Near-Earth Objects in Earth-Like Orbits

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A useful situational awareness exercise is to occasionally survey all known near-Earth objects (NEOs) in orbits similar to Earth's as catalogued by the Jet Propulsion Laboratory's (JPL's) Small Bodies Database (SBDB). Orbits with osculating semi-major axis *a* near 1 AU, osculating eccentricity *e* near zero, and osculating ecliptic inclination *i* also near zero tend to be the most accessible for human space flight (HSF) over time intervals of years to decades. Such accessibility is at a premium if a small NEO (or part of a larger one) is to be successfully retrieved into the Earth-Moon system by a future robotic asteroid redirection mission. Highly accessible NEO orbits also tend to pose the greatest threat of Earth impact, particularly if the NEO is sufficiently large or monolithic.

Results from the present survey of Earthlike NEO orbits are plotted in Figure 1 as points in (*a*, *e*) coordinates, generally for *i* < 5°. Many of these points are annotated with NEO HSF Accessible Targets Study (NHATS, pronounced "gnats") rankings. The metric for these rankings is *n*, a tally of NHATS-compliant missions with launch dates in years 2015 through 2040. The NEO ranked #1 in Figure 1 is 2000 SG_{344} at (*a*, *e*) coordinates (0.978 AU, 0.067) with *n* = 3,302,718. Criteria for NHATS-compliant missions are as follows.

1) Total change-in-velocity $\Delta v_{TOT} \leq 12$ km/s. In NHATS software, Δv_{TOT} is

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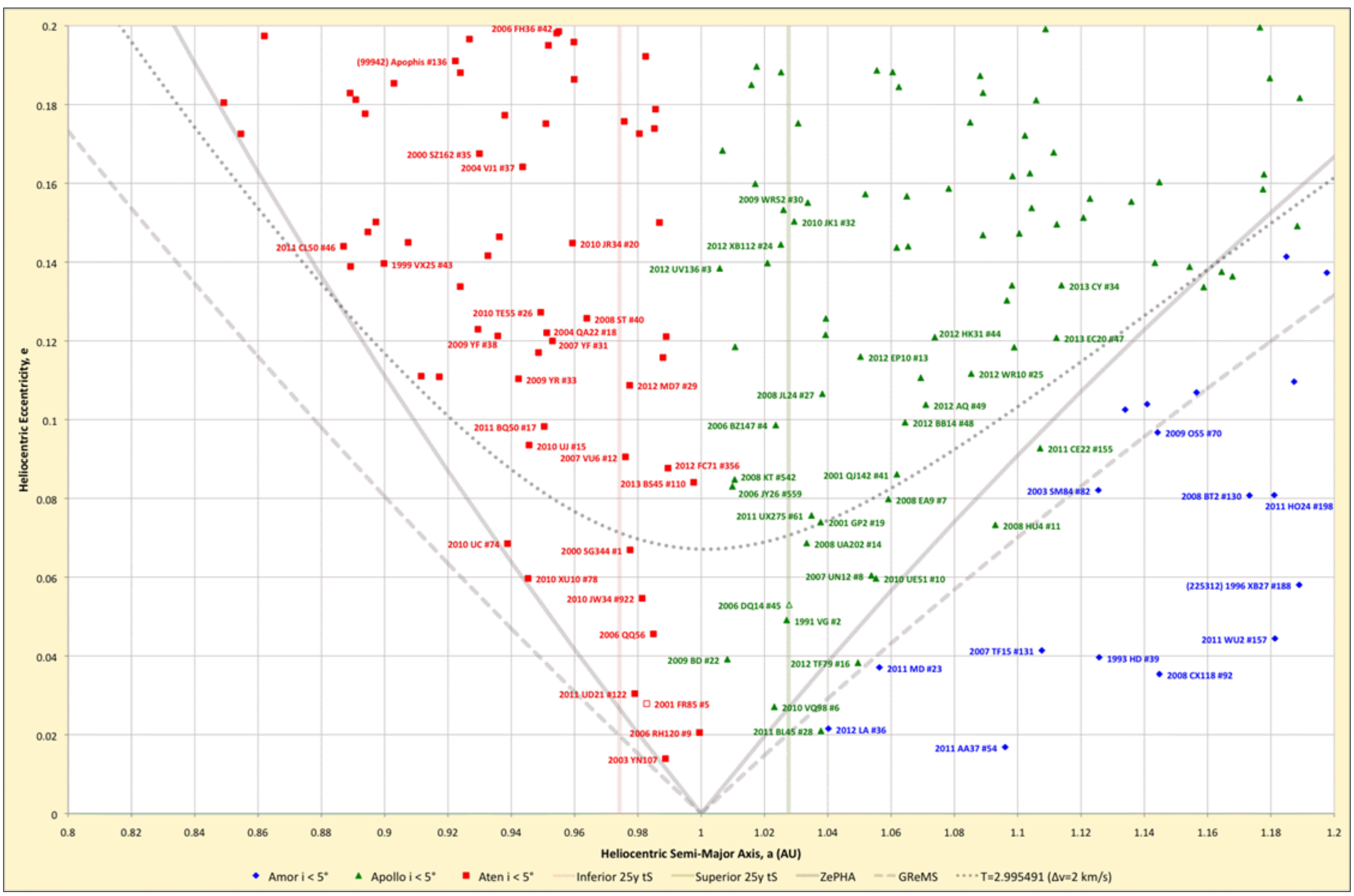

Figure 1. All NEOs catalogued in the SBDB with 0.8 AU < *a* < 1.2 AU, *e* < 0.2, and *i* < 5° are plotted according to their (*a*, *e*) coordinates. Those NEOs ranking in the top 50 according to the NHATS metric *n* are annotated with their SBDB designation, followed by their #*m* rank. Exceptions to these plotting and annotation rules are noted in the foregoing narrative along with the significance of loci plotted in gray. Supporting SBDB and NHATS data are time-sensitive and reflect downloads on 11 March 2013 UT.

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computed as the sum of impulses required to depart a circular Earth orbit at 400 km height targeting NEO intercept, achieve NEO rendezvous, perform NEO departure targeting Earth return, and ensure Earth's atmosphere is entered at a speed of 12.0 km/s if this value would otherwise be exceeded.

2) Roundtrip mission duration ≤ 450 d.

3) Post-rendezvous NEO loiter time ≥ 8 d.

Additional NHATS viability criteria optionally exclude any NEO whose absolute magnitude is too faint or whose orbit prediction uncertainty is too great. These optional criteria are not applied in computing NHATS rankings to annotate Figure 1.

Osculating orbit elements in the SBDB are dynamic on occasion due to NEO planetary encounters. These elements also change to reflect updates from new observations. Rankings under the NHATS *n* metric can change as these new observations are incorporated into the SBDB and as additional NEOs are discovered. Data and annotations in Figure 1 reflect downloads from the SBDB browser at this link and from the interactive NHATS table at this link performed on 11 March 2013 UT.

Each (*a*, *e*) marker plotted in Figure 1 has an appearance indicating the corresponding NEO's membership in one of four possible orbit groups. Blue diamond markers correspond to the Amor group, whose members have orbits completely exterior to Earth's. Green triangles indicate members of the Apollo group, whose orbits cross Earth's (in the sense perihelion is less than Earth's aphelion) and have periods exceeding Earth's. Red squares correspond to members of the Aten group, whose orbits cross Earth's (in the sense aphelion is greater than Earth's perihelion) and have periods less than Earth's. Atira group members have orbits completely interior to Earth's. No cataloged Atira has (*a*, *e*) coordinates within Figure 1 limits.

As noted in the Figure 1 legend, multiple loci are co-plotted with NEO (*a*, *e*) points. Two vertical "25y tS" lines are plotted, one "inferior" (interior) to Earth's orbit at *a* = 0.974 AU, and one "superior" (exterior) to Earth's orbit at *a* = 1.028 AU. Together, these lines denote a rectangular region in Figure 1 within which a plotted NEO (*a*, *e*) point is associated with a synodic period exceeding 25 years. Thus, it is possible for a NEO in this region to be on the other side of the solar system from Earth during years 2015 through 2040 and not tally a single NHATS-compliant mission. Notable examples of this outcome are 2003 YN_{107}, at the most Earthlike (*a*, *e*) = (0.989 AU, 0.014) catalogued, and 2006 QQ_{56} at (*a*, *e*) = (0.985 AU, 0.046). These are the only NEO annotations in Figure 1 not accompanied by #*m* suffixes indicating their NHATS *n* rankings.

The "ZePHA" locus referenced in Figure 1's legend is a mnemonic for <u>Ze</u>ro <u>P</u>erigee <u>H</u>eliocentric <u>A</u>psis. The shape of this locus gives Figure 1 its informal "V-plot" moniker, and it contains (*a*, *e*) points capable of very close Earth encounters near perihelion (for NEO members of the Apollo orbit group) or near aphelion (for NEO members of the Aten orbit group). Such close approaches possess low heliocentric radial velocity enhancing NHATS-compliant mission opportunities and *n*. The ZePHA locus also sets a minimum *e* limit on any orbit capable of crossing Earth's (in the sense perihelion is less than 1 AU and aphelion is greater than 1 AU) at an arbitrary *a*. Thus, trajectories between Earth and a NEO can be made short in distance and time only when that NEO is positioned near or above the ZePHA locus in a V-plot.

At a given *e* coordinate, note Figure 1 plots no NEO inferior to the inferior ZePHA branch (locus points with *a* < 1 AU). This dearth of NEOs at the left of Figure 1 is almost certainly a consequence of always observing these relatively small and faint objects from locations close to Earth's surface, where members of the Aten and Atira orbit groups never stray far from the Sun's glare.

A second V-shaped locus appearing in Figure 1 is dubbed "GReMS", a mnemonic for <u>G</u>eocentric <u>Re</u>lative <u>M</u>otion <u>S</u>tall conditions. Any (*a*, *e*) point on this locus corresponds to an orbit whose speed with respect to Earth would fall to nearly zero around perihelion (for NEO members of the Apollo orbit group) or around aphelion (for NEO members of the

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Aten orbit group). If a GReMS condition were to develop at a location near the Sun-Earth line, favorable mission opportunities and enhanced *n* could be expected for the associated NEO in that timeframe.

Although the ZePHA locus sets a minimum *e* limit on accessible orbits closely approaching Earth, it fails to constrain geocentric speed at approach. But achieving a NEO rendezvous within spacecraft performance limits is critically dependent on sufficiently constrained geocentric position *and* velocity. Selecting an appropriate value of Tisserand's parameter *T* to map onto the V-plot while assuming $i = 0$ imposes a maximum *e* accessibility constraint with a U-shaped locus. Furthermore, the value of *T* to be plotted can be selected based on a maximum acceptable geocentric speed at Earth intercept Δv equivalent to asymptotic Earth departure or arrival speed v_∞ (also equivalent to the square root of asymptotic energy). In Figure 1, the $T = 2.995491$ value plotted is equivalent to $\Delta v = 2$ km/s, as noted in the legend. On a V-plot, the ZePHA and *T* loci together bound a roughly triangular region of high accessibility. Orbits whose (*a*, *e*) coordinates lie within this region offer close Earth approaches with acceptably low speeds for NEO missions at times whose programmatic desirability can be further assessed.

Within Figure 1 (*a*, *e*) limits, the general intent is to annotate every NEO whose *n* ranking is #50 or less. Notes and exceptions relating to this intent are as follows.

1) Two members of the Aten orbit group meet the *n* ranking ≤ #50 criterion, but their *e* coordinates exceed the V-plot maximum of 0.2 and therefore do not appear in Figure 1. These exceptions are 2009 HE_{60} at (*a*, *e*) = (0.996 AU, 0.266) with *n* ranking #21 and 2011 CF_{66} at (*a*, *e*) = (0.997 AU, 0.270) with *n* ranking #50.

2) Two NEOs meet the *n* ranking ≤ #50 criterion and fall within Figure 1 axis limits, but they exceed the $i < 5°$ V-plot criterion by a small amount. These exceptions are 2001 FR_{85} at (*a*, *e*, *i*) = (0.983 AU, 0.028, 5.245°) with *n* ranking #5 and 2006 DQ_{14} at (*a*, *e*, *i*) = (1.028 AU, 0.053, 6.296°) with *n* ranking #45. Both of these NEOs are plotted in Figure 1 with unfilled markers.

3) Every NEO with $e < 0.1$ is annotated, even if its *n* ranking exceeds 50.

4) Due to perennial interest in its Earth collision possibilities, (99942) Apophis is annotated at (*a*, *e*) = (0.922 AU, 0.191) with *n* ranking #136.

On inspection, Figure 1's V-plot conveys a good deal of situational awareness regarding NEOs in Earthlike orbits and their relative accessibility under NHATS criteria. First, it appears orbits completely interior to Earth's (those of NEOs in the Atira group) within Figure 1 plotting limits cannot be found. This is likely due to these orbits' apparent proximity to the Sun when observed from Earth or its vicinity. Second, NEOs in more Earthlike orbits are generally more accessible under NHATS criteria, but there are exceptions. Most notably, a NEO whose synodic period exceeds 25 years may fail to achieve any degree of NHATS compliancy because it is too distant from Earth during years 2015 through 2040. Thus, the most Earthlike NEO orbit known, that of 2003 YN_{107}, has zero NHATS compliancy. Third, the ZePHA and *T* loci on a V-plot enclose a region of high accessibility defining NEO destination orbits for missions requiring acceptably low propulsion and duration. The "upper" boundary of this region can be selected based on the maximum acceptable speed at which a mission's NEO destination may approach Earth's vicinity.

At heliocentric (*a*, *e*) coordinates (0.998 AU, 0.084) on the V-plot of the first page of this article is the newly discovered NEO 2013 BS_{45}. The following article describes its unusual orbit.