Fusion Rockets for Planetary Defense

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Colloquium

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We have a paper coming out in the Journal of Fusion Energy, sometime soon.

How many ways is electricity made today?

Primary Energy Source	Nominally CO_2 Free	Current capacity (%)	Expected Lifetime (yrs)
Natural Gas	no		100
Coal	no	80.6	400
Oil	no		< 50
Biomass	neutral	11.4	> 400
Wind	yes	0.5	> 1000
Solar photovoltaic	yes	0.06	> 1000
Solar thermal	yes	0.17	> 1000
Hydro	yes	3.3	> 1000
Wave/Tidal	yes	0.001	> 1000
Geothermal	yes	0.12	> 1000
Nuclear fission	yes	2.7	> 400

[i] REN21–Renewable Energy Policy Network for the 21st Century Renewables 2012–Global Status Report, 2012, http://www.map.ren21.net/GSR/GSR2012.pdf , http://en.wikipedia.org/wiki/Energy_development

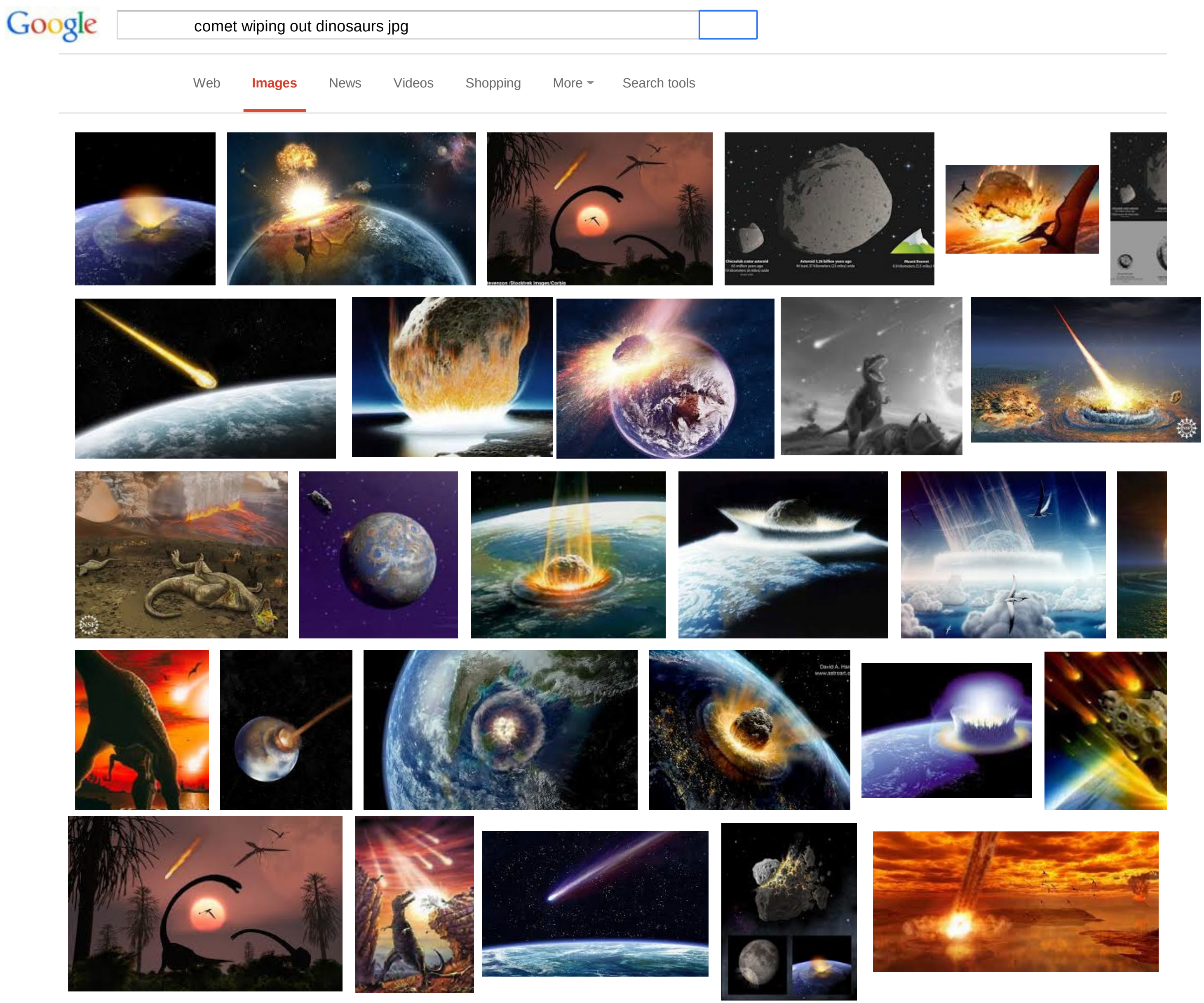
What is the most important product that fusion could deliver?

- Is it a 12th way to make electricity?
- Why are we researching and promising a 12th way to make electricity, which is more complex, (and therefore likely more costly), than any other approach?
- Is there something instead unique, that only fusion energy could do for the world?
- Is it something worth doing?

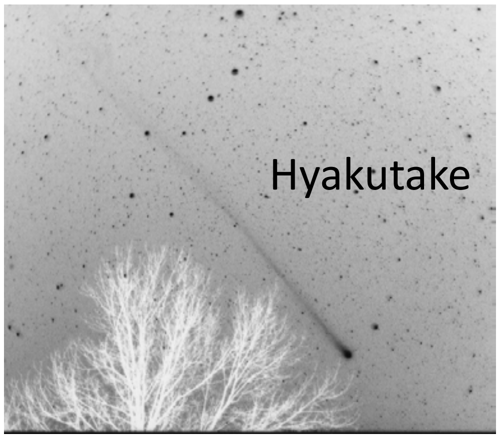
Outline of this talk

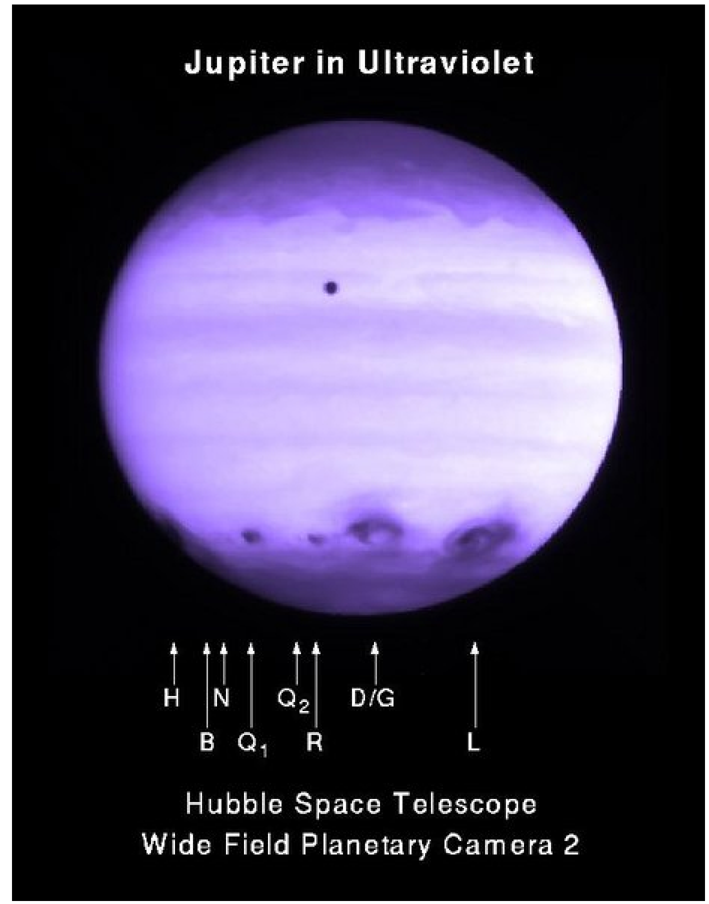
- Threat: Awareness
- Impact: Annihilation
- Solution: Detect, Intercept, Deflect
- The need for speed: Fusion Rockets
- A Program

A big comet/asteroid hit the Earth 65 million years ago

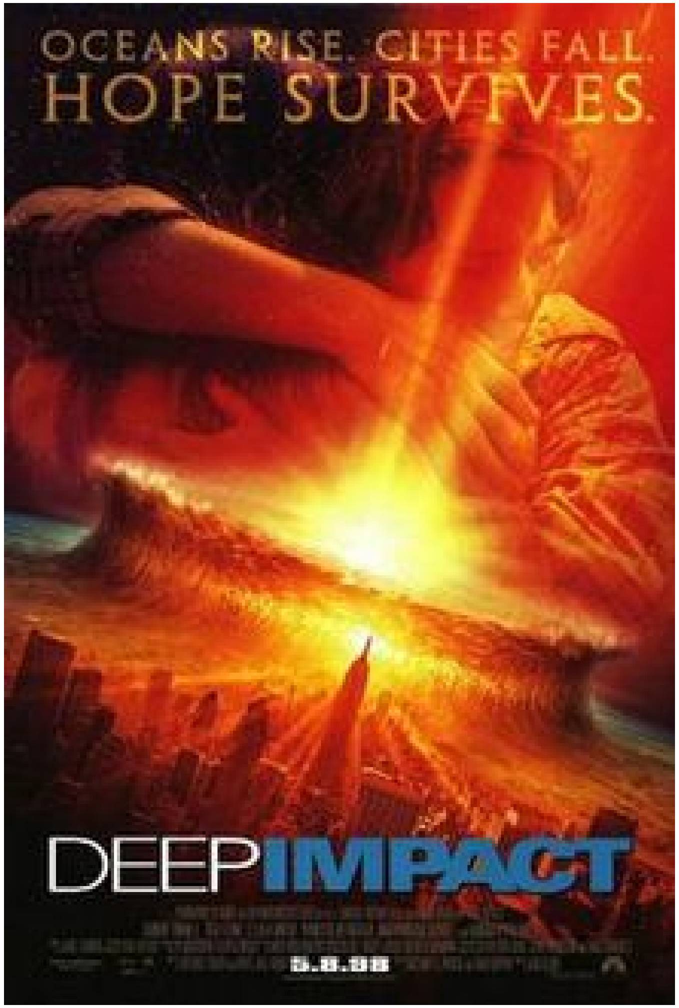


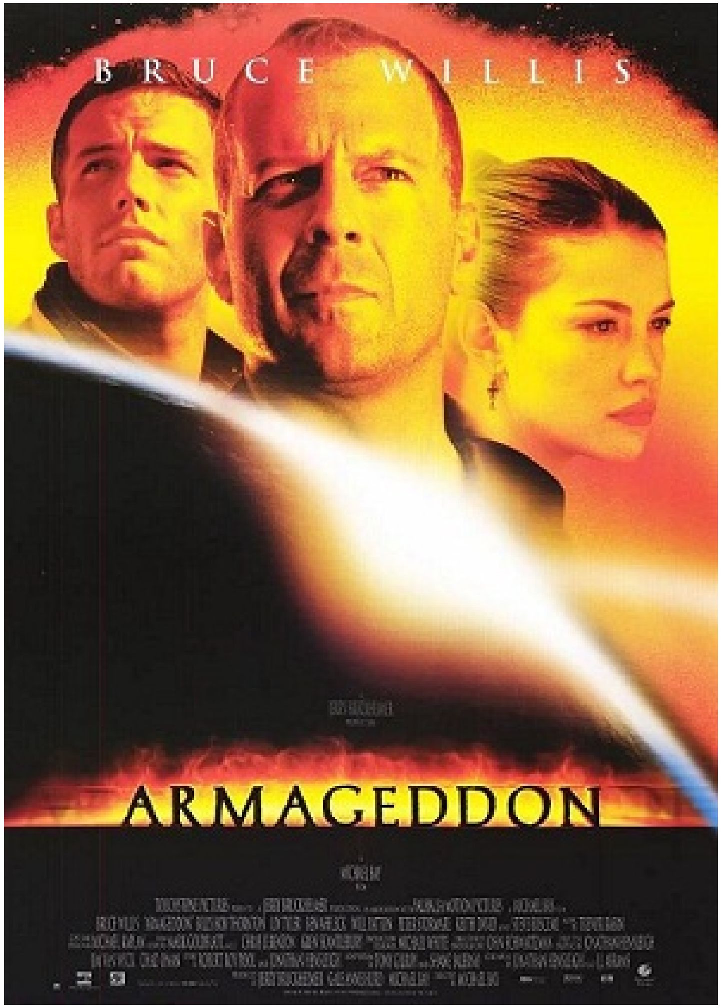
I've watched a lot of comets over the years… one crashed into Jupiter.





Are Collisions with the Earth only Science Fiction in art & movies?

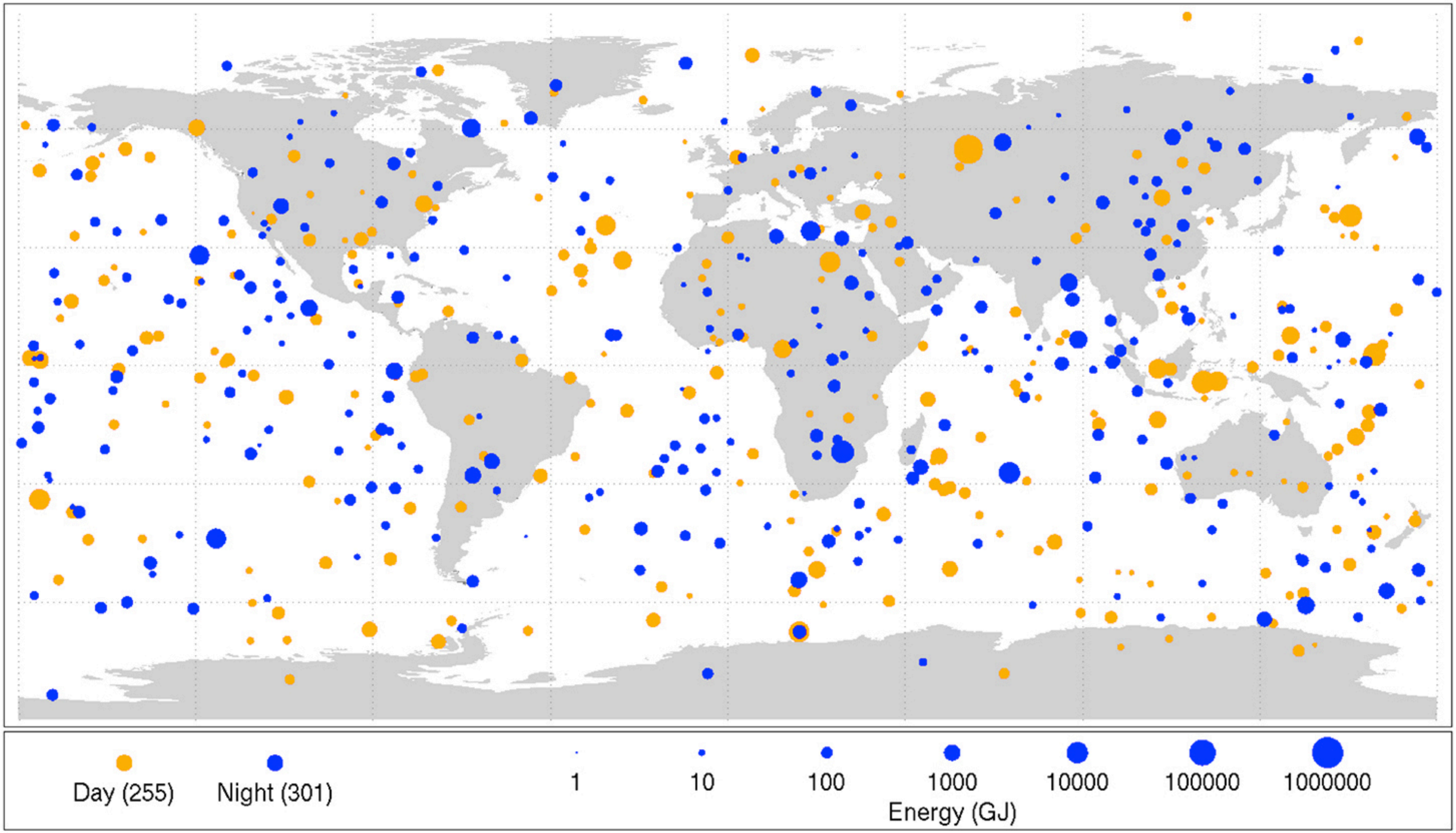




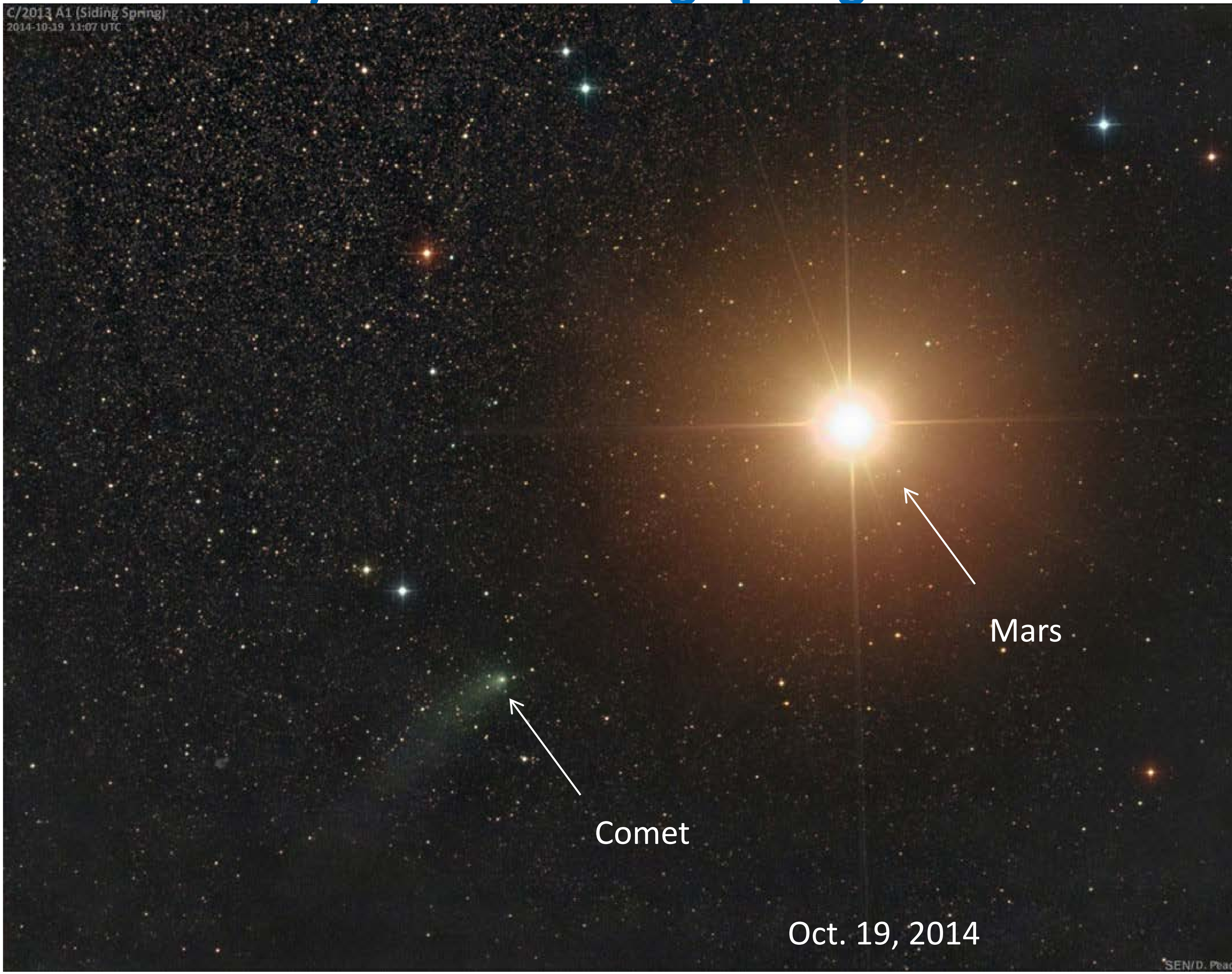
http://www.jpl.nasa.gov/news/news.php?release=2014-397

Bolide Events 1994–2013

(Small Asteroids that Disintegrated in Earth's Atmosphere)



Comet C/2013 A1 Siding Springs and Mars

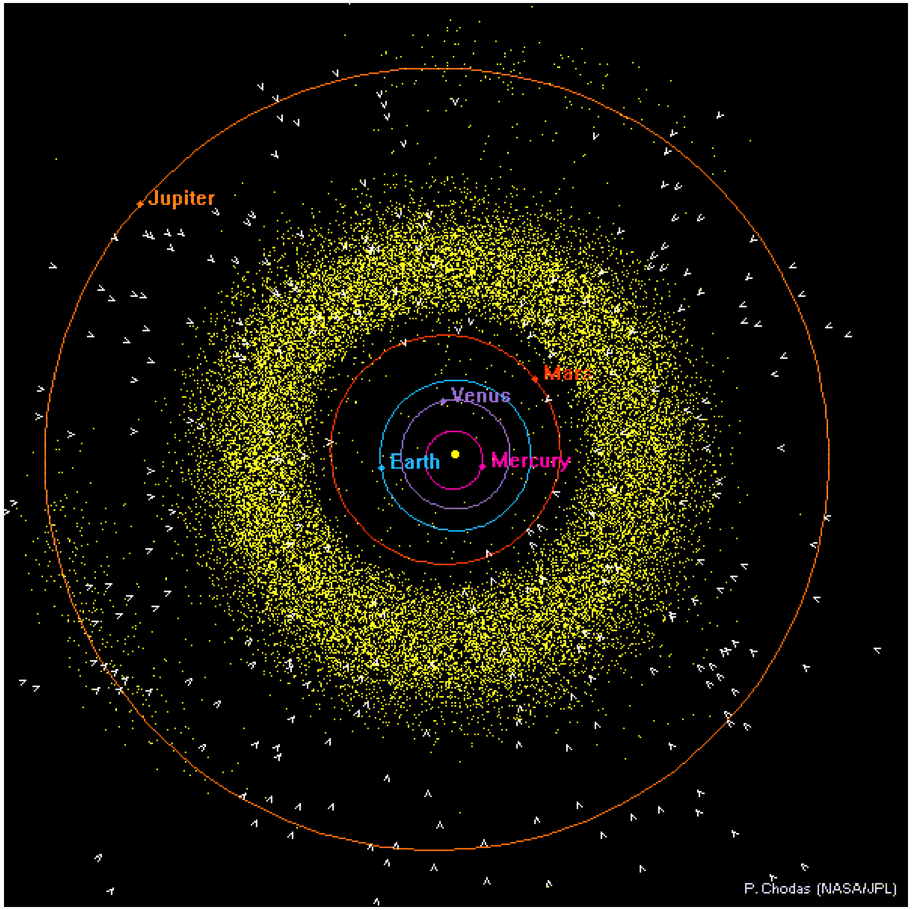


Comet C/2013 A1 Sidings Springs

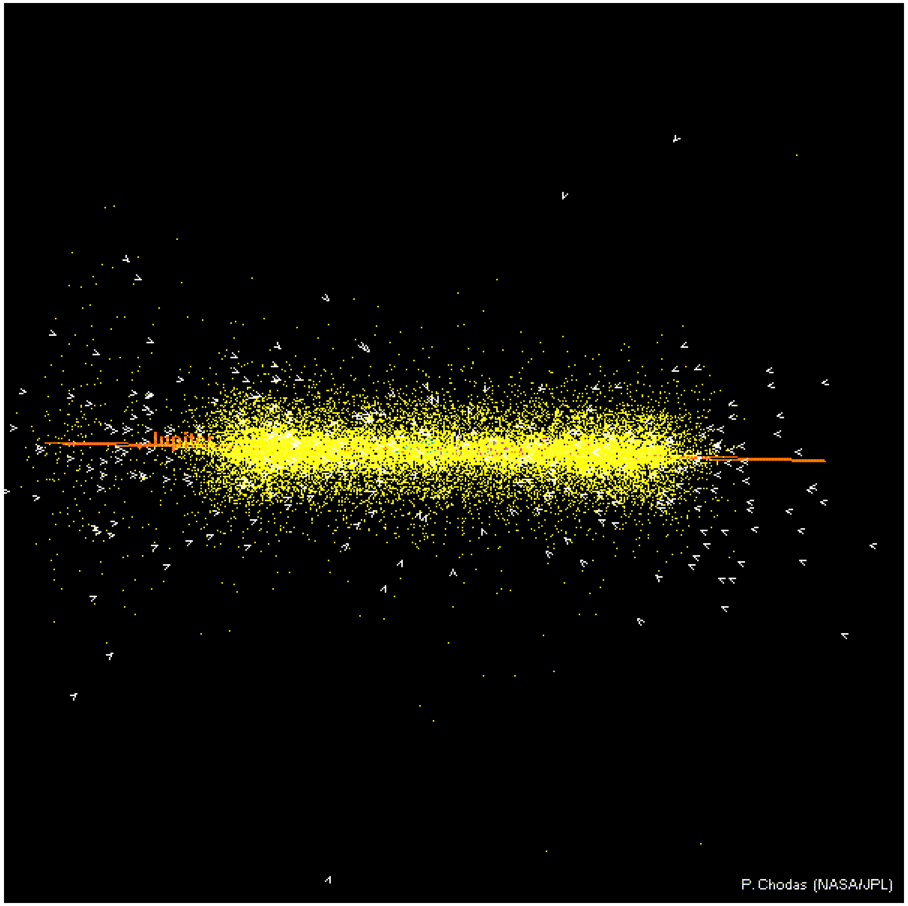
Passed by Mars at only 1/3 the Earth-Moon distance

Too bad it didn't clobber Mars,
destroying our landers and even orbiters!

Most asteroids orbit between Mars and Jupiter, and are found in the same plane as the planets, with 3-7 year orbits

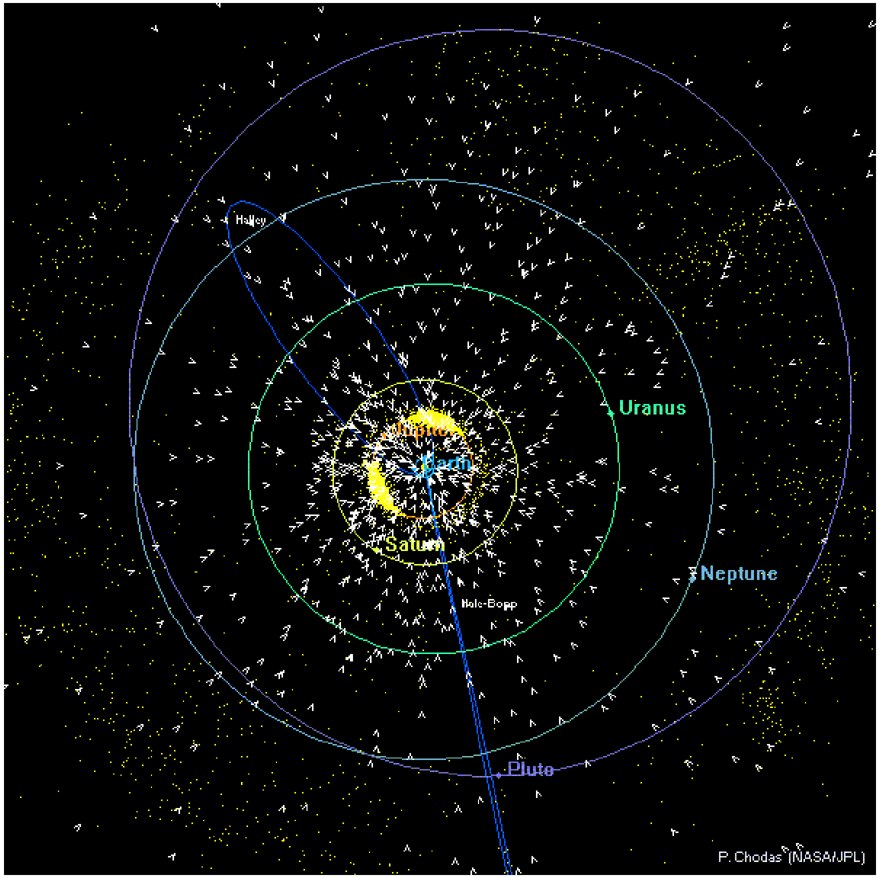


Top view

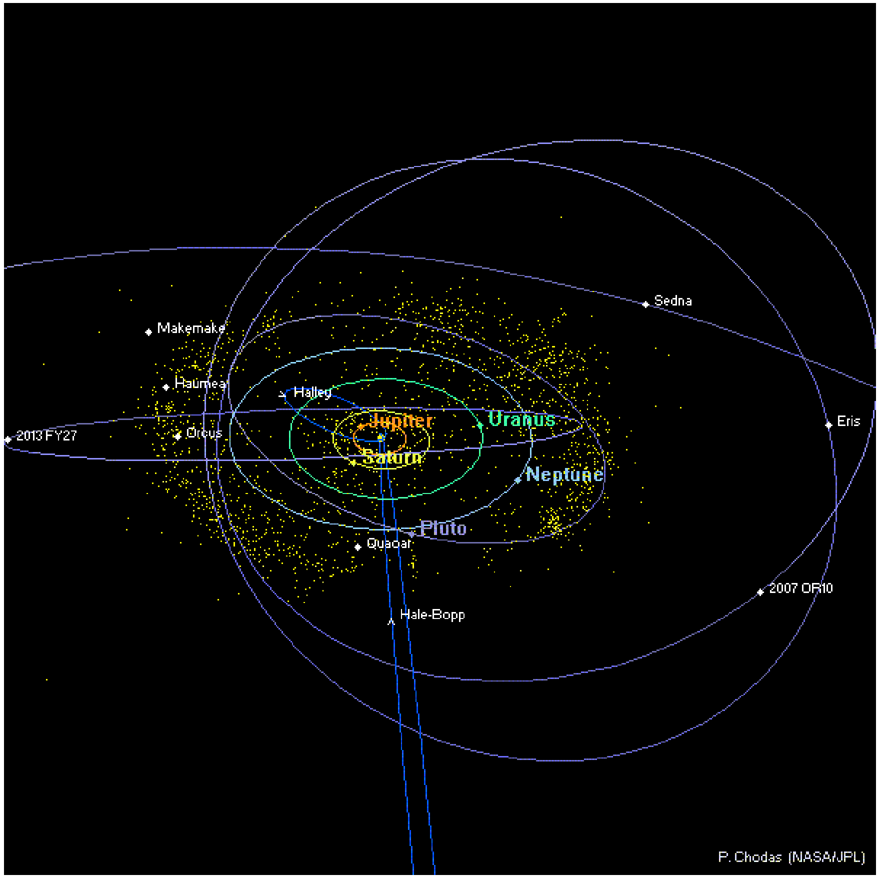


Side view

Asteroids are troubling enough, so why are comets worse?



Outer solar system



Even further out solar system!

The Ancients thought Comets were bad omens… and they were right!

Photo credit: Alex Wurden, Glen Wurden, Comet Hale-Bopp, 1997

Photo credit: Matt Wang, Flickr: anosmicovni. European Space Agency. Comet 67P/Churyumov–Gerasimenko Relative to Downtown Los Angeles

- They are the fastest objects in the solar system.
- Long-period comets are seen exactly once on the timescales of our civilization.
- They come with little warning (6-18 months).
- They tend to be big (1-40 km diameter).
- If (when) one has our name written on it…….

What should we do?

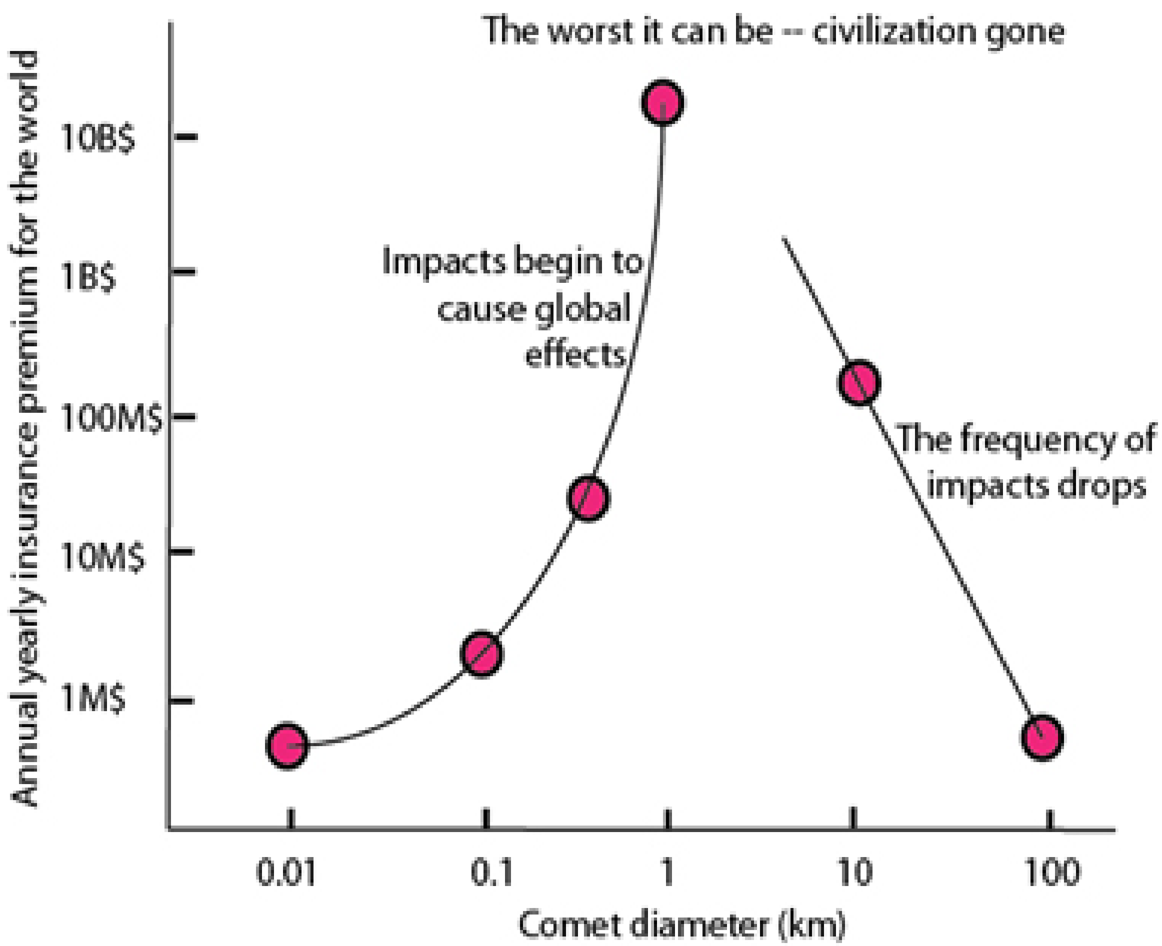
<u>Build an insurance policy for our Planet</u>

- Look harder…detect them sooner.
- Be able to intercept and deflect a threat.
- Use nuclear explosives to do the deflection, using radiation pressure to ablate comet material, causing an impulsive momentum change.
- Only nuclear explosives have the necessary energy density.

Weigh the likelihood, against the damages

The most frequent event that can end your civilization…
not merely destroy a city….is what you have to defend against.

1 km diameter objects impact every ~ 1 million years



Near-Earth Object Survey and Deflection Analysis of Alternatives NASA Report to Congress, March 2007

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

“In the impulsive category, the use of a nuclear device was found to be the most effective means to deflect a PHO”.

“It should be noted that because of restrictions found in Article IV of the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, use of a nuclear device would likely require prior international coordination. The study team also examined conventional explosives, but found they were ineffective against most threats”.*

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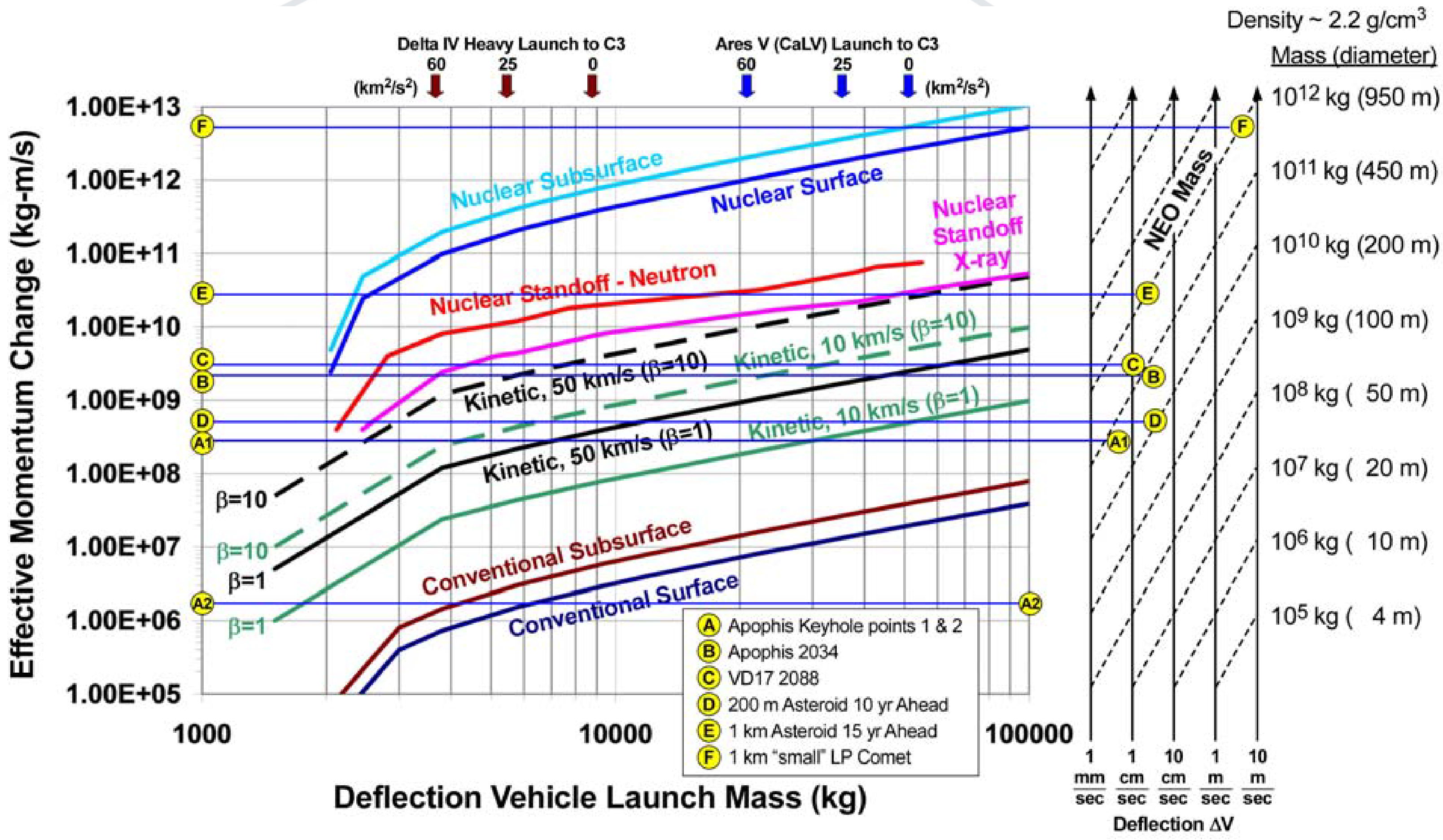
Six different scenarios

The hypothetical scenarios include missions to deflect:

- A. The 330-meter asteroid, Apophis, before its close approach to Earth in 2029. This scenario was divided into two design points:
  - A1. For the first, knowing the asteroid's orbit is assumed and a relatively large momentum change is required to deflect the object with the required certainty. Apophis must be deflected by at least one Earth radius or about 6,400 km to achieve a probability of collision of less than 10^{-6}.
  - A2. For the second, very accurate information about the object's orbit is assumed and the impetus necessary to divert the asteroid with certainty is substantially reduced. Apophis must be deflected by at least five km to achieve a probability of collision of less than 10^{-6}.
- B. Apophis after the close approach and before the 2036 Earth encounter, assuming a predicted collision.
- C. The 500-meter asteroid (VD17) that could be a threat in the year 2102.
- D. A hypothetical 200-meter asteroid, representative of 100-meter-class asteroids.
- E. A hypothetical asteroid larger than one km in diameter.
- F. A hypothetical long-period comet with a very short time (9-24 months) to impact.

The parameter space for deflection of a Potentially Hazardous Object (PHO) for a range of scenarios*



*From 2007 NASA Report to Congress, Fig. 4, pg. 23, "Deflection performance of Impulsive Alternatives"

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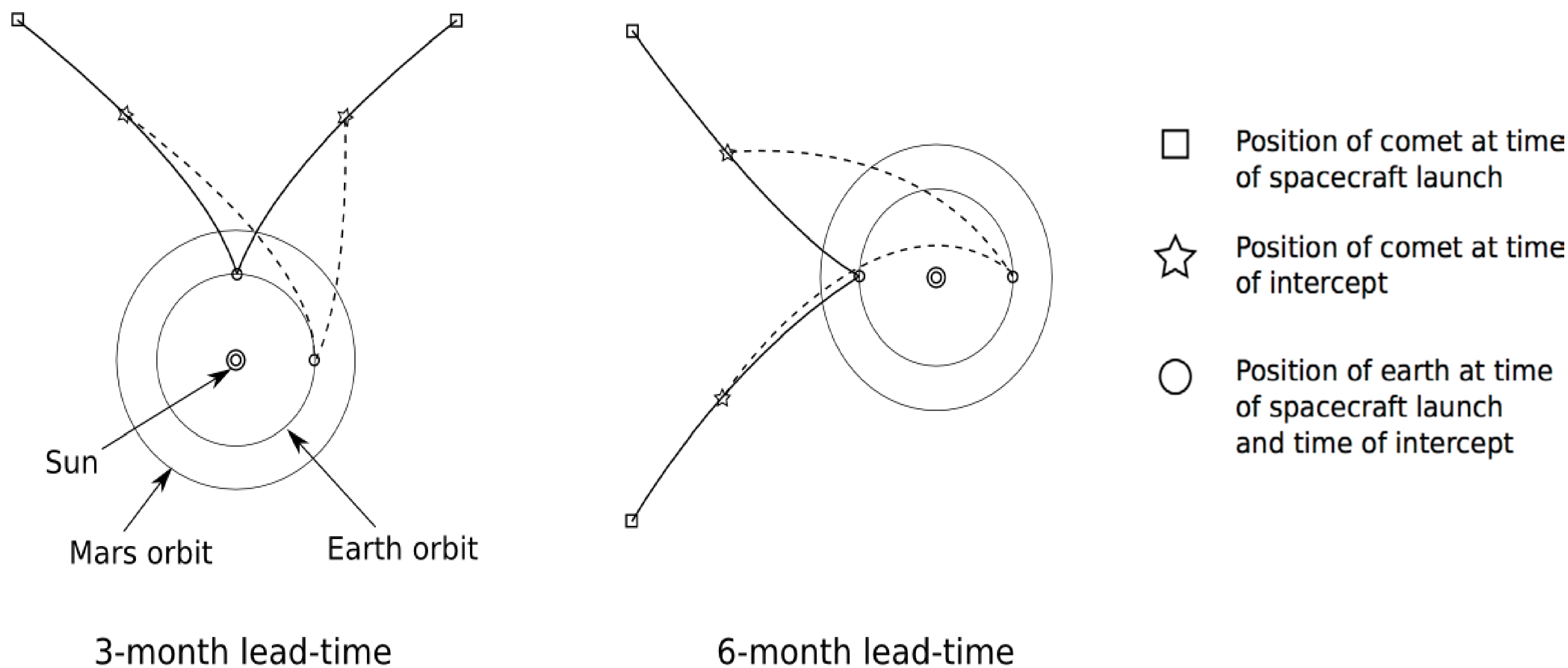
How far, and how fast for the intercept?

- Intercept in ½ the remaining time.
- Geometry tells us the answer, with the Earth's orbit radius of 1 AU, the Earth's orbital velocity of 30 km/second, and the comet speed of order 25 km/second.

5-10 AU Astronomical Units in 6 months……… a spacecraft speed of 50-100 km/sec



Delivering some Energy

- For lateral deflection v_o in an ideal, minimum energy, case, we would need an energy absorbed by the comet:

$$W_o = \mathbf{M} v_o^2/2$$

where **M** is the comet mass and the deflection velocity v_o is purely perpendicular to the comet's initial velocity V .

- A 1 km diameter comet, with density of 0.6 gm/cm^3 has a mass of $3x10^{11}$ kg, and a deflection of 10 m/sec corresponds to an energy $W_0 = 1.5 \times 10^7$ MJ.

Balancing Momentum

- Now if we consider (in the frame of motion of the comet) the ablated material to be treated as a rocket exhaust of average directed speed v, and we expel a mass m, then by momentum conservation:

$$\mathbf{M}v_o = mv$$

- The total (directed) kinetic energy in the exhaust (not counting internal energy of the plume or radiation losses) becomes:

$$mv^2/2 = \mathbf{M}vv_o/2$$

- Compared to the minimum energy W_o, we therefore need more energy by a factor of $K = v/v_o$. For example, for our deflection v_o = 10 m/s and an ablatant exhaust of v = 4 km/s, the yield of the nuclear explosive must increase by K = 400.

Some rocket terminology

- **Specific power** α *(w/kg)* **of the power source, including waste heat radiators (if any)**
- **The change in velocity that a rocket can achieve** ΔV *(m/sec)*
- **Propellant exhaust velocity** v_e *(m/sec)*
- **The rocket equation** $M_f / M_o = exp(-\Delta V / v_e)$
- **Specific impulse** $I = v_e / g$ *(seconds)*
- **Time τ to achieve ΔV (may be the mission duration)**
- **Then in the limit of zero payload mass, there are a couple of important relationships:**

$$v_e = 0.5\sqrt{\alpha\tau} \quad \textbf{and} \quad \Delta V = 0.81\sqrt{\alpha\tau}$$

- $\sqrt{\alpha\tau}$ **is known as the characteristic velocity**

(E. Stuhlinger, *Ion Propulsion for Space Flight,* McGraw-Hill, New York 1964.)

Time to intercept

With exhaust speed of the intercept vehicle $v_e = 0.5\ (2\alpha\tau)^{1/2}$

And the final $\Delta V = 0.81\ (2\alpha\tau)^{1/2}$

Then from the rocket equation, we have that the time for a flyby encounter (thrusting constantly all the way from the Earth) is:

$$\tau = \frac{(R_D - R_o)}{[\ 0.6 v_e + (V + V_E)]}$$

Where R_D and R_o are the radius of detection and radius of earth's orbit, respectively, V is the comet speed (assumed to be constant, even though it gets faster as it approaches the Sun) and V_E is the appropriate speed of the earth given the variation of angle during the comet's approach for an intercept time comparable to a quarter to half of the earth's period. The sum of $V + V_E$ represents the comet's closing speed on the Earth. The average speed of the craft, for constant exhaust velocity and constant thrust, integrating from 0 to τ, is the other term in the denominator.

Astrodynamics and nuclear explosives

- We take the solid angle represented by the comet at the intercept standoff distance r_i , the diameter of the comet d_c, and define the ablation efficiency factor ε_{abl} to include the fraction of the nuclear-explosive output in soft X-rays and the conversion of this output into the directed kinetic energy of the ablation-rocket exhaust.
- One can estimate how big of a yield is needed to deflect a comet, via an impulsive momentum change delivered by ablation,

$$Y = \frac{16 r_i^2}{d_c^2} \frac{K}{(0.5)\varepsilon_{abl}} \left(\frac{4\pi}{3} \frac{\rho_c d_c^3}{8} \frac{V^2}{2} \right) \frac{R_m^2}{(R_D - R_o)^2} \left[1 + \frac{(V + V_E)}{0.6\upsilon_e} \right]^2$$

- Where R_D and R_o are the radius of detection and radius of earth's orbit, respectively, V is the comet speed (assumed to be constant, even though it gets faster as it approaches the Sun) and V_E is the appropriate speed of the earth given the variation of angle during the comet's approach for an intercept time comparable to a quarter to half of the earth's period. The sum of $V + V_E$ represents the comet's closing speed on the Earth.
- For the case of a desired v_o = 10 m/s, with an initial comet velocity V = 25 km/s, if we can generate an ablatant exhaust velocity of 4 km/sec, then K=400. With detection/characterization at 10 AU, an average earth speed component of 0.7 x 30 km/s = 21 km/s, and an interceptor rocket exhaust speed of 200 km/s, we can intercept at about 4.9 AU in 93 days, but require a specific power α = 6153 W/kg, which is well beyond anything except fusion.
- **To generate an Earth miss distance R_m = 40,000 km, for a 1 km diameter comet with average density of 0.6 gm/cm^3, with a 25% ablation efficiency of a single detonation, at a distance r_i =1 km, a yield of 20 Megatons is needed.**

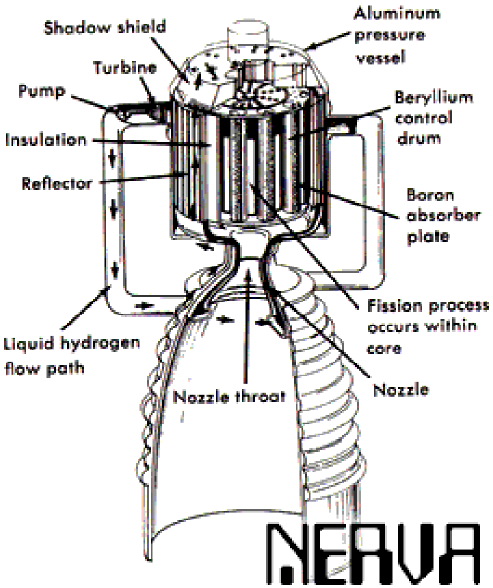
An important detail…

Our very best rockets, by a wide margin, don’t have the combination of speed and power to get out to 5-10 AU distances with a 25 metric ton payload in only 6 months.

The need for speed = faster exhaust velocity

How do we make faster launch vehicles?

- Nuclear Rocket engines have been shown to have twice the specific impulse (faster exhaust velocities) than chemical engines, while still achieving high thrusts.
- The ROVER program at Los Alamos, from 1957 to 1972 tested 18 fission engines, culminating in the NERVA engine, which was to be a drop-in replacement for the third stage on a Saturn V.
- A nuclear engine capability would decrease the time to intercept, and broaden the operational parameter space for any planetary defense mission (in particular, the most difficult Case F, the rapidly incoming comet scenario).

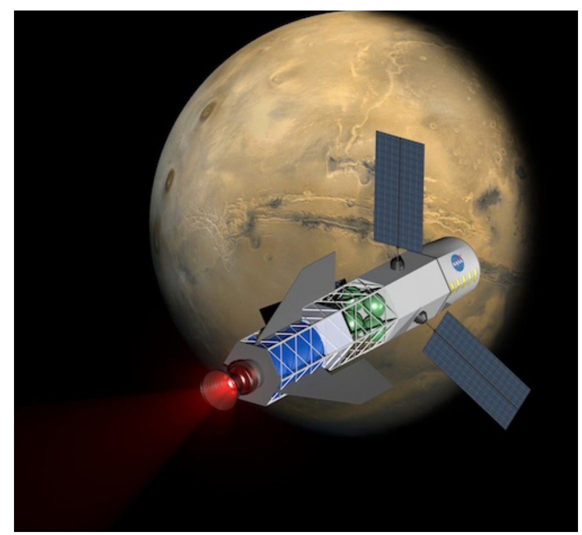


Faster Rockets = higher exhaust velocity = high specific impulse (I_{sp})

- Chemical rockets have I_{sp} ~ 450 seconds
- Fission rockets have I_{sp} ~ 900 seconds
- Fusion rockets could have I_{sp} > 10,000 seconds

Shuttle engine

NERVA



Conceptual fusion rocket

Many people have suggested fusion rocket engines for exploring the solar system

- The recognition that fusion might prove attractive for space applications is widespread.
- Fusion's advocates included Arthur C. Clarke, who wrote in 1961 that ``*The short-lived Uranium Age will see the dawn of space flight; the succeeding era of fusion power will witness its fulfillment.*''
- What we areproposing that is new, is the coupling of the need for a defense against long-period comets, with the need for speed, and the solution offered by fusion rocket engines.

You don't want to produce electricity through an intermediary form of energy

- Every time we convert between different forms of energy, there are losses. Waste heat has to be radiated to space by black body radiators, and that means more mass has to be carried. Even fission-driven high power electrical sources (for ion or plasma thrusters) would need massive radiators.
- Solar is 1/25 as effective at Jupiter, as it is at Earth. It is 1/100 as effective at Saturn distances. You can't rely on solar electric, because of its low power density, and therefore associated mass penalty.
- A primary power source that directly generates thrust is the most efficient: Chemical rockets are great, but their exhaust speed is too low…but fusion exhaust of charged particles on field lines via a magnetic nozzle …. WOW! Corollary: Neutrons are worse than useless!

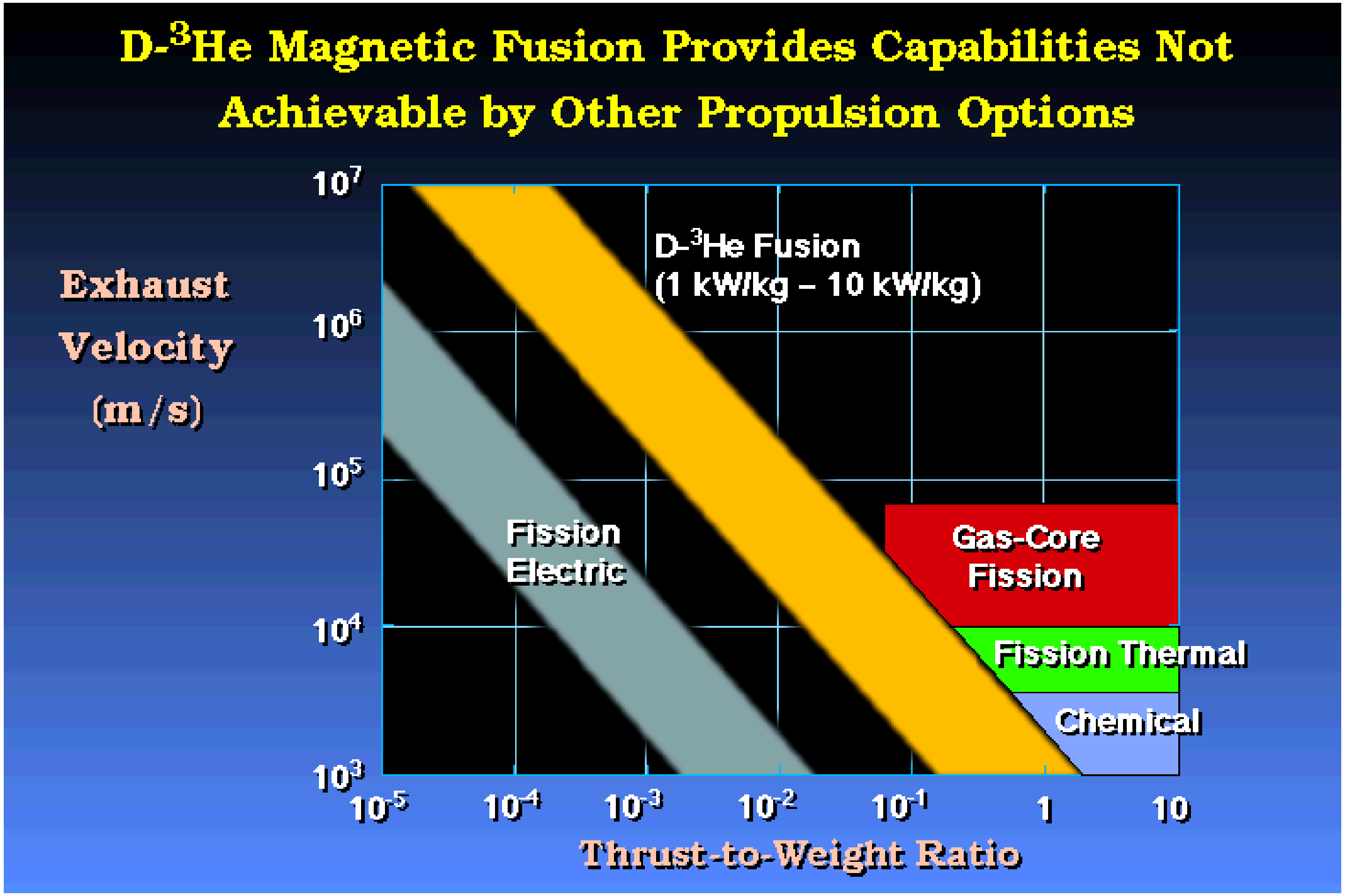
The preferred fusion reaction is

$D + {}^{3}He \rightarrow p\ (14.68\ MeV) + {}^{4}He\ (3.67\ MeV)$

Many fewer neutrons than DT, and at "only" 5-6 x the DT Lawson criterion

- For a planetary defense effort, make all the tritium you need with heavy water fission reactors on Earth, and then hopefully you can wait 50 years for it to decay into ^{3}He. Carry the fuel onboard the rocket.

UW propulsion class notes:



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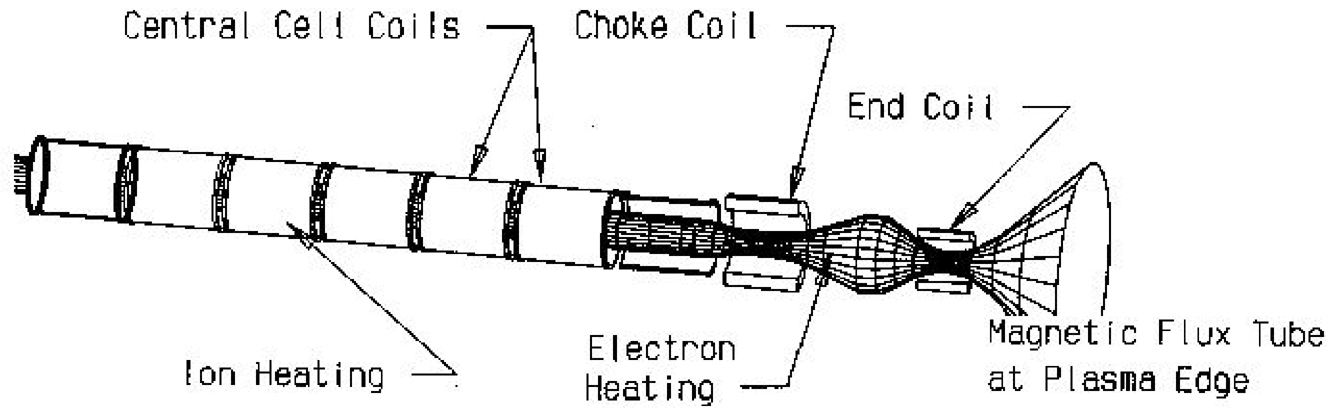
Three examples

- While **solar-electric systems** have a specific power (at the Earth distance from the Sun) of order ~ 100 w/kg, that decreases by a factor of 1/25 at Jupiter, and 1/100 at Saturn distances.
- Taking a **fission electric** example, the SAFE-400 nuclear Brayton cycle reactor and radiator system would produce 100 kW electric power, with a mass of 584 kg, for a specific power (without a thruster) of 171 w/kg. Coupling it to an 80% efficient ion thruster of the NSTAR type presently in use on the Dawn mission to Ceres, which has an specific impulse I_{sp} = 3100 seconds (but using 40 units, with a combined weight of 1000 kg, corresponding to 100 kW of available electric energy), one would have a system specific power of 63 W/kg, but with a thrust of only 4 Newtons.
- **ITER** weighs in at at least 23,000 metric tons. At its rated output of 500 MW (ignoring auxiliary systems, and whether neutrons are useful or not), then the specific power of ITER is only 22 W/kg. However, I am not suggesting that launching ITER into orbit would be a useful idea!

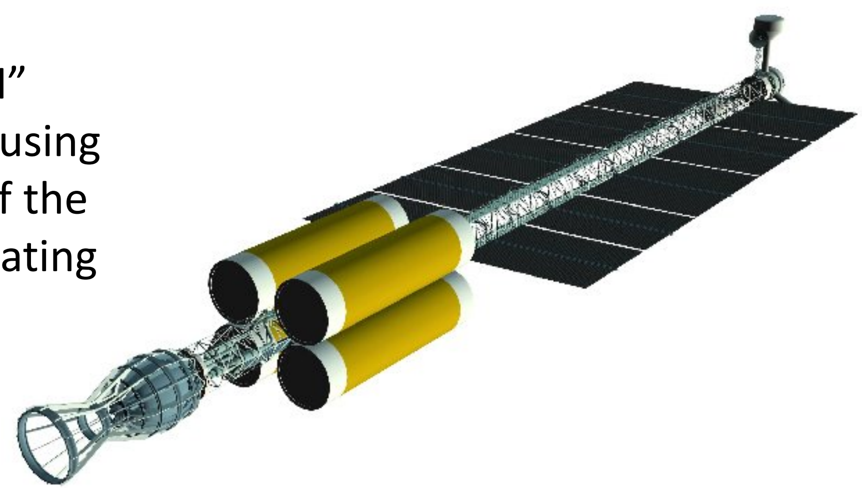
Clearly a different type of fusion engine than a conventional tokamak (or even a stellarator) would be required for a rocket engine (starting for example, with much higher beta).

Clearly, we have no fusion core from which to make a rocket engine…yet



Linear geometry, $\beta = 1$ has some attractive features…mirrors or FRC’s for example

Even so, there is a NASA “Discovery II” design study using a spherical torus, using the divertor exhaust at the bottom of the torus. (Notice the lack of auxiliary heating systems?)



UW propulsion class notes:

Advantages of D-^{3}He magnetic fusion for space applications

- No radioactive materials are present at launch, and only low-level radioactivity remains after operation.
- Conceptual designs project higher specific power values (1--10 kW-thrust per kg) for fusion than for nuclear-electric or solar-electric propulsion.
- Fusion gives high, flexible specific impulses (exhaust velocities), enabling efficient long-range transportation.
- D-^{3}He fuel provides an extremely high energy density.

D-^{3}He fuel is more attractive for space applications than D-T fuel.

- High charged-particle fraction allows efficient direct conversion of fusion power to thrust or electricity.
  – Increases useful power.
  – Reduces heat rejection (radiator) mass.
  – Allows flexible thrust and exhaust velocity tailoring.
- Low neutron fraction reduces radiation shielding.
- D-^{3}He eliminates the need for a complicated tritium-breeding blanket and tritium-processing system.

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There are many fusion rocket papers

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Specific power of a few fusion rocket design papers

First Author	Year	Configuration	Specific Power (kW/kg)
Borowski	1987	Spheromak	10.5
Santarius	1988	Tandem Mirror	1.2
Chapman	1989	FRC	--
Haloulakis	1989	Colliding Spheromaks	--
Bussard	1990	Riggatron Tokamak	3.9
Bussard	1990	Inertial-Electrostatic	>10
Teller	1991	Dipole	1.0
Carpenter	1992	Tandem Mirror	4.3
Nakashima	1994	FRC	1.0
Kammash	1995	Gas Dynamic Trap	21(D-T)
Kammash	1995	Gas Dynamic Trap	6.4(D-^{3}He)

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Fusion Rocket vs. Fusion Power Plant

Different design constraints

for the Rocket Engine:

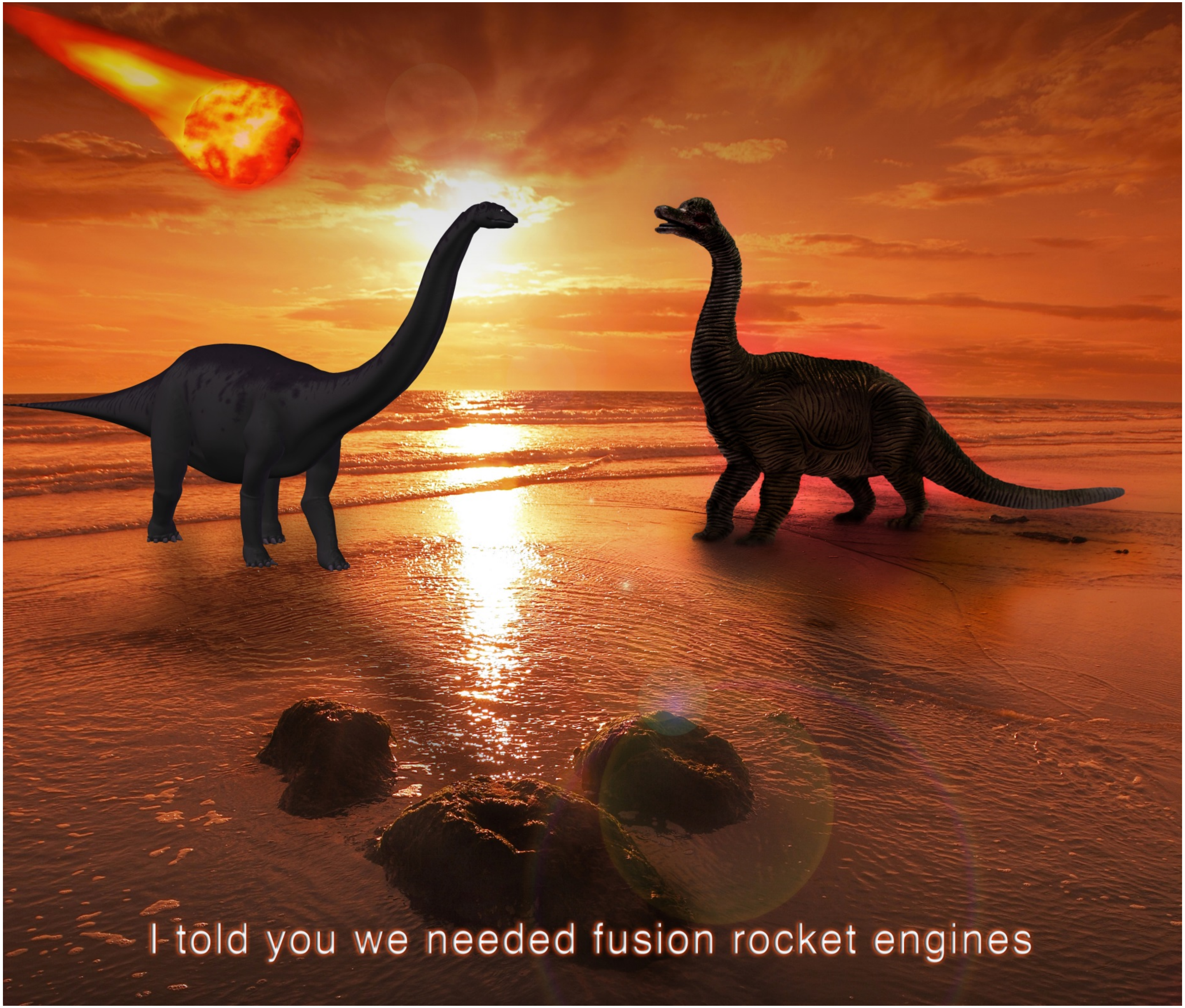
- No vacuum vessel, no vacuum pumps
- No first wall, no breeding blanket
- Design life: 6 months versus 25 years
- Neutron structural damage is not an issue…but magnets and payload still need shielding
- Carry all the fuel with you (even ^{3}He)
- Key design feature: specific power (kW/kg) (not $$/kwh)
- High beta is essential (to reduce the magnet mass)
- Assemble & load configuration in orbit
- Most likely only a few missions (at most) in any millenium! And then, only 3-5 rockets needed.

It will take years to build a Planetary Defense Program

- **Fortunately comet impacts (500 meter diameter or larger) are rare.**
- **But one is most certainly coming our way.**
- **The only question is, is it next week? Or 100,000 years from now? We don’t know.**
- **Shouldn’t we make an effort to insure our civilization against this foreseeable and preventable catastrophe?**

Summary

- The threat that long-period comets pose to our existence on Earth can be solved with nuclear explosives and fusion rockets.
- An international Planetary Defense program is needed, which can also deal with the easier problem of incoming asteroids.
- Long-term R&D on fusion energy systems for rocket propulsion would be a component of this Planetary Defense program.
- Finally, building a Planetary Defense effort, while developing a fusion rocket core and other needed tools, could attract a workforce like no other.


I told you we needed fusion rocket engines