Fireball Aerodynamics and Luminosity

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Interpretation of Earth observations

Photometric

$$I = -\tau \cdot \frac{dE}{dt}$$

Usually special case considered is:

$$\frac{dV}{dt} = 0$$

$$M = -\int_{t_1}^{t_0} \frac{I}{\tau V^2} dt$$

Dynamical

$$M \frac{dV}{dt} = -\frac{1}{2} c_d \rho_a V^2 S,$$

$$\frac{dh}{dt} = -V \sin \gamma,$$

$$H * \frac{dM}{dt} = -\frac{1}{2} c_h \rho_a V^3 S$$

Towards the analytical solution

$$m\frac{dv}{dy} = \frac{1}{2}c_d\frac{\rho_0 h_0 S_e}{M_e}\frac{\rho v s}{\sin\gamma}; \qquad \frac{dm}{dy} = \frac{1}{2}c_h\frac{\rho_0 h_0 S_e}{M_e}\frac{V_e^2}{H^*}\frac{\rho v^2 s}{\sin\gamma}$$

- $m = M/M_e$; M_e – pre-atmospheric mass
- $v = V/V_e$; V_e – velocity at the entry into the atmosphere
- $y = h/h_0$; h_0 – height of homogeneous atmosphere
- $s = S/S_e$; S_e – middle section area at the entry into the atmosphere
- $\rho=\rho_a/\rho_0$; ρ_0 – gas density at sea level

Two additional equations

- variations in the meteoroid shape can be described as (Levin, 1956)

$$\frac{S}{S_e} = \left(\frac{M}{M_e}\right)^{\mu}$$

- assumption of the isothermal atmosphere

$$\rho = \exp(-y)$$

Analytical solutions of dynamical eqs.

❑ Initial conditions

$y = \infty,\ v = 1,\ m = 1$

$$m(v) = \exp\left(-\beta \frac{1-v^2}{1-\mu} \right)$$

$$y(v) = \ln 2\alpha + \beta - \ln(\overline{E}i(\beta) - \overline{E}i(\beta v^2))$$

where by definition: $\overline{\mathrm{Ei}}(x) = \int_{-\infty}^{x} \frac{e^z dz}{z}$

The key dimensionless parameters used

$$\alpha = \frac{1}{2} c_d \frac{\rho_0 h_0 S_e}{M_e \sin\gamma}, \quad \beta = (1-\mu)\frac{c_h V_e^2}{2 c_d H^*}, \quad \mu = \log_m s$$

α characterizes the aerobraking efficiency, since it is proportional to the ratio of the mass of the atmospheric column along the trajectory, which has the cross section S_e, to the body's mass

β is proportional to the ratio of the fraction of the kinetic energy of the unit body's mass to the effective destruction enthalpy

μ characterizes the possible role of the meteoroid rotation in the course of the flight

Next step: determination of α and β

On the right:
Data of observations of Innisfree fireball (Halliday et al., 1981)

$$y(v) = \ln 2\alpha + \beta +$$

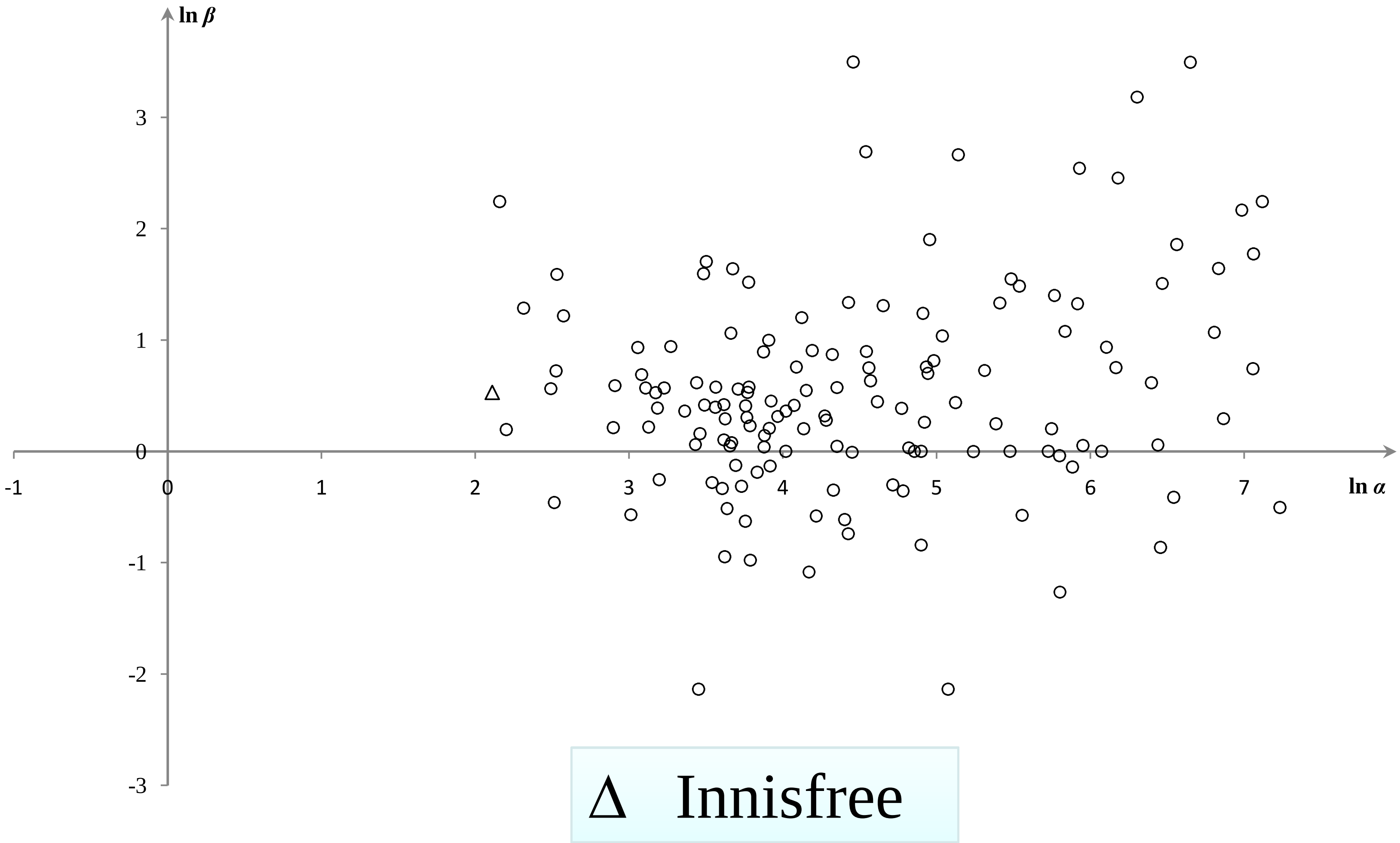
$$- \ln(\overline{Ei}(\beta) - \overline{Ei}(\beta v^2))$$

$$\overline{\mathrm{Ei}}(x) = \int_{-\infty}^{x} \frac{e^z dz}{z}$$

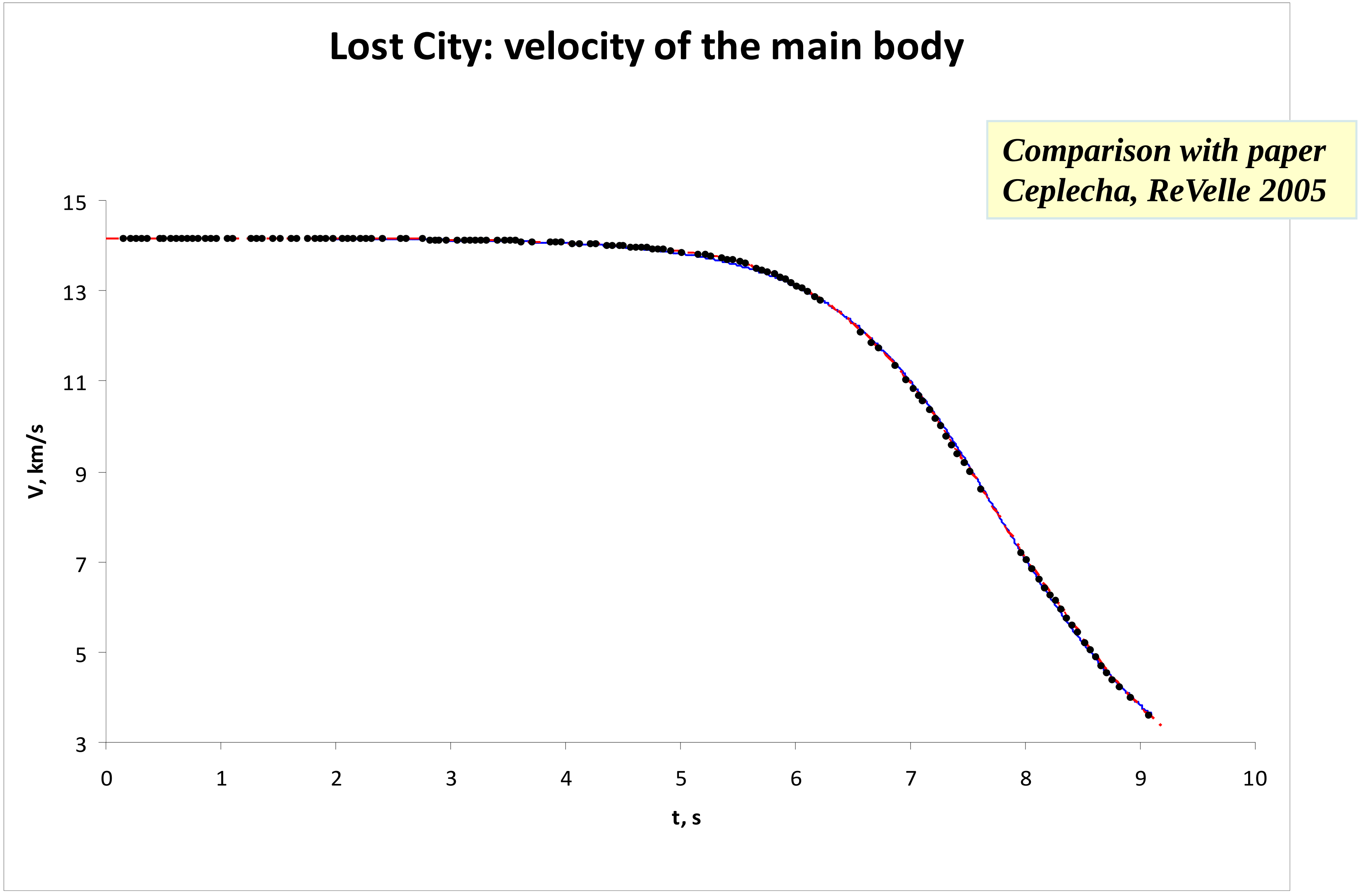
- **The problem is solved by the least squares method**

t, sec	*h, km*	*V, km/sec*
0,0	58,8	14,54
0,2	56,1	14,49
0,4	53,5	14,47
0,6	50,8	14,44
0,8	48,2	14,40
1,0	45,5	14,34
1,2	42,8	14,23
1,4	40,2	14,05
1,6	37,5	13,79
1,8	35,0	13,42
2,0	32,5	12,96
2,2	30,2	12,35
2,4	27,9	11,54
2,6	25,9	10,43
2,8	24,2	8,89
3,0	22,6	7,24
3,2	21,5	5,54
3,3	21,0	4,70

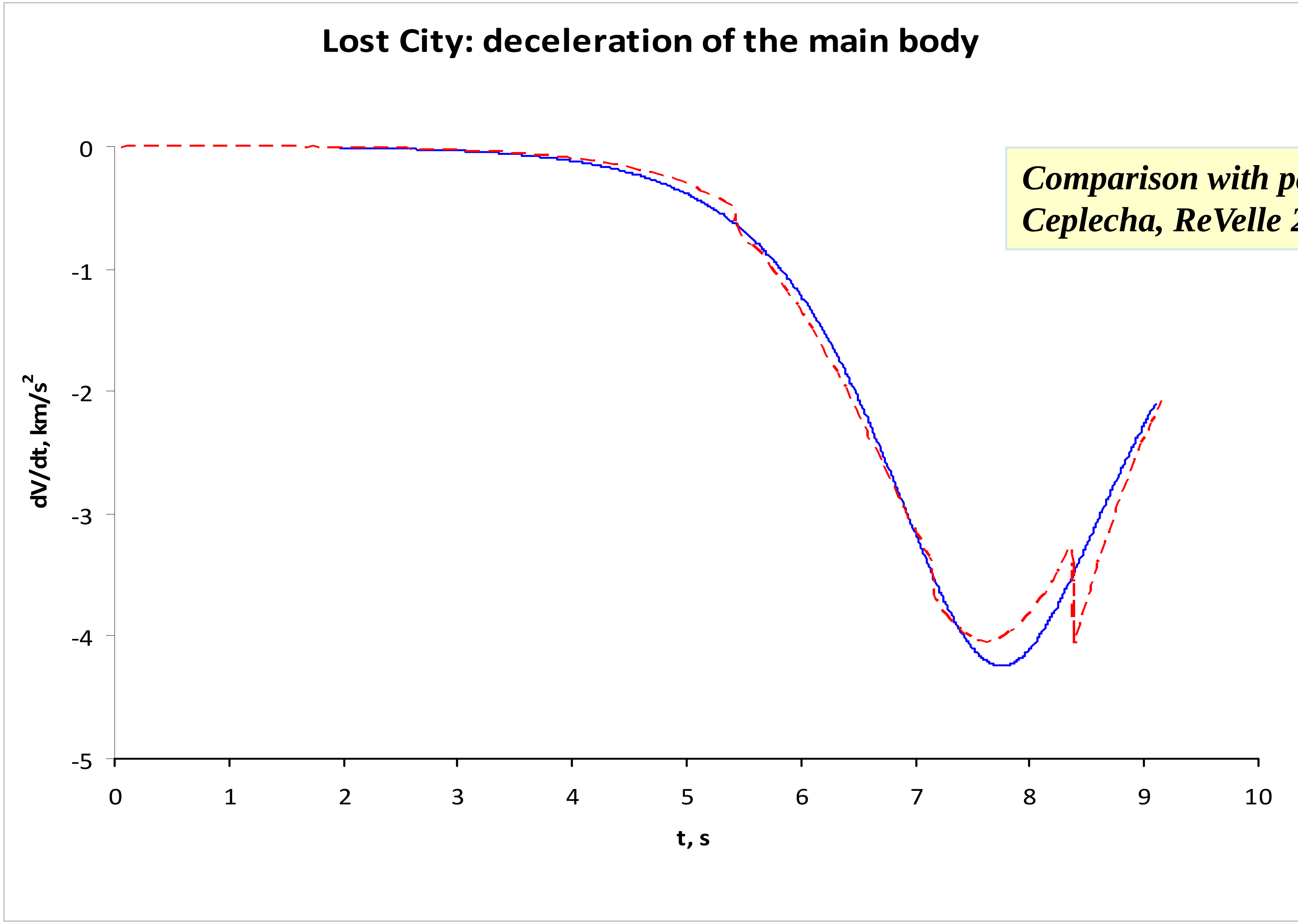
Distribution of parameters α and β



Coupling of parameters used in meteoroid entry modelling




Lost City: height of the main body
Comparison with paper
Ceplecha, ReVelle 2005
h, km
t, s
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10

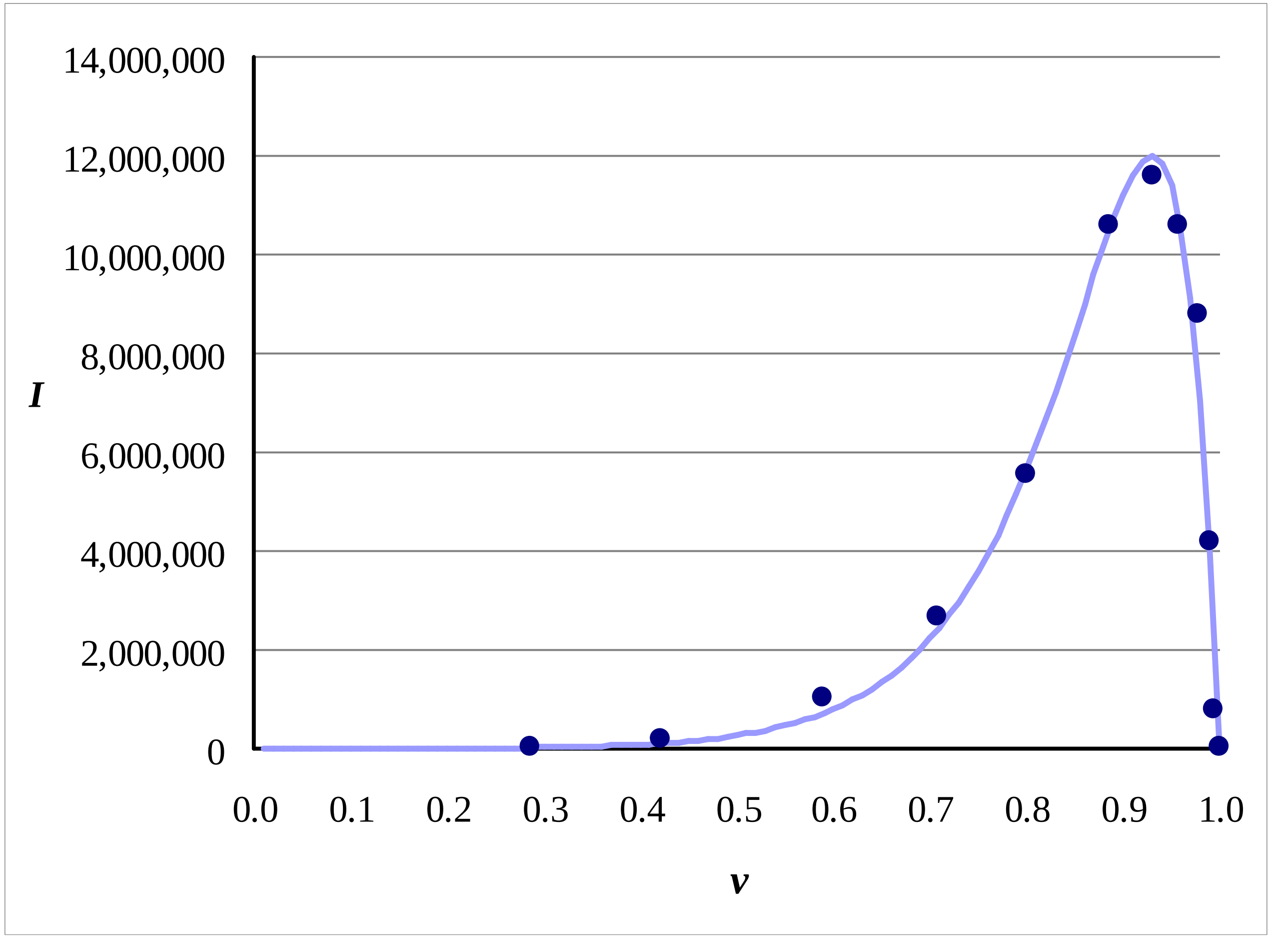


Lost City: deceleration of the main body
Comparison with paper
Ceplecha, ReVelle 2005
dV/dt, km/s²
t, s
0
-1
-2
-3
-4
-5
0
1
2
3
4
5
6
7
8
9
10

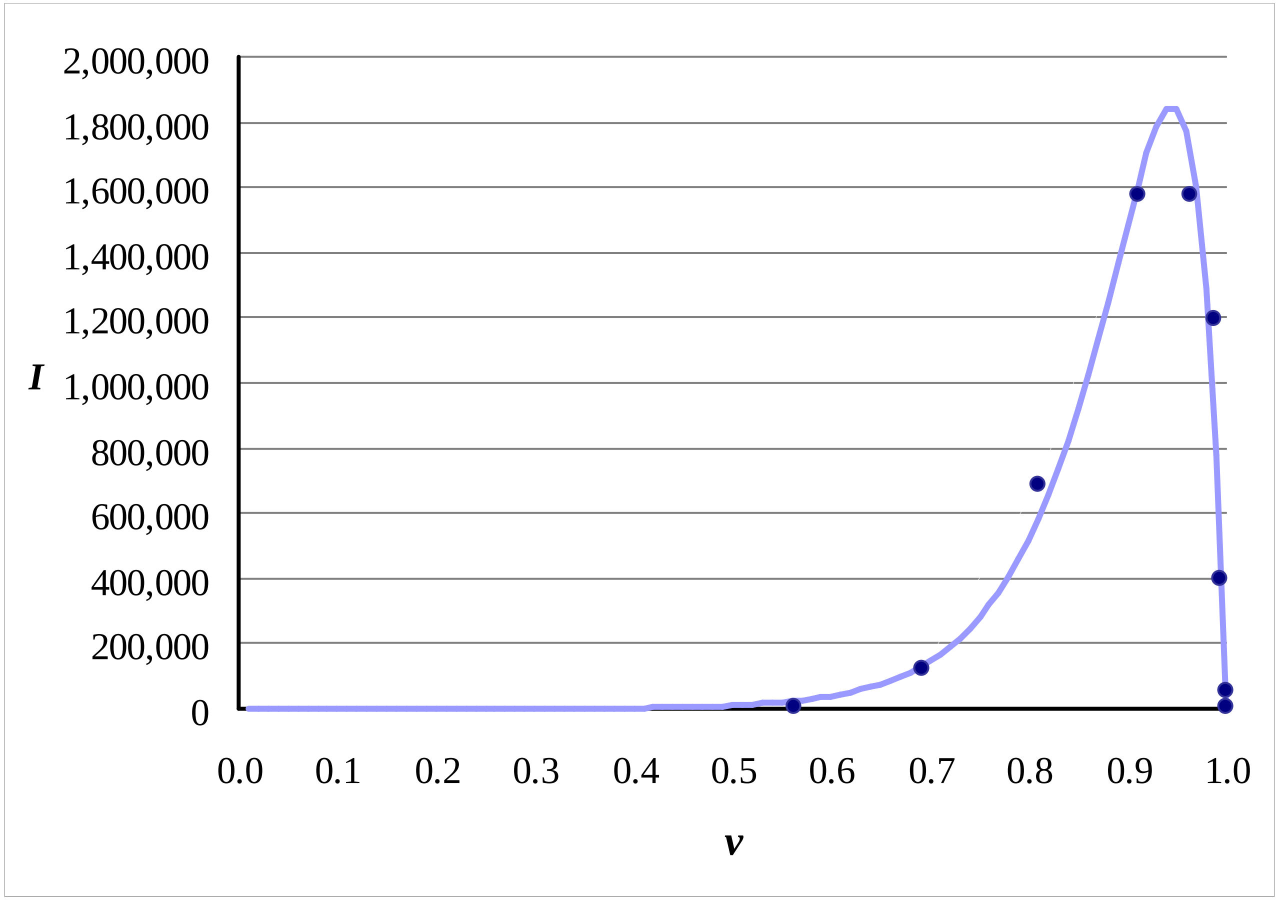
The values of the main parameters found according our model

MORP	α	β	μ	$\tau (c_d A_e)^3 \rho_m^{-2}$, cm^6/g^2
018	24.13	1.48	0.75	0.0036
138	38.90	2.89	0.67	0.0041

MORP 018


14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
I
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
v

MORP 138



2,000,000
1,800,000
1,600,000
1,400,000
1,200,000
I
1,000,000
800,000
600,000
400,000
200,000
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
v

Luminous efficiency coefficients

MORP 018

ρ_m, g/cm^3 →	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
$c_d A_e$ =1.2	0.83%	1.29%	1.86%	2.53%	3.30%
$c_d A_e$ =1.4	0.52%	0.81%	1.17%	1.59%	2.08%
$c_d A_e$ =1.6	0.35%	0.54%	**0.78%**	1.07%	1.39%
$c_d A_e$ =1.8	0.24%	0.38%	0.55%	**0.75%**	0.98%
$c_d A_e$ =2.0	0.18%	0.28%	0.40%	0.55%	0.71%

Luminous efficiency coefficients

MORP 138

ρ_m, g/cm^3 →	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
$c_d A_e$ =1.2	0.94%	1.47%	2.12%	2.88%	3.76%
$c_d A_e$ =1.4	0.59%	0.93%	1.33%	1.81%	2.37%
$c_d A_e$ =1.6	0.40%	0.62%	**0.89%**	1.22%	1.59%
$c_d A_e$ =1.8	0.28%	0.44%	0.63%	**0.85%**	1.11%
$c_d A_e$ =2.0	0.20%	0.32%	0.46%	0.62%	0.81%

Conclusions

During meteoroid entry into an atmosphere main physical dependencies M(t), h(t), V(t), I(t) can be approximated combining standard differential equations of Meteor Physics and their first integrals

Such analytical approach allow us to calculate basic non-dimensional parameters α, β, and μ. These values are an important tool in our right understanding the extensive observational data on the deceleration of meteors and bolides

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ARMAGH OBSERVATORY

IMO

Thanks for your attention!