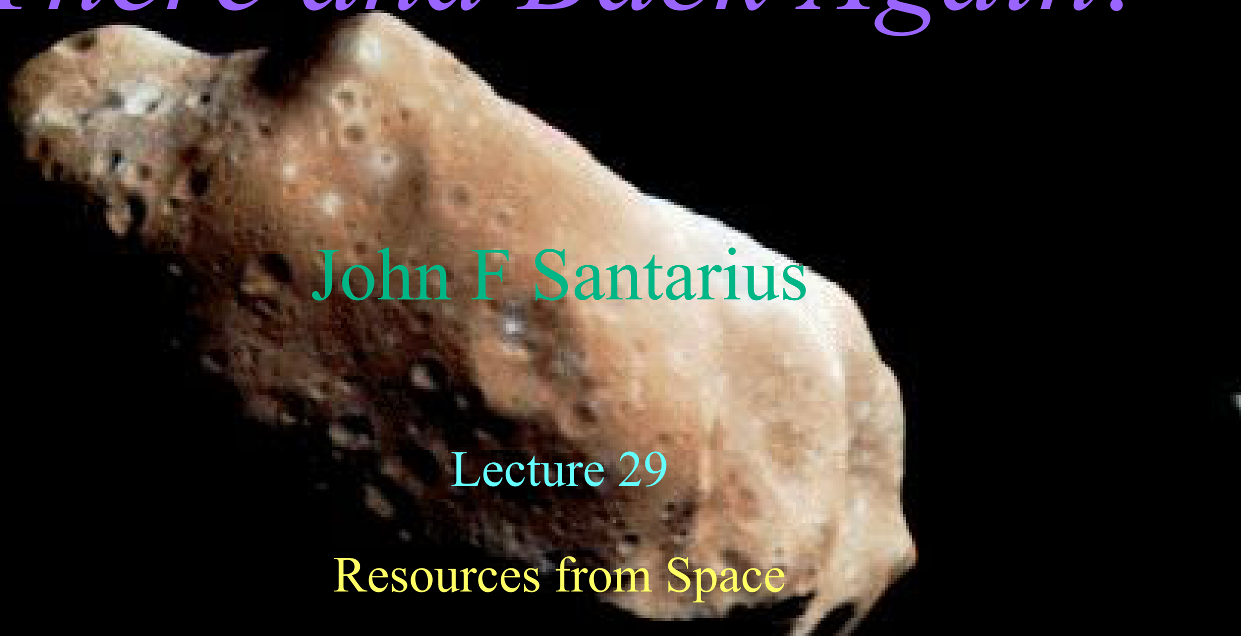
Travel to Asteroids and Moons

There and Back Again!



John F Santarius

Lecture 29

Resources from Space

NEEP 533/ Geology 533 / Astronomy 533 / EMA 601

University of Wisconsin

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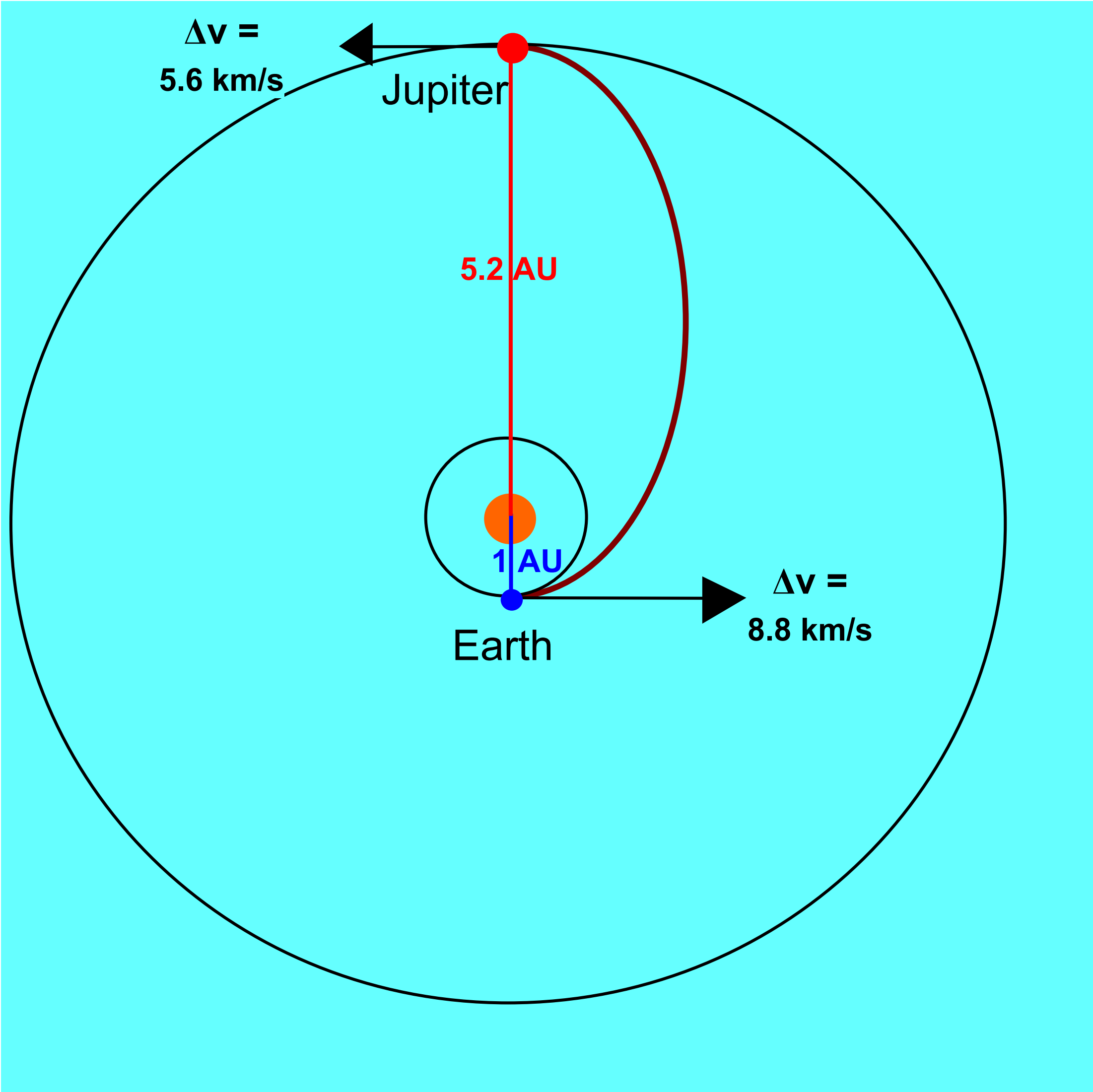
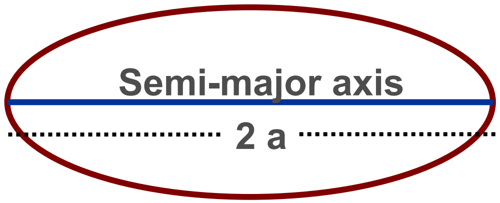
Use the Semi-Major Axis of the Ellipse to Calculate Hohmann Trajectory Parameters





$$\frac{T_1}{T_2} = \left(\frac{a_1}{a_2}\right)^{3/2}$$

Use Earth as reference:

$T_2 = 1$ year; $a_2 = 1$ AU

Earth-Jupiter:

$a = (1\text{ AU} + 5.2\text{ AU})/2$
$= 3.1$ AU

$T = 0.5\,(a\,/\,1\text{ AU})^{3/2}$ years $= \sim 2.7$ years

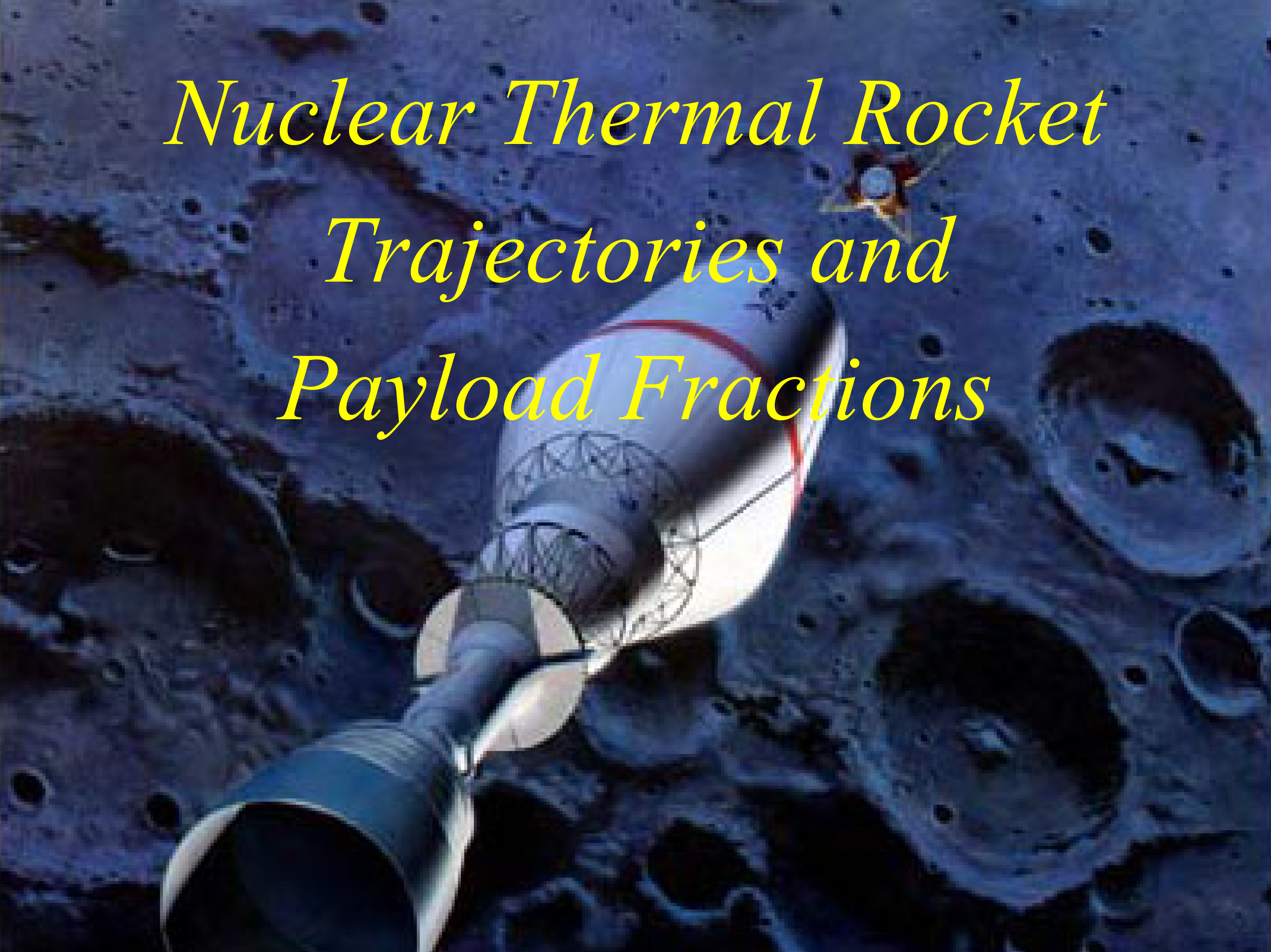
Characteristics of Hohmann Transfers from Earth into the Solar System

Planet	*Total Δv (km/s)*	*Travel time (year)*
Mercury	-17.2	0.29
Venus	-5.27	0.40
Mars	5.56	0.71
Asteroid belt	11.7	1.4
Jupiter	14.4	2.7
Saturn	15.7	6.0
Uranus	15.9	16
Neptune	15.7	30
Pluto	15.5	45

Hohmann Transfer Δv Values Drop Slightly for Outermost Planets

Planet	*First Δv (km/s)*	*Second Δv (km/s)*	*Total Δv (km/s)*
Saturn	10.30	5.44	15.7
Uranus	11.30	4.66	15.9
Neptune	11.60	4.05	15.7
Pluto	11.80	3.69	15.5

Nuclear Thermal Rocket Trajectories and Payload Fractions



Rocket Payload Fraction Increases Exponentially with the Inverse of the Exhaust Velocity

Rocket equation

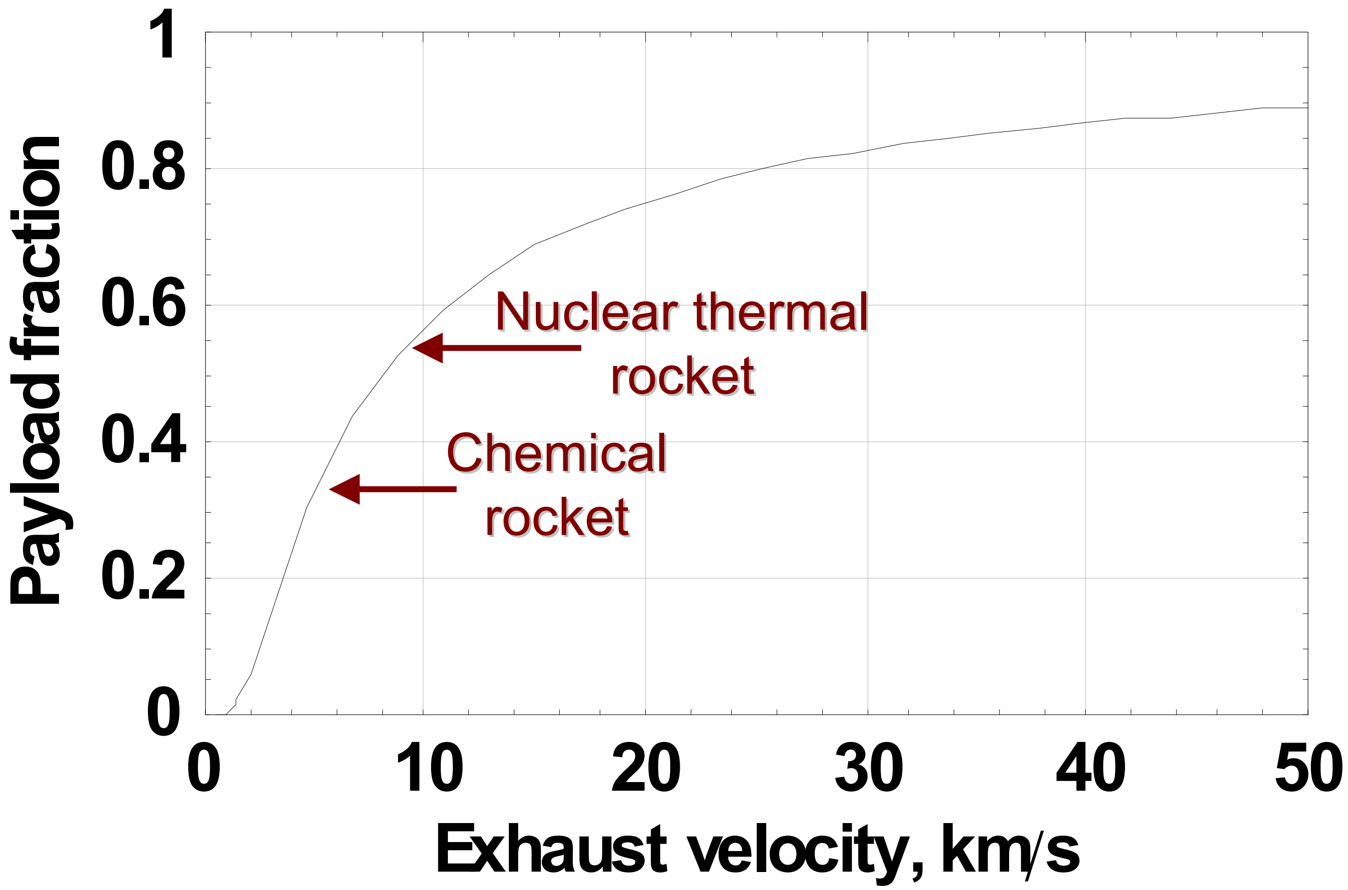
$$\frac{m_f}{m_i} = \exp\left(\frac{-\Delta v}{v_{ex}}\right)$$

$m_f \equiv$ **final mass**
$m_i \equiv$ **initial mass**
$\Delta v \equiv$ **velocity increment**
$v_{ex} \equiv$ **exhaust velocity**

- Chemical rocket
  - $v_{ex} \approx 4.5$ km/s (I_{sp}=450 s).
- Nuclear thermal rocket
  - $v_{ex} \approx 9.0$ km/s (I_{sp}=900 s).
- Nuclear electric rocket
  - v_{ex}~100 km/s (I_{sp}=10,000 s).

Nuclear Thermal Rockets Enable Larger Payloads than Chemical Rockets Can Provide

Earth-Mars one-way trip: Δv~5.6 km/s (Hohmann)



Considering a Round Trip Improves the Advantage of Nuclear Thermal Rockets Over Chemical Rockets

Earth-Asteroids round trip: Δv~11.7 km/s (Hohmann, each way)

Outbound: Earth to Asteroids

$$\frac{m_l + m_{p2}}{m_l + m_{p1} + m_{p2}} = \exp\left(\frac{-\Delta v_1}{v_{ex}}\right)$$

Inbound: Asteroids to Earth

$$\frac{m_l}{m_l + m_{p2}} = \exp\left(\frac{-\Delta v2}{v_{ex}}\right)$$

$m_l \equiv$ payload (+structure) mass

$m_{pi} \equiv$ stage *i* propellant mass

$\Delta v_i \equiv$ stage *i* velocity increment

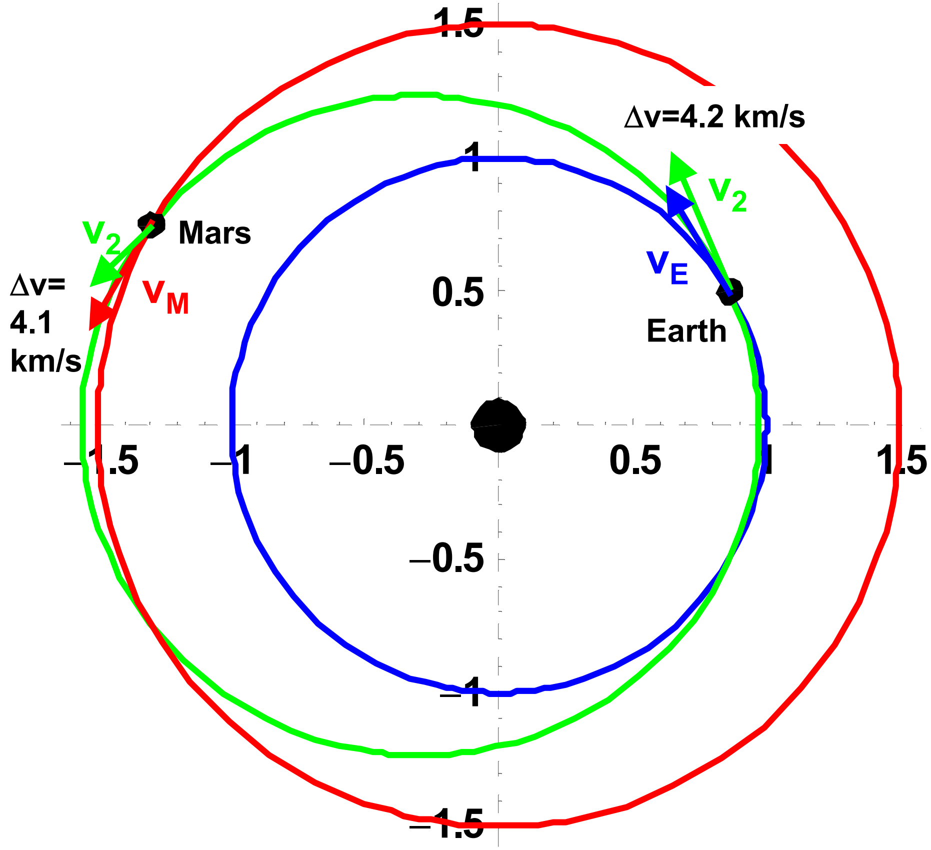
$v_{ex} \equiv$ exhaust velocity

- Solve these simultaneously to find payload ratio:
  - Chemical rocket: 0.0055
  - Nuclear thermal rocket: 0.074

$$\frac{m_l}{m_l + m_{p1} + m_{p2}}$$

Nuclear Thermal Rockets Follow Partial Conic-Section Trajectories

- Potential NTR trajectory
  - a=1.27, e=0.231
  - Total Δv = 8.3 km/s
  - Total time ~ 6 months
- For this trajectory, the rocket travels only part of an ellipse.
- This trajectory is faster than a Hohmann trajectory, but it requires more energy (Δv).




Accessing the Moons
of the Solar System

Launching from Moons Is Relatively Easy, but Planetary Gravitational Fields Can Be Large

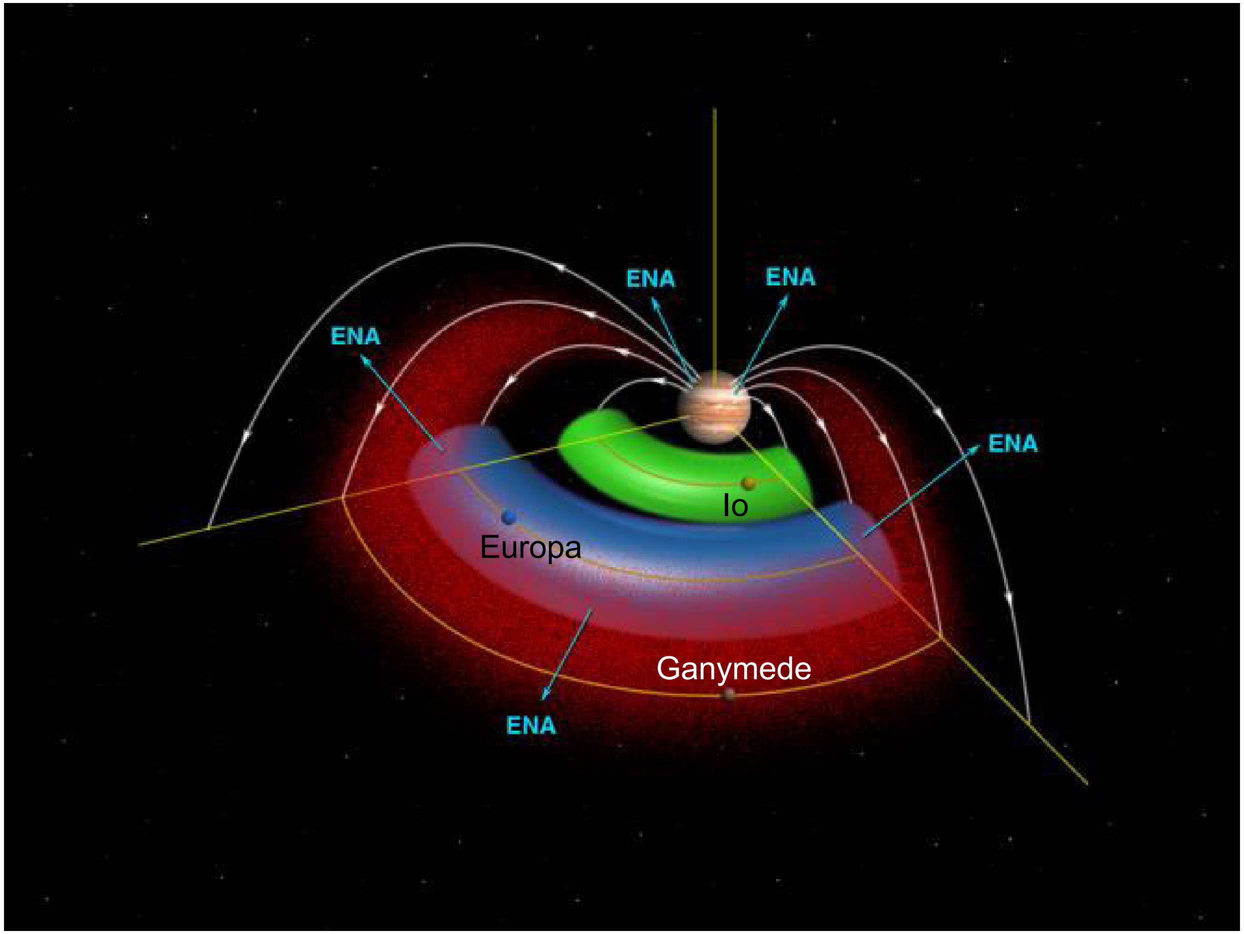
Moon	***Surface escape Δv (km/s)***	***Planet escape Δv (km/s)***
Moon (Earth)	2.37	1.44
Io (Jupiter)	2.56	24.5
Europa (Jupiter)	2.02	19.4
Ganymede (Jupiter)	2.74	15.4
Callisto (Jupiter)	2.44	11.6
Titan (Saturn)	2.54	7.88

Escape from Planetary "Surfaces" Can Be Difficult

Planet	*Surface escape Δv (km/s)*	*Sun escape Δv (km/s)*
Mercury	4.25	67.7
Venus	10.4	49.6
Earth	11.2	42.1
Mars	5.03	34.1
Jupiter	59.6	18.5
Saturn	35.5	13.7
Uranus	21.4	9.62
Neptune	23.8	7.69
Pluto	0.97	6.71

Jupiter's Satellites Exist in an Extreme Radiation Environment

- 1 Mrad environment at Europa

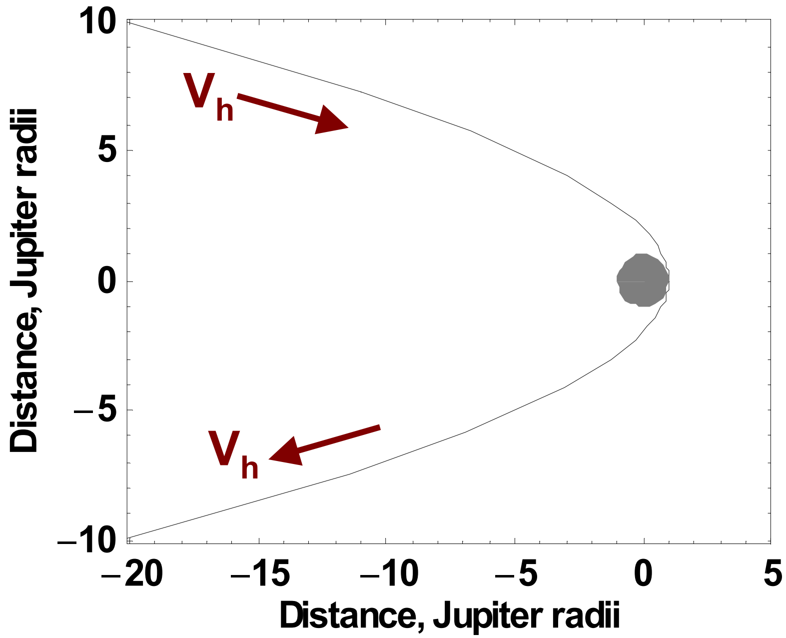


Travel to the Asteroids

Painting by Denise Watt

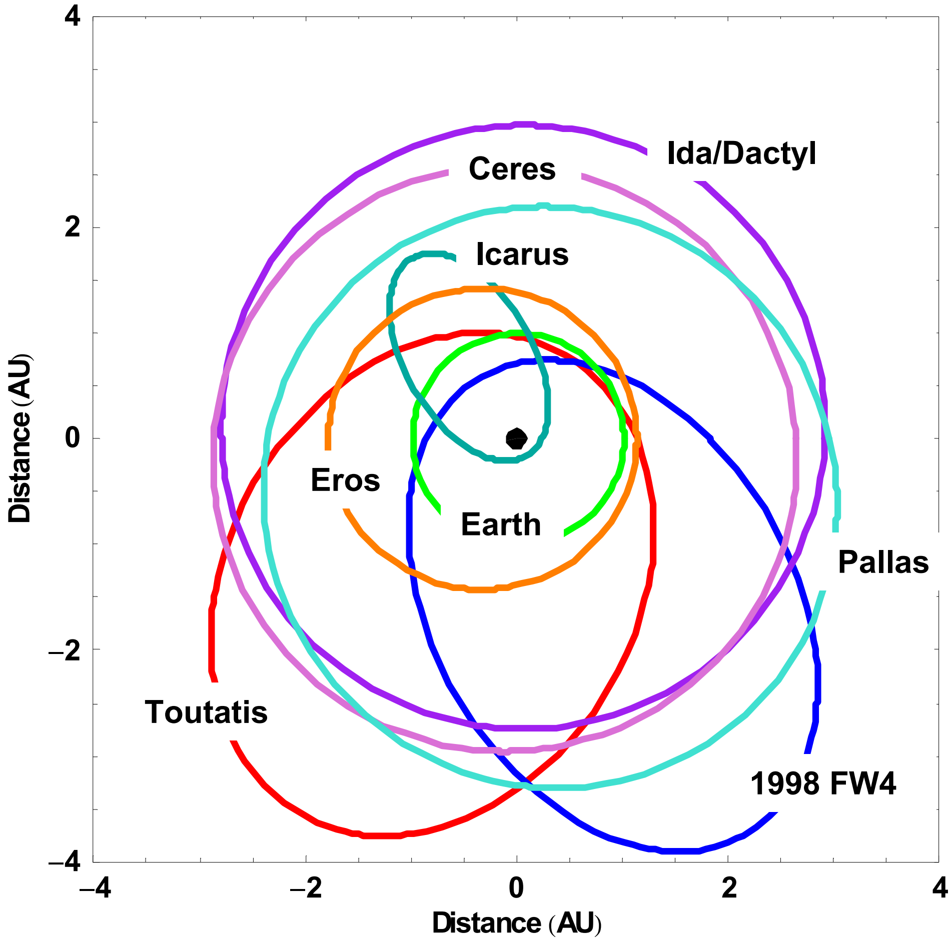
How Can Main-Belt Asteroids Best Be Moved to Earth?
Aim at Jupiter and Get a Gravity Assist!

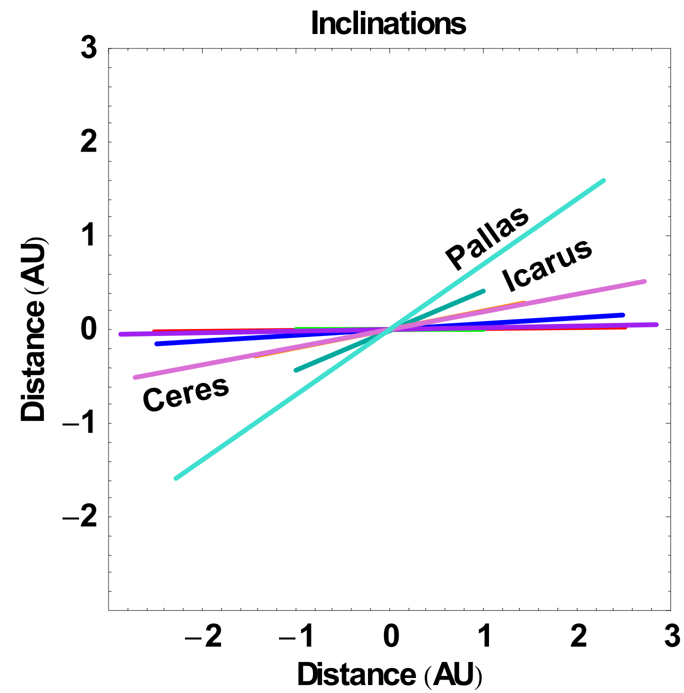
- Jovian fly-by's can give a very large Δv (~10 km/s) to the spacecraft.
- Earth-main asteroid belt
  - Δv ~ 11.7 km/s
  - Many asteroids require much higher Δv, because of inclination or eccentricity.
- Asteroid-Jupiter
  - Δv ~ 4.0 km/s
  - Hohmann travel time = 4.1 years



Many Asteroids Exist Outside of the Main Belt

- Selected asteroid trajectories

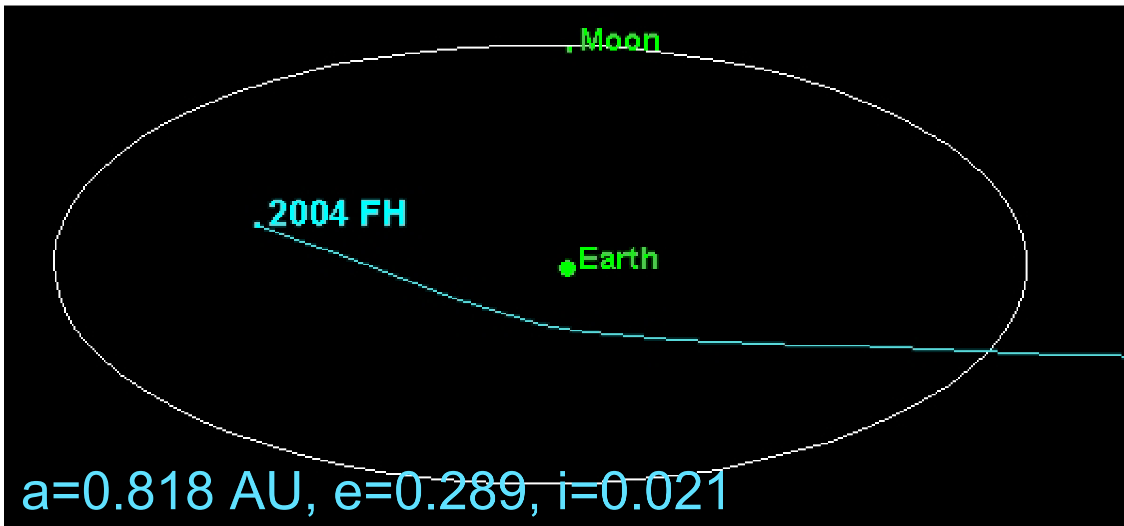




{a→2.51, e→0.634, i→0.47};	(* Toutatis *)
{a→2.5, e→0.73, i→3.6};	(* 1998 FW4 *)
{a→1, e→0.017, i→0};	(* Earth *)
{a→2.86, e→0.045, i→1.14};	(* Ida *)
{a→1.08, e→0.83, i→22.9};	(* Icarus *)
{a→1.46, e→0.22, i→10.8};	(* Eros *)
{a→2.77, e→0.079, i→10.6};	(* Ceres *)
{a→2.77, e→0.23, i→34.8};	(* Pallas *)

Asteroid 2004FH Recently Approached *Very* Near the Earth

- Point of closest approach was 49,000 km



Orbital period:

$a \approx 0.82$ AU

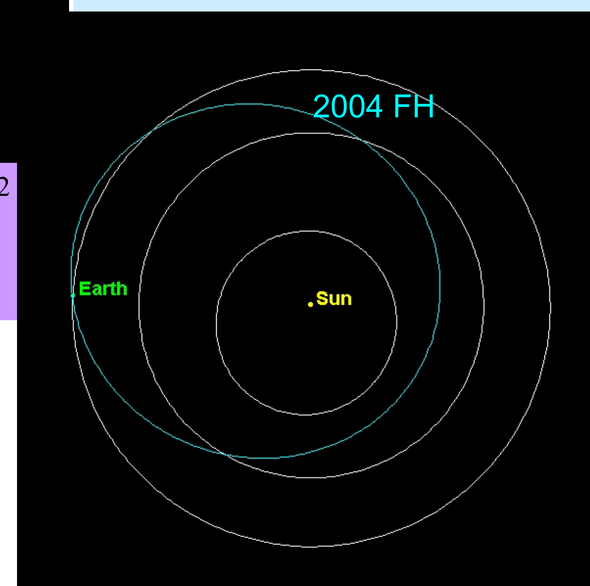
$T = (a\ /\ 1\ \text{AU})^{3/2}$ years

$= \sim 0.74$ years

$= \sim 8.8$ months

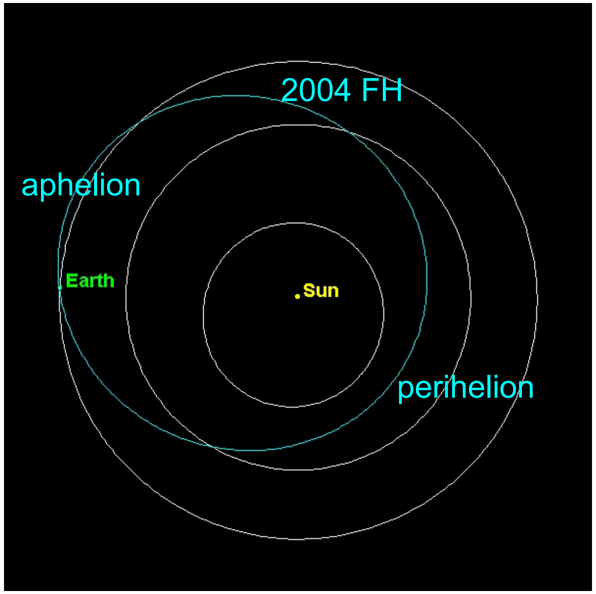
$$v = \left[GM \left(\frac{2}{r} - \frac{1}{a} \right) \right]^{1/2}$$

- Perihelion:
  - r = a(1-e) = 0.58 AU
  - v = 44.3 km/s
- Aphelion
  - r = a(1+e) = 1.05 AU
  - v = 24.5 km/s



An Impact of Asteroid 2004FH with Earth Would Not Have Caused Significant Damage

- Point of closest approach was 49,000 km
  - Velocity of 2004 FH at aphelion was 24.5 km/s
  - Earth's orbital velocity is 30 km/s
  - Velocity difference is v_{impact}~5.5 km/s
- Energy of 2004 FH impact would have been modest
  - $M \approx 3000\,\frac{\text{kg}}{\text{m}^3} \times \frac{4}{3}\pi (15\text{ m})^3 \approx 4\times 10^7\text{ kg}$
  - $E = \dfrac{M}{2} v^2 \approx 2\times 10^{14}\text{ J}$
  - This energy equals ~0.05 megatons of high explosive.



Large Asteroids Create Significant Damage

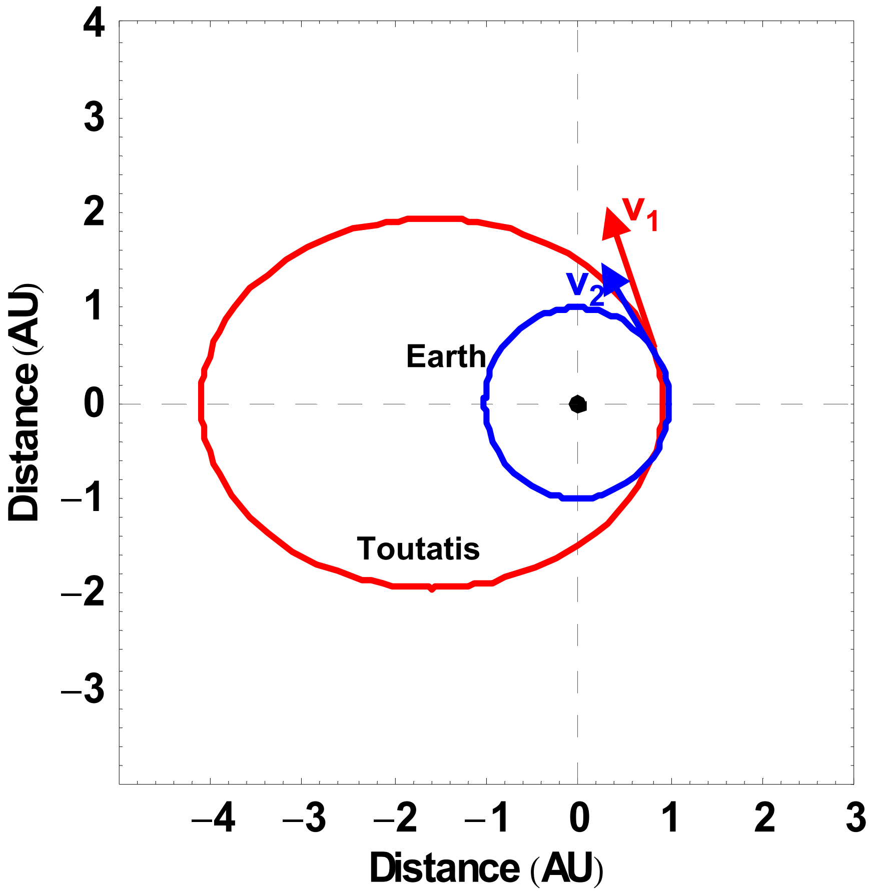
- Asteroids and comets ~ 10 m diameter:
  - Hit Earth approximately once a year.
  - Break up in the atmosphere and do little damage.
- Objects of ~100 m diameter:
  - Hit Earth at ~300 year intervals.
  - Do significant, localized damage.
    - The 1908 Tunguska object was of this class.
- Objects of ~1 km diameter can produce catastrophic global effects.

Deflecting Asteroids Poses Difficulties

- A Δv perpendicular to the asteroid's orbital plane cause it to oscillate about it original orbit.
  - Why? The asteroid's energy increases, but farther orbits have slower orbital speeds, so the equilibrium orbit becomes more elliptical.
- The most effective deflection technique is to give the asteroid a parallel Δv.
  - Adds or subtracts velocity magnitudes, as opposed to vector addition in perpendicular case.
  - Changes semi-major axis and period of orbit.
  - 1 Earth-radius deflection requires $\Delta v \sim 0.1\ m\ s^{-1} / \tau$ years for an initially circular orbit.

Large Eccentricities Lead to Large Δv's for Single-Impulse Deflection of Asteroid Orbits

- Toutatis: a=2.51 AU, e=0.63, i=0.5°



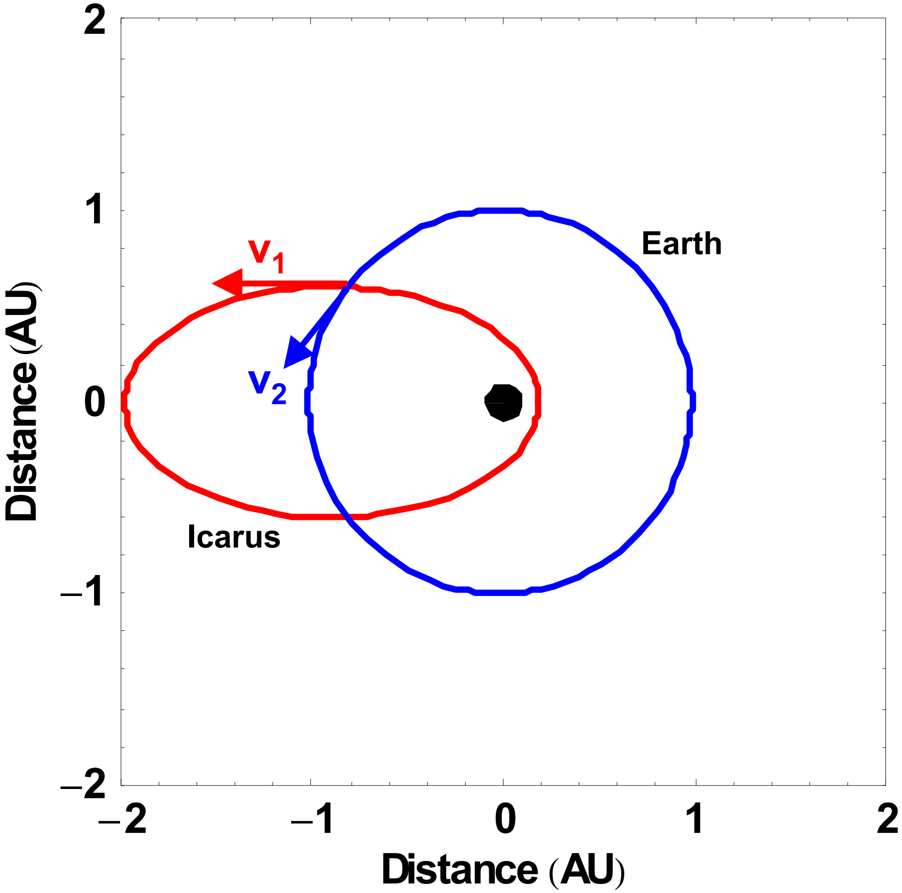
- Speed on an elliptic orbit is

$$v = \left[GM\left(\frac{2}{r} - \frac{1}{a}\right)\right]^{1/2}$$

- Speed of Toutatis as it crosses Earth's orbit is v_1 = 37.7 km/s.
- Earth's velocity is v_2=29.4 km/s (e=0.017 included).
- Angle between velocity vectors is 38°.
- Adding vectors gives Δv=10.8 km/s.

Large Inclinations Substantially Increase Δv's for Single-Impulse Deflection of Asteroid Orbits

- Icarus: a=1.08 AU, e=0.83, i=22.9°



- Velocity of Icarus as it crosses Earth's orbit is v_1 = 30.5 km/s.
- Earth's velocity is v_2=29.4 km/s (e=0.017 included).
- Angle between velocity vectors is 60°.
- Adding vectors *in plane* gives Δv=27.9 km/s.
- Inclination of orbits adds another 23.2 km/s
- Total Δv=51 km/s.

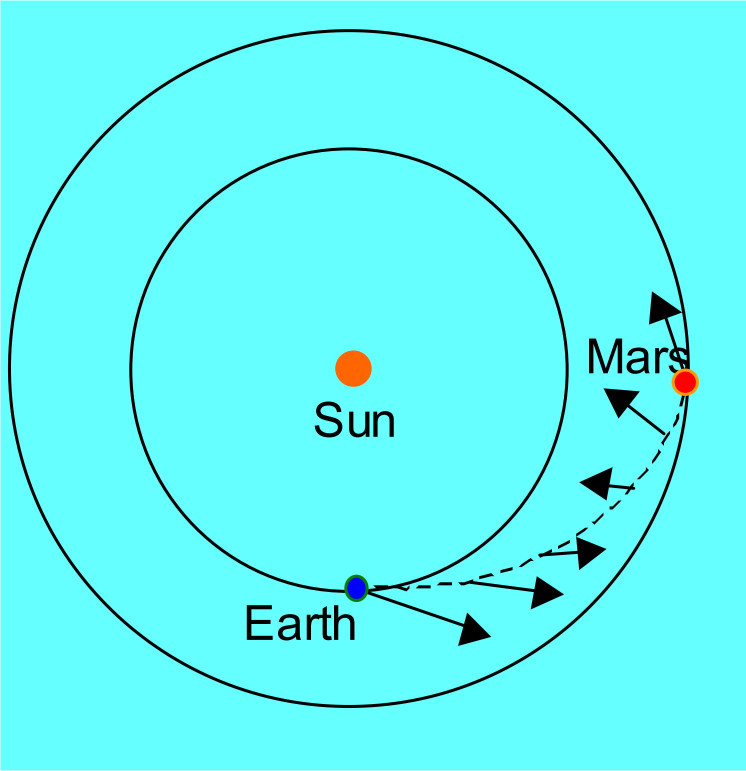
Hohmann Trajectories Can Give Low Δv's for Some Asteroids

- For asteroids with nearly circular orbits of low eccentricity and inclination, Δv's can be < 2 km/s.
  - For example, 1999 FA (~330 m diameter) has a=1.078, e=0.133, i=12.
    - The corresponding Hohmann trajectory to Earth has Δv=1.8 km/s.
  - Some asteroid resource literature quotes Δv's of 100's of m/s, but I have not personally verified these values.
- Note: the Moon can gravity assist with ~1 km/s.

Taking Full Advantage of High Exhaust Velocity Requires Optimizing Trajectories

- Power limitations typically mean that high exhaust velocity leads to low thrust.
- Low-thrust trajectories have the rockets powered on for much of the trip.
  - Such operation leads to high efficiency and relatively easy plane changes.

Low-thrust trajectory
(variable acceleration)



Note: Trajectory is schematic, not calculated.