Possibility of Moon formation from debris escaped after impacts on the Earth

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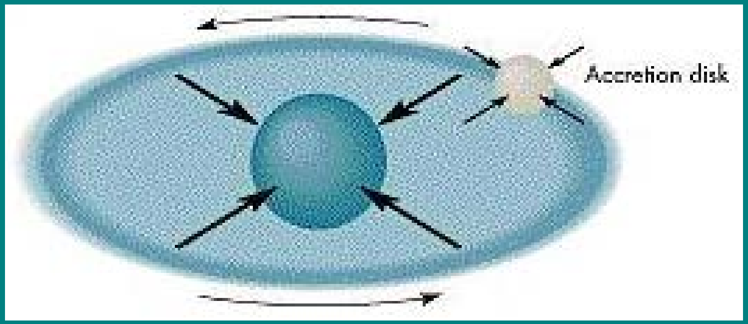
Coaccretion theory of Moon origin
(Ruskol, 1960)

Collisions of planetesimals within the Hill sphere lead to formation of prelunar swarm of debris. Satellites form from this swarm beyond the Roche limit.



Main problems:

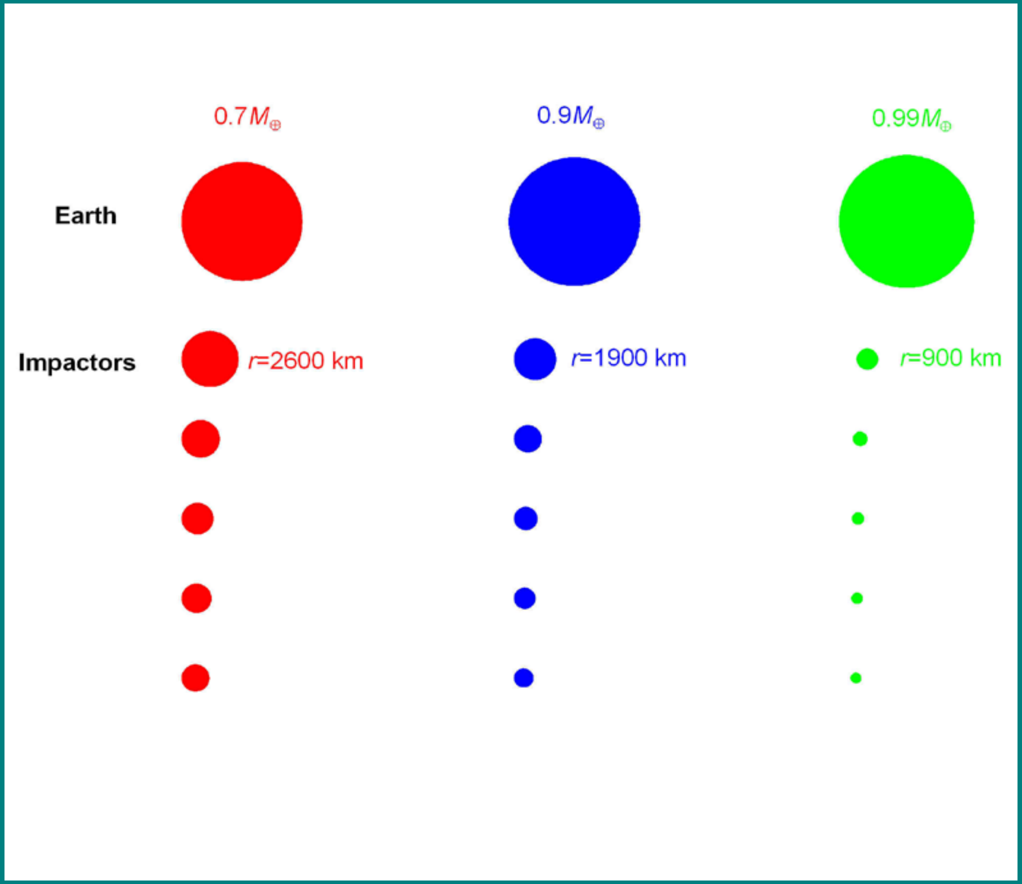
- The Moon is iron poor compared to the Earth
- Mass of prelunar swarm formed by planetesimal collisions is too small – 10^{-4} – 10^{-5} of the Earth's mass (Pechernikova et al., 1984)

Statistical impact model of Moon origin

(Pechernikova, Vityazev, 1996, 1998)

- Growing Earth underwent numerous impacts of large bodies which brought material to it. Some portion of debris and ejecta escapes the Earth gravity.
- Prelunar swarm is fed by escaped debris which reenter the Hill sphere.
- Moon is formed from the swarm when it becomes massive enough.

Sizes of five largest impactors



- According to the standard scenario of Earth formation the masses of largest impactors diminish from ~$3x10^{26}$ g to ~$1x10^{25}$ g when the Earth mass grows from 0.7 to 0.99 of its modern value.
- Giant impacts are probable at the earlier stage of Earth formation.
- Later stage – macroimpacts.

Impact velocities

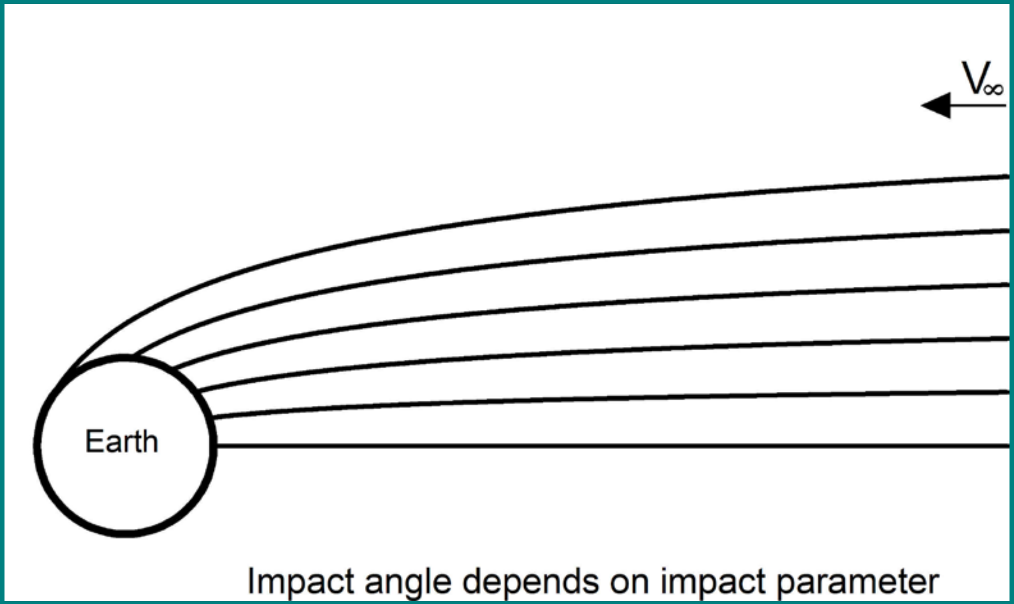
- Mean velocity of impactors at infinity is $V_{inf}=(GM/\theta R)^{1/2}$, where M is Earth mass, R is Earth radius, G is the gravitational constant, and θ is Safronov's parameter.
- For $M>0.7M_{Earth}$ $V_{inf}\sim 5$ km/s ($\theta=2$)
- Impact velocity $V_{imp}=(V^2_{esc}+V^2_{inf})^{1/2}$
- $V_{imp}\sim V_{esc}$, (impacts on a planar target give very small fraction of escaped material)

Impact angles

Probability of the impact within angles (θ, θ+dθ):

$$dP = 2\sin\theta\cos\theta\, d\theta$$

Most probable angle is θ=45°



50% - (30° -60°)
25% - (0° -30°)

25% - (60° -90°)
7% - (75° -90°)

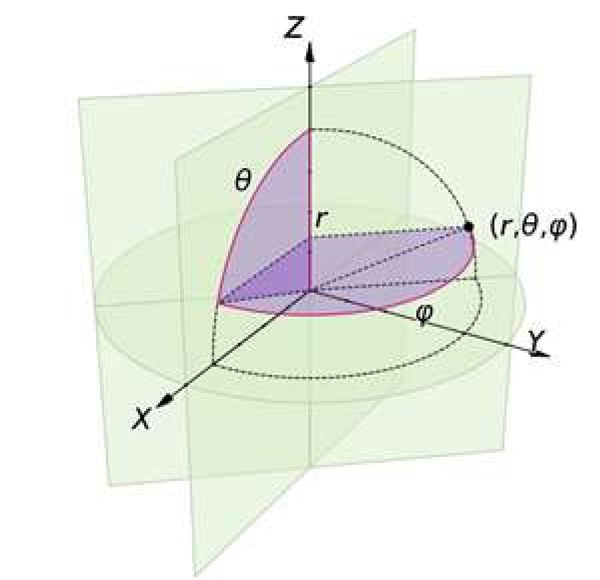
Questions of statistical model

- What is the total mass of debris which is ejected to Earth-bound and heliocentric orbits after large impacts on the Earth?
- What are the sizes of fragments?
- How often do the fragments moving along heliocentric trajectories intersect the Hill sphere of the Earth?
- How does the debris interact with the circumterrestrial swarm?
- How rapidly does the swarm grow?

Method of numerical simulations SOVA (Shuvalov, 1999)

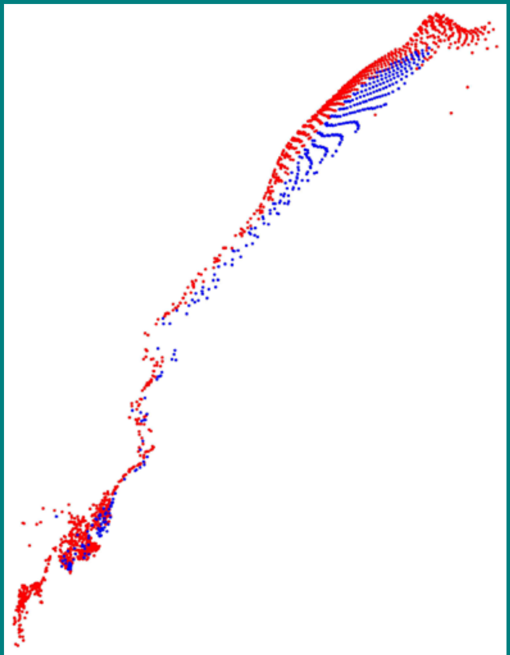
- 3D hydrodynamic equations, no strength
- ANEOS equation of state for mantle material (dunite) and Tillotson's EOS for iron cores
- Poisson equation for gravitational potential

Spherical coordinates



- Grid (r, θ, φ): 225x100x250
- 600,000 passive markers

Simulations of reaccumulation



- When fragments or a solid body are at about the Roche limit the markers are treated as fragments with certain masses and radii.
- Fragment motion is simulated taking into account attraction by Sun, Earth and mutual gravitational attraction between each pair of fragments.
- When a pair of fragments come close to each other they merge into one fragment with total mass and momentum.
- The simulations are made for a time span of about a year.

Estimates of fragment sizes

- For liquid fraction, droplet sizes are determined in hydrodynamic simulations using the model of Grady (1982)

$$d = 6\left(\frac{5\rho\gamma}{3\dot{\rho}^2}\right)^{1/3},$$

ρ is density, $\dot{\rho}$ is density rate, γ is surface tension

ν

- For sizes of solid fragments the model of Glenn and Chudnovsky (1986) is used

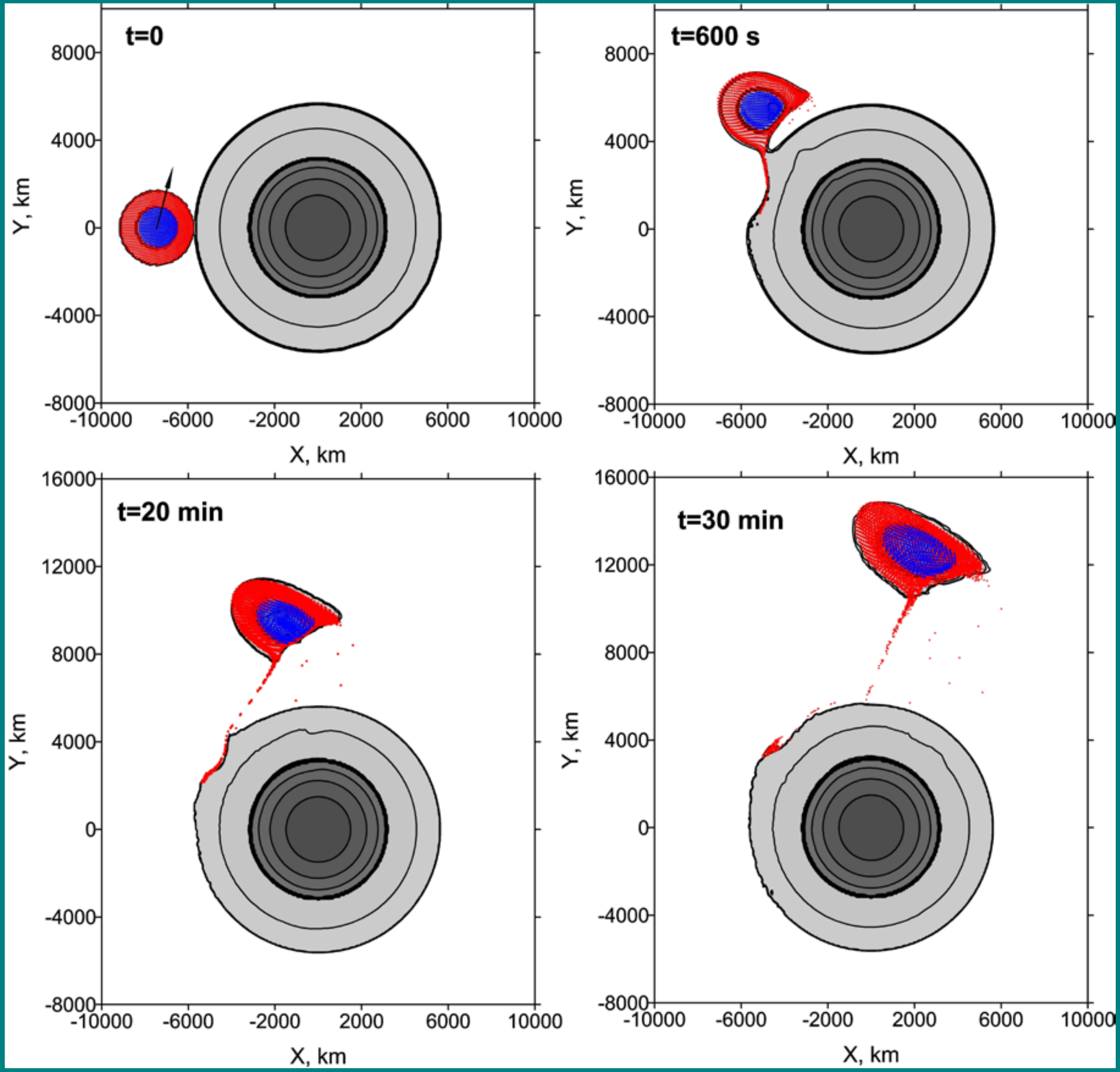
$$d = \frac{2K_{Ic}^2\hat{E}}{\rho c^2 \sigma_{\max}^2}, \quad \hat{E} = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$$

K_{Ic} is fracture toughness, c is elastic wave speed, $\sigma_{\max}$ is fracture strength, E is Young's modulus, ν is Poisson's ratio

Input parameters

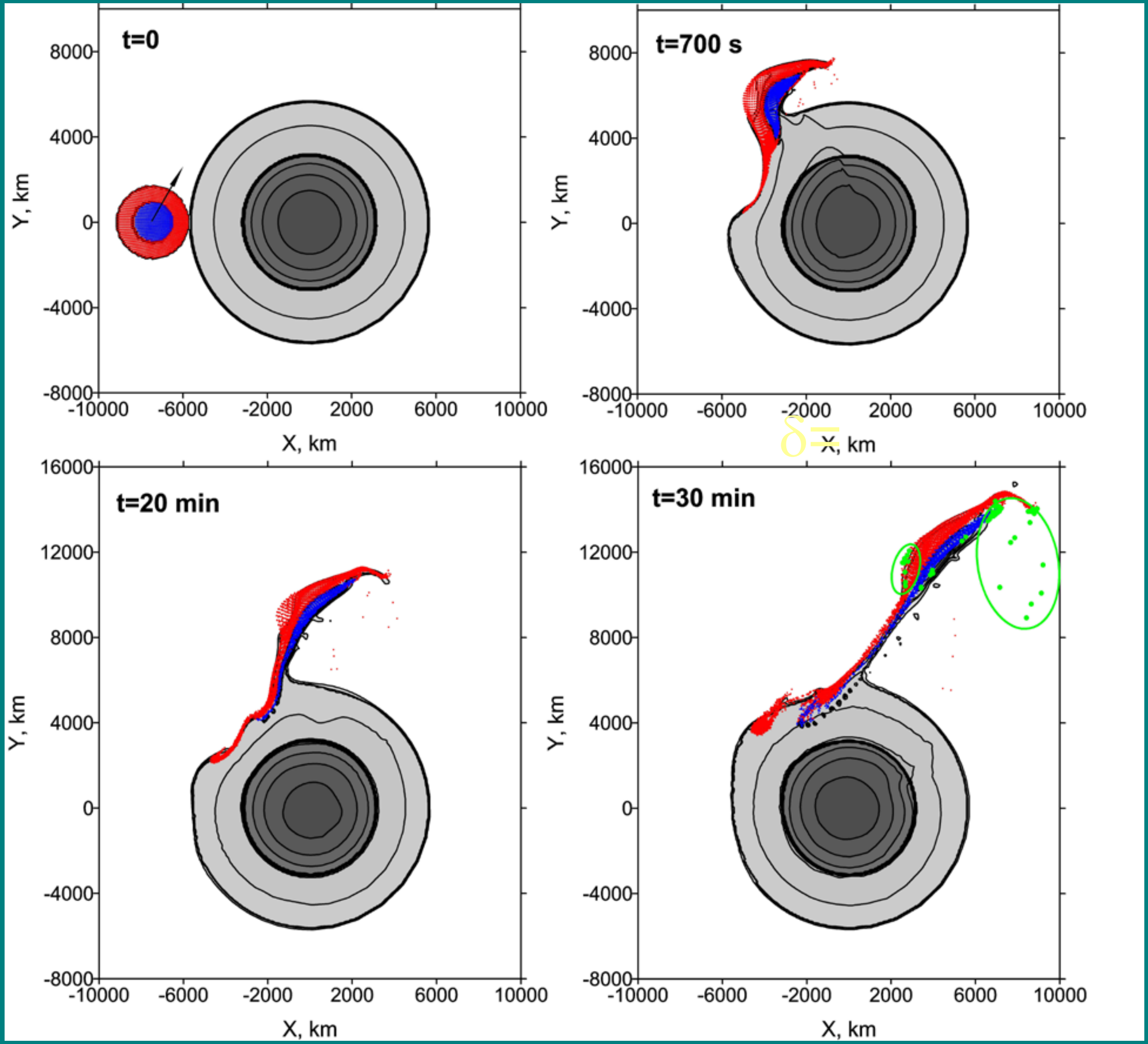
- Sizes of impactors – ratios of diameters to the Earth diameter $\delta < 0.3$
- Impact velocities – V_{inf}=5 km/s
- Impact angles – all
- Composition of impactors – differentiated with iron cores similar to the Earth (~0.3 by mass)
- Earth diameters > 0.5 of the modern diameter (0.7 for most runs)

Impact angle 75º, projectile relative diameter δ=0.3



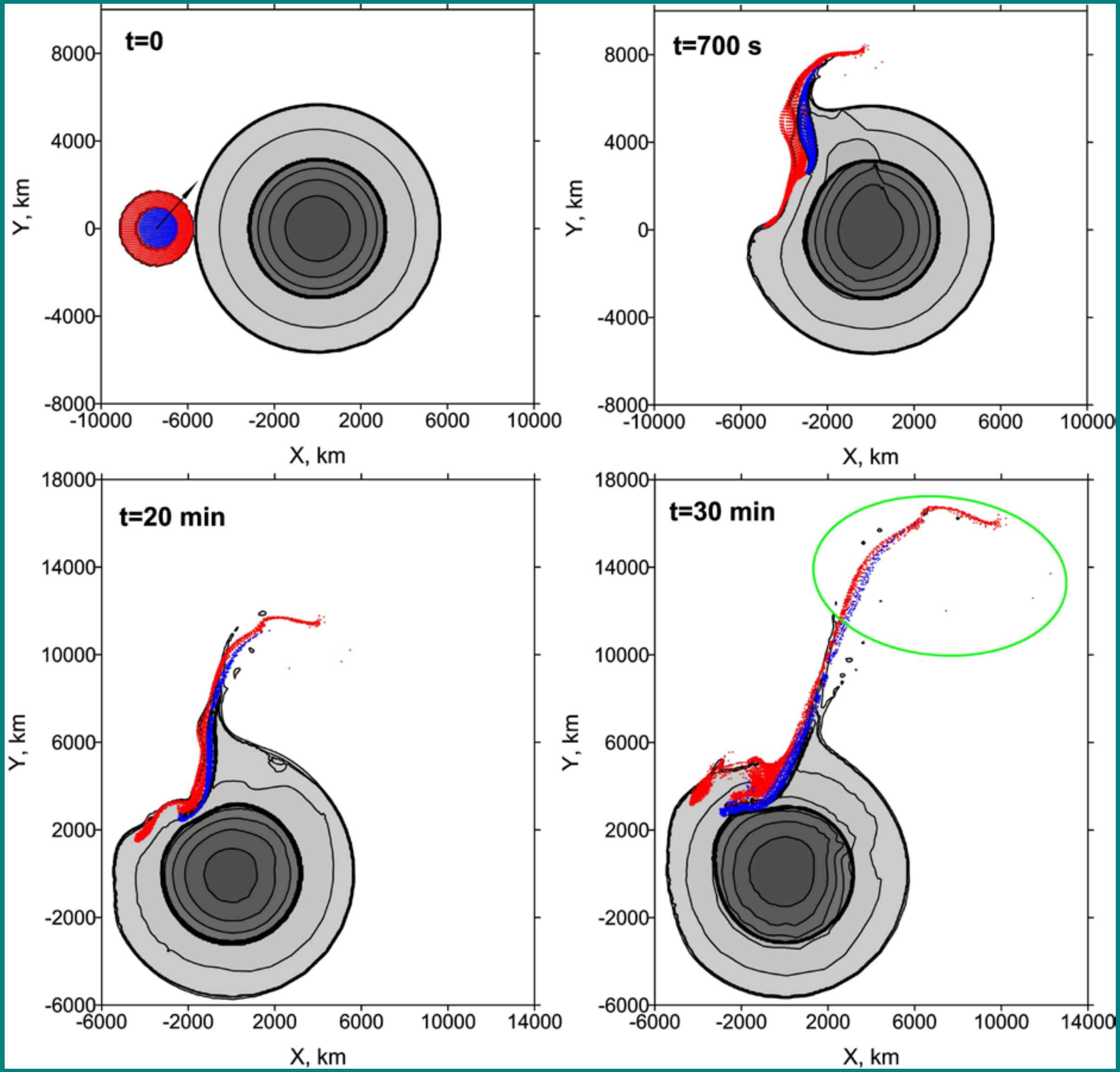
- Projectile is broken but remains mainly coherent.
- The crater is relatively small.
- Escaped dispersed material is about 1% of projectile mass.

Impact angle 60º, projectile relative diameter δ=0.3



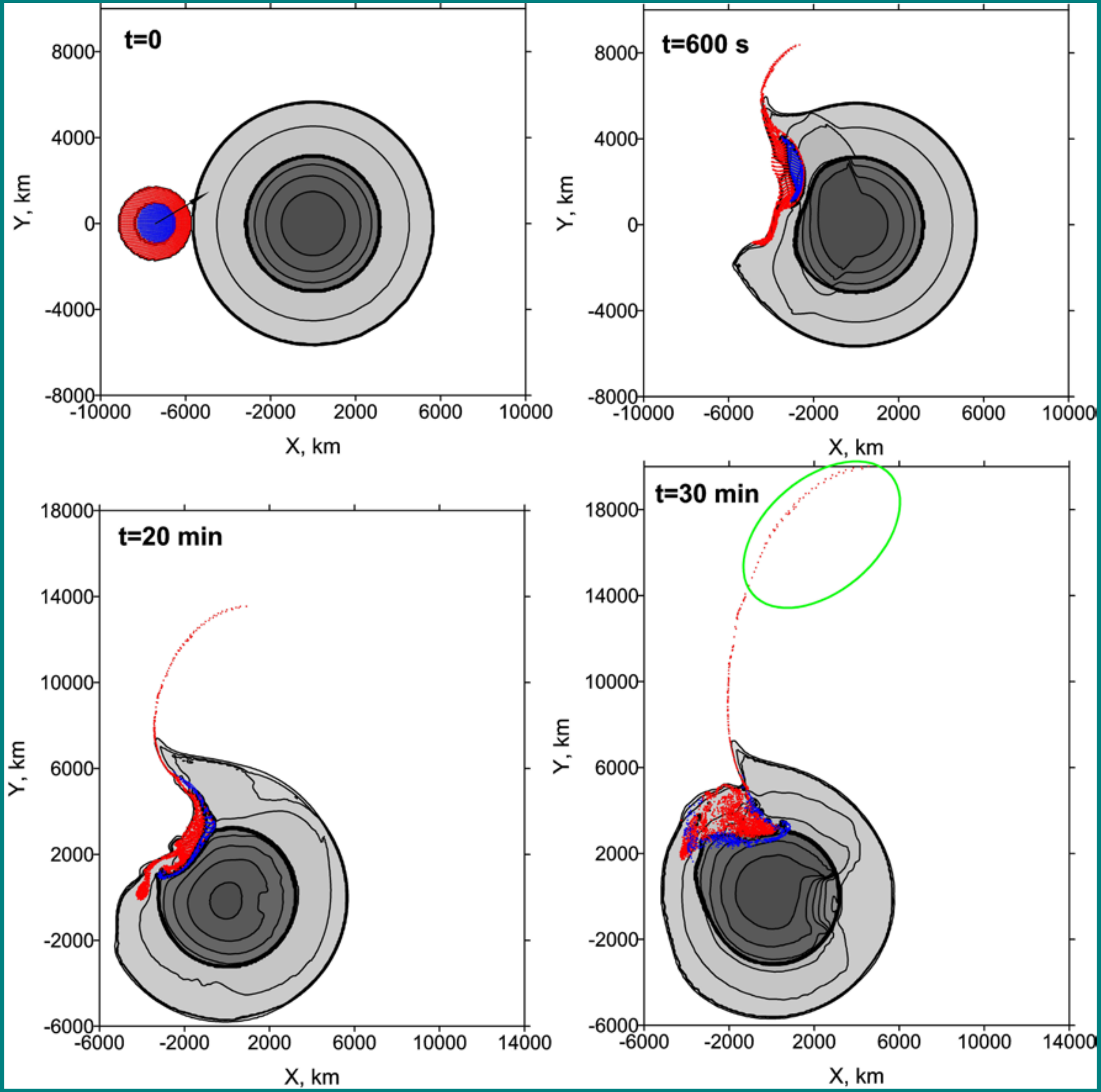
- Projectile is partly destroyed but substantially reaccumulates later.
- Large crater
- Escaped dispersed material is about 8.5% of projectile mass.

Impact angle 50º, projectile relative diameter δ=0.3



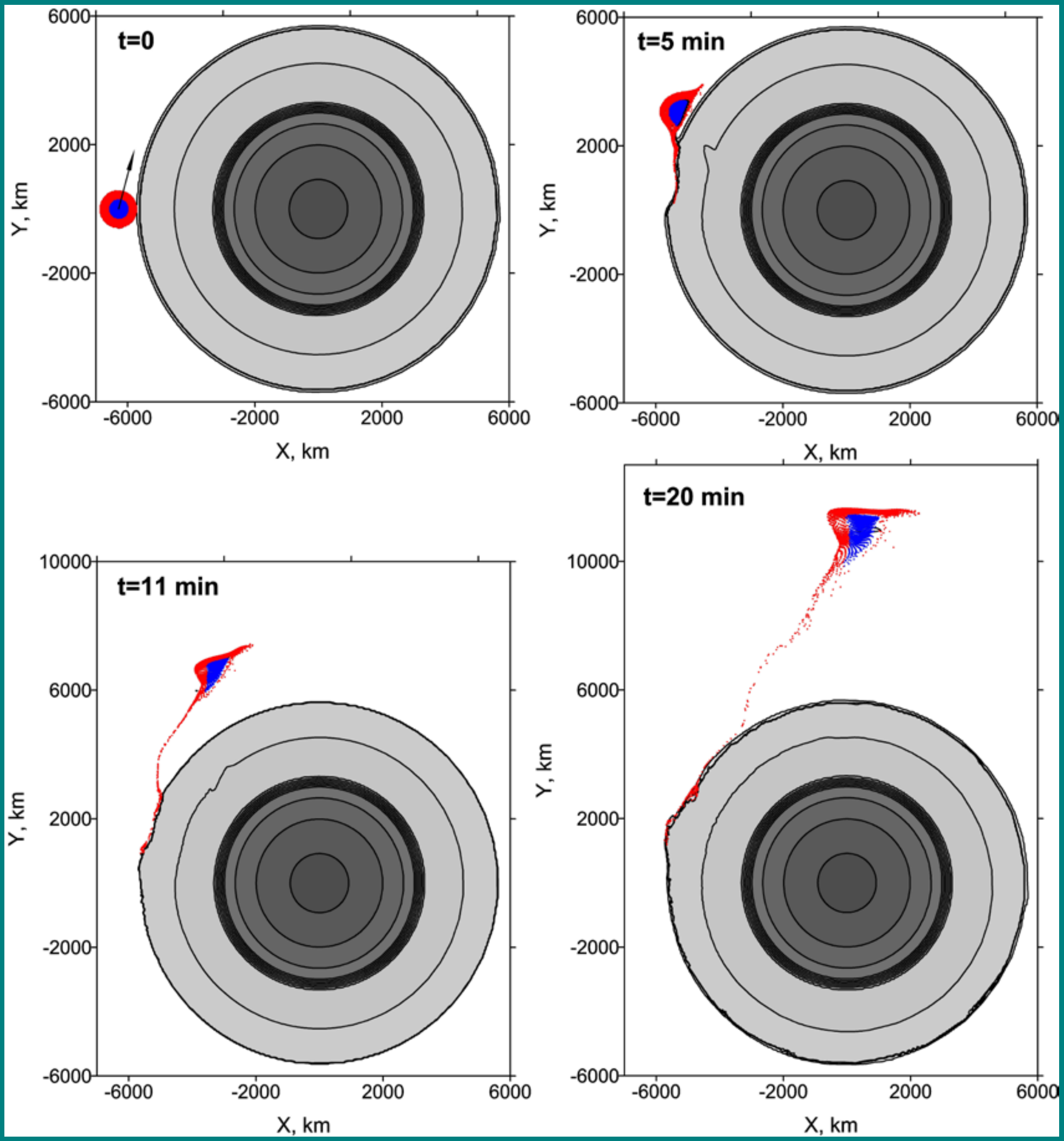
- Projectile is completely destroyed
- Very large crater
- Escaped dispersed material is about 15% of projectile mass.

Impact angle 30º, projectile relative diameter $\delta = 0.3$



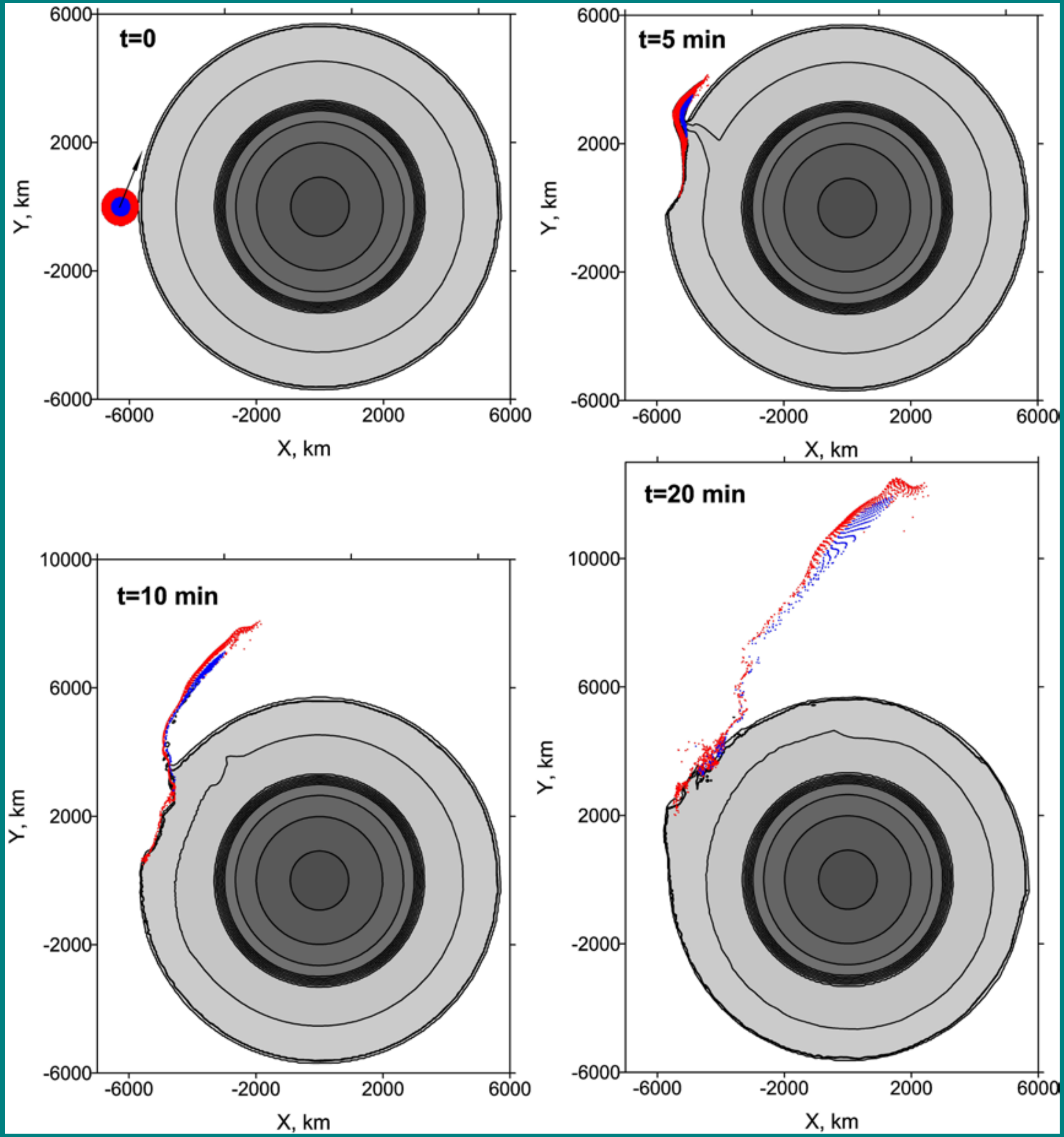
- Projectile melts and remains inside the crater.
- Huge crater
- Escaped material is about 7% of projectile mass.

Impact angle 75º, projectile relative diameter δ= 0.1



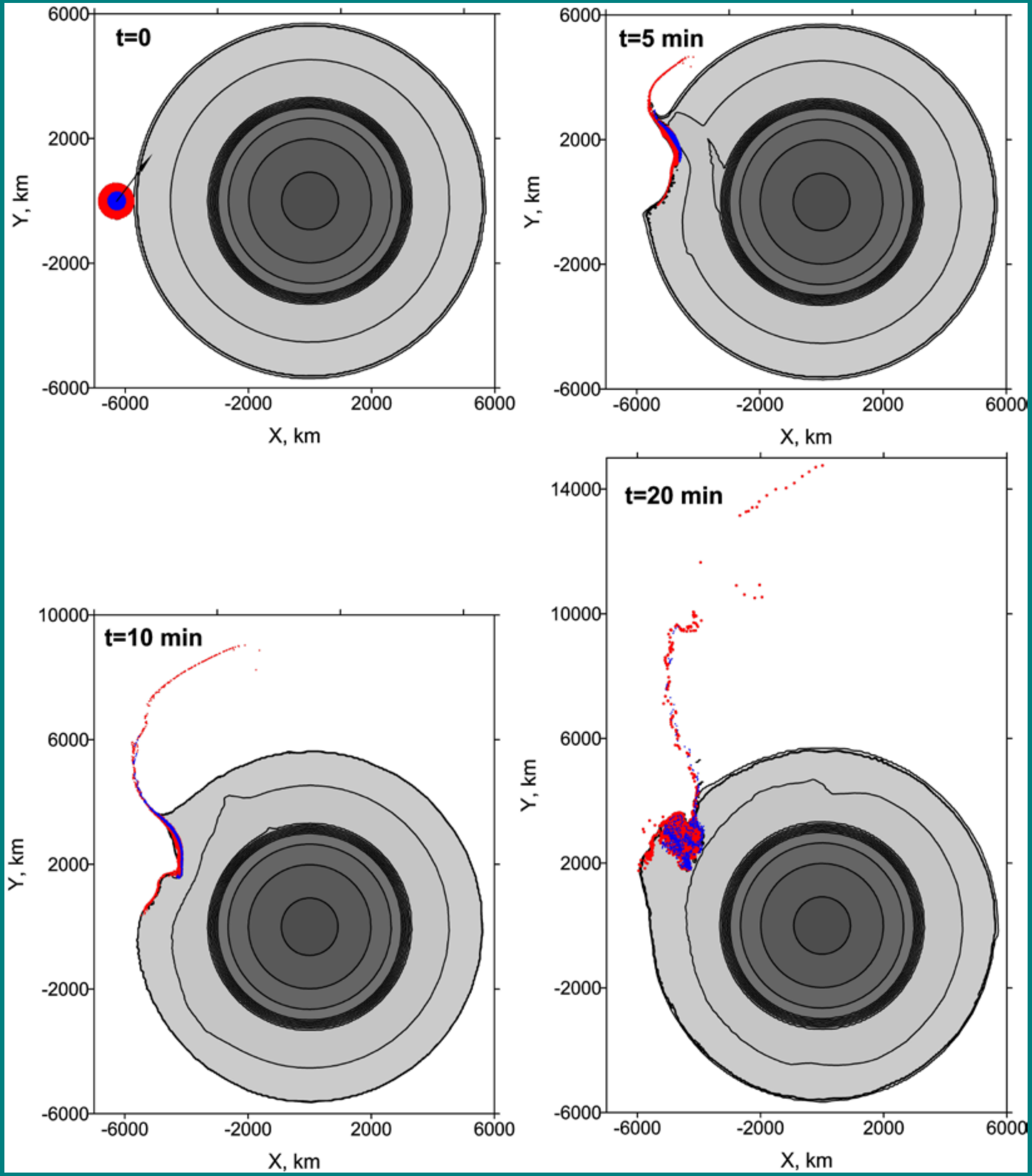
- Projectile is destroyed but remains mainly coherent.
- The crater is small.
- Escaped dispersed material is about 15% of projectile mass.

Impact angle 67º, projectile relative diameter δ= 0.1



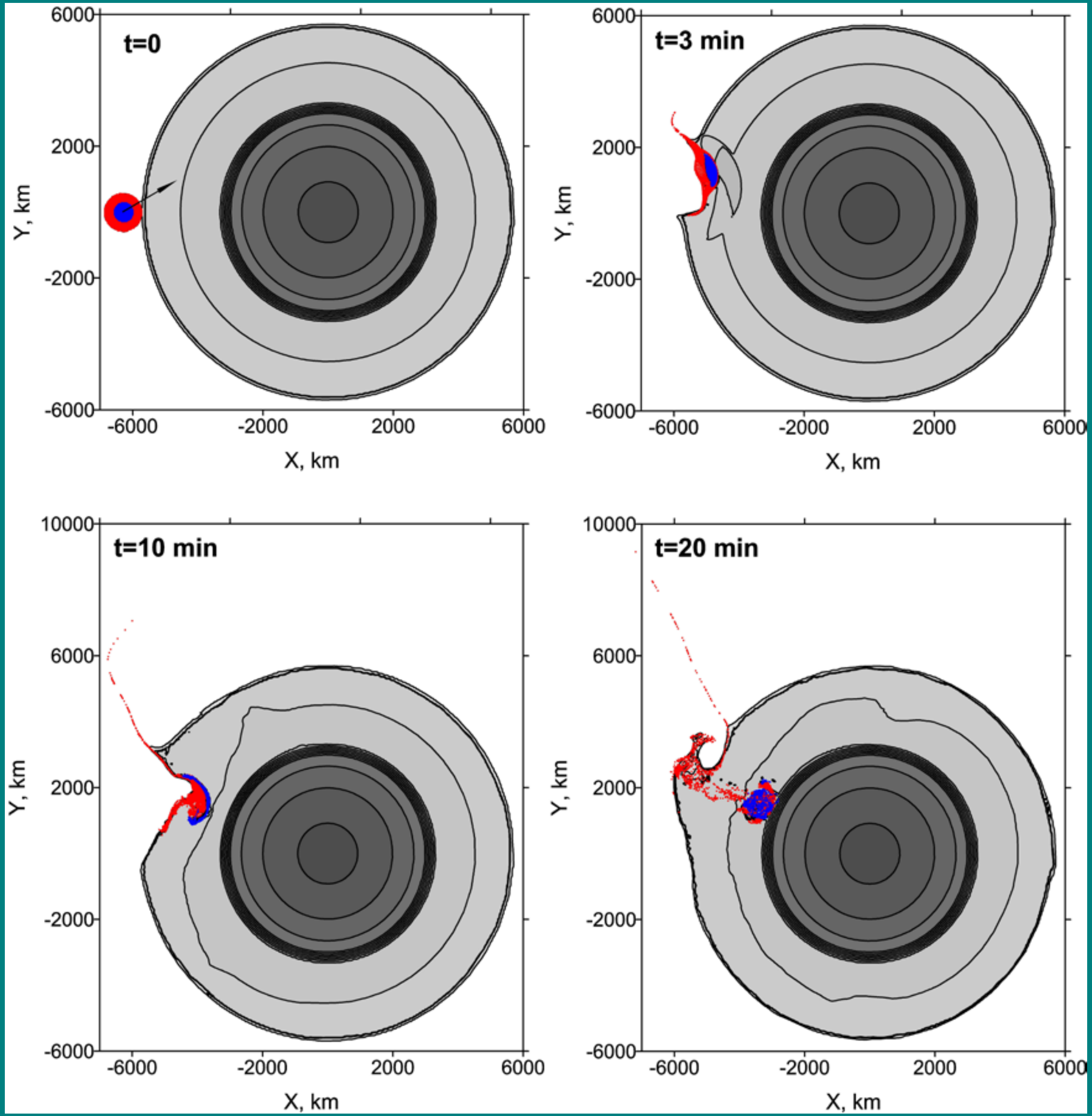
- Projectile is completely destroyed.
- The crater is relatively small.
- Escaped dispersed material is about 50% of projectile mass.

Impact angle 53º, projectile relative diameter δ= 0.1



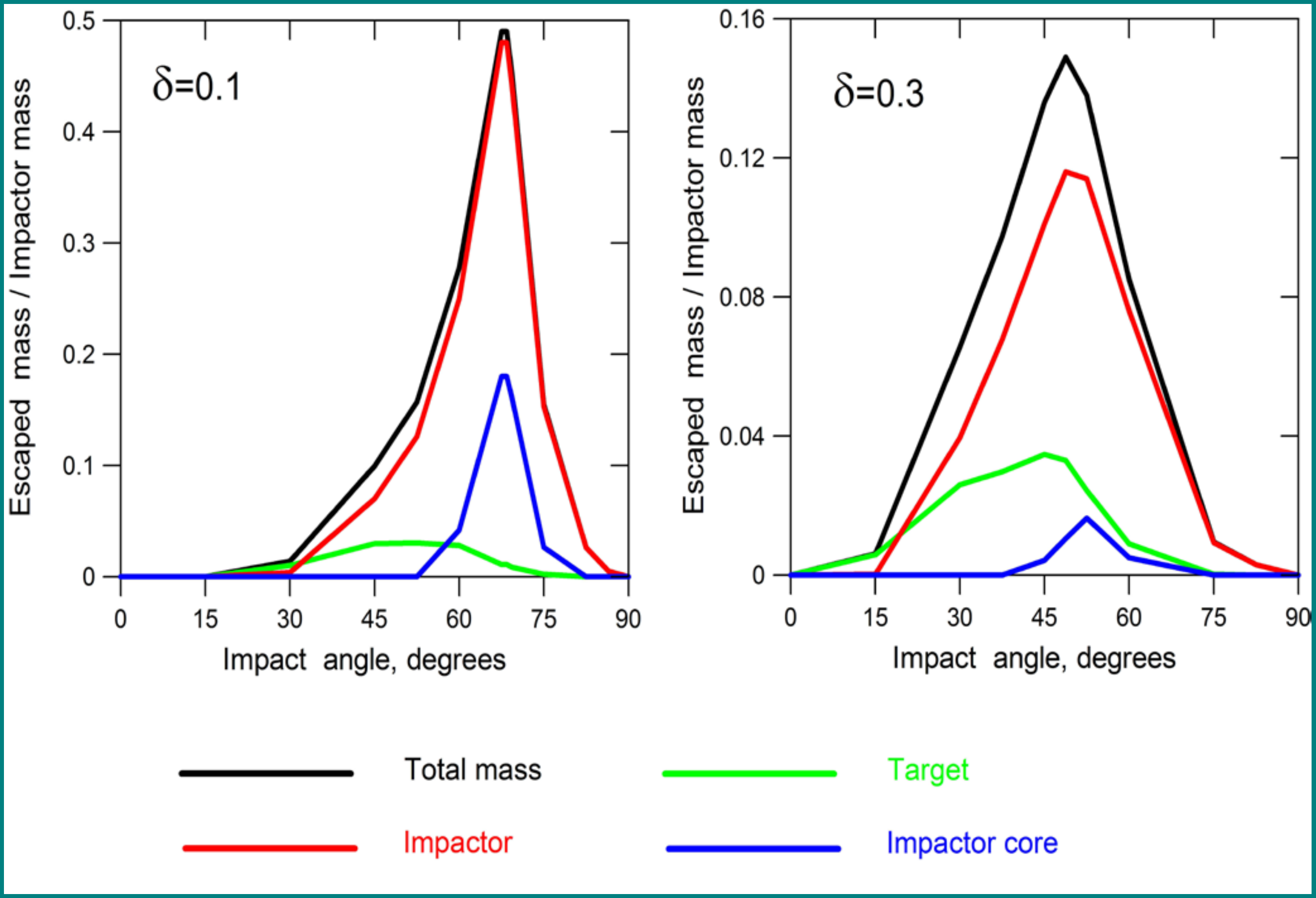
- Projectile remains inside the crater.
- Relatively large crater.
- Escaped material is about 15% of projectile mass.

Impact angle 30º, projectile relative diameter δ= 0.1

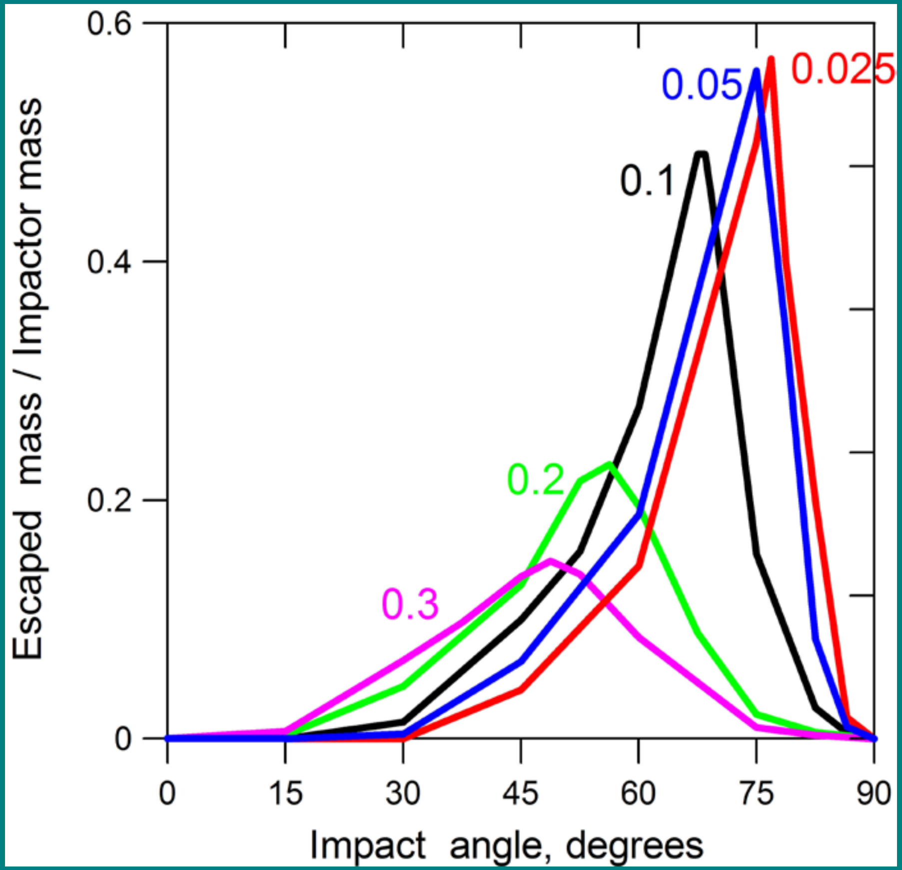


- Projectile penetrates inside the Earth
- Large crater.
- Escaped material is about 1% of projectile mass.

Relative mass of particles escaped to heliocentric orbits as a function of impact angles for two relative impactor diameters δ



Escaped dispersed mass

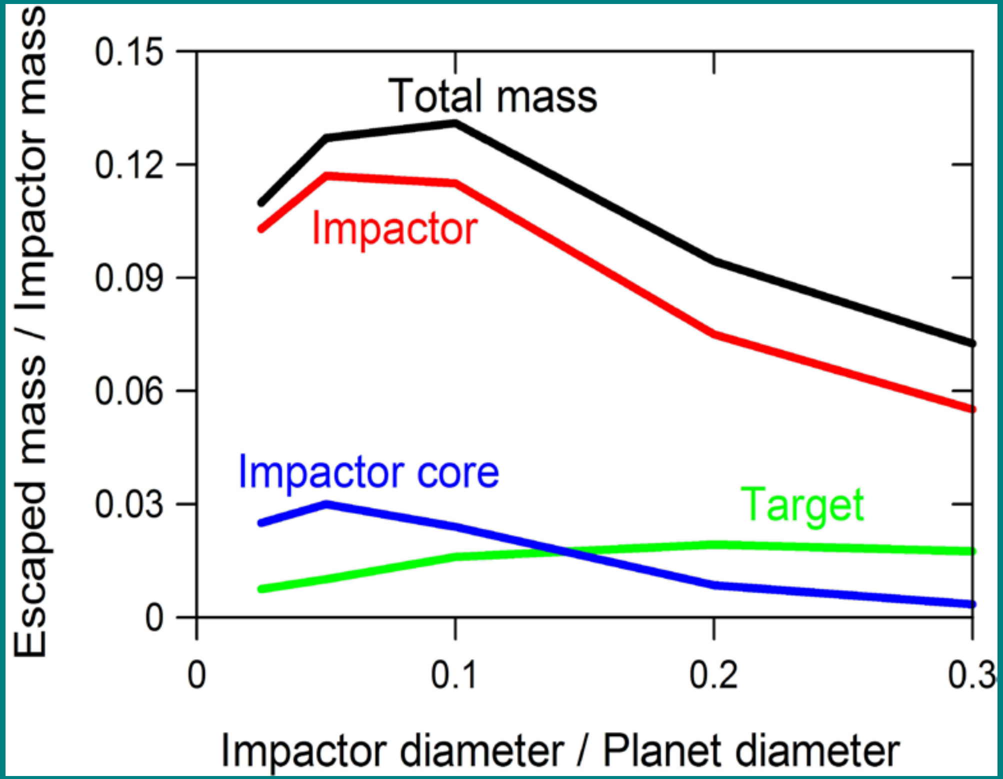


Relative total mass of particles escaped to heliocentric orbits as a function of impact angles.

Ratio of impactor diameter to planet diameter δ is indicated at the curves.

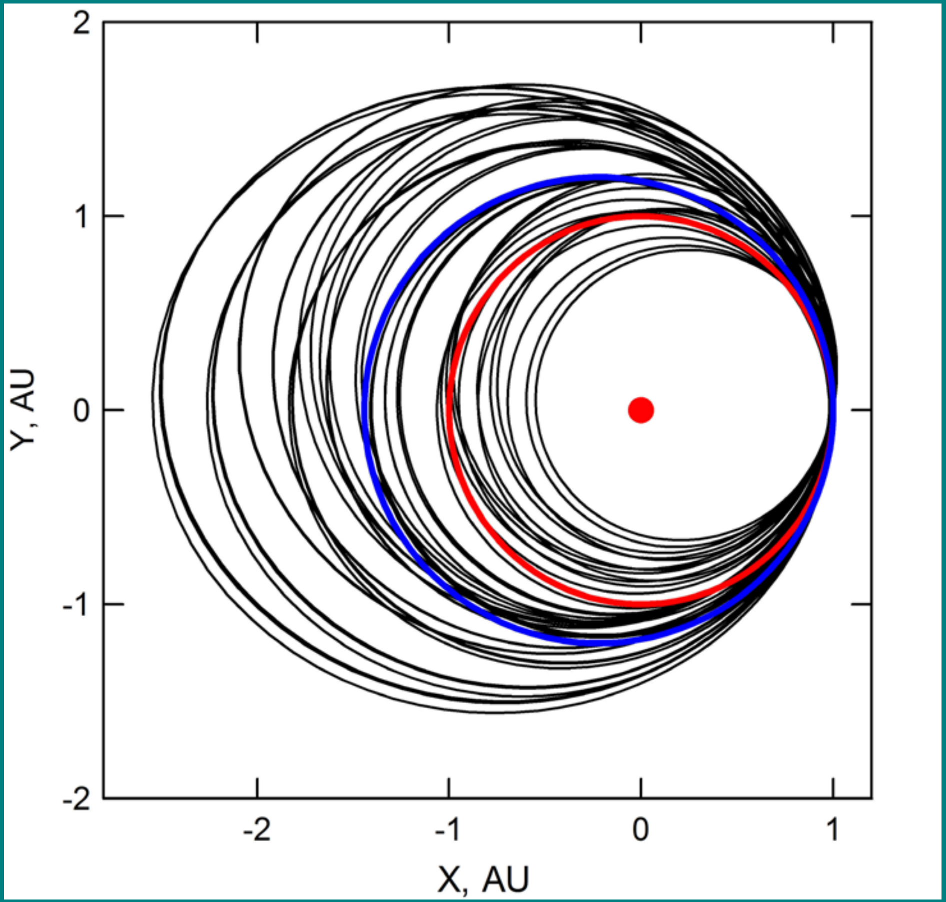
Averaging over impact angles

Averaged relative total mass of particles escaped to heliocentric orbits as a function of relative impactor diameter δ



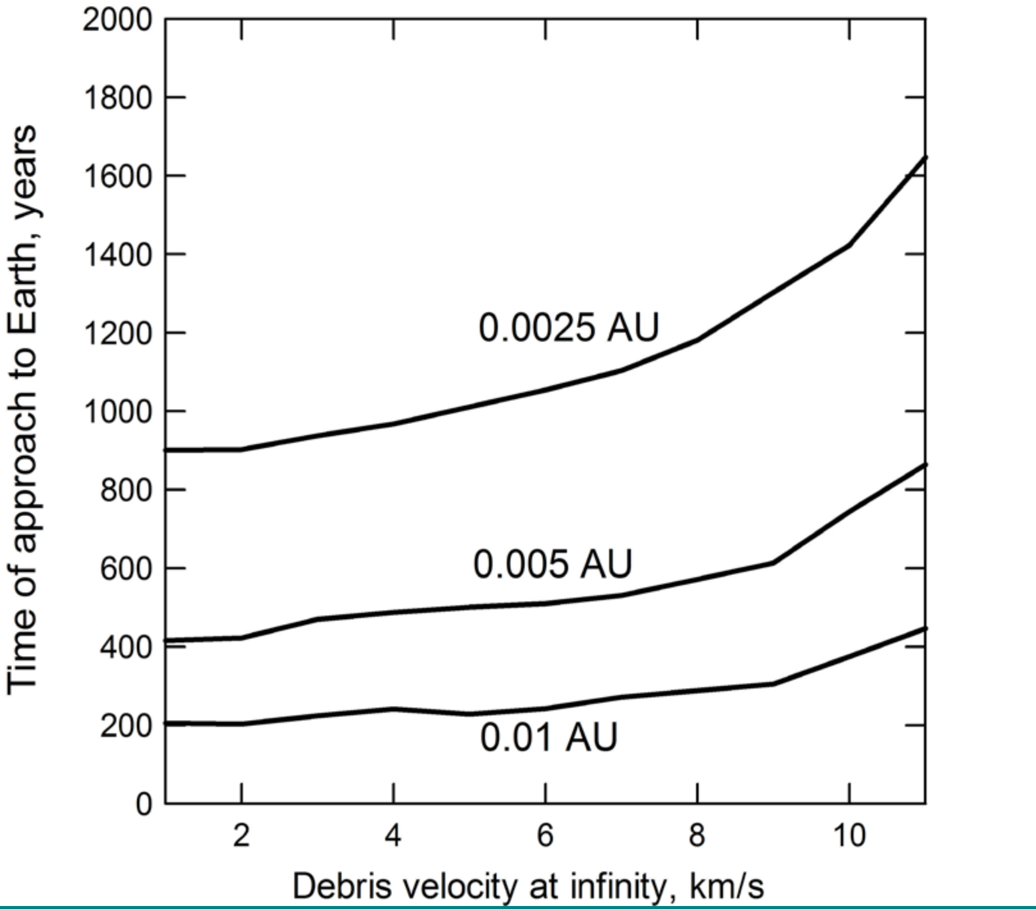
Heliocentric orbits of debris (shown for V_{inf} = 5 km/s)

- If particles leave the Earth at various angles, they move along heliocentric orbits which intersect the Earth orbit.
- Calculations of particle motion around the Sun determine the time when particles enter the Hill sphere of the Earth again.



Time of reentry into Hill sphere (R_H=0.01 AU) and smaller ones (0.005 and 0.0025 AU)

- Time of reentry into Hill sphere (R_H=0.01 AU) averaged over angles is about 200 years.
- Simulations give sizes of debris from 10 cm to 10 m.
- Yarkovsky's effect and Poynting-Robertson drag lead to substantial drift (~0.01 AU) during about 1 My.



Conclusions

- A mass of debris sufficient for Moon formation is ejected to heliocentric orbits after large impacts on the growing Earth.
- The sizes of particles are from 10 cm to 10 m.
- The ejected particles intersect the Hill sphere of the Earth once several hundred years.
- The mass of iron particles is from 5% to 20% of the total mass of debris (for δ from 0.3 to 0.05).

Tasks for the future

- How do the fragments escaped after the impacts interact with the circumterrestrial swarm?

- How does the mass of the swarm evolve? Does the prelunar swarm grow or not?

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