Planetary Defense

Space System Design, MAE 342, Princeton University

Robert Stengel

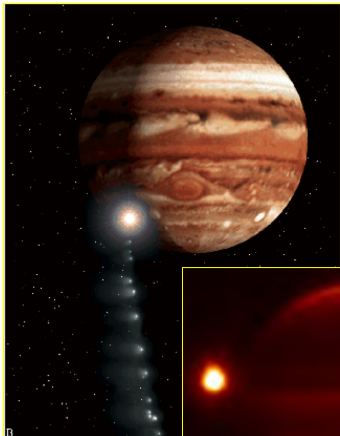
- Asteroids and Comets
- Spacecraft
- Detection, Impact Prediction, and Warning
- Options for Minimizing the Hazard
- The *2020 UA* Project

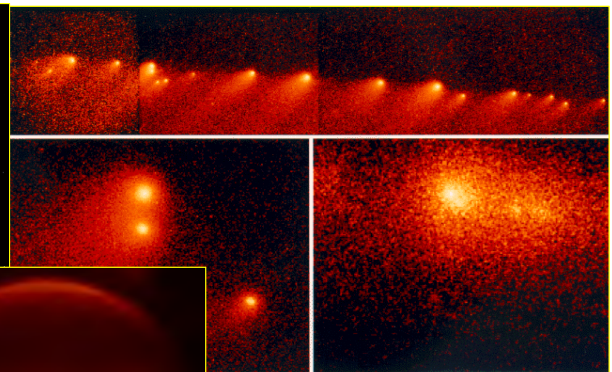
http://www.princeton.edu/~stengel/MAE342.html

What We Want to Avoid

Asteroids and Comets DO Hit Planets

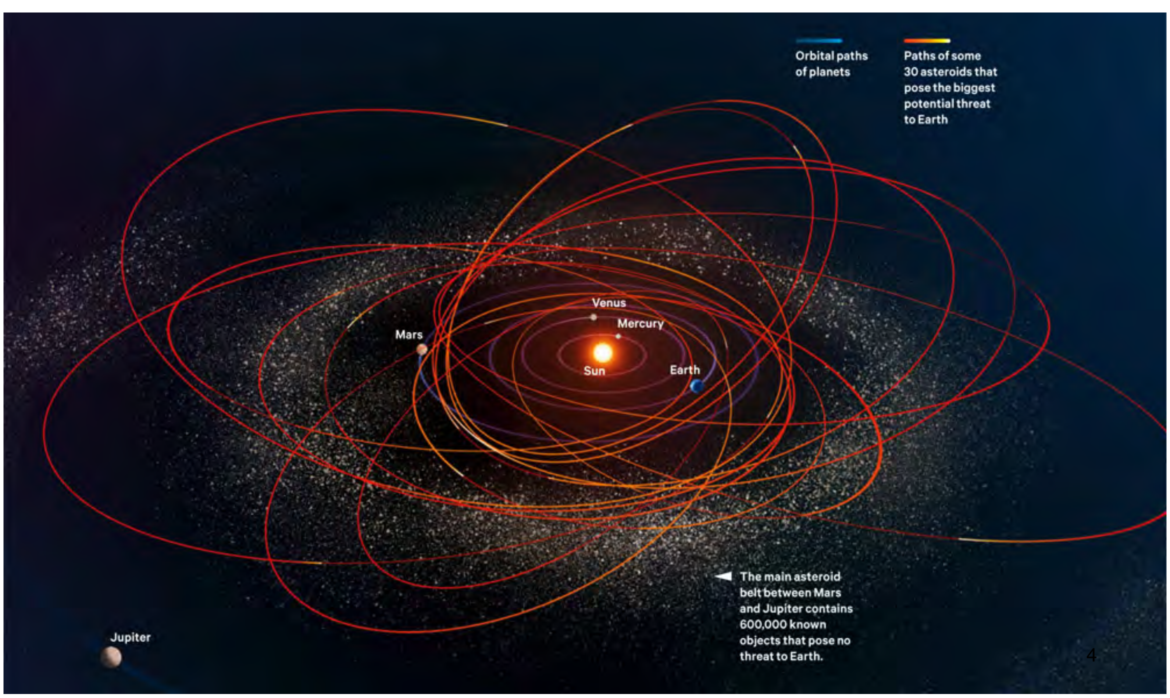
[Comet Schumacher-Levy 9 (1994)]



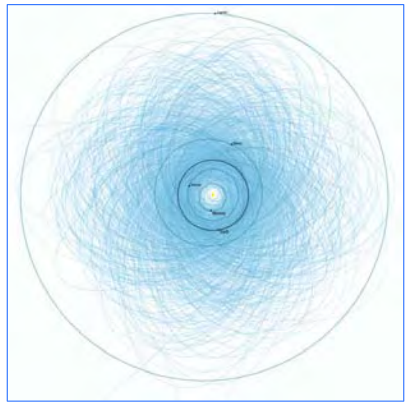


- **Trapped in orbit around Jupiter ~1929**
- **Periapsis within "The Roche Limit"**
- **Fragmented by tidal forces from 1992 encounter with Jupiter**

Asteroid Paths Posing Hazard to Earth



Potentially Hazardous Object/ Asteroid (PHO/A)

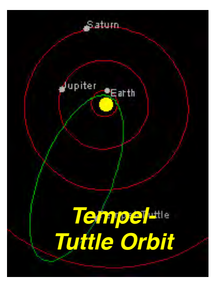


Physical Characteristics
- *Dimensions: 5 x 2 x 2 km*
- *Mass = 5 x 10^{13} kg*
- *Period = 4 yr*
- *Aphelion = 4.1 AU*
- *Perihelion = 0.94 AU*

PHA Characteristics (2013)
- *Diameter > 140 m*
- *Passes within 7.6 x 10^6 km of Earth (0.08 AU)*
- *> 1,650 PHAs (2016)*

Comets Leave Trails of Rocks and Gravel That Become Meteorites on Encountering Earth's Atmosphere

- Temple-Tuttle
  - Period ~ 33 yr
  - *Leonid* Meteor Showers each Summer
- Swift-Tuttle
  - Period ~ 133 yr
  - *Perseid* Meteor Showers each Summer

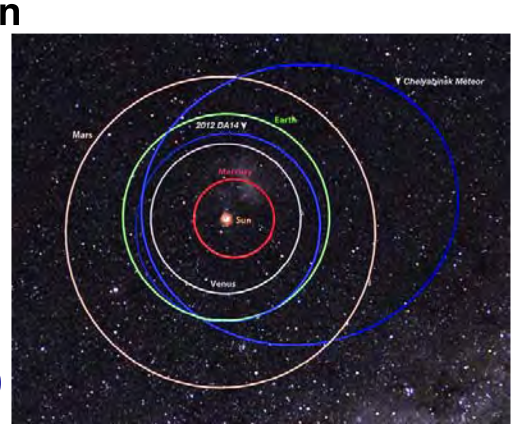


Known Asteroid “Impacts”, 2000 - 2013

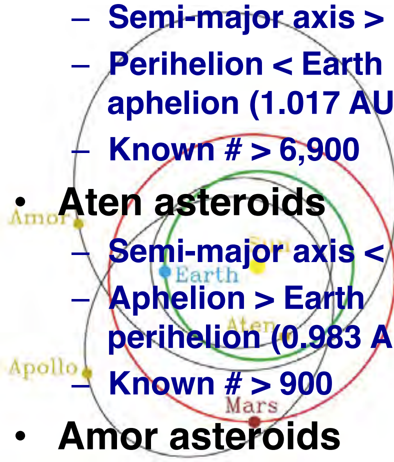
Chelyabinsk Meteor, Feb 15, 2013

Chelyabinsk Flight Path, 2013

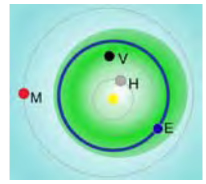
- **No warning, approach from Sun**
- **500 kT airburst explosion at altitude of 30 km**
- **Velocity ~ 19 km/s (wrt atmosphere), 30 km/s (V_∞)**
- **Diameter ~ 20 m**
- **Mass ~ 12,000-13,000 metric T**
- **1,500 injuries, damage to 7,200 buildings from blast wave**



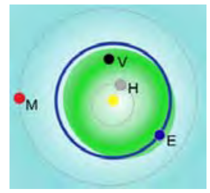
Near-Earth Objects



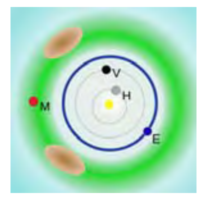
- Apollo asteroids
  - Semi-major axis > 1 AU
  - Perihelion < Earth aphelion (1.017 AU)
  - Known # > 6,900
- Aten asteroids
  - Semi-major axis < 1 AU
  - Aphelion > Earth perihelion (0.983 AU)
  - Known # > 900
- Amor asteroids
  - 1 AU ,Perihelion < 1.3 AU
  - Known # > 1,300



Apollo Asteroid Group



Aten Asteroid Group

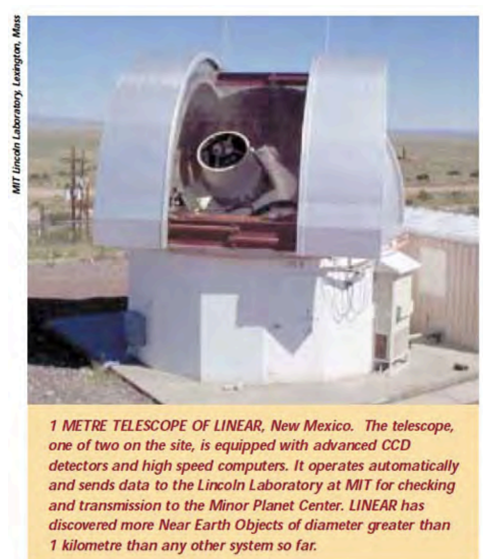


Amor Asteroid Group

Optical and Radio Telescopes

Deep Space Network (Goldstone)

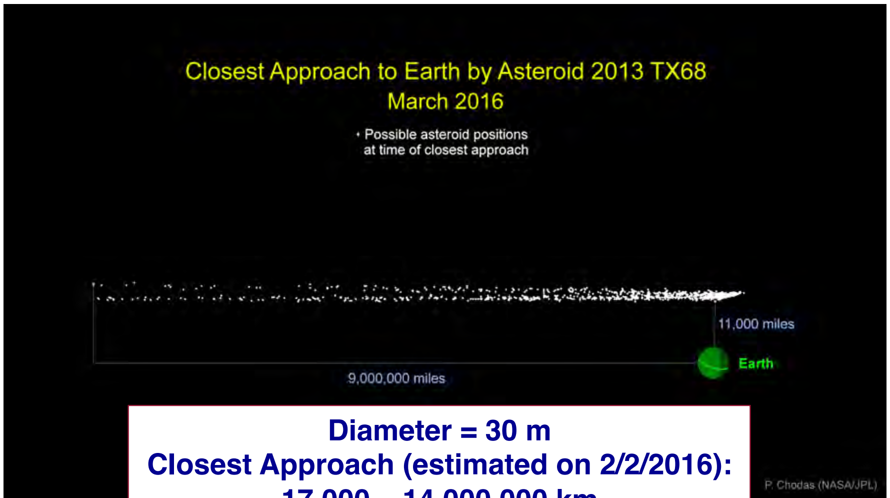
Lincoln Near-Earth Asteroid Research



Also Catalina Sky Survey, Pan-STARRS, Skywatch, …

Asteroid 2013 TX68
March 5, 2016 Encounter

Discovered on 10/16/2013
Catalina Sky Survey



Diameter = 30 m
Closest Approach (estimated on 2/2/2016):
17,000 – 14,000,000 km
"No possibility" of impact
1:250,000,000 chance of Sept 2017 impact

NASA Activities

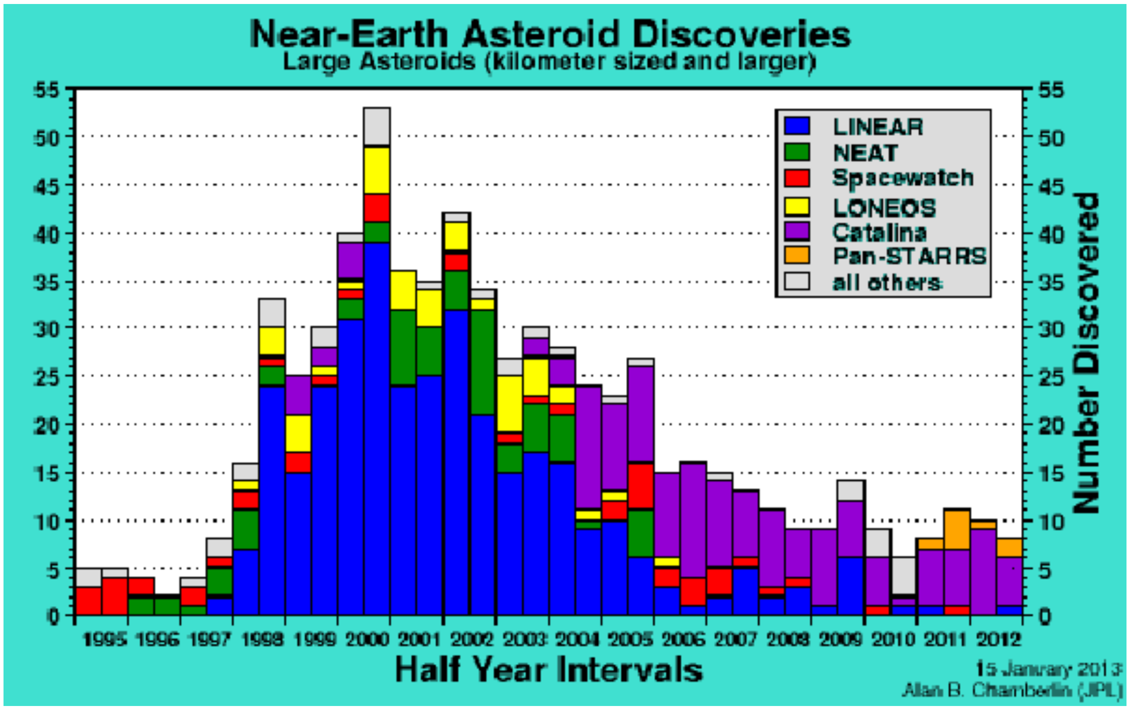
Jet Propulsion Laboratory
California Institute of Technology

NEWS I JANUARY 7, 2016

NASA Office to Coordinate Asteroid Detection, Hazard Mitigation

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

The Panoramic Survey Telescope & Rapid Response System (Pan-STARRS) 1 telescope on Maui's Mount Haleakala, Hawaii has produced the most near-Earth object discoveries of the NASA-funded NEO surveys in 2015. Image credit: University of Hawaii Institute for Astronomy / Rob Ratkowski


Near-Earth Asteroid Discoveries
Large Asteroids (kilometer sized and larger)
LINEAR
NEAT
Spacewatch
LONEOS
Catalina
Pan-STARRS
all others
Number Discovered
Half Year Intervals
15 January 2013
Alan B. Chamberlin (JPL)

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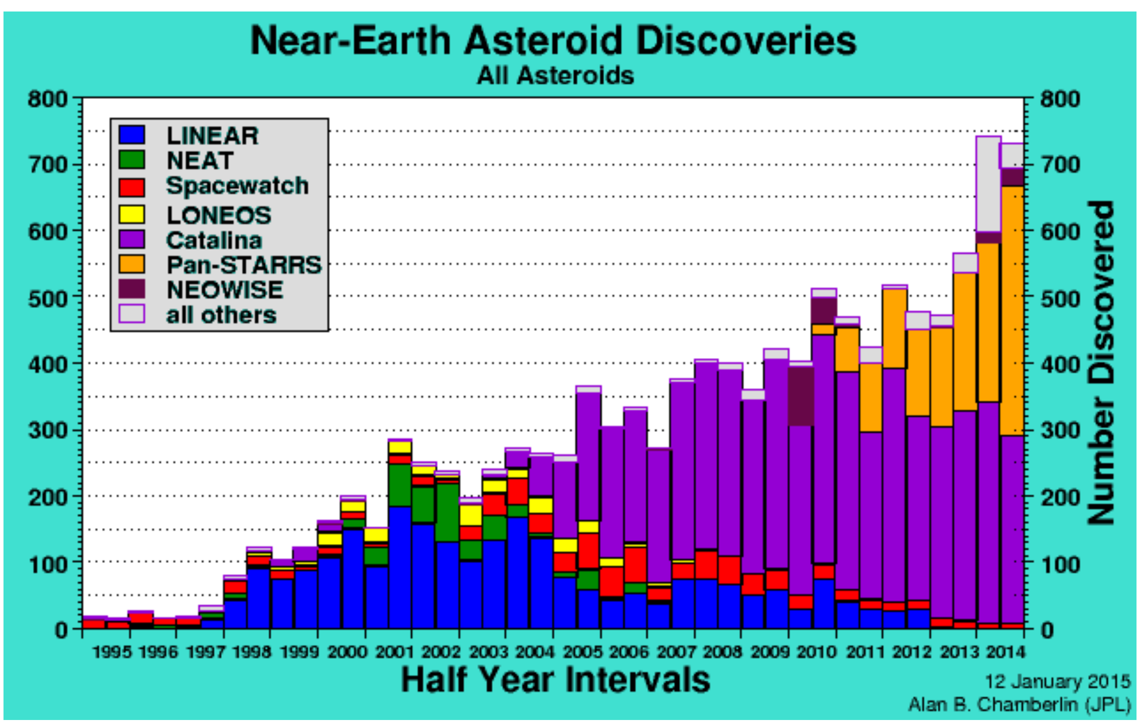

Near-Earth Asteroid Discoveries
All Asteroids
LINEAR
NEAT
Spacewatch
LONEOS
Catalina
Pan-STARRS
NEOWISE
all others
Number Discovered
Half Year Intervals
12 January 2015
Alan B. Chamberlin (JPL)

Numerous Close Encounters Each Year

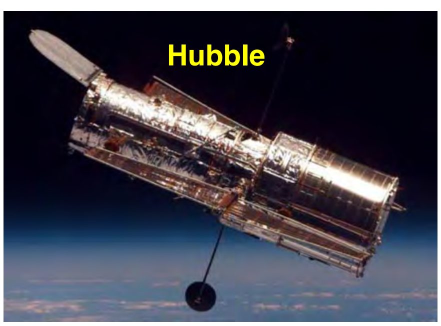
RECENT CLOSE APPROACHES TO EARTH

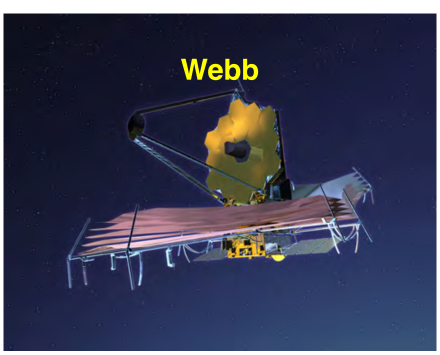
1 AU = ~150 million kilometers
1 LD = Lunar Distance = ~384,000 kilometers

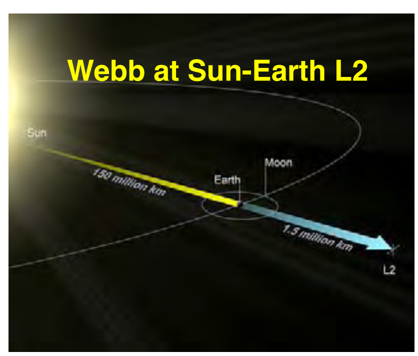
Object Name	Close Approach Date	CA Distance* (AU)	CA Distance* (LD)	Estimated Diameter**	H (mag)	Relative Velocity (km/s)
(2016 AV9)	2016-Jan-16	0.0643	25.0	28 m - 62 m	24.9	9.63
450263 (2003 WD158)	2016-Jan-16	0.1993	77.5	460 m - 1.0 km	18.8	16.26
(2015 KF)	2016-Jan-16	0.1730	67.3	25 m - 57 m	25.1	5.16
(2016 AR165)	2016-Jan-17	0.1099	42.8	70 m - 160 m	22.9	20.90
(2016 AJ165)	2016-Jan-18	0.0848	33.0	23 m - 52 m	25.3	14.26
454094 (2013 BZ45)	2016-Jan-19	0.1827	71.1	110 m - 250 m	21.9	6.29
(2010 BK2)	2016-Jan-19	0.1036	40.3	110 m - 240 m	22.0	16.68
(2012 DN31)	2016-Jan-19	0.1825	71.0	42 m - 94 m	24.0	13.28
(2016 AW64)	2016-Jan-20	0.1104	43.0	68 m - 150 m	23.0	16.21
(2016 AM165)	2016-Jan-20	0.1114	43.4	31 m - 69 m	24.7	1.63

* Close Approach (CA) Distance is the distance between the Earth center and asteroid center.
** Diameter estimates based on the object's absolute magnitude.

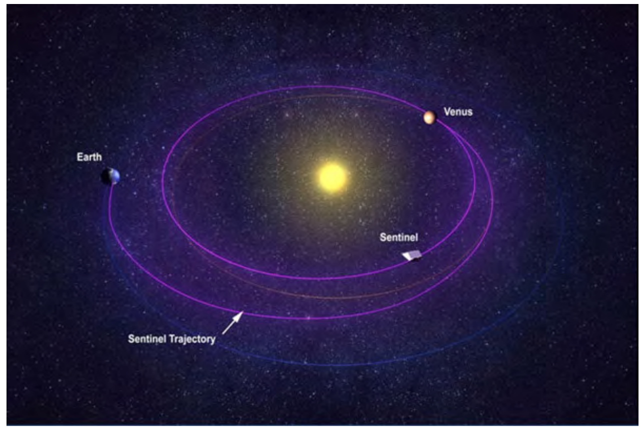
Orbiting Telescopes





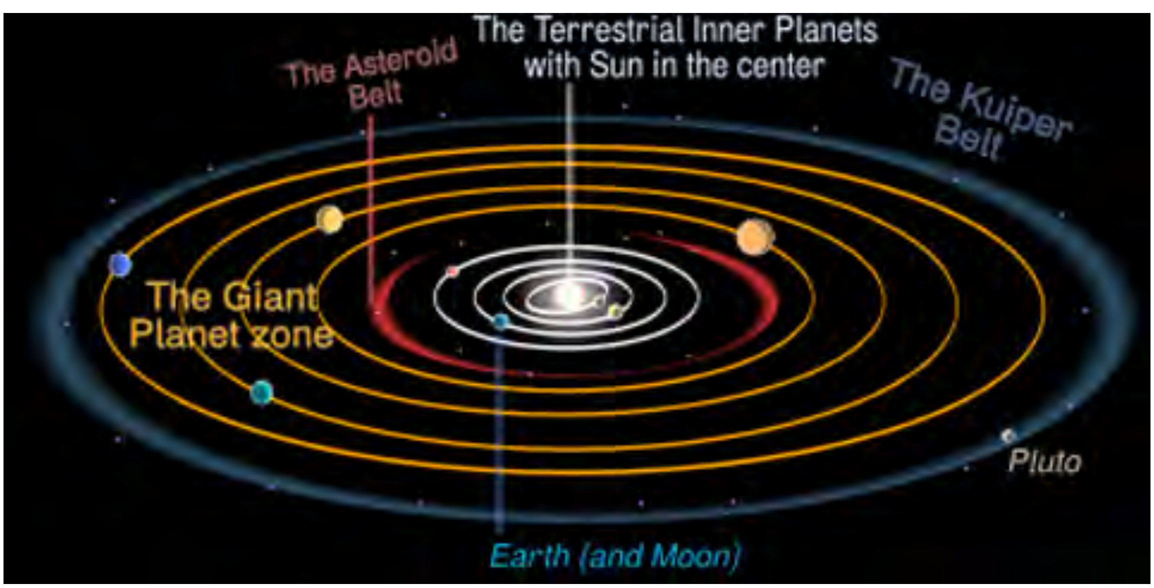


Proposed B612 Sentinel Space Telescope *(~2018?)*

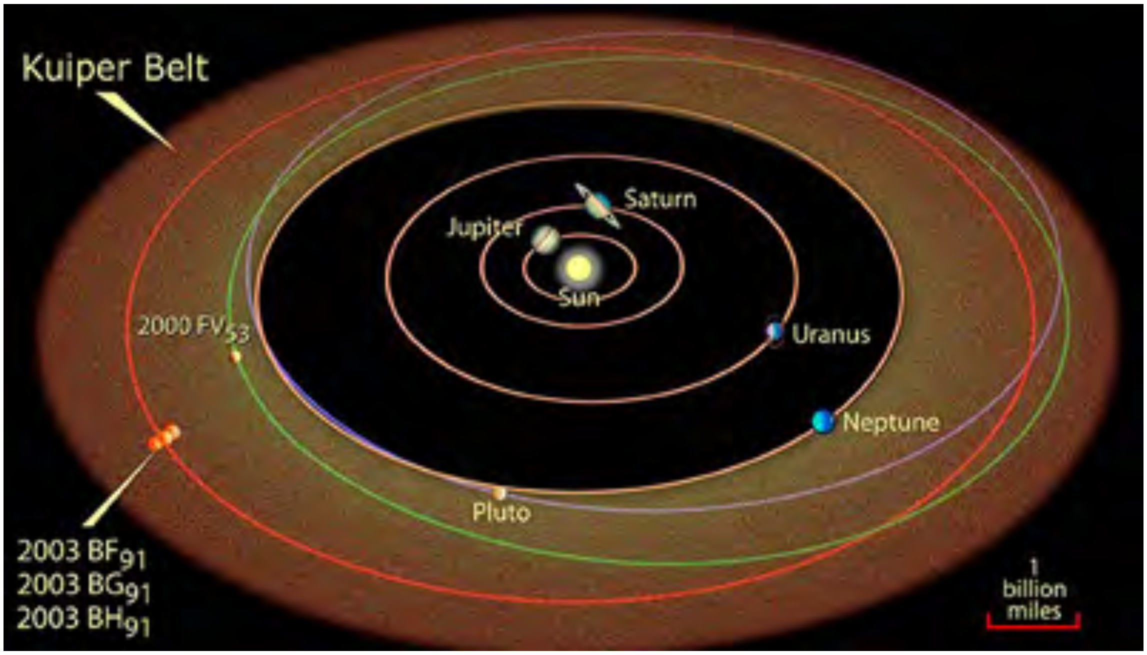


- **Infrared camera, to view 90% of NEOs with diameter > 140 m**
- **Heliocentric orbit between Earth and Venus**
- **Funding incomplete ($450M goal)**

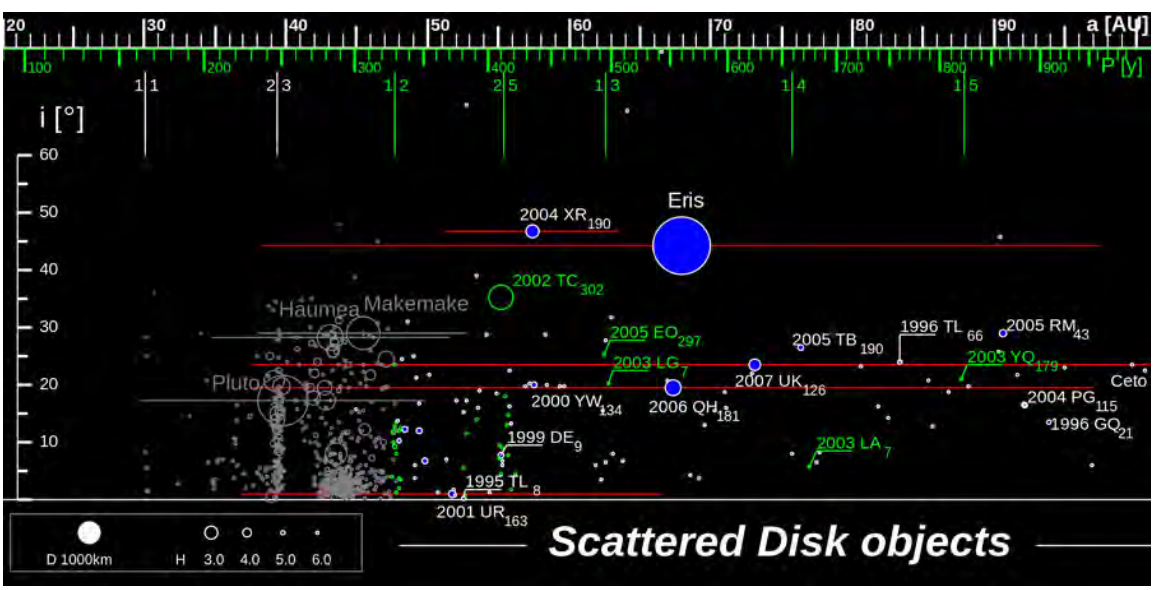
Asteroid Belt



Kuiper Belt (Trans-Neptunian Objects)

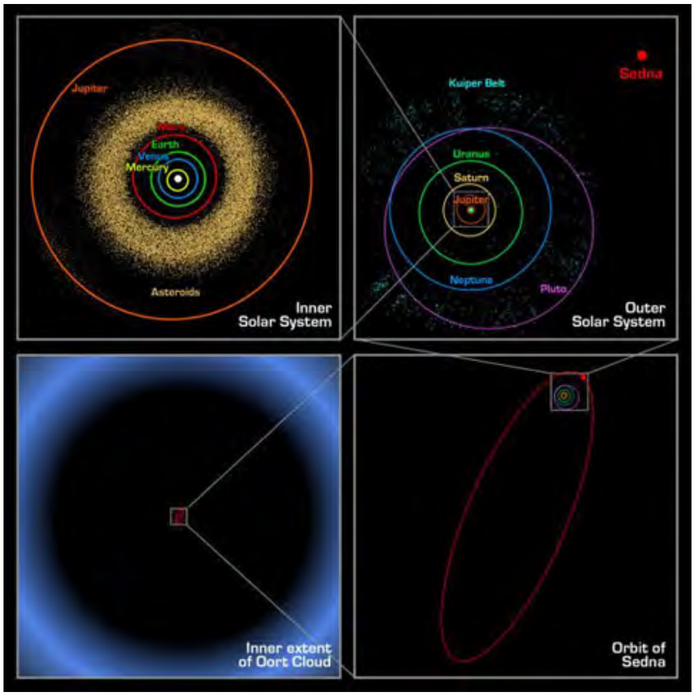


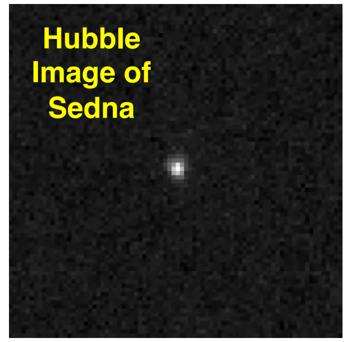
Scattered Disk Objects



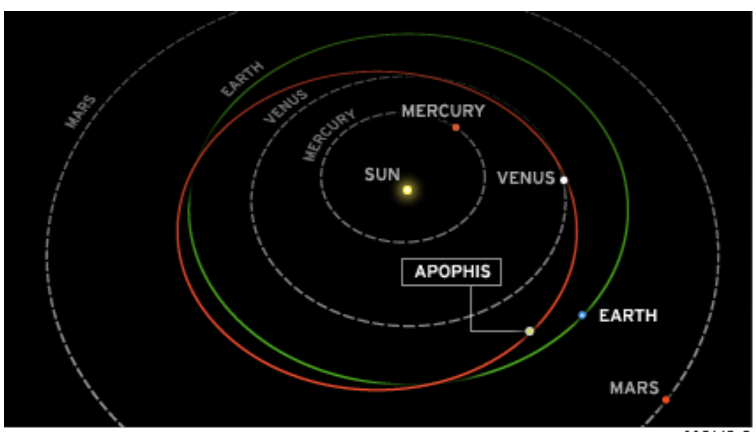
Chaotic, highly elliptical orbits near/in Kuiper Belt

The Outer Reaches





99942 Apophis

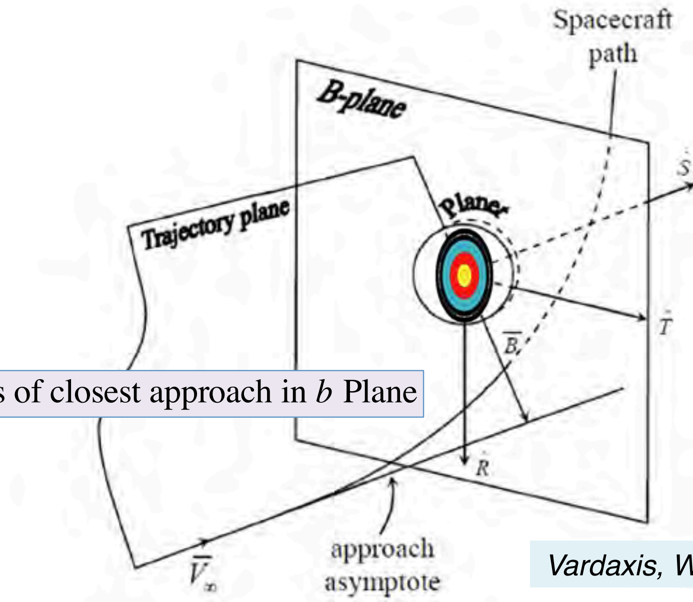


MSNBC

- Discovered in 2004; initially thought to have a 2.7% chance of impacting Earth in 2029
- Refined estimates reduced the 2029 probability
- Passage through a *gravitational keyhole* could increase probability of Earth impact in 2036

Trajectory Plane and b Plane Geometry

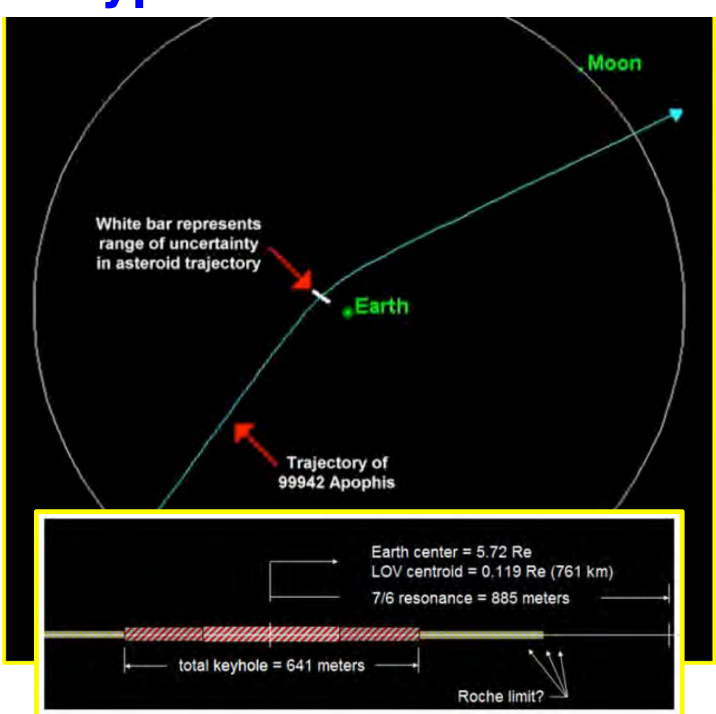
"Bull's eye" is in the b plane



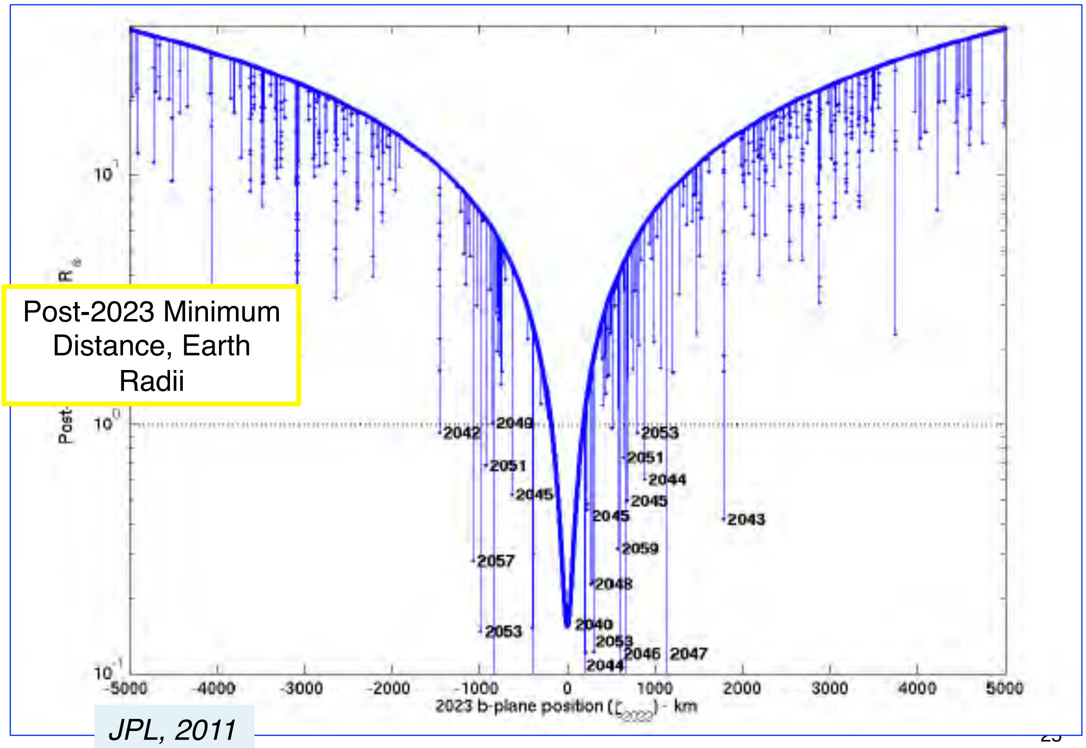
b : Radius of closest approach in b Plane

Vardaxis, Wie, 2011

Trajectory-Plane View of Apophis Hyperbolic Encounter

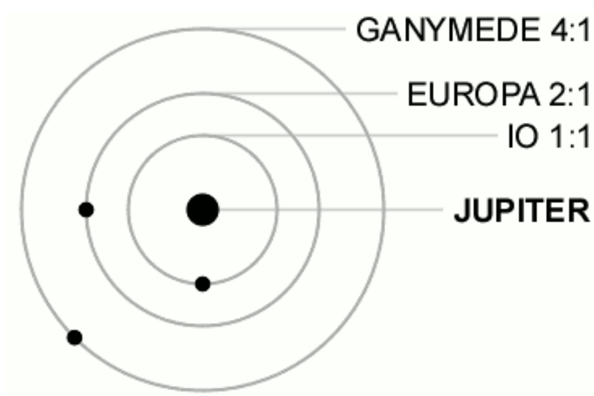


Apophis “Keyhole”



JPL, 2011

Orbital Resonance

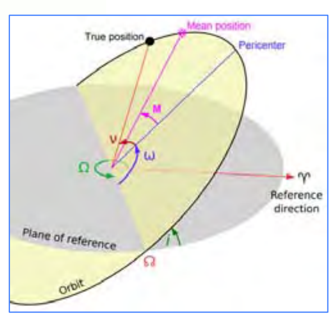


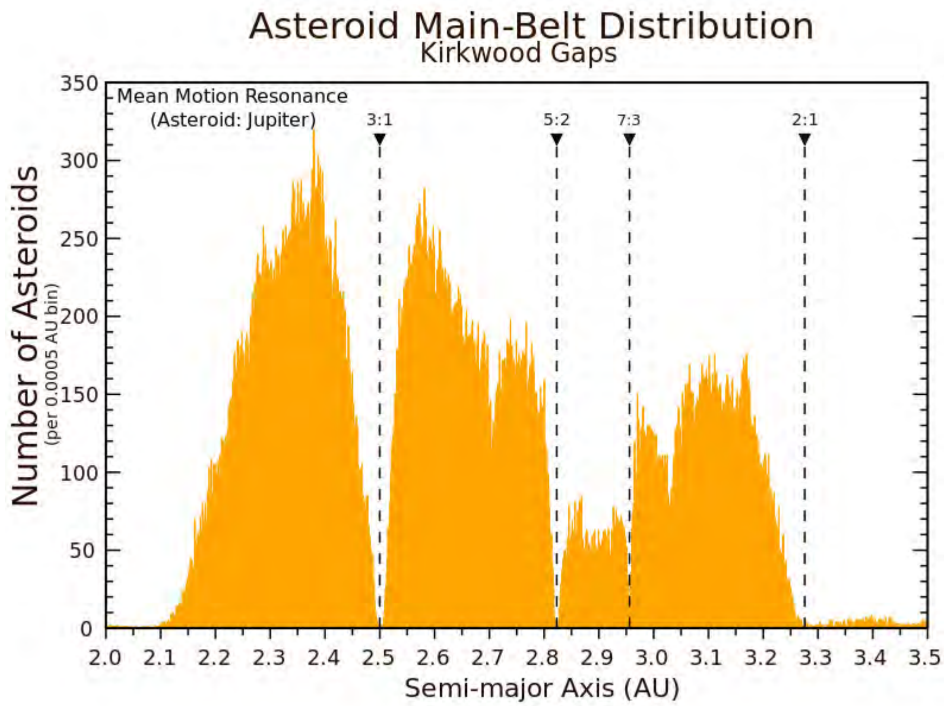
Laplace Resonance Locks Orbital Phase of Ganymede, Europa, and Io

$$\lambda_{Io} - 3\lambda_{Europa} + 2\lambda_{Ganymede} \triangleq \Phi_L = 180^\circ$$

$$\lambda\text{: Mean longitude of the moon}$$

$$= \Omega + \omega + M$$



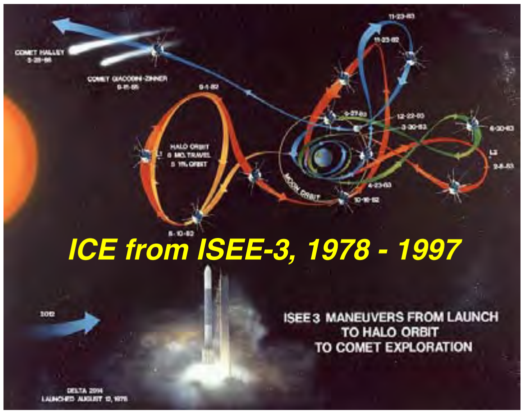


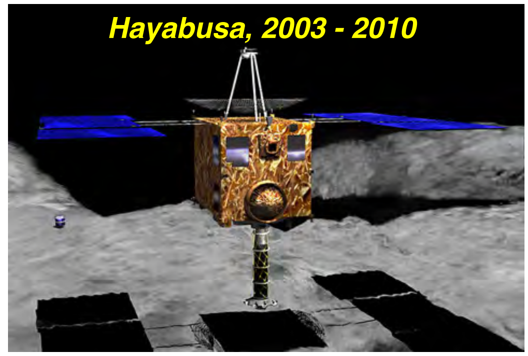
Gaps are a consequence of resonance

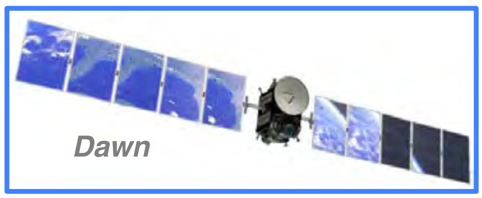
Past Missions to Asteroids and Comets

Rosetta to Comet 67P, 2004 – Present
Philae Landing, 2014

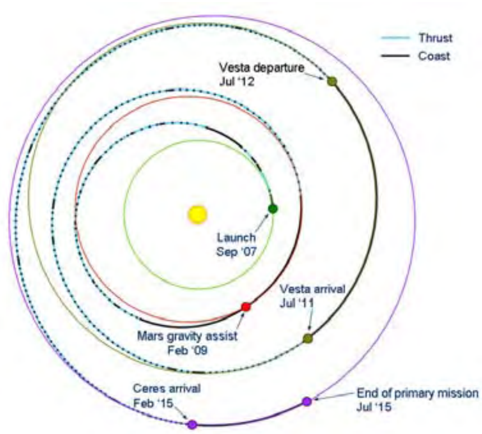
Past Missions to Asteroids and Comets

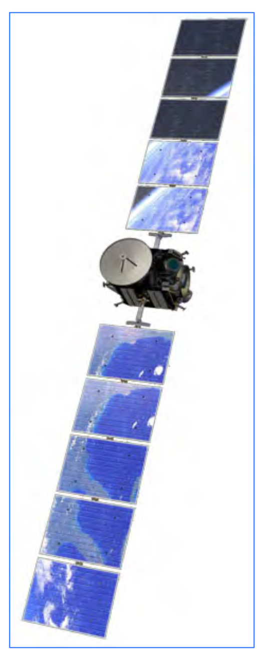






Dawn Mission to the Proto (Dwarf) Planets, Vesta and Ceres

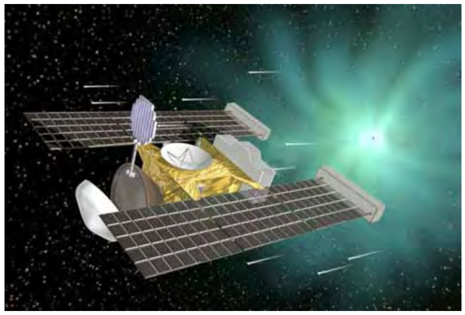


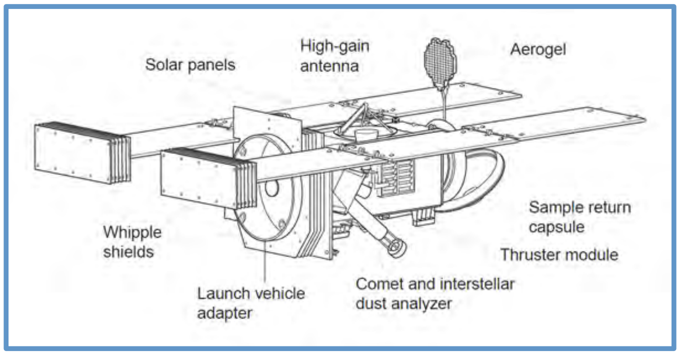


- 3 xenon ion thrusters
  - I_{sp} = 3,100 s
  - Thrust = 90 mN (per motor)
  - ΔV > 10 km/s
- 12 0.9-N hydrazine thrusters
- Orbits about both Vesta and Ceres

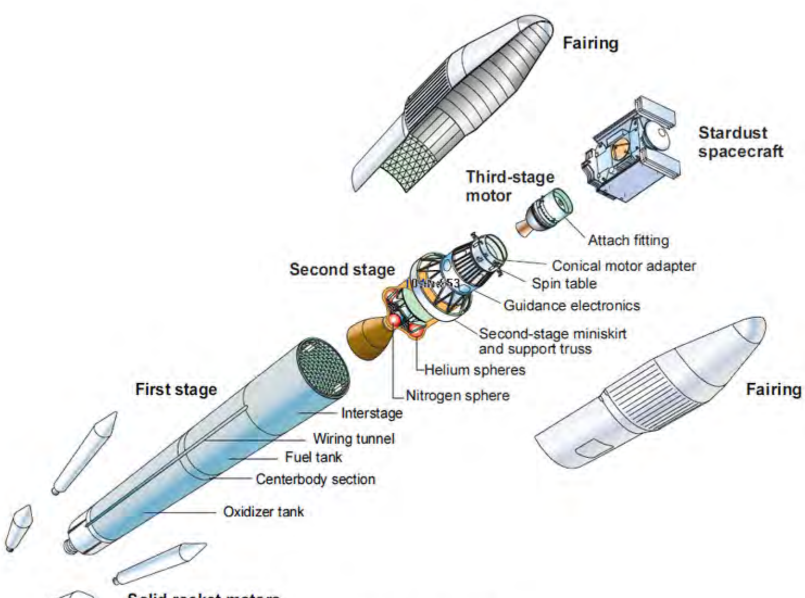
Stardust, 1999-2006

Sample return from Wild 2 Comet coma



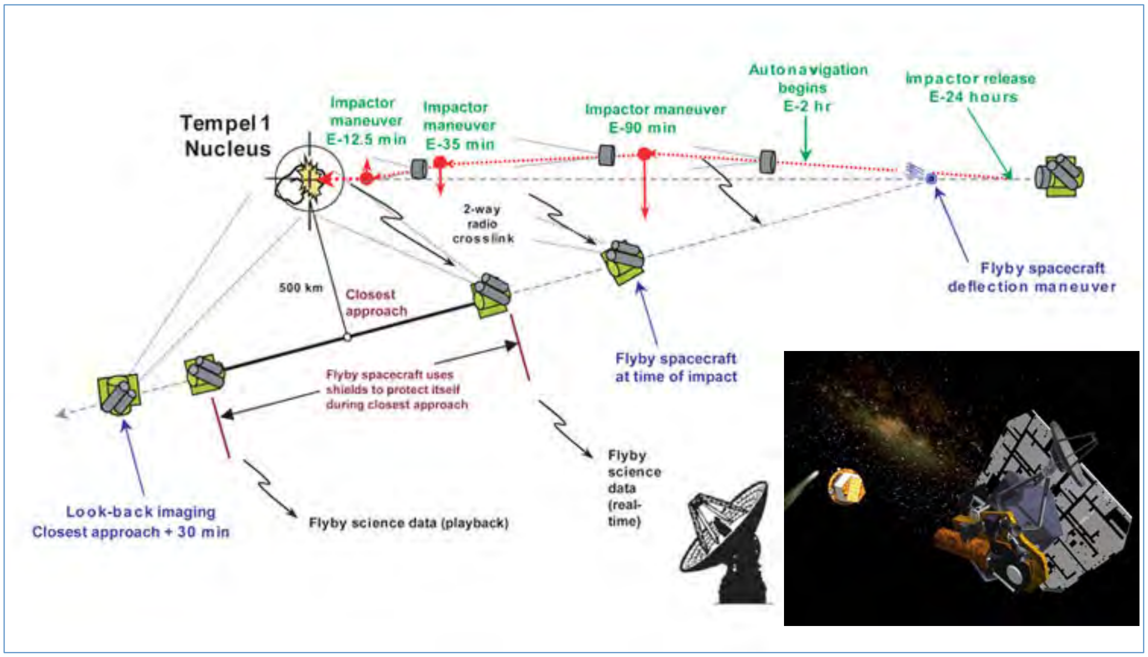


Stardust-Delta II Cutaway



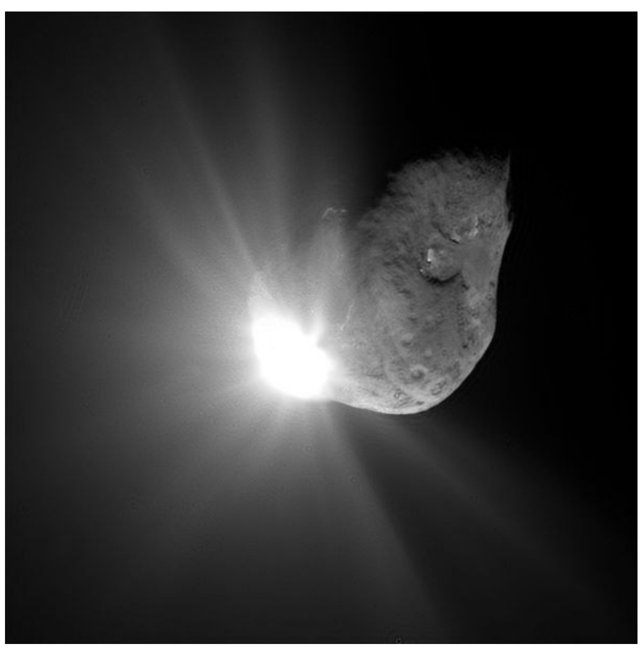
Delta launch vehicle

Deep Impact 1, 2005

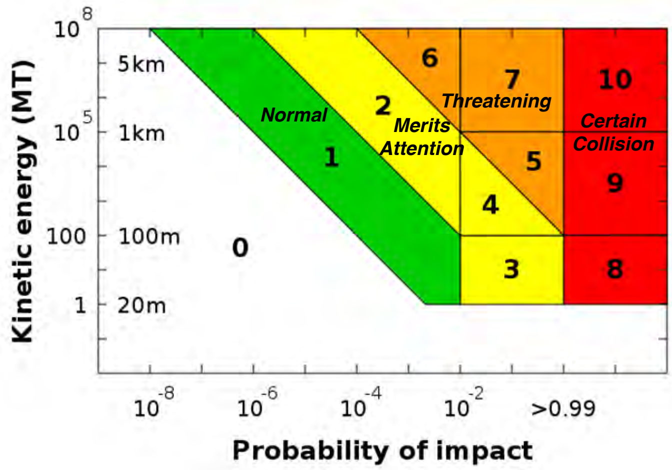


Deep Impact 1

385-kg impacter, 10.2 km/s impact velocity

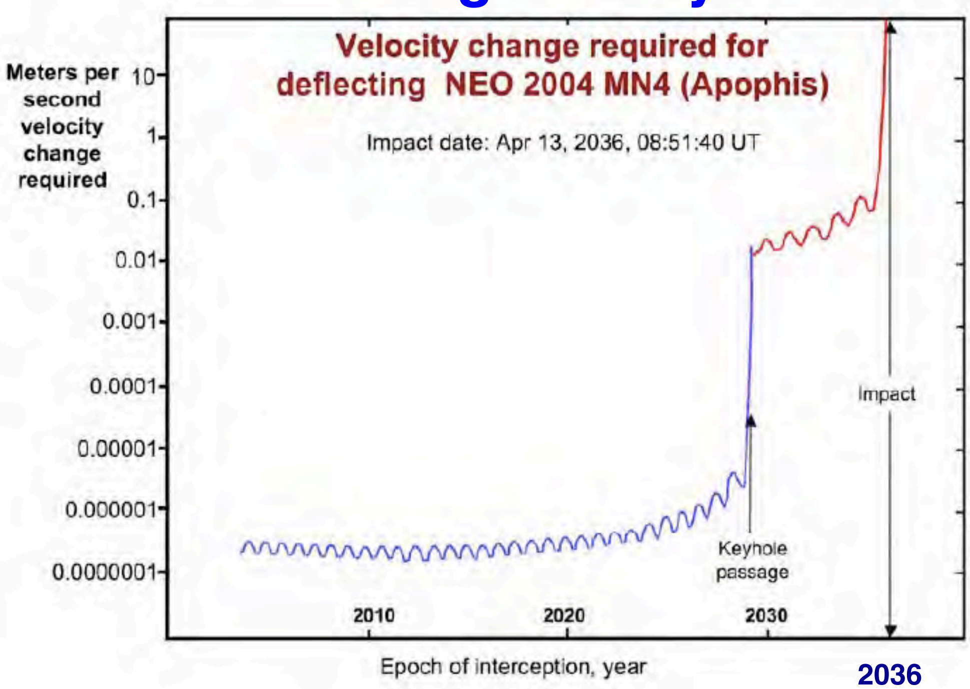


Torino Scale for Inpact Hazard Associated with NEOs



https://en.wikipedia.org/wiki/Torino_scale

Avoiding the Keyhole



Methods and Effectiveness of Deflection

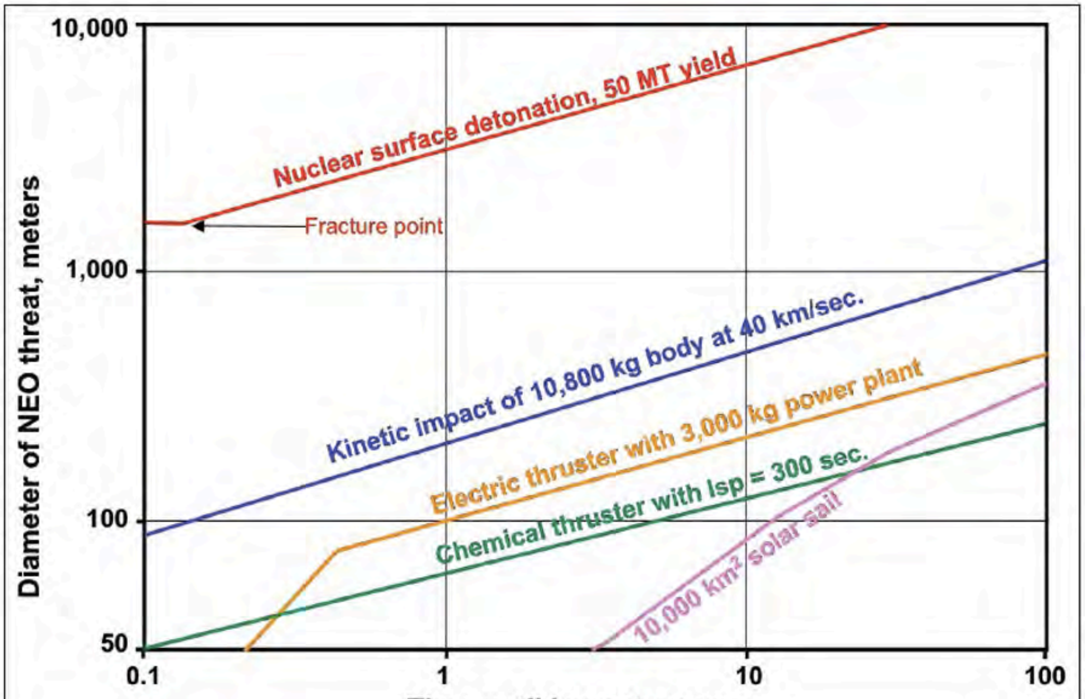
Impulsive Deflection/Mitigation Options

Impulsive Technique*	Description
Conventional Explosive (surface)	Detonate on impact
Conventional Explosive (subsurface)	Drive explosive device into PHO, detonate
Nuclear Explosive (standoff)	Detonate on flyby via proximity fuse
Nuclear Explosive (surface)	Impact, detonate via contact fuse
Nuclear Explosive (delayed)	Land on surface, detonate at optimal time
Nuclear Explosive (subsurface)	Drive explosive device into PHO, detonate
Kinetic Impact	High velocity impact

**A discussion of these techniques is found in a subsequent section of this report.*

NASA Report to Congress, 2007

Effectiveness of Deflection Techniques



IAS, 2009

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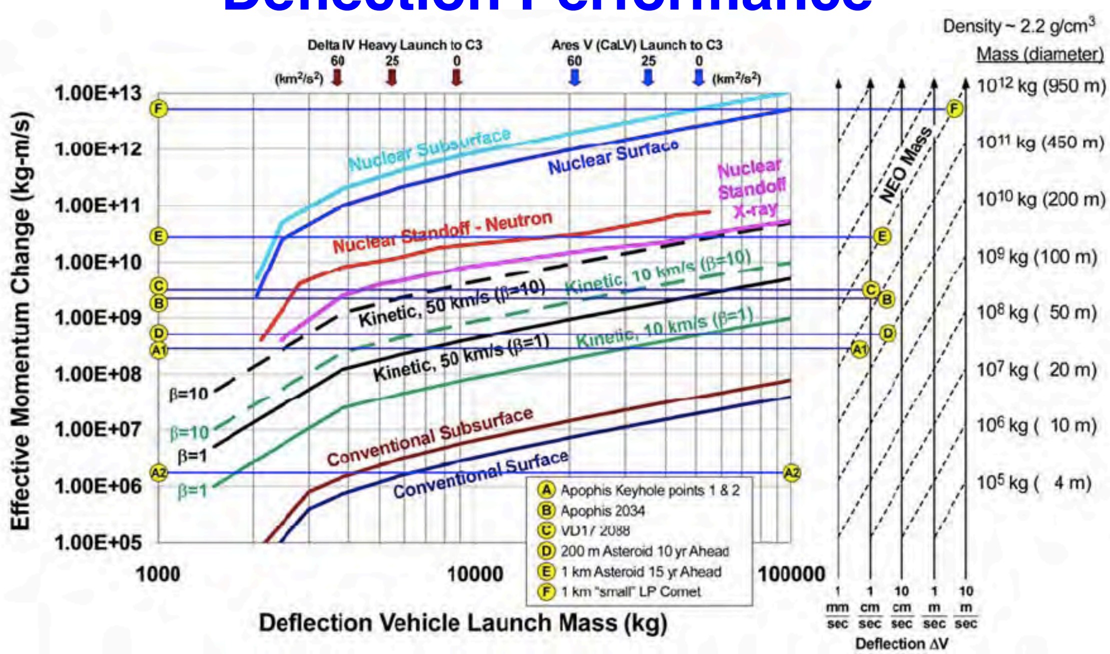
Kinetic and Nuclear Deflection Performance



NASA Report to Congress, 2007

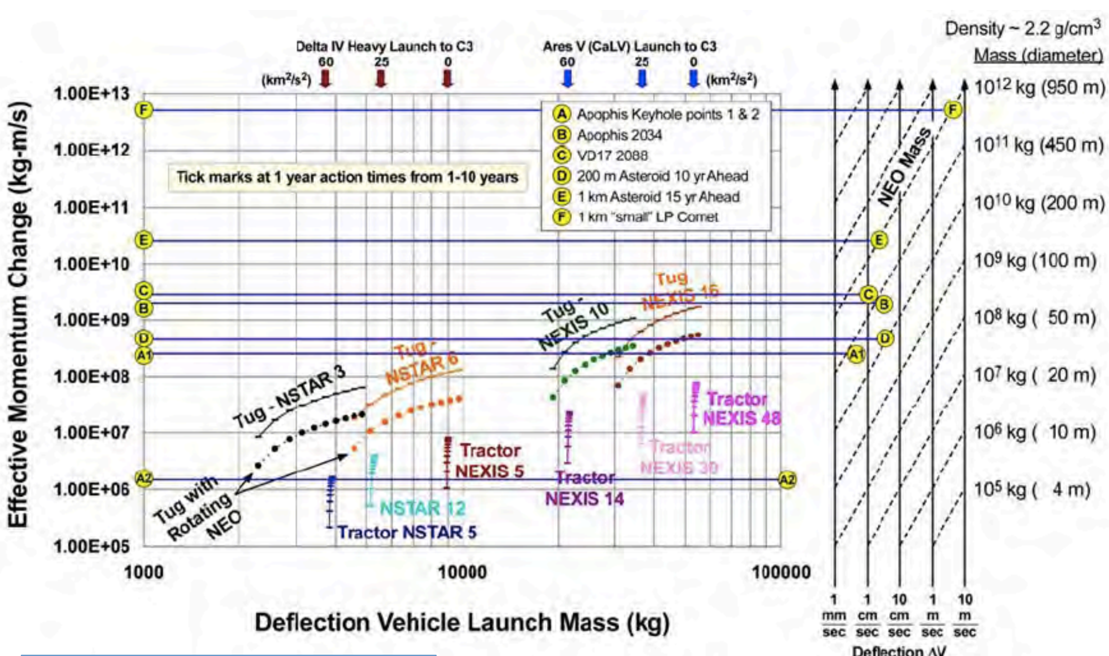
Slow Push Deflection/Mitigation Options

Slow Push Technique*	Description
Focused Solar	Use large mirror to focus solar energy on a spot, heat surface, "boil off" material
Pulsed Laser	Rendezvous, position spacecraft near PHO, focus laser on surface, material "boiled off" surface provides small force
Mass Driver	Rendezvous, land, attach, mine material, eject material from PHO at high velocity
Gravity Tractor	Rendezvous with PHO, fly in close proximity for extended period, gravitational attraction provides small force
Asteroid Tug	Rendezvous with PHO, attach to PHO, push
Enhanced Yarkovsky	Change albedo of a rotating PHO; radiation from sun-heated material will provide small force as body rotates

* *A discussion of these techniques is found in a subsequent section of this report.*

NASA Report to Congress, 2007

Tug and Tractor Deflection Performance



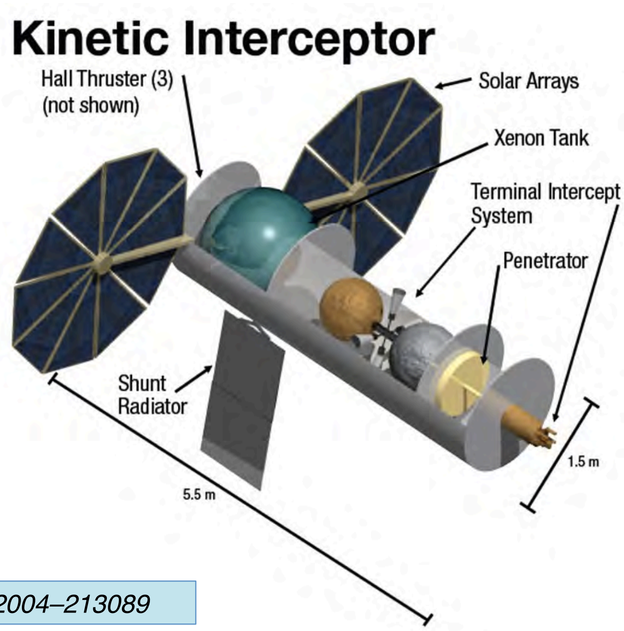
NASA Report to Congress, 2007

Precursor Spacecraft

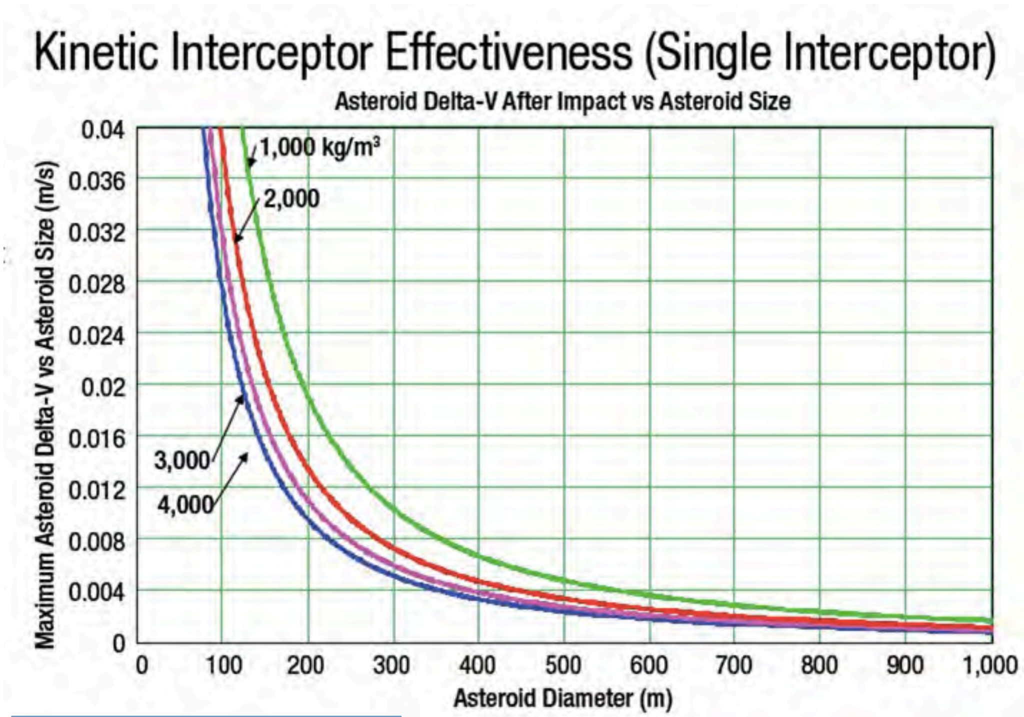
Stage	Fueled Mass (kg)
TAI	23,316
Rendezvous	4,640
Observer/lander	1,500
Total	29,456

NASA/TP—2004–213089

Interceptor Spacecraft

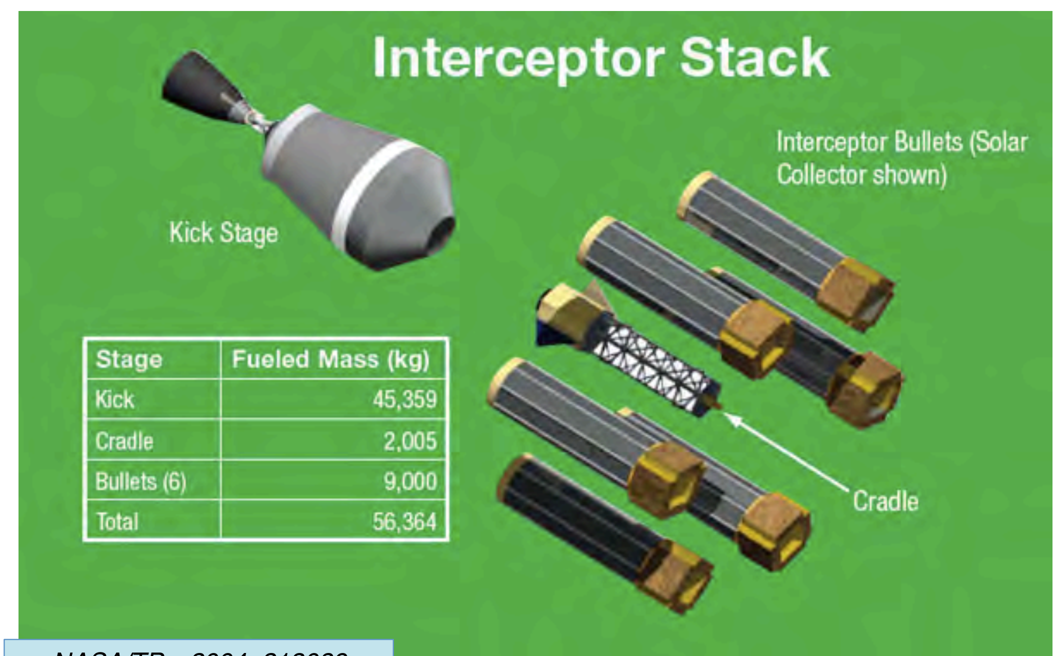


NASA/TP—2004–213089



NASA/TP—2004–213089

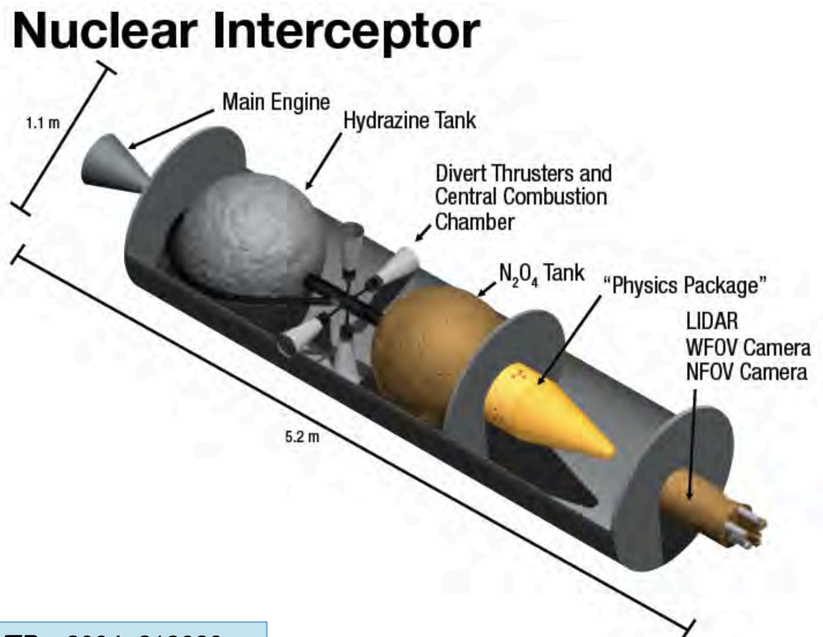
Spacecraft Concepts



Stage	Fueled Mass (kg)
Kick	45,359
Cradle	2,005
Bullets (6)	9,000
Total	56,364

NASA/TP—2004–213089

Nuclear Interceptor Spacecraft

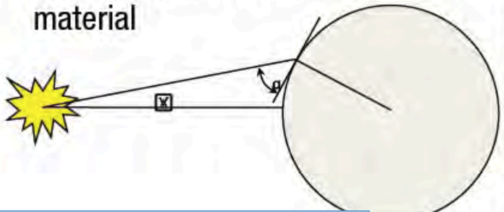


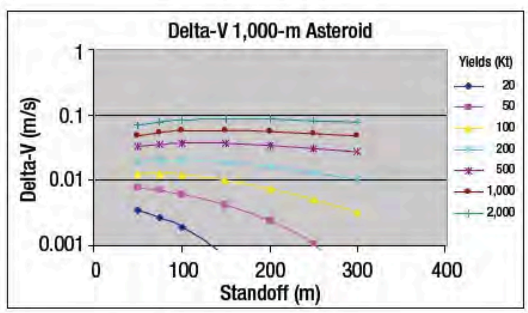
NASA/TP—2004–213089

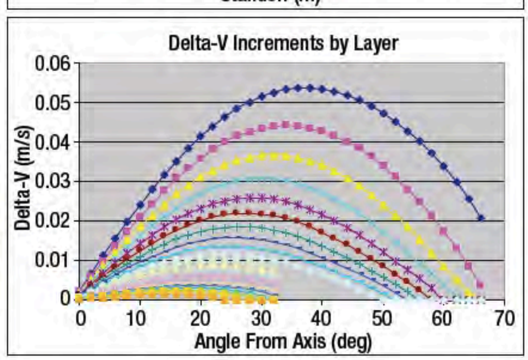
Effectiveness of Nuclear Interceptor

Physics of Nuclear Deflection

- Explosion at optimum standoff distance from NEO
- Explosion to cover maximum surface that can be ablated
- Only x-ray interaction with NEO considered here
- Monte Carlo model of x-ray penetration and absorption
- Spectral ejection of vaporized material

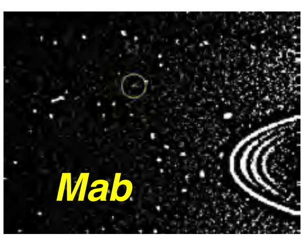






NASA/TP—2004–213089

Term Project: Defense Against a Long-Period Asteroid



Background for Term Project

May 31, 2016

- **Uranus's moon, *Mab*, is impacted by a long-period comet emanating from the *Scattered Disk***
  - **Bright flash in vicinity of Uranus is imaged by Hubble and nearby planetary exploration satellites**
  - **Event is odd but significant; as bright as a Super Nova, but in the wrong place**
  - **Coincidentally, this is Commencement Day at Princeton**

Background for Term Project

January 1, 2017

- ***Mab*** **imaging determines that:**
  - **Orbital elements w.r.t. Uranus have changed significantly**
  - **Mab is surrounded by a discernible debris field**
  - **A volume of Mab approximately 2-3 km in diameter is estimated to be missing**

Background for Term Project

January 1, 2020

- **1-km-diameter chunk of** ***Mab*** **is imaged**
  - **Escaped from Uranus's "sphere of influence" and in solar orbit**
  - **Object is given the preliminary designation,** ***2020 UA***
  - **Albedo brighter than other objects in the Uranus-moon system, and it is slowly varying, suggesting irregular shape, rotation, or multiple objects**
  - **Torino Scale (*TS*) = 0**

Background for Term Project

February 1, 2020

- Preliminary estimates of *2020 UA*'s orbit indicate that its perihelion is about 1 AU from the Sun
  - Orbital period is about 32 years
  - Time to perihelion is about 16 years from aphelion (2016-2032)
  - *2020 UA* estimated to pass within 1 AU of Earth
  - *TS* = 0

Background for Term Project

June 1, 2020

- Ground-based telescopes report sporadic sightings of *2020 UA*
  - Unstable orbit, suggesting effects of outgassing or more than one object of significant size
  - Radius from Sun is about 18 AU
  - Estimate of closest distance to Earth is 0.1 AU, ±0.01 AU
  - Probability of Earth impact estimated to be 0.01%
  - *TS* = 2

Background for Term Project
January 1, 2021

- ***2020 UA*** **imaged by increasing number of telescopes**
- **Deep-Space Network short-arc radar measurements refine orbital elements**
  - **Radius from Sun = 17.5 AU**
  - **Closest approach to Earth = 0.04 AU, ±0.005 AU, orbital elements remain unstable**
  - ***2020 UA*** **consists of one large object and smaller objects**
  - **Radar returns suggest that** ***2020 UA*** **is rubble aggregate**
  - **Spectral analysis suggests materials are primarily rock, iron, "dust", and ice, with mean density of about 2 g/cm^3**
  - **Probability of Earth impact by** ***2020 UA*** **estimated to be 0.05%**
  - ***TS*** **= 5**

Background for Term Project
June 1, 2021

- **Improved** ***n*****-body estimates of** ***2020 UA*****'s trajectory**
- **Closest approach to Earth = 0.01 AU, ±0.001 AU, orbital elements remain unstable**
- **Estimated probability of Earth impact in 2032 is increased to 10%.** ***TS*** **= 8**
- ***2020 UA*** **consists of** <u>**four significant objects**</u> **of undetermined shape**
  - ***2020 UA(1)*** **: mean diameter = 1 km**
  - ***2020 UA(2)*** **: mean diameter = 250 m**
  - ***2020 UA(3)*** **: mean diameter = 80 m**
  - ***2020 UA(4)*** **: mean diameter = 40 m**

The Threat: 2020UA

June 1, 2021

Background for Term Project

July 1, 2021

- ***TS*** **= 9-10**
- **NASA appoints a Task Force to design a *Planetary Defense System* to prevent *2020 UA* from impacting, causing "Extinction Event" on Earth**
- **Oddly enough, many members of the Task Force were students in MAE 342 during Spring 2016**
- **The Task Force has 12 weeks in which to create, document, and present the preliminary system design**
- **A principal reference for the Task Force is the 2016 *Princeton MAE 342 Final Report***

Scenario for Project 2020 UA

Three mission classes to mitigate the threat

1) **Fast-transfer Reconnaissance Flyby or Orbiter/ Impacter/Lander(s), RSC-1**
   - Objective: Physical, chemical characterization of 2020 UA
   - Launch year: 2022. Year of rendezvous: 2025-2027
2) **Deep-Space Deflection of 2020 UA, DSC-1**
   - Objective: Perturb 2020 UA orbit to prevent impact
   - Launch years: 2025-2026. Years of intercept: 2028-2029
3) **Near-Earth Deflection/Destruction of 2020 UA, NSC-1**
   - Objectives: Perturb 2020 UA orbit to prevent impact, or minimize the hazards of impact
   - Launch years: 2027-2032. Years of intercept: 2030-32

Next Time:

Spacecraft Guidance