Impact Deflection of Potentially Hazardous Asteroids Using Current Launch Vehicles

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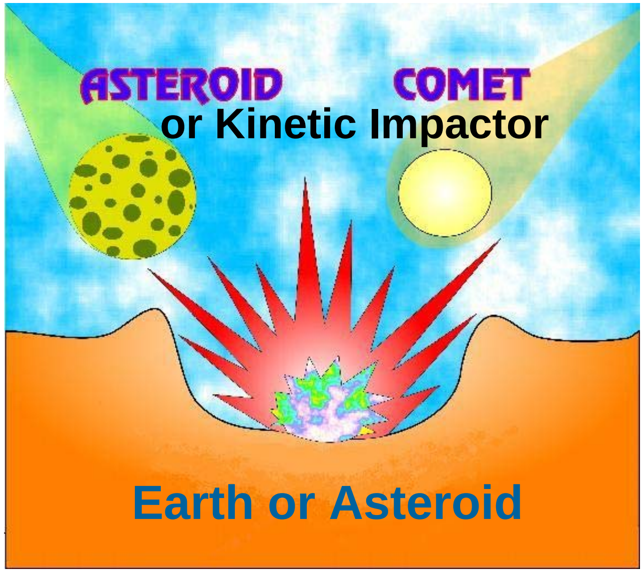
Why Kinetic Impact?

- ✓ Simple
- ✓ Inexpensive (relative to other methods)
- ✓ Fastest to effect
- ✓ Requires no new or exotic technology
- ✓ Doesn’t require building or testing nuclear warheads
- ✓ Highly capable
- ✓ We can do it NOW.

Why *Call* it Kinetic Impact?

- Kinetic Impact (like all deflection methods) involves momentum transfer, so why call it Kinetic Impact? Why not Momentum Impact?
  - → Just like asteroid striking Earth, impactor striking asteroid has huge kinetic energy which, upon impact, causes explosive cratering.
    - → Ejecta from crater acts as propulsion.



Study Overview

- We model kinetic impact missions to 795 PHAs taken from neo.jpl.nasa.gov on 6/21/06.

- All of our simulations use the actual first four orbital elements [a e i ω] for the all 795 asteroids. We assume a circular Earth orbit, and no knowledge of mission date.

- Other than orbits, we take a parametric approach, varying:
  - Asteroid size
  - Asteroid density
  - Cratering parameters
  - Warning time

Deflection Distance

- Start with a cube-shaped Earth, and an asteroid heading toward the center of an Earth face at 90° and Earth velocity.

  → Required deflection distance is 1 $R_\oplus$

- Factors that decrease required deflection distance:
  - Earth is sphere-like
  - Angle between Earth and asteroid velocities is < 90°
- Factor that increases required deflection distance:
  - Gravitational focusing makes Earth effectively ~1.4 times bigger at typical Earth-asteroid relative velocities

We use 1 $R_\oplus$ in our simulations.

(Distance is ~4 orders of magnitude less for keyholes.)

Orbit Perturbation

- In-track perturbation gives cumulative effect over time.
- For extremely short warning times (< 1 year), optimal perturbation may not be in-track, but for likely warning times, it will be almost purely in-track.

→ We use in-track perturbation only, with two body model:

$$\frac{da}{dt} = \frac{2a^{3/2}}{\sqrt{\mu(1-e^2)}}\left[\frac{dV}{dt}(1+e\cdot\cos\nu)\right]$$

$$dV = \frac{2\pi\cdot\delta\cdot a\cdot(1-e^2)^{0.5}}{3\cdot T\cdot C\cdot\left[e\sin\phi\sin\nu + K_\phi(1+e\cos\nu)\right]}$$

$$\phi = \cos^{-1} K_\phi$$

$$K_\phi = \left[\frac{(1+e\cos\nu)^2}{2(1+e\cos\nu)-(1-e^2)}\right]^{0.5}$$

$$\phi(\nu<\pi)>0$$
$$\phi(\nu>\pi)<0$$

$$C \approx \pi(a+b)\left[1+\frac{3x^2}{10+\sqrt{4-3x^2}}\right] \qquad x=\frac{a-b}{a+b}$$

a = semi-major axis
b = semi-minor axis
V = velocity
μ = sun grav. constant
e = eccentricity
ν = true anomaly
φ = flight path angle
δ = deflection distance
T = warning time
C = orbit circumference

Impact Location on Asteroid

- Assume that ejecta average momentum is normal to surface impacted.
- Impactor should strike asteroid at location where surface is normal to asteroid velocity vector, to give in-track ΔV.
- Imparting spin to asteroid is ok because linear and angular momentum are conserved separately.
- Final impactor targeting will not be trivial, but is doable with current technology.
  - ➢ See Deep Impact, MDA kinetic kill vehicles

Crater Dynamics

- Magnitude of ejecta momentum depends on cratering dynamics.
- We draw on work of Holsapple, Housen, Schmidt, and Melosh to model cratering event.
- Crater model is influenced strongly by three target dependant parameters: K, C_D, ζ (ζ is often called ν in literature)
- We use a parameter set that was determined experimentally for dry Ottawa sand:

  $K = 0.32 \quad C_D = 1.68 \quad \zeta = 1.22$

- This is a conservative set, i.e. gives low momentum ratios compared to others in literature.
- Also gives low momentum ratios compared to other cratering models.

Ejecta Momentum

$$\Delta P_{ej} = \int_{V_{esc}}^{\infty} V_{final} \cdot \sin\theta \cdot \frac{dm_{ej}}{dV_{ej}} \cdot dV_{ej}$$

$$V_{final} = \sqrt{V_{ej}^{\ 2} - V_{esc}^{\ 2}}$$

$\frac{dm_{ej}}{dV_{ej}}$ is derived from:

$$Vol_{ej}\left(> V_{ej}\right)R^{-3} = K\left(\sqrt{gR}\big/V_{ej}\right)^{\zeta}$$

(Use gravity scaling.)

R is derived from other
crater relations in the literature.

ΔP_{ej} = momentum imparted by ejecta
v_{esc} = asteroid escape velocity
v_{final} = ejecta vel. after escape
θ = ejecta angle (assumed = 45°)
V_{ej} = ejecta velocity
m_{ej} = ejecta mass
V_i = impact velocity
m_{ast} = asteroid mass
Vol_{ej} = ejecta velocity

ζ = cratering constant
K = cratering constant

Impactor Mass Calculation

$$m_i = \left(-B - \sqrt{B^2 - 4AC}\right)/2A$$

where

$$A = k_1 k_4$$
$$B = -\Delta V \cdot k_3 k_4 - k_1 k_3 - k_2 k_3$$
$$C = \Delta V \cdot k_3^2$$

and

$$\mathrm{k}_1 = V_i \left|\sin \omega_i\right|$$

$$\mathrm{k}_2 = \sin\theta \cdot \zeta K C_D^{3+\zeta/2}\, 2^{\frac{3(1+\beta)}{\beta-1}} V_i^{\zeta} \rho_a^{-\zeta/6} \rho_i^{\zeta/6} \cdot \int_{V_{esc}}^{\infty} \left(V_{ej}^2 - 2\mu_a / r_a\right)^{0.5} V_{ej}^{-\zeta-1} dV_{ej}$$

$$\mathrm{k}_3 = \mathrm{m}_{\mathrm{ast}}$$

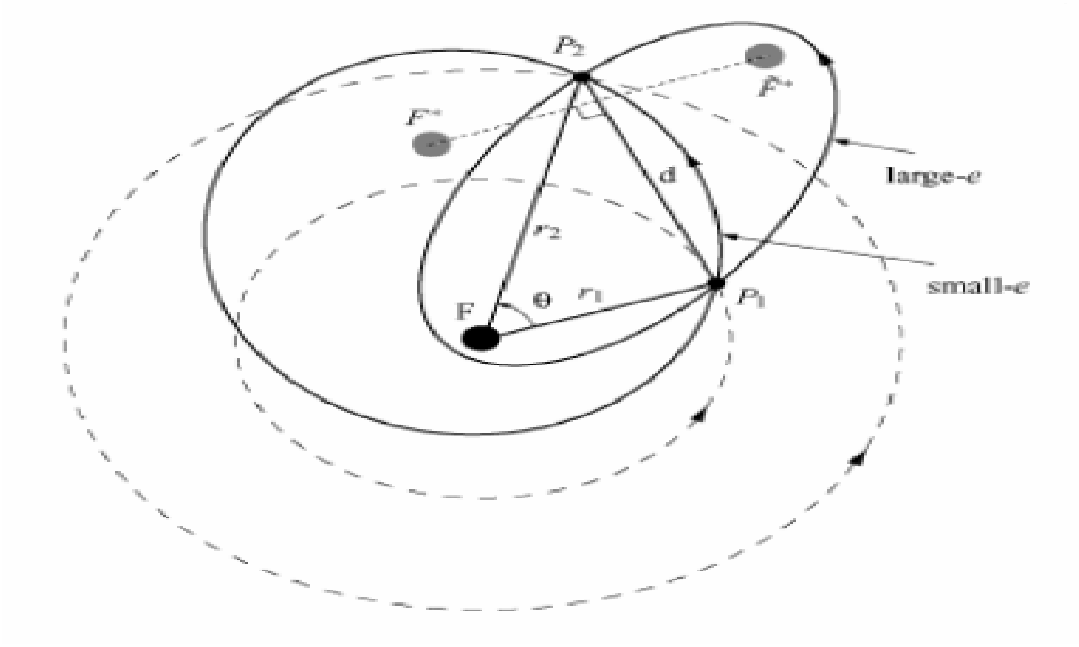
$$\mathrm{k}_4 = \tfrac{1}{2} K C_D^{3+\zeta/2}\, 2^{\frac{3(1+\beta)}{\beta-1}} V_i^{\zeta} \rho_a^{-\zeta/6} \rho_i^{\zeta/6} V_{esc}^{-\zeta}$$

V_i = impact velocity
ω_i = impact angle
ρ_i = impactor density
ρ_a = asteroid density
m_{ast} = asteroid mass
θ = ejecta angle (assumed = 45°)
V_{esc} = asteroid escape velocity
V_{ej} = ejecta velocity

ζ = cratering constant
K = cratering constant
C_D = cratering constant
β = $\zeta/(\zeta+6)$

Trajectories

- In real mission, some JPL-types would find optimal interplanetary trajectory, maybe using gravity assist fly-by's.
- To model large number of missions, and to be conservative, we use Lambert trajectories.
- For each given departure and arrival point, simulations analyze all four trajectories for a range of intercept semi-major axes.



Earth-Asteroid Geometry

- We could calculate the most efficient deflection theoretically possible by allowing the impactor to depart any point in Earth orbit and arrive at any point in asteroid orbit.
- However, in reality, the resulting optimal geometry might not be present during the time frame in which we want to launch our mission.
- Instead, we use a separate Monte-Carlo analysis to select Earth-asteroid geometries for which we have a certain probability of achieving that geometry or better within a certain time frame.
- There is a 60% chance of achieving our results or better within a 10 year launch window, 80% within 20 years.

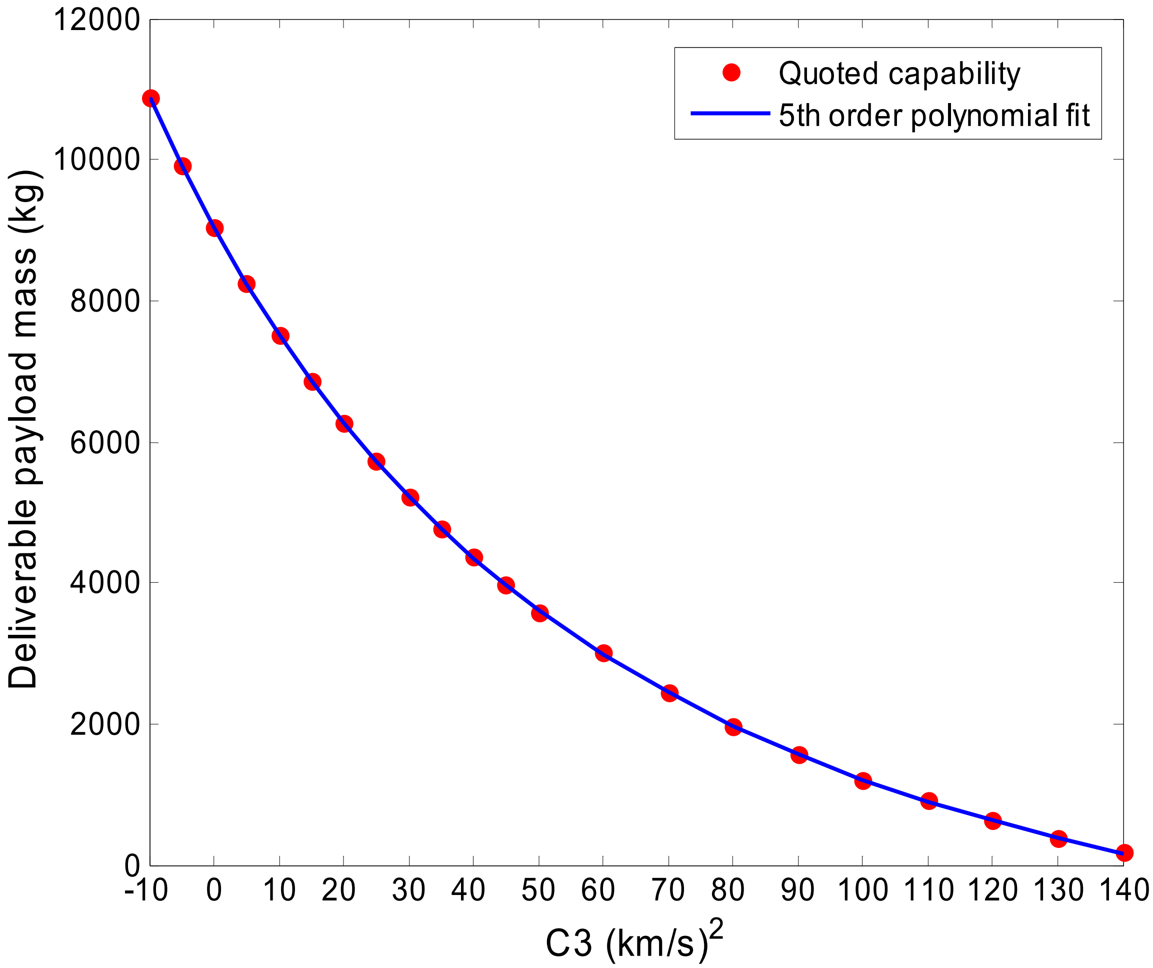
(Remember, this assumes we are limited to simple Lambert trajectories.)

Launch Vehicle

- We assume only present launch vehicle capability.

  (Not including Ares V)
- Our model uses Atlas V Heavy Lift Version, Single Engine Centaur upper stage.

- Note: There is an option to leave SEC attached to payload. This adds another ~2500 kg to delivered impactor mass. We do not include this in our model, but instead leave it as a source of margin for our results.



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Parameterization of Results

- For every intercept trajectory analyzed:
  - Compute required impactor mass for specified deflection.
  - Compute max possible payload mass (using fit function of quoted launch vehicle performance) for the associated C3.

$$\frac{\text{Required Mass}}{\text{Deliverable Mass}} = \lambda_{mass}$$

- λ_{mass} is our metric to optimize, and to evaluate the viability of kinetic impact method.
- Rounding up λ_{mass} to the next integer gives the number of launches required.

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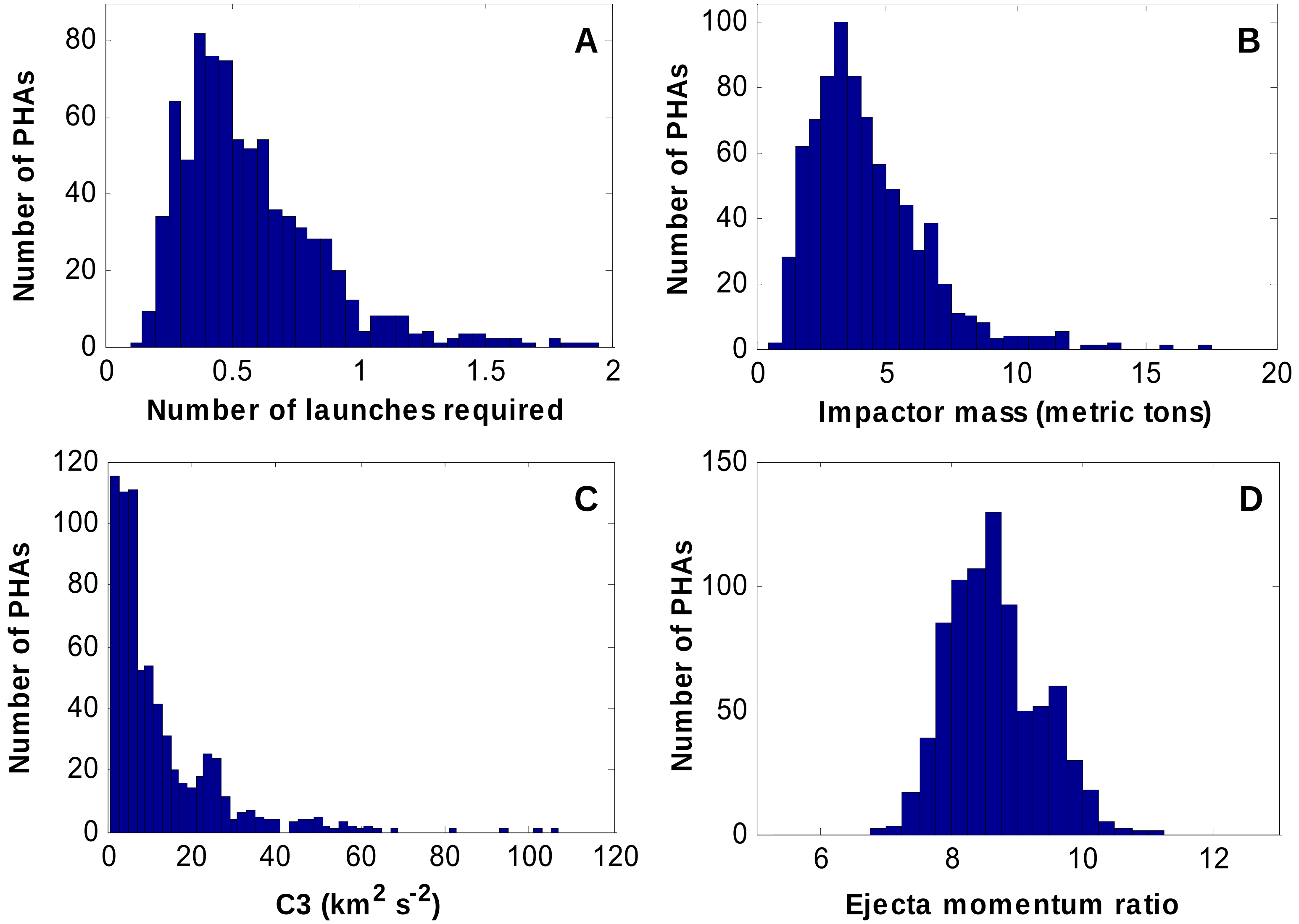
Results

Simulation	Asteroid diameter (m)	Asteroid density (g cm^{-3})	Impactor density (g cm^{-3})	Time from deflection impact to predicted Earth collision (years)	Crater model	Number of launches / Percentage of PHAs that can be deflected with that number of launches or fewer	
1	1000	3	19	100	Ottawa sand	1 / 55%	2 / 94%
2	1000	3	19	20	Ottawa sand	5 / 55%	10 / 94%
3	500	3	19	20	Ottawa sand	1 / 93%	2 / 100%
4	250	3	19	5	Ottawa sand	1 / 100%	
5	1000	3	8.9	100	Ottawa sand	1 / 44%	2 / 91%
6	1000	1.5	19	100	Ottawa sand	1 / 97%	2 / 100%
7	1000	0.5	19	20	Ottawa sand	1 / 95%	2 / 100%
8	500	1.5	19	10	Ottawa sand	1 / 100%	
9	500	0.5	19	3	Ottawa sand	1 / 99%	2 / 100%
10	1000	3	NA	50	P ratio = 38.5	1 / 99%	2 / 100%
11	1000	3	NA	100	No ejecta	10 / 57%	30 / 97%
12	750	0.5	NA	100	No ejecta	1 / 74%	2 / 95%
13	400	3	NA	100	No ejecta	1 / 78%	2 / 97%
14	500	0.5	NA	20	No ejecta	1 / 54%	3 / 96%
15	250	3	NA	20	No ejecta	1 / 71%	3 / 99%
16	250	1.5	NA	20	No ejecta	1 / 92%	2 / 100%
17	250	0.5	NA	5	No ejecta	1 / 86%	2 / 99%
18	150	3	NA	20	No ejecta	1 / 100%	

Results for Sim 3 (500 m, 3 g/cm^3, 20 years)

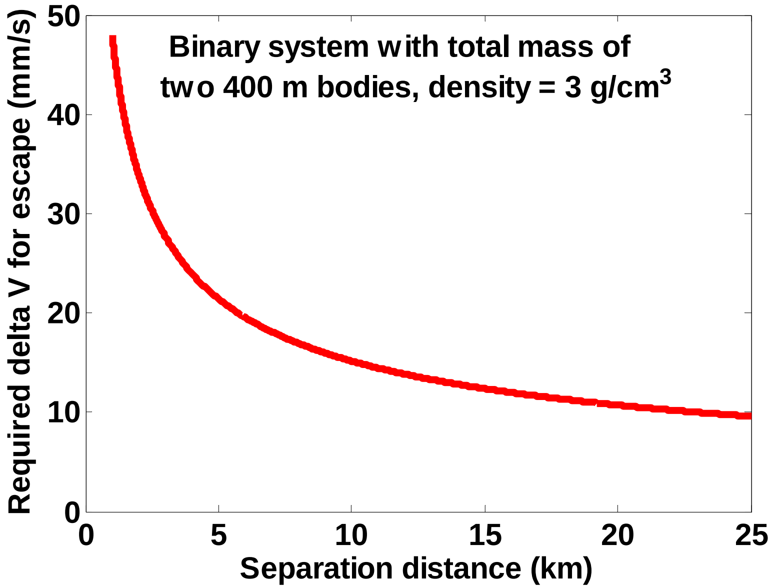


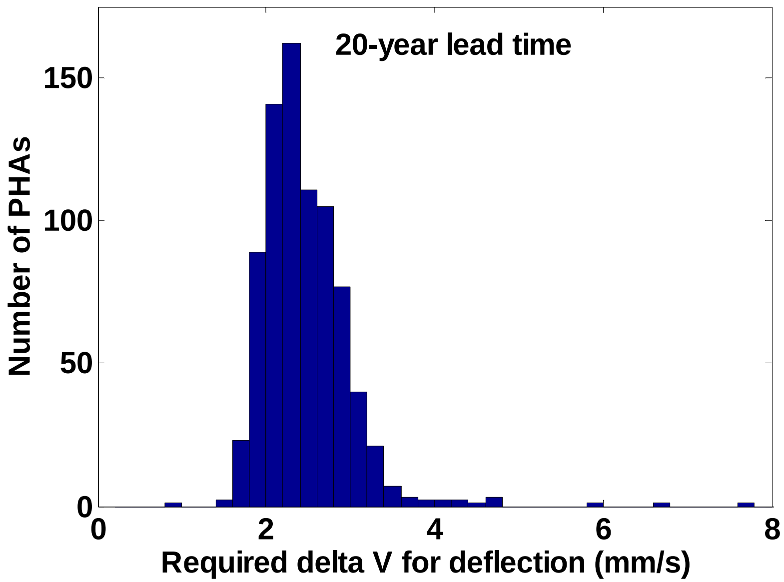
Binary Asteroids

- 3 cases:
  A) ΔV is large enough and in precise direction to permanently separate two bodies
  B) Binary orbit is perturbed such that bodies stick together, forming "contact binary"
  C) The two bodies remain in orbit around each other

- In Cases B and C, momentum is conserved, and the impact has the same effect as on a single body of similar mass.
- Case A requires ΔV at least as big as the difference between the bodies' relative velocity, $V_{rel} = \sqrt{G(m_1 + m_2)/\text{distance}}$, and their mutual escape velocity, $V_{eM} = \sqrt{2} \cdot V_{rel}$.
  - For a given total mass, Case A is less likely for greater size disparity between the two bodies, assuming an impact to the larger body.

Binary Asteroids





Consider binary with two 400 m bodies (~ mass of single 500 m body):

- At 23 km separation, minimum ΔV for mutual escape is 10 mm/s.
- This ΔV must be parallel to impacted body's velocity relative to CoM.
- 10 mm/s for one body corresponds to 5 mm/s for the system.
- In vast majority of deflection cases (for lead time >= 20 years), required ΔV is < 5 mm/s. → Mutual escape is unlikely.

Conclusions

- In our cratering model, ejecta imparts 6-12 times the momentum of the impactor.
- With this class of cratering event, kinetic impact is a viable method for the vast majority of threats.
- Even without cratering, kinetic impact is viable for large portion of threats, including keyhole deflection.
- We should start doing fast cheap scaled down kinetic impact missions to build our ability to predict and model cratering effects for various asteroid types.
  - Make it not so “uncontrolled”
- We should not shut down Arecibo. Radar gives:
  - Characterization which will allow better mission planning, results prediction
  - Precise measurement of deflection results
  - Longer lead times