On NEO Threat Mitigation

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Disclaimer

- This is not a detailed analysis of technology requirements
- This presentation does not describe an official position by the USAF

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What is the Real Threat ?

- What is appropriate measure of threat?
  - Death rate: # fatalities/time interval ? (< 1000/yr)
  - From Poisson statistics get the average # fatalities within next 20 or 100 yrs:

Order of magnitude(s) less than disease (biological or social)

Type of Event	Diameter of Object	Fatalities per Impact	Typical Impact Interval (years)
High altitude break-up	< 50 m	~0	annual
Tunguska-like event	> 50 m	~5,000	250 - 500
Regional event	> 140 m	~50,000	5,000
Large sub-global event	> 300 m	~500,000	25,000
Low global effect	> 600 m	> 5 M	70,000
Nominal global effect	> 1 km	> 1 B	1 million
High global effect	> 5 km	> 2 B	6 million
Extinction-class Event	> 10 km	6 B	100 million

Ø	Fatalities (20 yrs)	Fatalities (100 yrs)
< 50 m	0	0
> 50 m	750	3400
> 140 m	540	2700
> 300 m	1,100	5400
> 600 m	3,900	19,400
> 1 km	54,000	272,000
> 5 km	18,000	90,000
> 10 km	3,300	16,000

From 2006 Near-Earth Object Survey and Deflection Study, Final Report, NASA, March 2007.

Focus on "Extinction" Events ?

- End of human life
- End of modern civilization
- No place to go..

$\varnothing > 1$ km

- Unlikely events….but surprises still possible
- How do we typically handle such situations? Which is most feared? Where are resources spent? Examples:
  - Global Nuclear War – versus – small regional conflicts
  - Global Bio/Nuclear-terror – versus – roadside bombs

Best Approach?

- 3 categories:
  - Large objects (> 1 km): threaten species or civilization
  - Medium-objects (>140m): kill significant fraction of population
  - Small objects: scale of catastrophic natural events

Notes:

- Large: Most difficult to handle – may be impossible to deflect <u>if</u> insufficient warning or <u>if</u> no infrastructure in place
- Small: Most difficult to detect – may be impossible to deflect <u>because</u> of insufficient warning
- All mitigation solutions will be expensive: what is the ROI?
  - "small" objects more likely to fall below ROI threshold
  - "large" objects mitigation has no cost-limits, only technical limits

Best Strategy?

1. Solve technical problems
2. Develop necessary infrastructure
3. Reduce costs

- (1)+(2) solve threat of large bodies
- (3) allows application of solution to medium-sized objects

How is the ROI defined? What is the threshold for intervention? This discussion must take place elsewhere…

Large Body deflection problem

- Slow-push versus impulsive…
- Slow-Push (e.g. space Tug)
  - How much propellant/power do we need?
  - Assume Mp=100 Ton, nominal 1-year mission

Launch constraint

Electric propulsion only

Impulse	Isp	Energy	Thrust	Power (η=50%)	TRL
10^9 kg.m/s	1,000 s	≥ 10^{13} J	32 N	≥ 320 kW	<5 yrs
10^{10} kg.m/s	10,000 s	≥ 10^{15} J	320 N	≥ 32 MW	5-15 yrs
10^{11} kg.m/s	100,000 s	≥ 10^{17} J	3.2 kN	≥ 3.2 GW	>15 yrs
10^{12} kg.m/s	1,000,000 s	≥ 10^{19} J	32 kN	≥ 320 GW	> 25 yrs

- Large power required: nuclear power is only option.
- Revolutionary engine designs needed (I_{sp} >> 10 ksec)

The issue of power… and heat

- Heat rejection limits (need very large radiator)
  - Currently, $\alpha \approx 20$ kg/kWe (mostly radiator)
  - Very hard-driven R&D program → $\alpha \approx 3$ kg/kWe
  - At $P_e = 1\ GW_e$ → 3,000 Tons system
- Other options?
  - Solar heating: same basic approach, but Isp (V_{abl}) is more limited (≈10,000 s)
  - For $\Delta I = 10^{10}$ kg.m/s → P=3.2 MW
    - 50m x 50m at 1 AU, 500m x 500m at 10 AU
  - For $\Delta I = 10^{11}$ kg.m/s → P=32 MW
    - 150m x 150m at 1 AU, 1.5km x 1.5km at 10 AU

Large structures needed

Other slow push

- Laser: poor conversion efficiency
- Gravity–Tug: very low thrust
- Mass driver: potentially attractive if low velocity of ejected material (Power $\approx F \times v_{ej}$) – difficult to implement (asteroid mining)
- But in a sense… all schemes with mass ablation are mass drivers; for available power, we need to maximize ablated mass, minimize v_{abl}

A Twist on Space tug…

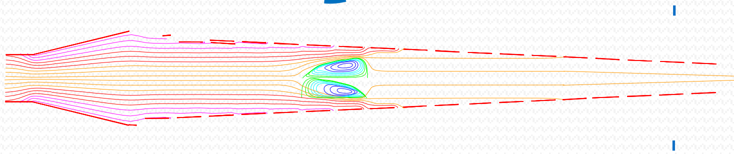
- Use propulsion system… as a mass-driver!

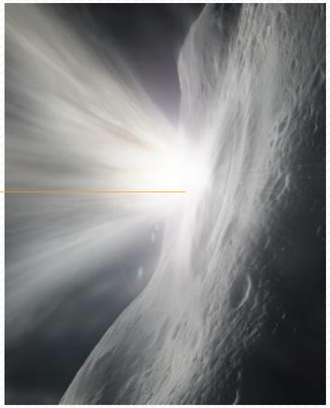
Magnetically-Accelerated Plasmoid (MAP) (Cambier & Slough, 2007)

- MAP would provide very high power, variable thrust and Isp for optimal transit to NEO
- MAP thruster has demonstrated operation at 70 MW @ Isp =20,000 sec
- After rendezvous, thruster used to ablate NEO surface for energy transfer.
- Even with kinetic conversion efficiency $\eta_E \approx 20\%$, for plasmoid velocities ~ 500 km/s the propellant requirement is <u>very</u> modest:

$$\frac{1}{2} m_{prop} v_{plas}^2 = 2E_{defl} \rightarrow \quad m_{prop} = \frac{2\Delta I \cdot v_{abl}}{\eta_E v_{plas}^2} \leq 4MT$$

(for $\Delta I = 10^{11}$ kg.m/s)





MAP thruster configured as impactor

Impulsive Maneuvers

- Take previous maneuvers and let $\Delta t \to 0$
- Space-Tug → Kinetic Impact $\Delta I = M \Delta V = m_{sc} v_{sc}$
  - Only scales linearly with v_{sc}

    $\Delta I = 10^{11}$, $v_{sc} = 10$ km/s → $m_{sc} = 10{,}000$ Tons !!
  - Practical only for medium objects, but…. There is momentum multiplication factor (β):
    - $\beta \approx 1$–5 ($\beta < 1$ for porous rock), maybe up to 20 for v=100 km/s
    - Initial mass: $M_0 = \frac{\Delta I}{\beta \, v_p} e^{v_p / v_e} \to 120\, T$ (for $\beta \approx 10$, $v_p = 100$ km/s, $v_e = 500$ km/s)
    - Power: $P_e = \left(\frac{v_e^2/2}{\eta \Delta t} \right) M_0 \left(1 - e^{-v_p/v_e} \right) \to 100 \text{ MWe}$

      For $\alpha = 3$ kg/kWe → $M_0 \approx 735$ T

$\Rightarrow$ Solar sail? (McInnes, 2003)

Nuclear Option

- $\Delta I = 10^{11}$ kg·m/s, $V_a \approx 30$ km/s → $\Delta E = 3\times10^{15}$ J

  Equivalent to 750 kt TNT

- Current arsenal has devices up to* ≈ 1 mt
- Largest weapon tested** ≈ 50 mt
- Largest weapon designed** ≈ 150 mt

Nuclear weapons can theoretically be used for the largest objects and speeds (comets if enough time)

- $\Delta I = 10^{13}$ kg·m/s, $V_a \approx 30$ km/s → $\Delta E = 3\times10^{17}$ J ≈ 70 mt

…assuming coupling is sufficiently efficient

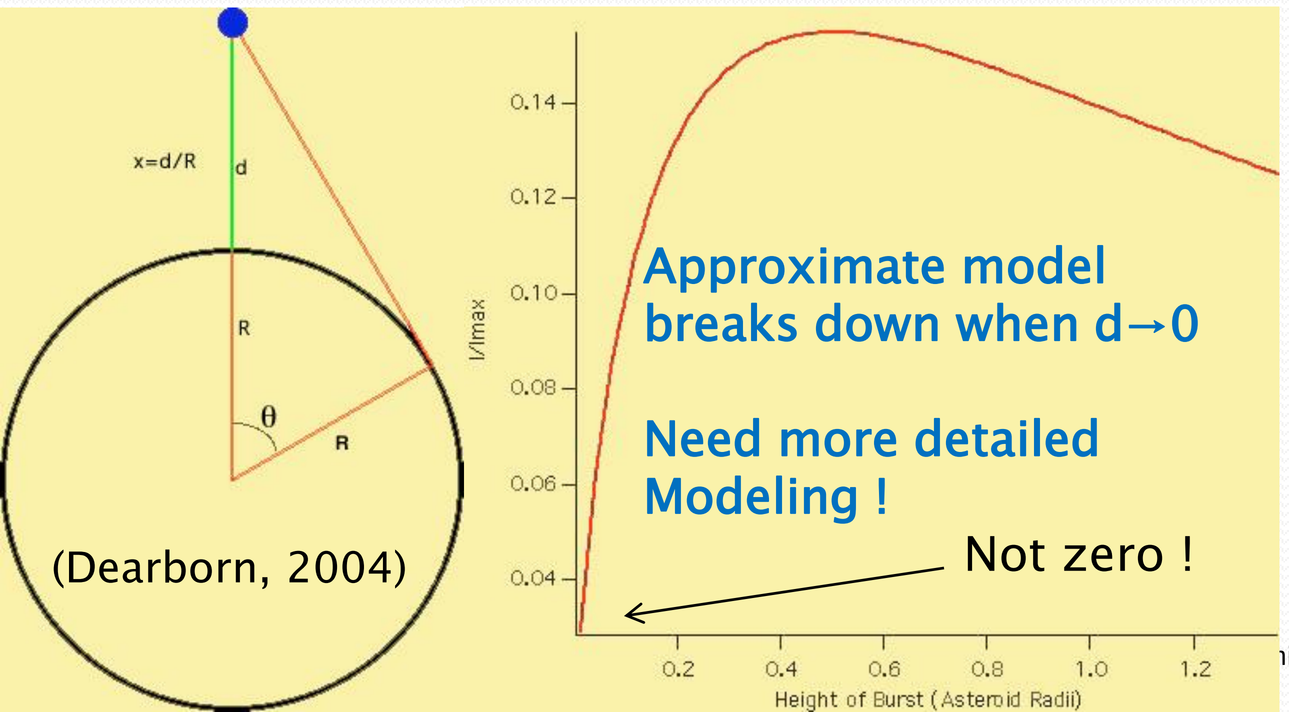
*http://nuclearweaponarchive.org/Usa/Weapons/Wpngall.html
**http://www.johnstonsarchive.net/nuclear/multimeg.html

Nuclear Option

- Fearing fragmentation…

Stand-off detonation

X-ray /neutron coupling

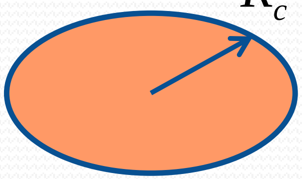


(Dearborn, 2004)

ited.

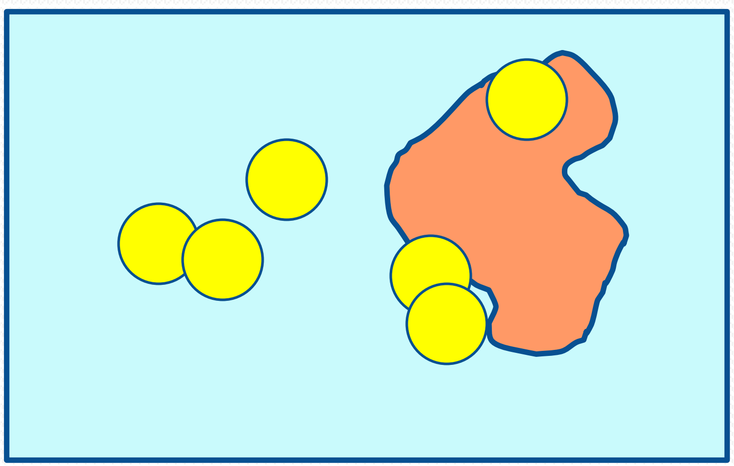
Buried/Surface Detonation

Impact of Fragments



$$R_c \approx \left(\frac{E_0}{p_c}\right)^{1/3}$$

$$N \cdot A_{kill}^{(N)} = N\left(\frac{E_0/N}{p_c}\right)^{2/3} \rightarrow A_{kill}^{(N)} = \frac{A_{kill}^{(1)}}{N^{2/3}}$$



$$p_{kill} = N\pi - \left[(1+\pi)^N - 1 - N\pi\right] = 1 + 2N\pi - (1+\pi)^N$$

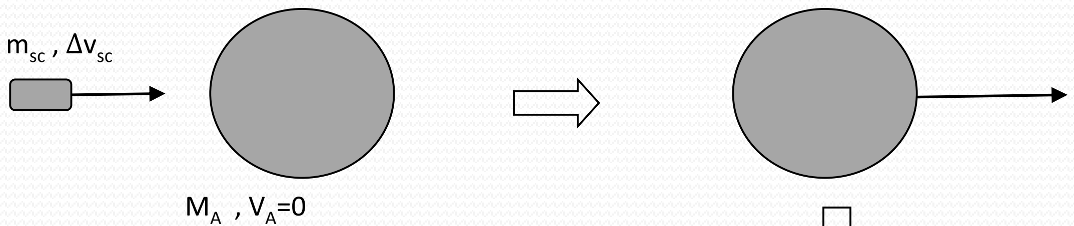
$$p_{kill} = 1 + 2\tilde{\pi}_1 N^{1/3} - \left(1+\frac{\tilde{\pi}_1}{N^{2/3}}\right)^N$$

Higher probability of kill, IF simple Sedov model is valid.

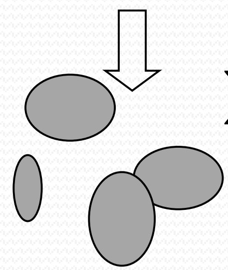
Need better modeling !

Playing Billiard..

- Similar to problem of fragmentation



$$\Delta\vec{V}_A = \frac{m_{sc}\Delta\vec{\mathrm{v}}_{sc}}{M_A + m_{sc}}$$



$$\sum m_i(\Delta\vec{\mathrm{v}}_i + \Delta\vec{V}_A)$$

Δv_i measured with respect to CoM after collision: $\sum m_i \Delta\vec{\mathrm{v}}_i = 0$

$$\sum m_i (\Delta\vec{\mathrm{v}}_i)^2 = M_A \sigma^2$$

$$\frac{1}{2} m_{sc}(\Delta \mathrm{v}_{sc})^2 = \sum \frac{1}{2} m_i (\Delta\vec{\mathrm{v}}_i + \Delta\vec{V}_A)^2 + E_{diss} = \frac{1}{2} M_A (\Delta\vec{V}_A)^2 + \sum \frac{1}{2} m_i (\Delta\vec{\mathrm{v}}_i)^2 + \Delta\vec{V}_A \cdot \underbrace{\sum m_i (\Delta\vec{\mathrm{v}}_i)}_{0} + \underbrace{E_{diss}}_{\approx 0}$$

$$\boxed{\sigma = \left(\frac{m_{sc}}{M_A}\right)^{1/2} \left[1 - \frac{m_{sc}}{M_A}\right] \Delta \mathrm{v}_{sc} \approx \sqrt{\frac{M_A}{m_{sc}}} \Delta V_A >> \Delta V_A}$$

(same as Sanchez Vasile, Radice, 2008)

No guarantee there are no fragments with $v_i \approx V_A$

Pure Fragmentation

- No kinetic impact – just fragment object and supply kinetic energy to debris
  - All debris have at least escape velocity ($\approx$1 m/s)
  - Total kinetic energy: $E_{kin} \approx \frac{1}{2} M_A (v_{esc})^2 \approx 10^{13}$ J
  - Add dissipated energy (e.g. 3x) $\Rightarrow E_{tot} \approx 10$ kt !!
  - Dissipated energy highly variable:
    - Fragmentation: $E \approx \Lambda M^{2/3}$

      $\Lambda \rightarrow f$ (material strength)
  - Use as large a total yield as possible
  - Use several warheads – location? timing?

Need more modeling !

Controlling Fragments

- Why can't we "bag" the debris?
  - If we can build km^2 sails/solar arrays, we can build nets
- Why can't we use smaller yields, more often (to achieve "gentle" push)
- Why can't we detonate at a farther distance? (less efficient, but we have >10,000 warheads)

Concluding Remarks

1. Slow-Push approaches require significant technology development:
   - Large power systems (nuclear)
   - Large structures (radiators or solar arrays/sails)
2. Kinetic Impact possible for medium-size objects: very difficult for km-class objects
3. Nuclear devices still best option: stand-off vs. surface detonation TBD
   - Need more, detailed simulations
   - Need some validation data (how?)

Concluding Remarks

4. All options require advances in propulsion systems (performance & reliability) and/or space power (nuclear)
   - Isp >> 10,000 s for (a) getting there; (b) deflecting target:
   - Multi-MW power for EP
5. Controversial: Large-yield nukes may be needed
   - Keep current ones in stockpile?
   - Design new warheads?
6. Not discussed – need <u>reliable</u> heavy lift
7. Not discussed – need lots of robotic missions
8. Not discussed – need more effort in detection

The Future*….(and potential DoD role/use)*

- All requirements belong to components of a large-scale, futuristic space architecture
  - *Low-cost, reliable heavy lift*
  - Long-duration, high-performance OTV
    - *Isp≈20,000 of benefit to DoD – maybe*
  - Power-generation/beaming
    - *Revolutionary space access, missile defense,…*
  - *Advanced Robotics/AI*
  - Large-scale in-space assembly/manufacturing
    - *Large solar arrays, antennas, telescopes…*

Final Note

There is no better justification for developing a large-scale space infrastructure than self-preservation

Corollary: Even if the threat does not materialize, the effort can (and must) greatly facilitate space exploration, permanent human presence in space (and possibly National Security)