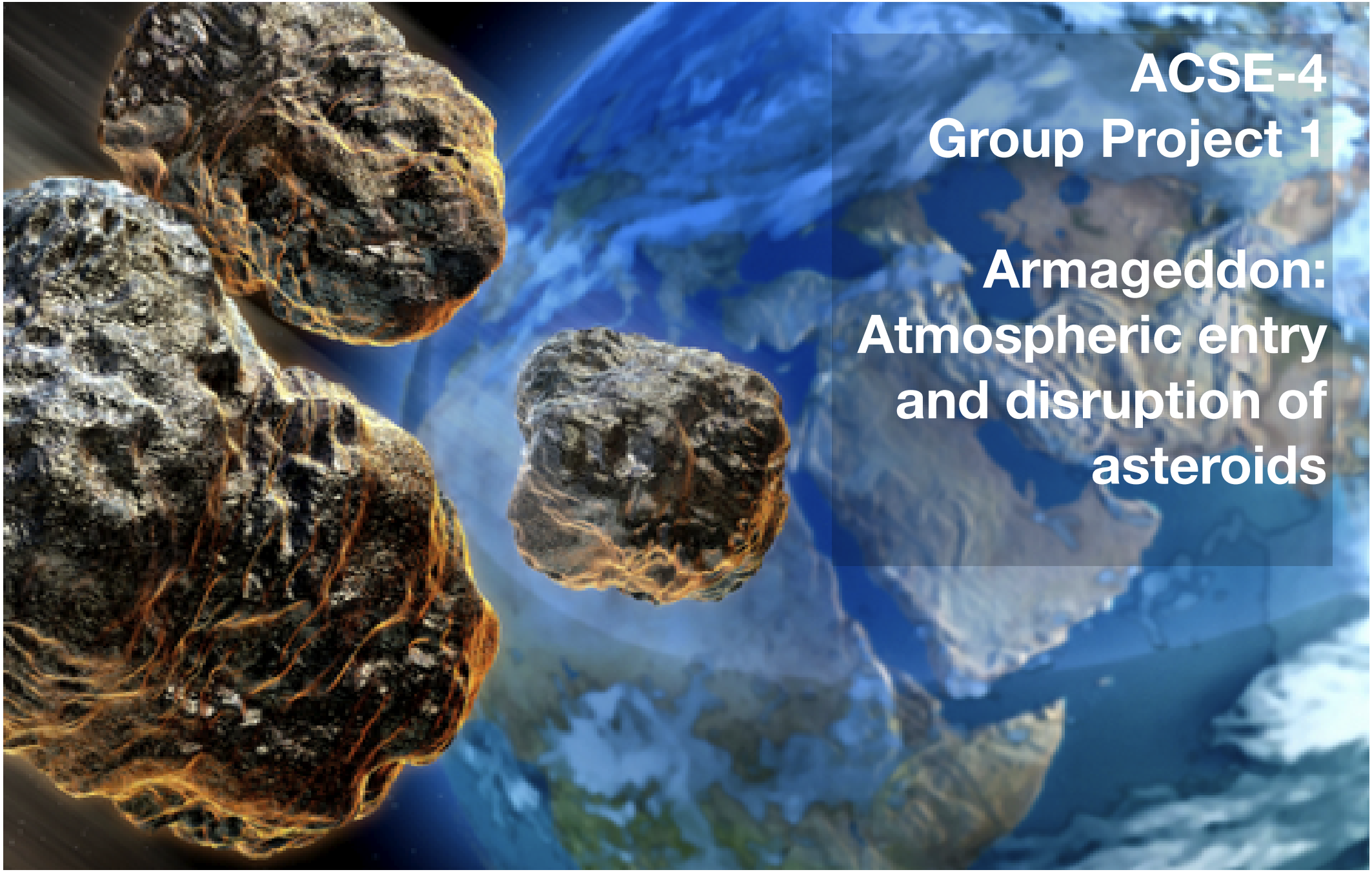
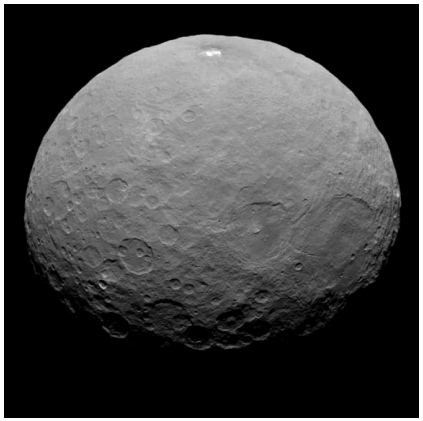


ACSE-4
Group Project 1

Armageddon: Atmospheric entry and disruption of asteroids

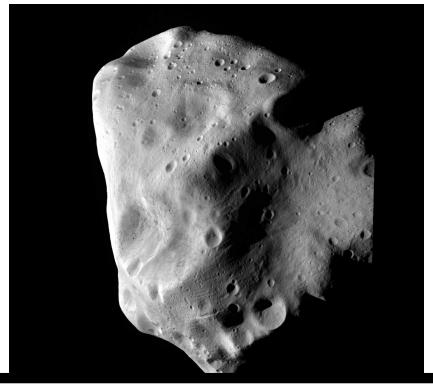
Imperial College London

DEPARTMENT OF
EARTH SCIENCE AND ENGINEERING



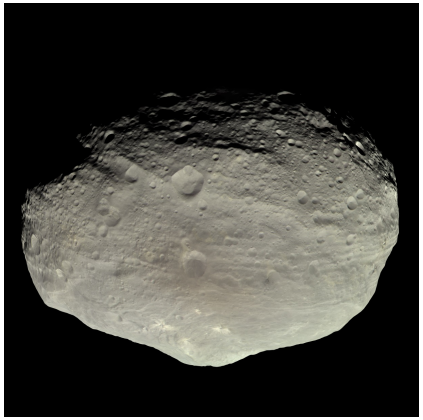
1 Ceres

Kevin Fung
Keer Mei
Deborah Pelacani Cruz
Ma



21 Lutetia

Adanna Akwataghibe
Tayfun Karaderi
Hitesh Kumar
Dongzhen Li
Xianzheng Li



4

Ric
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433 Eros

Hameed Khandahari
Laura Su
Michael Trapp
Sanaz Salati
Oliver Boom

43 Ida

n Walding
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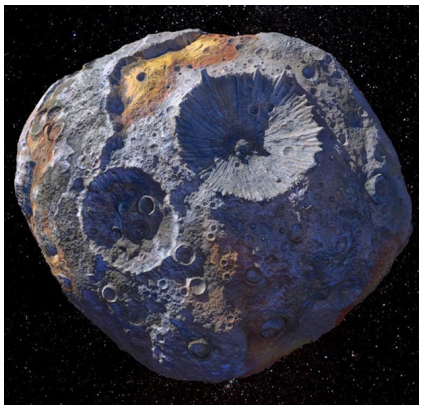
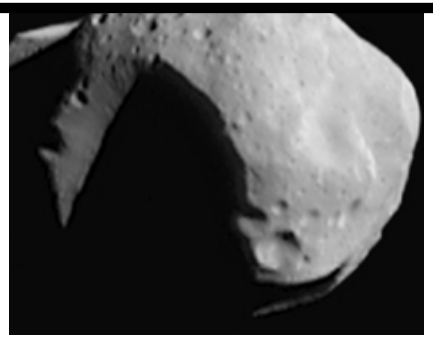
zhi Zhou



16 Psyche

Mattia Guerri
Duncan Hunter
Nitchakul Pipitvej
Liu Yuxuan



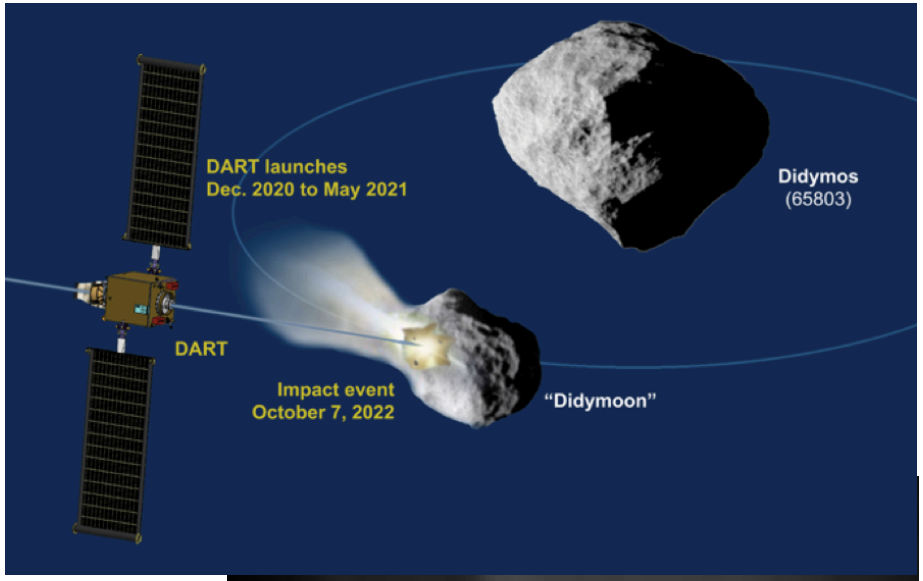
53 Mathilde

Gareth Lomax
Mingrui Zhang
Yusuf Falola
Yujie Zhou
Hugo Coussens

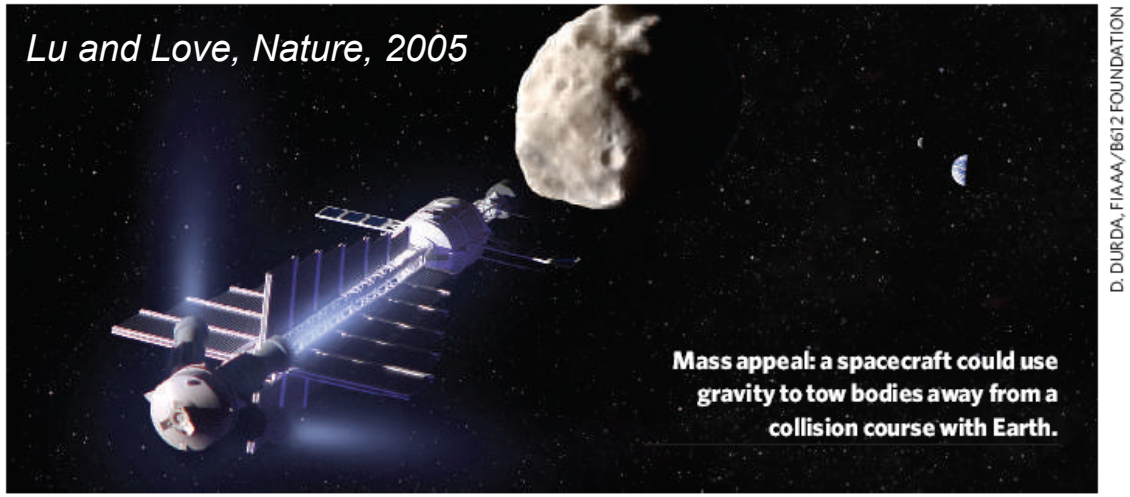
ZDF-Doku-Drama „Armageddon - Der Einschlag“, 2007

Asteroids <1-km in size could be deflected with ~10 years warning (cm/s Δv)

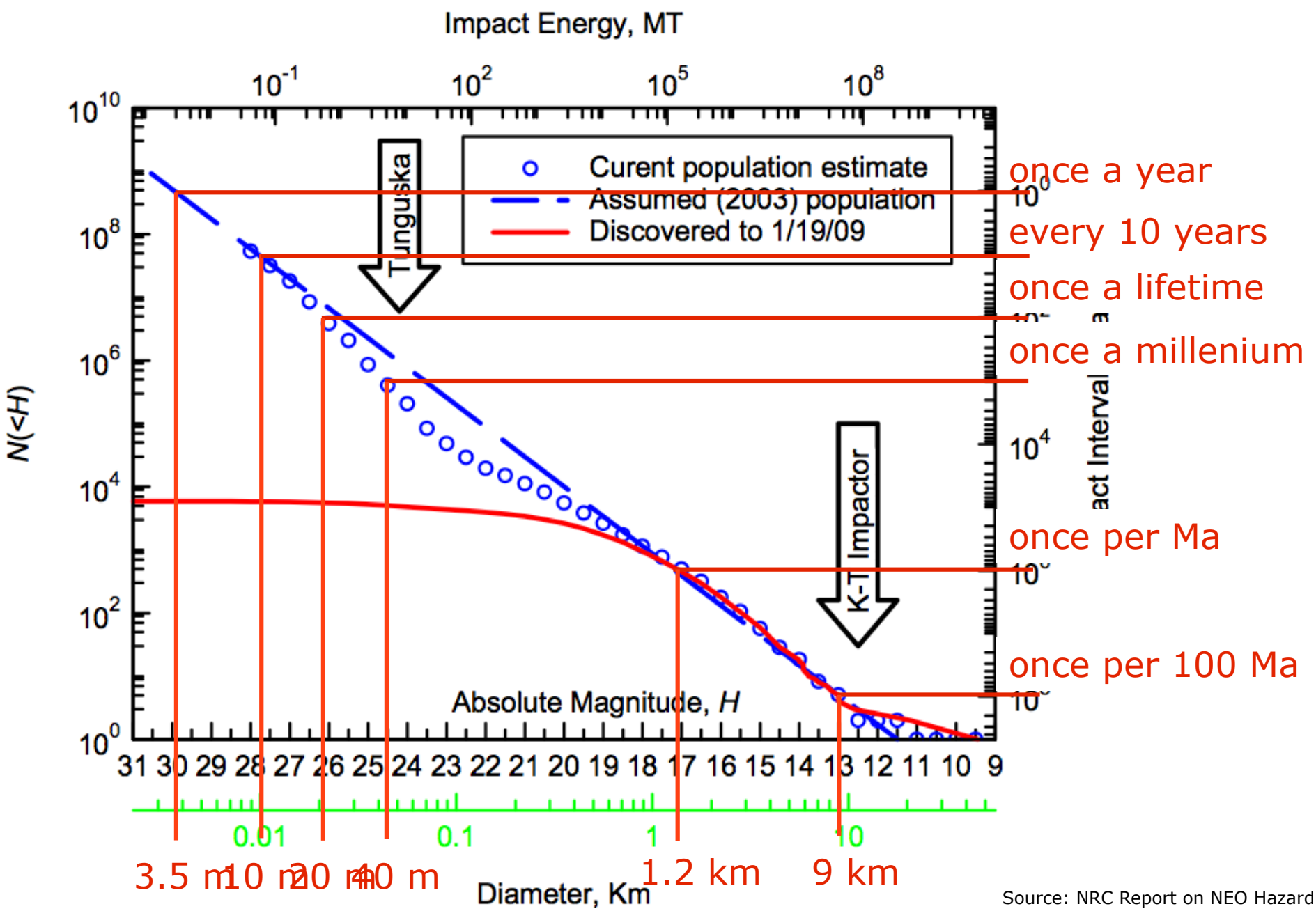
Stand-off nuclear explosion



Gravity tractor

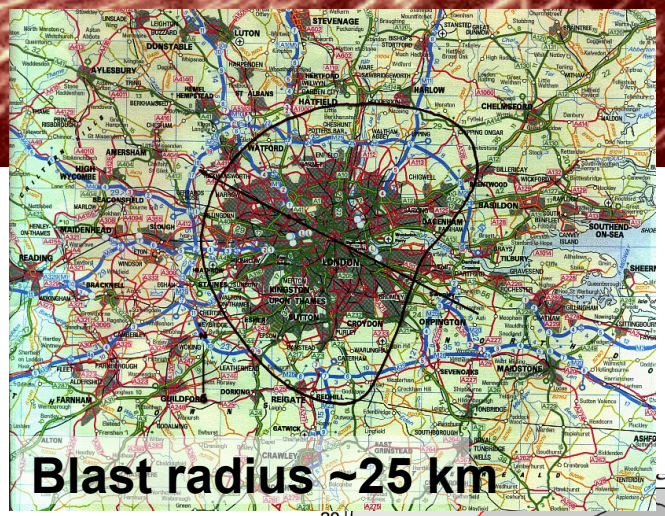


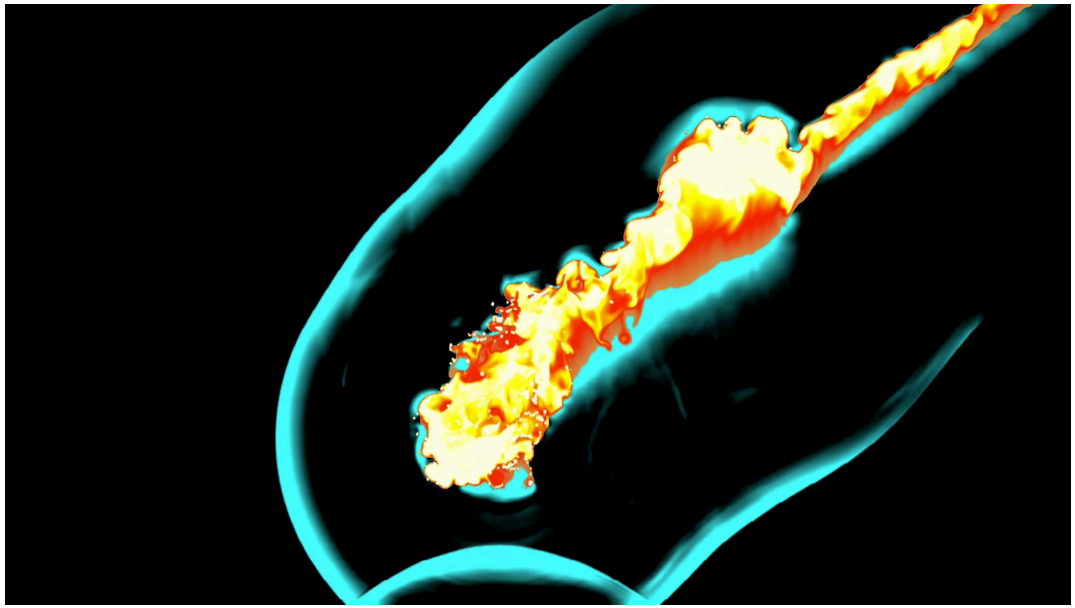
Spacecraft impact



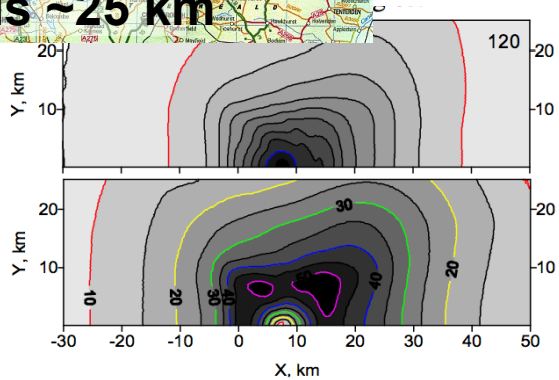
Source: NRC Report on NEO Hazard

Famous airbursts: 1908 - Tunguska, Siberia.

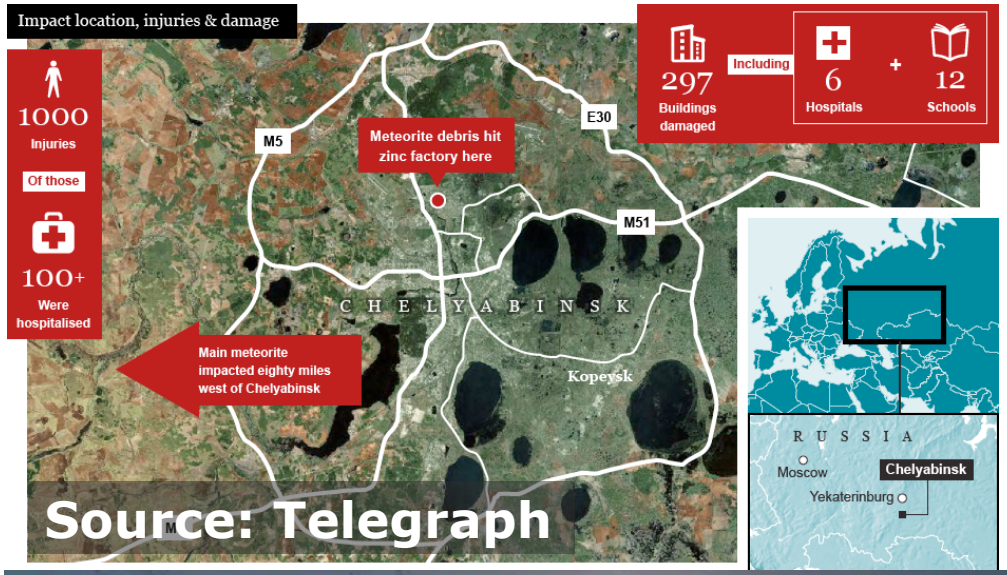




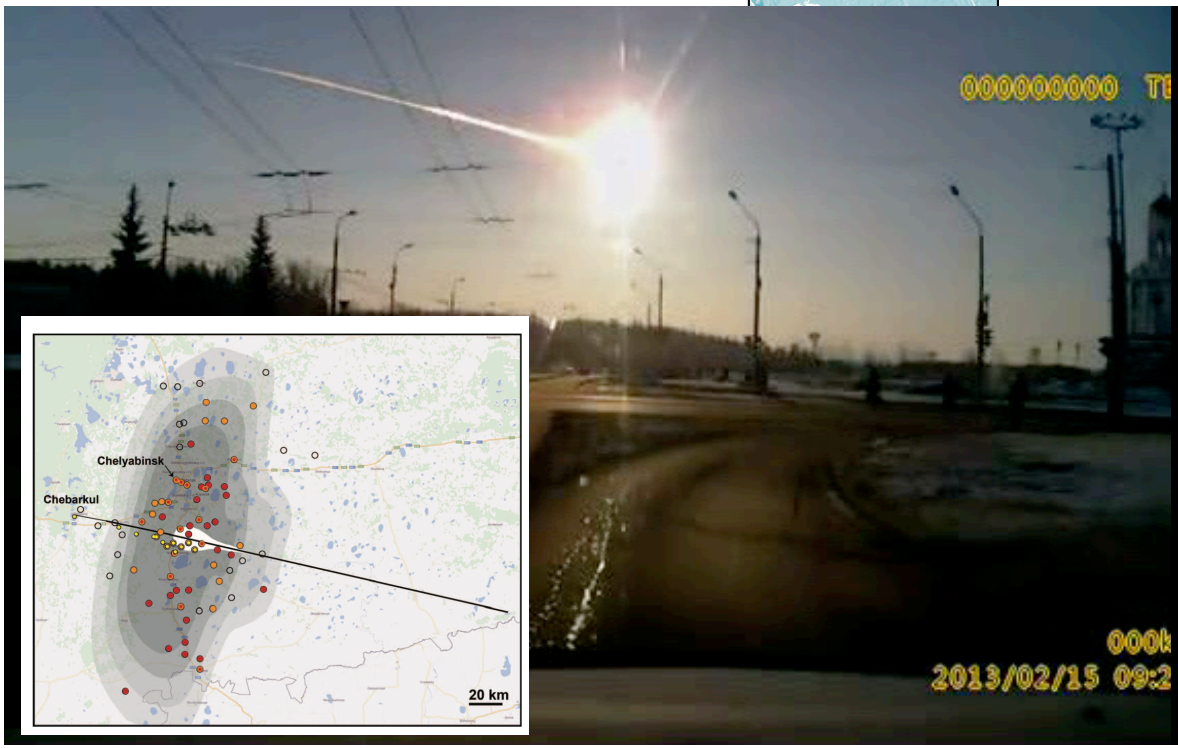
Plan view of blast contours (Artemieva & Shuvalov 2007)



Famous airbursts: 15th Feb. 2013 - Chelyabinsk, Russia



- Estimated mass: ~10,000 Tons (~20 m diameter; 19 km/s; 18 degrees).
- ~500 kTon energy
- Disrupted at 26-30 km altitude
- Blastwave shattered windows over a large area, injuring >1000 people



Airbursts are a low-frequency/high-consequence hazard

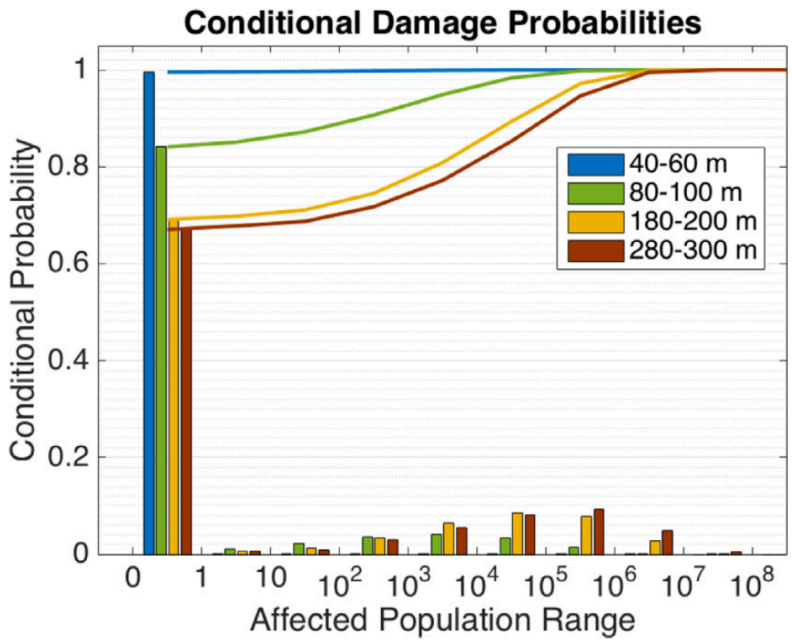


Fig. 9. Conditional probabilities of impacts within four size ranges causing varying levels of population damage, given an impact in each size group. The bars represent the relative probabilities of each population range, while the lines represent the cumulative probability up to each range.

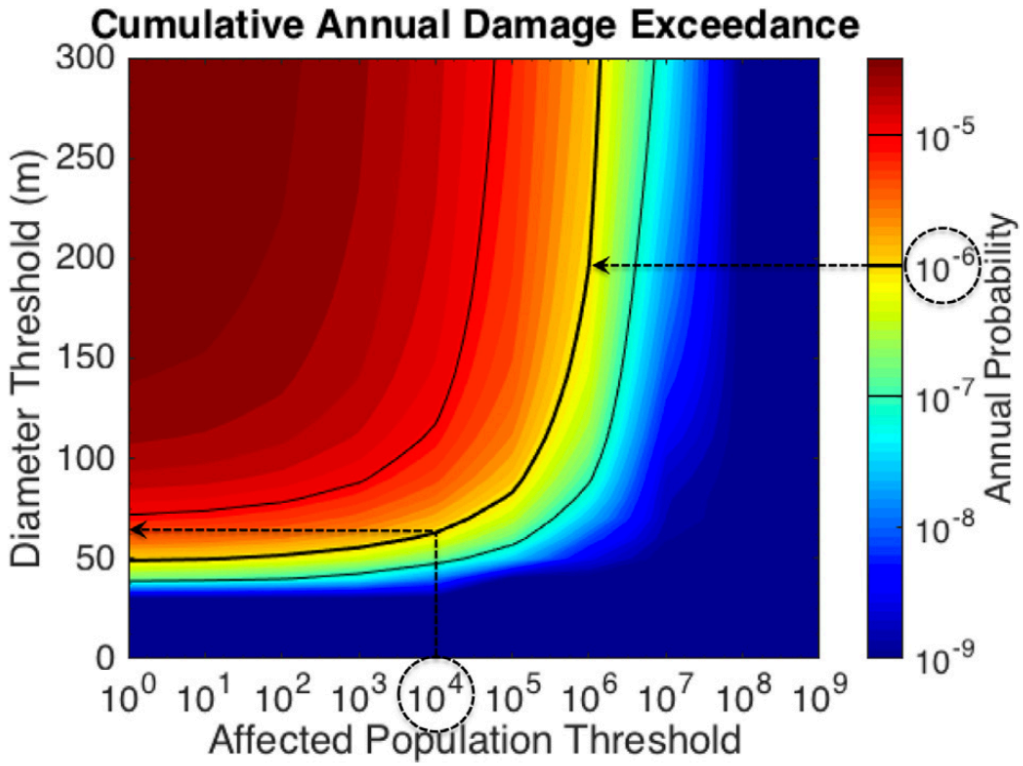


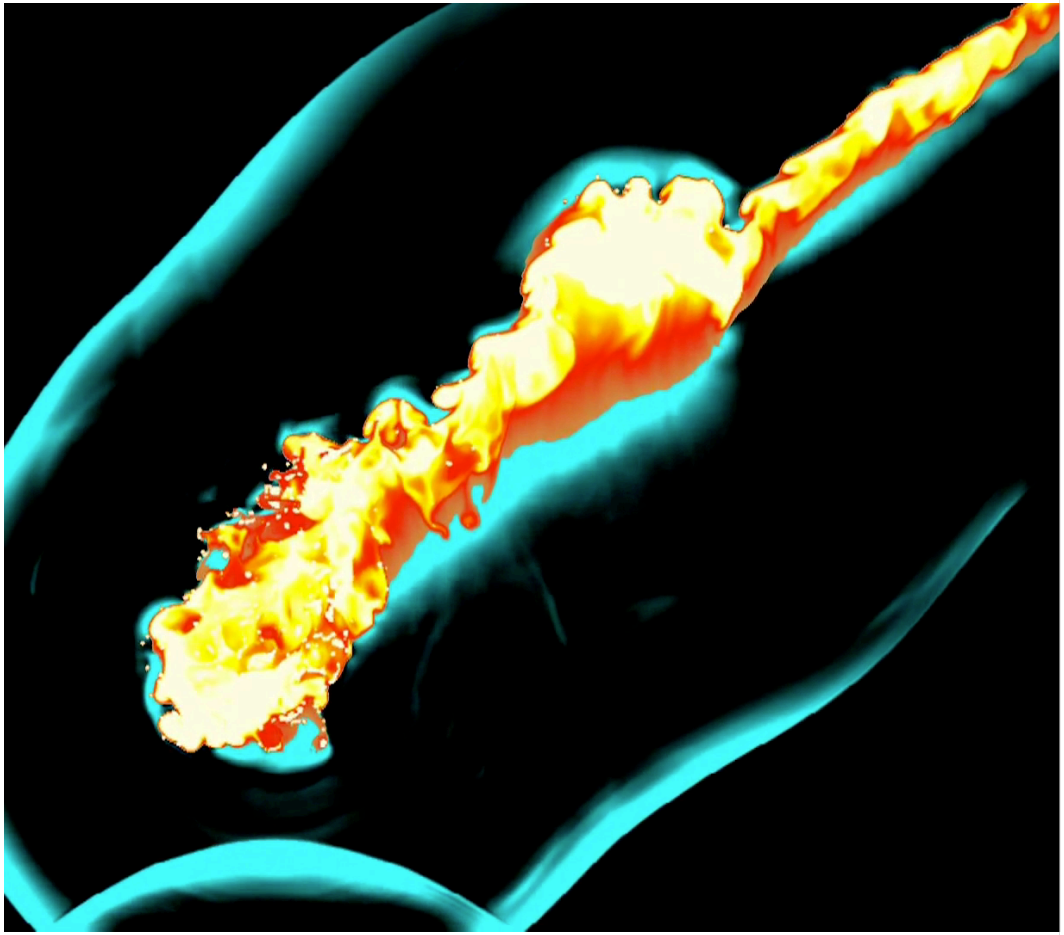
Fig. 12. Probability per year (color contours) of an asteroid up to a given size threshold (y-axis) impacting Earth and causing damage that affects at least a given population threshold or more (x-axis). The black lines show the 10^{-5}, 10^{-6}, and 10^{-7} probability contours. The dashed arrows show an example of how impact risk probability distributions can provide a size threshold for a sample risk tolerance level of a one-in-a-million probability per year of an impact affecting at least 10,000 people or more. For the modeling and parameter assumptions used in this assessment, the size threshold for this sample risk posture is around 65 m in diameter.

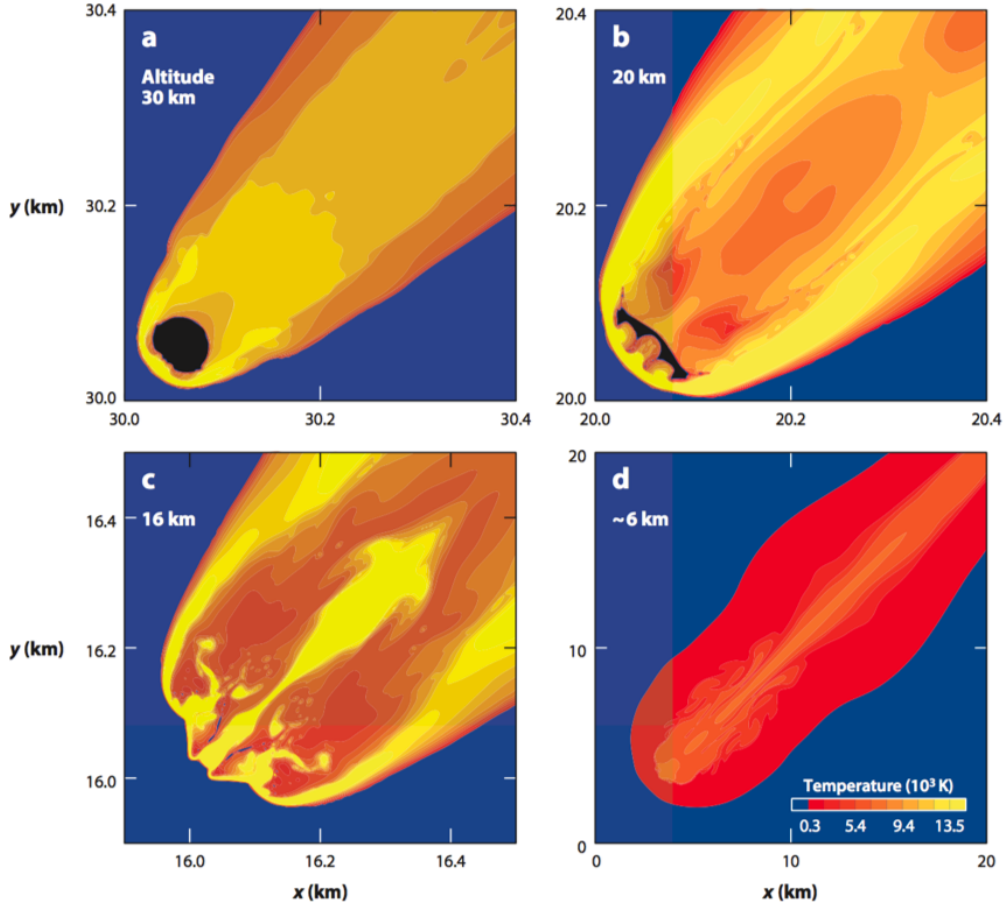
Mathias, et al. 2017. Icarus 289, 106–119. https://doi.org/10.1016/j.icarus.2017.02.009

Probability of Damage per kyr:
Town (~50k people): 1/100
City (~1.4M people): 1/1000
Big City (~6M people): 1/10,000

Dynamic modelling of airbursts is a huge computational challenge

Artemieva & Shuvalov, 2016, *Ann. Rev. Earth Planet. Sci.*





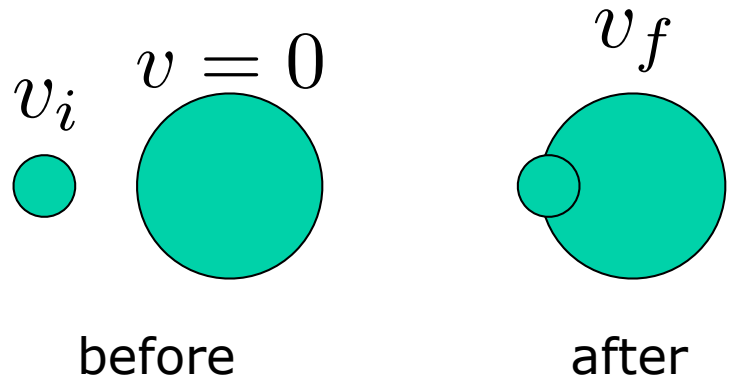
Boslough, 2013, pers. comm.

…there is a need for fast simulators that solve approximate equations

Meteor dynamics: conservation of momentum

For an inelastic collision that conserves momentum:

$$(m_1 + m_2)v_f = m_1 v_i$$



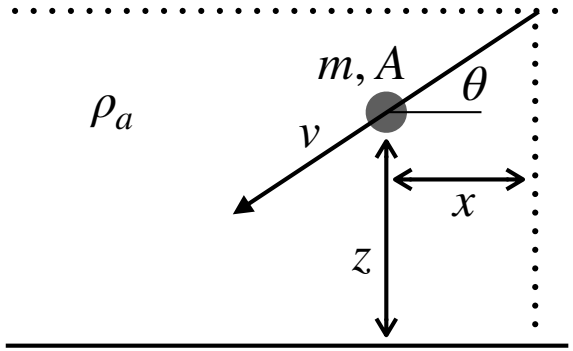
$$v_f = \frac{m_1}{(m_1 + m_2)} v_i \approx \frac{m_1}{m_2} v_i \text{ for } m_2 >> m_1$$

Hence, an impactor that encounters a fluid mass ten times greater will slow to ca. one-tenth its initial speed

Planet	Surface pressure	Atmospheric mass	Equivalent thickness of rock
Earth	100 kPa	5.2×10^{18} kg	3 m
Mars	600 Pa	2.35×10^{16} kg	5 cm
Venus	9.3 MPa	5×10^{20} kg	344 m

Meteor dynamics: no ablation; no gravity; no lift; flat planet

$$\frac{dv}{dt} = \frac{-C_D \rho_a A v^2}{2m}$$

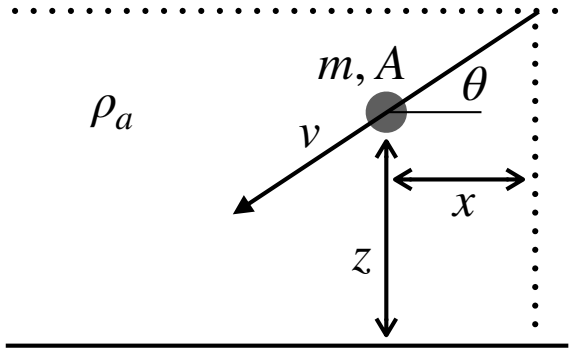


$$\frac{dz}{dt} = -v \sin\theta \qquad \frac{dx}{dt} = v \cos\theta$$

Meteor dynamics: with ablation; no gravity; no lift; flat planet

$$\frac{dv}{dt} = \frac{-C_D \rho_a A v^2}{2m}$$

$$\frac{dm}{dt} = \frac{-C_H \rho_a A v^3}{2Q}$$



$$\frac{dz}{dt} = -v \sin\theta \qquad \frac{dx}{dt} = v \cos\theta$$

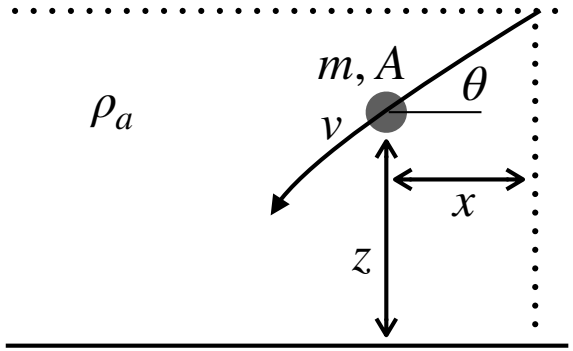
Meteor dynamics: with ablation and gravity; no lift; flat planet

$$\frac{dv}{dt} = \frac{-C_D \rho_a A v^2}{2m} + g \sin\theta$$

$$\frac{dm}{dt} = \frac{-C_H \rho_a A v^3}{2Q}$$

$$\frac{d\theta}{dt} = \frac{g \cos\theta}{v}$$

$$\frac{dz}{dt} = -v \sin\theta \qquad \frac{dx}{dt} = v \cos\theta$$



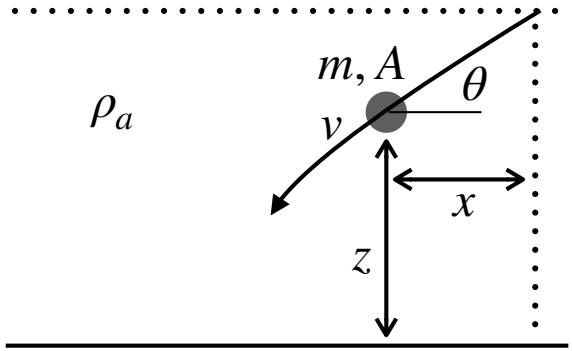
Meteor dynamics: with ablation, gravity and lift; flat planet

$$\frac{dv}{dt} = \frac{-C_D \rho_a A v^2}{2m} + g \sin\theta$$

$$\frac{dm}{dt} = \frac{-C_H \rho_a A v^3}{2Q}$$

$$\frac{d\theta}{dt} = \frac{g \cos\theta}{v} - \frac{C_L \rho_a A v}{2m}$$

$$\frac{dz}{dt} = -v \sin\theta \qquad \frac{dx}{dt} = v \cos\theta$$



Meteor dynamics: with ablation, gravity, lift and planet curvature

$$\frac{dv}{dt} = \frac{-C_D \rho_a A v^2}{2m} + g \sin\theta$$

$$\frac{dm}{dt} = \frac{-C_H \rho_a A v^3}{2Q}$$

$$\frac{d\theta}{dt} = \frac{g\cos\theta}{v} - \frac{C_L \rho_a A v}{2m} - \frac{v\cos\theta}{R_P + z}$$

$$\frac{dz}{dt} = -v\sin\theta \qquad \frac{dx}{dt} = \frac{v\cos\theta}{1 + z/R_P}$$

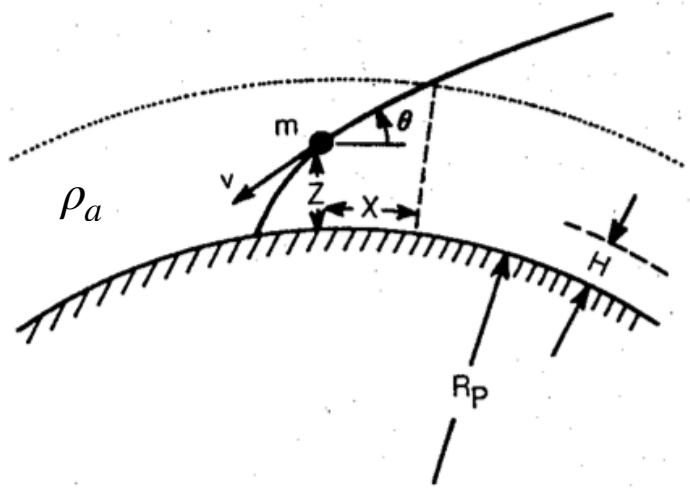


Fig. 11.1 Variables used to describe the path of a meteoroid of mass m as it descends through the atmosphere of a planet with radius R_P. The atmospheric density at any given altitude is ρ_g and its scale height is H. The meteoroid's altitude is Z, its instantaneous speed is v, and its trajectory forms an instantaneous angle θ with the local horizontal. The meteoroid's distance downrange from an arbitrary initial position is X. In this figure the initial position is determined by the intersection between the meteoroid's trajectory (solid line) and an arbitrary shell located well outside the planet's atmosphere (dotted line).

Meteoroids break-up under drag forces:

density of atmosphere

impactor speed

$$Y \approx \underline{\rho_a(z) v_i^2}$$

Meteoroid strength

Ram pressure on meteoroid

Break-up altitudes on Earth are typically 30-70 km, implying stony meteoroid strengths of 0.1-10 MPa

After break-up fragments spread, which increases drag, leading to rapid deceleration and extreme heating of atmosphere

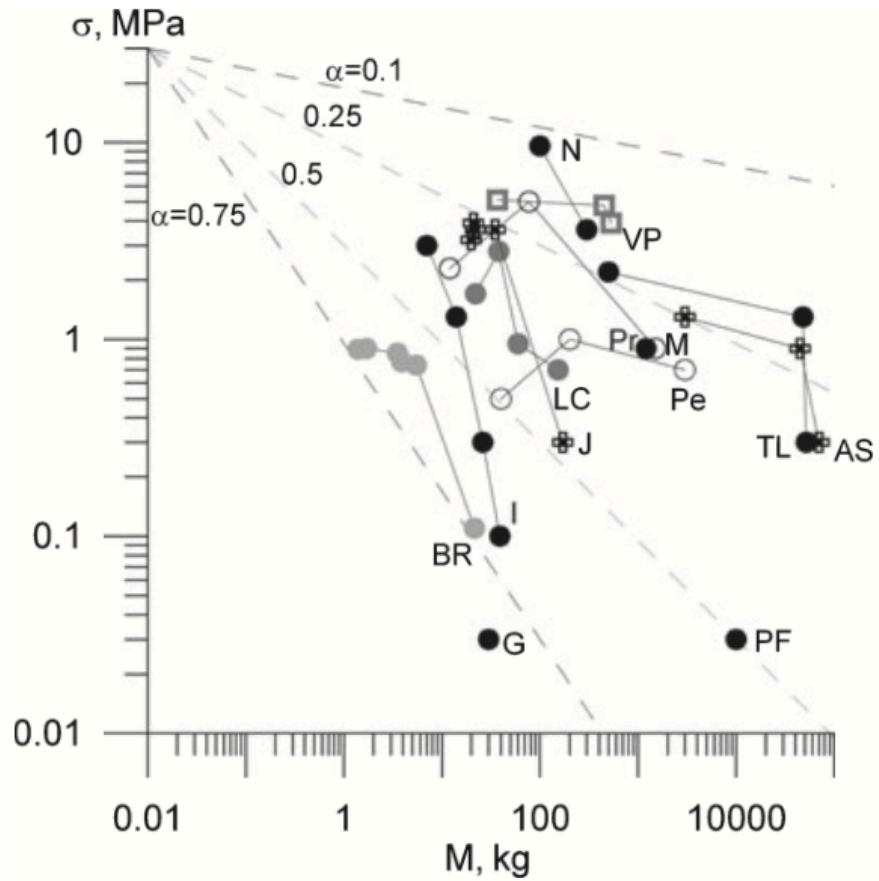


Fig. 4. Estimated apparent bulk strength (=ram pressure in Table 4) at first, second, and third breakups as a function of mass for our 13 cases (Pr—Příbram; LC—Lost City; I—Innisfree; Pe—Peekskill; TL—Tagish Lake; M—Morávka; N—Neuschwanstein; PF—Park Forest; VP—Villalbeto de la Pena; BR—Bunburra Rockhole; AS—Almahata Sitta; J—Jesenice; G—Grimsby). In some cases, other breakups predated the first listed breakup. In the case of Peekskill, for example, there is evidence of breakup before our first observed event. The dashed lines represent power law function, which relates laboratory strength data to bulk rock strength data.

Debris Cloud Model of Meteoroid Disruption

- **Treats disrupted meteoroid as an impermeable debris cloud (with circular cross-section).**

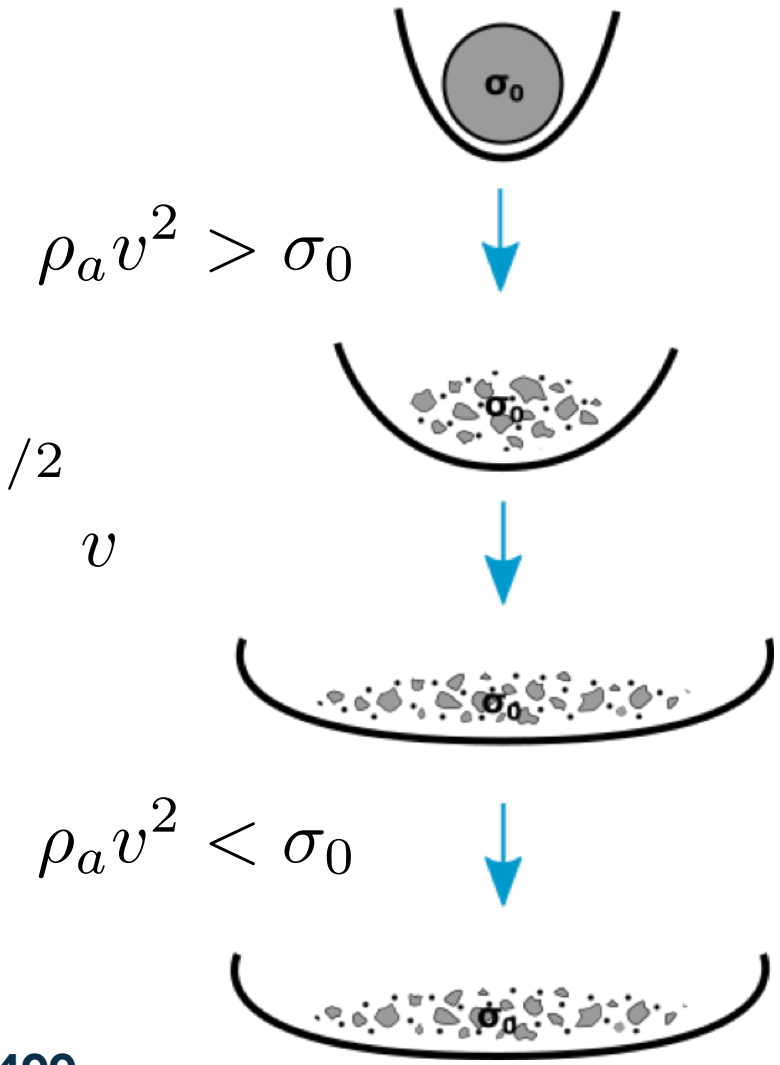
- **Cloud expands while the ram pressure at it's front exceeds the meteoroid strength**

- **Spreading equation:**

$$\frac{dr}{dt} = \left[\frac{7}{2}\alpha\frac{\rho_a}{\rho_m}\right]^{1/2} v$$

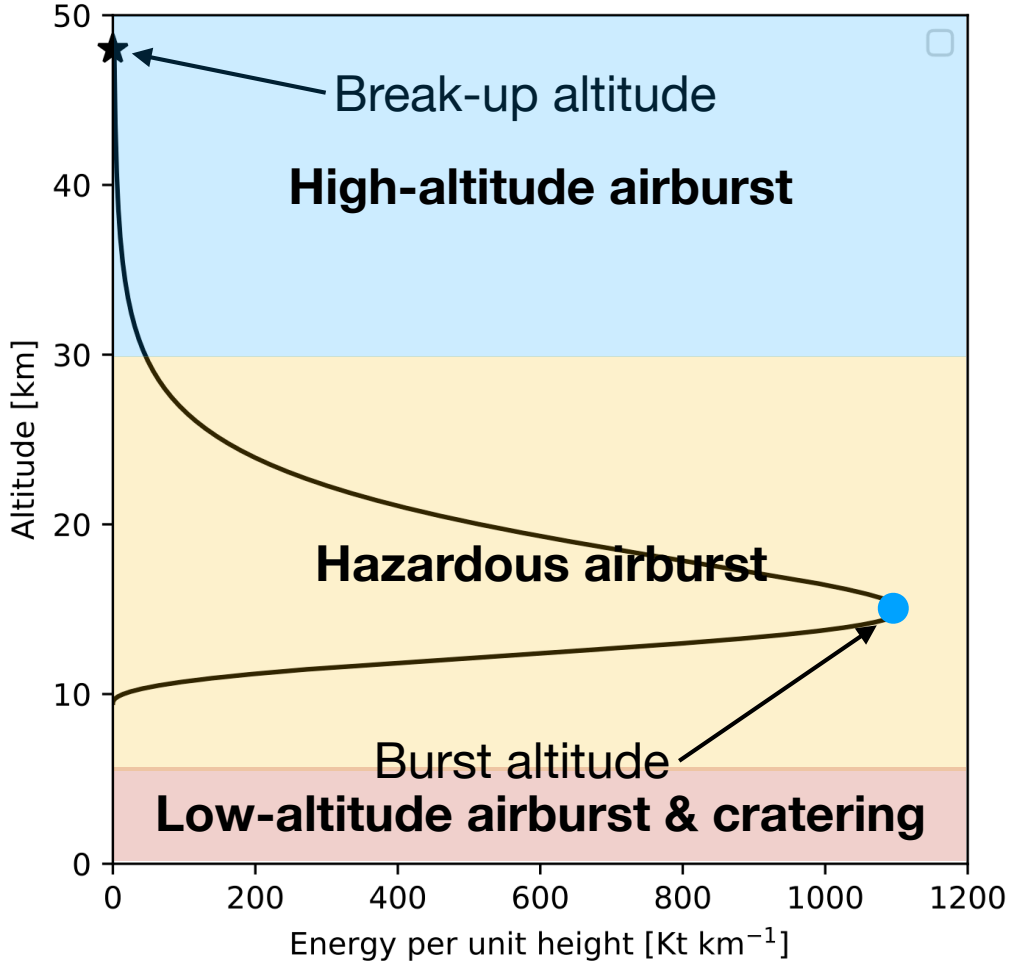
r **is radius,** α **is dispersion coefficient.**

- **Fragmentation ceases when ram pressure drops below strength of the meteoroid**



Hills and Goda (1993) http://doi.org/10.1086/116499

An example solution



Break-up of iron meteorites produces crater strewn fields

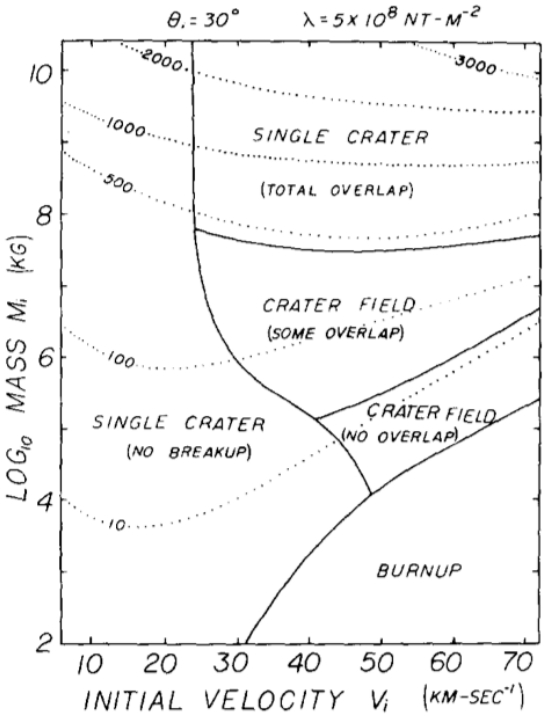
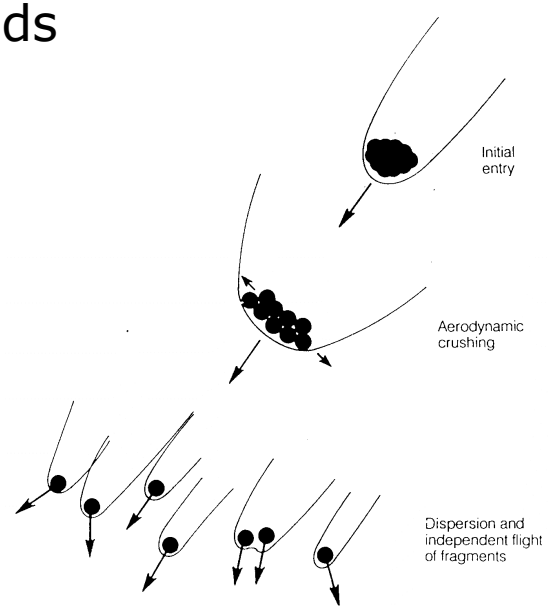
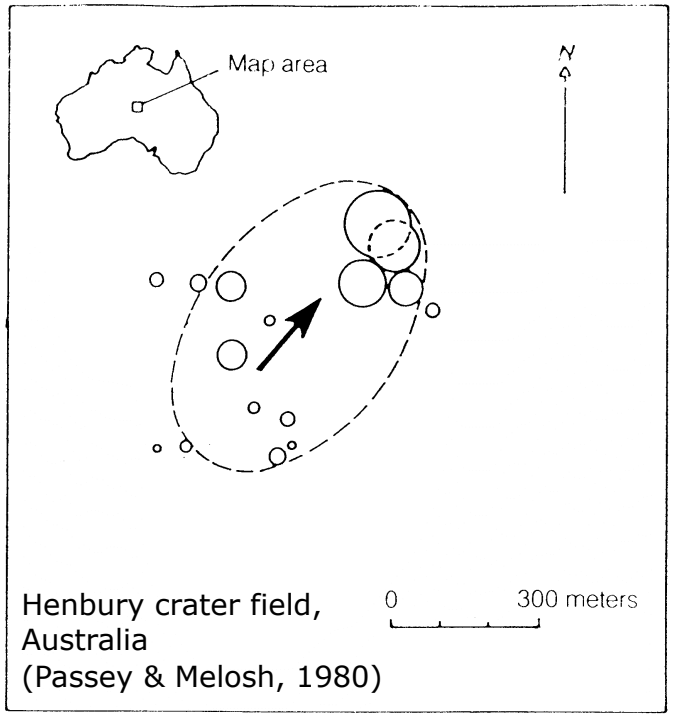
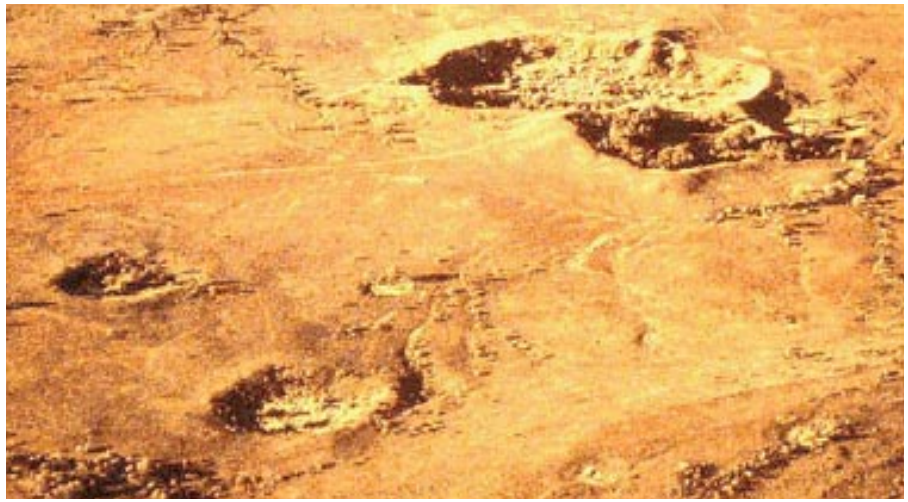


FIG. 11. Diagram showing the zones of crater field formation or burnup for meteoroids with a yield strength (λ) of 5×10^8 N m^{-2} and an entry angle (θ_i) of 30° with respect to the horizontal. The dotted contours indicate the diameter (in meters) of a crater produced by a fragment with an initial mass of one-half the mass of the meteoroid at the time of breakup. This should only be used as a guide for the approximate diameter of the largest crater in a given crater field.





Henbury crater field, Australia
(Passey & Melosh, 1980)