Response of NEO's to Mitigation Techniques

(And comments on the Impact Method)

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- **Asteroid**
- An asteroid's coming.
- There's no use in running
  to the other side of town
  when it starts to come down.
- Priests all over the stations,
  proclaiming to the nations of people trying to understand God better.
  We're going to die.
- We can't ignore Him forever.
  What's the point of staying round
  at work for the rest of my life?
  I'm going back home to my beautiful wife.
- Give thanks for the things that I've had in the past.
- Oh, and it feels that sometimes/ I think that I'm wasting my life.
  Sometimes/ I think that I'm wasting my life.
  Sometimes/ I think that I'm wasting my life.
  Sometimes/ I think that I'm wasting my life.

•I think of Bruce Willis.
•Get sent out to space.
•Save the Human race.
•But that's all just fiction.
•We're up for extinction.
•Why would Osama bin Laden
•go and send any nuclear bombs?
•He's thrown down his guns.
•The United Nations abandon their stations.
•There's no need for power or smashing down towers.
•The world sits and cowers at home with their kids as destruction looms on.
•What's the point in keeping this fifty bucks
•that I've got in my hand?
•I've probably got fifty times more in the bank.
•Give it to some hombre that begs for his bread.
•Oh, and it feels that sometimes/ I think that I'm wasting my life.
•Sometimes/ I think that I'm wasting my life.
•Sometimes/ I think that I'm wasting my life.
•Sometimes/ I think that I'm wasting my life.I think that I'm wasting my life.
•**An asteroid's coming.**
•**It's time to start summing up what we think is best,**
•in the time we've got left.
•An asteroid's coming.
•An asteroid's coming.
•An asteroidɔs coming.
•An asteroid's coming.....

What do we need to do??

- Change its velocity along its path
  - Direct Approach: ~1-2 cm/s 10 years prior
  - Prior Flybys: Depends, but could be much less? Strong non-linear effects..
  - Keyholes: Just miss it baby! (<1 mm/s)
- Destroy It (get Bruce Willis approach..)

How might we deflect it?

- Nuclear Explosives: standoff, surface
- Impacts
- Gravity Tractor

Can do now

- Buried Nuclear Explosives
- Attached Rockets
- Focused Solar Energy
- Solar Sail
- Mass Driver
- Focused Laser
- Yarkovsky
- Prayer

Unanswered Questions,
Major developments necessary

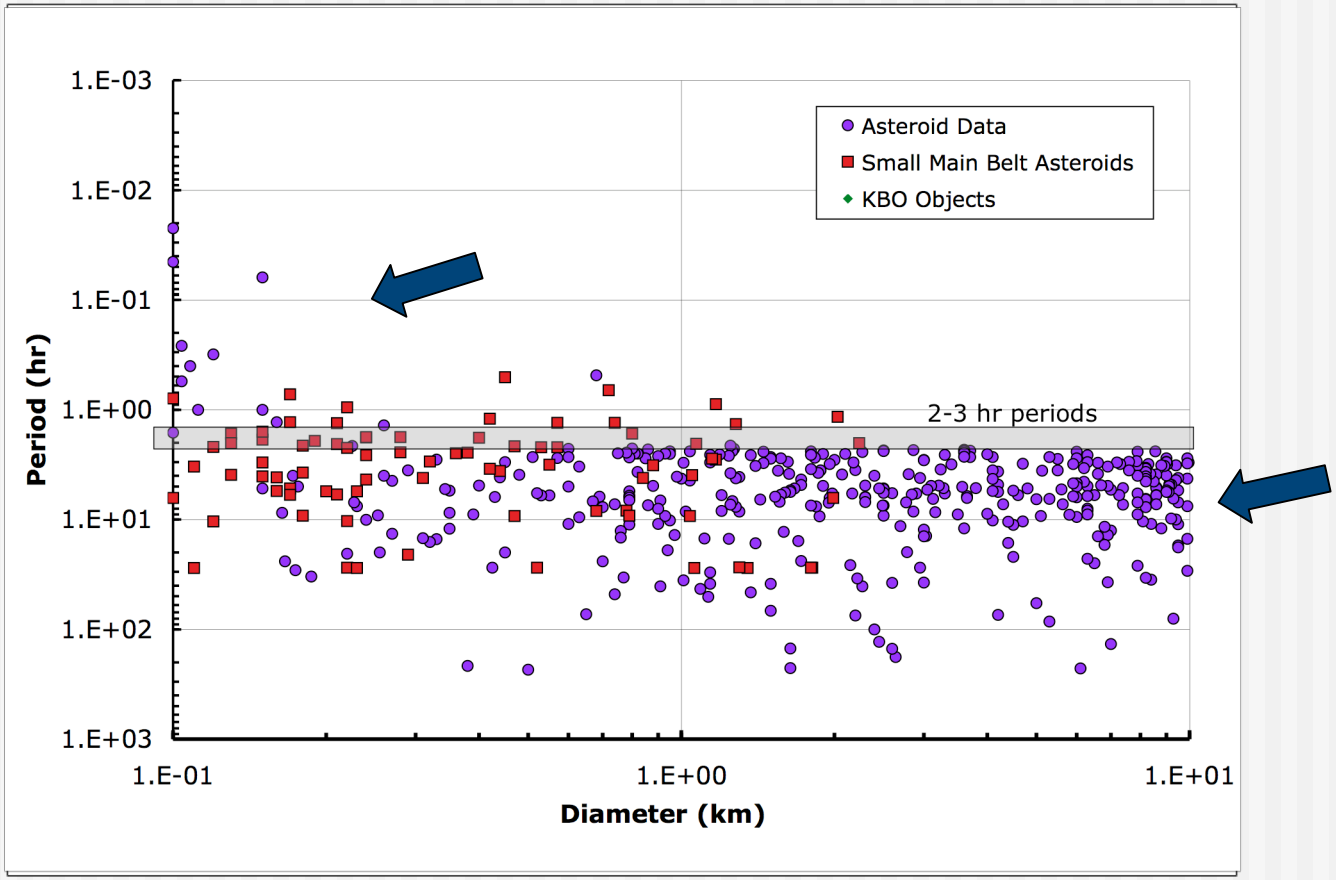
These group into the:

- Slow Methods:
  - Gravity Tractor
  - Attached Rockets
  - Focused Solar Energy
  - Solar Sail
  - Mass Driver
  - Focused Laser
  - Yarkovsky
  - Prayer?
- Impulsive Methods:
  - Impacts
  - Nukes

Questions

- These methods may have problems with one or more of the following:
  - Body Spin
  - Body Composition
  - Engineering
    - Attachment
    - Reliability
  - Controllability
  - Political

They are spinning,
at an average of once every few hours



The methods having problems with spin

- Rockets
- Mass drivers
- Solar Sail
- Gravity Tractor (for elongated or binary bodies)

Problems with Composition: Rubble Piles v. Rocks

In the main belt, they regularly impact, disrupt (broken up) and disperse (broken and scattered):

And little ones are disrupted and dispersed **much** ones:

$t_{disrupt} \sim 1.8\ 10^5\ R_{(km)}^{1.9}$ years (300 m, 18,000 yr)

$t_{disperse} \sim 8.4\ 10^6\ R_{(km)}^{1.9}$ years (300 m, 0.8 My)

On average, an asteroid is disrupted 40 times for every dispersion!

And a 300 m asteroid is disrupted every 20,000 years, and destroyed every million years, ==> many rubble piles??

Present state: Rubble pile v. coherent:

- We don't know, but many might be rubble piles
- And it would seem that little ones are more likely to be rubble pile bodies than large ones ??

Those having problems with Composition:
(Rubble Piles v. Rocks)

- Impacts
- Nukes
- Mass drivers
- Focused Energy??

And the composition also creates serious questions about attachment/ anchoring/ digging:

- Rockets
- Mass Drivers
- Buried Explosive
- Solar Sails

And what about controllability?

- Slow Methods: Can measure and modify outcome during the process: *Controllable*
- Impulsive (Fast) Methods: One shot, take what we get.
  - But repeated fast methods: Use as needed.

So, those having problems with controllability

The impulsive methods:

- Impacts
- Explosives

These may require a second, third.., further missions and an observing spacecraft (Sancho)

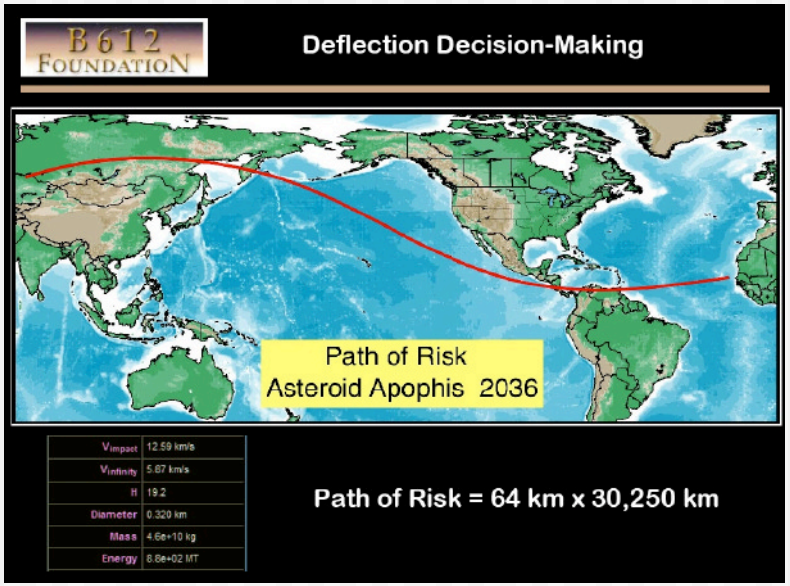
And the environment is difficult..

Creating questions about Reliabilty

- The extended period, slow methods:
  - Rockets
  - Gravity Tractor
  - Focused energy
  - Solar Sail
  - Mass Driver

Those having problems with politics

- *Nukes in space.*
- Any slow method as The *"path of risk"* moves across the Earth



Summary of Problems/ Questions

Method	Spin?	Compos-ition?	Attach-ment?	Controll-abiltiy?	Reli-ability?	Engin-eering?	Politics
Direct Impact	**None**	**Magnitude ?**	**None**	**Follow-up**	**None**	**None**	**None**
Nuke	**None**	**Magnitude ?**	**None**	**Follow-up**	**None**	**None**	**Serious**
Rockets	**Serious**	**None**	**Serious**	**Monitor**	**Some**	**None**	**Some**
Gravity Tractor	**Some**	**None**	**None**	**Monitor**	**Serious**	**Some**	**Some**
Concentrated Solar	**None**	**Little?**	**None**	**Monitor**	**Serious**	**Serious**	**Some**
Mass Driver	**Serious**	**Serious**	**Serious**	**Monitor**	**Serious**	**Serious**	**Some**
Solar Sail	**Serious**	**None**	**Serious**	**Monitor**	**Serious**	**Serious**	**Some**
Yarkovsky	**None**	**None**	**None**	**Direction ?**	**None**	**Serious**	**Some**

The Direct Impact Method

"The Kinetic Energy Method"

(But it's the momentum that counts)

Issues

- How large, how fast?
- Might it disrupt the body? Is that a problem?
- What if it spalls off back-surface material?
- Does it require a precise center hit?
- Does it require an approach along the path of the NEO orbit?
- Can we hit a 100*m* NEO?

How large, how fast?

$$\Delta v = \frac{\text{Transmitted Momentum}}{mass_{neo}}$$

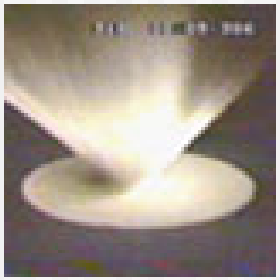
But the momentum transmitted can be quite different than the momentum $M_{impactor}U$:

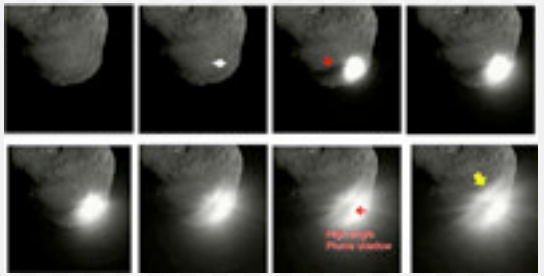
$$\Delta v = \beta \frac{\text{Delivered Momentum}}{mass_{neo}} = \beta \frac{Mass_{asteroid} U}{mass_{neo}}$$

What is the value of the "momentum multiplication factor" β?

Momentum Multiplication..

Momentum is increased by a factor β due to blow-back ejecta launched at $v > v_{esc}$

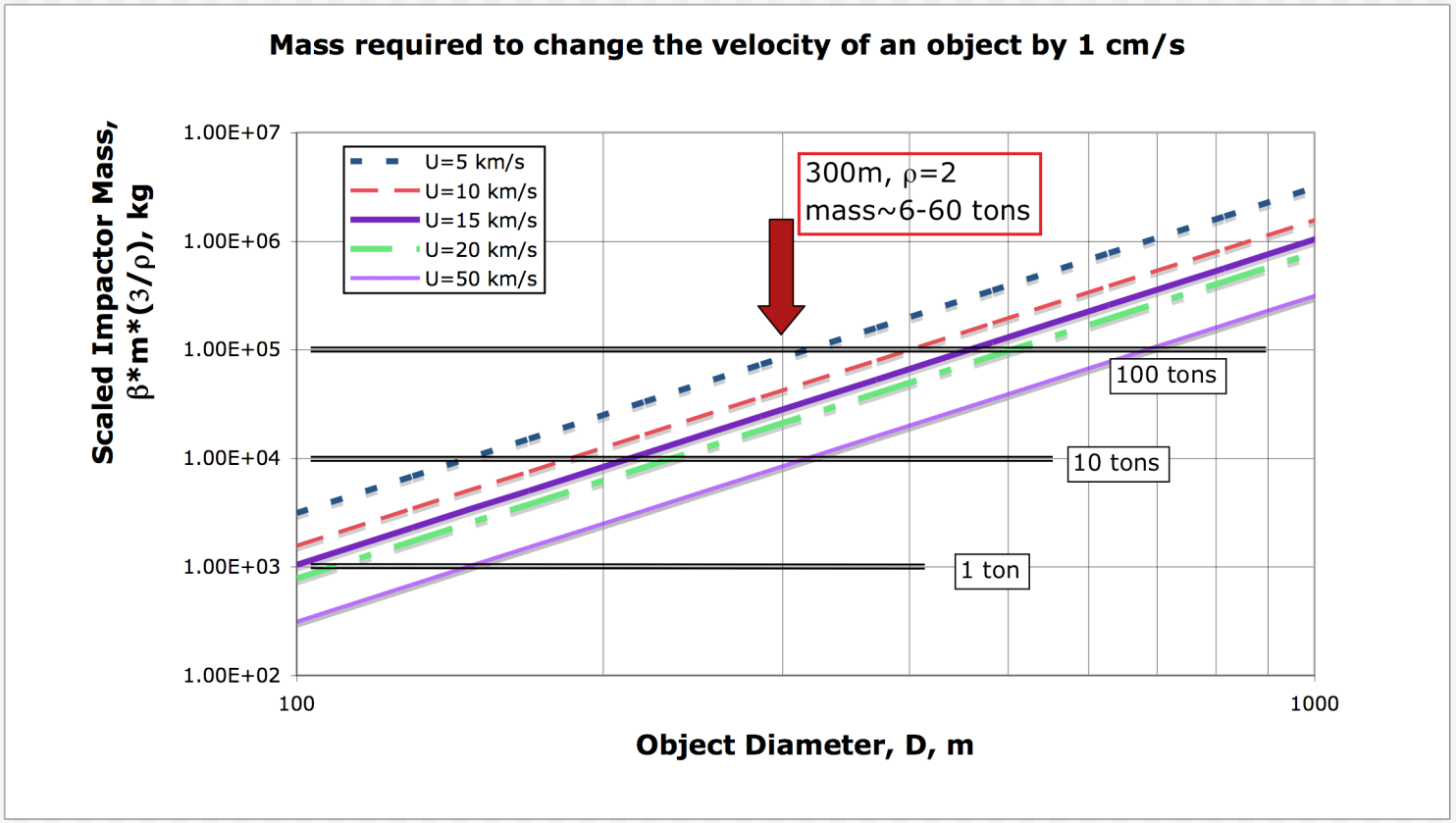




Decreased if spall from back-surface

Decreased in a glancing blow, in which part of the impactor is not stopped

Mass Required



Momentum Multiplication

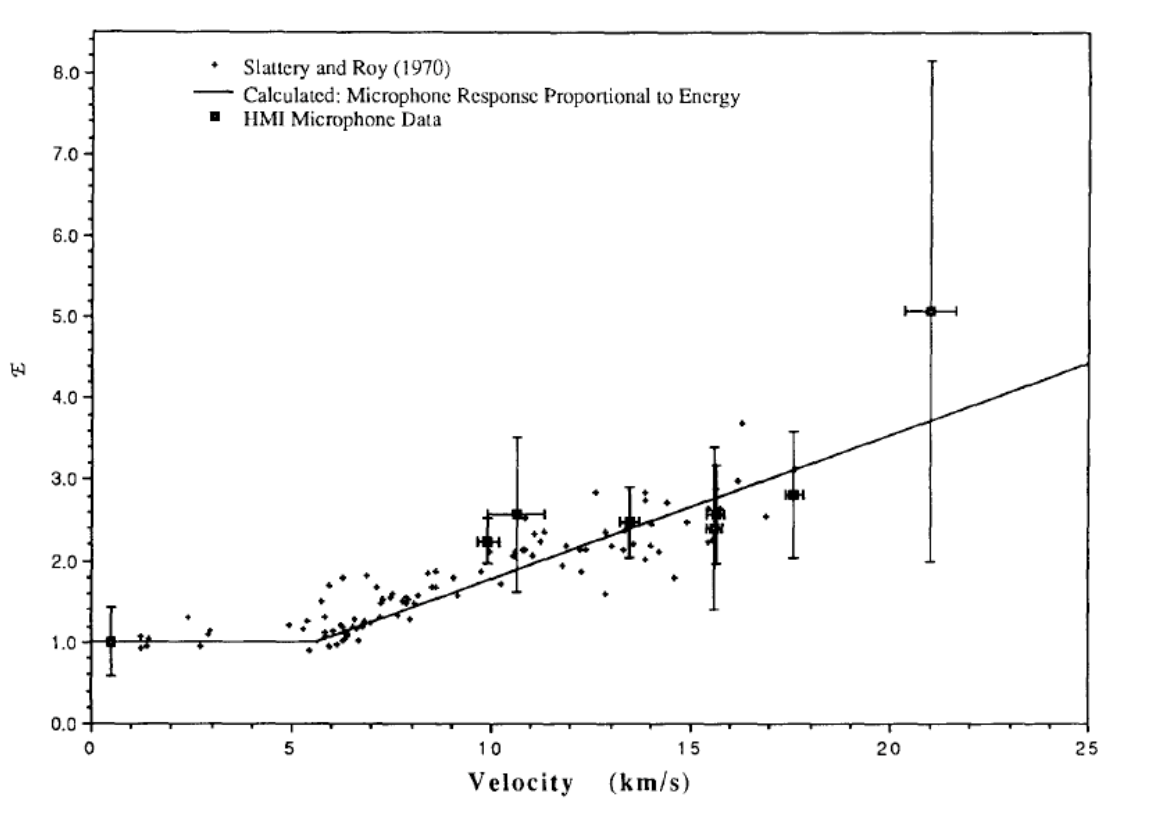
Past studies have shown that for projectile velocities up to 20 km/s the total momentum conveyed by a projectile to the target may be enhanced by a factor approaching 10 by the recoil from the blowoff material (Walsh and Johnson, 1965, Dienes and Walsh, 1969, Dienes and Walsh, 1970, Slattery and Roy, 1970). Numerical simulations of particle impacts in the 100km/s regime predict momentum multiplication factors of up to 20 (Scharff, et al., 1987, Scharff, et al., 1988). We are measuring momentum transfer and momentum enhancement of microparticle impacts.

We report data in the velocity range 10km/s to 20km/s.

Int. J. Impact Engng Vol. 10, pp. 555 570, 1990

But what is the β factor??

- Direct Measurements

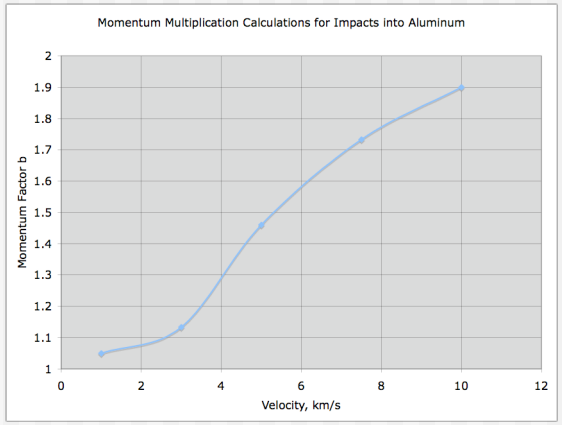


What is the β factor??

I. Estimates from Code calculations:

a. ESA Don Quixote into rock: $\beta \sim 4$ (SPH, Willy Benz)

b. Impacts in Aluminum



c. Impacts w/ Porous Impactor

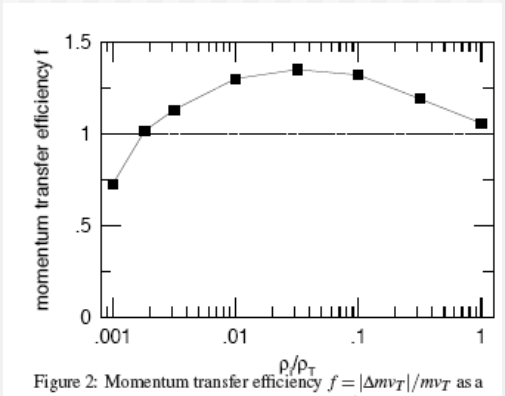
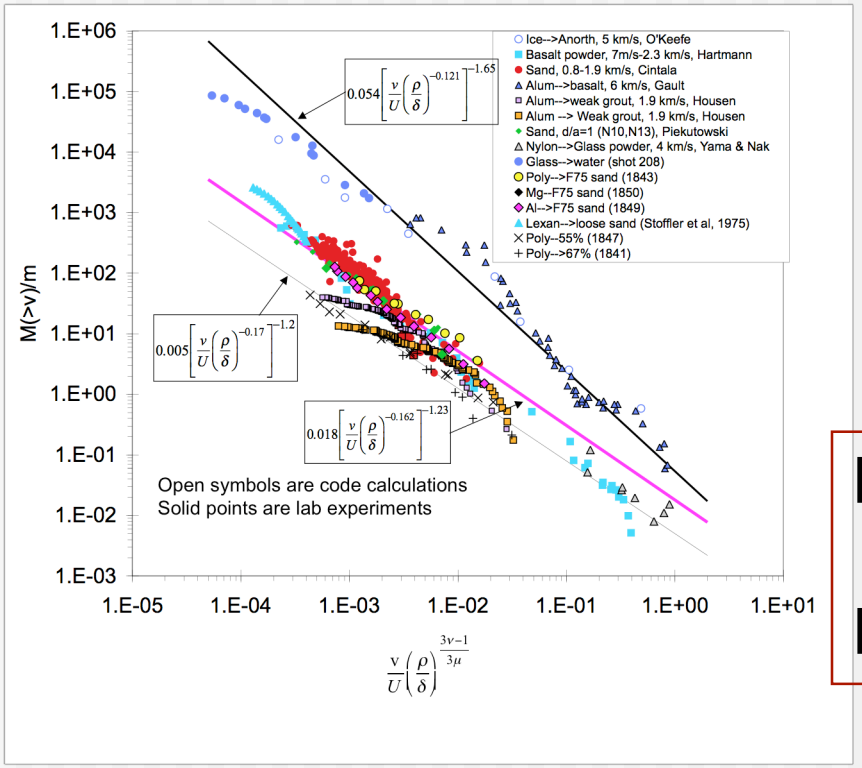


Figure 2: Momentum transfer efficiency $f = |\Delta m v_T|/m v_T$ as a function of impactor/target density ratio ρ_i/ρ_T for mass ratio $m_i/m_T = 10^{-3}$.

What is the β factor??

- Method II: Ejecta Measurements from Experiments:



$$M(v > v_0) = Km\left(\frac{v_0}{U}\right)^{-3\mu}$$

$$dM = -(3\mu)Km\left(\frac{v_0}{U}\right)^{-3\mu-1}\frac{dv}{U}$$

$$\beta = \frac{1}{mU}\int_{v_{small}}^{v_{largest}} v\,dM = \left(\frac{3\mu K}{3\mu - 1}\right)\left[\left(\frac{v_{small}}{U}\right)^{1-3\mu} - \left(\frac{v_{large}}{U}\right)^{1-3\mu}\right]$$

Non-porous (calculation)
β =38.6 (oops!)
Porous: β=1.2

What is the β factor??

- Deep Impact into Tempel 1:
  - Ejecta velocity~100-200 m/s
  - Mass~10^5-7x10^7 kg
    - If v=150*m/s*, mass=10^6, then
      - β=40
    - If v=200*m/s*, mass=7 10^7, then
      - β =3000!!

    (but this is a comet..)

And how should β scale??

- Strength targets:

$$\beta \propto \left(\frac{\rho U^2}{Y}\right)^{\frac{3\mu-1}{2}}, \quad \mu \approx 0.55, \quad \beta \propto \left(\frac{\rho U^2}{Y}\right)^{0.325}$$

$$\Delta v \propto \text{mass}^{\ } U^{1.6}$$

- Gravity targets:

$$\beta \propto \left(\frac{U^2}{ga}\right)^{\frac{3\mu-1}{2+\mu}}, \quad \mu \approx 0.4, \quad \beta \propto \left(\frac{U^2}{ga}\right)^{0.08}$$

$$\Delta v \propto \text{mass}^{\ } U^{1.2}$$

β increases with velocity,

decreases with strength,

decreases with body size

If so, then much larger power off velocity than unity!

How does β scale??

- IT IS NOT A CONSTANT:
  - Increases markedly with impact velocity
  - It increases markedly with decreasing strength
  - It decreases markedly with porosity>30%

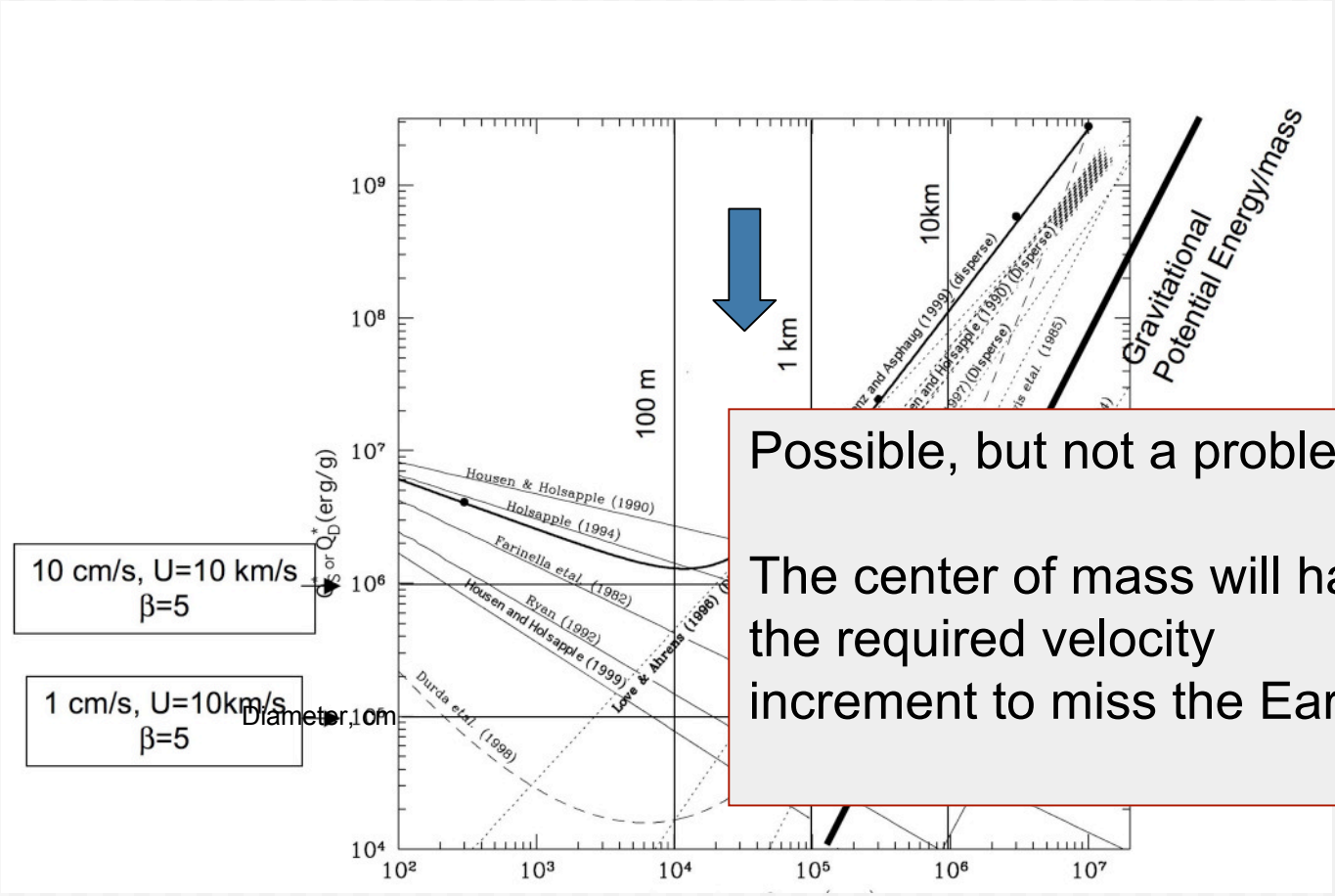
Summary: momentum coupling:

- We know very little, except $\beta>1$.
- *It might be very large for a non-porous body with small strength*
- It will depend on structure and geology of the NEO
- It may be large for a very weak target
- Experiments are essential…both for strength and gravity materials

Tentative answers (guesses) to some additional questions:

- Back surface spall?
  - The crater is very small compared to the body…
    - Insufficient stress will be transmitted to the back (especially no concern for porous)

Tentative answer to disruption question..

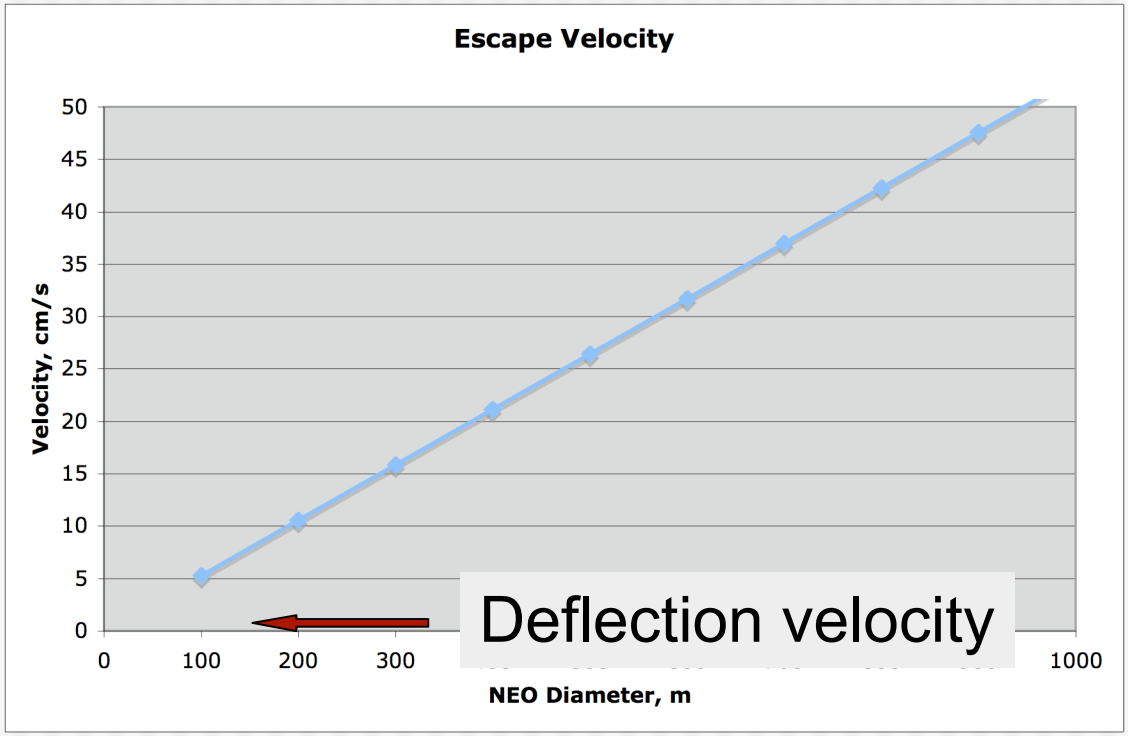


Possible, but not a problem?

The center of mass will have the required velocity increment to miss the Earth

Disrupt and disperse?

No problem, except if at last minute (well, year!)



Tentative answers to binary question:

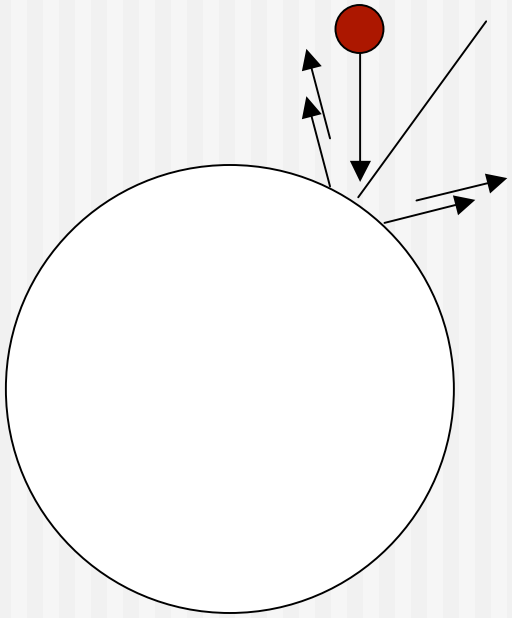
Bound bodies have a total energy that is negative, the energy added by an impact is very small.

Or: Velocity imparted substantially less than binary escape velocity..

Therefore, it would be expected that the system would remain bound.

Tentative answers to some additional questions:

- Is a direct center hit required?
  - No: anywhere in the central part:

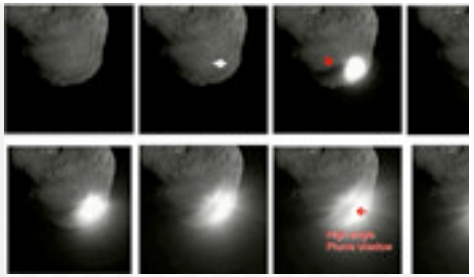


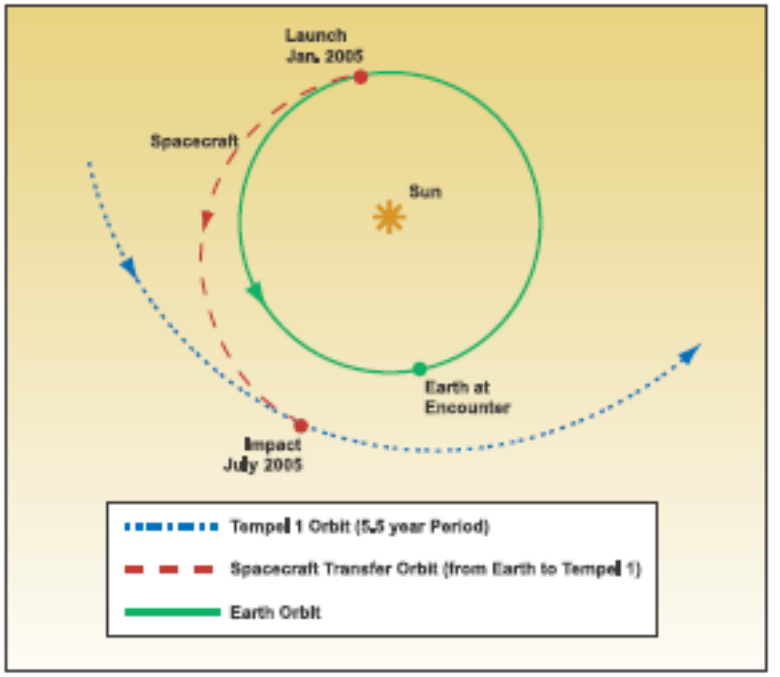
1. As long as the projectile is stopped, linear momentum balance requires $\beta>1$.

2. Since the ejecta is on average normal to the surface, there is only a Cosine factor on the β factor.

3. About the center 50% of cross-section would be effective

Deep Impact Mission





And we don't need to approach along the trajectory, just get in the way..

- Is an approach along the trajectory required?
  - No, just get in the way of the NEO: no excess velocity is required. (ala Deep Impact)
- Can we hit an NEO of several hundred meters?
  - Deep Impact hit within 250 meters, and was autonomous and optical only for last *3600 km* (6 minutes).. And it suffered two significant hits with particles on the way in.
  - So, targeting should not be a problem?..

Comparison of Impact to Gravity Tug

An example: *200 m* diameter, ρ=*2.0* NEO
20 ton space craft

Gravity Tug: (Lu et al., Nature)

d=1.5R 1 year tugging can impart **Δv=0.19 cm/s**

Direct Impact:

20 ton craft at 10 km/s

==> **Δv=2.3 cm/s** (β=1)
==> **Δv=23. cm/s** (β=10)

10-100 times more effective, And no waiting!

Comparison of Impact to Gravity Tug

- Gravity Tug:
  - Good Features:
    - Contollable
    - Gentle
  - Problems:
    - Path of Risk
    - Reliability?
    - Small capacity
    - Highly elongated and binary bodies
    - Rendevous, stationkeeping necessary

- Impacts:
  - Good Features:
    - Simple
    - 10-100* higher capacity
    - Leaves time for assessment, backup
    - Rendevous not required
  - Problems:
    - Exact Outcome uncertain
    - Disruption?
    - Hit the target?

Final Conclusions

- A direct impact is the simplest and most effective technique currently available.
- It can work for bodies up to several hundred meter diameter.
- At present there is a large uncertainty in the actual deflection,but little doubt about the lower limit. It will work at some level.
- Larger bodies may require multiple impacts, and in all cases a sentry spacecraft is indicated.

Recommendations

- Clearly there are a wide variety of asteroids and small bodies
- We have little actual knowledge of mitigation techniques, especially those requiring large energy into small areas and for highly porous bodies
- There is much research that can, and should be done to refine our analysis of mitigation methods: both laboratory and code studies
- Those are necessary to judge mitigation scenarios and make preliminary planning of actual or characterization missions.
- And they are cheap…

Thank You..