Near-Earth Asteroids: Destinations for Human Exploration

Presented to the AIAA Mid-Atlantic Section Awards Dinner

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NASA/GSFC

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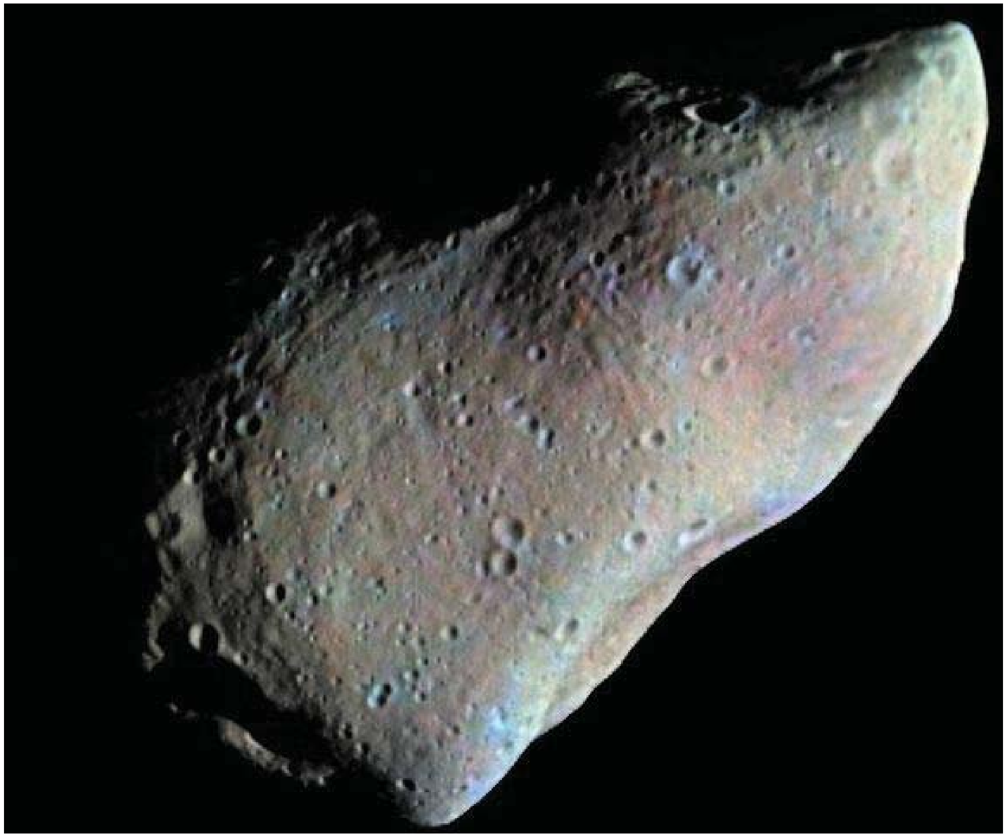
What are near-Earth objects?

- Near-Earth objects (NEOs) consist of asteroids and comets whose orbits are in close proximity to Earth's orbit
  - Perihelia < 1.3 AU
  - Usually rocky, sometimes metallic, small celestial bodies
  - Several meters to several kilometers in size
  - Near-Earth asteroids (NEAs) are numerous; near-Earth comets (NECs) are relatively rare
    - Comets are characterized by long orbit periods, highly eccentric orbits, and active jets of volatiles that create the familiar "tail" when close enough to the Sun
- NEOs are distinct from Main Belt Asteroids (MBAs) that inhabit the famous "asteroid belt" between the orbits of Mars and Jupiter

Asteroids and Comets

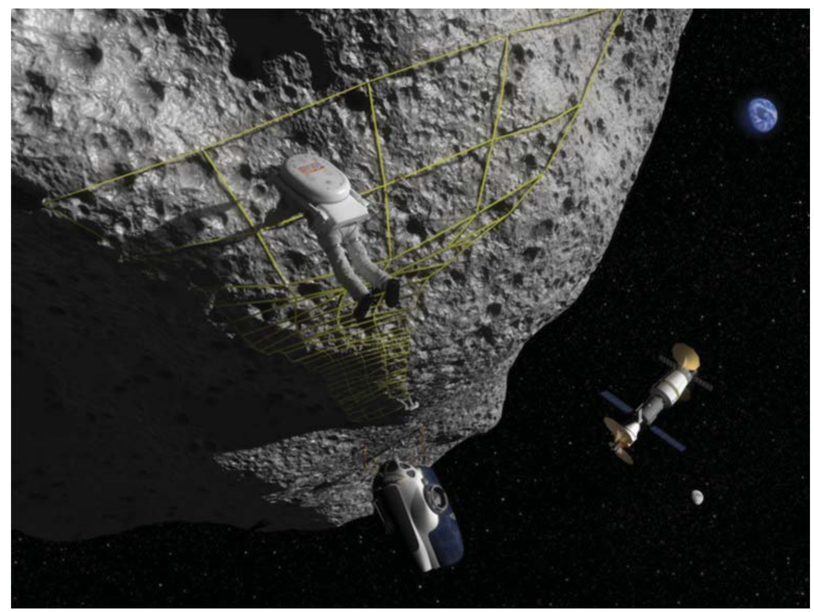


Asteroid 951 Gaspra imaged by Galileo in 1991

Comet Giacobini-Zinner

Motivations for NEA Exploration

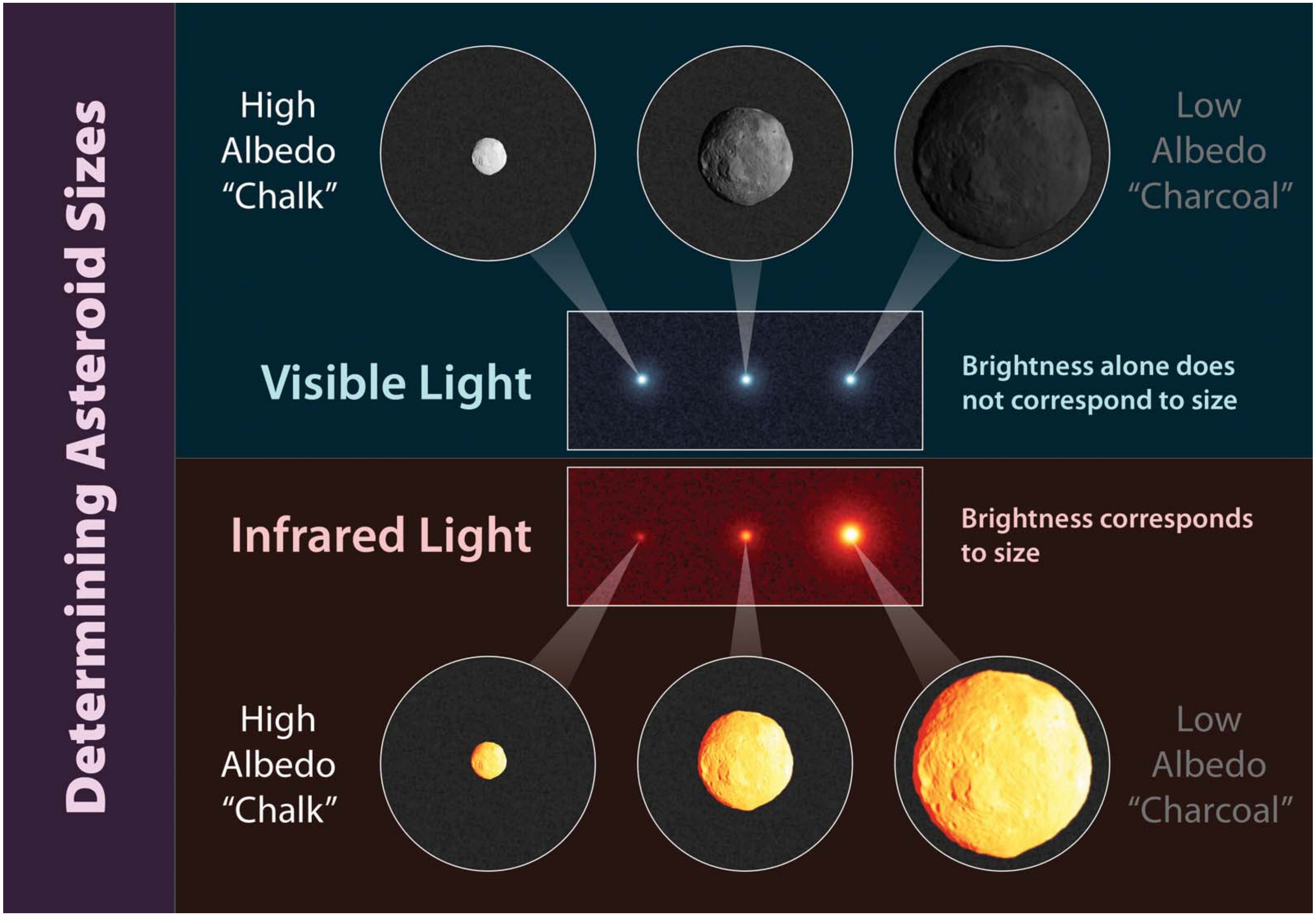
- **Solar System Science**
  - NEAs are largely unchanged in composition since the early days of the solar system
  - Asteroids and comets may have delivered water and even the seeds of life to the young Earth
- **Planetary Defense**
  - NEA characterization
  - NEA proximity operations
- ***In Situ* Resource Utilization**
  - Could manufacture radiation shielding, propellant, and more
  - Construction of rotating space stations
- **Human Exploration**
  - The most ambitious journey of human discovery since Apollo
  - Learn to operate successfully in deep space



NEA Classification

- NEAs are classified according to:
  - **Orbit**
    - Earth-crossing, Earth-approaching
    - Exterior or interior to Earth's orbit
  - **Composition**
    - The (surface) composition of some NEAs has been inferred from the spectra of the sunlight they reflect
    - Most asteroids (75%) are thought to be carbonaceous
    - Some asteroids (17%) are thought to be stony (silicates)
    - Relatively few asteroids (8%) are thought to be metallic (nickel-iron)
  - **Potential to pose a hazard to Earth**
    - To be classified as a Potentially Hazardous Asteroid (PHA), a NEA must have a Minimum Orbit Intersection Distance (MOID) with Earth's orbit $\leq$ 0.05 AU (20 LD, 7.5M km) **and** an estimated diameter $\geq$ 150 m
    - Without radar observations or *in situ* measurements made by spacecraft, a NEA's diameter can only be estimated by combining its absolute magnitude (a measure of brightness) with an *assumed* albedo (indicative of surface reflectivity)

Visible vs. Infrared NEA Observations

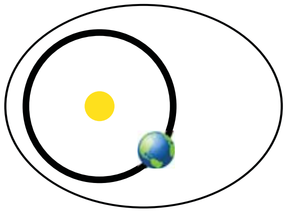


http://wise.ssl.berkeley.edu/gallery_asteroid_sizes.html

NEA Groups According to Orbit Type

Amors

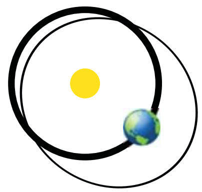
Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars' (named after asteroid (1221) Amor)



$$a > 1.0 \text{ AU}$$
$$1.017 \text{ AU} < q < 1.3 \text{ AU}$$

Apollos

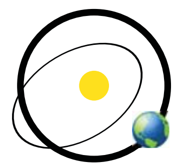
Earth-crossing NEAs with semi-major axes larger than Earth's (named after asteroid (1862) Apollo)



$$a > 1.0 \text{ AU}$$
$$q < 1.017 \text{ AU}$$

Atens

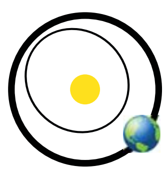
Earth-crossing NEAs with semi-major axes smaller than Earth's (named after asteroid (2062) Aten)



$$a < 1.0 \text{ AU}$$
$$Q > 0.983 \text{ AU}$$

Atiras

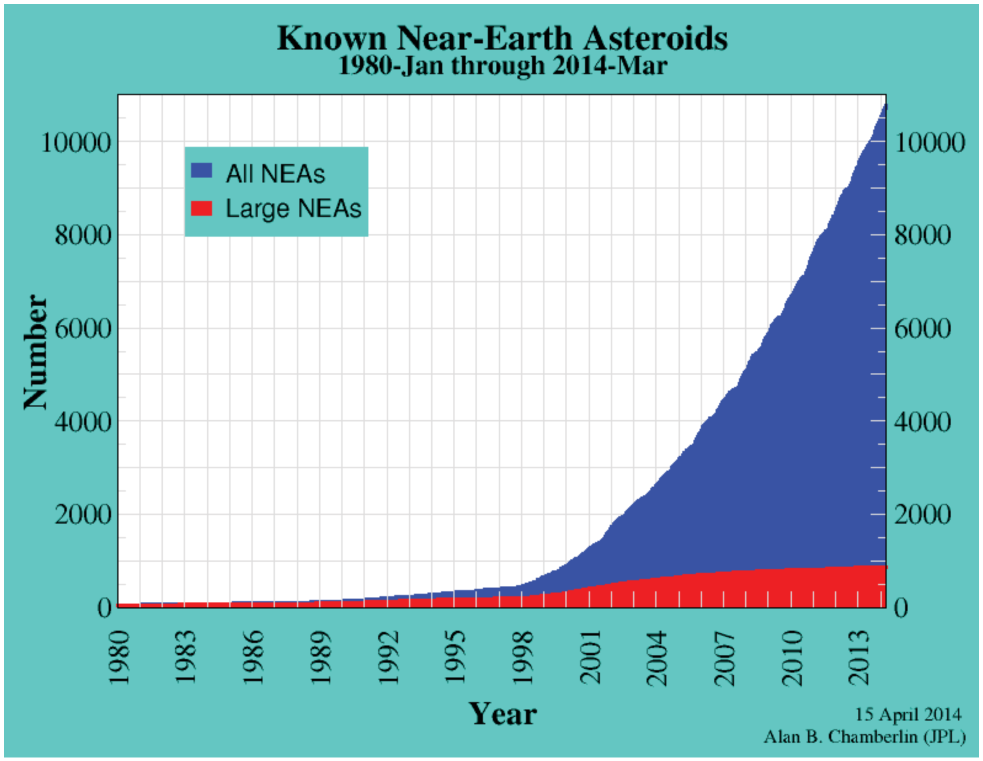
NEAs whose orbits are contained entirely within the orbit of the Earth (named after asteroid (163693) Atira)

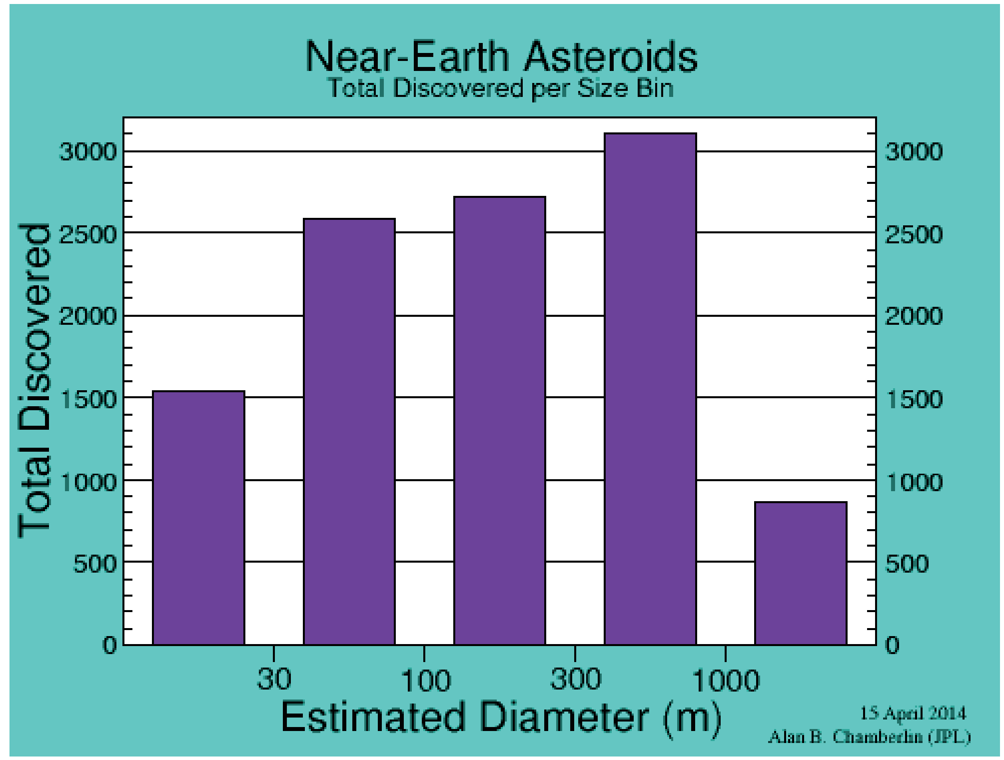


$$a < 1.0 \text{ AU}$$
$$Q < 0.983 \text{ AU}$$

(q = perihelion distance, Q = aphelion distance, a = semi-major axis)

NEO Discovery Statistics





http://neo.jpl.nasa.gov/stats/

http://neo.jpl.nasa.gov/stats/

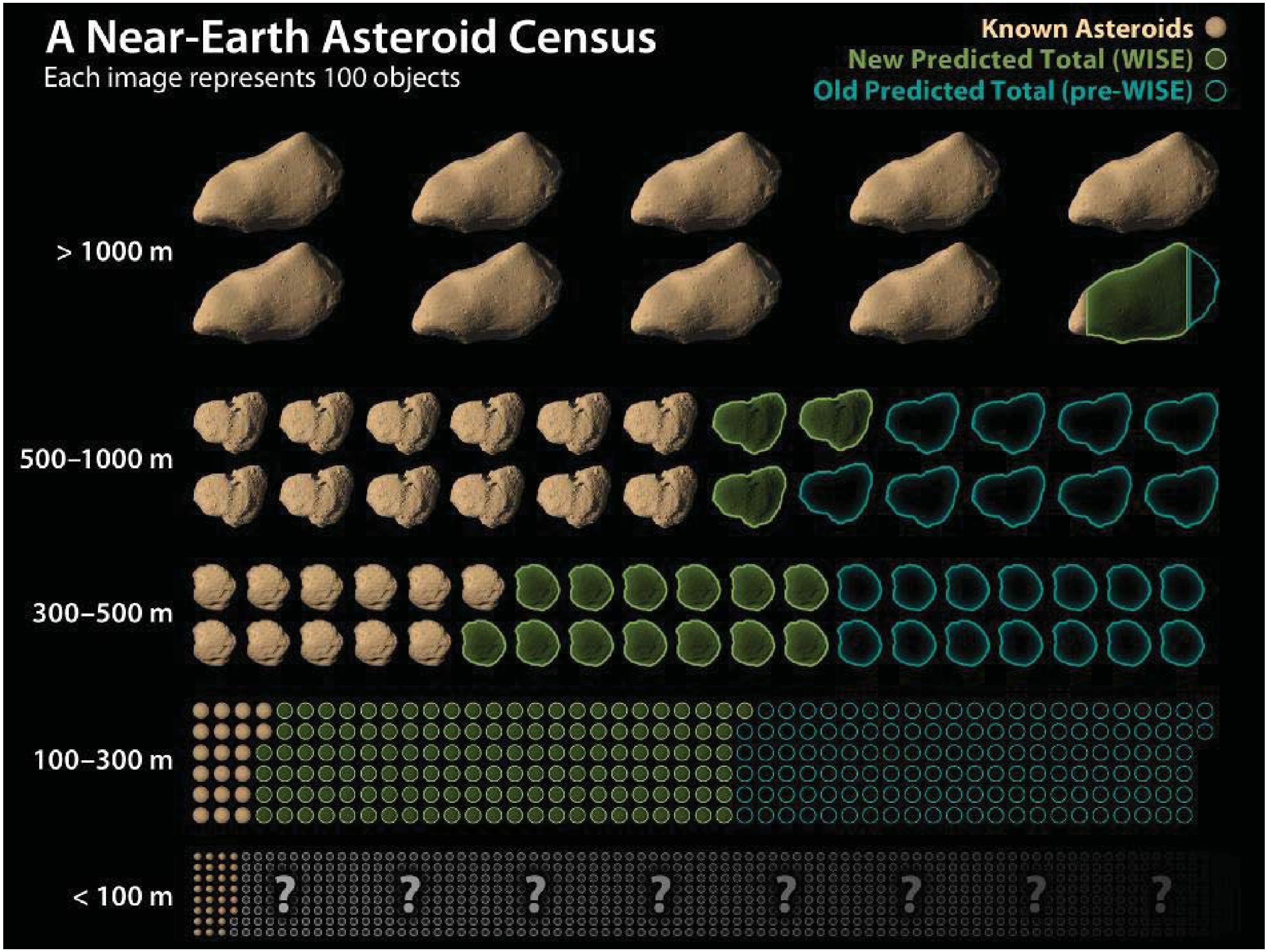
Totals as of 2014-05-27:

Atiras	14
Atens	843
Apollo	5973
Amor	4163
Total NEAs	10993
Total NECs	94
Total NEOs	11087
Potentially Hazardous NEAs	1478 (153 w/ est. diameter $\geq$ 1 km)

Estimates for undiscovered NEAs:

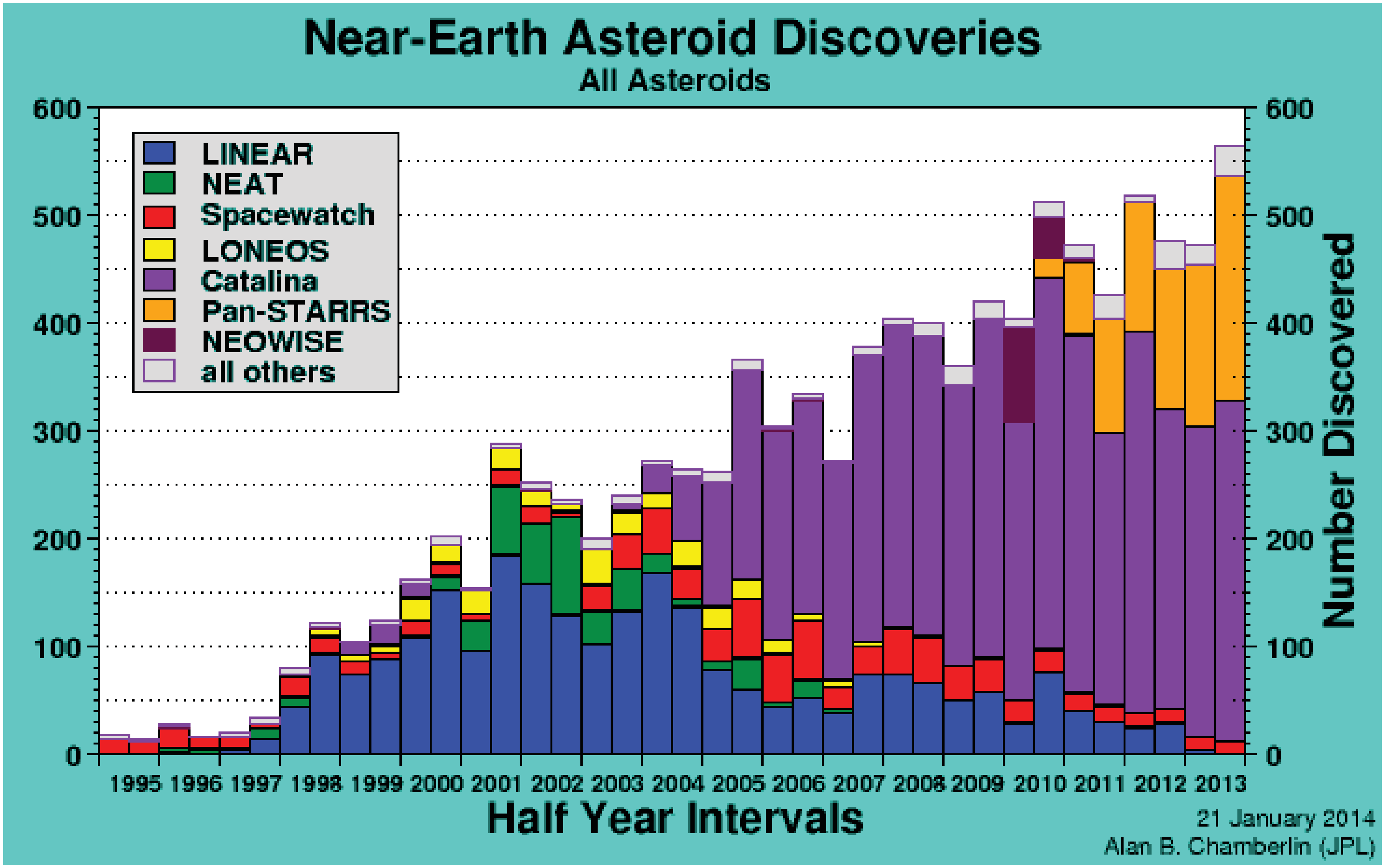
- $\sim$70 NEAs $>$ 1 km in diameter
- $\sim$16,000 NEAs 100 to 1000 m in diameter
- $\sim 10^6$ NEAs with diameter $<$ 100 m

NEA Population Census (2011)



http://www.nasa.gov/mission_pages/WISE/multimedia/gallery/neowise/pia14734.html

NEA Survey Programs



http://neo.jpl.nasa.gov/stats/

Robotic Exploration of Asteroids & Comets

- **Galileo (en route to Jupiter) (NASA)**
  - Flew by asteroid 951 Gaspra in 1991
  - Flew by asteroid 243 Ida (and its moon, Dactyl!) in 1993
- **Near-Earth Asteroid Rendezvous (NEAR) - Shoemaker (NASA)**
  - Launched in 1996
  - Flyby of asteroid Mathilde in 1997
  - Orbit of asteroid Eros in 2000
  - "Soft" landing on Eros in 2001
- **Deep Space 1 (NASA)**
  - Launched in 1998
  - Performed flybys of asteroid Braille and comet Borrelly
- **Stardust (NASA)**
  - Launched in 1999
  - Investigated asteroid 5535 Annefrank and comet Wild 2
  - Wild 2 coma samples returned to Earth in 2006
  - Flyby of comet Tempel 1 in February of 2011 (Stardust-NExT)
- **Hayabusa/MUSES-C (ISAS/JAXA)**
  - Launched in 2003
  - Visited asteroid Itokawa
  - Samples returned in 2010

Robotic Exploration of Asteroids & Comets

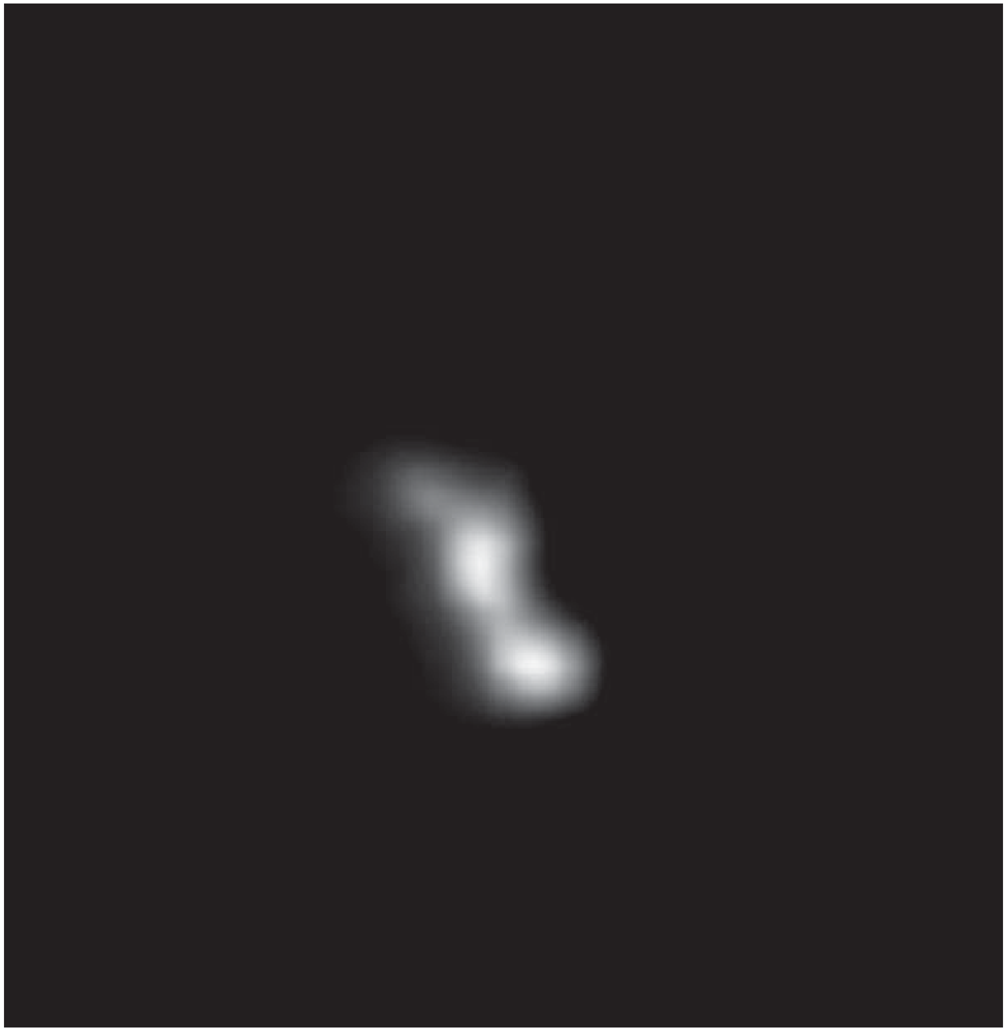
- **Rosetta (ESA)**
  - Launched in 2004; 2 asteroid flybys (Steins in 2008, Lutetia in 2010)
  - Will rendezvous with and deploy a lander to comet Churymov-Gerasimenko in 2014
- **Deep Impact (NASA)**
  - Launched in 2005
  - Delivered an impactor to the comet Tempel 1 in the same year, observed impact ejecta
  - Flyby of comet Hartley 2 in November of 2010 (EPOXI)
- **Dawn (NASA)**
  - Launched in 2007
  - Orbited Vesta (2nd most massive main belt asteroid (protoplanet)) 2011–2012
  - Currently on its way to rendezvous with and study Ceres (main belt dwarf planet)
- **Chang'e 2 (lunar orbiter) (China)**
  - Flew within 3.2 km of NEA 4179 Toutatis (1989 AC)
- **Hayabusa 2 (JAXA)**
  - Launch planned for early 2015
  - Return samples of NEA 162173 (1999 JU_3) in 2020
- **OSIRIS-REx (NASA)**
  - Launch planned for September 2016
  - Return samples of NEA 101955 Bennu (1999 RQ_{36}) in 2023

Robotic Exploration of Asteroids & Comets

Asteroid 253 Mathilde (NEAR-Shoemaker)

Asteroid 433 Eros (NEAR-Shoemaker)

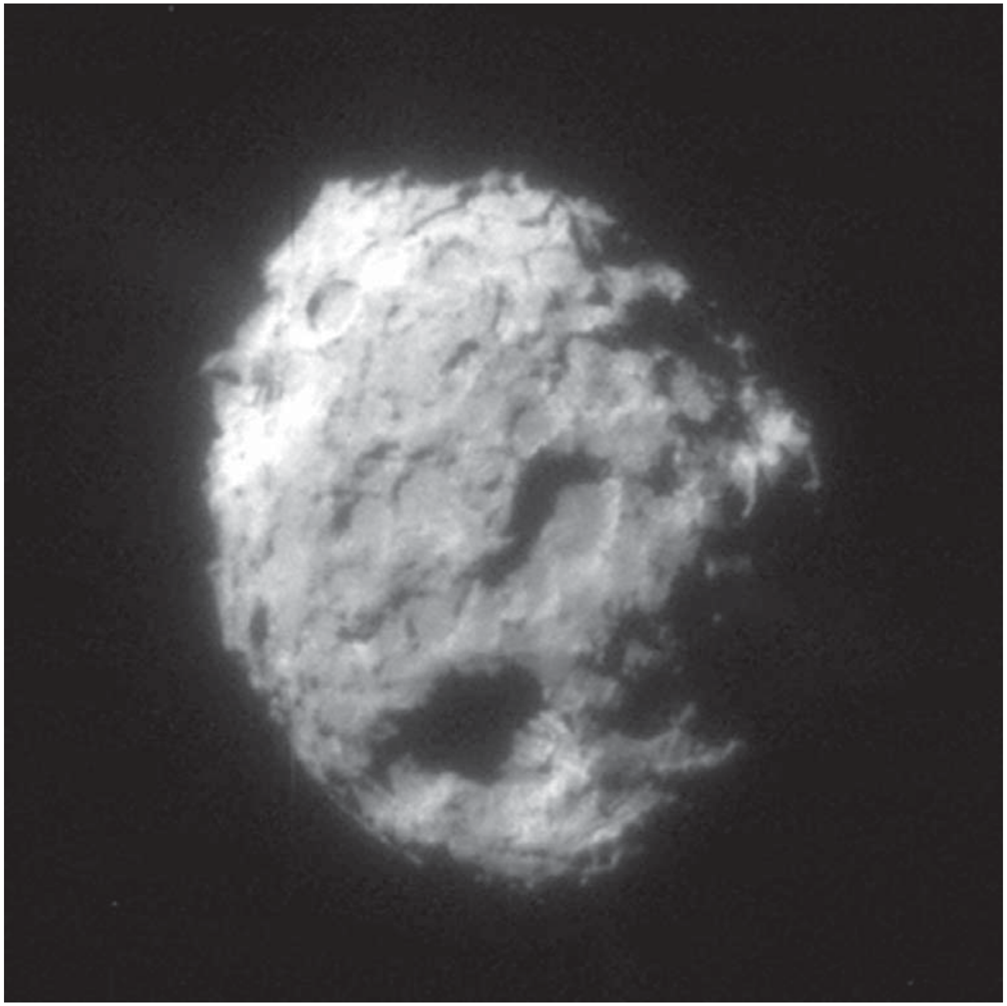
Robotic Exploration of Asteroids & Comets



Asteroid 9969 Braille (Deep Space 1)

Nucleus of comet 19P/Borrelly (Deep Space 1)

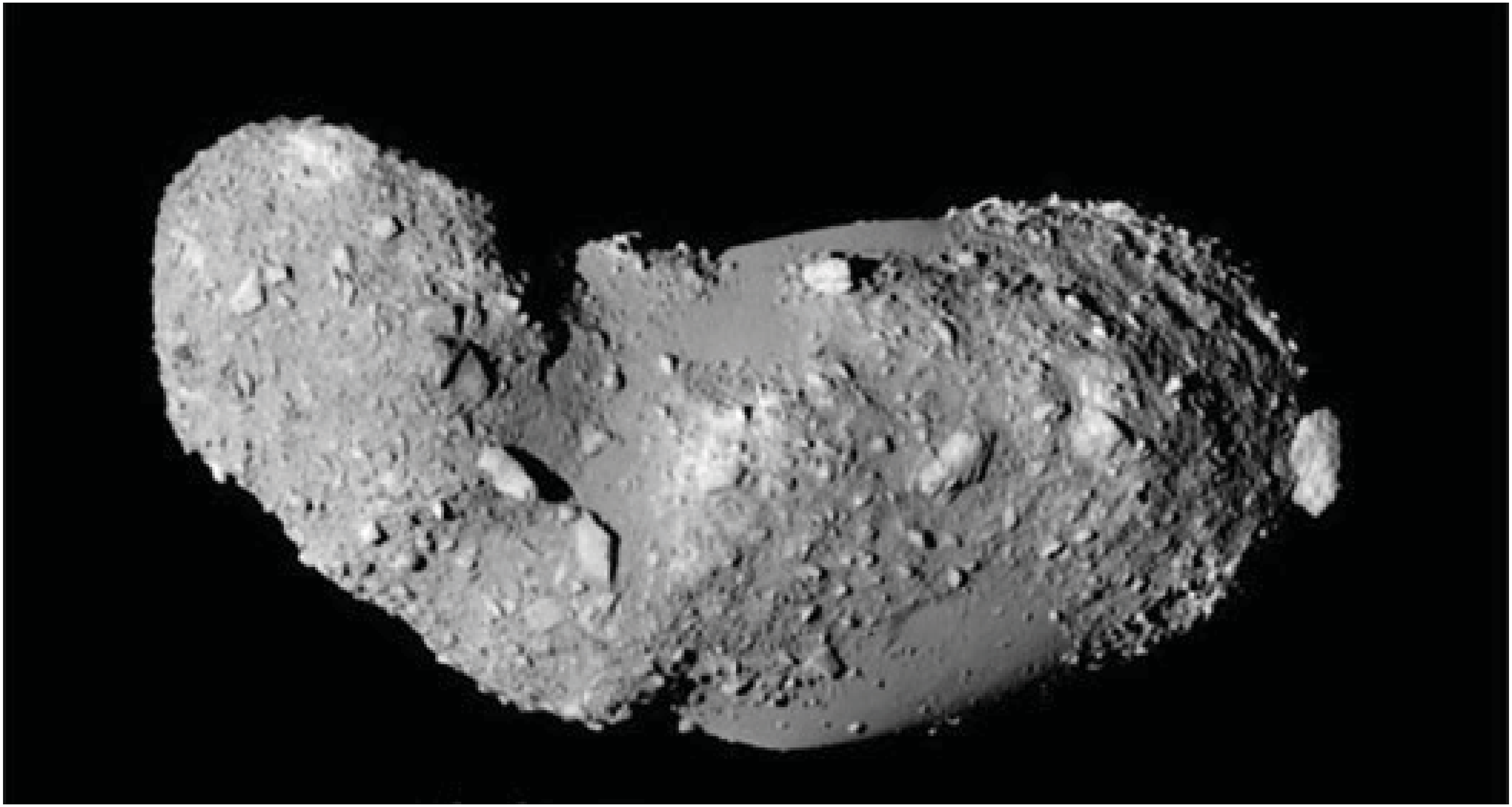
Robotic Exploration of Asteroids & Comets



Nucleus of comet 81P/Wild (aka Wild 2) (Stardust)

Nucleus of comet 9P/Tempel (aka Tempel 1) (Stardust-NExT)

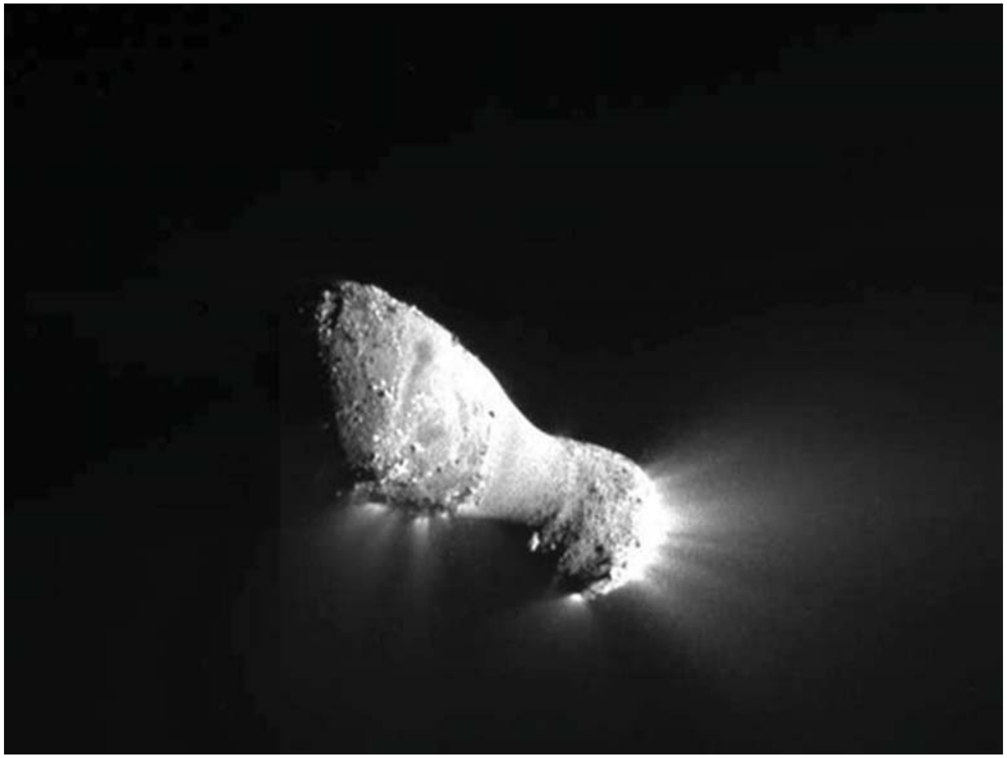
Robotic Exploration of Asteroids & Comets



Asteroid 25143 Itokawa (Hayabusa/MUSES-C)

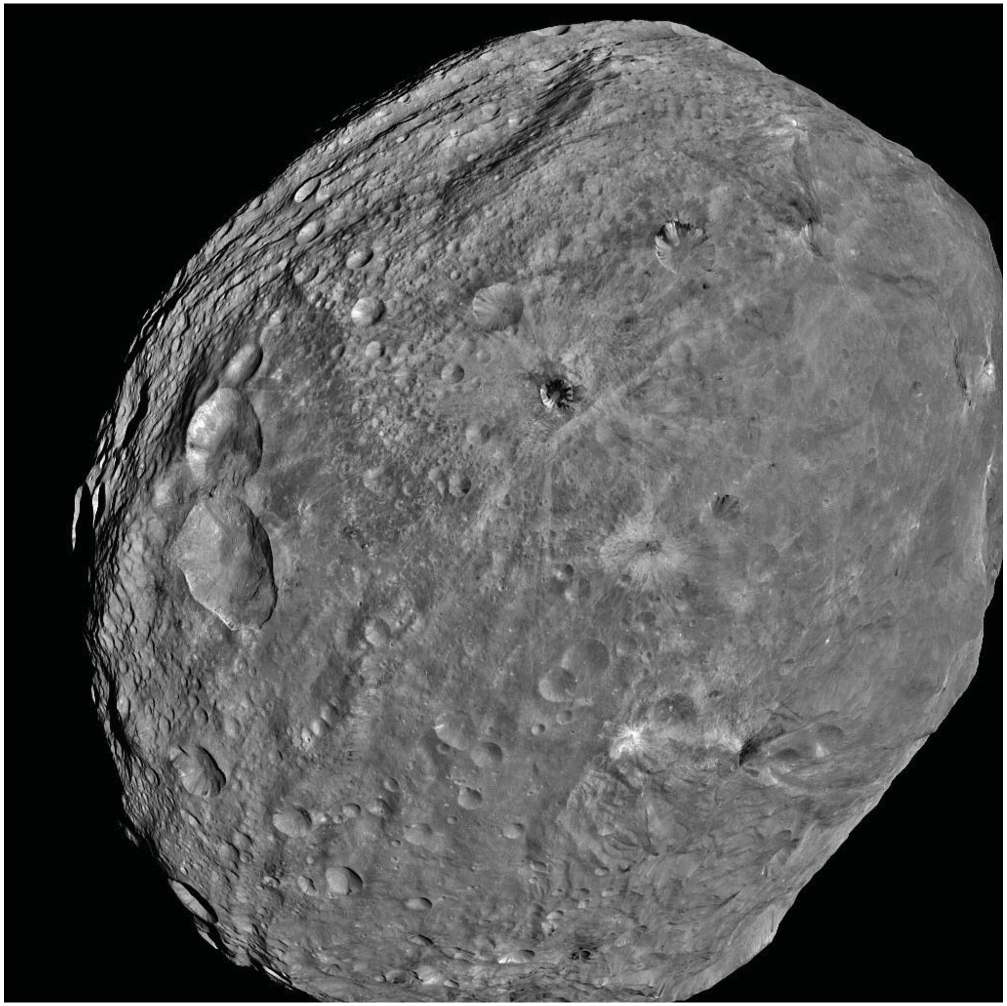
Robotic Exploration of Asteroids & Comets

Nucleus of comet 9P/Tempel (aka Tempel 1) during impact (Deep Impact)

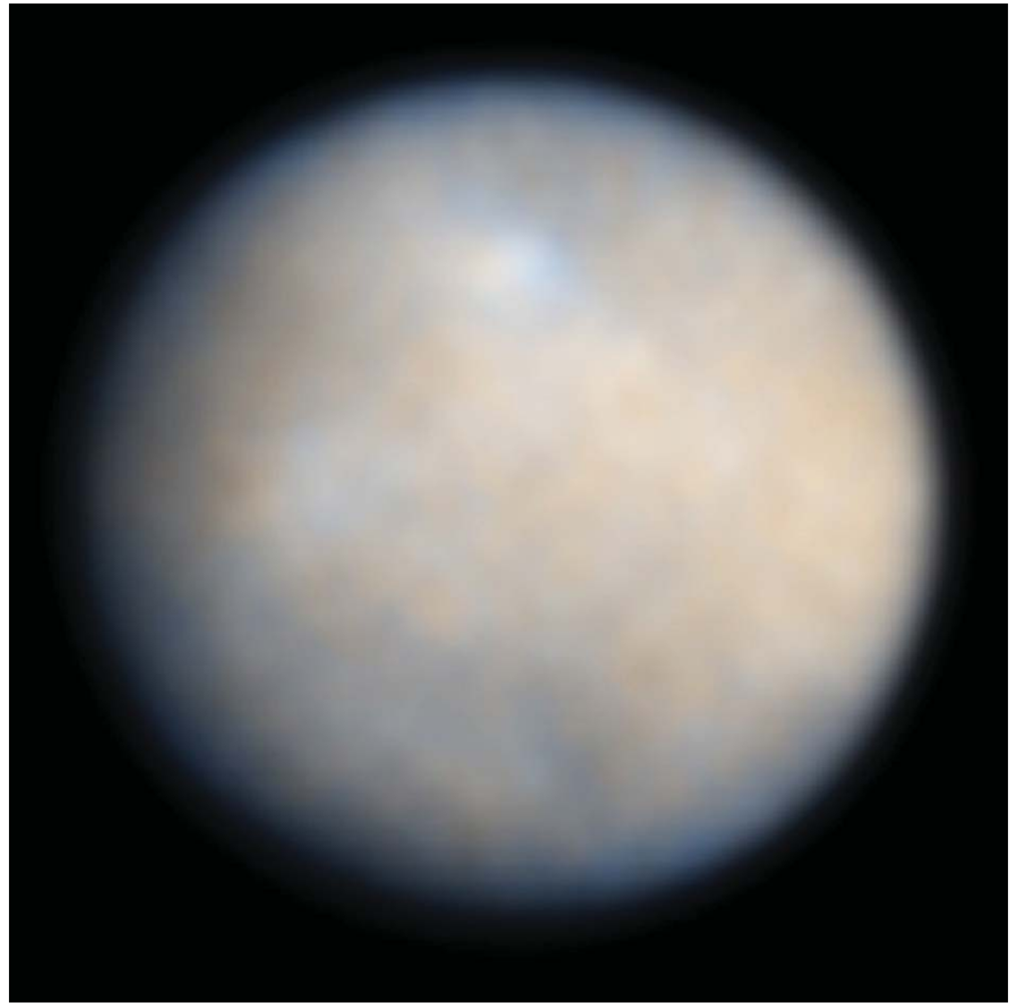


Nucleus of comet 103P/Hartley (aka Hartley 2) (Deep Impact / EPOXI)

Robotic Exploration of Asteroids & Comets

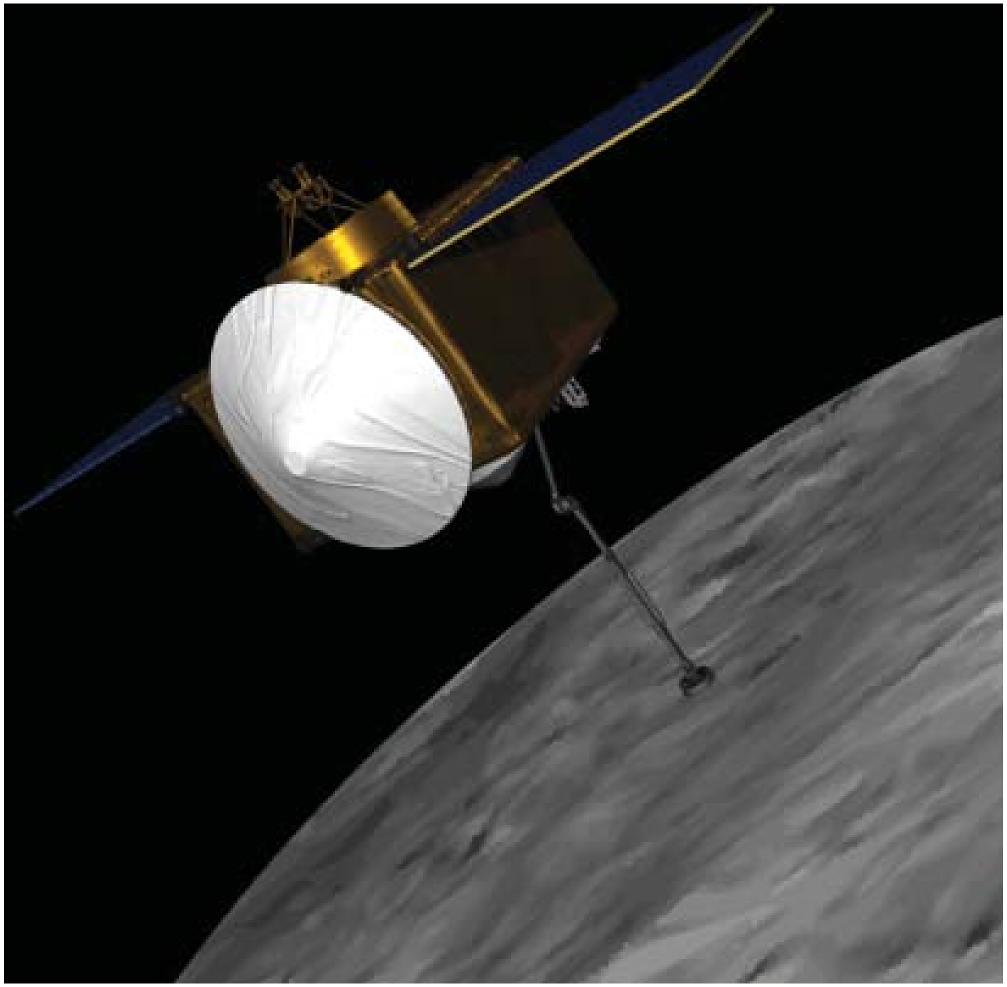


Asteroid 4 Vesta (Dawn)



Dwarf planet Ceres (as seen by the Hubble Space Telescope)

Robotic Exploration of Asteroids & Comets

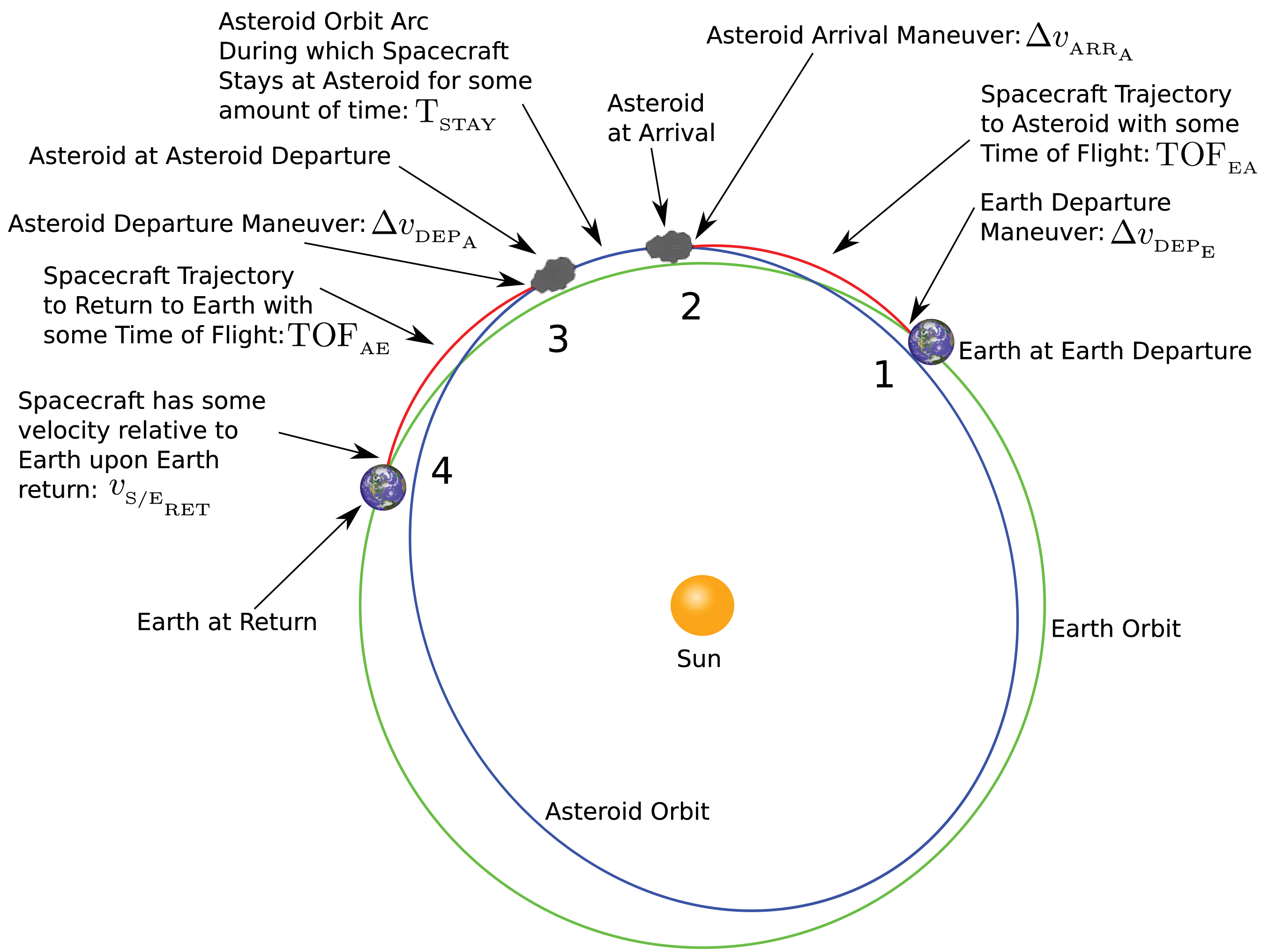


Artistic Rendering of OSIRIS-REx Spacecraft

Simulated image of Bennu - topography overlaid on radar imagery.

Profile of a Human Mission to an NEA

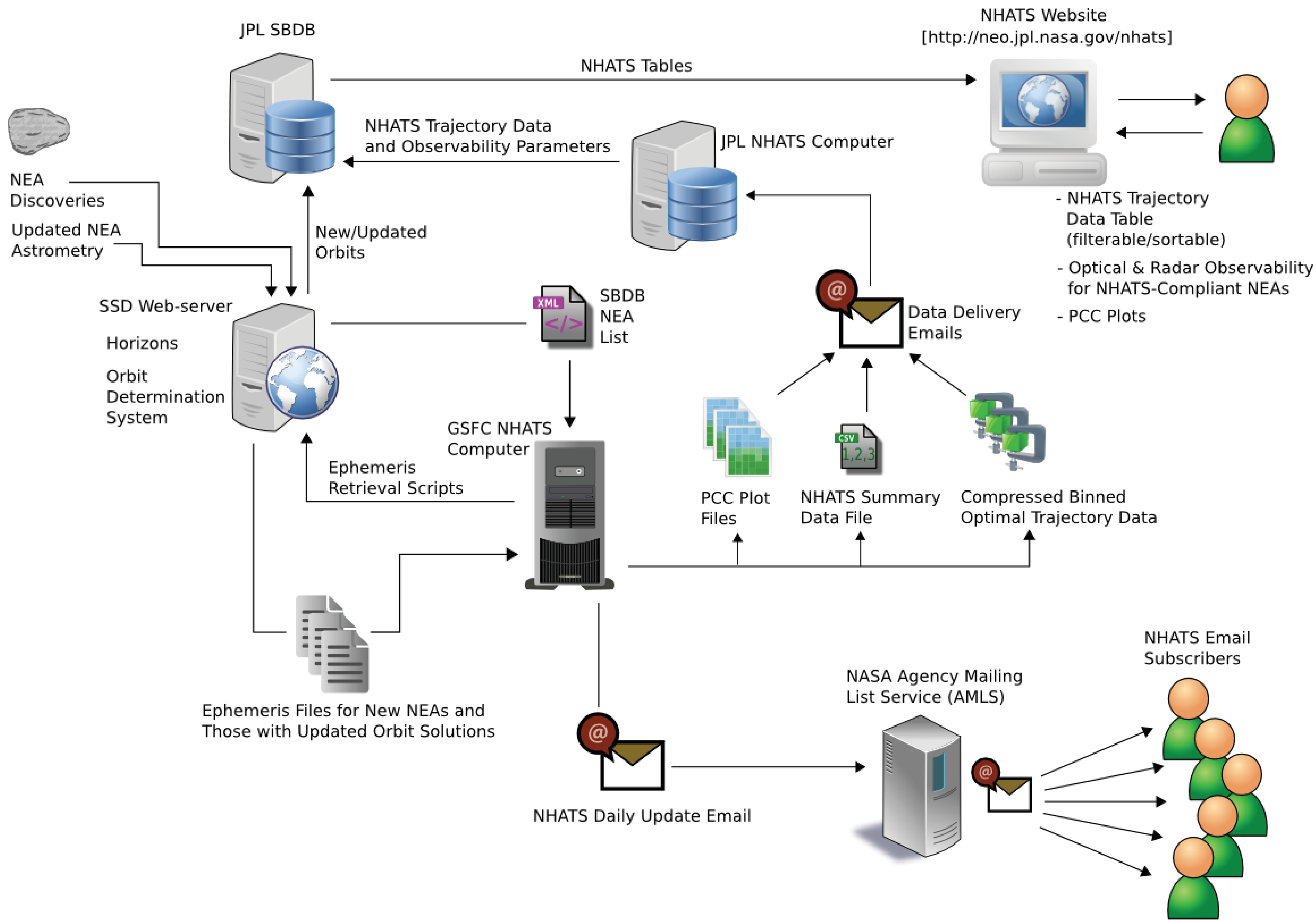
The purpose of NASA's Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) (pron.: /næts/) is to identify known near-Earth objects (NEOs), particularly near-Earth asteroids (NEAs), that may be accessible for future human space flight missions. The NHATS also identifies low Δv robotic mission opportunities.



NHATS Online System Overview

- **Main NHATS Web-site:**
  - http://neo.jpl.nasa.gov/nhats/
  - Link to NHATS data table, provides background, assumptions & caveats, and description of NEA observability calculations
- **NHATS Data Table:**
  - http://neo.jpl.nasa.gov/cgi-bin/nhats
  - The data table is automatically updated each day as NHATS processes new NEAs and NEAs with updated orbit solutions
  - Sortable/filterable according to total Δv, mission duration, minimum stay time at NEA, Earth departure date range, H, OCC, next optical or radar observing opportunity, etc
  - Shows two optimal round-trip spacecraft trajectory solutions for each NEA: minimum Δv and minimum mission duration
  - Clicking on a NEA designation opens a trajectory details page for that NEA that shows additional trajectory information and the NEA's Pork Chop Contour (PCC) plot
- **NHATS Daily Updates Mailing List:**
  - https://lists.nasa.gov/mailman/listinfo/nhats
  - Subscribe to this mailing list to receive daily NHATS processing results via email
  - Provides notification to observers to facilitate timely acquisition of follow-up NEA observations during the critical time period around NEA discovery
  - Also provides a mechanism for public engagement
- **Supported by NASA's Near-Earth Objects Observations (NEOO) program**

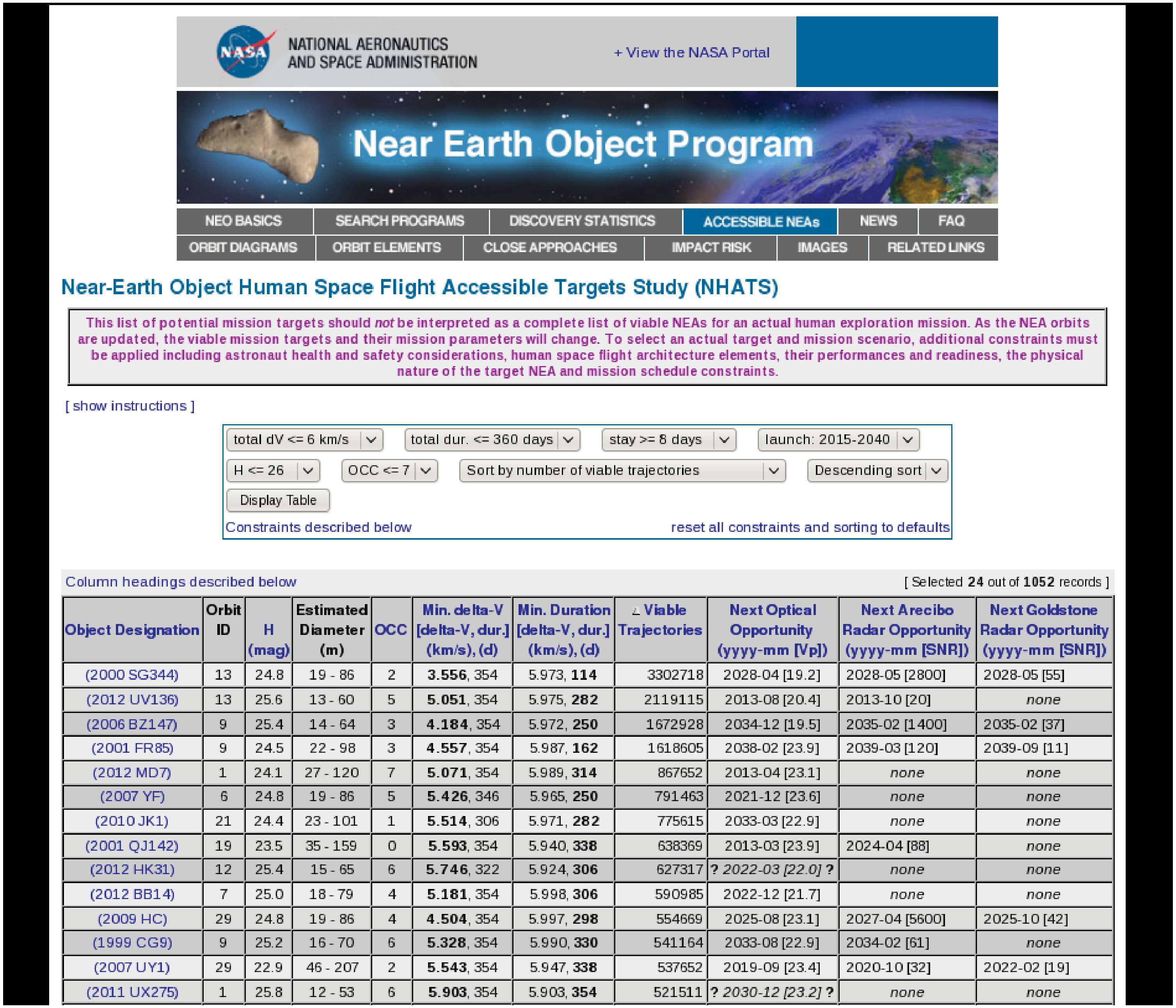
Automated NHATS Processing



NHATS Analysis Constraints

- In order to be classified as NHATS-compliant, a NEA must offer at least one round-trip trajectory solution that meets the following constraints:
  1. Earth departure date between 2015-01-01 and 2040-12-31.
  2. Earth departure $C_3 \leq 60$ km^2/s^2.
  3. Total mission $\Delta v \leq 12$ km/s. The total mission Δv includes the Earth departure maneuver from a 400 km altitude circular parking orbit, the maneuver to match the NEA's velocity at arrival, the maneuver to depart the NEA, and, when necessary, a maneuver to meet the following Earth atmospheric entry speed constraint (item 6).
  4. Total round-trip mission duration ≤ 450 days.
  5. Stay time at the NEA ≥ 8 days.
  6. Earth atmospheric entry speed ≤ 12 km/s at an altitude of 125 km.
- The trajectory calculations are performed using patched conics with Lambert solutions for the spacecraft and with full precision high-fidelity ephemerides for the Earth and NEAs obtained from JPL's Horizons system.

NHATS Web-site Table



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Near-Earth Object Human Space Flight Accessible Targets Study (NHATS)

This list of potential mission targets should *not* be interpreted as a complete list of viable NEAs for an actual human exploration mission. As the NEA orbits are updated, the viable mission targets and their mission parameters will change. To select an actual target and mission scenario, additional constraints must be applied including astronaut health and safety considerations, human space flight architecture elements, their performances and readiness, the physical nature of the target NEA and mission schedule constraints.

[show instructions]

total dV <= 6 km/s | total dur. <= 360 days | stay >= 8 days | launch: 2015-2040

H <= 26 | OCC <= 7 | Sort by number of viable trajectories | Descending sort

Display Table

Constraints described below — reset all constraints and sorting to defaults

Column headings described below — [Selected **24** out of **1052** records]

Object Designation	Orbit ID	H (mag)	Estimated Diameter (m)	OCC	Min. delta-V [delta-V, dur.] (km/s), (d)	Min. Duration [delta-V, dur.] (km/s), (d)	Viable Trajectories	Next Optical Opportunity (yyyy-mm [Vp])	Next Arecibo Radar Opportunity (yyyy-mm [SNR])	Next Goldstone Radar Opportunity (yyyy-mm [SNR])
(2000 SG344)	13	24.8	19 - 86	2	**3.556**, 354	5.973, **114**	3302718	2028-04 [19.2]	2028-05 [2800]	2028-05 [55]
(2012 UV136)	13	25.6	13 - 60	5	**5.051**, 354	5.975, **282**	2119115	2013-08 [20.4]	2013-10 [20]	*none*
(2006 BZ147)	9	25.4	14 - 64	3	**4.184**, 354	5.972, **250**	1672928	2034-12 [19.5]	2035-02 [1400]	2035-02 [37]
(2001 FR85)	9	24.5	22 - 98	3	**4.557**, 354	5.987, **162**	1618605	2038-02 [23.9]	2039-03 [120]	2039-09 [11]
(2012 MD7)	1	24.1	27 - 120	7	**5.071**, 354	5.989, **314**	867652	2013-04 [23.1]	*none*	*none*
(2007 YF)	6	24.8	19 - 86	5	**5.426**, 346	5.965, **250**	791463	2021-12 [23.6]	*none*	*none*
(2010 JK1)	21	24.4	23 - 101	1	**5.514**, 306	5.971, **282**	775615	2033-03 [22.9]	*none*	*none*
(2001 QJ142)	19	23.5	35 - 159	0	**5.593**, 354	5.940, **338**	638369	2013-03 [23.9]	2024-04 [88]	*none*
(2012 HK31)	12	25.4	15 - 65	6	**5.746**, 322	5.924, **306**	627317	? *2022-03 [22.0]* ?	*none*	*none*
(2012 BB14)	7	25.0	18 - 79	4	**5.181**, 354	5.998, **306**	590985	2022-12 [21.7]	*none*	*none*
(2009 HC)	29	24.8	19 - 86	4	**4.504**, 354	5.997, **298**	554669	2025-08 [23.1]	2027-04 [5600]	2025-10 [42]
(1999 CG9)	9	25.2	16 - 70	6	**5.328**, 354	5.990, **330**	541164	2033-08 [22.9]	2034-02 [61]	*none*
(2007 UY1)	29	22.9	46 - 207	2	**5.543**, 354	5.947, **338**	537652	2019-09 [23.4]	2020-10 [32]	2022-02 [19]
(2011 UX275)	1	25.8	12 - 53	6	**5.903**, 354	5.903, **354**	521511	? *2030-12 [23.2]* ?	*none*	*none*

NHATS Web-site Trajectory Details

NHATS Object/Trajectory Details

This page provides some details about the selected target NEA (near-Earth asteroid) and related mission/trajectory parameters. The table below shows parameters specific to the selected NEA. The **Mission Trajectories Table** (second table below) provides information for two mission scenarios to the target NEA: one for the minimum delta-V mission and one for the minimum duration mission (in some cases the two missions may be identical). Next to the **Mission Trajectories Table** is the plot of total mission dV as a function of departure date and roundtrip flight time (mission duration), which summarizes the many potential mission trajectories. Note that these mission trajectories span a range of possible stay times at the NEA, though this cannot be shown in a two-dimensional plot. Please consider the assumptions and caveats related to these data.

Constraints: [total dV <= 6 km/s] [total dur. <= 360 days] [stay >= 8 days] [launch: 2015-2040]

Column headings described below

Object Designation	Orbit ID	H (mag)	Estimated Diameter (m)	OCC	Min. delta-V [delta-V, dur.] (km/s), (d)	Min. Duration [delta-V, dur.] (km/s), (d)	Viable Trajectories	Next Optical Opportunity (yyyy-mm [Vp])	Next Arecibo Radar Opportunity (yyyy-mm [SNR])	Next Goldstone Radar Opportunity (yyyy-mm [SNR])
(2000 SG344)	13	24.8	19 - 86	2	**3.556**, 354	5.973, **114**	3302718	2028-04 [19.2]	2028-05 [2800]	2028-05 [55]

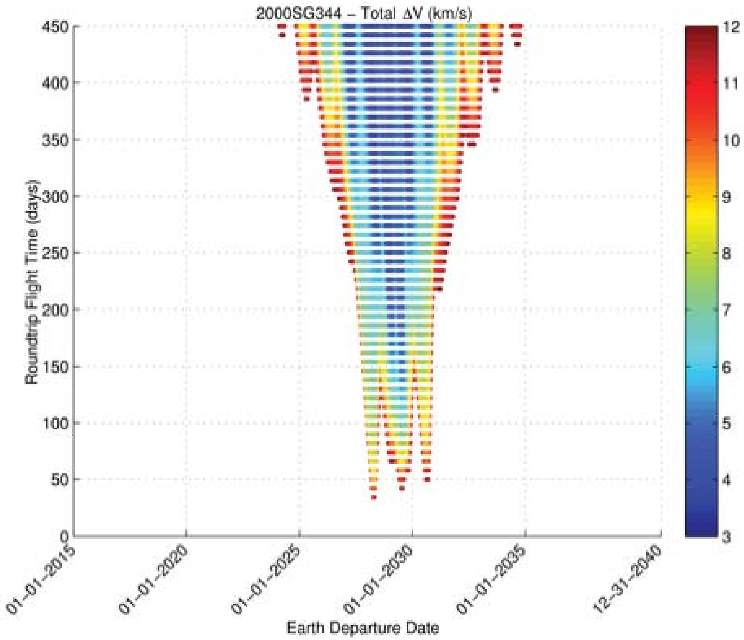
Mission Trajectories Table

Column headings described below

(2000 SG344)	Min. delta-V Parameters	Min. Duration Parameters
Total Mission delta-V (km/s)	**3.556**	5.973
Total Mission Duration (d)	354	**114**
Outbound Flight Time (d)	145	49
Stay Time (d)	8	8
Inbound Flight Time (d)	201	57
Launch date (YYYY-MM-DD)	2028-04-22	2029-07-22
C_3 (km^2/s^2)	1.737	3.009
Departure $V_{infinity}$ (km/s)	1.318	1.735
Earth Departure dV (km/s)	3.256	3.314
dV to Arrive at NEA (km/s)	0.113	1.067
dV to Depart NEA (km/s)	0.187	1.592
Earth return dV (km/s)	0.000	0.000
Entry Speed (km/s)	11.133	11.214
Depature Declination (deg)	-8.950	-22.493
Return Declination (deg)	-5.933	22.663
NHATS Trajectory Solution ID	890465	2046652

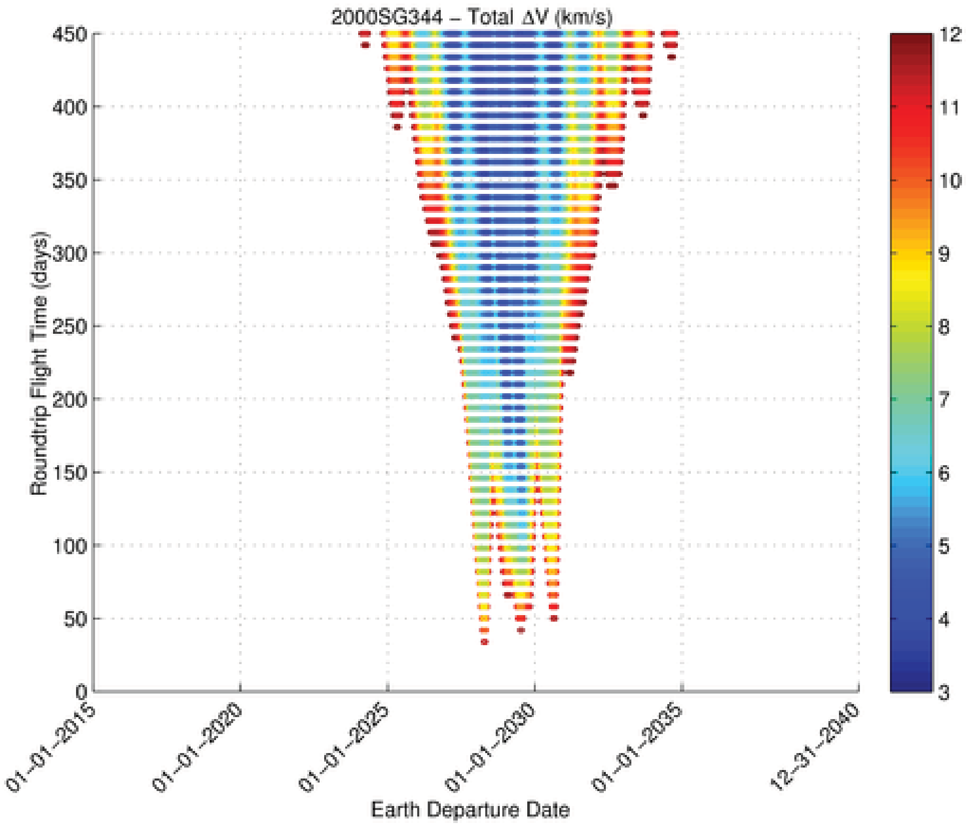
These data were computed on 2012-01-06 using the latest available orbital parameters.

Total Mission delta-V as a Function of Departure Date and Mission Duration

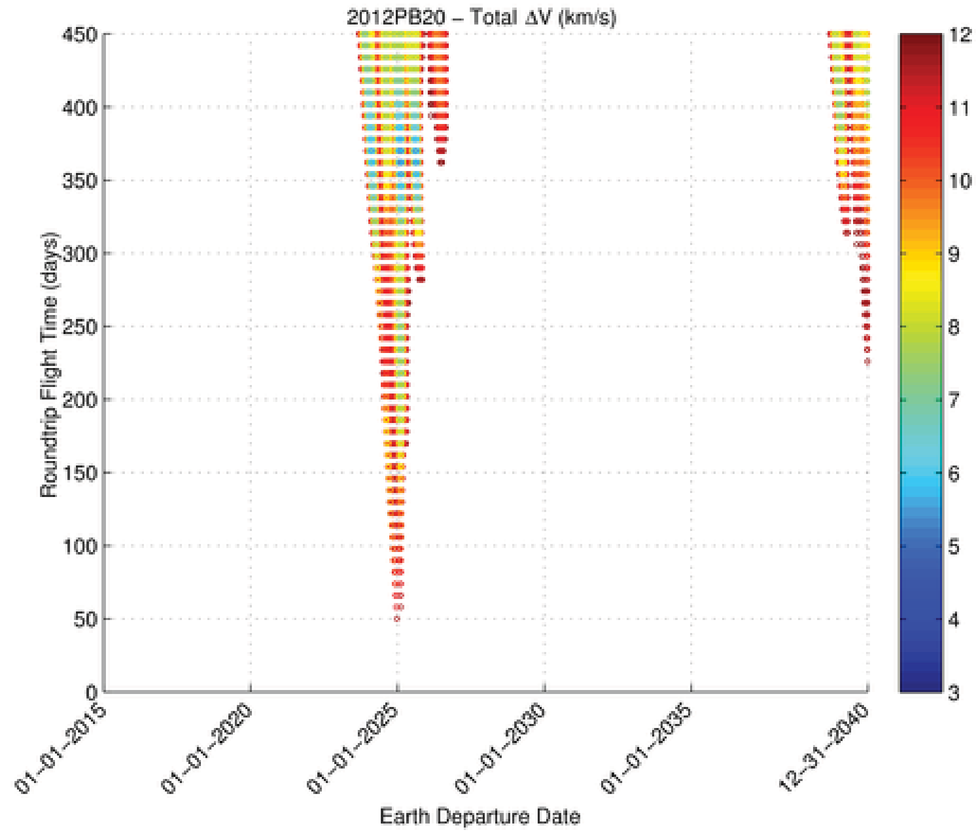


The plot above shows total mission delta-V as a function of Earth departure date and total round-trip flight time (mission duration). It summarizes the many potential mission scenarios by plotting, for each case, the total round-trip delta-V values (color-coded) required for each launch date and round trip flight time considered. Note that these trajectories span a range of possible stay times at the NEA.

Pork Chop Contour (PCC) Plots



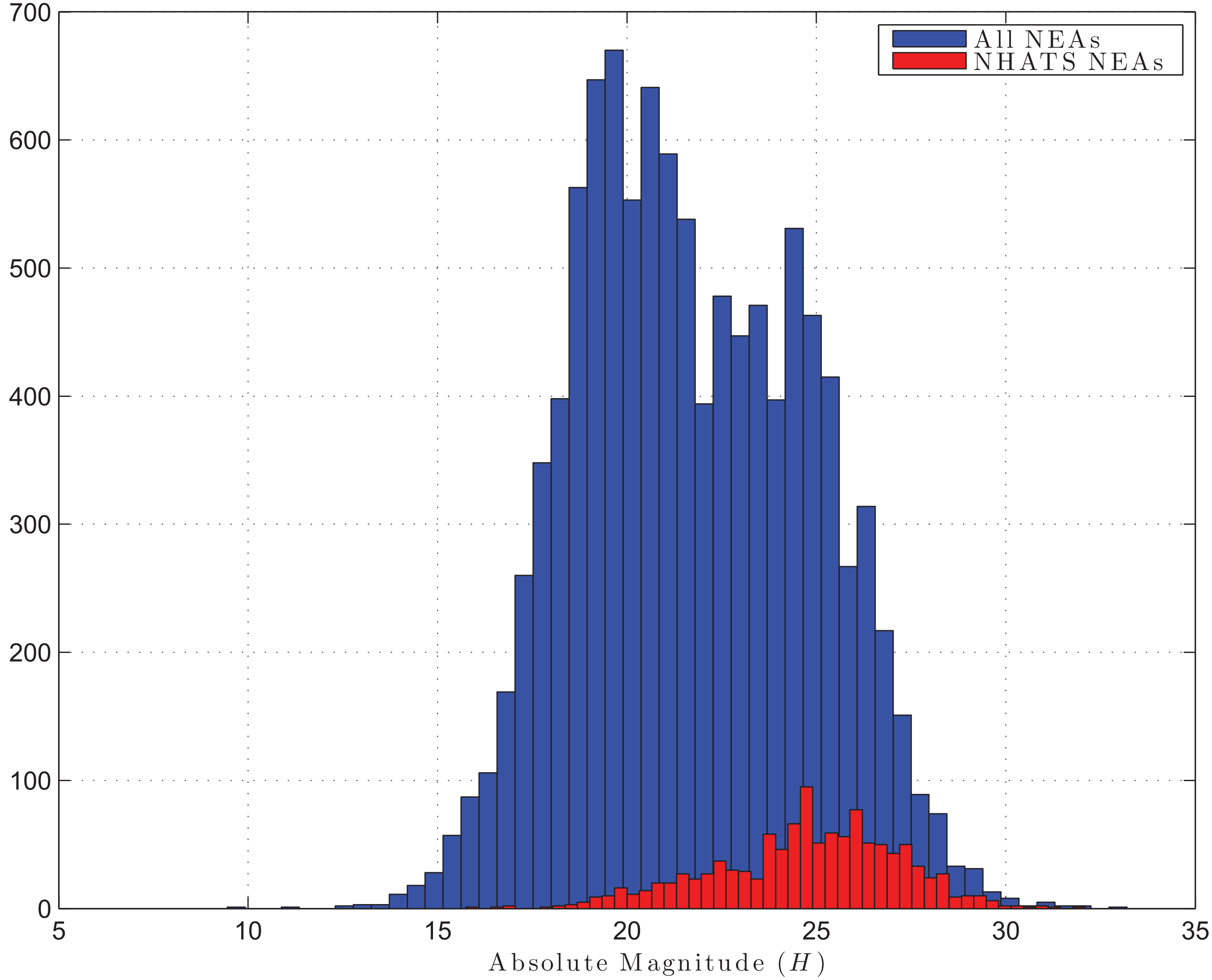
NHATS PCC plot for 2000 SG_{344}.



NHATS PCC plot for 2012 PB_{20}.

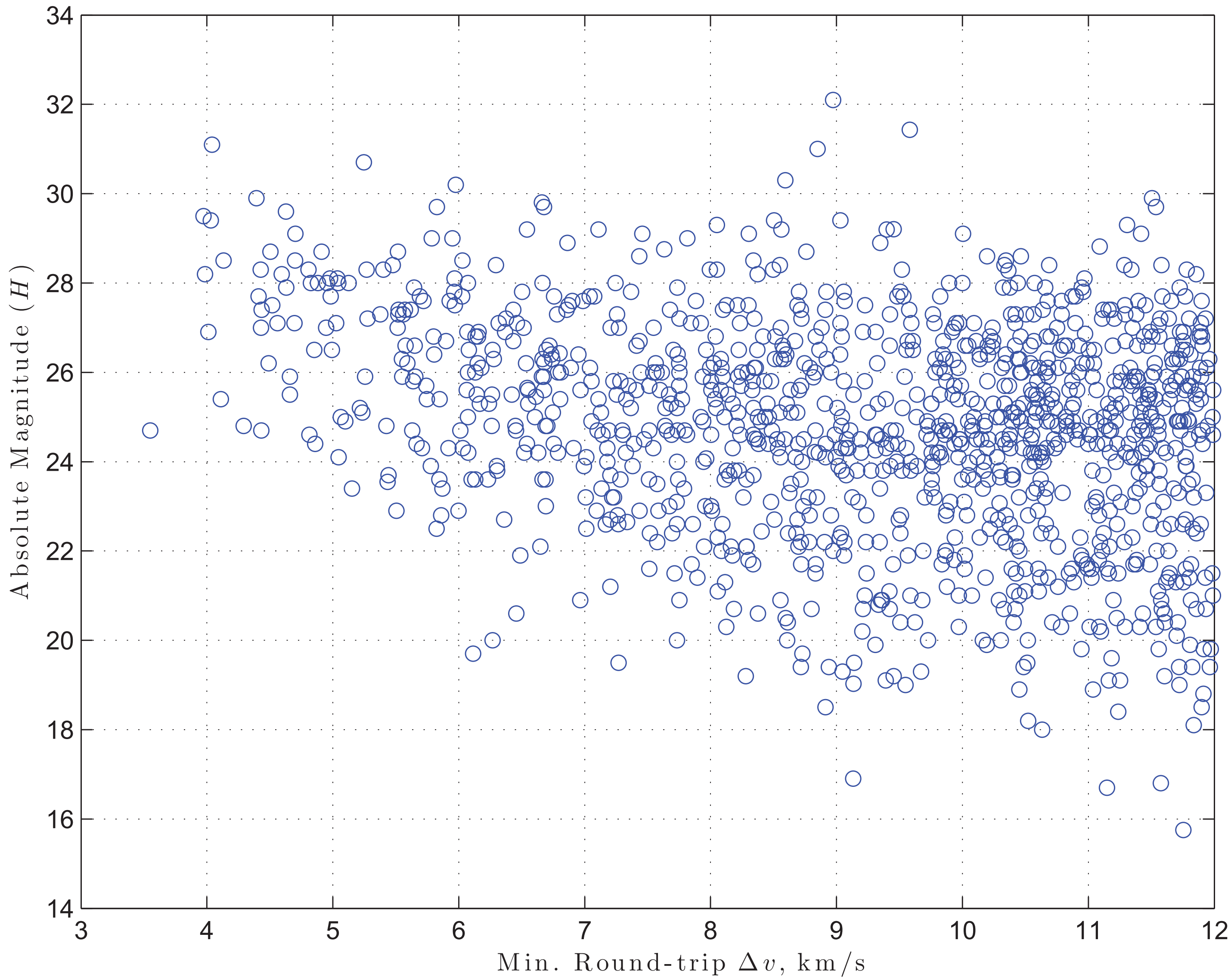
Absolute Magnitudes (H) of NHATS NEAs

NHATS-compliant NEAs Tend to Have Larger H (smaller diameter) Than Other NEAs



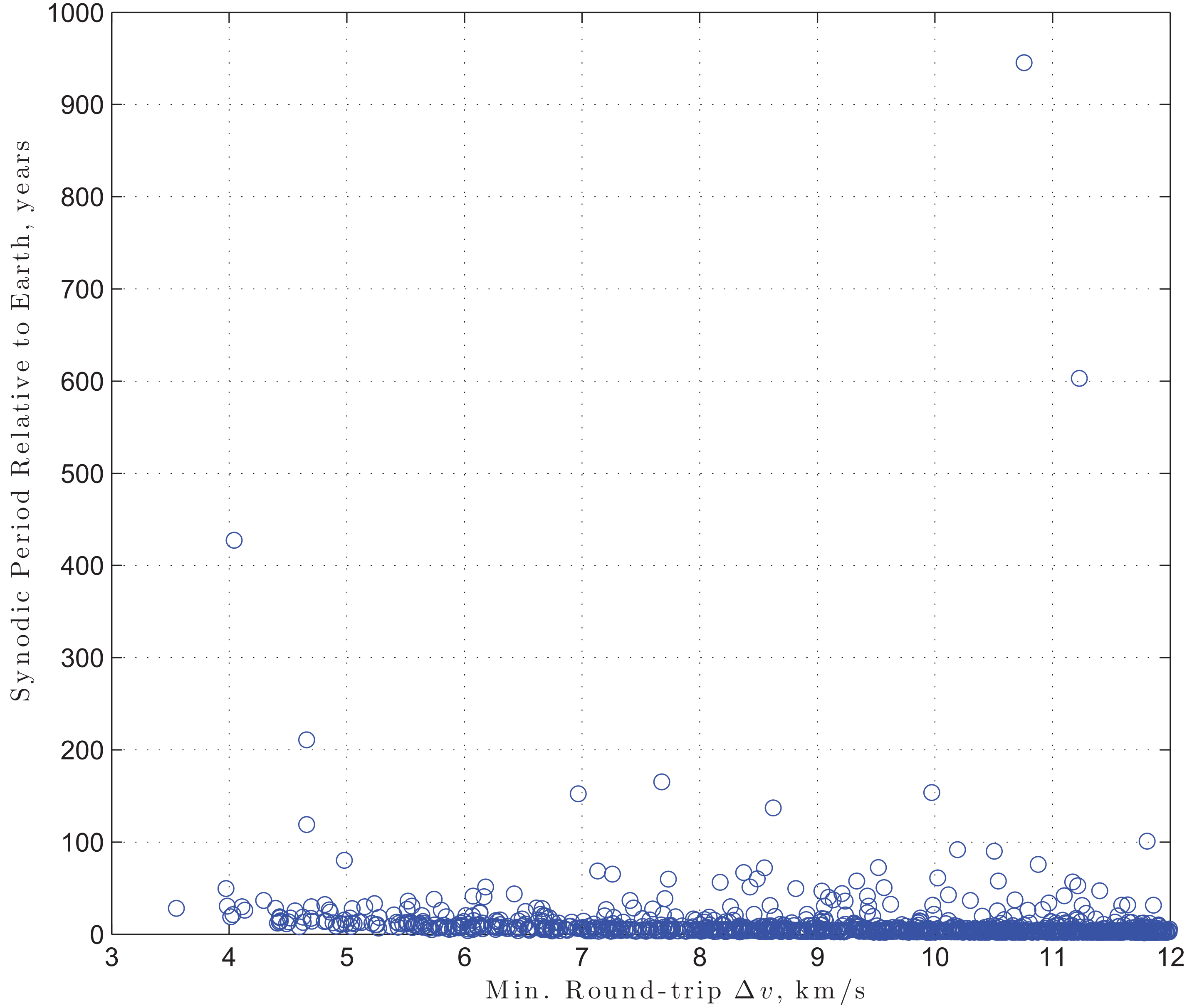
Absolute Magnitudes (H) of NHATS NEAs

Low Δv NHATS-compliant NEAs Tend to Have the Largest H (smallest diameters)

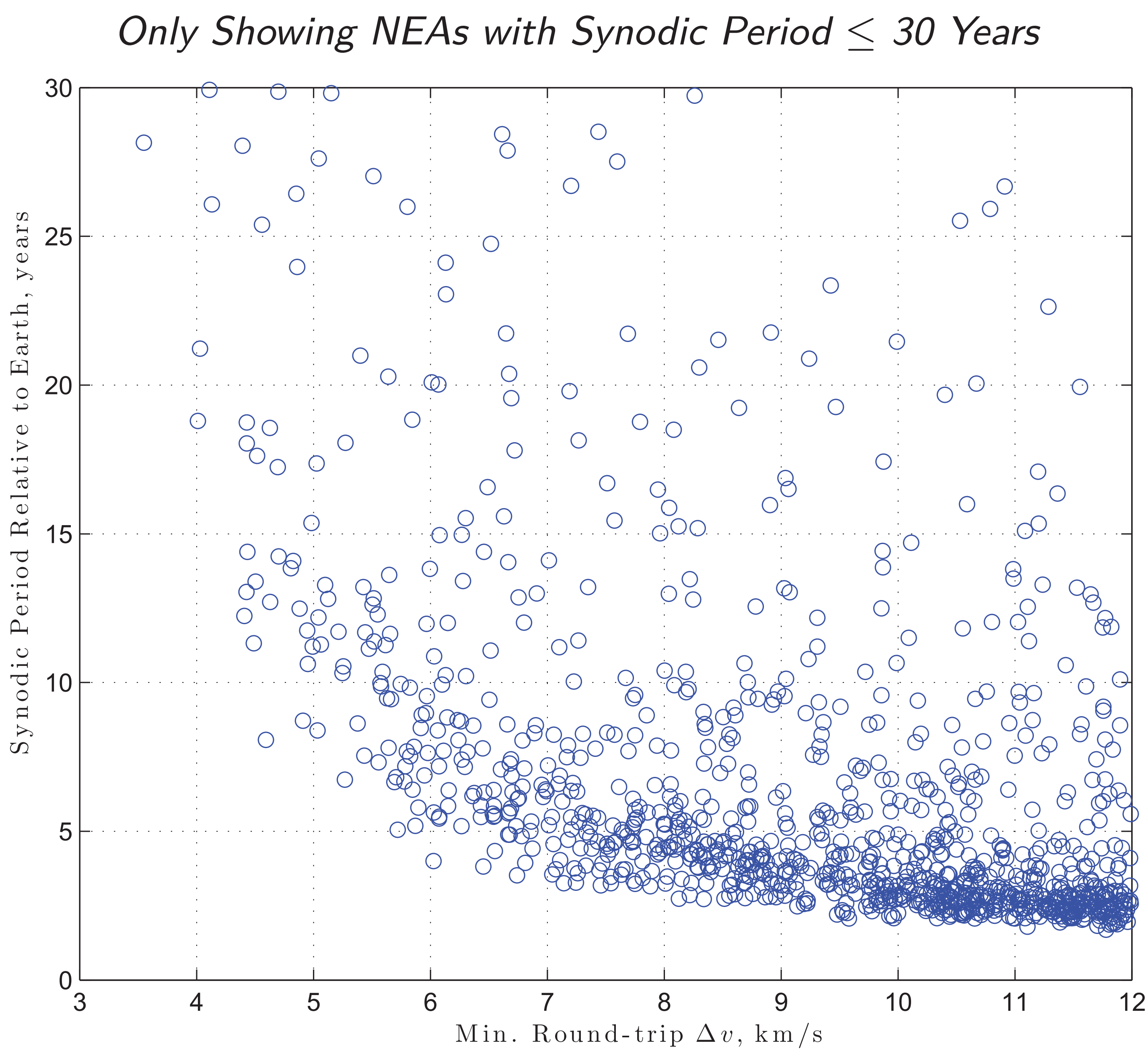


NHATS-compliant NEA Synodic Periods

Minimum Round-Trip Δv versus Synodic Period for all NHATS-compliant NEAs



NHATS-compliant NEA Synodic Periods



Example Round-Trip Trajectory Solutions

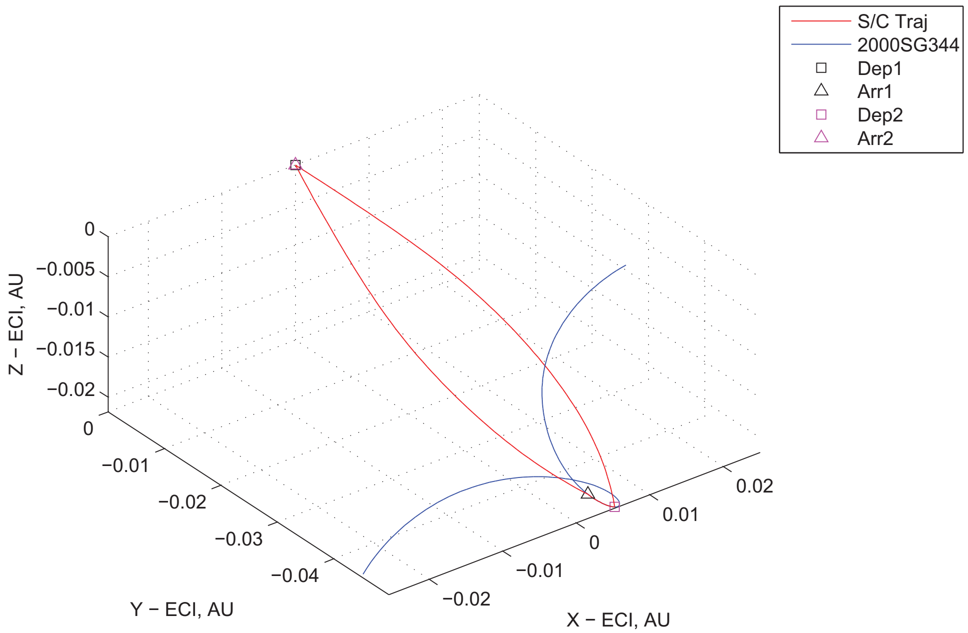
Round-trip mission opportunities departing Earth between 2024 and 2029 for selected NHATS-compliant NEAs.

	2000 SG_{344}		341843 (2008 EV_5)	2001 QJ_{142}		2011 DV	2012 PB_{20}	99942 Apophis
Estimated Diameter (m)	19–86		450	35–159		128–573	18–81	325
OCC	2		0	0		2	4	0
Total Δv (km/s)	**3.601**	**4.989**	**6.654**	**6.440**	**6.915**	**6.875**	**5.443**	**6.155**
Total Mission Duration (days)	**346**	**154**	**354**	**354**	**178**	**354**	**354**	**354**
Outbound Flight Time (days)	137	65	121	73	73	193	41	49
Stay Time (days)	32	16	64	16	16	32	32	16
Inbound Flight Time (days)	177	73	169	265	89	129	281	289
Earth Departure Date	2028-04-22	2029-07-14	2024-06-30	2024-03-18	2024-04-19	2024-10-28	2025-02-09	2029-04-09
Earth Departure C_3 (km^2/s^2)	1.737	1.990	25.051	2.897	5.818	28.035	17.053	26.201
Earth Departure Δv (km/s)	3.256	3.268	4.276	3.309	3.441	4.400	3.936	4.324
Earth Departure Declination	$-8.723°$	$-22.498°$	$-20.430°$	74.941°	27.574°	65.776°	$-37.266°$	16.894°
NEA Arrival Δv (km/s)	0.128	0.754	1.227	1.912	1.287	0.779	0.437	0.522
NEA Departure Δv (km/s)	0.217	0.968	1.152	1.219	2.186	1.696	1.069	1.310
Earth Return Δv (km/s)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Atmospheric Entry Speed (km/s)	11.141	11.157	11.692	11.244	11.396	11.996	11.592	11.734

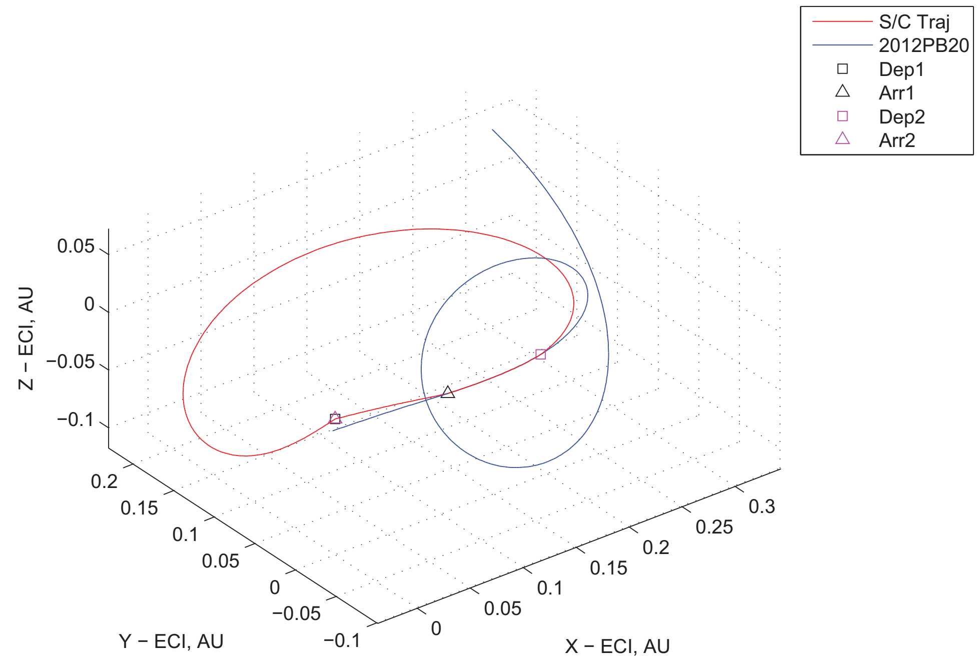
Osculating orbital elements at epoch 2013-04-18.0 TDB and orbit group classifications.

	2000 SG_{344}	341843 (2008 EV_5)	2001 QJ_{142}	2011 DV	2012 PB_{20}	99942 Apophis
Semi-major Axis (AU)	0.9775	0.9582	1.0618	0.9567	1.0541	0.9223
Eccentricity	0.0669	0.0835	0.0861	0.0496	0.0948	0.1910
Inclination	0.1112°	7.4370°	3.1031°	10.594°	5.8384°	3.3319°
Classification	Aten	Aten, PHA	Apollo	Aten, PHA	Apollo	Aten, PHA

Geocentric Trajectory Views



154 day round-trip trajectory to 2000 SG_{344}.

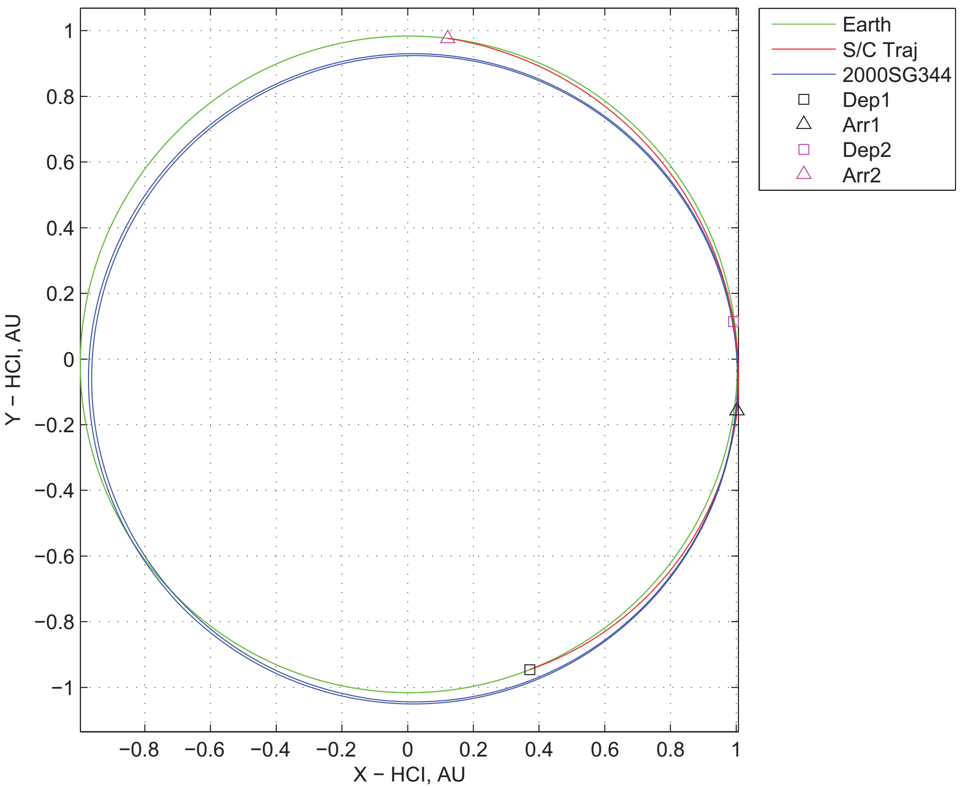


354 day round-trip trajectory to 2012 PB_{20}.

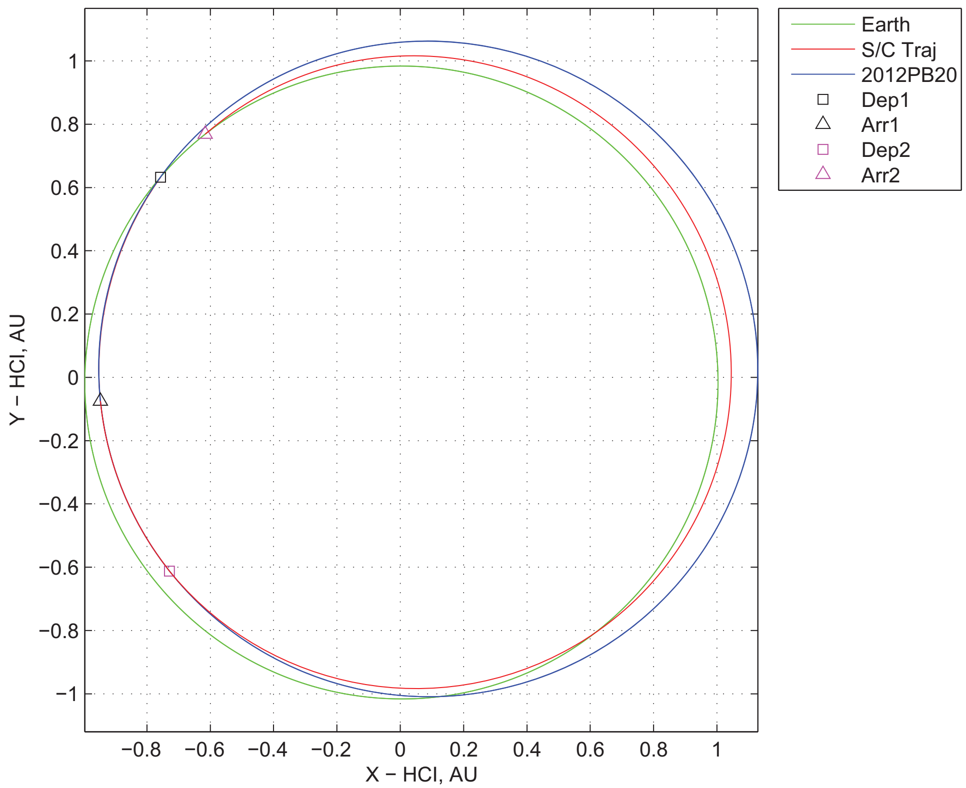
Distances from Sun and Earth for selected round-trip NEA mission trajectories.

	2000 SG_{344} (154 day)	2008 EV_5	2012 PB_{20}	99942 Apophis
Minimum Distance to Sun (AU)	0.976	0.912	0.951	0.893
Maximum Distance from Sun (AU)	1.027	1.074	1.052	1.109
Maximum Distance from Earth (AU)	0.055	0.343	0.224	0.499
Maximum Distance from Earth (LD)	21.226	133.325	86.987	194.211

Heliocentric Trajectory Views



154 day round-trip trajectory to 2000 SG_{344}.



354 day round-trip trajectory to 2012 PB_{20}.

(Available Online at: http://www.lpi.usra.edu/sbag/science/)

Accessible Near-Earth Asteroids (NEAs)

Goals of the Near-Earth Object Human Space Flight Accessible Targets Study (**NHATS**):

- Monitor the accessibility of the NEA population for exploration missions.
- Characterize the population of **accessible NEAs**.
- Rapidly notify observers so that crucial follow-up observations can be obtained.

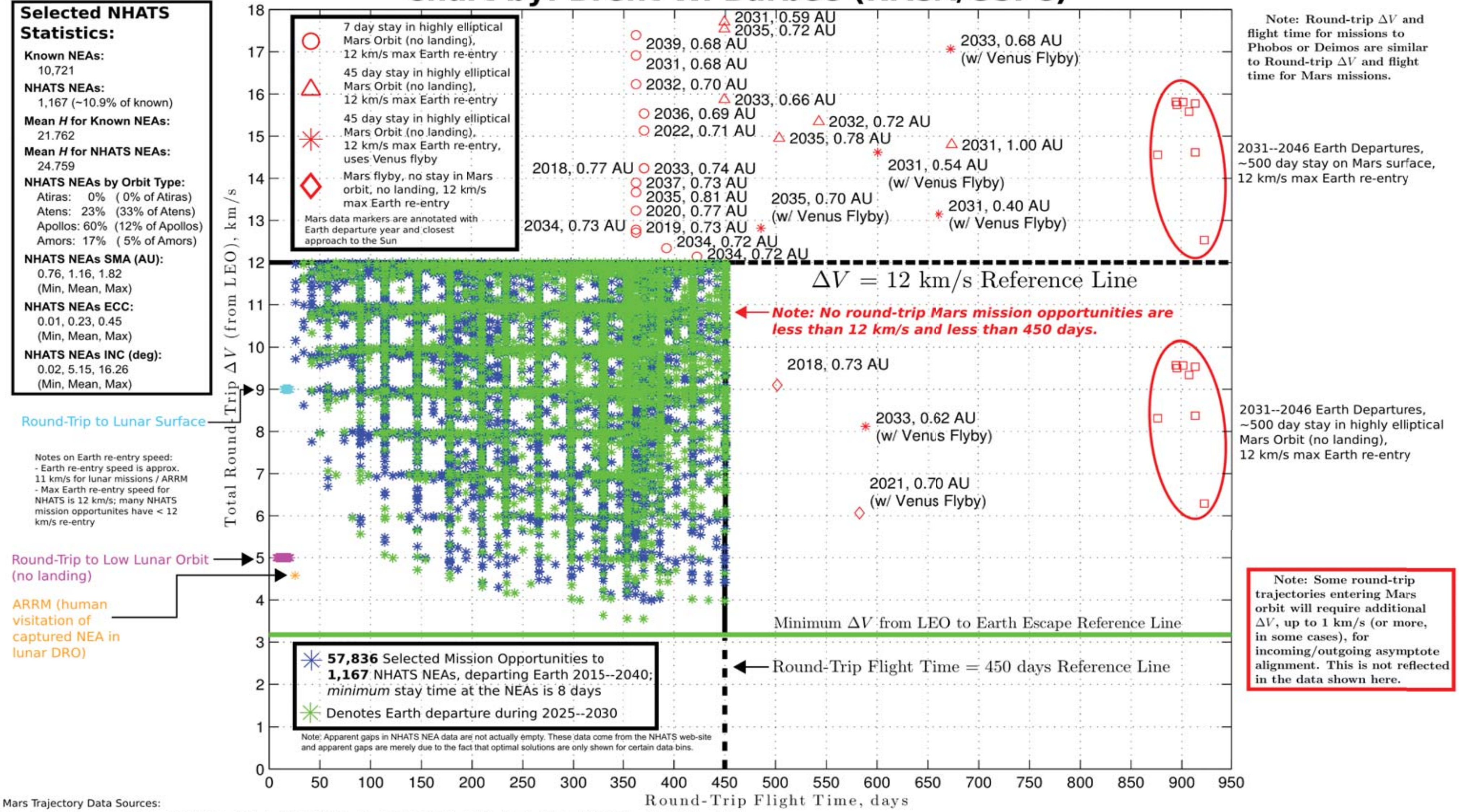
NHATS data shown here current as of: 2014-03-20

NHATS Web-site: http://neo.jpl.nasa.gov/nhats/ **NHATS Daily Updates:** https://lists.nasa.gov/mailman/listinfo/nhats

Chart by: Brent W. Barbee (NASA/GSFC)

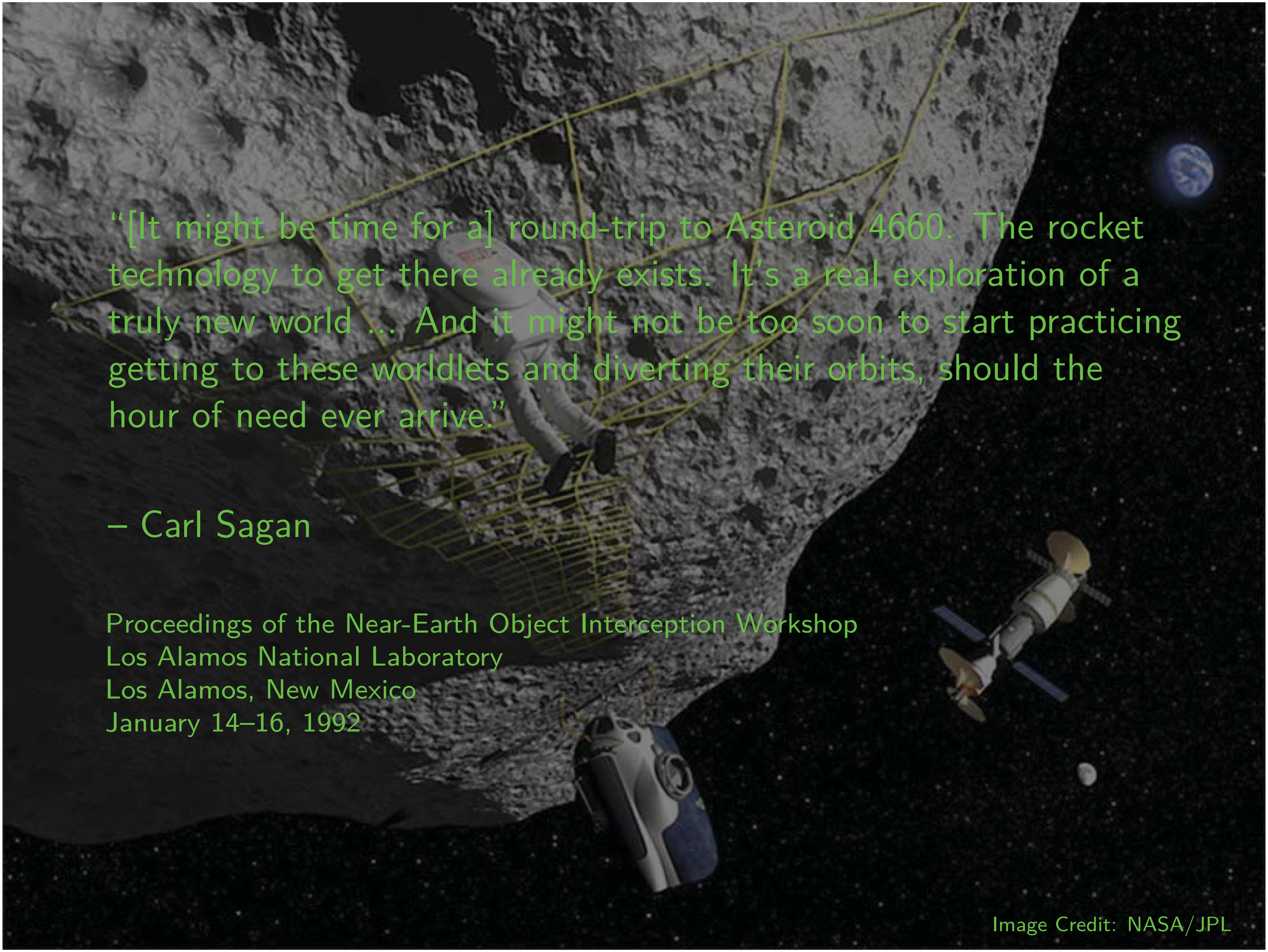
Selected NHATS Statistics:

Known NEAs: 10,721
NHATS NEAs: 1,167 (~10.9% of known)
Mean *H* for Known NEAs: 21.762
Mean *H* for NHATS NEAs: 24.759
NHATS NEAs by Orbit Type:
Atiras: 0% (0% of Atiras)
Atens: 23% (33% of Atens)
Apollos: 60% (12% of Apollos)
Amors: 17% (5% of Amors)
NHATS NEAs SMA (AU): 0.76, 1.16, 1.82 (Min, Mean, Max)
NHATS NEAs ECC: 0.01, 0.23, 0.45 (Min, Mean, Max)
NHATS NEAs INC (deg): 0.02, 5.15, 16.26 (Min, Mean, Max)



Mars Trajectory Data Sources:

7 day stay Mars data:	Folta, D., Barbee, B. W., Englander, J., Vaughn, F., Lin, T. Y., "Optimal Round-Trip Trajectories for Short Duration Mars Missions," AAS/AIAA Paper AAS 13-808, August 2013
45 day stay Mars data:	Folta, D., Barbee, B. W., Vaughn, F., "Analysis of Short Duration Round-Trip Mars Mission Opportunities During the Mid-2030s," Internal NASA/GSFC presentation, November 2011
500 day stay Mars data*:	Drake, B. G., ed. "Human Exploration of Mars Design Reference Architecture 5.0 Addendum," NASA/SP-2009-566-ADD, July 2009, http://www.nasa.gov/pdf/373667main_NASA-SP-2009-566-ADD.pdf *(w/ adjustments by B. W. Barbee for 12 km/s max Earth re-entry)
Mars flyby data:	Adamo, D. R. analysis of http://inspirationmars.org/Written_Testimony_DTito_Nov2013.pdf and http://www.youtube.com/watch?v=pdu7Kk5si1k", with input from Loucks, M.



"[It might be time for a] round-trip to Asteroid 4660. The rocket technology to get there already exists. It's a real exploration of a truly new world ... And it might not be too soon to start practicing getting to these worldlets and diverting their orbits, should the hour of need ever arrive."

– Carl Sagan

Proceedings of the Near-Earth Object Interception Workshop
Los Alamos National Laboratory
Los Alamos, New Mexico
January 14–16, 1992

Image Credit: NASA/JPL