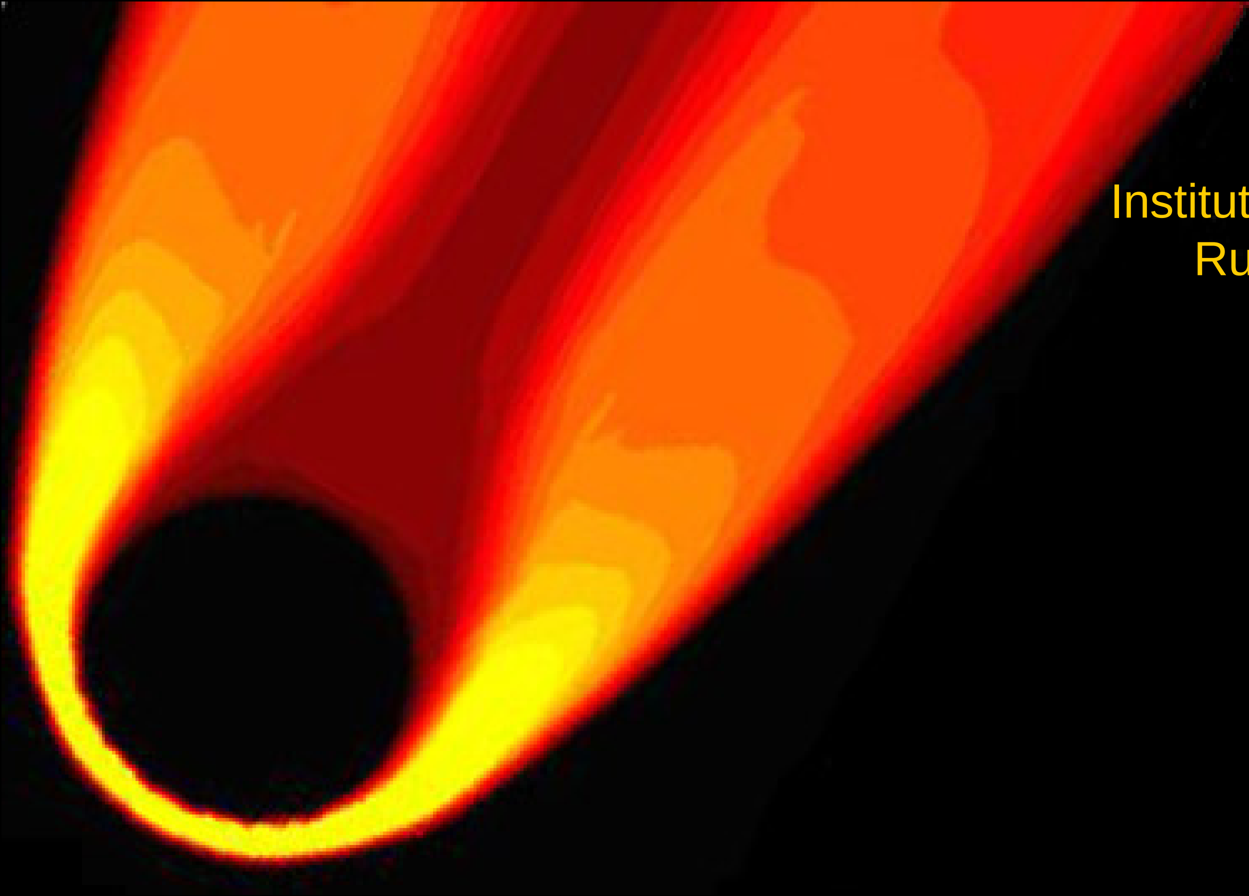

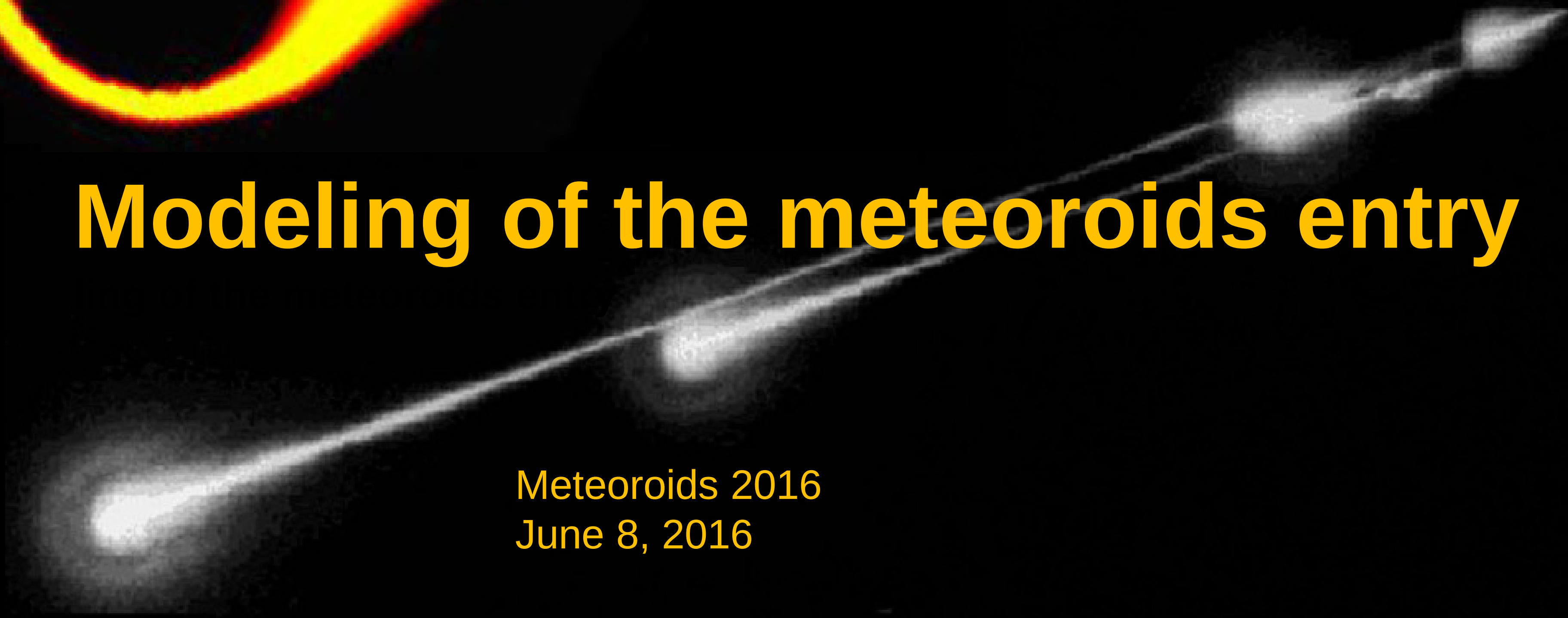

Popova Olga

Institute for Dynamics of Geospheres
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Modeling of the meteoroids entry

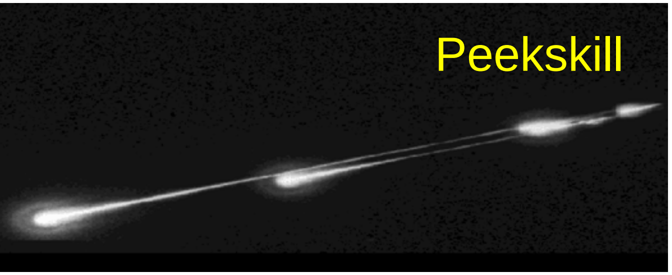
Meteoroids 2016
June 8, 2016

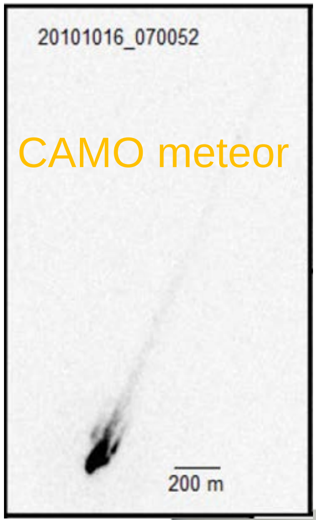
Meteoroid in the atmosphere: Ablation and Fragmentation

Ablation rate determines
- deposition of mass, momentum, energy into the atmosphere,
- meteoroid radiation and ionization
- is dependent on size/mass, velocity and altitude of flight, meteoroid properties and fragmentation

$$\alpha = -\frac{\beta}{\mu V}\frac{dM}{dt}$$

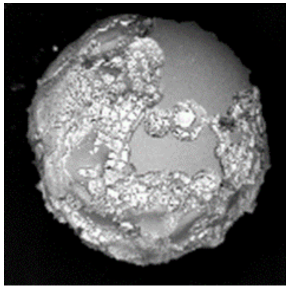
$$I = -\tau\left(\frac{V^2}{2}\frac{dM}{dt} + MV\frac{dV}{dt}\right)$$





I – light intensity
α- linear electron density
τ, β - luminous and ionizing efficiencies,
μ - average mass
μ of ablated atom

Meteoroids in the size range
10^{-4} cm<R<100-1000 m
are ablated and could be fragmented

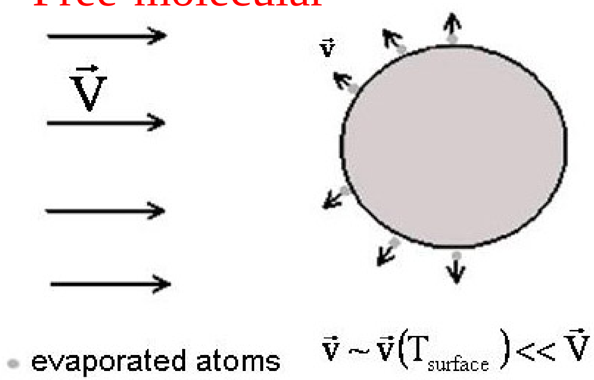


R~f(V,α,material/structure)

<H>~130-20 km
(extreme cases – up to 200 km atmospheric density–10^{-13} 10^{-3} g/cm^3)

Meteoroid – atmosphere interaction

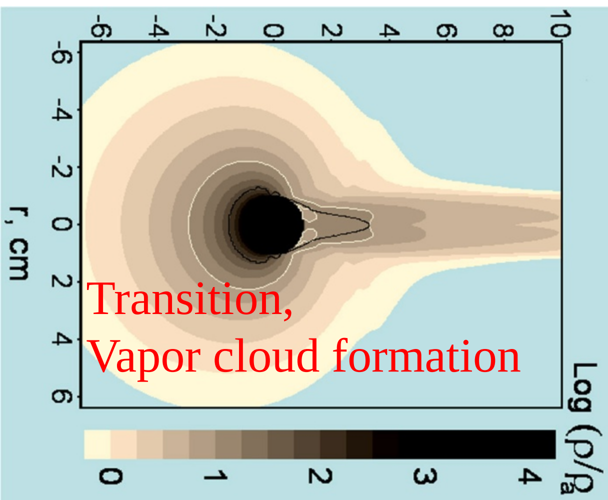
Free-molecular

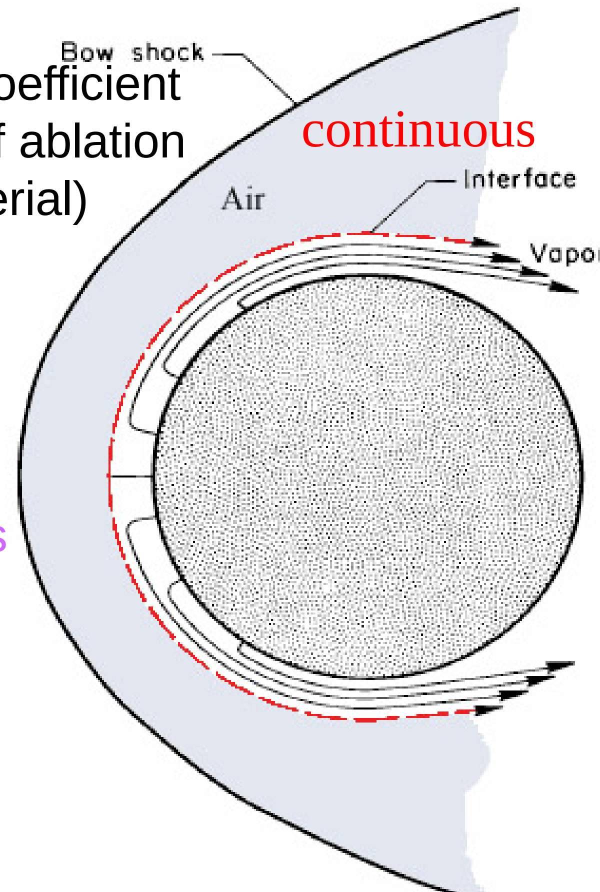


Large meteoroids:
main ablation occurs at middle-low altitudes- in continuous flow conditions
(shock wave formation)

Ablation equation $$\frac{dM}{dt} = -C_h\left(\frac{S\rho V^3}{2Q}\right)$$

C_h – dimensionless heat transfer coefficient
Q – effective heat of ablation
$C_h = C_h(R,V,H, \text{material})$

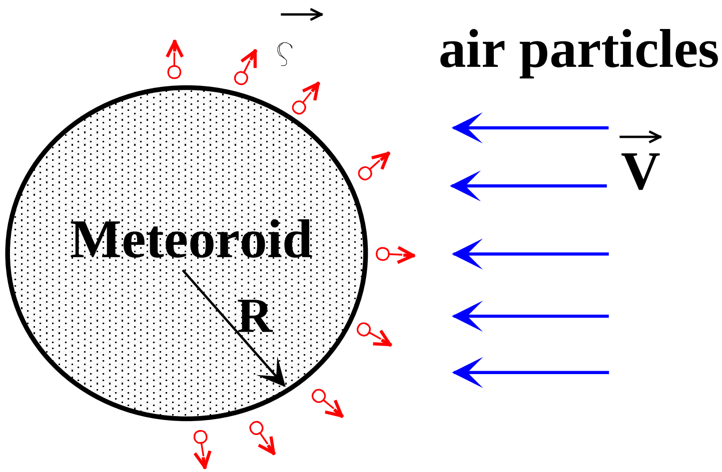




Free-molecular → transitional → continuous

Heat transfer from air flux to meteoroid:
- direct impact of air particles *in free molecular regime*
- combination of convection and radiation
  (in transitional and continuous regimes)

Non-thermal mass loss



Usually assumed start of ablation 90-130 km ($T_{surface}$~2000K) - altitude of intensive evaporation

Above (~110-130 km) direct impacts of air particles:

- heating of meteoroid
- sputtering of meteoroid surface

○ **sputtered and reflected particles**

Sputtering

-was supposed as explanation of high altitude (above 130 km) ionization and luminosity (*Brosch et al, 2001*)

-occurs for high velocity meteors **(V> 30 km/s)***(Popova et al, 2004)*

-causes mass losses for high-velocity meteors (up to 35% for M~10^{-16} kg); *(Vondrak et al 2008)*

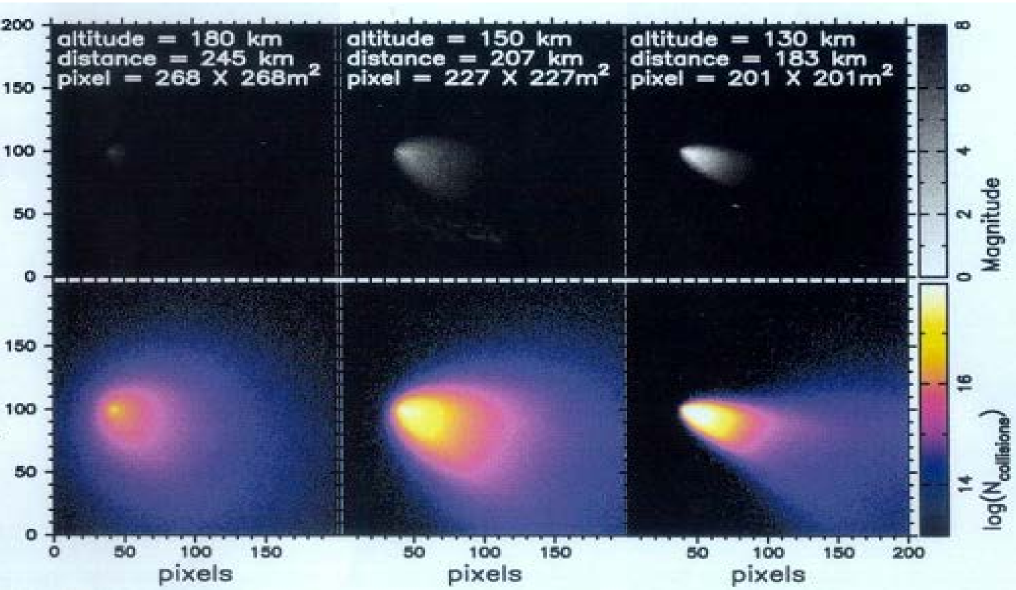
Sputtered particles

carry out about 10-20% of incoming energy *(Popova et al, 2004)*

Interaction of sputtered atoms with atmosphere

Formation of disturbed area at high altitudes *(Vinkovic, 2004)*

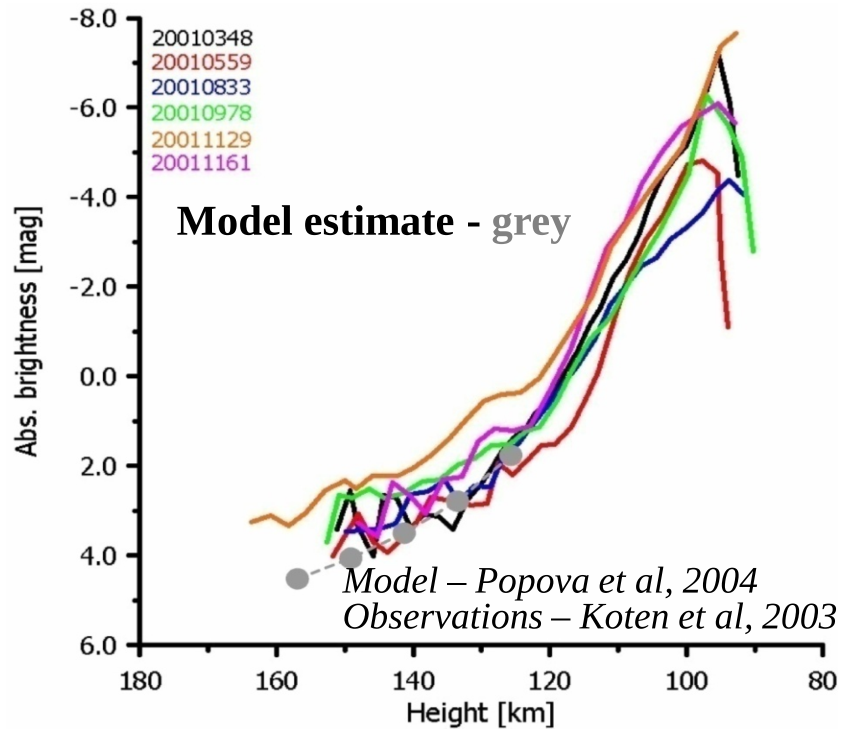
H: 180 km 150 km 130 km



- DSMC modeling, V=70 km/s
- only elastic collisions are considered, no radiation
- sputtering efficiency used γ~ 1

Oxygen radiation (777 nm)

(main component at high altitudes)



- model brightness changes with altitude similarly to observations
- bigger meteoroid size than photometric estimate
- only first collisions considered

- uncertainties in cross-sections and sputtering efficiencies
- modeling of radiation is not complete

Free molecule regime

Solution of equations of meteoroid flight under various assumptions

(about emissivity, evaporation rate etc.)

- to determine fate of incoming material in the Earth atmosphere, to predict mass/energy deposition at different H

  (Flynn,1989; Love and Brownlee 1991, Hunten 1997, Plane et al 2015 and others)
- to predict ionization *(for example Close et al., Hunt et al. 2004;Cervera&Elford, 2004)*
- to consider meteors in different planets' atmospheres

  (Moses 1992; Moses et al,2000; Pesnel et al.,2002;2004 and others)
- to reproduce light curves/deceleration *(Campbell-Brown&Koschny,2004; Campbell-Brown et al 2013 and others)*
- to estimate masses and densities of meteoroids *(Kikwaya et al., 2010; Close et al. 2012;Stokan&Campbell-Brown 2015 etc);*

Free molecule regime Ch=1 and - know something about ablation rate

What is known about state of ablated material?

Ionization:

– formation of initial radius *(Jones, 1995)*

– head echo formation

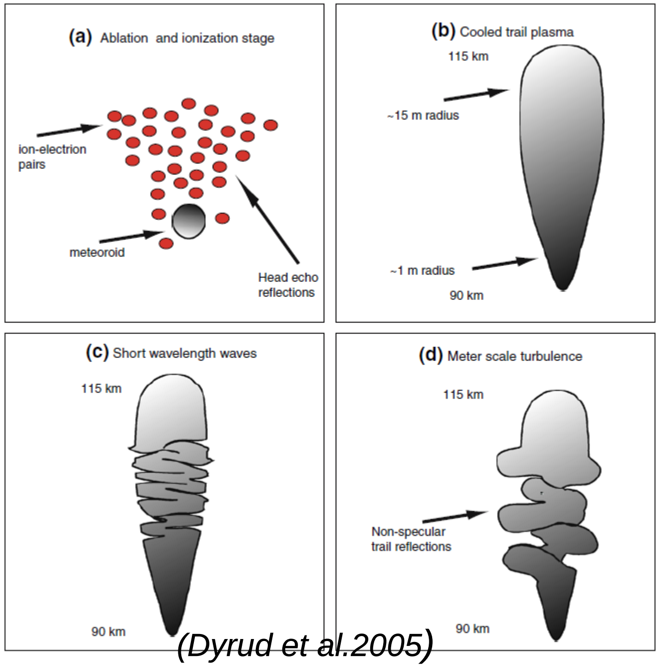
(Jones et al., 1998; Close 2004,2005 etc)

–- formation of non-specular meteor trails

(Dyrud et al.2005, 2008)

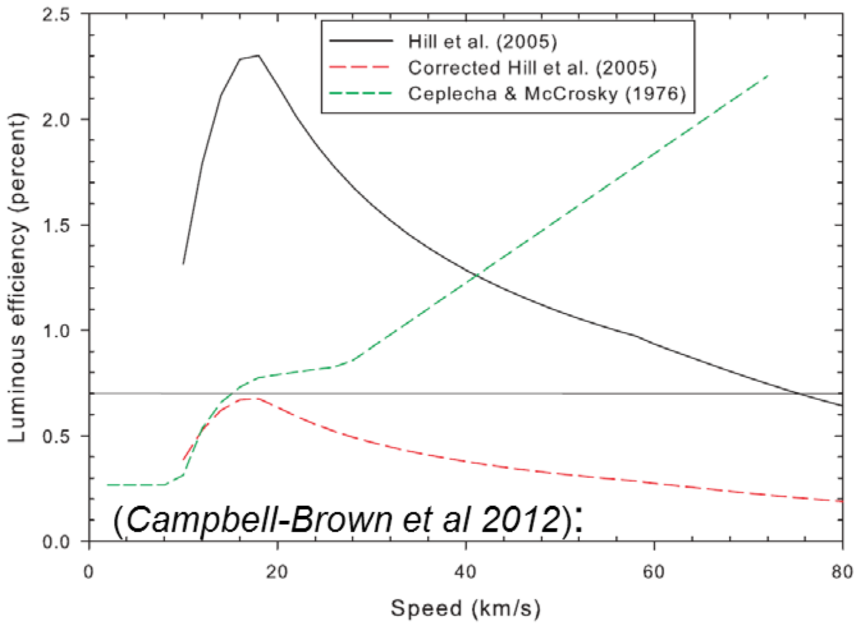
Radiation:

no models, which describe the conditions in luminous area (T, density) and allow to predict spectrum

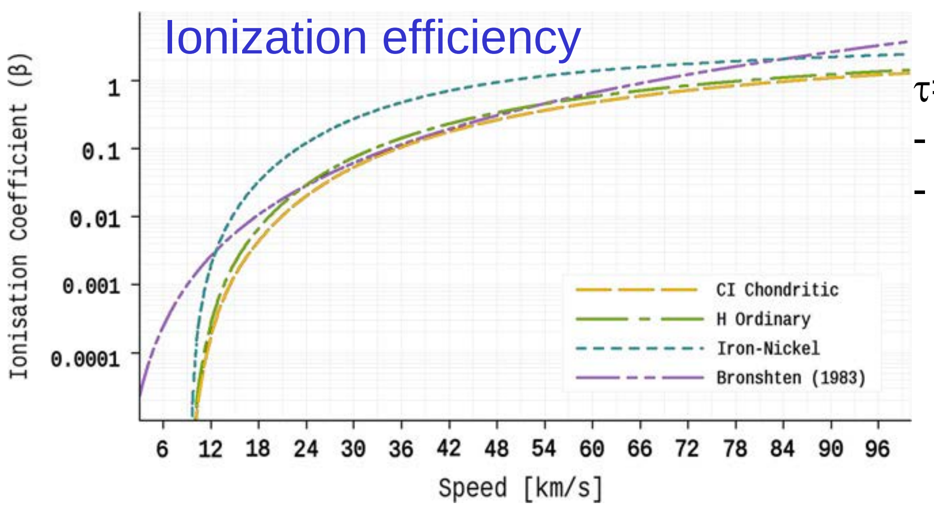


(Dyrud et al.2005)

Free molecule regime



Luminous efficiencies by different authors



Luminous and ionization efficiencies *(used for masses estimates)* large scatter

- *estimates based on collisions consideration,*
- *interpretation of observational data,*
- *data on artificial meteors;*
- *often are extrapolated from assumed range*

Ionization and luminous efficiency

Weryk&Brown 2013:

- β following Jones (1997)
- the assumed composition greatly affects the result

Simultaneous radar and optical :

$M \sim 10^{-2}\ 10^{-5}$ g, q/I ⇨ β/τ

τ=f(V):

- may be dependent on M,
- dependent on composition and spectra

Simultaneous radar and optical observations (*Campbell-Brown et al 2012*): 4 meteors:

H~90-100 km, V~25-40 km/s; $M \sim 10^{-3}$ g

Mass uncertainty

- about an order of magnitude

Interpretation of observation – model dependent (Bello-Rubio et al 2002);
Besides, observations – fragmentation evidences

Dustball model *(Hawkes and Jones, 1975)*

cometary meteoroid consists of grains *(with high boiling T)*
connected by some glue *(low T).*
Luminosity – by ablating grains,
grains may be released before H_b for small particles.

Grain mass – based on analyses of 108 meteor flares by Simonenko(1968) ~10^{-6}g

Model of ablation of faint meteors *(Campbell-Brown and Koschny, 2004)*

M~10^{-6} - 4 10^{-2} g (R~0.01– 0.2 cm), radar and video observations

release of grains when reached some $T_{surface}$
typically grains are released close to the onset of luminosity
Grain distribution is determined – grain masses 10^{-4} 10^{-8} g

Quasi-continuous fragmentation *(Babadzhanov 2002 and references there)*

gradual release of the smallest fragments from the surface and their subsequent evaporation
M>10^{-2} g; 111 of sample of 197 are fitted by QCF (44%)

Different mechanisms (detachment of fragments (husking); thermodestruction and blowing off surface layer; the ejection of heated surface due to fast evaporation of volatiles)

Thermal erosion model (QCF type) *(Borovicka et al.2007) -* Draconids, small grains continuously detach from the surface, separation continued during the first half of meteor trajectories M~10^{-3} - 10 g, grain masses-10^{-6} 10^{-7} g, $Q_{erosion}$~0.03-0.06 Q_{evap}

High resolution modeling of meteoroid ablation

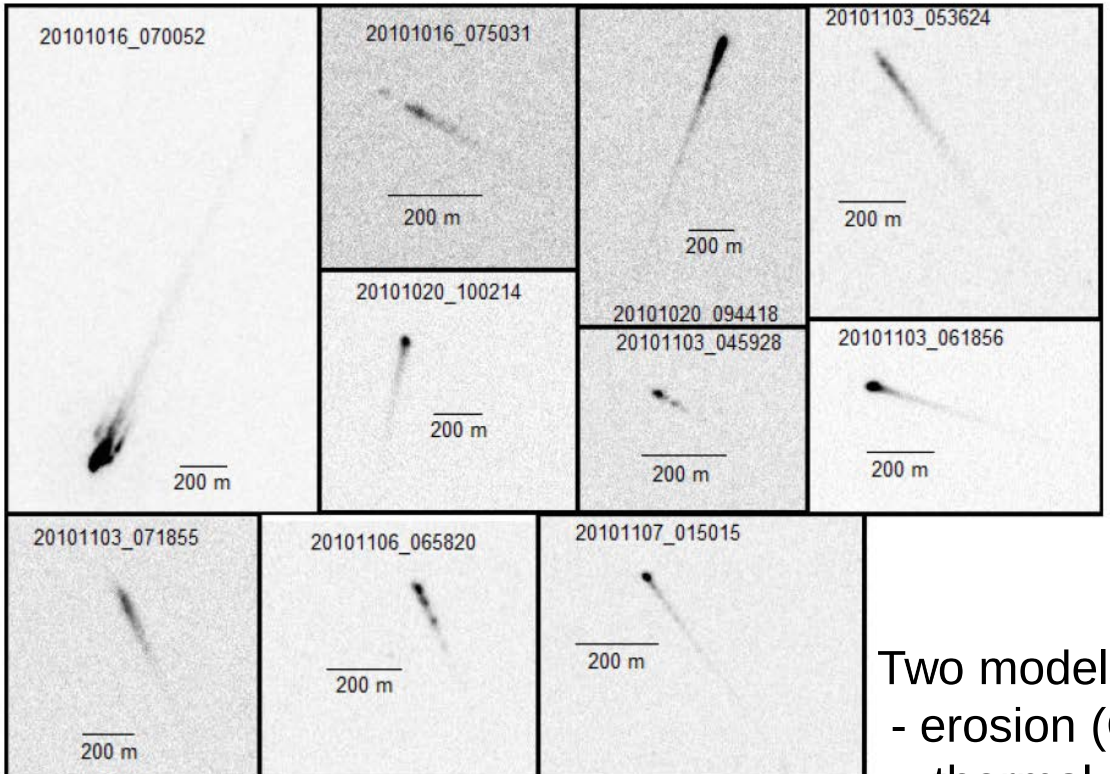


Fig. 2. Narrow field images from each of the events, with scale bar. The meteors show a range of different characteristics, including different amounts of wake and fragmentation.

Campbell Brown et al. 2013

10 meteors
Canadian Automated Meteor Observatory (CAMO)
resolution - up to 3 meters per pixel.

V~20-70 km/s, H~122-70 km;
-0.7 2.8 mag; 10^{-7} 10^{-4} g
wake length<150 m

Two models
- erosion (QCF)
- thermal disruption (dustball)

- to fit light curves/deceleration
- the wakes predicted by each model were compared to the wakes measured

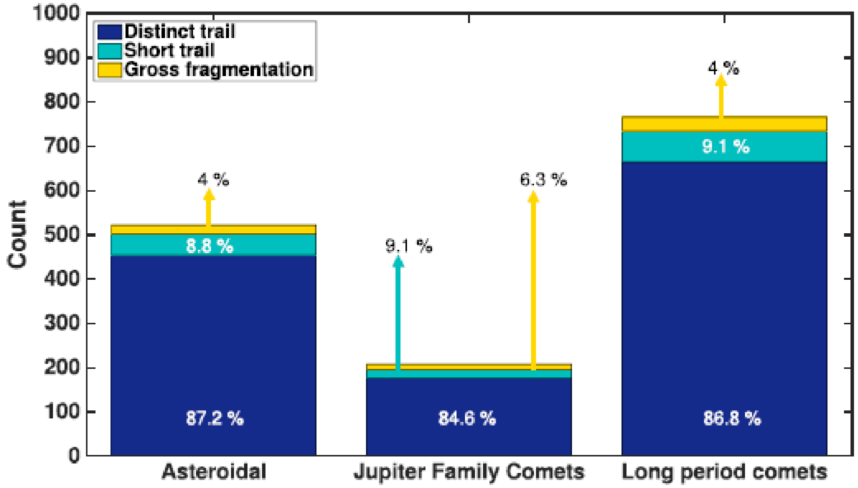
Both models produced satisfactory fits to light/deceleration,
but failed to predict brightness profiles - both predict far more wake than is seen.

Different type of fragmentation? Not fragmentation but differential ablation?

How often is fragmentation in optical meteors?

Optical faint meteors (M~10^{-7} 10^{-4}kg) Subasinghe et al.2016
Canadian Automated Meteor Observatory

- ~90% of meteors – some form of fragmentation

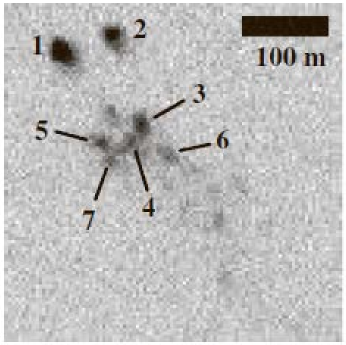


1496 high-resolution meteors:
1296 meteors - having distinct trails (>190 m);
135 meteors - short trails(<90 m);
65 meteors - gross fragmentation.

- most meteor light curves are symmetric - light-curve shape is not an indication of fragility or fragmentation behavior

- dynamically asteroidal meteors fragment as often as dynamically cometary

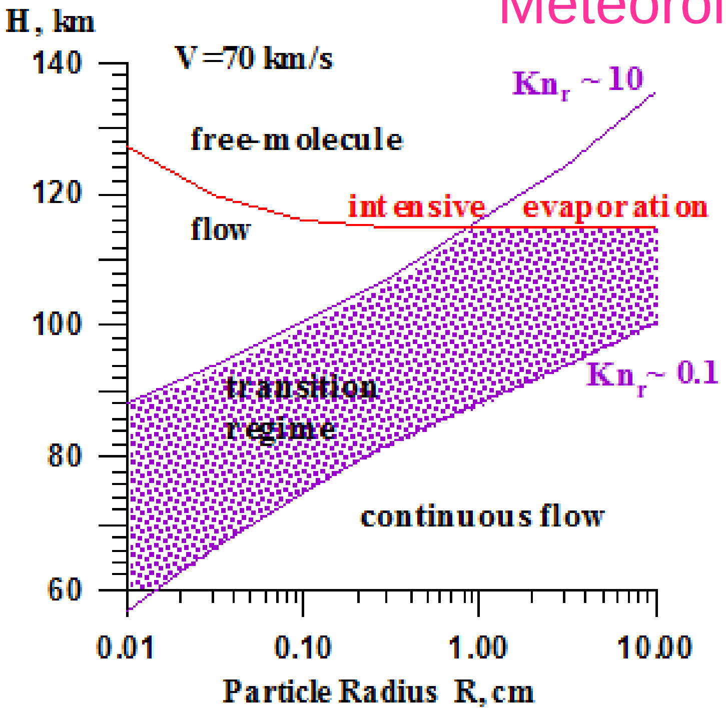
-proportions are almost equal: fragmentation is not an indicator of the object's origin



(a) 0.02 s, 102.0 km

9 meteors (M<10^{-4}kg) (Stokan&Campbell-Brown 2014)
- significant transverse motion, U~100 m/s
(aerodynamic loading – U~1m/s)
- mechanism of fragment spreading are poorly known -
- meteoroid strengths of the order 10^6 Pa were derived

Meteoroid – atmosphere interaction



Regime boundaries **size/velocity** dependent

Modified Knudsen number $Kn_r = \frac{V_r}{V} Kn$ $\quad$ $\mathbf{Kn = \ell / R}$

(Lebedinets, 1980; Bronshten, 1983)

ℓ - free path length

V - meteor velocity,

V_r - thermal velocity

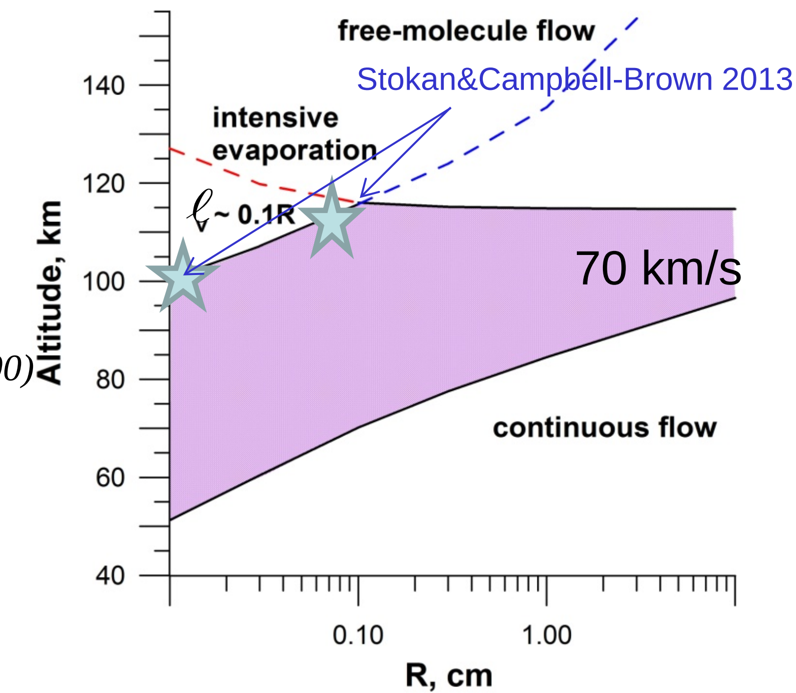
Altitude of intensive evaporation - H~90-130 km
(Ceplecha et al, 1998)

(T~2000K; incoming energy flux >>thermal radiation cooling+meteoroid heating)

Simple estimates:
vaporization rate ⇒ vapor density/pressure

if aerodynamic loading $p_a = \rho_a V^2 < p_v$

then vapor cloud screening *(Popova et al., 2000)*

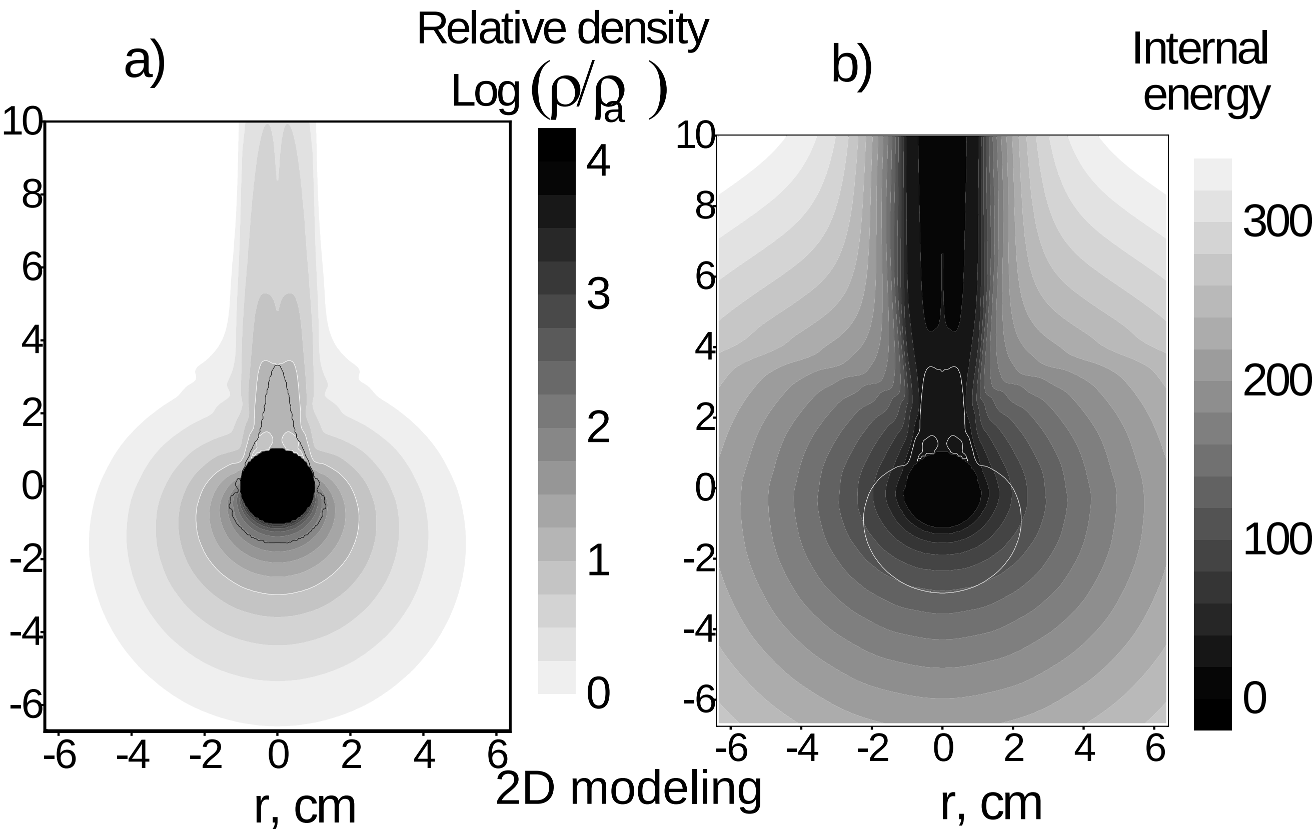


Stokan&Campbell-Brown(2013):
based on estimates of particle collisions

0.1 cm at 70 km/s 90 km – transition regime

Air beam model

formation of a vapor cloud around fast meteor – in the framework of the air beam model



R=1 cm, H=100 km, V=70 km/s

- for vapor – hydrodynamic description
- for air - beam of air molecules with flux $\rho_a V^3/2$
- effective absorption coefficient for air molecules energy transfer to vapor $\mathbf{k} = (\mathbf{n}\ell_a\rho)^{-1}$

where - free path length of air in the vapor, ρ - vapor density (κ ~ 10^7 cm^2/g), n ~ $10\ell_a$

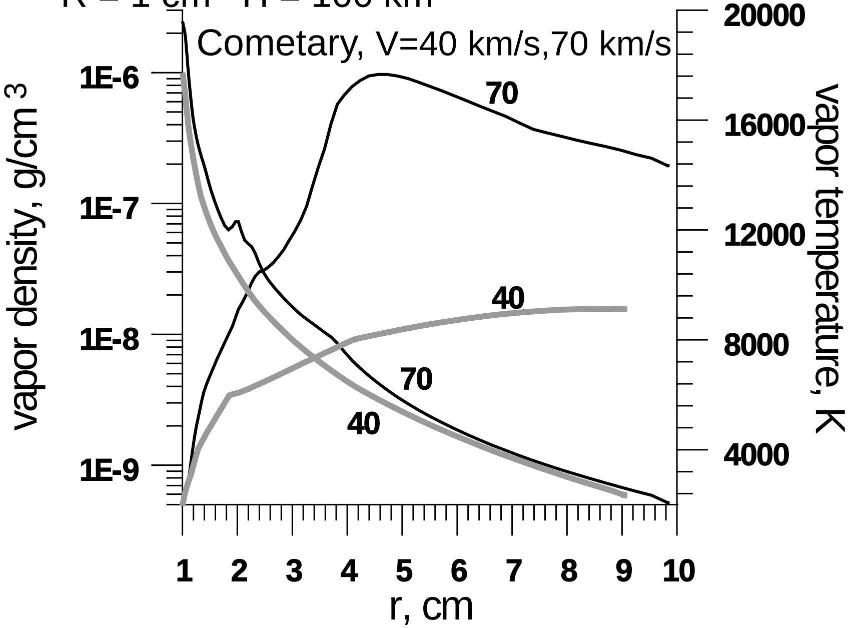
The energy transfer during the penetration of the air into the layer of evaporated material could be described similar to radiative transfer assuming some effective mass absorption coefficient

Vapor cloud is formed around meteor body

(Popova et al, 2000)

Vapor cloud parameters

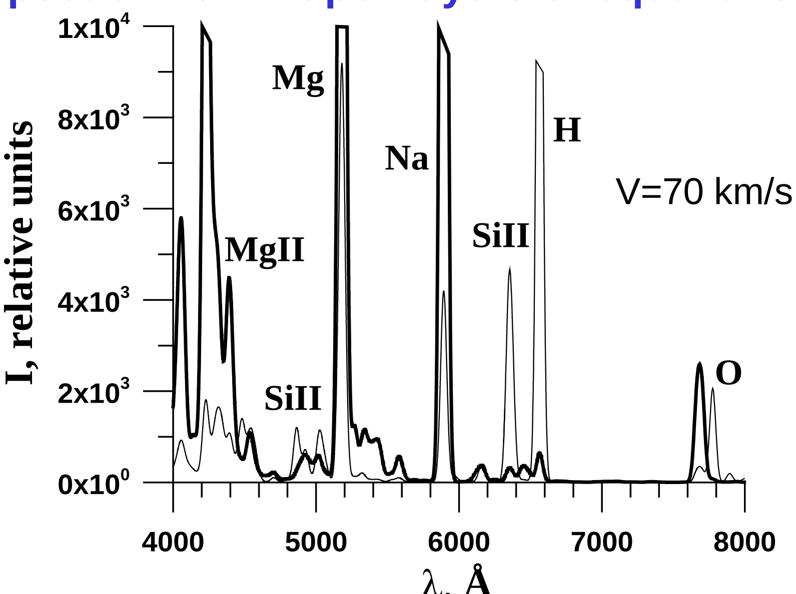
R = 1 cm   H = 100 km



Vapor cloud and comparison with observations

- vapor T behavior with R, V, H do not contradict to spectra changes with H *(Abe et al. 2000)*
- presence of high temperature component in both cases (MgII, CaII, SiII, HI, FeII, CrII, OI) with T~10000 K *(Borovička et al, 1999; Borovička and Jenniskens, 2000)*
- radiative area diameter essentially exceeds body size
- vapor density estimates are close
- (10^{-5}-10^{-10} g/cm^3)

Spectra from vapor layers of equal thickness



thin - close to meteor head
thick - farther from meteor head

But:

- only vapor radiation considered whereas 2/3 radiation in observations belongs to air
- temperature in model seems too high – we don’t taken in to account non-elastic processes in air-vapor collisions

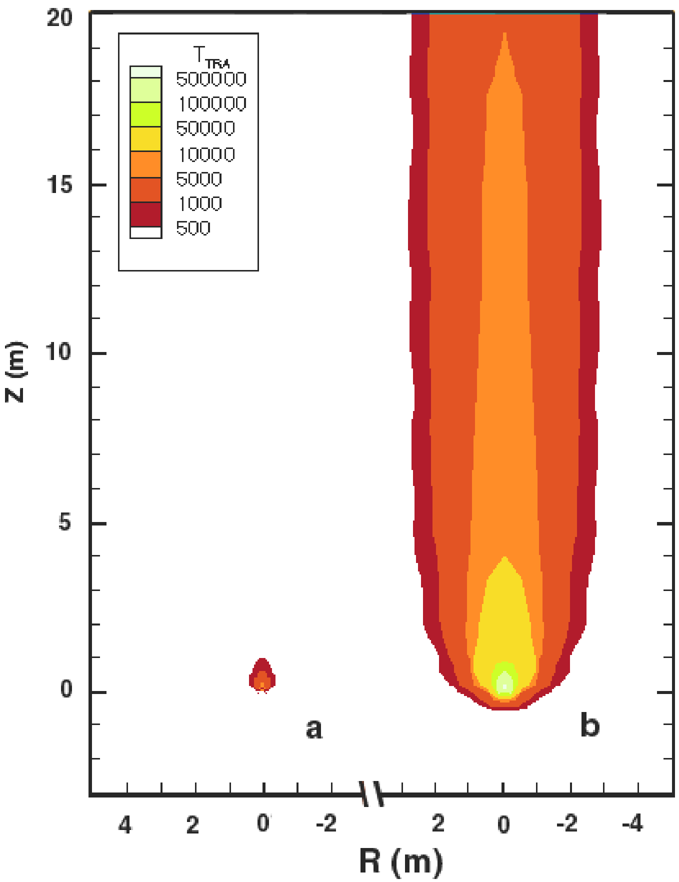
DSMC modeling (*Boyd, 2000*)

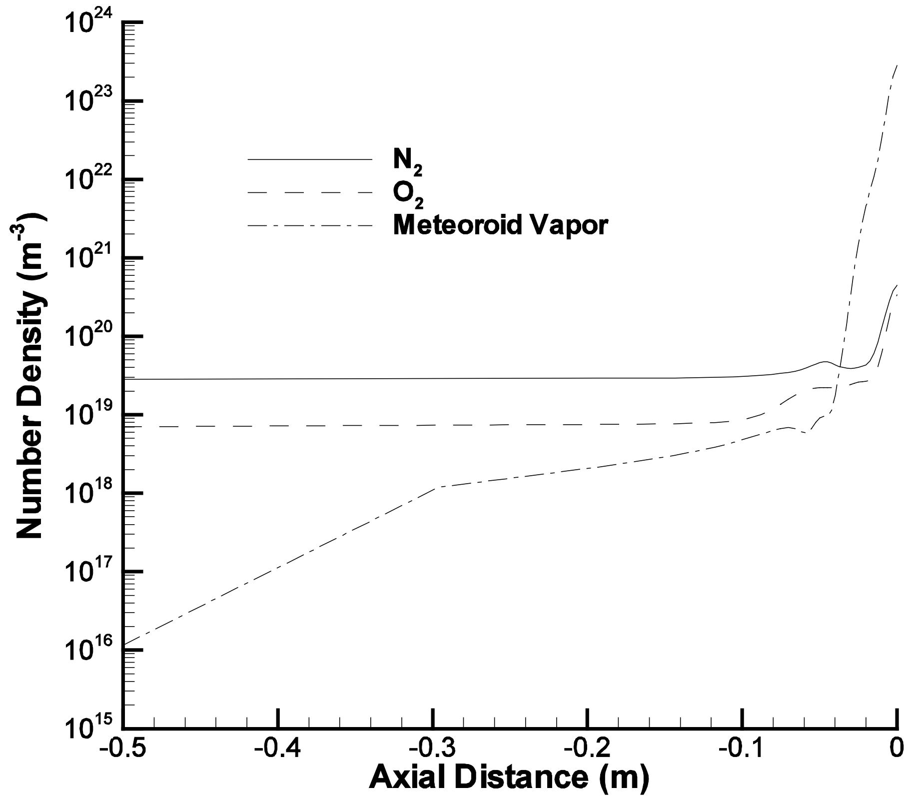
R~0.5 cm

H=95 km

V=70 km/s

Translational temperature field no ablation (a) with ablation (b)





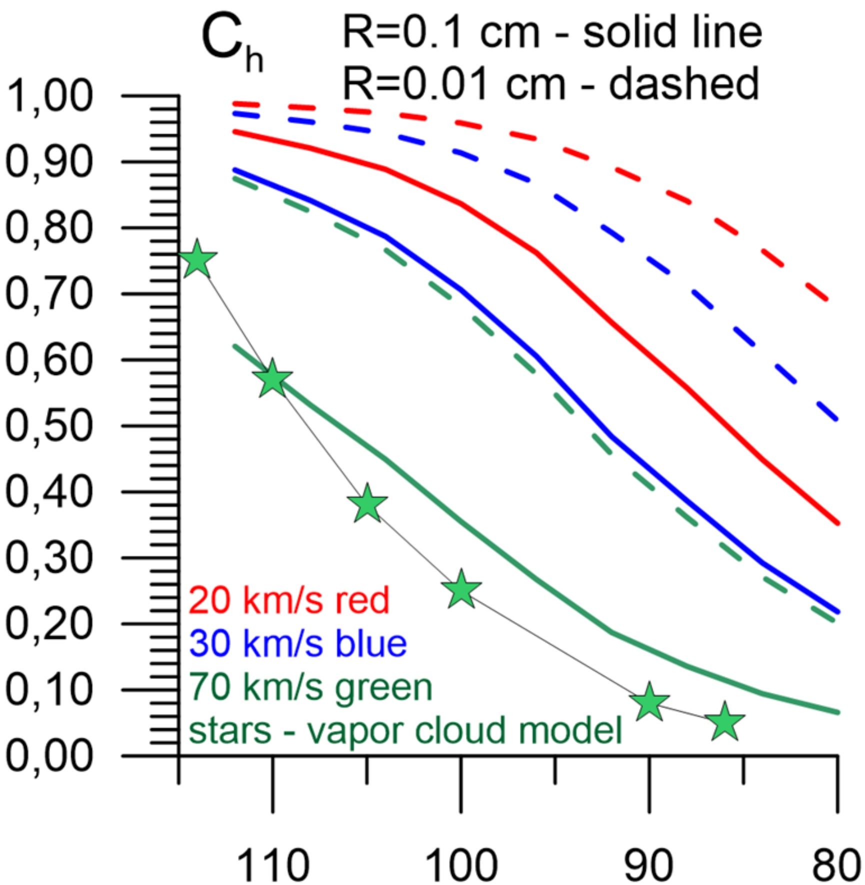
Number density in front of the body

Main source of radiation – meteor wake

Radiation is not included into modeling , only elastic collisions

Effect of mass transfer on heat transfer and drag in rarefied flows

Nelson, Baker and Yee, 2003



Nelson et al, 2003

- direct Simulation Monte Carlo
  V=30, 50, 70 km/s
  R=1, 8 cm; Kn~0.44 - 175
- extrapolation formulae for outside range
- cloud of ablation products is formed $\rho >> \rho_a$ *(several orders of magnitude)*
- the efficiency of heat transfer decreases in comparison with free-molecule value (Ch=1) even for 0.1 cm at 90 km
- Air-beam model results are in agreement (only 70 km/s given)

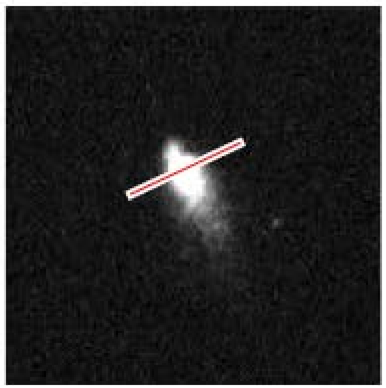
Shape and size of luminous area in meteors

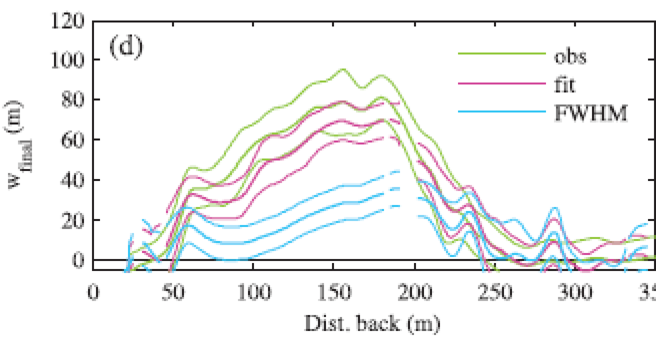
Attempts to measure – since 1960th

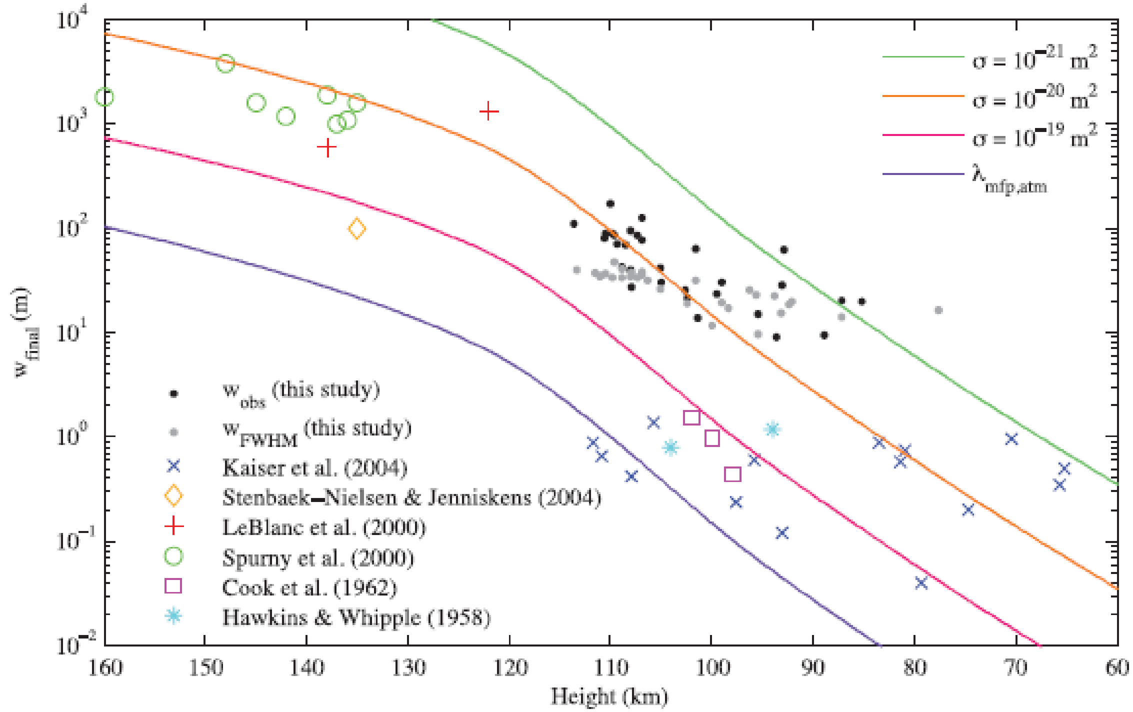
Width:

1-3 m (up to 9 m) at altitudes 90-110 km, optical meteors +5 +10; radar meteors (ion radius)

Stokan et al (2013): 30 meteors; ~+3, *m ~ 10^{-4} kg, exposure time 10^{-3} s*







-changes with distance from the head

- decreases with atmosphere free path length
- peak values – up to 40-100 m (above 105 km), 10-20 m below
- difference with other surveys: -camera spectral response/sensitivity?,

  - different populations (higher V)?

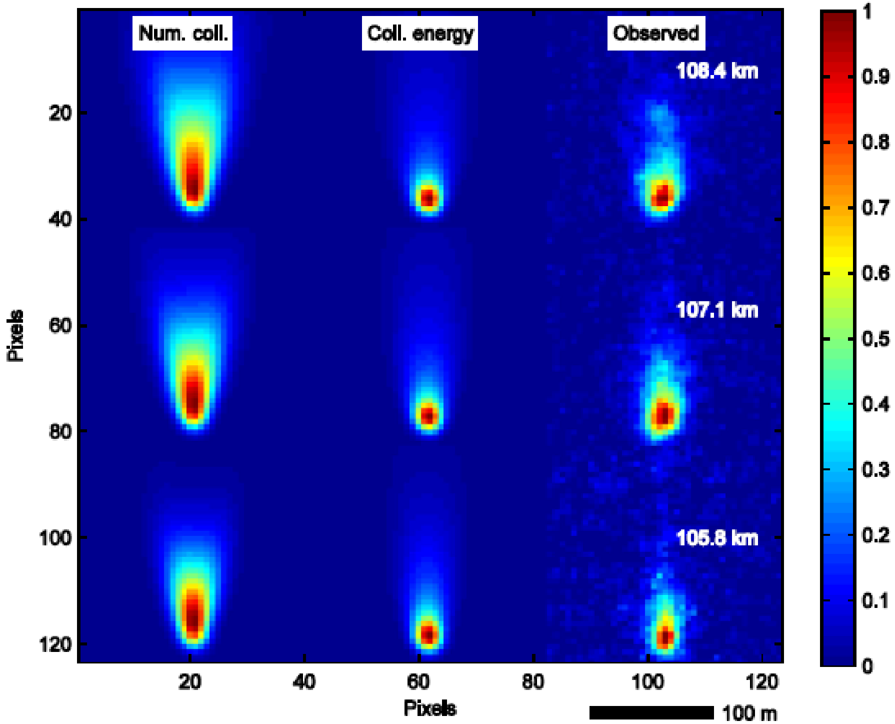
Shape and size of luminouse area in meteors

Length: 50-150 m, up to 500-1900 m, different types (Babadzhanov&Kramer 1968, Fisher et al 2000)

Stokan &Campbell-Brown 2015: 100-250 m observed 9 non-fragmenting meteors

H~114-78 km, V~19-70 km/s
M~10^{-4} - 10^{-3} g (R~0.1 cm)

A particle-based model for ablation and wake formation in faint meteors



- elastic collisions considered
- widths of simulated wakes agree with observations (width is related to the collisional processes of evaporated particles),
- beginning heights tend to be higher than observed
- light curves are in agreement
- simulated meteoroids less decelerated
- wakes shorter compared to observations

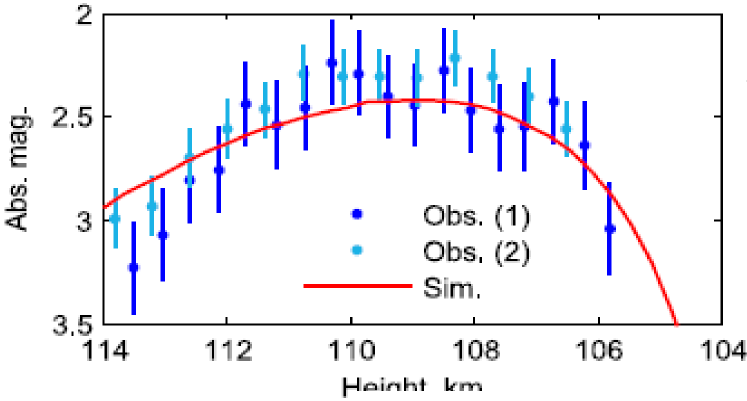
- fragmentation influence?
- absence of inelastic losses, cross sections could be different?
- other ablation coefficient, losses on heating&re-readiation etc?

Important to compare with other observations in similar conditions – H,V, M

Influence of model assumptions

meteor 20101103_063032 light curve (Stokan et al.2015)

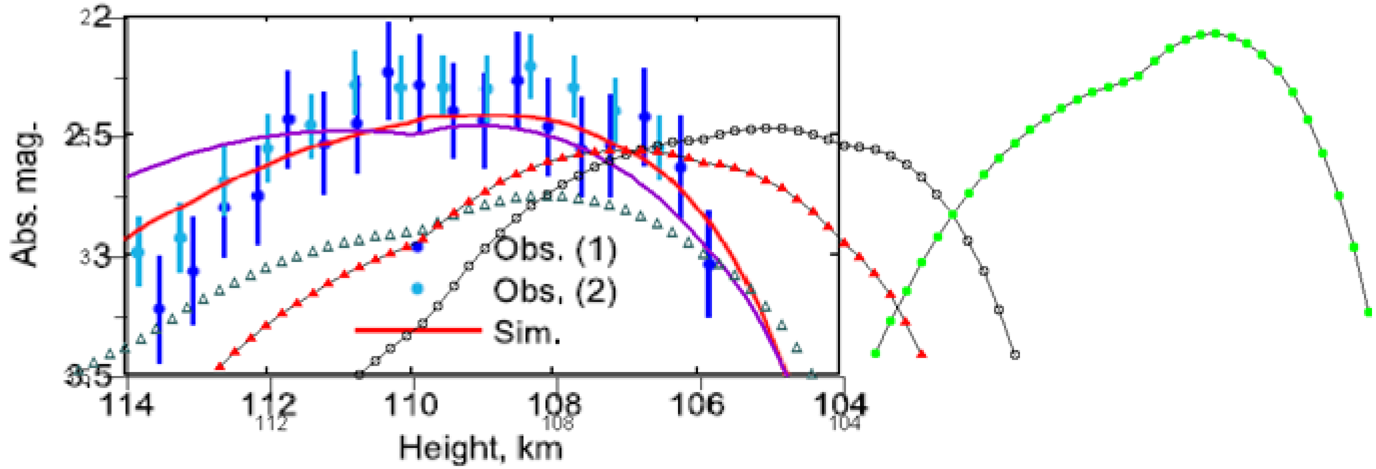
blue points – observations
red - model result



(a)

Ablation model – mass-loss equation,
- no vapor screening C_h~1
- the meteoroid T is constant,
- all of the incoming particle energy - evaporation
- V~71 km/s

M,ρ - estimated

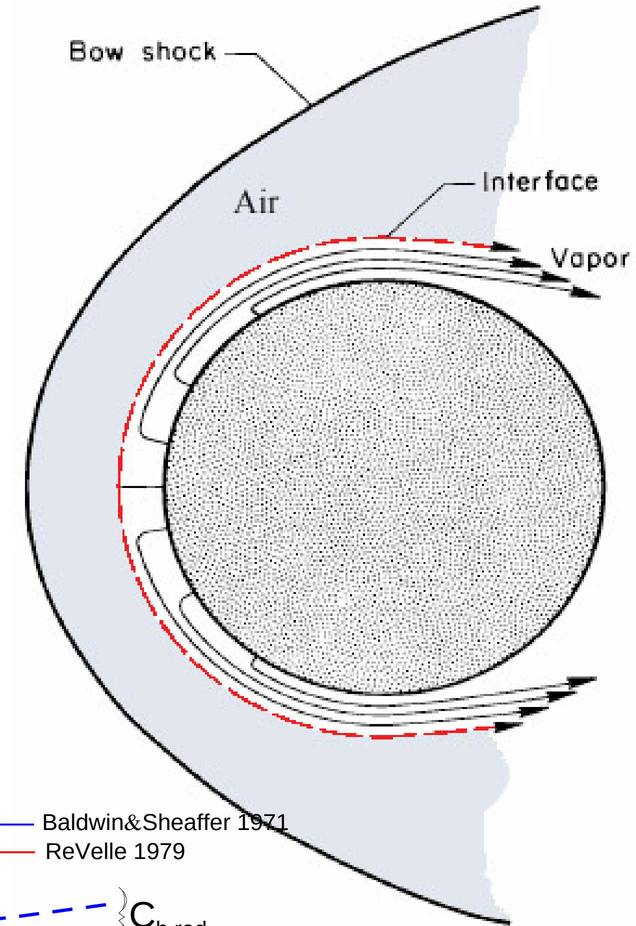


(a) Light curve

The same M, ρ - different model parameters:
- energy loss on meteoroid heating
- different vapor pressure dependences
- C_h with screening effects
- luminous efficiency is the same ☺

Continuouse flow regime

Large meteoroids (> cm-sized):
 ablation occurs at middle-low altitudes- *shock wave formation*



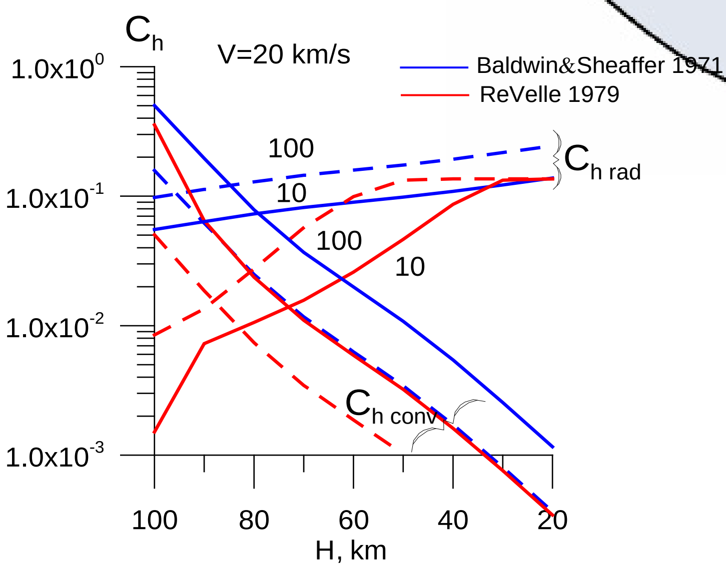
Main considered ablation process - evaporation

Ablation equation
$$\frac{dM}{dt} = -C_h\left(\frac{S\rho V^3}{2Q}\right)$$

$C_h = C_h$(R, V, H, material) – heat transfer coefficient;
Q – effective heat of ablation

C_h - sum of convective and radiative coefficients;
$C_h = C_h(R,V,H)$

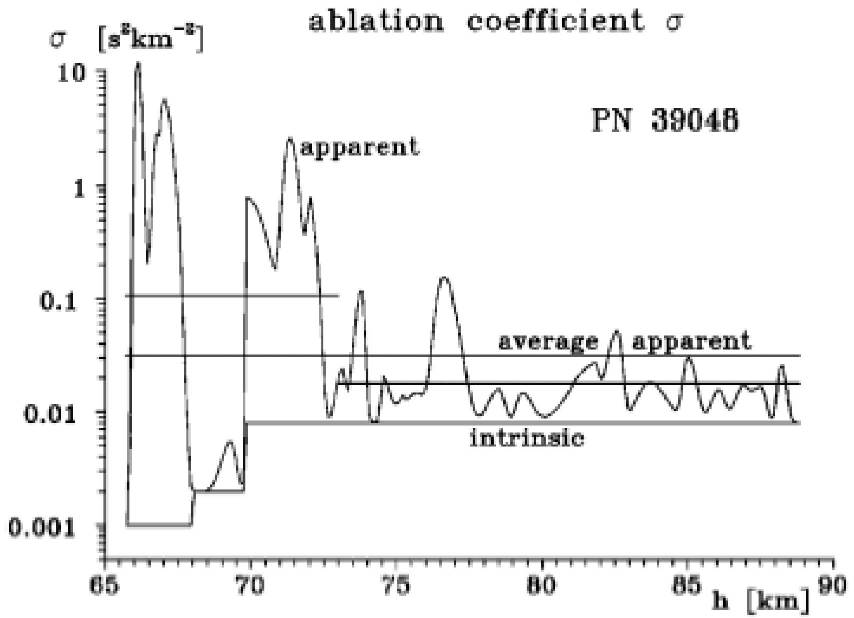
Convective heat transfer - is more important at high H, smaller sizes R and low V;
radiative – at low H, larger R, higher V.



Estimates of C_h :
 - demonstrate wide dispersion,
-are often extrapolated out of the range of initially obtained approximations;
 - have different restrictions

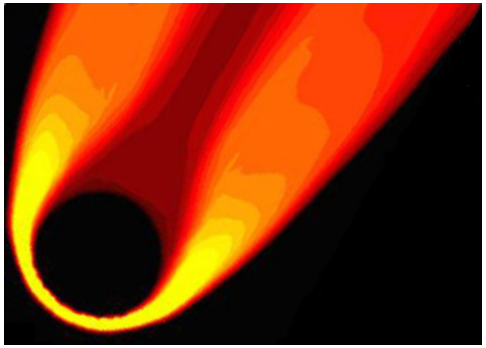
Modeling of meteoroid passage

• **fitting of observational data** *(deceleration and/or light curves)* **and determination meteoroid parameters** (*ablation coefficient, amount of mass loss, fragmentation points etc)*: **gross-fragmentation model** *(Ceplecha et al, 1993)*, **FM model** *(Ceplecha and ReVelle 2005)*

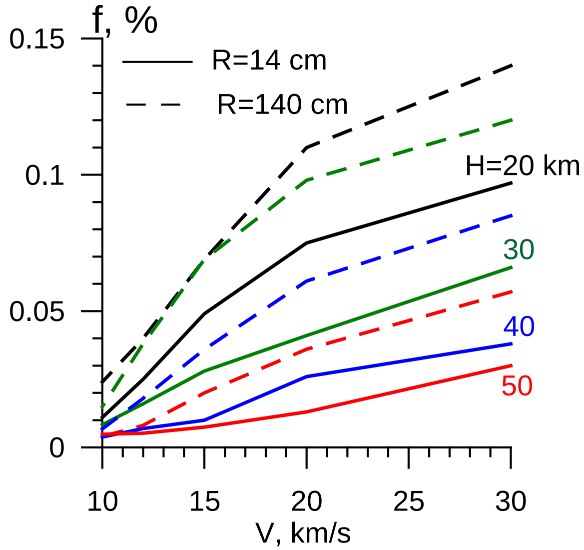


• **application of standard equations for large meteoroids entry, reproduction of dynamics and/or radiations for different bolides** *(often supplemented by different fragmentation models) (Baldwin&Sheaffer, 1971; ReVelle, 1978;1980;Borovicka et al.,1998; Nemtchinov et al, 1997; ReVelle 2002; ReVelle&Ceplecha,2002 and others)*

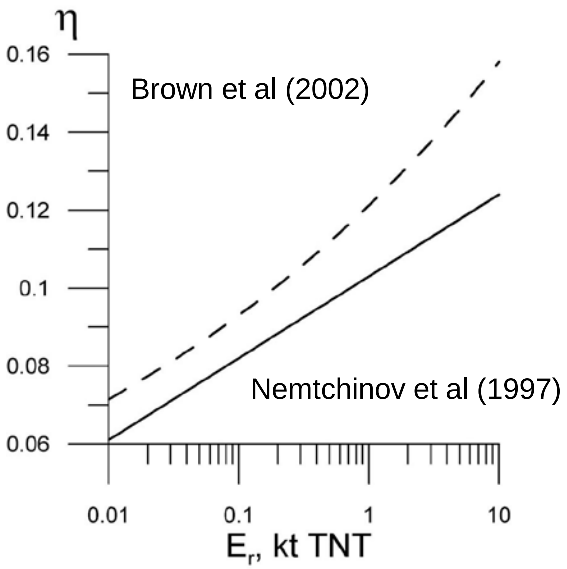
▪**hydrodynamical models, describing the entry of the meteoroid, including evolution of material** (*Ahrens et al, 1994; Boslough et al, 1994; Svetsov et al, 1995; Ivanov et al, 1992; Shuvalov&Artemieva, 2002 and others); mainly for large bodies D>10-30 m*



Luminous efficiencies



Luminous efficiency from AP model *Golub et al 1997;Borovicka et al, 1998*



Luminous efficiencies – uncertainty;
often are extrapolated from initially assumed range

Obtained from:

- interpretation of observational data
  Ceplecha and ReVelle 2005: $\tau = \tau\left(m, v, \rho_{air} / \rho_{air\,\max light}\right)$
  0.2-10% for PN, EN bolides
- data on artificial meteors (gram-sized, V~10-16 km/s Ayers et al 1968);
- models
- AP values were used to determine (*Nemtchinov et al (1997)*)

Integral luminous efficiency $\eta = E_r / E_k$

E_r – optical energy; E_k – kinetic energy

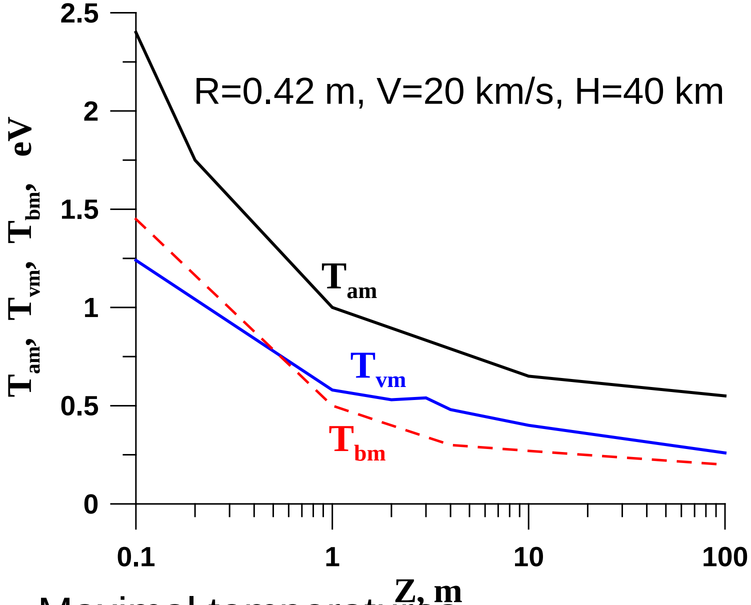
Independent estimate η based mainly on infrasound registrations (13 events, 3 meteorite falls) (*Brown et al 2002*) agrees with theoretical estimates based on AP model

Moravka: ~10±5% (Borovicka et al 2003); Almahata Sitta ~6-9% (Jenniskens et al 2009; Popova 2011)

Hayabusa: 1.3% (Borovicka et al 2011)

Ablating piston model

Systematic calculations of radiation efficiency and ablation rate for H-chondrites (OC) and irons were done in the ablating piston model (AP) *(Golub' et al. 1996;1997)*.



- is based on analogy between 1D nonstationary motion of a cylindrical piston and 2D quasistationary flow around the body
- Radiation transfer *(in the vapor and in the air)* are taken into account
- Strict boundary between vapor and air is assumed *(no mixing)*
- Determines T, ρ, Ch, τ , spectra

Maximal temperatures

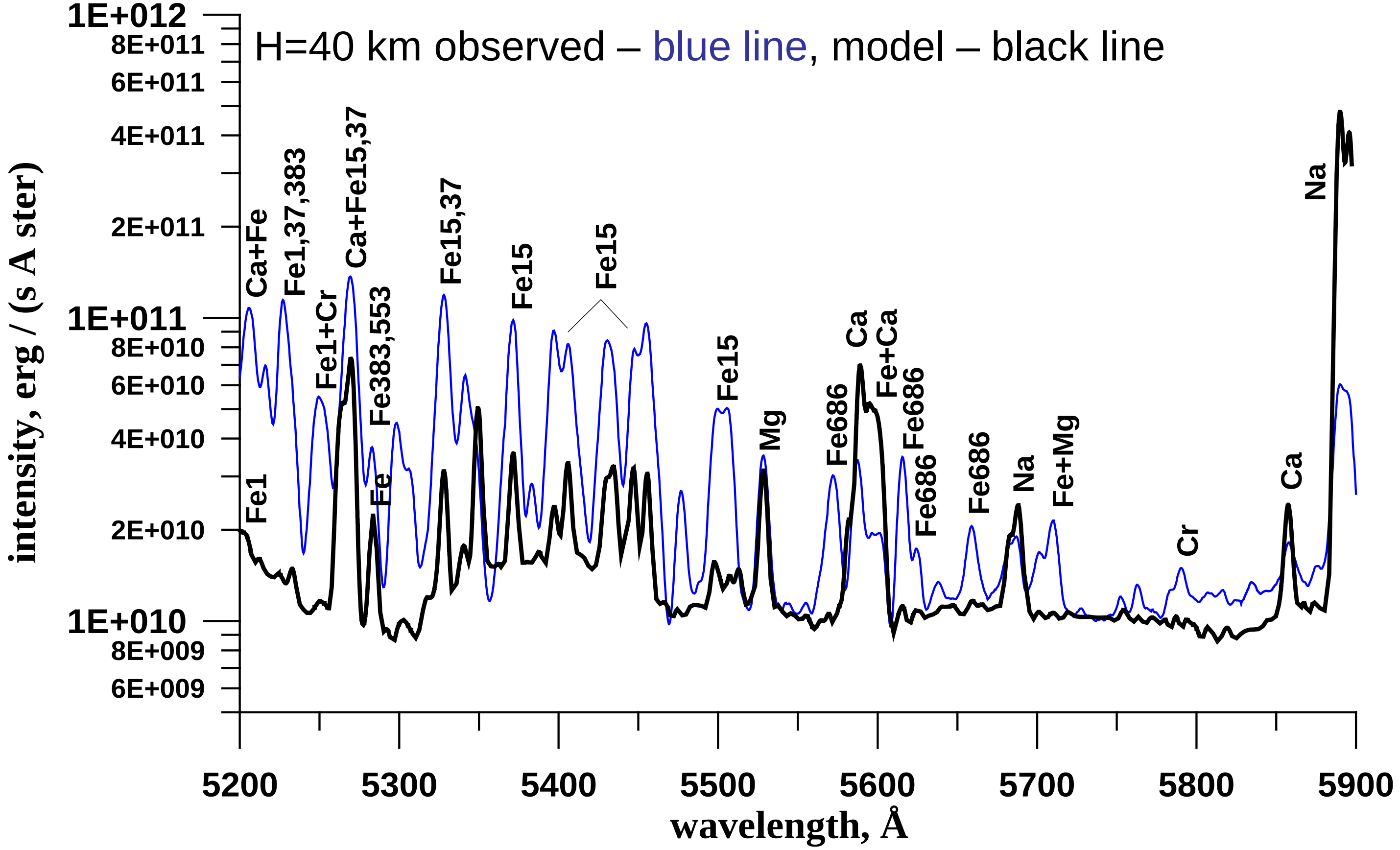
- of the air T_{am}
- of the vapor T_{vm}
- the brightness T_{bm} *(panchromatic)* in the cross-section of the bolide versus the distance along the axis Z

Predicts:

- a large part of energy is radiated out of registration passband
- the luminous efficiencies in different passbands differ
- different parts of bolide are responsible for emission in the different spectral ranges

- Model σ~**0.002 - 0.003** s^2/km^2 (14 cm; 20 km/s, 40-30 km) – does not contradict to σ, extracted from observations

Theoretical and observed spectra of Benešov bolide



In the model:

- **FeI** lines are too faint
- CaI lines are too bright
- the continuum level is larger
- absence of SiII, NII

Possible explanation:

vapors occupy larger volume and have lower density than model predicted - probably a consequence of mutual interaction of fragments after the meteoroid fragmentation and of a not well understood ablation process (air-vapor mixing)

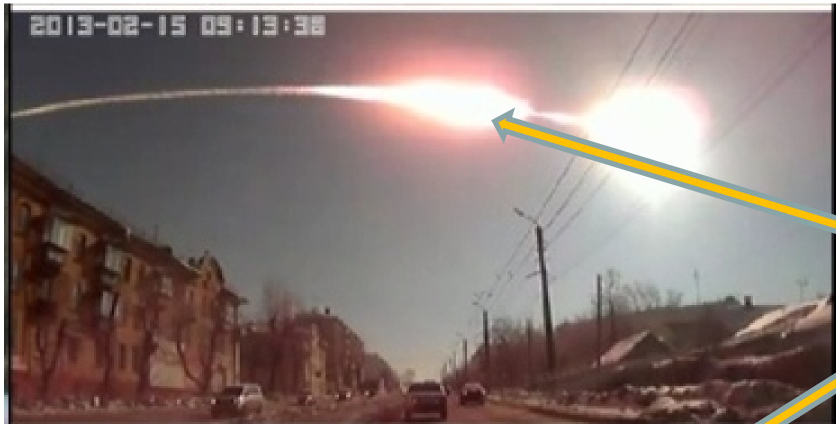
First and still last detailed comparison of a purely theoretical radiative-hydrodynamic spectral model and the observed spectrum of a bolide

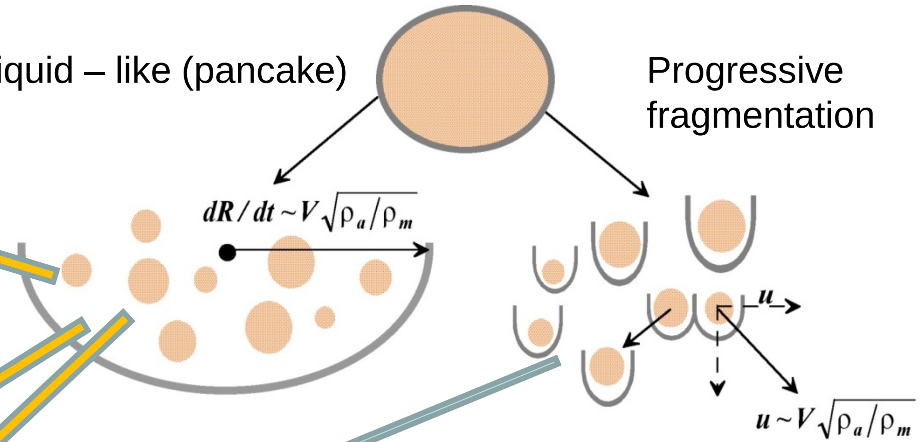
Consistent picture of the Benešov bolide, including its mass, dynamics, fragmentation and radiation was obtained *(Borovička et al, 1998a; 1998b)*

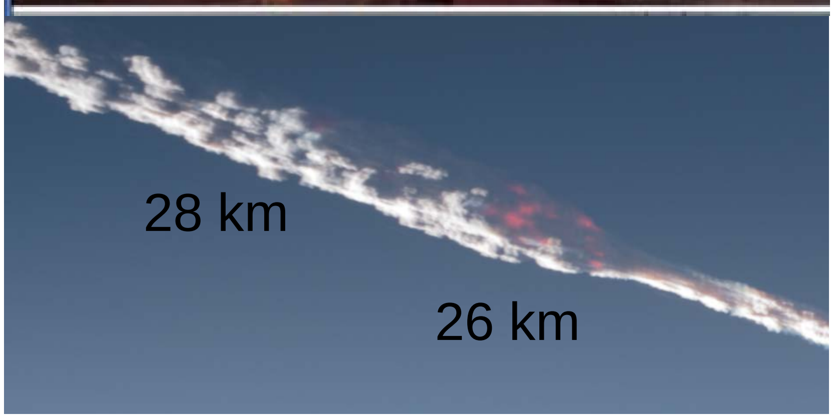
Meteoroid fragmentation

Video records demonstrated complicated character of meteoroid disruption:
- formation of decelerated debris cloud and independent fragments continued their flight with subsequent further disruption

Modeling of meteoroid fragmentation







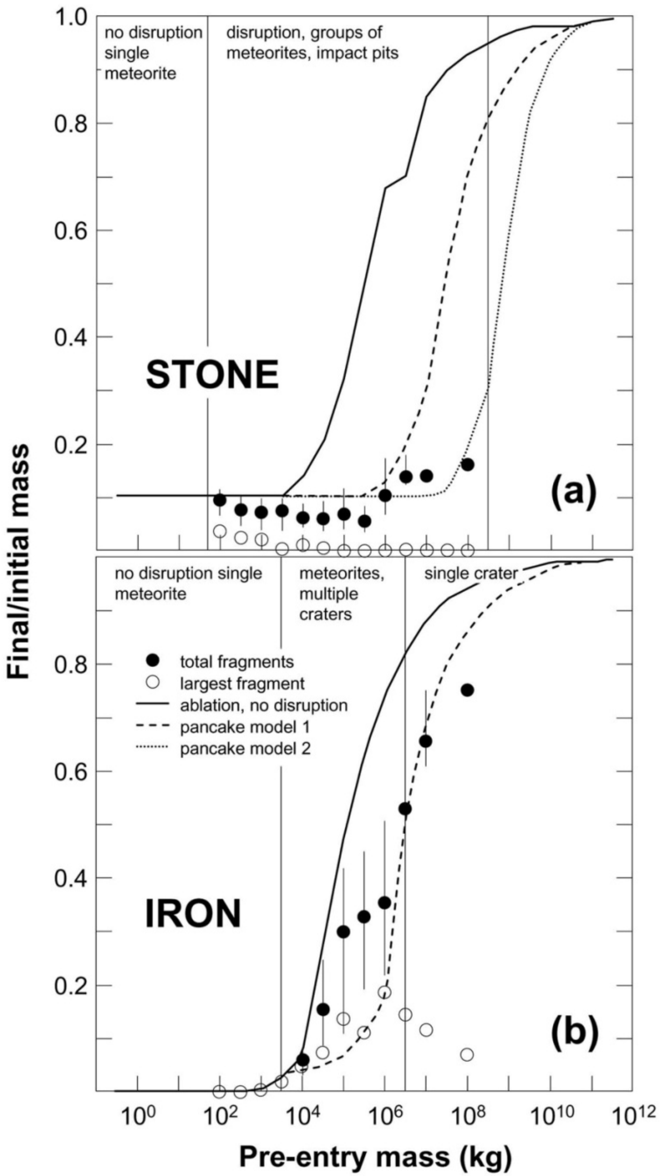
Meteoroid fragmentation:

- formation of separated fragments
- cloud of small fragments and vapor united by a common shock wave

Both types are realized in real events:

Benesov, Almahata Sitta, Tagish Lake,

+Chelyabinsk



Detailed study in the frame of **model of separated fragments** *(Artemieva, Shuvalov 2002; Bland Artemieva 2006)* – one of progressive fragmentation type models

V~18 km/s; M>few kg

Iron and stones

for stones σ_0~4 10^7dyn/cm^2

Strength scaling law

$\sigma = \sigma_s (m_s / m)^\alpha$ *(σ, m – the strength and mass of the larger body; σ_s , m_s – those of tested specimen); small deviations are allowed ~10%*

M_{fall}/M~5-10% for M~100 kg-1000 t stones

Larger for irons (0.05-0.5)

No fragmentation for M<50 kg

Result are dependent on assumed strength and fragment distribution at breakup

Fragmentation has no influence on entry of body larger 10 km (t_{flight}<$t_{fragmentation}$)

Moravka (06 May 2000) *(Borovička et al., 2003)*

M~ 1500 ± 500 kg, V~22.5 km/s

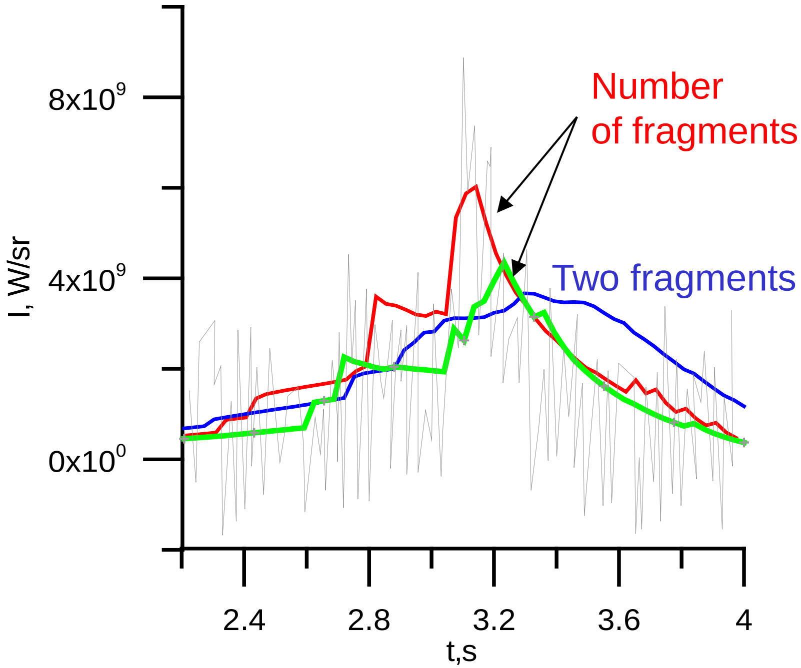
6 fragments H5-6 chondrite
(0.09-0.33 kg)
$\sum M \sim 1.4$ kg (~0.1% M_0)
(predicted $\sum M \sim 100$ kg~7% M_0)

along 10 km strewn field

Progressive fragmentation at 36-29 km,
possible disruption >46 km

Modeling: progressive fragmentation provides some agreement of fallen meteorites masses and numbers , strewn field size

Light curve fitting:
many small fragments formed,
probably another mass distribution at breakup;
does not suggest large amount of dust formed



Strewn fields are another source of information about fragmentation behavior

Mbale meteorite fall

Jenniskens et al., 1994

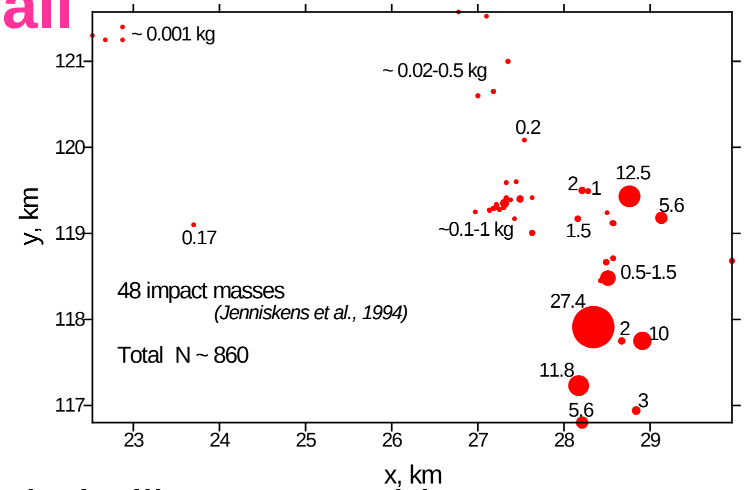
14.08.1992, L5/6

$\Sigma M_{collected}$ ~150 kg; ΣN~850;

Estimated

M_{fall} ~190±40 kg

V~13.5 km/s; M_0~1000 kg

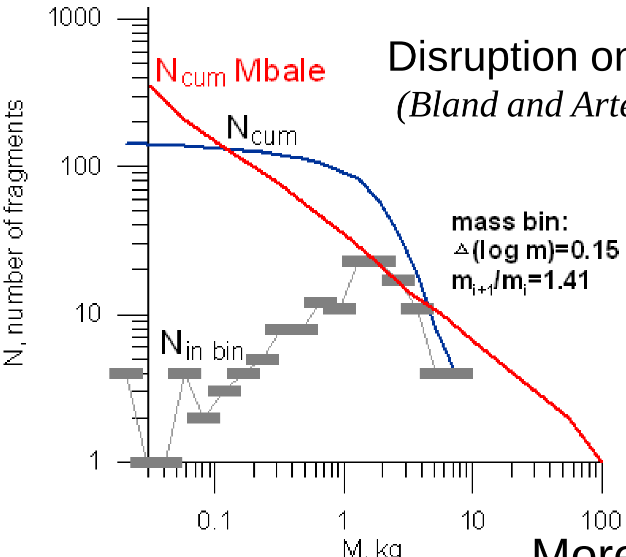


Progressive fragmentation model: M_0~1000 kg, Mbale-like meteoroid

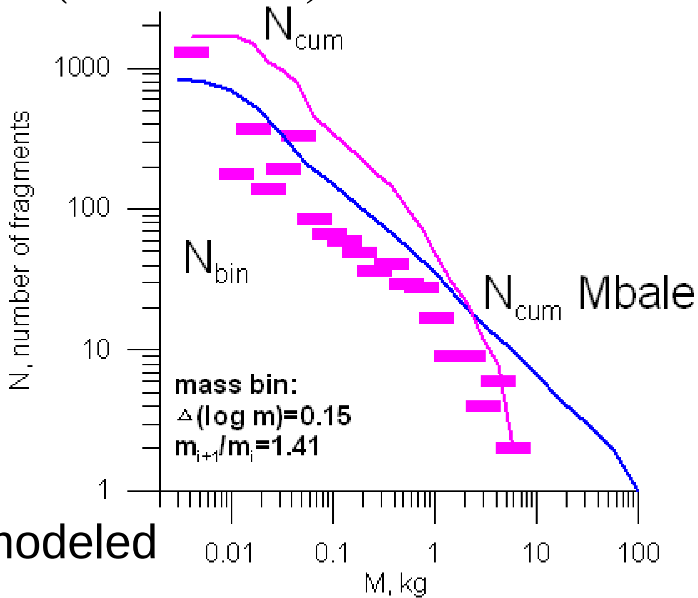
-ΣM_{fall} ~220-240 kg; ΣN~100 – 3000 ; size of strewn field – close to observed one

Formation a number of pieces at breakup seems describe the observed distribution better

Disruption onto two fragments *(Bland and Artemieva, 2006)*



Forming a number of pieces following power law distribution *(Hartmann 1968)*



More strewn fields should be modeled

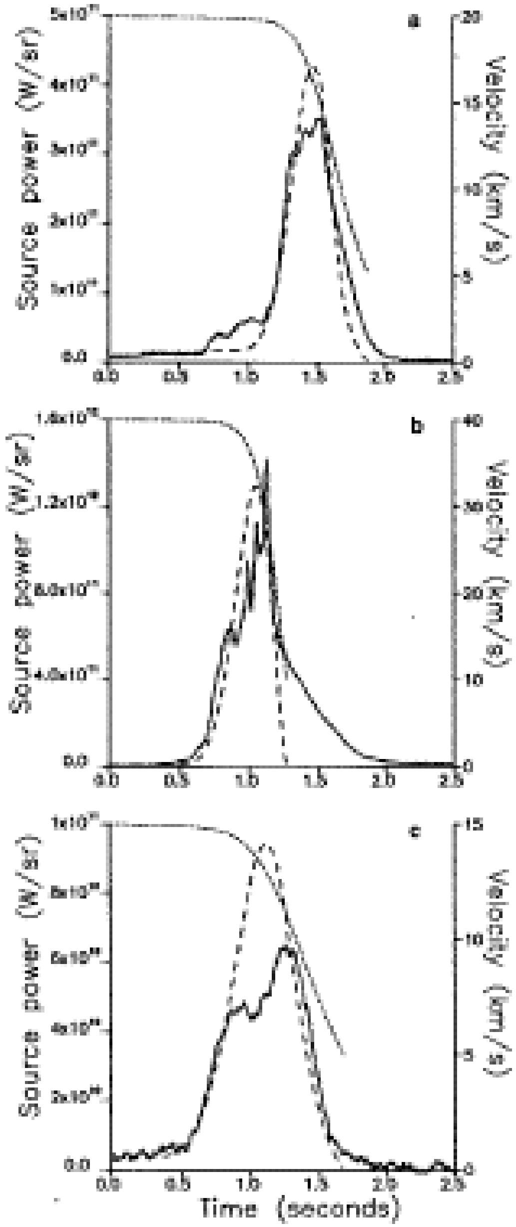


FIG. 13. Comparison of the registered power of light flashes (solid lines) with the results of calculations based on the analytical model (dashed lines). Time dependence of calculated velocity is shown by dotted lines. (a), (b), and (c) represent the 1 October 1990, 15 April 1988, and 4 October 1991 events, respectively.

Liquid like models

are applicable for **large impactors**,

which are destroyed so intensively that fragments couldn't be separated (>~4-10 m in size)

(Svetsov et al., 1995; Bland and Artemieva 2006: estimates are parameters dependent),

say nothing about fragments size

But its modifications provide reasonable energy release (similar to progressive fragmentation models)

were used to explain light curves meter in size bodies (Satellite Bolides and others) *(Svetsov et al.,1995; Nemtchinov et al., 1997)*

Formation of debris cloud - directly observed for

Benešov bolide (M~3000 kg),

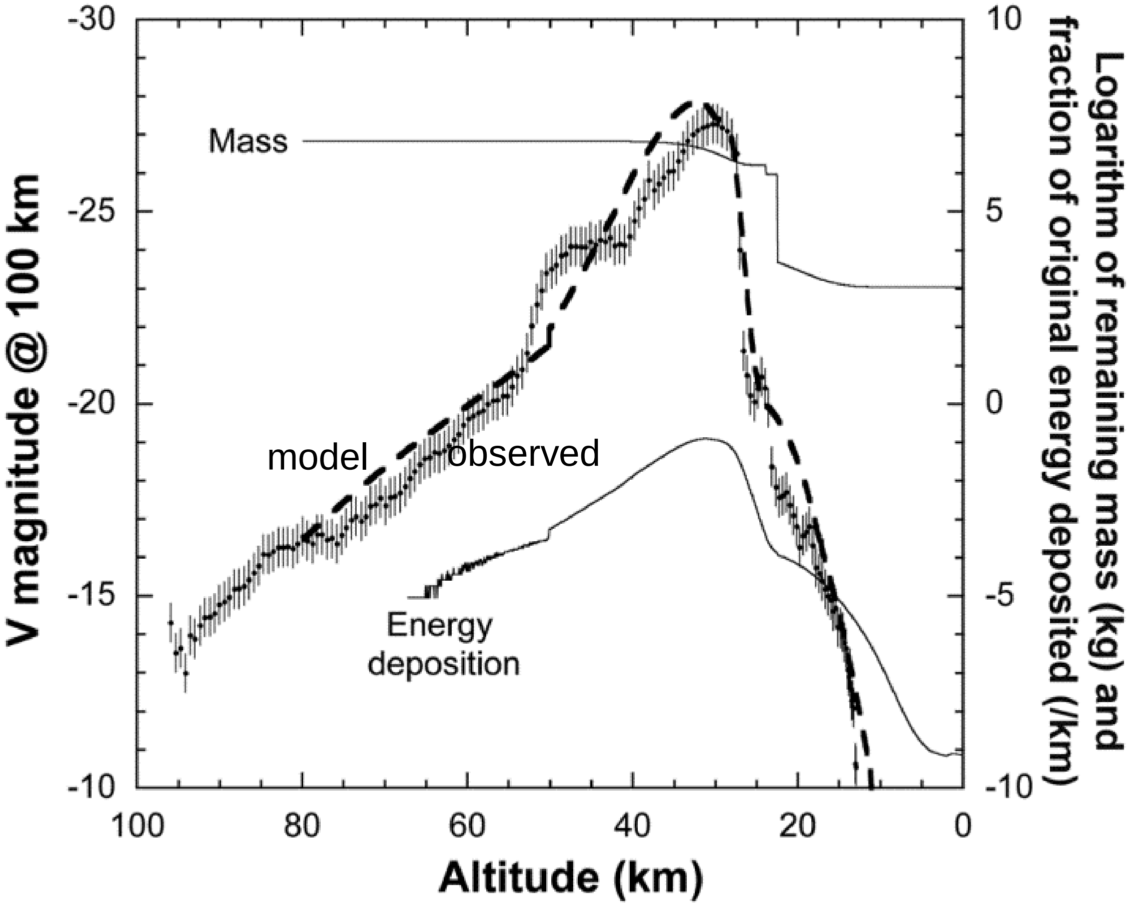
Marshal Island bolide (M~400 ton);

TC_3 2008 (Almahata Sitta; M~80 t);

and others, including

Chelyabinsk, 15 February 2013 (12 000 t)

Modeling efforts



Lightcurve, model fit (dashed),
mass passing given altitude (thin),
normalised rate of energy deposition (low thin)

Hybrid model:

- part of mass – independent fragments
- part of mass - spreading debris clouds
- fragmentation occurred at loadings ~P~0.3-10 MPa

allows to reproduce the observed light/deceleration curves

M_{vapor}~76% M_0;
M_{dust}~24% M_0
$M_{meteorites}$~0.03-0.06% M_0

Many models *(Borovicka et al 2013, Brown et .al 2013, Avramenko et al. 2014 etc):*

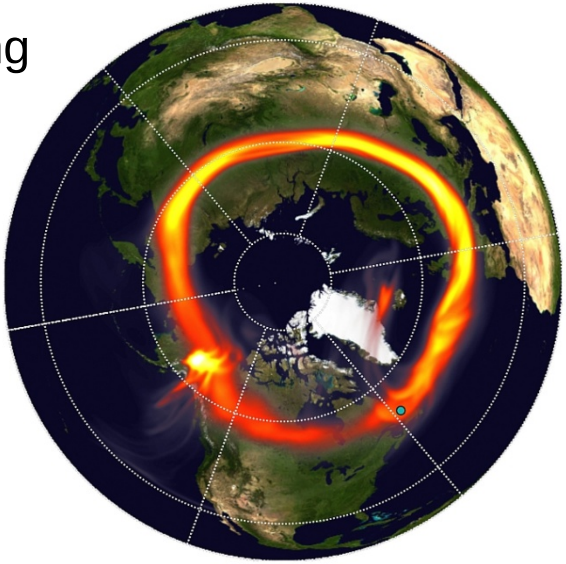
-complicated character of fragmentation

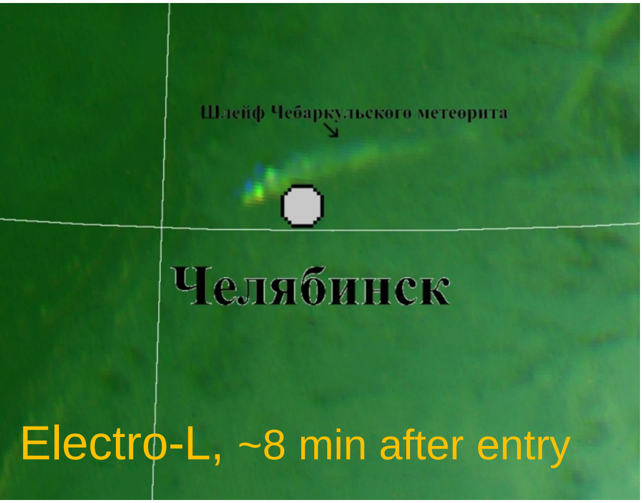
- H~ 50-20 km

Chelyabinsk dust trail

Detail of the train's thermal emission (5-6 s after formation)

Dust cloud – formed during fragmentation,
at 80-20 km,
more massive 40-25 km





After 3 hours – at L~1000 km
After 4-7 days – dust ring around pole (H~30-40km,
5 km thick, ~300 km wide; 0.9-0.05 μm)
After 3 months – still existed *Gorkavyi et al. 2013*

Other events:

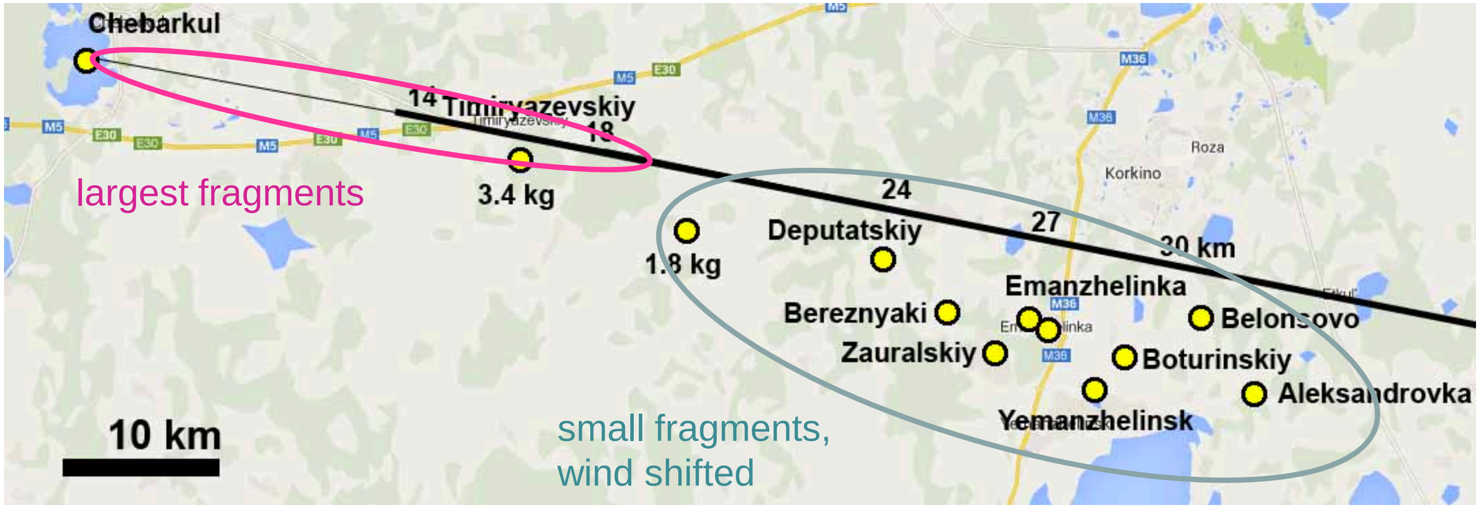
3 September 2004 *(Klekociuk et al., 2005)*:
M~650 – 1400 ton, M_{dust}~1100 t, μm-sized

4-m sized 2008 TC_3 :
M_{dust}~25% M_0 (5%- recondensed)
(Borovicka and Charvat, 2009)

Our modeling suggests that a similar value applies to **Chelyabinsk**

Meteorites strewn field

60,32°E, 54,959°N - ~ 54,7°N, 61,3°E, >80 km length



Confirmed locations of meteorite finds. Numbers on trajectory indicate meteor height

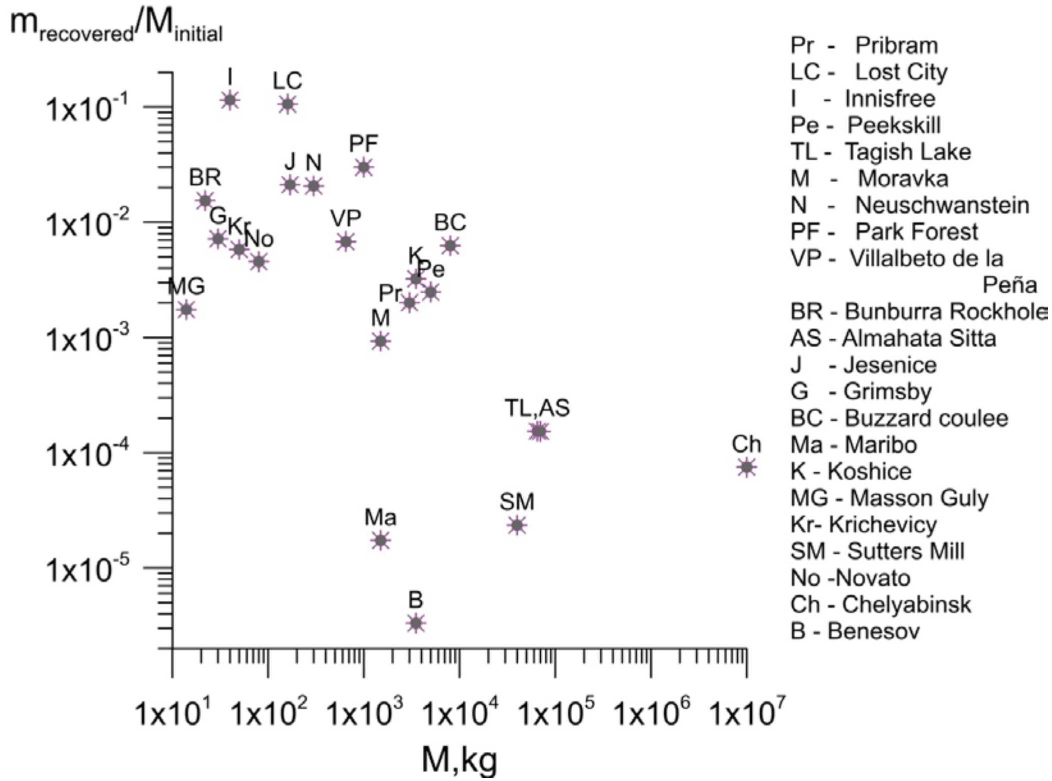
Light curve and speed of fragments <20 km altitude - provide information on the deeply penetrating fragments

-positions (0.01-100 kg) fragments are in agreement with observations
-model overestimate number of fragments
-more fragments >kg still not found?

Borovicka et al 2013 – treated individual light/deceleration curves – good agreement with found meteorites mass/locations

Total meteorites mass

The relation of m_{rec} to initial M



Old estimates:
$M_{meteorites}$ ~10% M_o

Data on 22 falls with tracking data:

m_{rec}/M~0.1-3 % mainly (0.001-10%);

Smallest: <0.01%
Some trend:
larger mass-smaller fraction

Ablation is more effective for fragments flying together in the same hot area (volumetric evaporation), resulting in decreased fraction of survived mass.

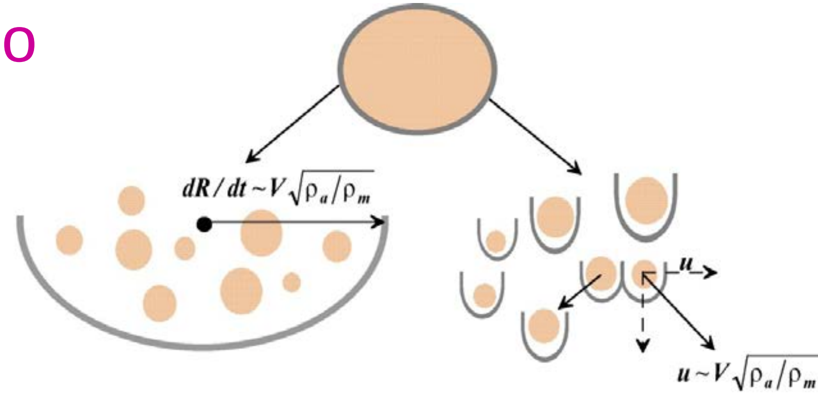
The larger body – then probably the larger part of fragments continue flight together and the smaller meteorites mass (Tunguska case).

Our estimates

(model for largest fragments+strewn field density for small ones)

Chelyabinsk: $\sum$M~4-9 ton - is only 0.03-0.06% M

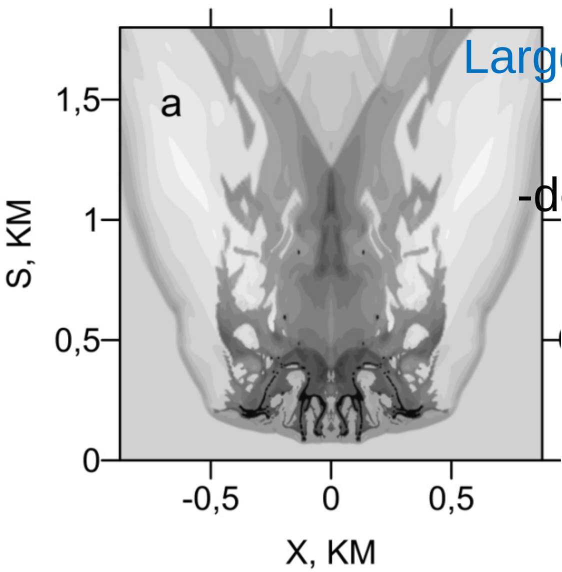
Fragmentation scenario



Small meteoroids (<1-20 m):

complicated fragmentation, where fragments:

- may form debris cloud,
- may move as individual bodies,
- decelerate before total evaporation
- produce meteorites and dust deposition in the atmosphere



Larger (30-300 m) meteoroids (hydrodynamical modeling), their fragments

-move as a cloud surrounded by a common shock,

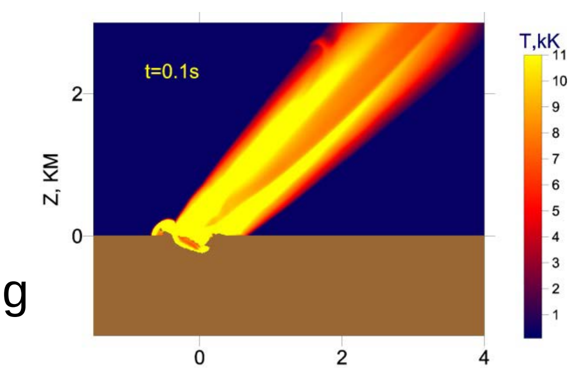
-decelerate later and have more chances to be totally evaporated

Aerial bursts - "burning out" of comparatively large (D~ 100 m) bodies in the atmosphere *(Wasson and Boslough, 2000)*

- the entire energy is released in the atmosphere
- no observable crater is formed
- affect the Earth's surface *(fires, shock waves)*
- typical example - Tunguska event

Large meteoroids (>100-1000 m):

- do not decelerate in the atmosphere,
- produce craters

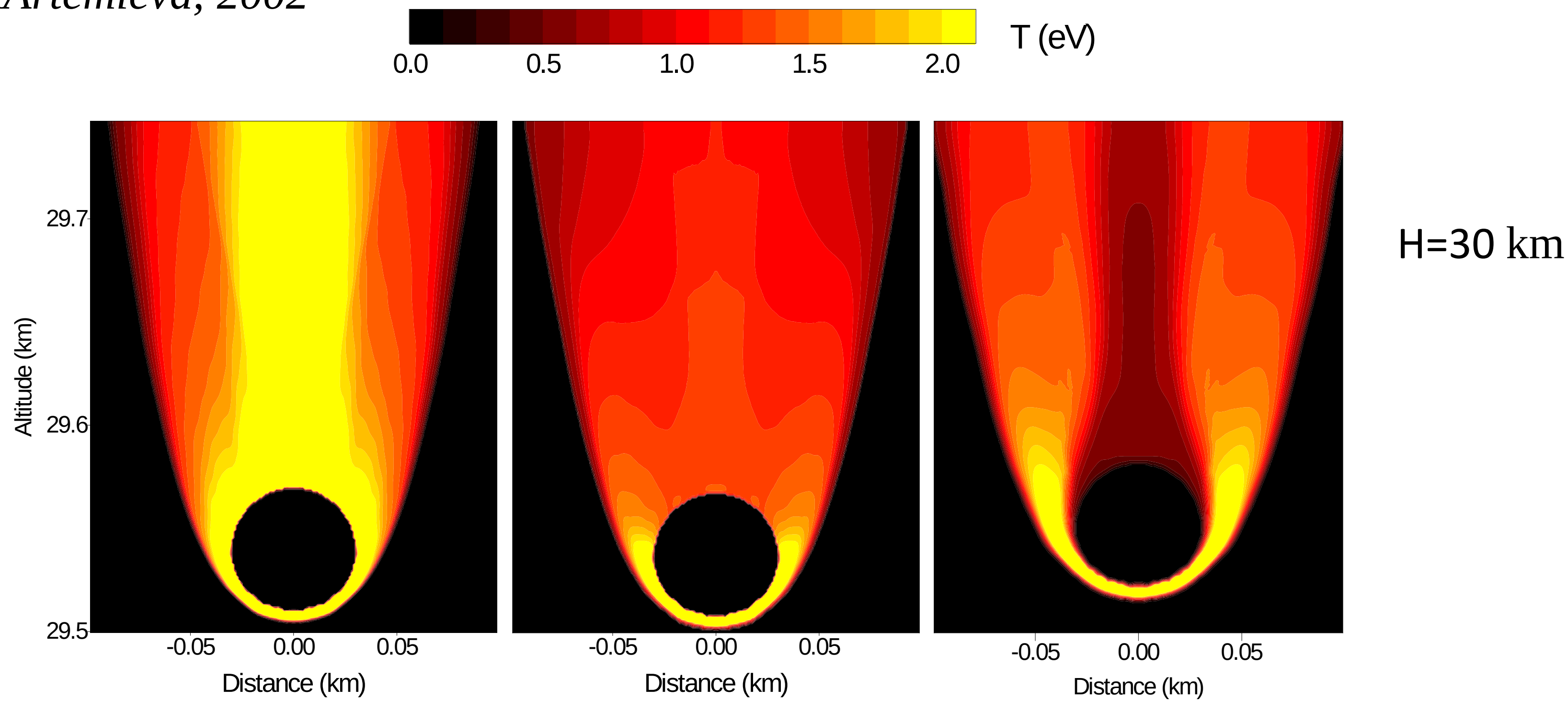


The boundaries between these regimes

- on projectile composition, entry V and impact ang

Temperature distribution, quasi-liquid, R=30 m, cometary meteoroid, V=30 km/s

Shuvalov&Artemieva, 2002



pure gasdynamic run **with radiative transfer** **with ablation and radiation**

Ablation as evaporation (vapor flux $\Delta m = q \Delta t / Q$, q-heat flux; Q-heat of evaporation), radiation in thermal conductivity assumption

Radiation transfer:

- considerably diminishes the near wake temperatures
- increases wake radius
- causes energy redistribution in the near wake

Ablation:

- increases effective meteoroid size,
- increases wake size,
- wake core with vapor is colder than outer layers

One of possible scenarios of the Tunguska event
(D=100 m; cometary; 45^0 ; V~ 50km/s)

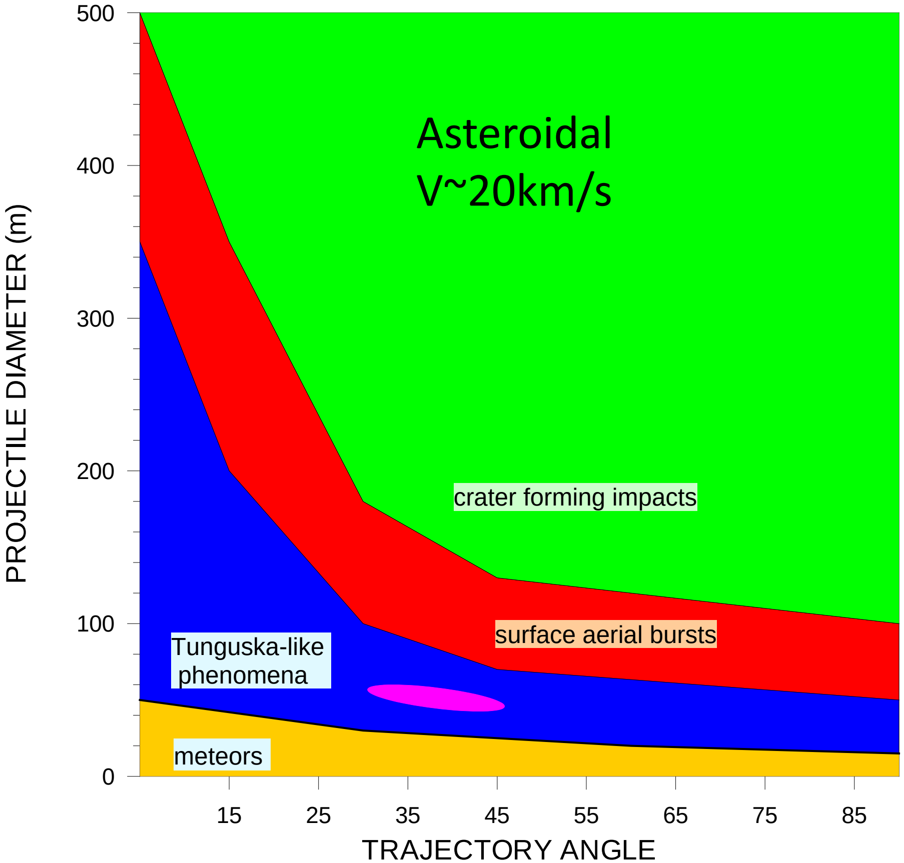
Main stages of evolution

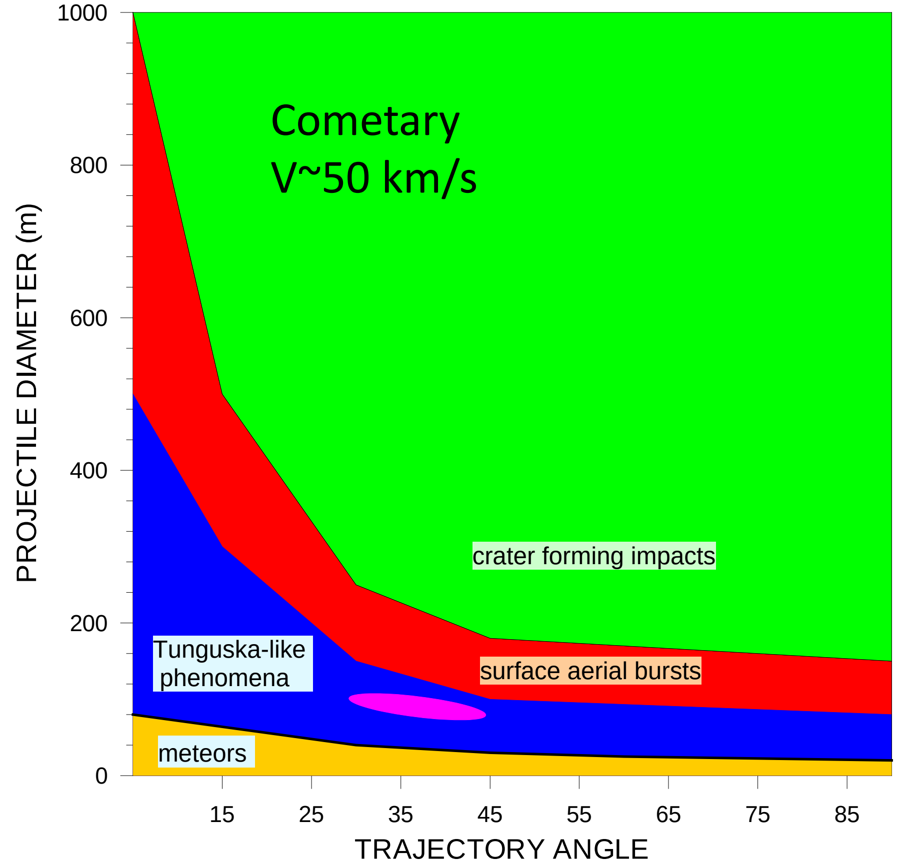
- body deformed, flattned and fragmented into nonuniform debris jet
- debris jet evolution – the most energy release
- explosive – type evaporation and jet formation, its fast deceleration
- upward deceleration of hot vapor along the wake and plume formation

(Shuvalov, Artemieva, 2007)

Different styles of impact

(Shuvalov and Trubetskaja, 2007)





Dependent on projectile **sizes/material** and trajectory **angles** α*(to horizon) ; note different vertical scale.*

Solid fragments of comet D>100 m reach the ground at α ~90^0 ; 300-m asteroid could mainly burn in the atmosphere in 5^0 oblique impact. Violet ellipse - parameters of Tunguska body

The height of energy release may be essentially decreased (10-20 km) if **internal friction effect** is included *(Shuvalov and Trubetskaya 2010)*

Concluding remarks

Interaction of meteoroid with atmosphere is dependent on size/mass, velocity and altitude of flight, meteoroid properties

Fragmentation is important for different sized body,
neglecting fragmentation in interpretation of observations may led to erroneous results

- **Free-molecule regime and Transition regime**

Uncertainty: luminous/ionizing efficiencies
importance of fragmentation – question about meteoroid structure
state of ablated material, spectra

High-resolution video observations - provide strong constraints for models, will allow to improve understanding of both meteor-atmosphere interactions, and the physical properties (strength, density, mass) of meteoroids and their parent bodies

progress during last years
DSMC and hybrid modeling are good tools here

- **Continuous flow regime**

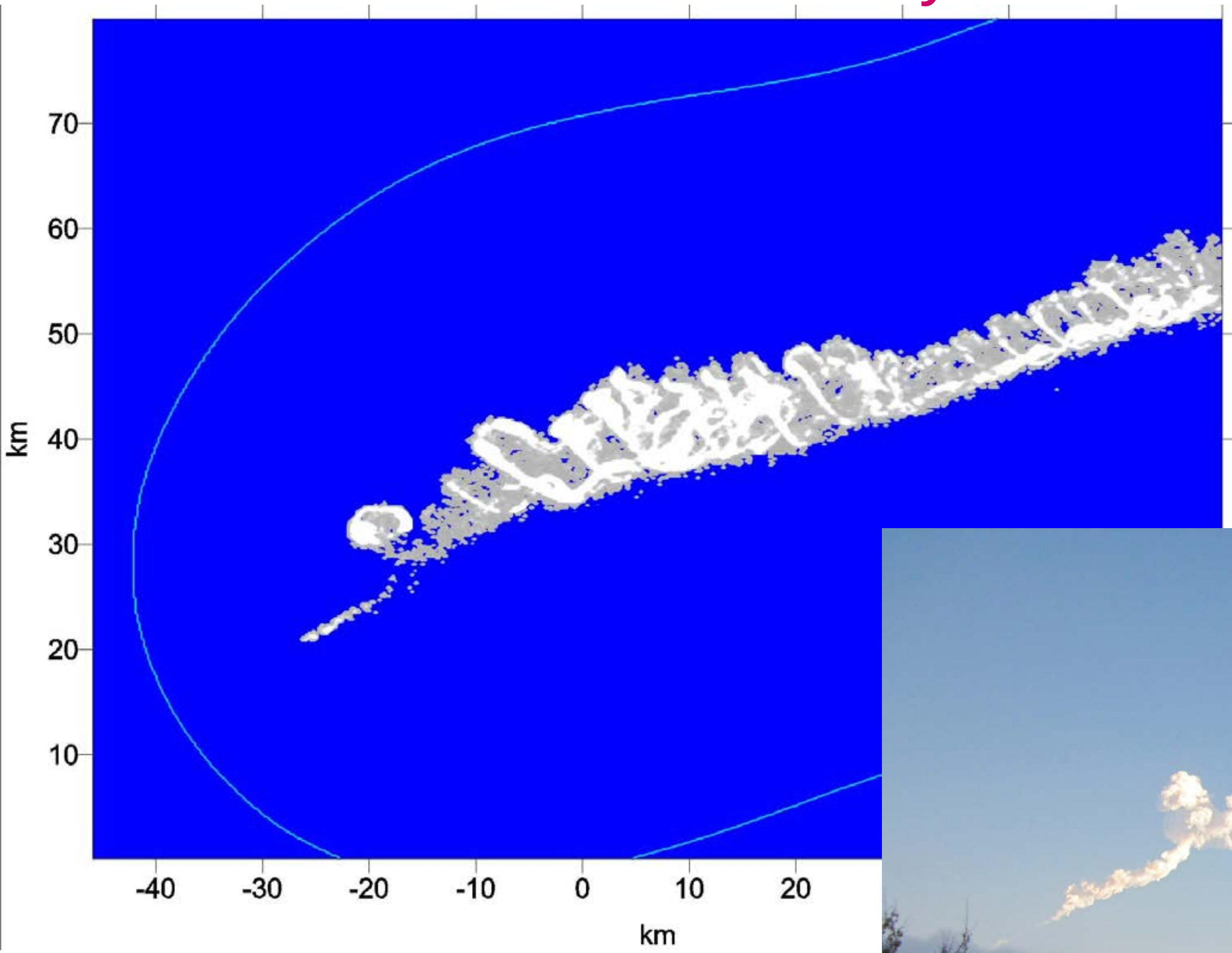
Still there are no totally self-consistent 2D-3D model with radiation/ablation for whole range of R/V/H and compositions;

Estimates of C_h and luminous efficiencies used - demonstrate wide dispersion,

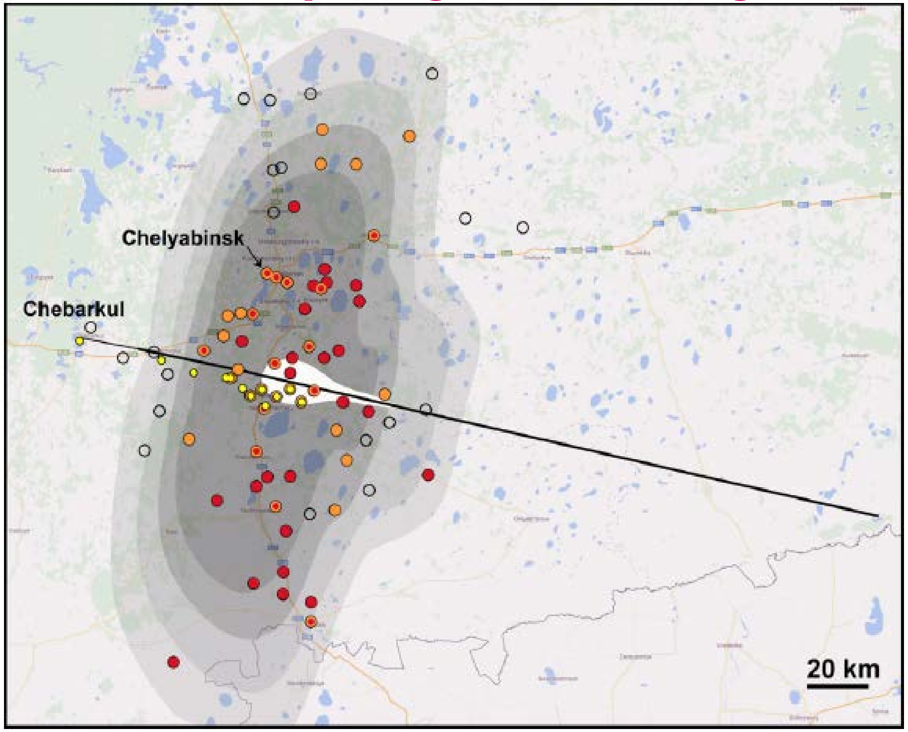
Strength, fragment distribution at breakup, realization of peculiar type of fragmentation, influence of QCF on C_h – are still not well determined

Detail comparison of observational and model results is done for limited number of events due both to incomplete observational data and modeling problems

Shock wave of Chelyabinsk meteoroid



Map of glass damage on the ground



Contours :
(from dark to light)
300 kt $\Delta p>1000$ Pa,
520 kt $\Delta p>1000$ Pa,
300 kt $\Delta p>500$ Pa,
520 kt $\Delta p>500$ Pa

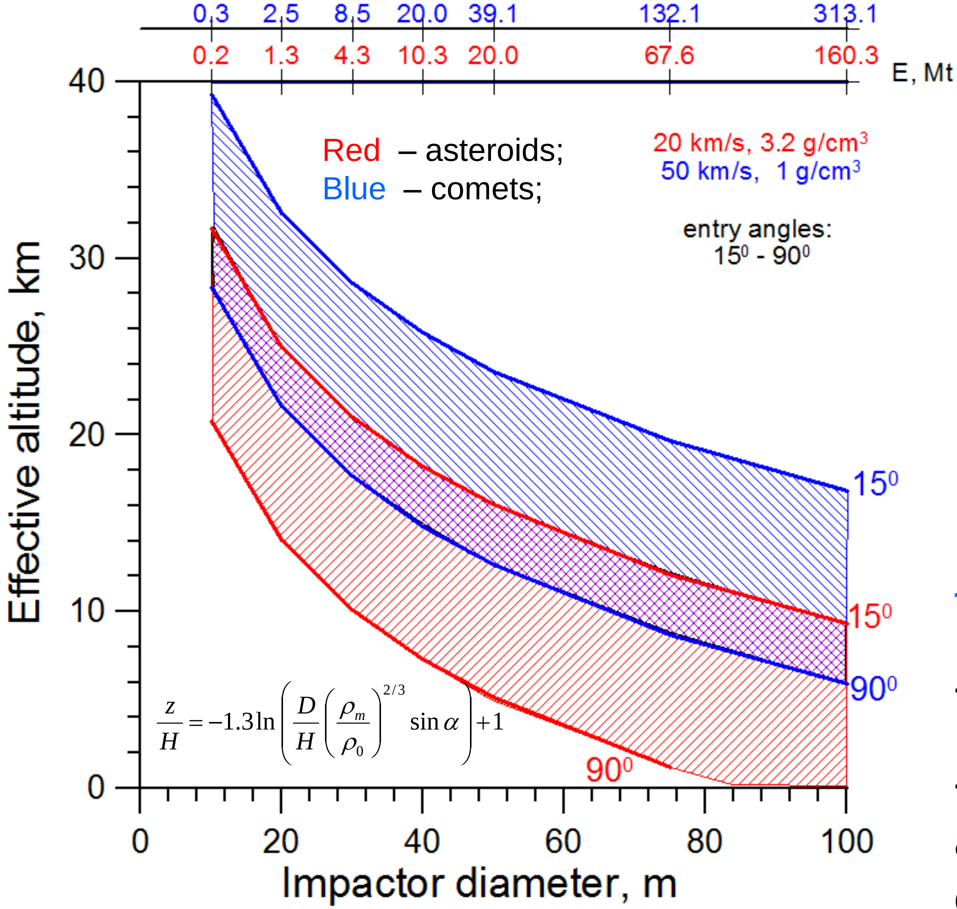
The shape of damaged area – corresponds to energy deposition along extended part of trajectory

$P_{max}>4.3$ kPa

-solid orange circles - for reported damage
-open black circles - for no damage;
-solid red circles the most damaged villages in each district (as reported by the government)..
White - the fireball brightness on a linear scale.

Chelyabinsk, Korkino
model ~2-4kPa
Korkino: P>1.2-2.5 kPa
Brown et al.(2013):
P~2.6-3.8 kPa in Chelyabinsk

Effective airburst altitude



Effective altitude Z dependence on meteoroid size

For quick rough evaluation of the impact consequences

(levels of damage, area of the damage, etc)

at large distances from the ground zero spherical source - reasonable SW evaluation

if the altitude Z of E-equivalent point explosion is correctly determined

QL model was used to determine Z

This approach:

=f(D,density,α) (Shuvalov et al. 2014)

-Precision of estimates - 2-3 km

(random character of disruption)

(there is no velocity dependence as the deceleration efficiency and increase of disrupted meteoroid cross-section are both dependent on entry V)

-Is applicable for D>10-30 m when strength and fragmentation features are not essential

- for D~10-30 m the uncertainty in effective altitude may reach 10-15 km (Chelyabinsk, $TC_3$2008 and other cases)

-(strength, fragmentation features etc)