Near-Earth Asteroids: Destinations for Human Exploration

Presented to the AIAA Mid-Atlantic Section Awards Dinner

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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
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

Determining Asteroid Sizes

Visible Light
- High Albedo “Chalk”
- Low Albedo “Charcoal”

Brightness alone does not correspond to size

Infrared Light
- High Albedo “Chalk”
- Low Albedo “Charcoal”

Brightness corresponds to size

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)

\[ \alpha > 1.0 \text{ AU} \]
\[ 1.017 \text{ AU} < q < 1.3 \text{ AU} \]

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

\[ \alpha > 1.0 \text{ AU} \]
\[ q < 1.017 \text{ AU} \]

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

\[ \alpha < 1.0 \text{ AU} \]
\[ Q > 0.983 \text{ AU} \]

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

\[ \alpha < 1.0 \text{ AU} \]
\[ Q < 0.983 \text{ AU} \]

\( q = \) perihelion distance, \( Q = \) aphelion distance, \( \alpha = \) semi-major axis
NeO Discovery Statistics

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 ≥ 1 km)

Estimates for undiscovered NEAs:

- ~70 NEAs > 1 km in diameter
- ~16,000 NEAs 100 to 1000 m in diameter
- ~10^6 NEAs with diameter < 100 m
NEA Population Census (2011)

A Near-Earth Asteroid Census
Each image represents 100 objects

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.
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 $\Delta v$ 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 \( \Delta v \), 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 \( \Delta v \) 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

JPL SBDB

NHATS Tables

JPL NHATS Computer

NHATS Website
[http://neo.jpl.nasa.gov/nhats]

- NHATS Trajectory Data Table (filterable/sortable)
- Optical & Radar Observability for NHATS-Compliant NEAs
- PCC Plots

NEA Discoveries
Updated NEA Astrometry

SSD Web-server
Horizons
Orbit Determination System

New/Updated Orbits

NHATS Trajectory Data and Observability Parameters

SBDB NEA List

GSFC NHATS List

Ephemeris Retrieval Scripts

Ephemeris Files for New NEAs and Those with Updated Orbit Solutions

Data Delivery Emails

PCC Plot Files

NHATS Summary Data File

Compressed Binned Optimal Trajectory Data

NASA Agency Mailing List Service (AMLS)

NHATS Email Subscribers

NHATS Daily Update Email
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 $\Delta v$ 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 $\leq 450$ days.
5. Stay time at the NEA $\geq 8$ days.
6. Earth atmospheric entry speed $\leq 12$ 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.
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.

| Column headings described below | Selected 24 out of 1652 records |

<table>
<thead>
<tr>
<th>Object Designation</th>
<th>Orbit ID</th>
<th>H (mag)</th>
<th>Estimated Diameter (m)</th>
<th>OCC</th>
<th>Min. delta-V (km/s)</th>
<th>Min. Duration (km/s)</th>
<th>&lt; Viable Trajectories</th>
<th>Next Optical Opportunity (yyyy-mm [YJ])</th>
<th>Next Arecibo Radar Opportunity (yyyy-mm [SNR])</th>
<th>Next Goldstone Radar Opportunity (yyyy-mm [SNR])</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2006 BZ47)</td>
<td>6</td>
<td>25.4</td>
<td>14 - 64</td>
<td>3</td>
<td>4.184, 354</td>
<td>5.972, 250</td>
<td>1572528</td>
<td>2034-12 [15.5]</td>
<td>2035-02 [14600]</td>
<td>2035-02 [37]</td>
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<tr>
<td>(2012 MD7)</td>
<td>7</td>
<td>24.1</td>
<td>27 - 120</td>
<td>7</td>
<td>5.071, 354</td>
<td>5.989, 314</td>
<td>697652</td>
<td>2013-04 [23.1]</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>(2012 Q142)</td>
<td>19</td>
<td>23.5</td>
<td>35 - 196</td>
<td>0</td>
<td>5.563, 354</td>
<td>5.940, 358</td>
<td>683986</td>
<td>2013-03 [23.9]</td>
<td>2024-04 [38]</td>
<td>none</td>
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<tr>
<td>(2012 HK31)</td>
<td>12</td>
<td>25.4</td>
<td>15 - 65</td>
<td>6</td>
<td>5.746, 322</td>
<td>5.924, 366</td>
<td>827317</td>
<td>2022-03 [22.0]</td>
<td>none</td>
<td>none</td>
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<tr>
<td>(2011 UX27b)</td>
<td>1</td>
<td>25.8</td>
<td>12 - 53</td>
<td>6</td>
<td>5.903, 354</td>
<td>5.903, 354</td>
<td>521511</td>
<td>2030-12 [23.2]</td>
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<td>none</td>
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</table>
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 delta-V 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: \( \text{total } \Delta V \leq 6 \text{ km/s} \) \( \text{total dur.} \leq 360 \text{ days} \) \( \text{stay} \geq 8 \text{ days} \) \( \text{launch: 2016-2040} \)

Column headings described below

<table>
<thead>
<tr>
<th>Object Designation</th>
<th>Orbit ID</th>
<th>H (mag)</th>
<th>Estimated Diameter (m)</th>
<th>OCC</th>
<th>Min. delta-V (km/s, d)</th>
<th>Min. Duration (km/s, d)</th>
<th>Viable Trajectories</th>
<th>Next Optical Opportunity (yyyy-mm [Vp])</th>
<th>Next Arecibo Radar Opportunity (yyyy-mm [SNR])</th>
<th>Next Goldstone Radar Opportunity (yyyy-mm [SNR])</th>
</tr>
</thead>
</table>

Column headings described below

<table>
<thead>
<tr>
<th>(2000 SG344)</th>
<th>Min. delta-V Parameters</th>
<th>Min. Duration Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Mission delta-V (km/s)</td>
<td>3.556</td>
<td>5.973</td>
</tr>
<tr>
<td>Total Mission Duration (d)</td>
<td>354</td>
<td>114</td>
</tr>
<tr>
<td>Outbound Flight Time (d)</td>
<td>145</td>
<td>49</td>
</tr>
<tr>
<td>Stay Time (d)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Inbound Flight Time (d)</td>
<td>201</td>
<td>57</td>
</tr>
<tr>
<td>Launch date (YYYY-MM-DD)</td>
<td>2028-04-22</td>
<td>2029-07-22</td>
</tr>
</tbody>
</table>

\( C_0 \) (km^2/s^2) | 1.737 | 3.009 |
Departure \( V_{infty} \) (km/s) | 1.318 | 1.735 |
Earth Departure \( \Delta V \) (km/s) | 3.256 | 3.314 |
d\( \Delta V \) to Arrive at NEA (km/s) | 0.113 | 1.067 |
d\( \Delta V \) to Depart NEA (km/s) | 0.187 | 1.592 |
Earth return \( \Delta V \) (km/s) | 0.000 | 0.000 |
Entry Speed (km/s) | 11.133 | 11.214 |
Departure Declination (deg) | -8.950 | -22.493 |
Return Declination (deg) | -5.933 | 22.663 |
NHATS Trajectory Solution ID | 890465 | 2048662 |

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

The plot above shows total mission delta-V as a function of Earth departure date and total roundtrip 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 SG344.

NHATS PCC plot for 2012 PB20.
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 $\Delta v$ NHATS-compliant NEAs Tend to Have the Largest $H$ (smallest diameters)
NHATS-compliant NEA Synodic Periods

Minimum Round-Trip $\Delta v$ versus Synodic Period for all NHATS-compliant NEAs
NHATS-compliant NEA Synodic Periods

Only Showing NEAs with Synodic Period ≤ 30 Years
Example Round-Trip Trajectory Solutions

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

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Diameter (m)</td>
<td>19–86</td>
<td>450</td>
<td>35–159</td>
<td>128–573</td>
<td>18–81</td>
<td>325</td>
</tr>
<tr>
<td>OCC</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Total Δv (km/s)</td>
<td>3.601</td>
<td>4.989</td>
<td>6.654</td>
<td>6.440</td>
<td>6.915</td>
<td>6.875</td>
</tr>
<tr>
<td>Total Mission Duration (days)</td>
<td>346</td>
<td>154</td>
<td>354</td>
<td>354</td>
<td>354</td>
<td>354</td>
</tr>
<tr>
<td>Outbound Flight Time (days)</td>
<td>137</td>
<td>65</td>
<td>121</td>
<td>73</td>
<td>73</td>
<td>193</td>
</tr>
<tr>
<td>Stay Time (days)</td>
<td>32</td>
<td>16</td>
<td>64</td>
<td>16</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>Inbound Flight Time (days)</td>
<td>177</td>
<td>73</td>
<td>169</td>
<td>265</td>
<td>89</td>
<td>129</td>
</tr>
<tr>
<td>Earth Departure Date</td>
<td>2028-04-22</td>
<td>2029-07-14</td>
<td>2024-06-30</td>
<td>2024-03-18</td>
<td>2024-04-19</td>
<td>2024-10-28</td>
</tr>
<tr>
<td>Earth Departure C₃ (km²/s²)</td>
<td>1.737</td>
<td>1.990</td>
<td>25.051</td>
<td>2.897</td>
<td>5.818</td>
<td>28.035</td>
</tr>
<tr>
<td>Earth Departure Δv (km/s)</td>
<td>3.256</td>
<td>3.268</td>
<td>4.276</td>
<td>3.309</td>
<td>3.441</td>
<td>4.400</td>
</tr>
<tr>
<td>Earth Departure Declination</td>
<td>−8.723°</td>
<td>−22.498°</td>
<td>−20.430°</td>
<td>74.941°</td>
<td>27.574°</td>
<td>65.776°</td>
</tr>
<tr>
<td>NEA Arrival Δv (km/s)</td>
<td>0.128</td>
<td>0.754</td>
<td>1.227</td>
<td>1.912</td>
<td>1.287</td>
<td>0.779</td>
</tr>
<tr>
<td>NEA Departure Δv (km/s)</td>
<td>0.217</td>
<td>0.968</td>
<td>1.152</td>
<td>1.219</td>
<td>2.186</td>
<td>1.696</td>
</tr>
<tr>
<td>Earth Return Δv (km/s)</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Atmospheric Entry Speed (km/s)</td>
<td>11.141</td>
<td>11.157</td>
<td>11.692</td>
<td>11.244</td>
<td>11.396</td>
<td>11.996</td>
</tr>
</tbody>
</table>

Osculating orbital elements at epoch 2013-04-18.0 TDB and orbit group classifications.
154 day round-trip trajectory to 2000 SG\textsubscript{344}. 354 day round-trip trajectory to 2012 PB\textsubscript{20}.

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

<table>
<thead>
<tr>
<th></th>
<th>2000 SG\textsubscript{344} (154 day)</th>
<th>2008 EV\textsubscript{5}</th>
<th>2012 PB\textsubscript{20}</th>
<th>99942 Apophis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Distance to Sun (AU)</td>
<td>0.976</td>
<td>0.912</td>
<td>0.951</td>
<td>0.893</td>
</tr>
<tr>
<td>Maximum Distance from Sun (AU)</td>
<td>1.027</td>
<td>1.074</td>
<td>1.052</td>
<td>1.109</td>
</tr>
<tr>
<td>Maximum Distance from Earth (AU)</td>
<td>0.055</td>
<td>0.343</td>
<td>0.224</td>
<td>0.499</td>
</tr>
<tr>
<td>Maximum Distance from Earth (LD)</td>
<td>21.226</td>
<td>133.325</td>
<td>86.987</td>
<td>194.211</td>
</tr>
</tbody>
</table>
154 day round-trip trajectory to 2000 SG₃₄₄.

354 day round-trip trajectory to 2012 PB₂₀.
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.

Selected NHATS Statistics:
- Known NEAs: 10,721
- NHATS NEAs: 1,167 (~10.9% of known)
- Mean H for Known NEAs: 9.71
- Median H for NHATS NEAs: 24.750
- NHATS NEAs by Orbit Type:
  - Apollo: 86% (~2% of Apollo)
  - Amor: 17% (~5% of Amors)
  - Atens: 2% (~33% of Atens)
  - Apollon: 60% (~12% of Apollons)

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

Note: Round-trip ΔV and flight time for missions to Phobos or Delos are similar to Round-trip ΔV and flight time for Mars missions.

2031–2046 Earth Departures,
- 500 day stay on Mars surface,
- 12 km/s max Earth re-entry

Mars Trajectory Data Sources:
“[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