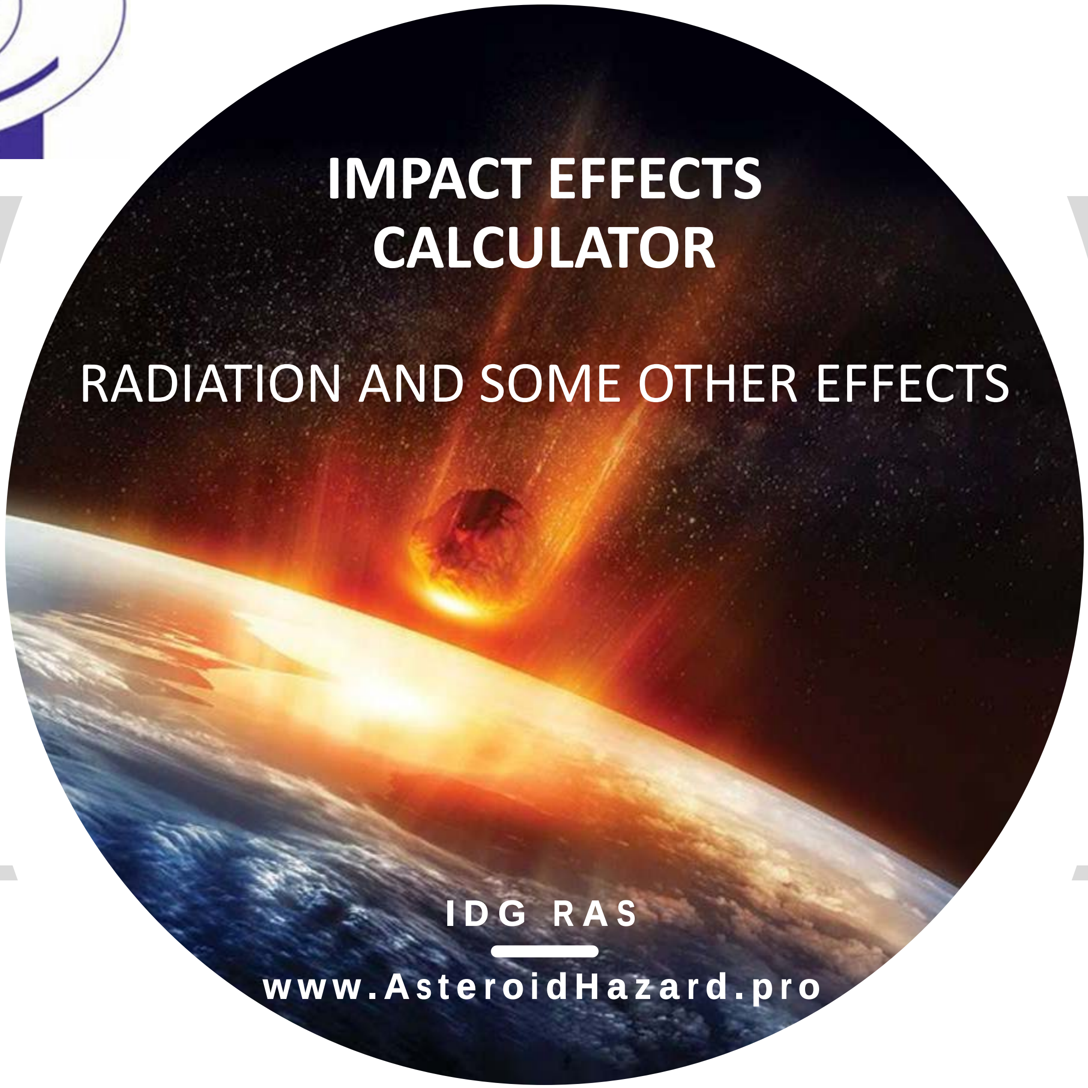

Olga Popova
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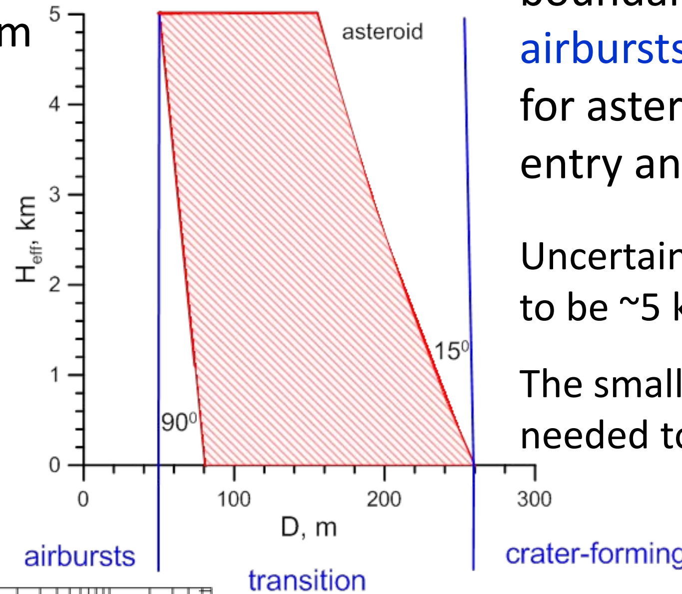
IAA PLANETARY DEFENSE CONFERENCE 2021
26-30 APRIL 2021

TYPE OF IMPACT

Asteroids and cometary objects from 20 m to 3 km in diameter were considered

Entry angles - from 15° to 90°;
Entry velocity - from 15 to 70 km/s

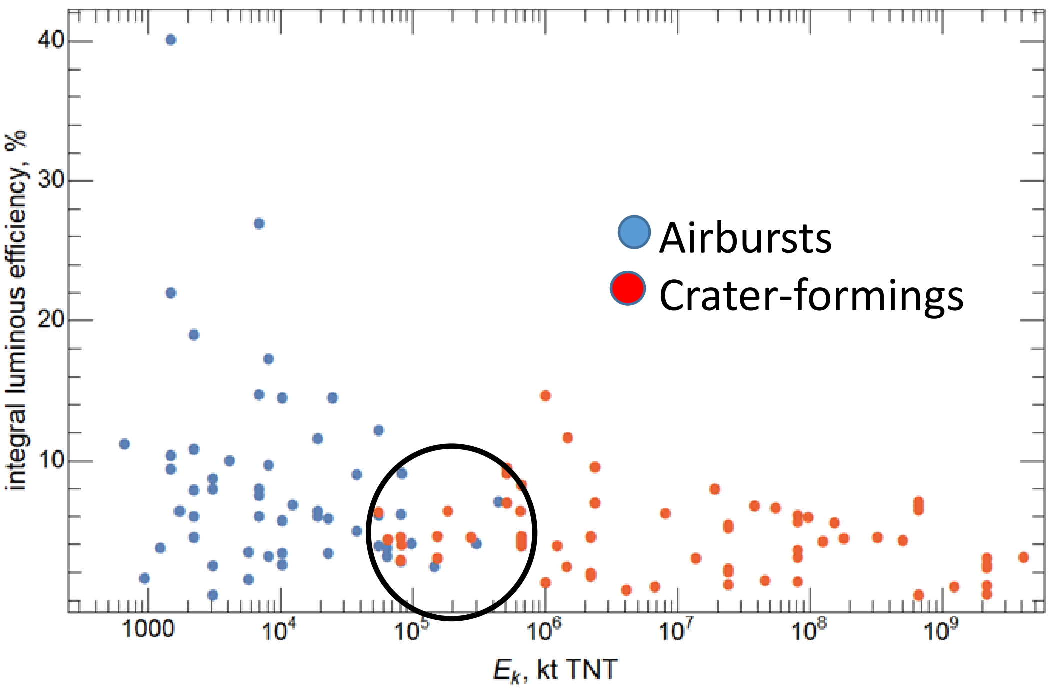
Total 122 cases:
56 airbursts, 66 crater-forming (including transitional)



boundaries
airbursts - crater-formings
for asteroids with uncertain entry angle ~15-90^0

Uncertainty in Heff is assumed to be ~5 km

The smaller α the larger D is needed to create a crater



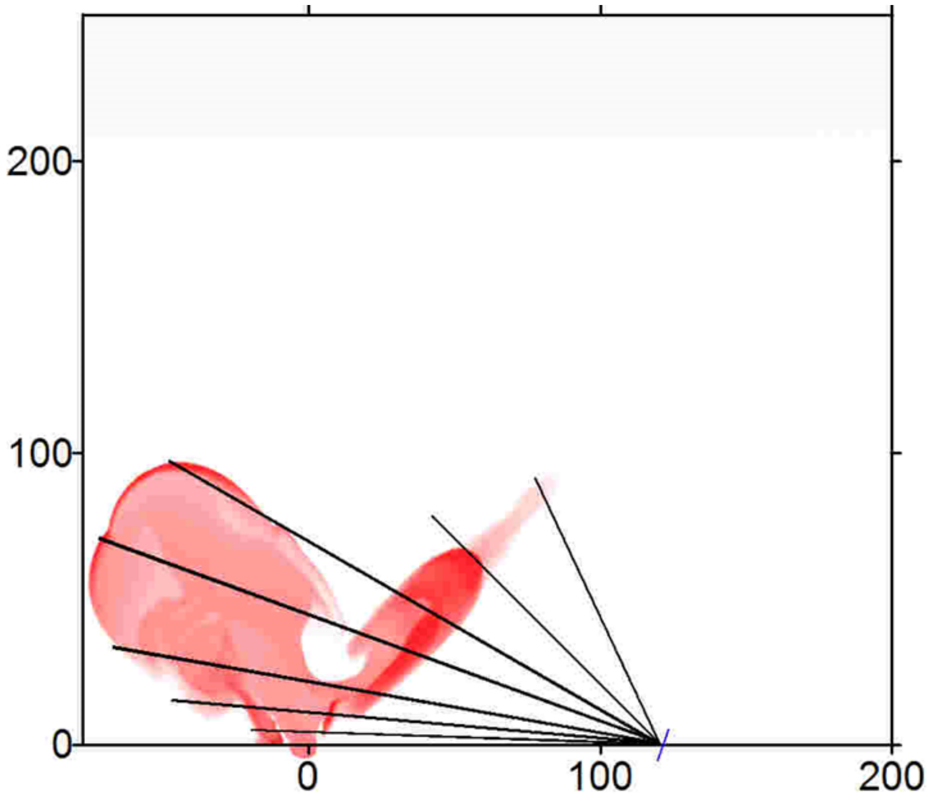
Transition sizes for asteroids:
~60 – 250 m
based on Heff ~ f(α)

Kinetic energy range
~3 10^4 – 5 10^5 kt TNT
based on serial simulations

2021 PDC probable impactor: asteroid, V~15 km/s D~35 - 700 m, α~3-90^0

Can be both an airbust and crater-forming

RADIATION FLUXES AND THERMAL EXPOSURE ON THE GROUND



The equation of radiative transfer

$$\frac{dI_\varepsilon}{ds} + k_\varepsilon I_\varepsilon = k_\varepsilon B_\varepsilon$$

is solved along rays crossing the heated volume of air and vapor.

The total radiation intensity on the surface for a given angle of a ray is obtained by summing the intensities of radiation over photon energies.

Radiative flux density in a given point on the Earth's surface is calculated by integrating the radiation intensity, multiplied by the cosine of the angle between the ray and the normal to the irradiated surface, over all angles.

The integration of the flux over time allows us to determine radiant exposure (radiation energy received by a surface per unit area).

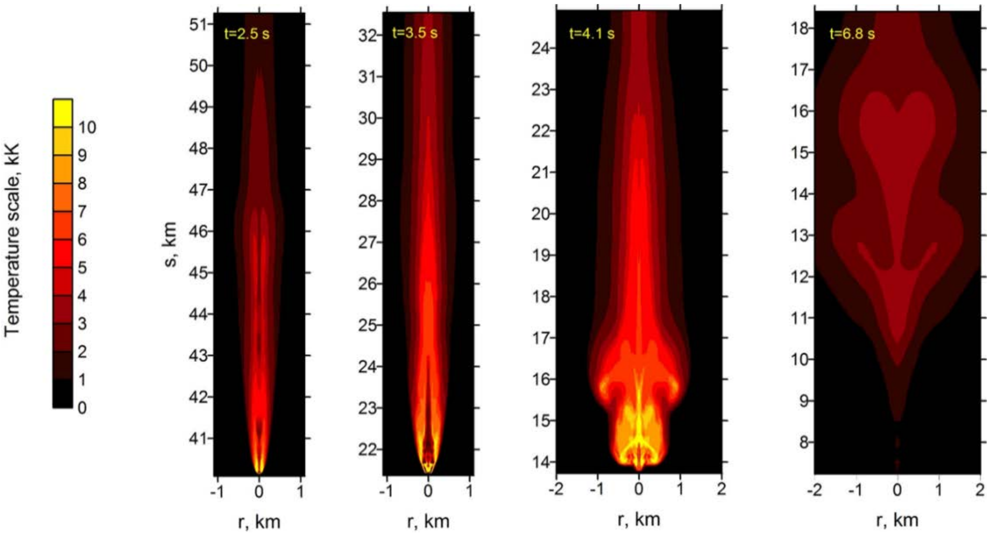
Thermal radiation – one of the main dangerous consequences of cosmic object impacts.

Direct thermal radiation from fireballs and impact plumes poses a great danger to people, animals, plants, and economic objects.

THERMAL EXPOSURE ON THE GROUND

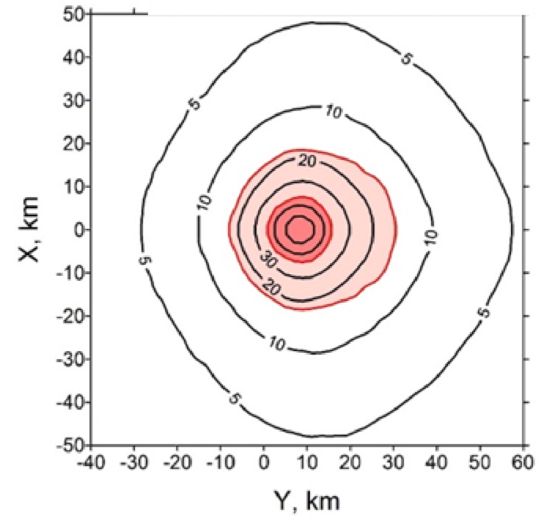
Airburst - bolide radiation

50 m, asteroid, 20 km/s, 45^0, *Svetsov&Shuvalov 2018*

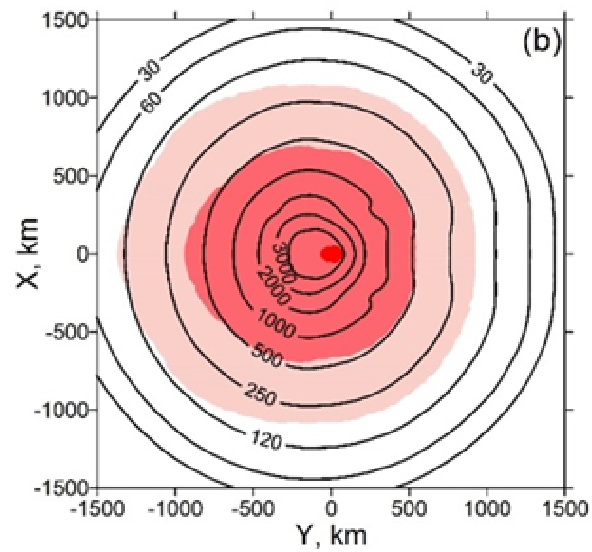


Ignition of dry leaves litter

Ignition of pine wood



Thermal exposure, J/cm^2



Ignition of dry leaves litter

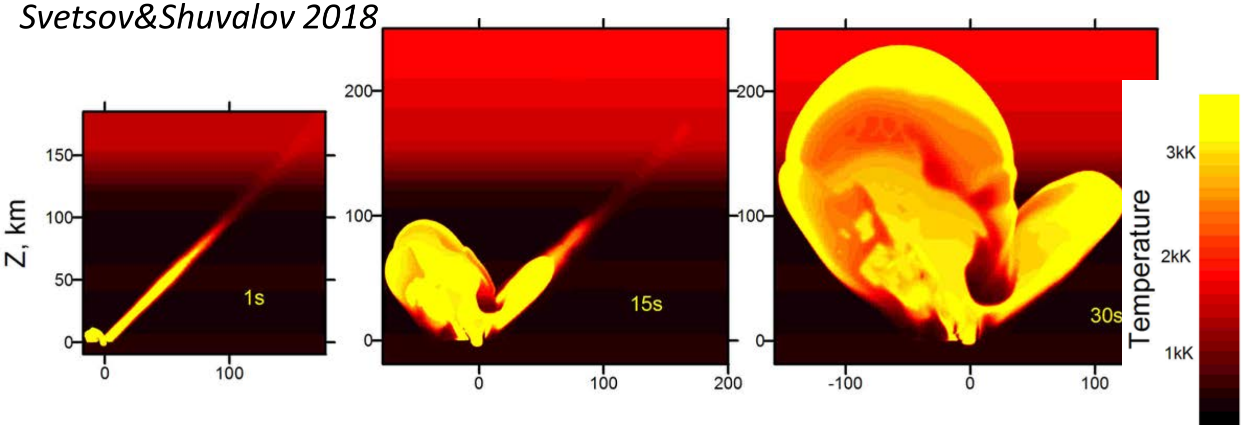
Ignition of pine wood

Melting of quartz (1 cm thick)

Crater-forming - plume radiation

1 km, asteroid, 20 km/s, 45^0

Svetsov&Shuvalov 2018



In dependence on impact scenario the thermal radiation is produced by fireball or/and impact plumes.

SCALING RELATION FOR THERMAL EXPOSURE

Analyzes of serial simulations permit to suggest **scaling relations (SC)**,
- allow us to estimate radiation field on the surface based only on impactor properties (D,V,α, ρ)

To describe the thermal exposure Q [J/cm^2] the point source approximation, corrected on spatial heterogeneity is suggested:

$$Q = 4.184 \cdot 10^{12} \cdot \frac{1}{4\pi} \cdot \frac{\eta}{100} \cdot \frac{E_{kt}}{10^{10}\left(H_{rad}^2 + x^2 + el \cdot y^2\right)}$$

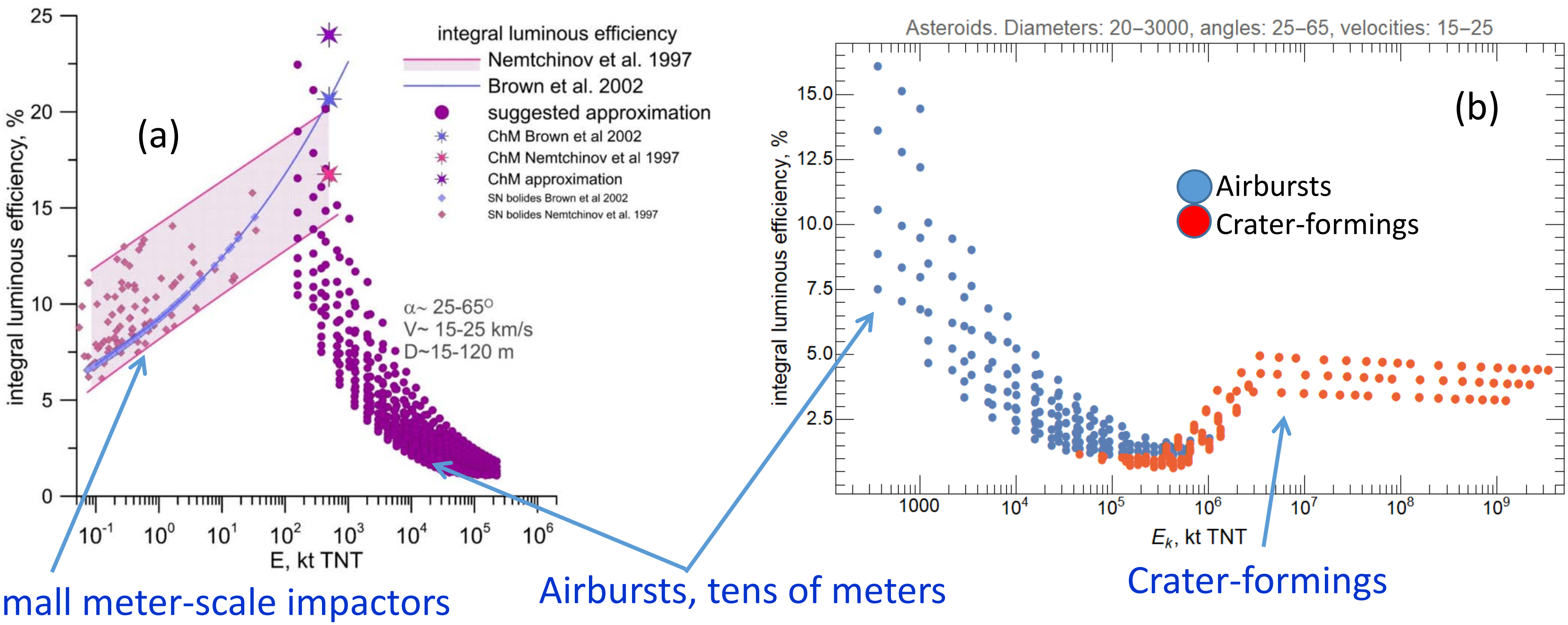
x,y – spatial coordinates (km) (point of origin is under point of maximal thermal effect) ,
H_{rad}- radiative altitude (km), el - ellipticity parameter, E_{kt} – kinetic energy of impactor in kt TNT
η – integral luminous efficiency in %

The thermal exposure value of 10 J/cm^2 roughly corresponds to the first degree burn.
The value of about 500 J/cm^2 essentially exceeds the amount needed to ignite most materials
(Glasstone&Dolan 1977)

Scaling relation (SC) for Q was aimed to be applicable in the range 10-500 J/cm^2

INTEGRAL LUMINOUS EFFICIENCY

η – the fraction of the impactor kinetic energy, which is converted into the radiation

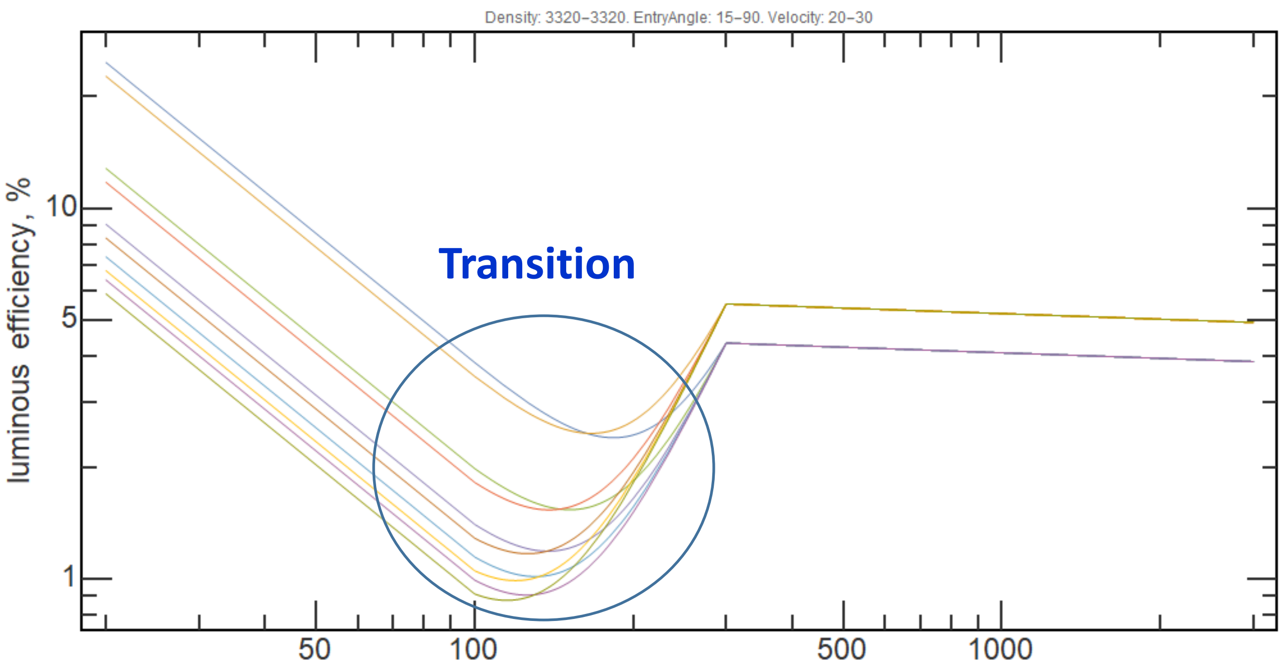


η for asteroids of different sizes entering at α~25-65° with V~15-25 km/s obtained based on SC
(a) is compared with η for meter-scale meteoroids (b); is extended to larger energies

(a) η is increasing with size up to ~20% at E~500 -1000 kt and is decreasing for large objects. This decrease is probably connected with an increase of the optical thickness of the emitting region, which leads to radiation losses mainly from its surface.
(b) Minimal efficiency is obtained for transition between airbusts-crater-formings, probably connected with change of the main input from bolide to the rarefied plume. Need to be clarified further.

SCALING RELATION FOR INTEGRAL LUMINOUS EFFICIENCY

η – the fraction of the impactor kinetic energy, which is converted into the radiation



Integral luminous efficiency for asteroids V~20-30 km/s α~15-90^0 based on SC

Crater-formings:

$$\eta_{crater} = \frac{0.021 \cdot D^{1.3} \cdot v^{1.5}}{E_{kt}^{0.45}}$$

Airbusts:

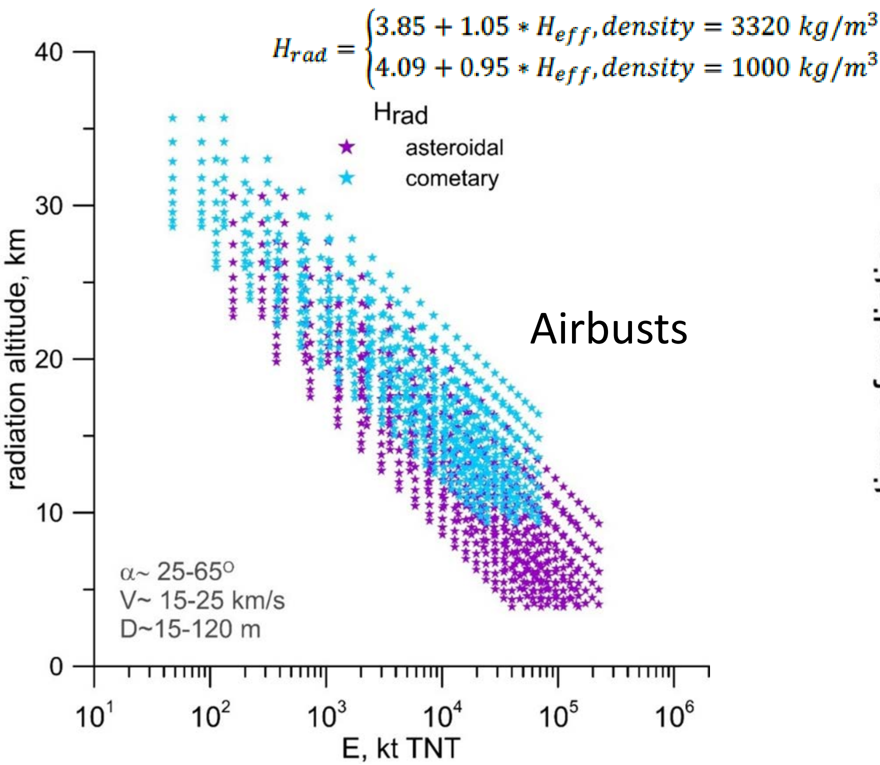
$$\eta_{airbust} = \begin{cases} 100 \cdot \frac{10939 \cdot v^{0.56}}{E_{kt} \cdot Sin\alpha}, \rho = 3320\ kg/m^3 \\ 100 \cdot \frac{1225 \cdot v^{0.39}}{E_{kt}^{0.3} \cdot Sin\alpha}, \rho = 1000\ kg/m^3 \end{cases}$$

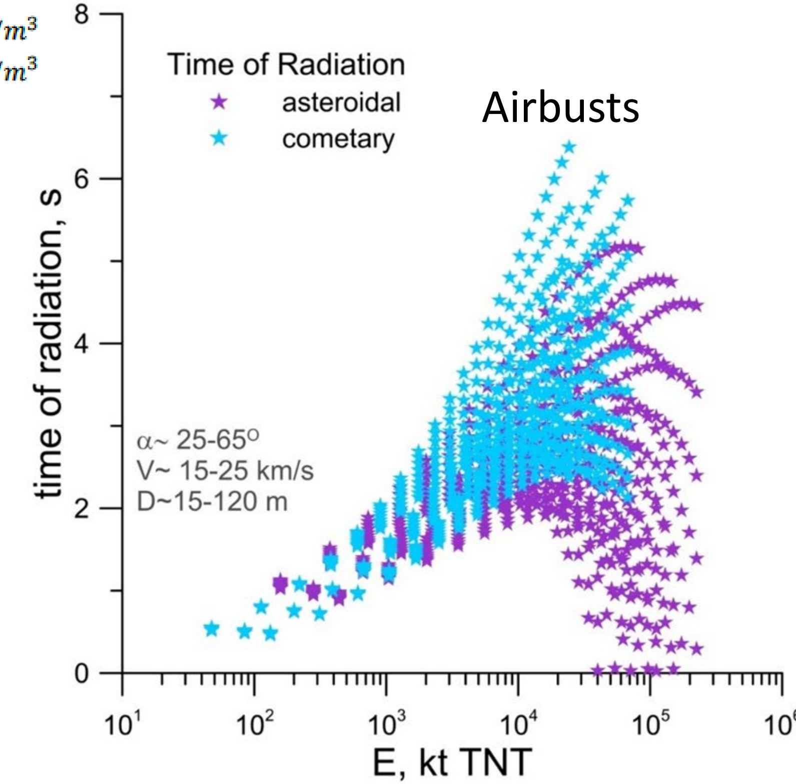
for any other density of the impactor - line interpolation by density is working well

Transition : conventional division by impactor diameter, if D ≤ 100-150 m AB values are used, if D ≥ 300 m CF values are applied, inbetween the linear interpolation by E_{kt} is used

Real dependence of η on V, α etc is quite complicated, but nevertheless suggested SC provides satisfactory agreement with modeling results with precision about 2 times.

RADIATIVE ALTITUDE AND TIME





(a) H_{rad} in dependence on E_{kt} based on SC (b) The characteristic time of radiation (80% of total thermal exposure is irradiated)

Airbursts radiation can be represented as radiation of the source at H_{rad} (from 20–30 to several km) with spatial heterogeneity and duration ~1-4 s.

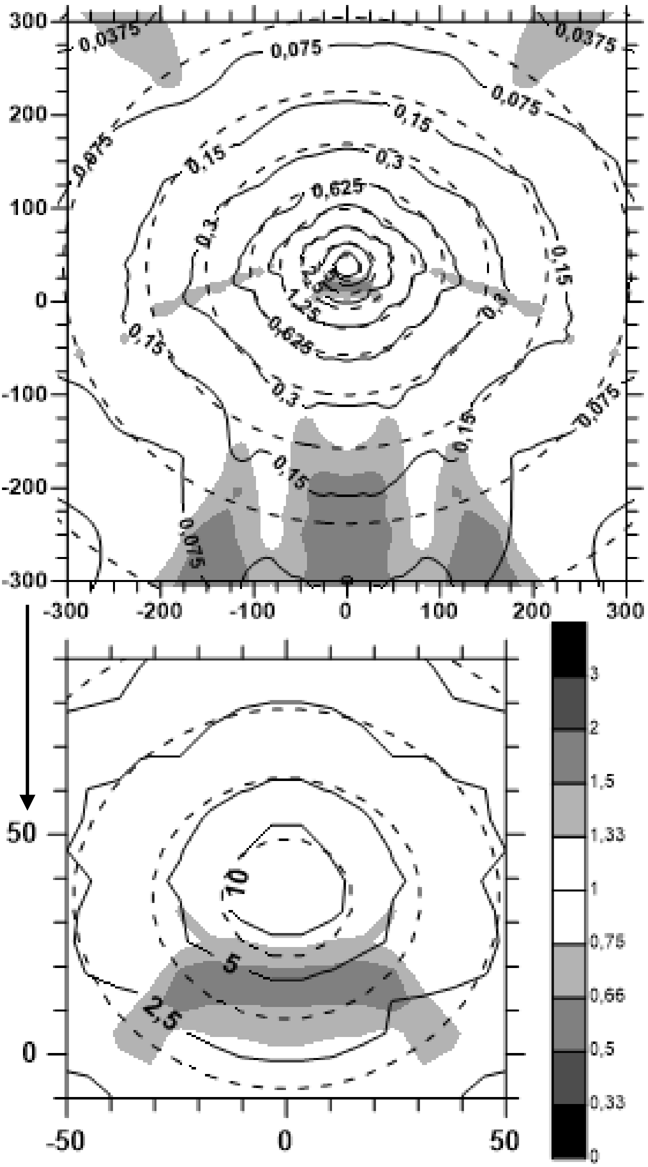
$H_{rad} > H_{eff}$ and maximal thermal effect is shifted relatively the overpressure maximum.

H_{rad} for **crater-formings** is an adjustable parameter, is not the effective source height, affects Q only in the central zone, where Q has a complex structure (due to the complex nature of the flow, propagation, interaction and mixing of emissions from the crater with the atmosphere).

H_{rad} is fixed as 100 km for large impacts.

AIRBURST THERMAL EXPOSURE BASED ON SC

comet, D=30 m, $\alpha=45^0$, V=20 km/s



Ellipticity ***el*** allows to take into account the spatial inhomogeneity of the radiation field; ***el***=f(E_{kt}, α, H_{eff}).

Ingomogenity is more evident forward along the trajectory (after the epicenter)

Q (values are shown on contours, J/cm^2) obtained in the numerical simulations – solid lines.

Dashed – Q based on SC, Q_sc

Gray - the ratio of Q_sc/Q

Bottom panel - central part on a larger scale.

Suggested scaling relations allow us to estimate thermal exposure and radiative flux distributions based on the impactor parameters with uncertainty of about two times.

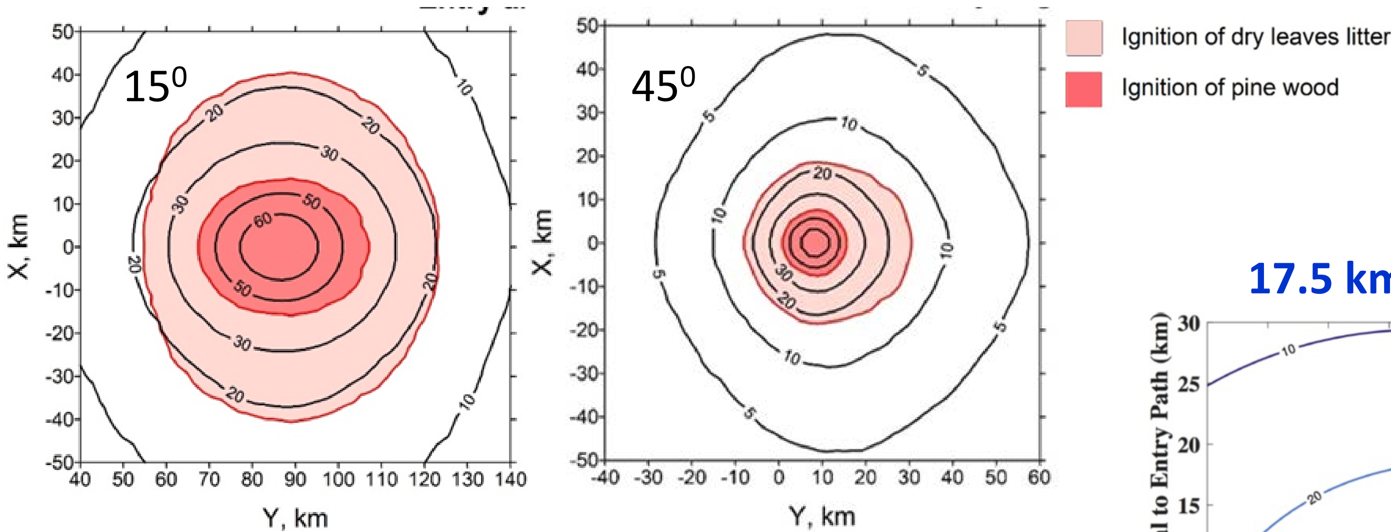
Trajectory is top – bottom

Axes origin – trajectory intersection with ground (no deceleration)

TUNGUSKA THERMAL RADIATION

Data to fit – area of burn trees, visible charring - at 40 J/cm^2 (Svetsov 1996)

Impactor parameters uncertain, numerical simulations results : **50 m, 20 km/s, 3300 kg/cm^3**



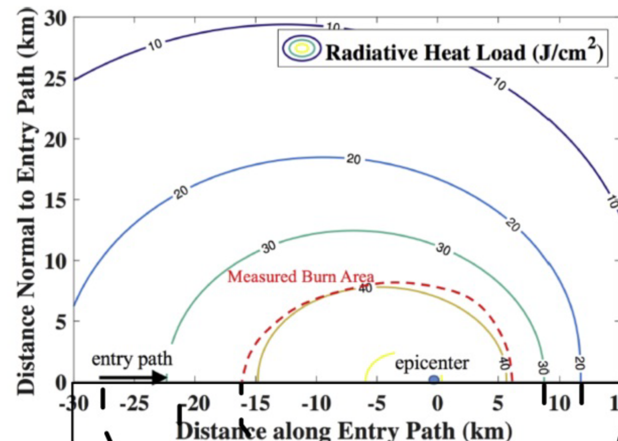
Model by Johnston&Stern 2019

Carbonaceous chondrite 3000 kg/m^3

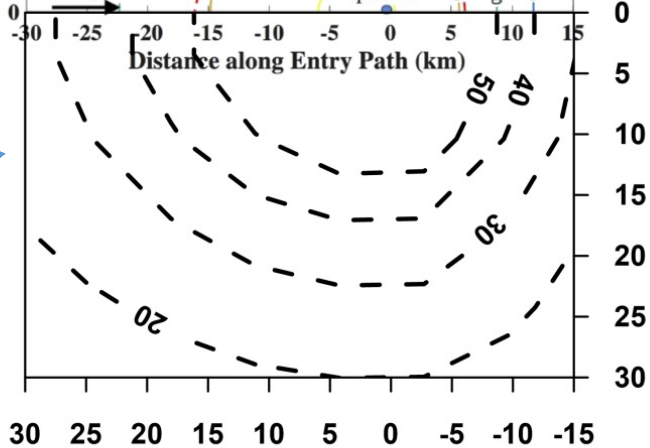
D~50-400 m, V~6-18 km/s, H~10-30 km,

pancake fragmentation model

17.5 km/s, 72 m, 30°



Scaling relation distribution Q_sc example



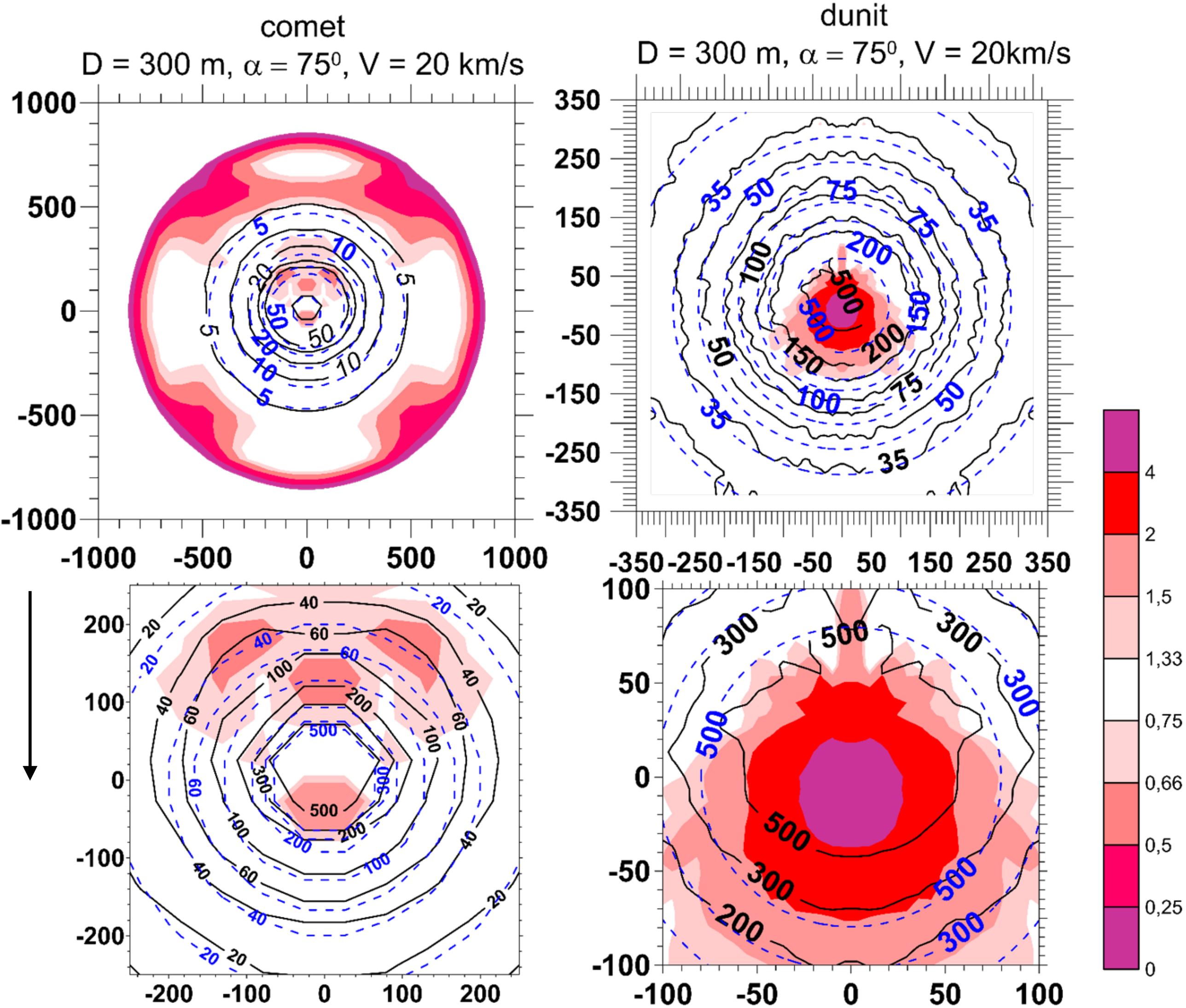
20 km/s, 68 m, 15°

Despite a range of impactor parameters allows to describe burn area,

different model results are quit close,

our modeling suggested more oblique impact.

THERMAL EXPOSURE BASED ON SC FOR CRATER-FORMINGS



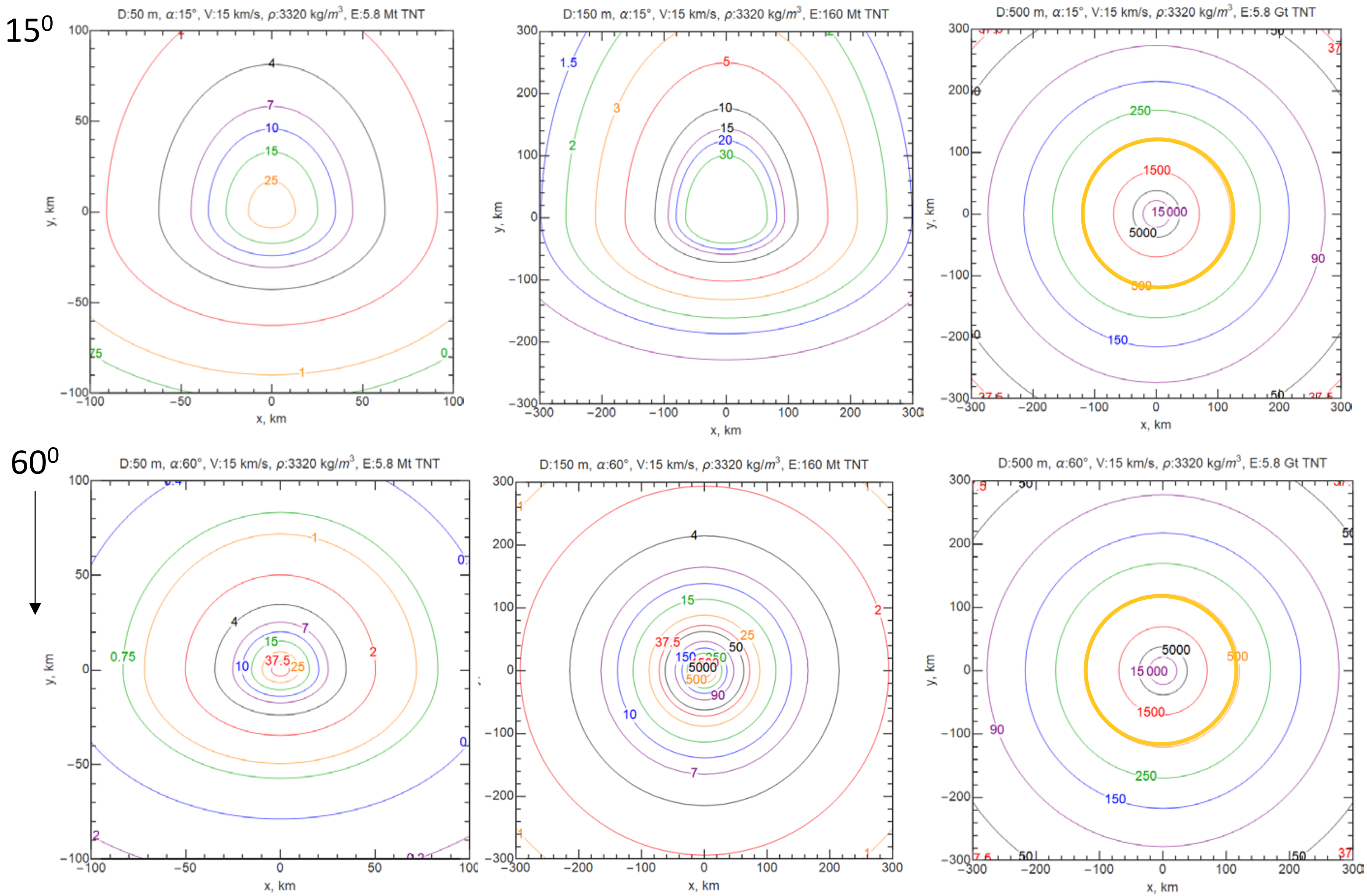
Spatial heterogeneity is excluded from Q_sc (no ellipticity)

Additional multiplier is included – to limit Q at the outer areas.

In most cases an uncertainty in estimates based on this scaling relation does not exceed 4 times in the range Q~ 10-500 J/cm^2.

Thermal exposure Q obtained in the numerical simulations - solid contours with black labels and Q_sc based on scalings (dashed contours with blue labels [J/cm2]
Bottom panels - central part on a larger scale. Color - the ratio of Q_sc/Q
Trajectory is top -bottom

PDC 2021 PROBABLE IMPACTOR RADIATION

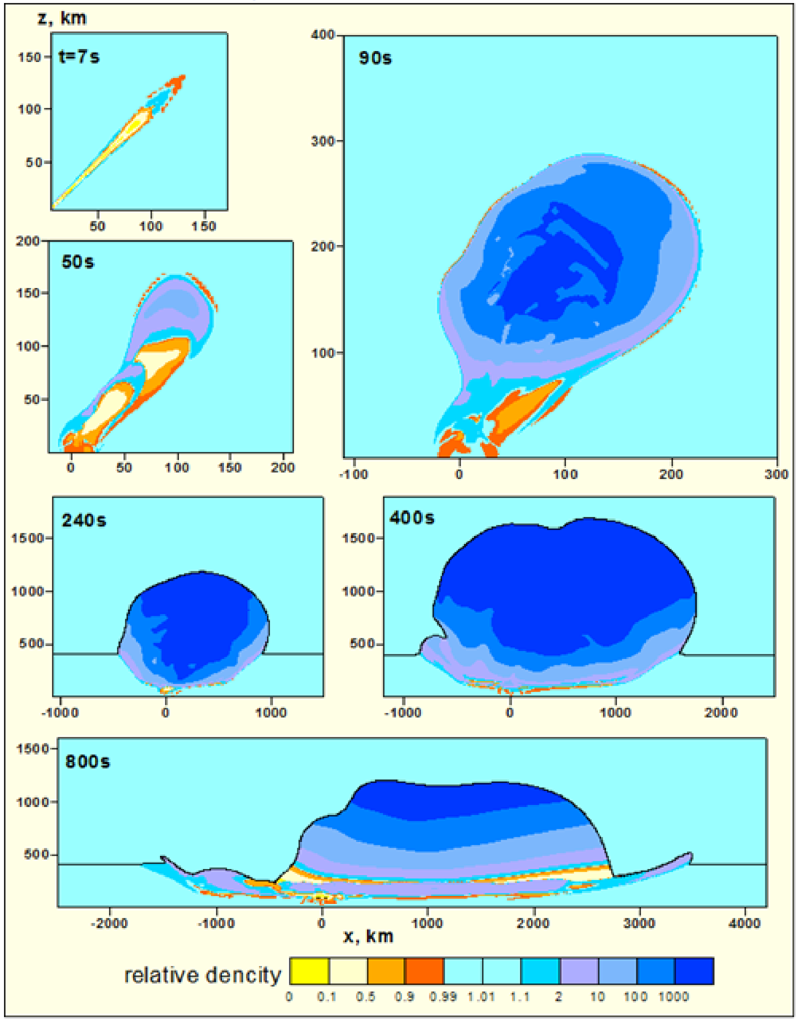


As expected the radiatively damaged area is dependent on entry angle and size

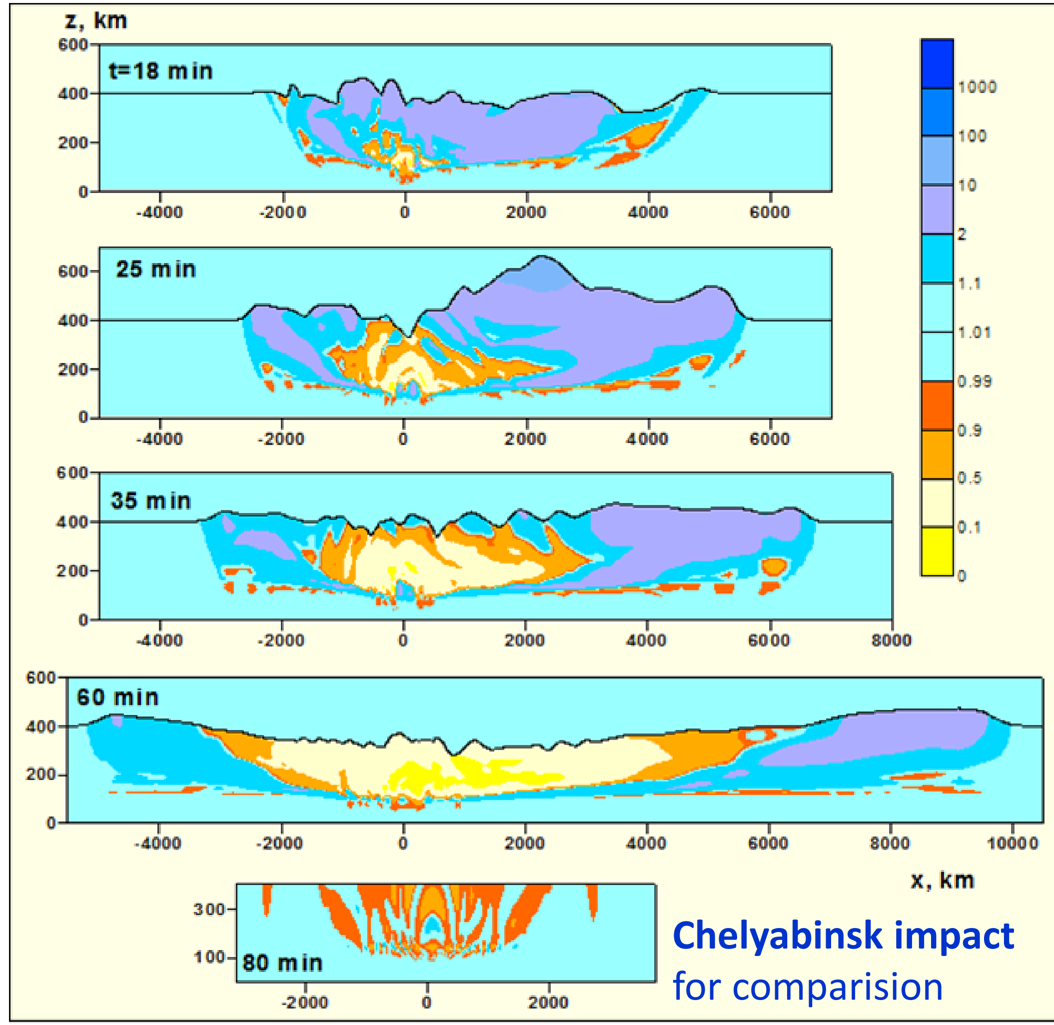
IONOSPHERIC DISTURBANCES

Impact -> plume formation -> its deceleration/oscillation at H>100 km -> energy is transformed into heat -> heated region expands laterally -> disturbances spread over thousands of km

Initial plume formation



Further evolution



distributions of relative density $\xi=\max(\mathrm{abs}(\rho/\rho^{*}-1))$ at different time moments

$\alpha=45^0$ D=80 m V=30 km/s, comet (Shuvalov&Khazins 2017; Artemieva et al.2018)

IONOSPHERIC DISTURBANCES

Disturbances parameter ξ - relative density

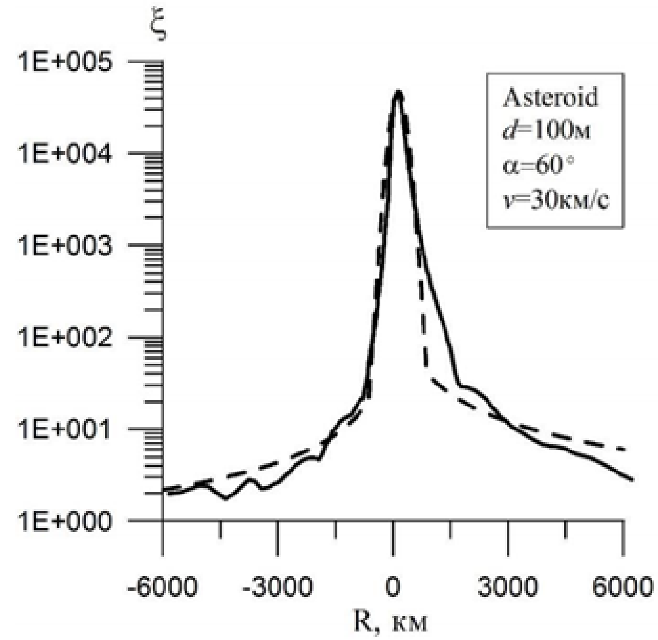
ξ=max(abs(ρ/ρ* -1)) - asymmetric:

Two factors: - asymmetry of the initial disturbances; - maximum H reached by plumes.

Asymmetry is the most prominent in the 45° scenario.

Maximal ξ is largest in the vicinity of the epicenter and decreases at the scale of thousands km.

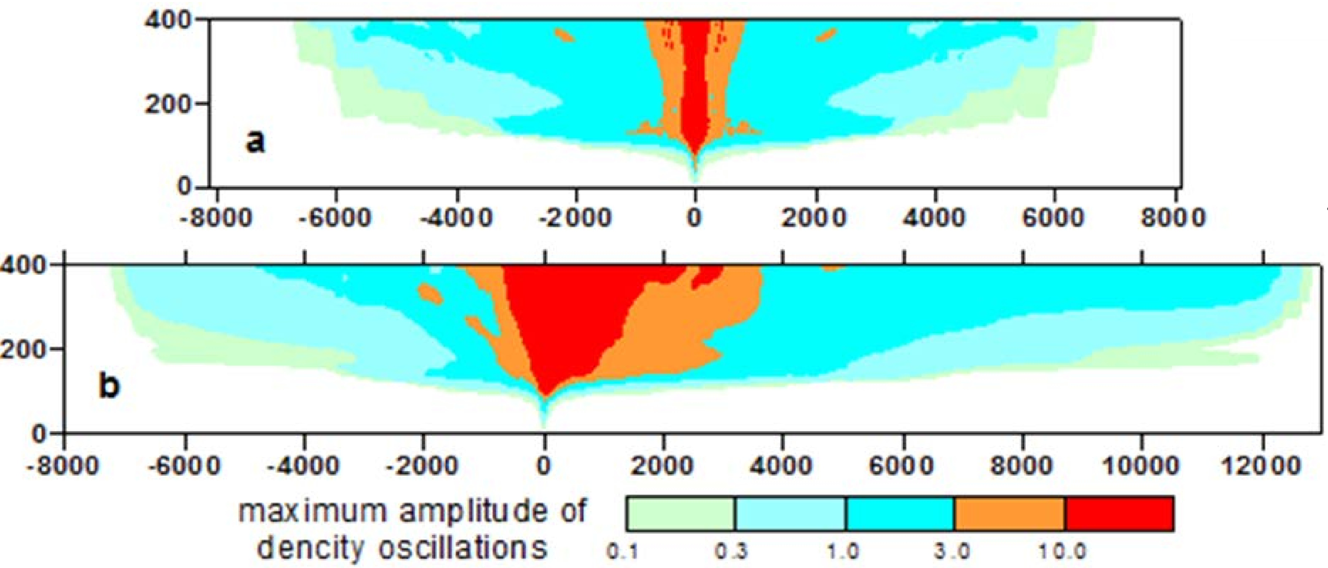
ξ is oscillating at a point (x,y).



Distribution of maximal ξ at H=300 km in a plane perpendicular to the Earth's surface and passing through the impactor trajectory.

Solid - numerical modeling,
dashed - interpolation.

Shuvalov&Khazins 2017;
Artemieva et al.2018

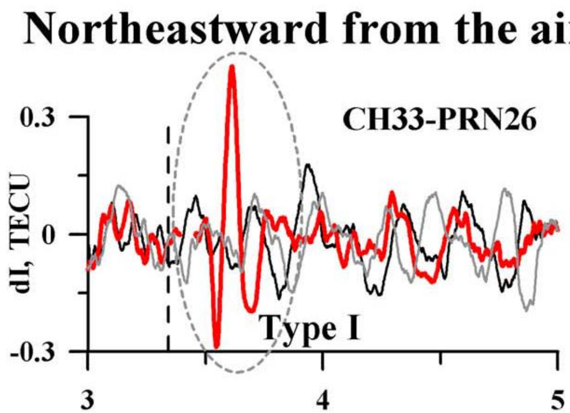


Distributions of disturbances parameter ξ : (a)13 Mt spherical explosion at H~ 10 km
(b) 13 Mt impact ($\alpha=45^0$, D=80 m, V=30 km/s, comet)
The explosion produces smaller disturbances than a real impact.

IONOSPHERIC DISTURBANCES

The only instrumental data on ionospheric disturbances – Chelyabinsk event

Well-pronounced TEC disturbances with an average period ~10 min and amplitude of 0.07–0.5 TECU (total electron content unit, 1 TECU = 10^{16} el/m^2) were detected (Perevalova et al. 2015).



observed

observed – grey

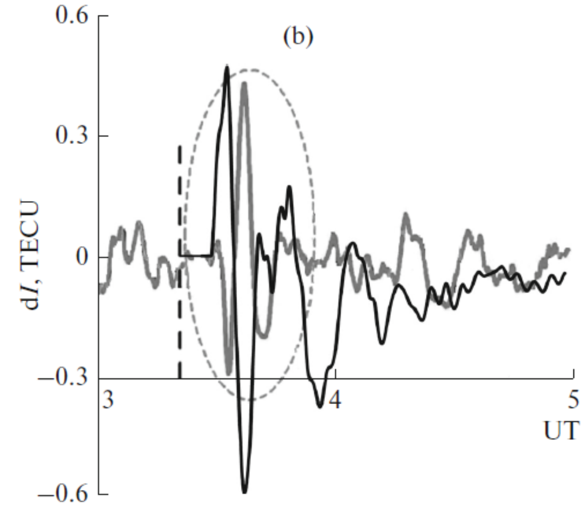
model at 300 km from epicenter – black

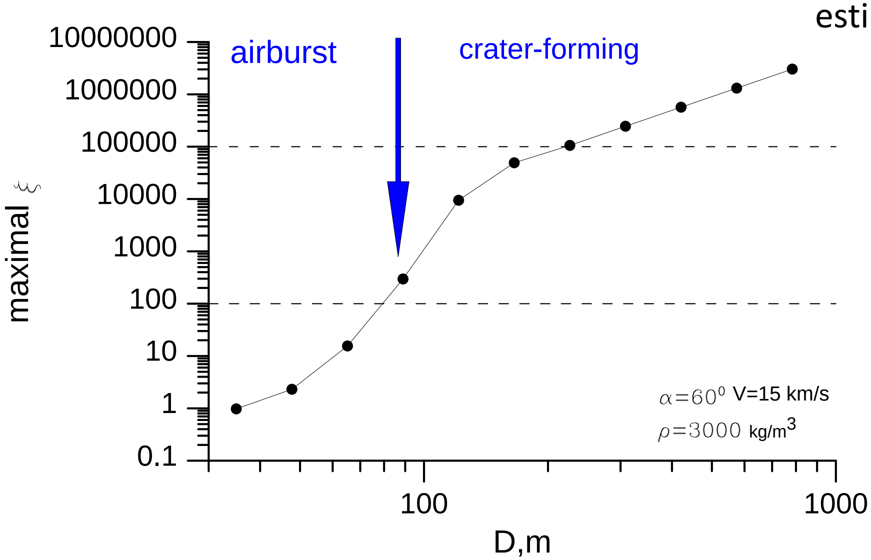
T~8-16 min

It is assumed that

TEC ~ρ~ ξ ,

value of ξ at H~300 km is considered as basis to estimate of TEC





Dependence of disturbances parameter ξ on impactor size

2021 PDC probable impactor:

asteroid, V~15 km/s

D~35 - 700 m

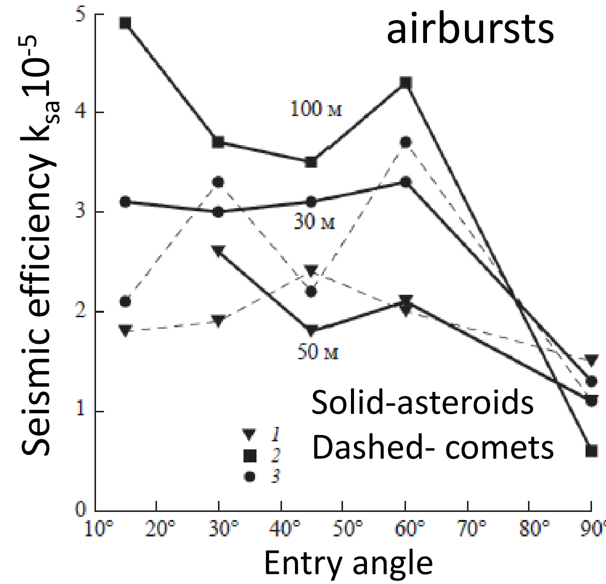
entry angle – 3-90^0, more probable 50-80^0

SEISMIC EFFECTS

To calculate the seismic magnitude of an impact event – one needs to know "seismic efficiency" k_s

the fraction of the kinetic energy of the impact E_{kt} that ends up as seismic wave energy E_{seism}

Modeling: Svetsov et al. (2017) , Khazins et al. (2018)

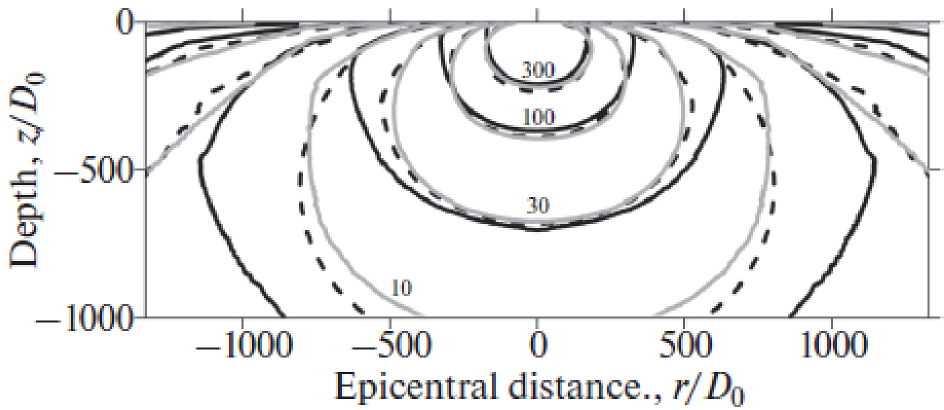


Airbursts: causes a seismic effect due to the impact of a shock wave on the surface.

Average seismic efficiency $\mathbf{k_{sa} = 2.5\ 10^{-5}}$

Lower for vertical impacts (upward motion influence)

Isolines of overpressure(p–p0, atm)



black - underground explosion with E_0 at a depth of $40D_0$

dotted - surface explosion with energy $8E_{kt}$

gray – impact with energy $2.5E_{kt}$ (vertical sizes coincide)

Crater-forming impacts:

comparative calculations of SW generation by crater-forming impacts and explosions

seismic efficiency $\mathbf{k_{sc} = 10^{-3}}$ (vertical impact)

$k_{sc}(\alpha) = k_{sc}(90°)\bullet\sin(\alpha)$

Collins et al. (2005): $k_{sc} = 10^{-4}$

Intermediate cases:

If impactor energy is dissipated both in the air (Ea) and in crater formation (Ec) then

$$E_{seism} = k_{sa}Ea + k_{sc}Ec$$

SEISMIC EFFECTS

Seismic effect

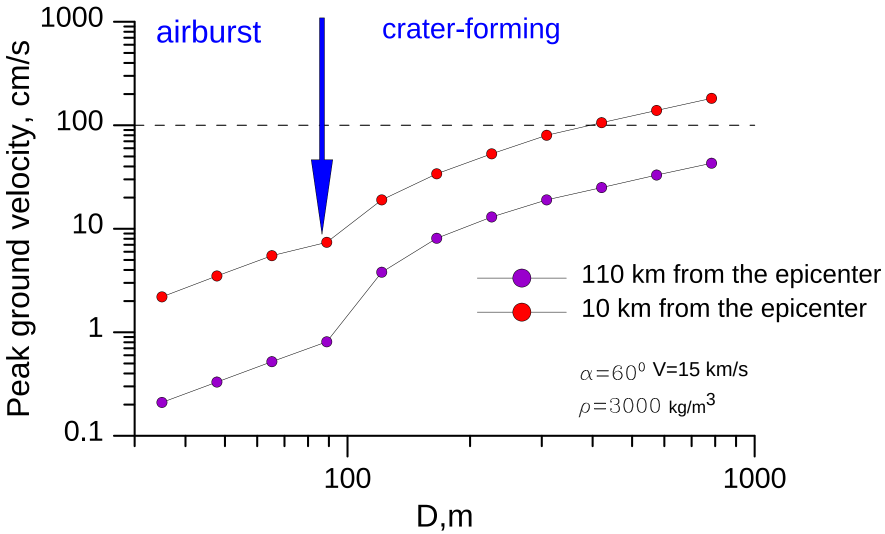
Magnitude: 5.8

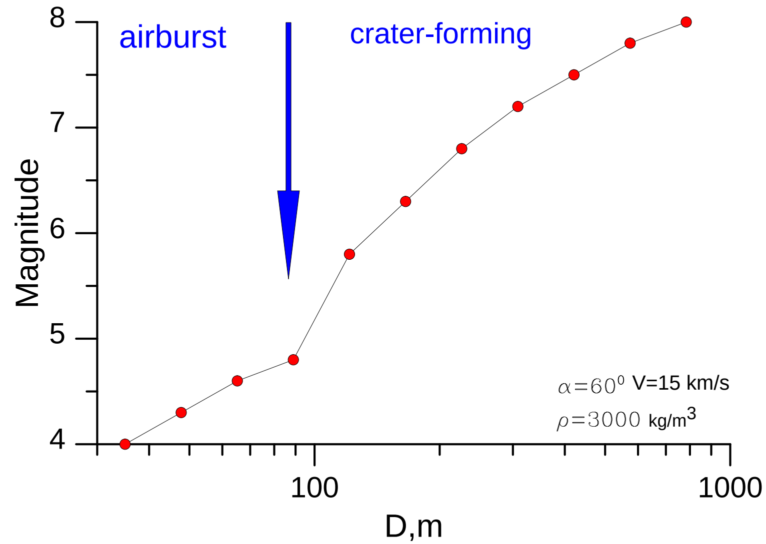
The seismic magnitude of the impact event is estimated for bothcrater forming impacts and aerial bursts. The magnitude is used for determination of the instrumental characteristicsof a seismic disturbance in the observational point.

Richter scale magnitude of the impact event: 5.8
Mercally scale intensity: IV-V
The peak ground velocity: 3.8 cm/s
The peak ground acceleration: 42 cm/s^2
Time of arrival to the observation point (started from moment of maximal energy deposition): 0:00:21

2021 PDC probable impactor: asteroid, V~15 km/s

- as small as 35 meters to as large as 700 meters
- entry angle – 3-90^0, more probable 50-80^0





catastrophic destruction
PGV>100 cm/s

Chelyabinsk: M~3.7-4 Tunguska: M~4.8-5.2

CONCLUDING REMARKS

Serial numerical calculations of the cosmic objects impacts were conducted in a frame of special gasdynamic model with radiative transfer.

Results of these simulations allowed us to construct scaling relations, which permit one to quickly assess different dangerous consequences of impacts based on impactor parameters.

First time modeling and scalings for airbust radiation are suggested and demonstrated satisfactory agreement with existing observational data and other modeling.

First time modeling and scalings for ionispheric disturbances are suggested.

Scalings for seismic efficiency are improved based on impact modeling, the efficiency essentially differ from seismic efficiency for explosions.

Described scaling relations are implemented into web-based calculator.

Scalings in transition region of sizes/energies should be considered in more detail.

PDC probable impactor parameters are very uncertain and its impact may result in consequences of different scale.