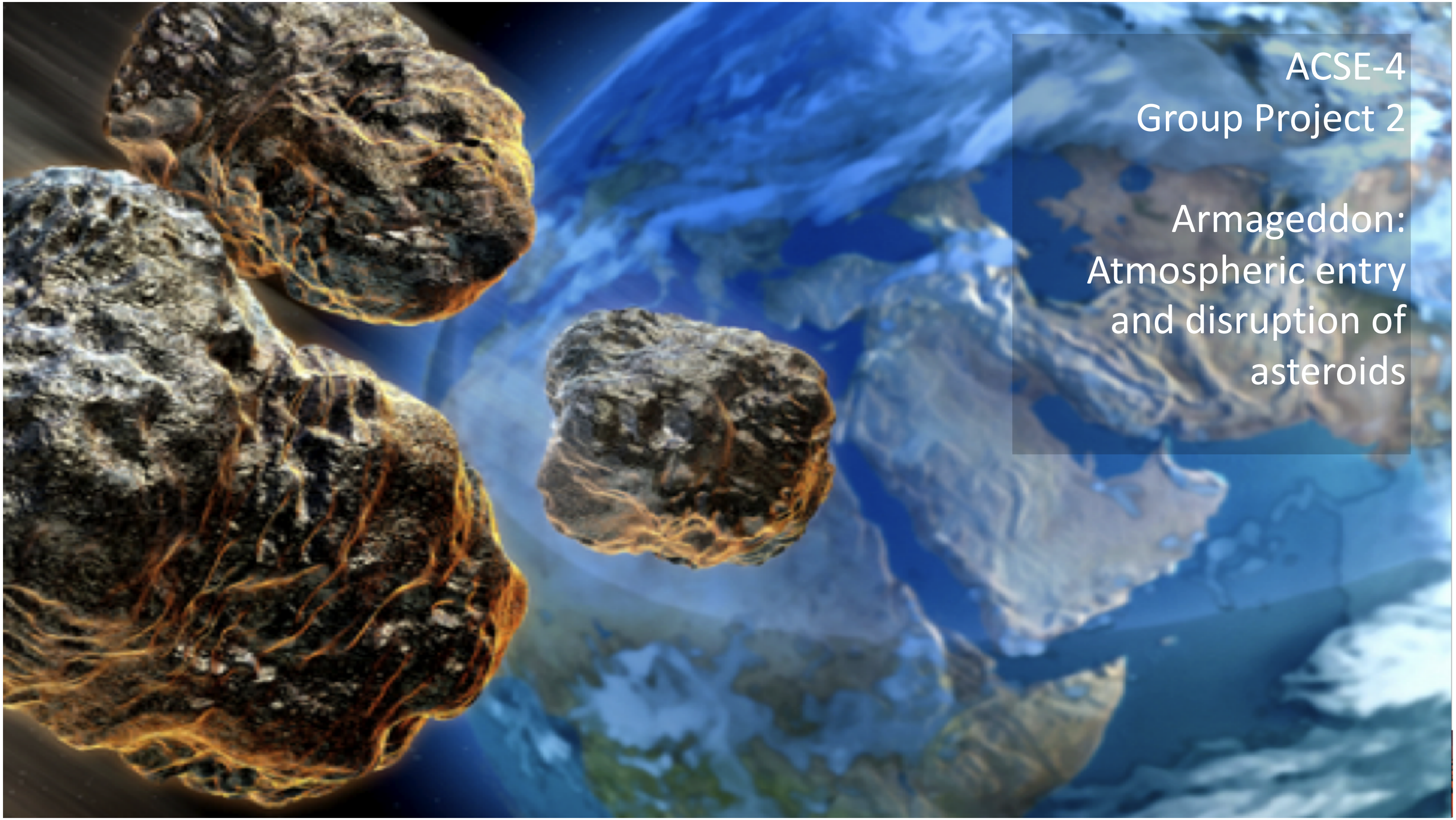
ACSE-4 Project Timetable

	Monday	Tuesday	Wednesday	Thursday	Friday
09:00–12:00	Lecture / Group assignment / Q & A	Group working	Group working	Group working	Group working
12:00					12 pm Deadline
14:00–17:00	Group working	Group working	Reserved For Sports	Group working	Group Presentations + Social event

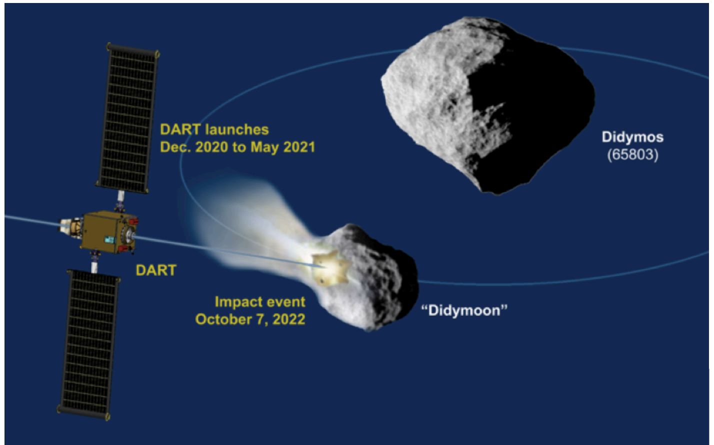
Technical report and software submission **deadline: Friday 12:00**

Our expectation is that you will each spend approximately **45 hours** on these projects, over the course of the week (9 hours / day): The project should be your focus for the whole week.

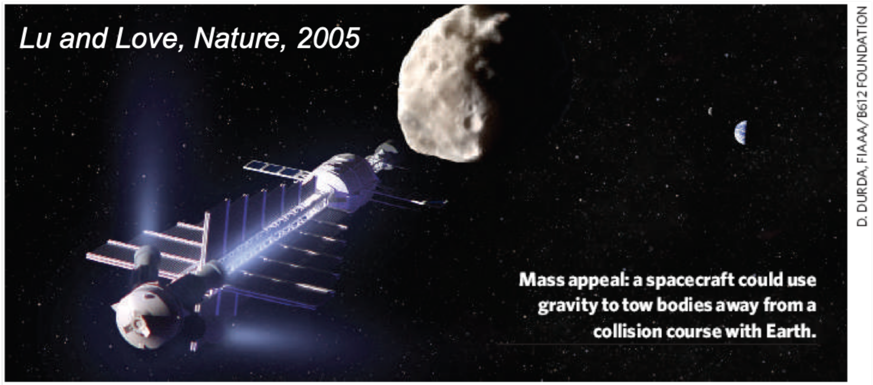

ACSE-4
Group Project 2
Armageddon:
Atmospheric entry
and disruption of
asteroids

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

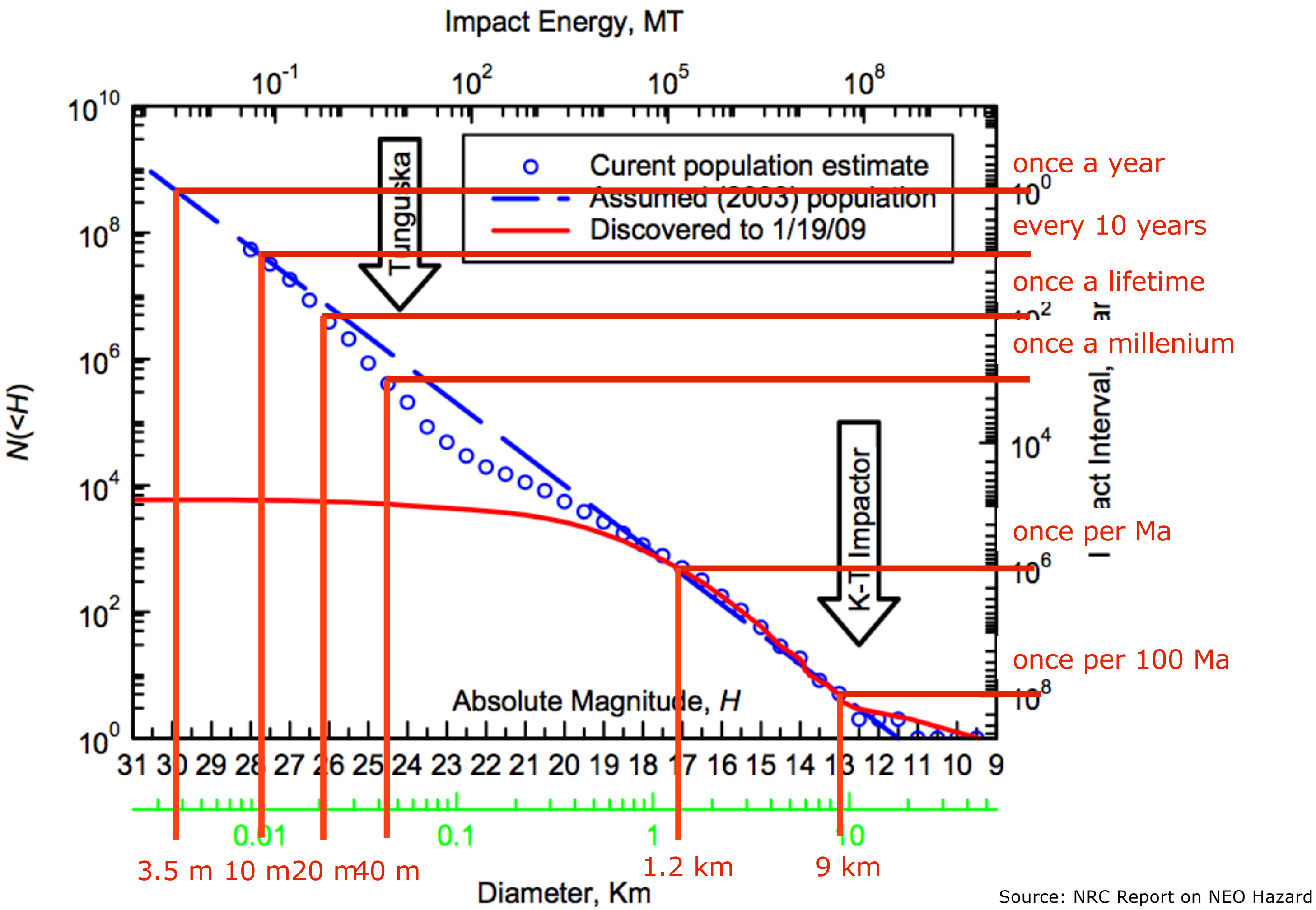
Stand-off nuclear explosion



Gravity tractor

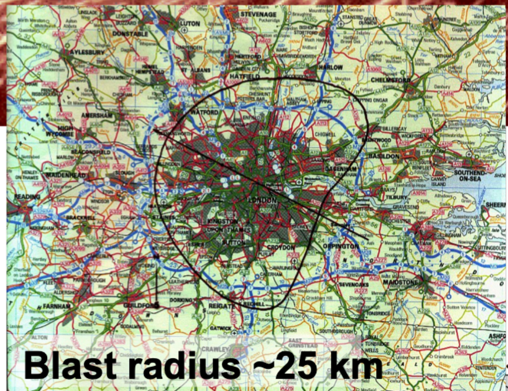


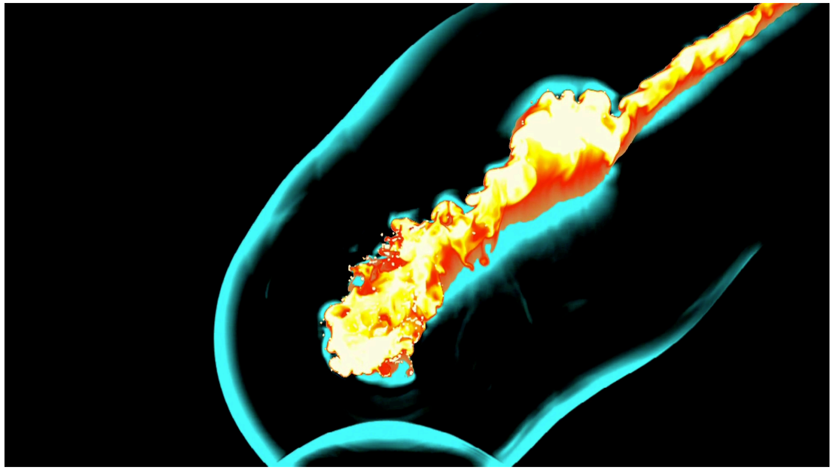
Spacecraft impact

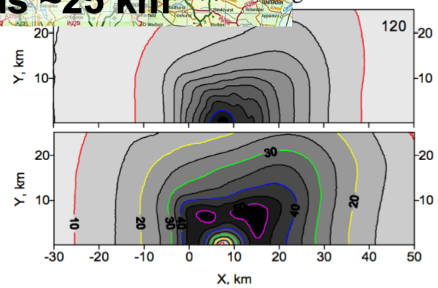


Source: NRC Report on NEO Hazard

Famous airbursts: 1908 - Tunguska, Siberia.

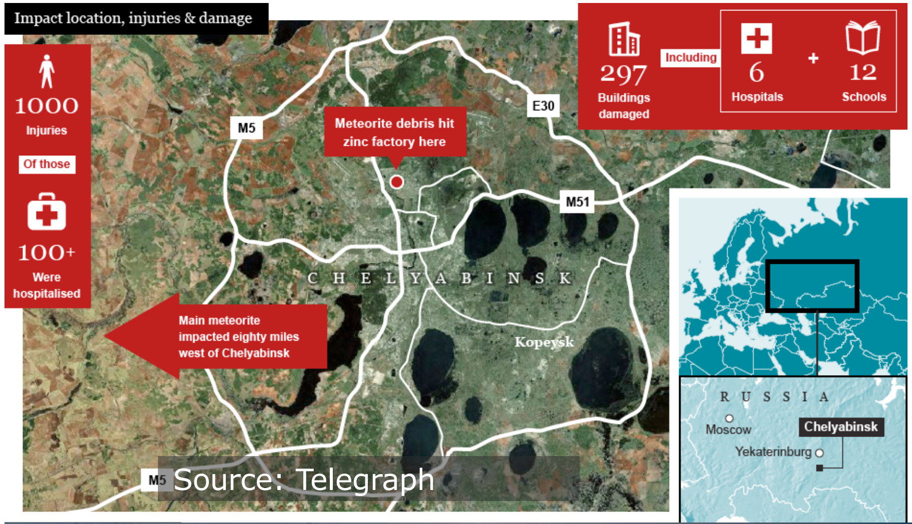




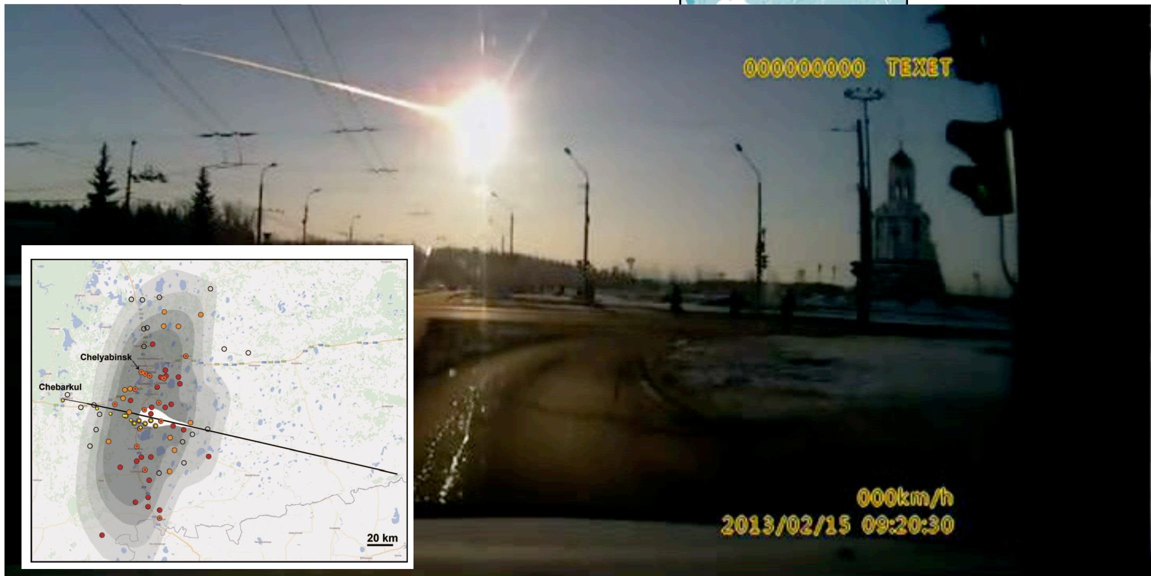


Plan view of blast contours (Artemieva & Shuvalov 2007)

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



The “Carancas“ impact, Lake Titicaca, Peru, Sep. 15, 2007

Airbursts are a low-frequency/high-consequence hazard

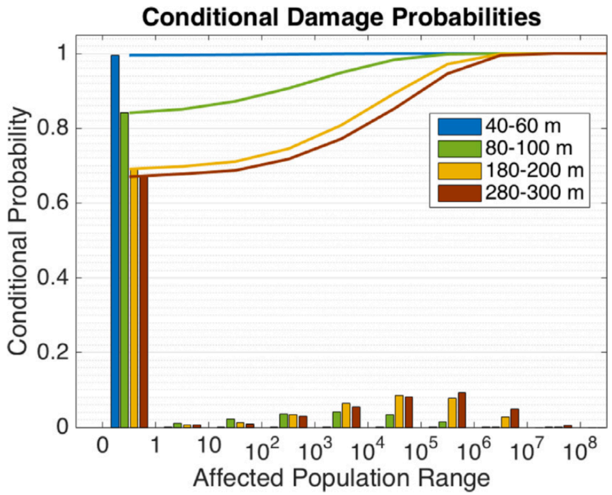


Fig. 9. Conditional probabilities of impacts within four size ranges causing varying levels of population damage, given an impact in each size group. The bars represent the relative probabilities of each population range, while the lines represent the cumulative probability up to each range.

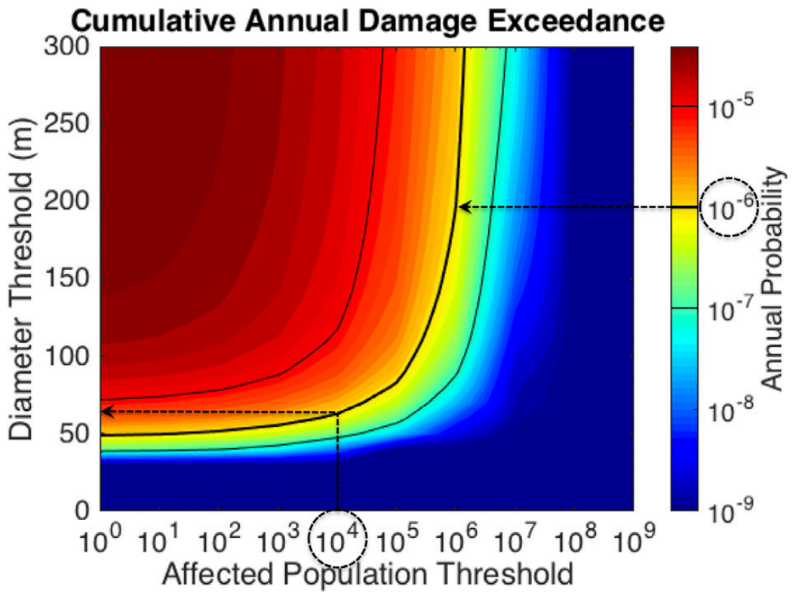
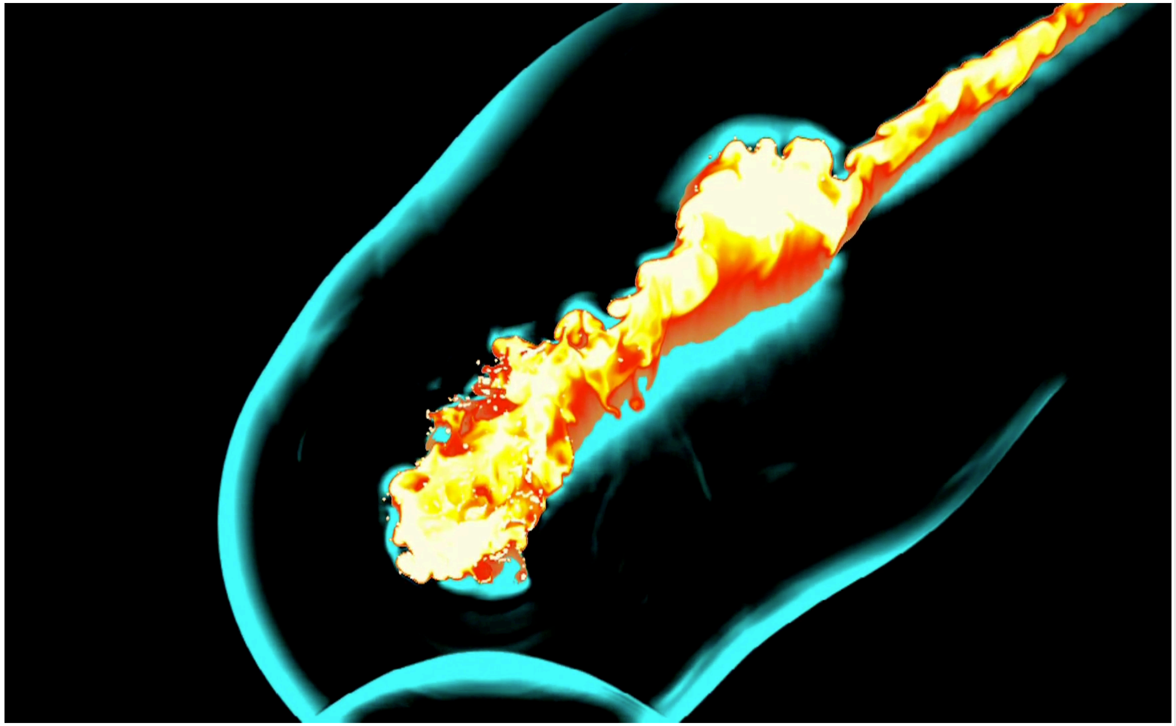


Fig. 12. Probability per year (color contours) of an asteroid up to a given size threshold (y-axis) impacting Earth and causing damage that affects at least a given population threshold or more (x-axis). The black lines show the 10^{-5}, 10^{-6}, and 10^{-7} probability contours. The dashed arrows show 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.

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

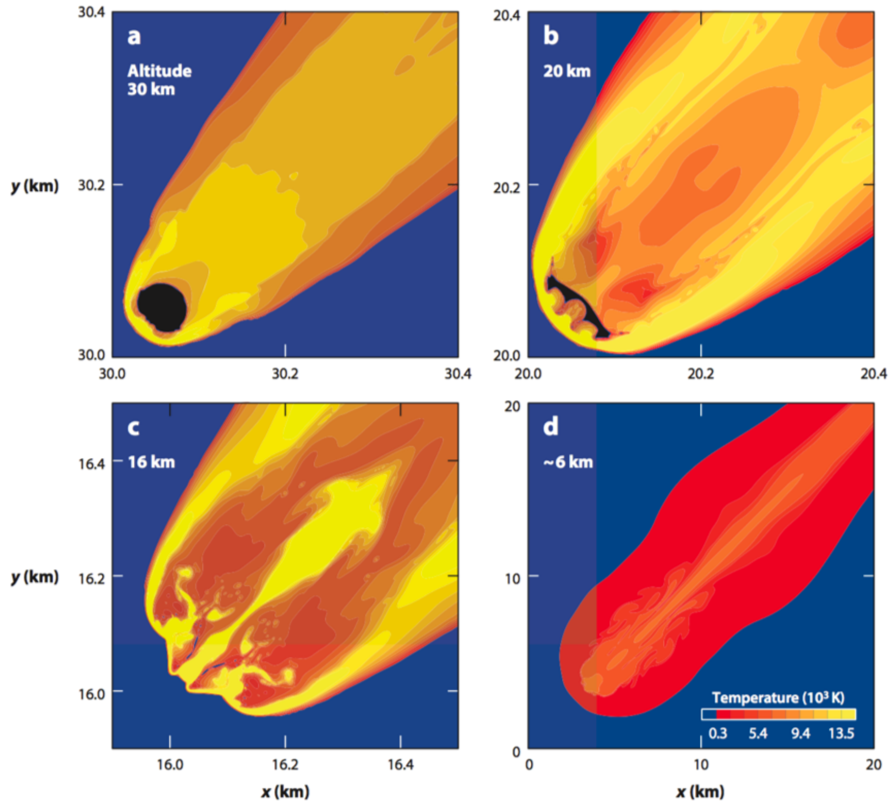
Mathias, et al. 2017. Icarus 289, 106–119. https://doi.org/10.1016/j.icarus.2017.02.009

Dynamic modelling of airbursts is a huge computational challenge



Bosslough, 2013, pers. comm.

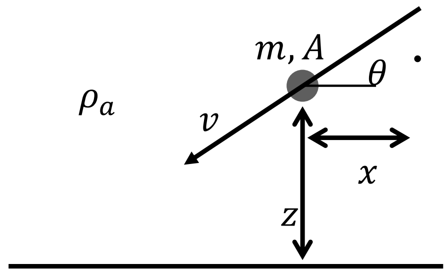
Artemieva & Shuvalov, 2016, *Ann. Rev. Earth Planet. Sci.*



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

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

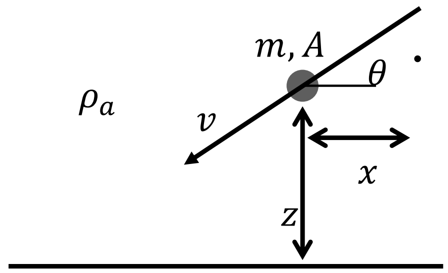
$$\frac{dv}{dt} = \frac{-C_D \rho_a A v^2}{2m}$$



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

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

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



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

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

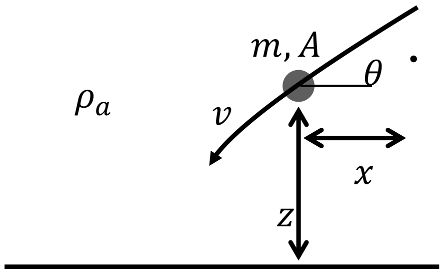
Meteor dynamics: with ablation and gravity; no lift; flat planet

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

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

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

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



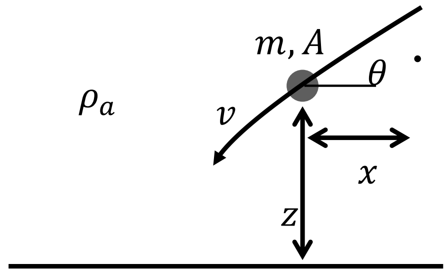
Meteor dynamics: with ablation, gravity and lift; flat planet

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

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

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

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



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

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

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

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

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

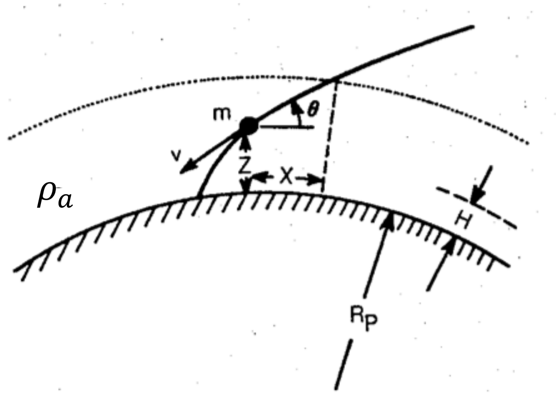


Fig. 11.1 Variables used to describe the path of a meteoroid of mass m as it descends through the atmosphere of a planet with radius R_P. The atmospheric density at any given altitude is ρ_g and its scale height is H. The meteoroid's altitude is Z, its instantaneous speed is v, and its trajectory forms 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

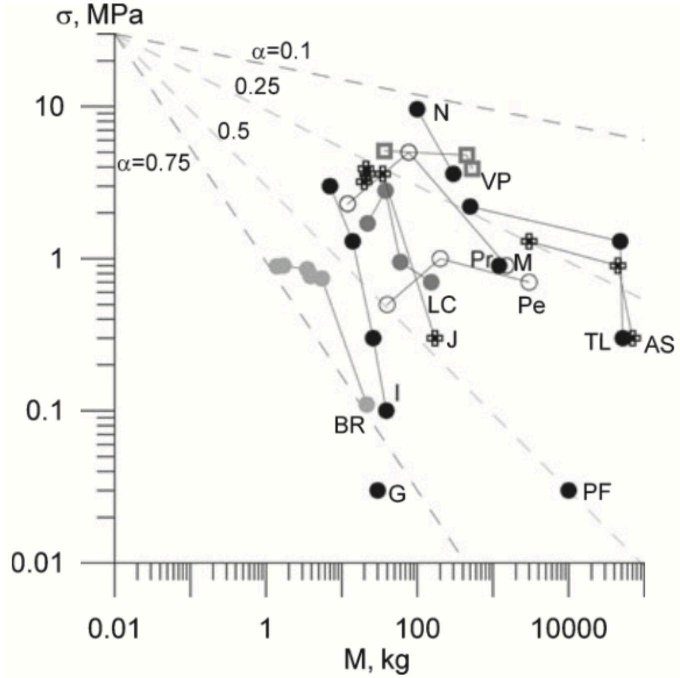


Fig. 4. Estimated apparent bulk strength (=ram pressure in Table 4) at first, second, and third breakups as a function of mass for our 13 cases (Pr—Příbram; LC—Lost City; I—Innisfree; Pe—Peekskill; TL—Tagish Lake; M—Morávka; N—Neuschwanstein; PF—Park Forest; VP—Villalbeto de la Pena; BR—Bunburra Rockhole; 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.

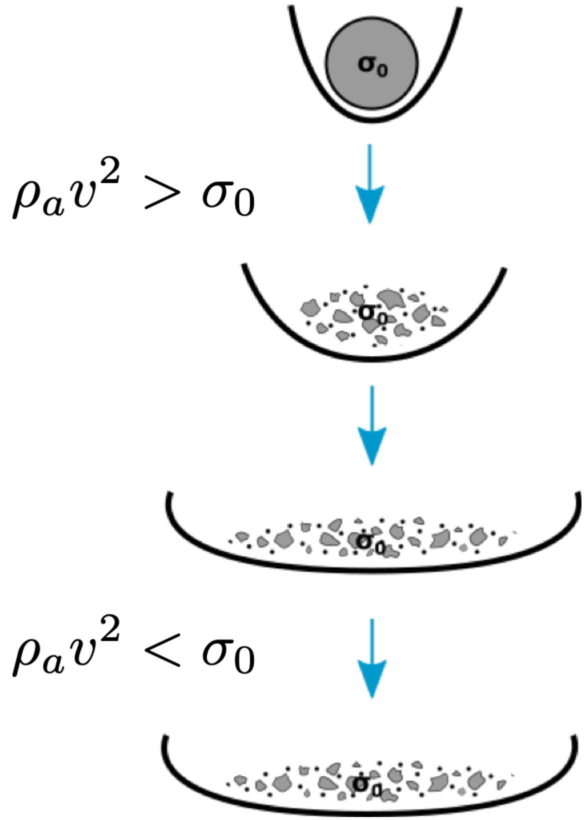
Debris Cloud Model of Meteoroid Disruption

- 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:

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

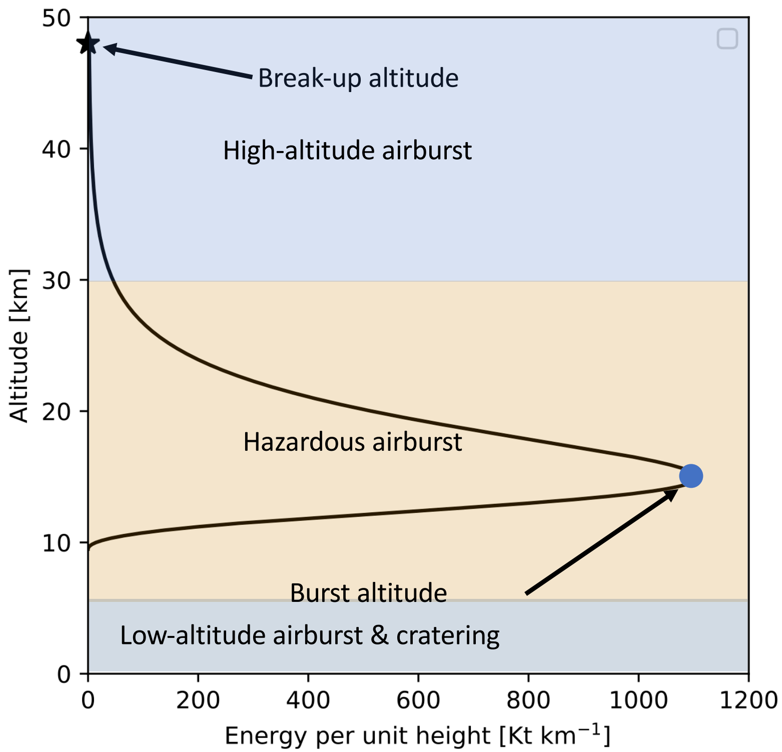
r is radius, α is dispersion coefficient.

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



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

An example solution



Challenge

(1) To develop a Python program to **solve the meteor equations**

- **Simple user interface**
- Ability to **graphically display** results.

(2) To verify your tool against an analytical solution and quantify accuracy

(3) To find asteroid radius and strength that gives best match to Chelyabinsk observation

(4) To perform a simple uncertainty quantification for a Chelyabinsk-scale event

Challenge: core functionality

The program should take as inputs:

- Asteroid radius
- Asteroid speed
- Asteroid density
- Asteroid strength
- Asteroid trajectory angle

For the core task you can assume an exponential (isothermal) atmosphere:

$$\rho_a = \rho_0 \exp(-z/H)$$

The program should be return a dataframe including the following variables:

- time, altitude, (horiz.) distance, velocity, mass, radius, **kinetic energy loss per km**

It should also return the following **four key results**:

- **Airburst** or a **cratering** event

  +

- The **peak kinetic energy loss per km** (airburst)
- The **burst altitude** (airburst)
- The **total kinetic energy loss at burst** (airburst)

  or

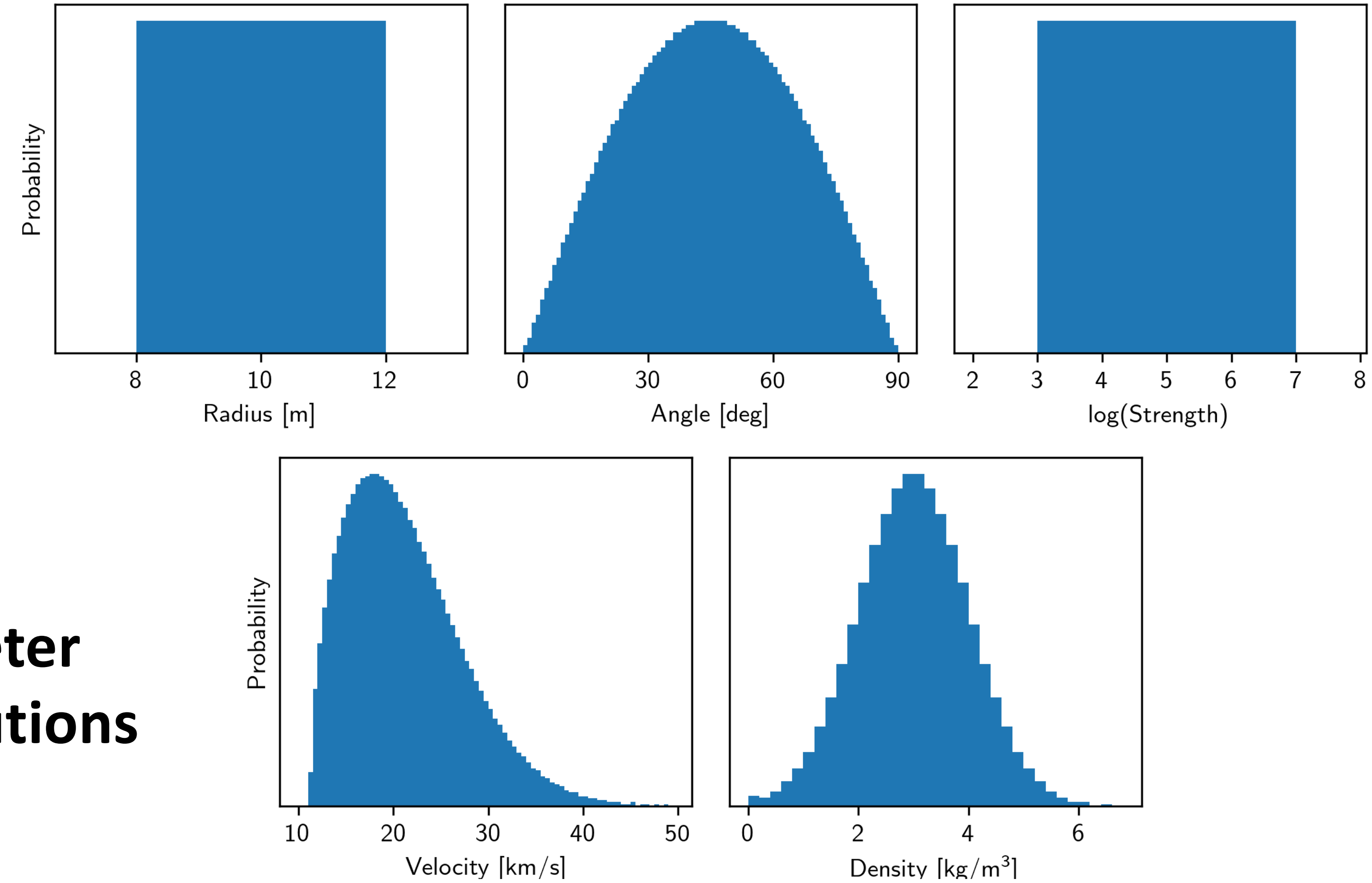
- The **time** of impact (cratering)
- The **mass** and **speed** of the remnant of the asteroid that strikes the ground (cratering)

Challenge: extended functionality

Additional tasks in increasing order of difficulty:

1. **Verify** your solver for a simplified scenario against an **analytical solution**
2. Implement an analytical approximation for **Mars' atmosphere** density
3. Implement a **tabular atmosphere** for Earth
4. Develop an **optimisation method** for finding the asteroid radius and strength that gives the best fit to an observed energy deposition curve for the Chelyabinsk meteor
5. Implement a wrapper to your solver that performs a **statistical ensemble** using prescribed distributions of the input parameters and returns the distribution of burst altitudes

Input parameter distributions



Assessment

Scoring algorithm (50%)
(functionality & performance)

Core solver / outcomes
Analytical solution verification
Mars atmosphere
Tabular atmosphere
Statistical ensemble

Presentation (20%)
(understanding & creativity)

Methodology
User-interface / plotting
Accuracy / convergence
Optimisation method
Statistical ensemble

Sustainability (20%)
Testing
Documentation
GitHub usage

Teamwork (10%)

Peer-evaluation

Presentations: Micro-symposium

- Two presentation sessions on Friday pm (1.47):
  - 14:00-15:30 – 7 groups (TBA)
  - 15:30-17:00 – 7 groups (TBA)

- 90-minute virtual “poster” session where groups demonstrate their software to staff

- Five staff will each assess one aspect of your tool

Learning Outcomes

At the end of this exercise, you should have learned:

- To develop software collaboratively
  - The value of automated testing
  - Effective teamwork
- New technical skills:
  - Solve a coupled ODE system
  - Simple uncertainty quantification
  - Manipulate data using Pandas
- Reinforced knowledge from ACSE-1:
  - Programming with Python
  - Using GitHub for collaborative software maintenance
  - Using Travis CI for automated testing
  - Using Pandas for data manipulation
  - Using Sphinx for automated documentation

Final thoughts…

- Choose a leader
- Make a sensible division of labour (e.g.):
  - ODE solver
  - Analysis of results and outcome calculator
  - Uncertainty quantification framework (size and type of sampling)
  - User-interface, plotting, documentation
  - Testing, verification and validation
- Questions we will answer:
  - Clarification about problem/requirements/assessment
  - Help with git / GitHub / Travis / Sphinx
- Questions we won't answer:
  - Choice of algorithm / approach
  - Help with debugging your code