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

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What We Want to Avoid

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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:** $5 \times 10^{13}$ kg
- **Period:** 4 yr
- **Aphelion:** 4.1 AU
- **Perihelion:** 0.94 AU

**PHA Characteristics (2013)**
- **Diameter:** > 140 m
- **Passes within:** $7.6 \times 10^6$ 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

Asteroid impacts larger than 1 kiloton*
2000-13

Kilotons:
- 1-10
- 10-20
- >20

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 ($V_\infty$)
- 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

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

Closest Approach to Earth by Asteroid 2013 TX68
March 2016
- Possible asteroid positions at time of closest approach

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

NASA Office to Coordinate Asteroid Detection, Hazard Mitigation

http://neo.jpl.nasa.gov/risk/
Numerous Close Encounters Each Year

<table>
<thead>
<tr>
<th>Object Name</th>
<th>Close Approach Date</th>
<th>CA Distance (AU)</th>
<th>CA Distance (LD)</th>
<th>Estimated Diameter (km)</th>
<th>H (mag)</th>
<th>Relative Velocity (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2016 AV/9)</td>
<td>2016-Jan-16</td>
<td>0.0643</td>
<td>25.0</td>
<td>28 m - 62 m</td>
<td>24.9</td>
<td>9.63</td>
</tr>
<tr>
<td>450263 (2003 WD158)</td>
<td>2016-Jan-16</td>
<td>0.1993</td>
<td>77.5</td>
<td>460 m - 1.0 km</td>
<td>18.8</td>
<td>16.26</td>
</tr>
<tr>
<td>(2015 KF)</td>
<td>2016-Jan-16</td>
<td>0.1730</td>
<td>67.3</td>
<td>25 m - 57 m</td>
<td>25.1</td>
<td>5.16</td>
</tr>
<tr>
<td>(2016 AR165)</td>
<td>2016-Jan-17</td>
<td>0.1099</td>
<td>42.8</td>
<td>70 m - 160 m</td>
<td>22.9</td>
<td>20.90</td>
</tr>
<tr>
<td>(2016 AJ165)</td>
<td>2016-Jan-18</td>
<td>0.0848</td>
<td>33.0</td>
<td>23 m - 52 m</td>
<td>25.3</td>
<td>14.26</td>
</tr>
<tr>
<td>454094 (2013 BZ45)</td>
<td>2016-Jan-19</td>
<td>0.1827</td>
<td>71.1</td>
<td>110 m - 250 m</td>
<td>21.9</td>
<td>6.29</td>
</tr>
<tr>
<td>(2010 BK2)</td>
<td>2016-Jan-19</td>
<td>0.1036</td>
<td>40.3</td>
<td>110 m - 240 m</td>
<td>22.0</td>
<td>16.68</td>
</tr>
<tr>
<td>(2012 DN31)</td>
<td>2016-Jan-19</td>
<td>0.1825</td>
<td>71.0</td>
<td>42 m - 94 m</td>
<td>24.0</td>
<td>13.28</td>
</tr>
<tr>
<td>(2016 AW64)</td>
<td>2016-Jan-20</td>
<td>0.1104</td>
<td>43.0</td>
<td>68 m - 150 m</td>
<td>23.0</td>
<td>16.21</td>
</tr>
<tr>
<td>(2016 AM165)</td>
<td>2016-Jan-20</td>
<td>0.1114</td>
<td>43.4</td>
<td>31 m - 69 m</td>
<td>24.7</td>
<td>1.83</td>
</tr>
</tbody>
</table>

* 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

- **Hubble**
- **WISE**
- **Webb**
- **Webb at Sun-Earth L2**
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)

Chaotic, highly elliptical orbits near/in Kuiper Belt
The Outer Reaches

- 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

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**99942 Apophis**

- 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

Trajectory-Plane View of Apophis Hyperbolic Encounter

The white bar represents range of uncertainty in asteroid trajectory.
Apophis “Keyhole”

Post-2023 Minimum Distance, Earth Radii

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

Hayabusa, 2003 - 2010

ICE from ISEE-3, 1978 - 1997

Dawn

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

- 3 xenon ion thrusters
  - $I_{sp} = 3,100$ s
  - Thrust = 90 mN (per motor)
  - $\Delta V > 10$ 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
Deep Impact 1, 2005

385-kg impacter, 10.2 km/s impact velocity
Torino Scale for Impact Hazard Associated with NEOs

Avoiding the Keyhole

https://en.wikipedia.org/wiki/Torino_scale
Methods and Effectiveness of Deflection

### Impulsive Deflection/Mitigation Options

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

*<em>A discussion of these techniques is found in a subsequent section of this report.</em>

[NASA Report to Congress, 2007](#)
Effectiveness of Deflection Techniques

- Nuclear surface detonation, 50 MT yield
- Fracture point
- Kinetic impact of 10,000 kg body at 40 km/sec.
- Electric thruster with 3,000 kg power plant
- Chemical thruster with ISP = 300 sec.
- 50,000 km solar sail

IAS, 2009

Kinetic and Nuclear Deflection Performance

- Mass (diameter)
- Density ~ 2.2 g/cm²
- Effective Momentum Change (kg·m/s)

NASA Report to Congress, 2007
**Slow Push Deflection/Mitigation Options**

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

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

**Tug and Tractor Deflection Performance**

- Delta IV Heavy Launch to G3
- Area II (Duke) Launch to G3
- Tractor NESS 5
- Tractor NESTAR 5
- Tractor NESTAR 12
- Tractor NEXIS 5
- Tractor NEXIS 14

**NASA Report to Congress, 2007**
Precursor Spacecraft

Observer Stack

Observer Stack assembled from components stored at facility

Trans-Asteroid Insertion Stage

Rendezvous Stage

Observer Satellite

NEO Lander

<table>
<thead>
<tr>
<th>Stage</th>
<th>Fueled Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trans-Asteroid</td>
<td>23,316</td>
</tr>
<tr>
<td>Rendezvous</td>
<td>4,640</td>
</tr>
<tr>
<td>Observer/lander</td>
<td>1,500</td>
</tr>
<tr>
<td>Total</td>
<td>29,456</td>
</tr>
</tbody>
</table>

Interceptor Spacecraft

Kinetic Interceptor

Solar Arrays

Xenon Tank

Terminal Intercept System

Penetrator

Shunt Radiator

Half Thruster (3) (not shown)

NASA/TP—2004–213089
Spacecraft Concepts

Interceptor Stack

<table>
<thead>
<tr>
<th>Stage</th>
<th>Fueled Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kick</td>
<td>45,359</td>
</tr>
<tr>
<td>Cradle</td>
<td>2,005</td>
</tr>
<tr>
<td>Bullets (6)</td>
<td>9,000</td>
</tr>
<tr>
<td>Total</td>
<td>56,364</td>
</tr>
</tbody>
</table>

NASA/TP—2004–213089
Nuclear Interceptor Spacecraft

Nuclear Interceptor

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
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, $\pm 0.01$ 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/cm³
  – 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 four significant objects 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

Estimated Earth arrival date: July 17, 2032

Background for Term Project
July 1, 2021

- \( TS = 9-10 \)
- NASA appoints a Task Force to design a \textit{Planetary Defense System} to prevent \textit{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 \textit{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