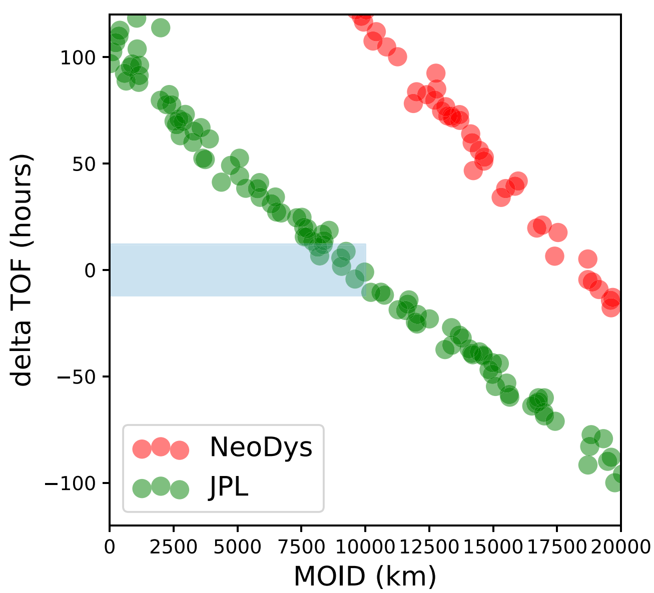

Figure 6. The MOID − ΔToF plot for the 2026 December approach of asteroid 2016 CL18 to 99942 Apophis (10^3 clones). The threshold region of Equation (4) is shown in light blue. The JPL and NeoDys solutions put the asteroid into nonoverlapping regions of space approximately 10,000 km apart.

Xanthus described earlier, both encounters taking place in late 2026 December.

3.3. Low Probability of an Encounter

The "low probability" objects in Table 1 are those for which only one or two clones in either of the asteroid catalogs matched the criteria of Equation (4). These universally have poorly known orbits, and so the chance of collision is hard to assess. We list them here because improvements in their orbit determinations, from recovery or precovery observations or other means, would be useful and would allow us to assess the probability of a collision better. We will only discuss one in detail.

3.3.1. 2001 FB90

Asteroid 2001 FB90 was observed for only 11 days (orbit code 9), making it difficult to localize in its orbit. We mention it here because of its large size ($H = 19.8$ or 380 m), the third-largest object in Table 1, and because it is the only object in that table with a Tisserand parameter with respect to Jupiter ($T_J = 2.976$) in the cometary regime. Both of these increase the probability of material following along with 2001 FB90 and posing a risk of collision with Apophis. The approach takes place in 2028 September and will be unobservable, as Apophis will be less than 10° from the Sun on the sky. If an impact occurs, the effects (e.g., dust production) may be visible when Apophis moves farther away from the Sun in late 2028.

3.4. Other Cases of Note

We include in our discussion a few cases that are not strictly within our chosen threshold for an encounter but are otherwise of interest.

3.4.1. 373135

Asteroid 373135 (orbit code 0) has a MOID of 73,700 ± 13 km and a ΔToF of 4.11793 ± 0.00005 days (Figure 7) during its well-localized encounter with Apophis in late 2023. It is mentioned because of its relatively large size of 1050 ± 400 m (Nugent et al. 2016), which may increase the likelihood of material in its vicinity. The diameter measurement is from NEOWISE and indicated a low (0.025) albedo. If the low albedo is taken as a sign of a possible carbonaceous composition, 373135 may resemble 101599 Bennu, which is known to have 1–10 cm particles in its vicinity (Hergenrother et al. 2019; Lauretta et al. 2019). Apophis passes its MOID with 373135 while within 30° of the Sun and will not reemerge to easy visibility for some months later.

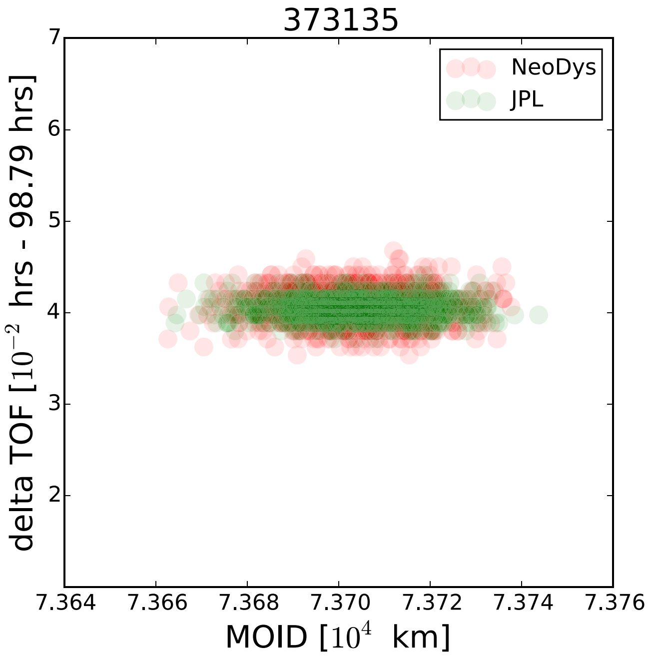

Figure 7. The MOID – ΔToF for the 2023 December approach of asteroid 373135–99942 Apophis (10^3 clones).

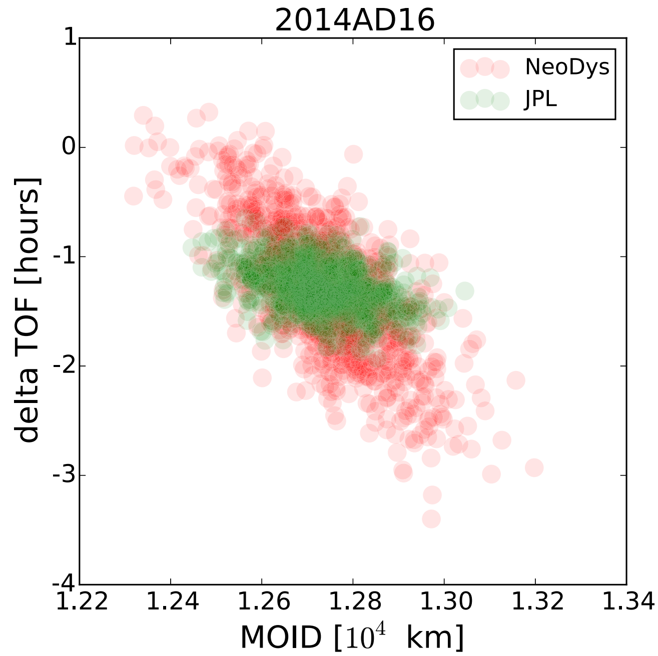

Figure 8. The MOID – ΔToF for the 2017 July approach of asteroid 2014 AD16 to 99942 Apophis (10^3 clones).

3.5. 2014 AD16

Asteroid 2014 AD16 was observed only briefly (3-day arc). However, it was observed by radar, and its orbit is consequently quite well-known (orbit code 4). It is included here because, during its 2027 encounter with Apophis, though its MOID (12,700 km) is just outside our threshold, its |ΔToF| at just over 1 hr is among the shortest computed in this work (Figure 8). The asteroids will approach to within 133,000 km of each other in 2027 July. To an observer on 2014 AD16, Apophis will reach a visual magnitude of 6.9 at a phase of 75 deg during this approach; 2014 AD16 will have $m_v = 14$ when viewed from Apophis at this time.

Though the formal chance of a collision with Apophis is zero, 2014 AD16's orbit determination is highly dependent on a small number of radar observations and might benefit from a reanalysis. 2014 AD16 is a small object ($H = 27.4$, 10 m class) and so is unlikely to have substantial amounts of material around it. Apophis will be at its MOID with 2014 AD16 under difficult observing circumstances from Earth, while 49° from the Sun in Leo at $m_v = 21.3$.

3.5.1. 25143 Itokawa

Asteroid 25143 Itokawa (orbit code 0) has a MOID with Apophis of 77,000 km and passes that MOID 35 days before Apophis in 2025 (Figure 9). This event does not meet our usual threshold, and there is no chance of direct collision, but it is mentioned because Itokawa is known to have accompanying material, in the form of the MINERVA lander released by JAXA's Hayabusa mission and which is expected to have escaped Itokawa's gravity well. MINERVA is only 10 cm in size and 591 g (Yoshimitsu et al 2006).

Though the chance of MINERVA impacting Apophis is very low, such an event, given the relative speed of 6.8 km s^{-1}, would release approximately 14 MJ of kinetic energy, equivalent to 3 kg of TNT. For reference, the 370 kg Deep Impact probe's 2005 collision with comet 9P/Tempel at a relative speed of 10.2 km s^{-1} released 19 GJ of energy (Taylor & Hansen 2005); the Double Asteroid Redirection Test (DART) 580 kg impactor released 11 GJ of energy in its 2022 collision at a relative speed of 6.1 km s^{-1} (Daly et al. 2023). The 2025 approach of Itokawa to Apophis will occur while Apophis is 9° from the Sun, and Apophis will not reemerge into the night sky until some months later, making monitoring of this event quite difficult.

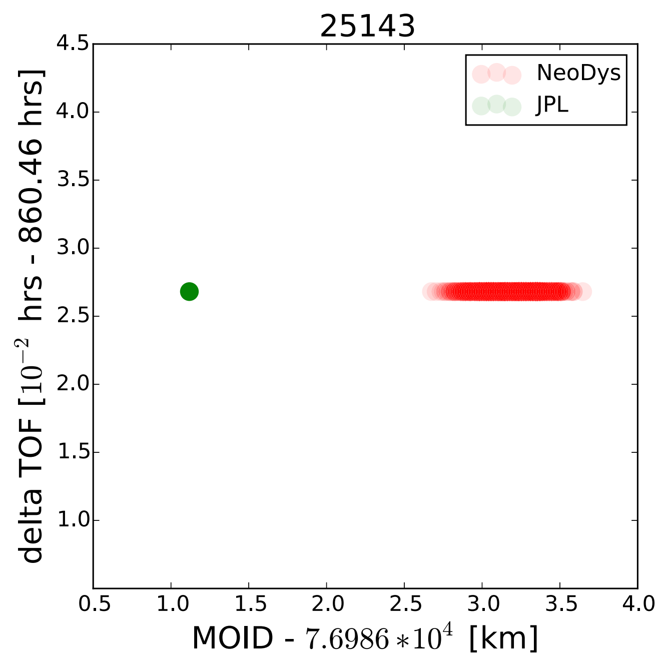

Figure 9. The MOID – ΔToF for the 2025 October approach of asteroid 25143 Itokawa to 99942 Apophis (10^3 clones).

3.5.2. Comets

Seven comets appear in the subsample we analyzed in Section 2.2: C/1882 F1 (Wells), C/1917 F1 (Mellish), C/1917 H1 (Schaumasse), C/1961 T1 (Seki), C/1990 N1 (Tsuchiya-Kiuchi), C/2015 P3 (SWAN), and C/2021 P4 (ATLAS). Each is currently far from the inner solar system, and they pose no danger of a direct collision with Apophis. However, these comets are the most likely objects in our sample to have substantial material moving along their orbits. Because these comets have large orbits, the density of material along their orbits is on average low. The two with the smallest orbits (Mellish: $a \approx 27$ au; Seki: $a \approx 87$ au) are Halley-type comets. Comet Mellish has been associated with the weak December Monocerotids meteor shower, among others (Drummond 1981; Neslušan et al. 2016), so there is known to be some material along its orbit. This work has not examined the possibility of Apophis encountering material in the meteoroid stream of these comets in detail; this possibility remains to be looked at in future work.

4. Conclusions

We have detailed the encounter circumstances of asteroid 99942 Apophis with other asteroids and comets in the catalogs of known solar system objects, taking full account of the observational uncertainties on the orbit determinations. No cases likely to result in direct collisions of known small bodies with Apophis were found. Instances where there is some risk of impact on Apophis by material accompanying known small bodies were identified. These objects could benefit from additional study to confirm or deny the presence of material along their orbits. Times of close approach of asteroids with Apophis are listed and the observing circumstances detailed to assist with observational monitoring of those times at which an impact with debris might occur, to maintain situational awareness.

We also identified a number of known asteroids whose encounter circumstances could be better assessed if more recovery or precovery observations were available, as the quality of an orbit determination is directly related to the time span of observations available. We stress, however, that the shortage of observations of these objects does not indicate any lack of effort on the part of the global astronomical community to track these objects: astronomers both professional and amateur alike often go to great lengths to observe minor bodies under very difficult conditions. But small bodies can often only be telescopically observed for a brief period after discovery, because they move away from us and become too faint; because they move into the daytime sky, where the glare of the Sun prevents them from being observed; or as a result of poor weather at observing sites.

The likelihood of a known small solar system body (or any material released therefrom) colliding with Apophis is extremely low. The most likely outcome of careful monitoring of the encounters between Apophis and the asteroids and comets discussed in this work is that no impact will be observed. The small probability of collision is, however, counterbalanced by disproportionately large consequences. Because of the hazard associated with even a small perturbation to this Earth-threatening asteroid, there is ample motivation to determine the risk as precisely as possible, and we encourage future efforts in that direction.

Acknowledgments

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