Meteor clusters: tracing meteoroid fragmentation in near-Earth space

Pavel Koten
Department of Interplanetary Matter, Astronomical Institute
Ondřejov observatory, Czech Republic

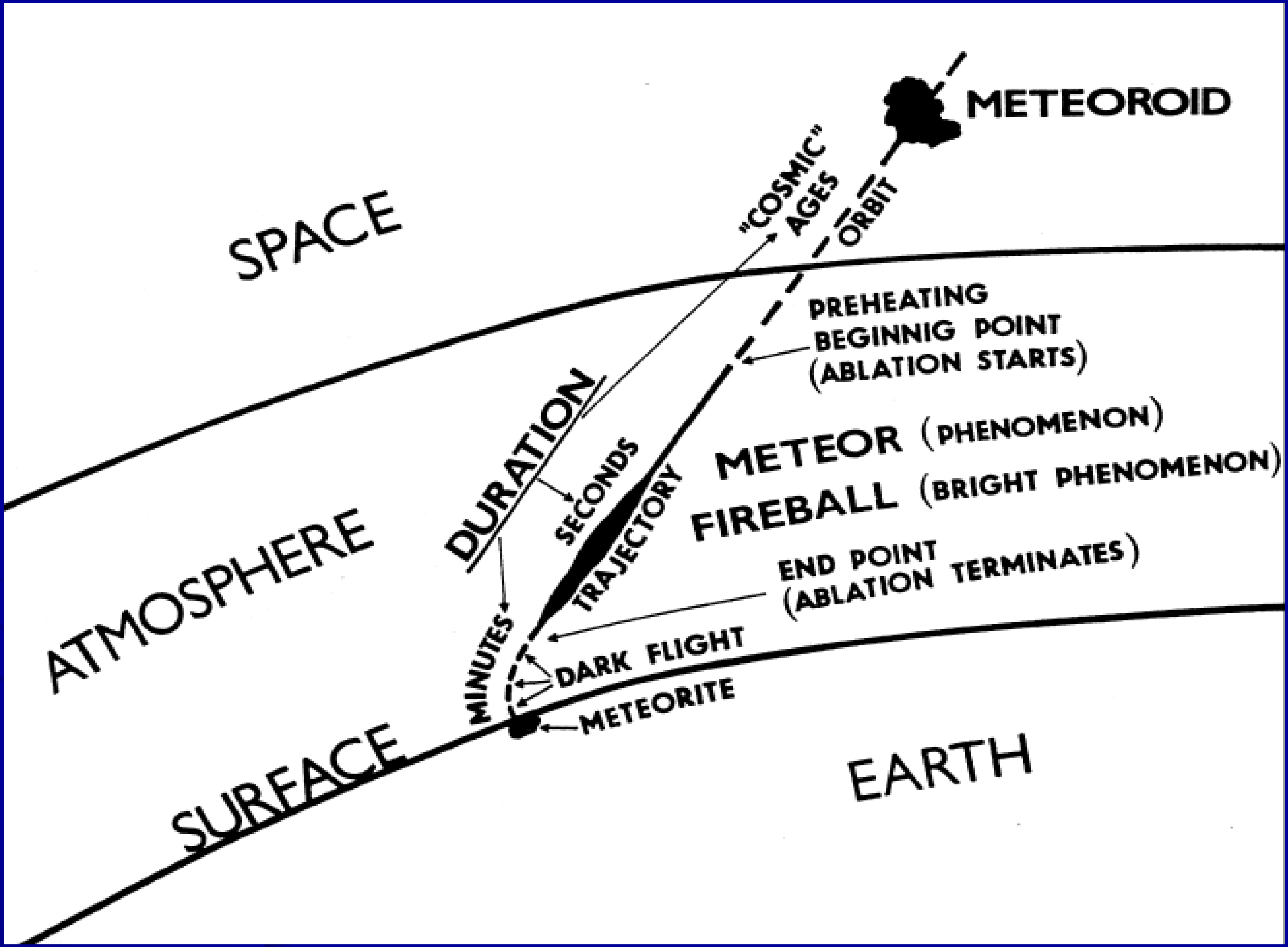
Outline

1. Basics of meteor science

2. Meteor clusters examples

3. Current knowledge summary

Basic terms of meteor science



Ceplecha et al., Space Science Reviews 84, 327, 1998

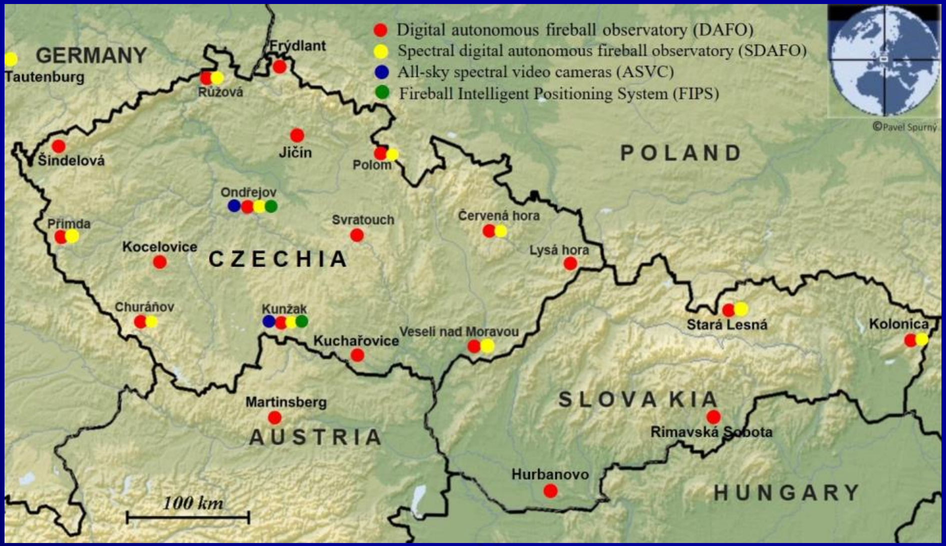
Optical observation of meteors

Photographic – fireballs

European Fireball Network

1 million km^2 area of central Europe

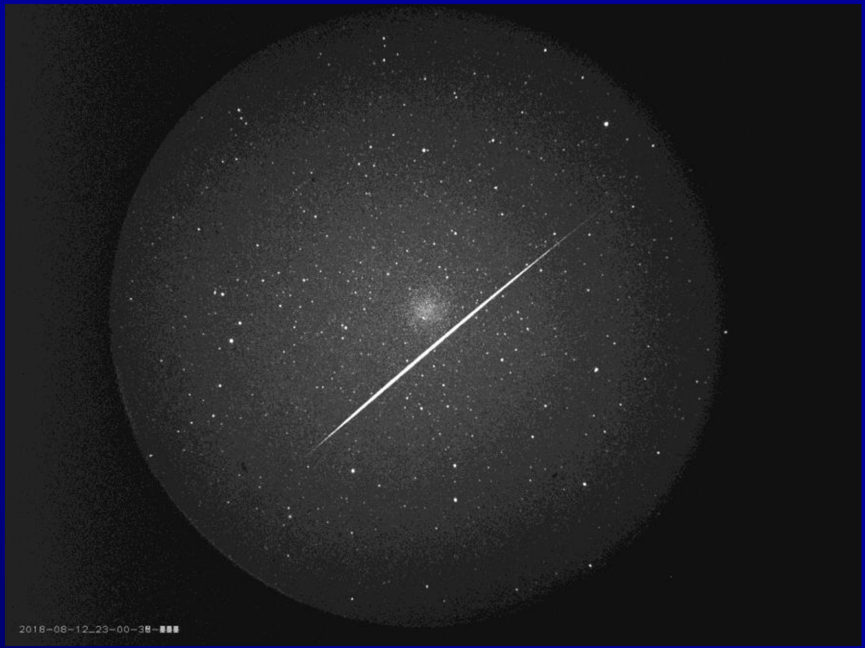
~1300 multi-station fireballs/year

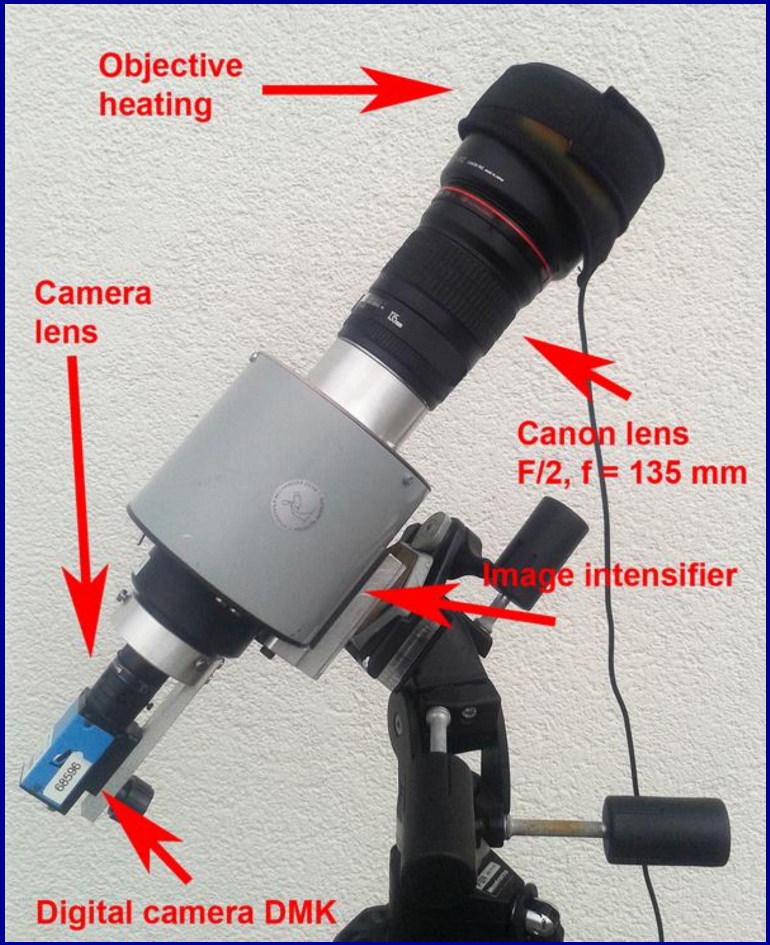


Fireball 27.2.2017, Kocelovice station

Optical observation of meteors

Video:
Global networks, double station obs.
fainter meteors (up to +7 mag.)
temporal evolution of the meteors
lower resolution, limited FOV





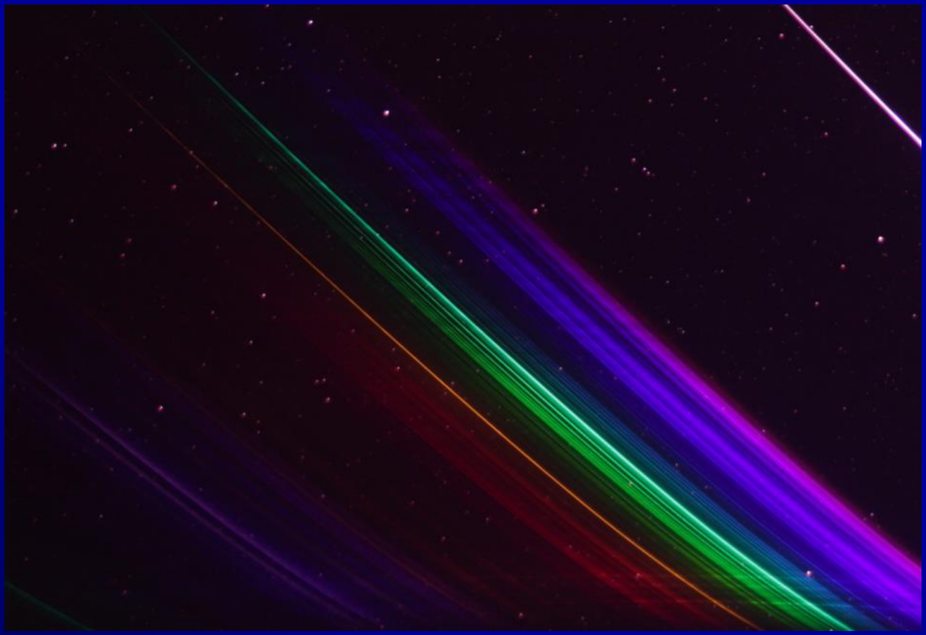
Optical observation of meteors

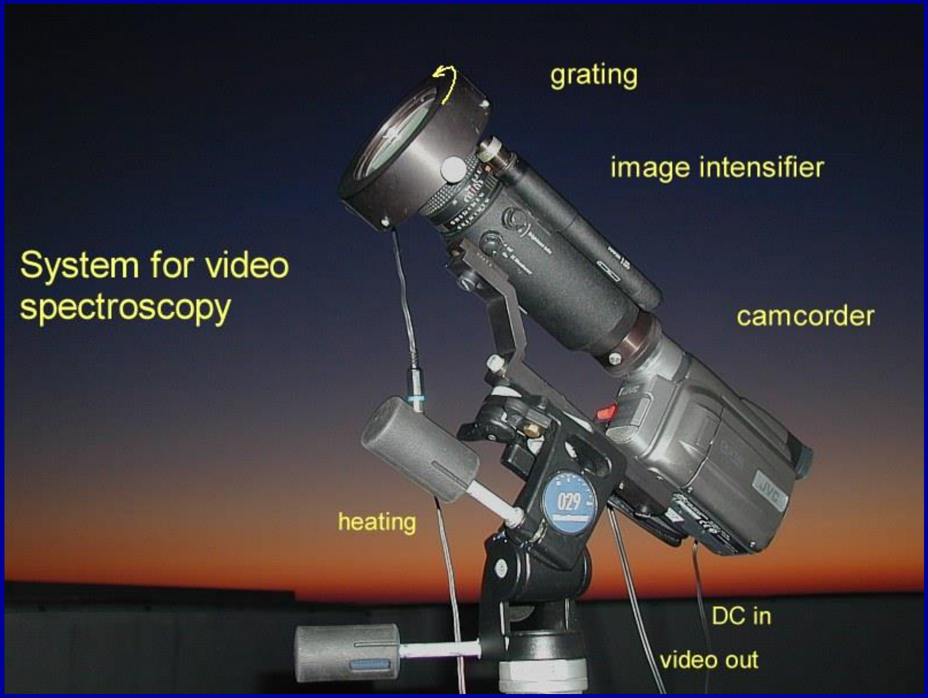
Spectral:

photographic + video

spectral grating in the front of the camera lens

chemical composition of the meteoroids





Meteor research

atmospheric trajectories of meteors, heliocentric orbits of meteoroids

initial mass of meteoroid

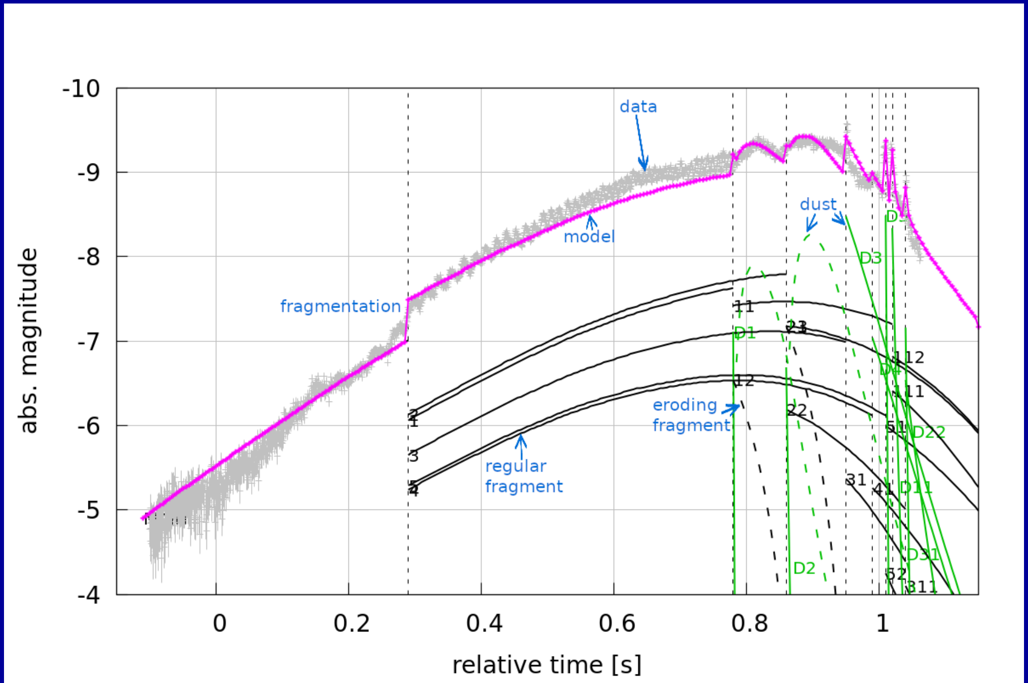
exceptional cases – meteorite fall => strewn field determination (search)

modelling of meteoroid ablation, fragmentation

properties of meteor showers

meteor shower activity

etc.



Příbram meteorites

<u>First meteorites with known orbit:</u>

central Bohemia, April 7th, 1959

fireball -19 mag.

4 meteorites found

the biggest – 4.48 kg

Dr. Zdeněk Ceplecha (1929 – 2009)

Meteor clusters

- No exact definition – meteors close in space and time, same radiant
- Hapgood & Rothwell (1981), Piers & Hawkes (1993) – two small groups of meteors
- Porubčan et al. (2002) – Leonid, Lyrid radar data statistical analysis: younger streams – possible groupings
- Leonid meteor storms – 1997, 2002:

  - 3 clusters of 15 – 150 meteors within few seconds
- Several analysed clusters in recent years by our team:

– September ϵ-Perseids cluster: fireball + 9 faint meteors (2016)

– Cluster over Scandinavia: 22 meteors over 10 seconds (2022)

– τ-Herculid cluster: 51 meteors (2023)

Huge meteor cluster over Scandinavia 30 October 2022

- 22 meteors over 10 seconds
- bright fireball + faint meteors
- Norwegian AllSky7 bolide network + Czech video camera

Composite image by S. Midtskogen

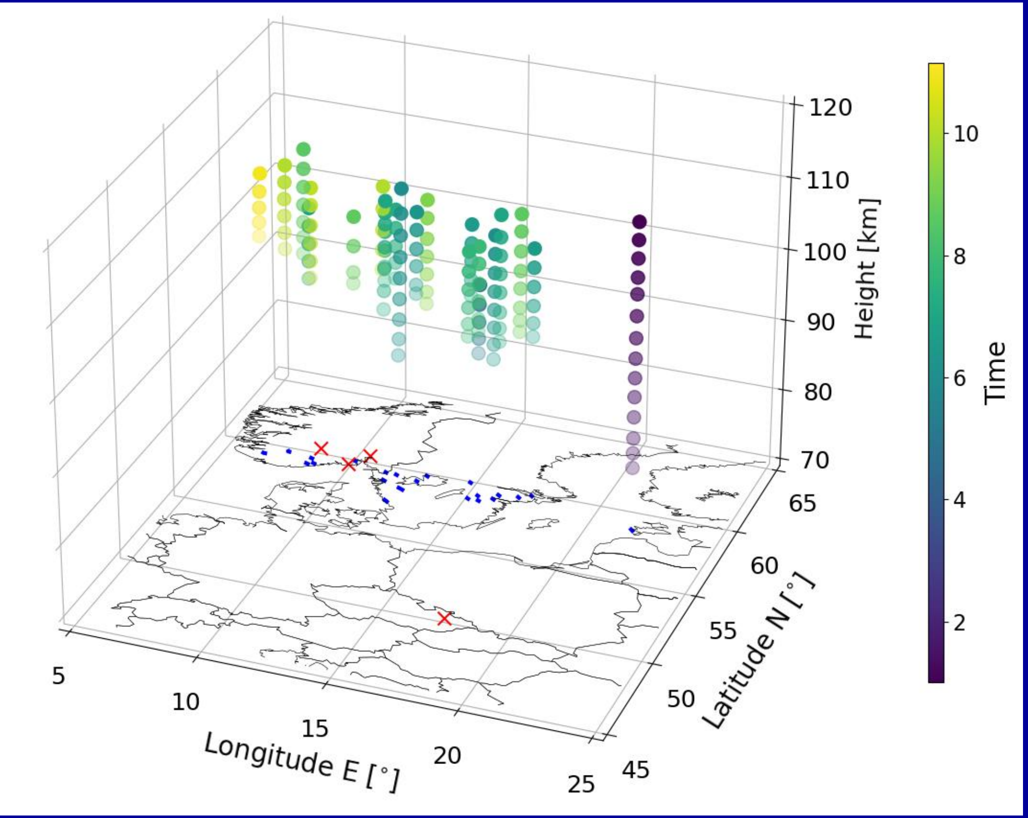
3D trajectories

- Fireball above Saaremaa island (Estonia)
- 700 – 800 km from Norwegian stations, angle 9º
- Červená hora IP cam

~ 900 km => reliable trajectory

start 1.5º above horizon

- next 5 s later
- move to the west
- 880 km over 10.2 s
- real distribution of fragments



Cometary origin

Fireball: type C2, incl. 140.6º, V_∞ = 68 km/s

D_d = 0.11 for October Lyncid shower – more likely sporadic

similar orbit to fireball EN261022_010011 (D_d = 0.078)

met #	time [s]	H_{BEG} [km]	λ_{BEG} [°]	ϕ_{BEG} [°]	H_{END} [km]	l [km]	t_{dur} [s]	M_{MAX} [mag]	m_{phot} [kg]
01	04.08	115.9±0.3	21.89031	58.15847	74.2±0.2	43.8	0.52	-10.8	1.2e-01
02	08.92	114.4±0.1	16.23592	58.50805	89.2±0.1	26.9	0.28	-4.6	3.8e-04
03	09.32	110.5±0.1	13.03281	58.78302	96.6±0.1	14.9	0.20	-2.2	5.6e-05
04	09.52	110.0±0.1	17.49133	59.26087	92.4±0.1	18.6	0.20	-3.8	1.9e-04
05	09.68	109.3±0.1	14.97878	59.40142	95.6±0.1	14.6	0.18	-3.2	6.1e-05
06	09.96	108.8±0.1	15.75913	58.20703	90.9±0.1	19.7	0.19	-3.3	1.1e-04
07	10.00	111.9±0.2	16.31756	58.86474	91.1±0.2	22.2	0.28	-5.1	3.0e-04
08	10.20	112.2±0.1	11.70162	58.99163	95.1±0.1	18.3	0.22	-1.5	2.0e-05
09	10.32	110.0±0.1	12.13192	58.96526	97.4±0.1	13.5	0.16	-1.7	1.8e-05
10	10.60	108.7±0.1	15.30498	58.22478	92.7±0.1	17.4	0.20	-2.9	9.3e-05
11	10.84	110.1±0.1	15.58398	58.55315	93.2±0.1	18.0	0.20	-3.2	1.7e-04
12	11.60	112.0±0.1	10.29596	59.39472	94.0±0.1	19.3	0.28	-1.6	2.9e-05
13	11.64	113.0±0.2	17.08626	58.97879	93.3±0.2	20.9	0.28	-4.2	2.5e-04
14	12.20	111.6±0.1	13.27000	59.28336	94.4±0.1	18.3	0.24	-3.1	8.8e-05
15	09.72	113.2±0.1	8.66083	58.99468	95.3±0.1	19.4	0.16	-2.6	5.3e-05
16	11.64	116.2±0.1	8.62990	58.55921	98.8±0.1	18.8	0.27	-2.1	2.7e-05
17	13.16	111.2±0.1	8.86014	58.66481	96.4±0.1	16.1	0.20	-2.0	3.5e-05

Origin of cluster

- Fireball meteoroid 1000 times higher mass than other fragments
- Distances less than 1000 km

- Possible origin:

1. Fragments released directly from the parent body
2. Within the atmosphere
3. Very close to the Earth

Scenarios 1 and 2 very improbable or even impossible.

Age of cluster

Motion of meteoroids:

$$\vec{r}_i = \frac{1}{2}\vec{a}_i t^2 + \vec{v}_i^{ej} t,$$

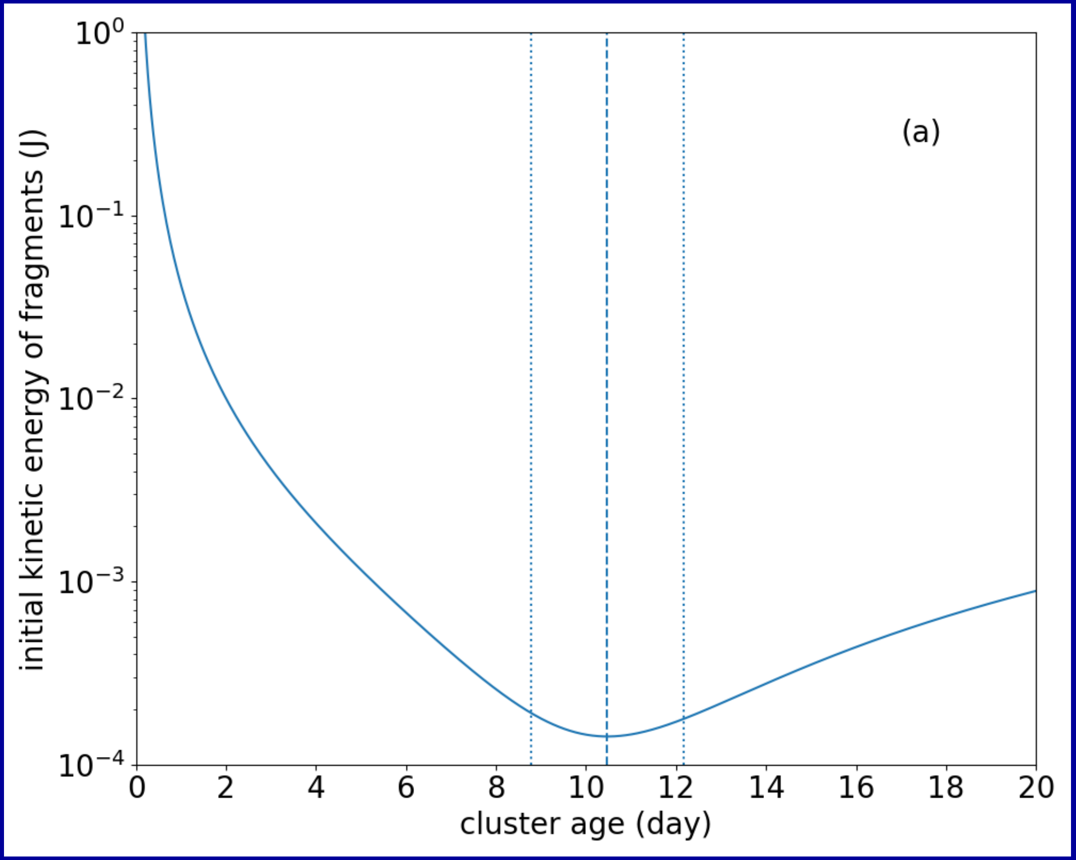
$i = 0, \dots, 9$

t … time from ejection

v_i … ejection velocities

a_i … SRP acceleration

r_i … positions



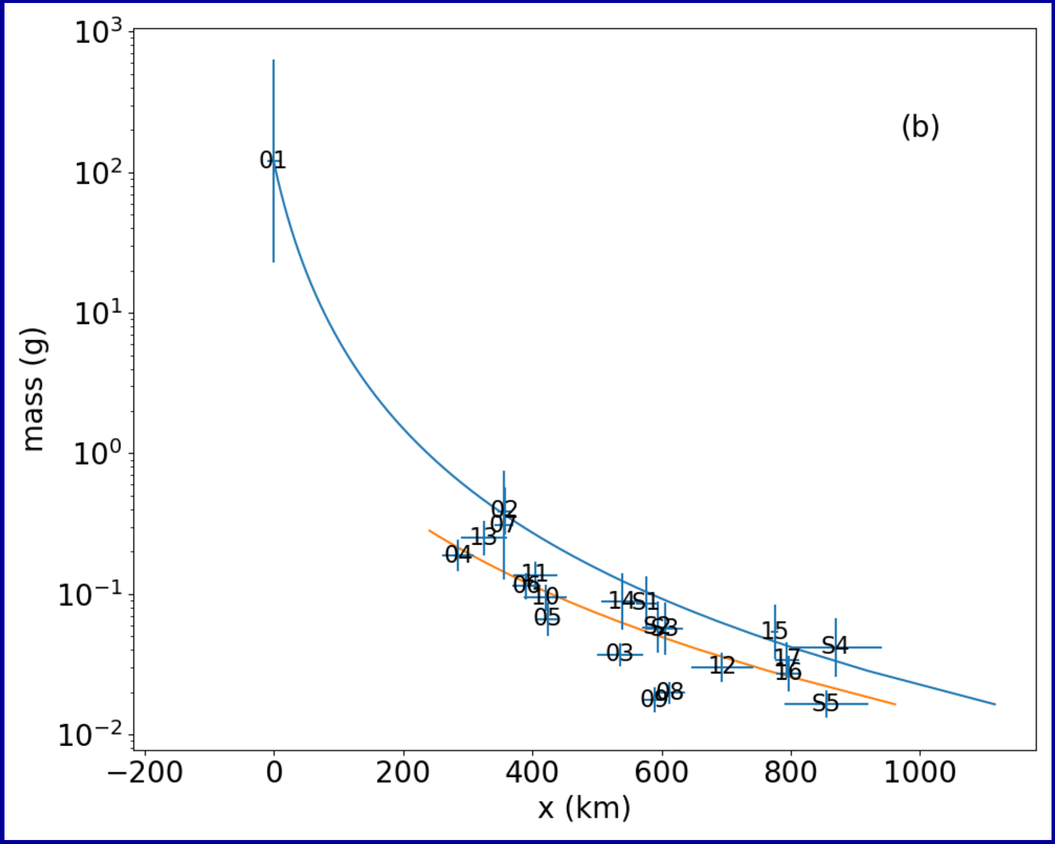
Minimal value of total kinetic energy => age of cluster

10.6 ± 1.7 days

62 ± 10 million km from Earth

Mass separation of fragments

- lower mass, larger shift in antisolar direction
- positions, masses and their uncertainties
- ejection velocities 0.16 – 0.61 m/s
- ejection directions cone 43° ± 11°
- 147° away from impact directions



(blue – zero ejection velocity, orange 0.39 m/s)

Fragmentation scenarios

- Impact and no-catastrophic disruption

low ejection velocities inconsistent with this scenario

age higher than 30 days or lower than 3.3 days

- Separation due to fast rotation

corresponding mechanical stress orders of magnitude lower than the mechanical strength

- Thermal stresses

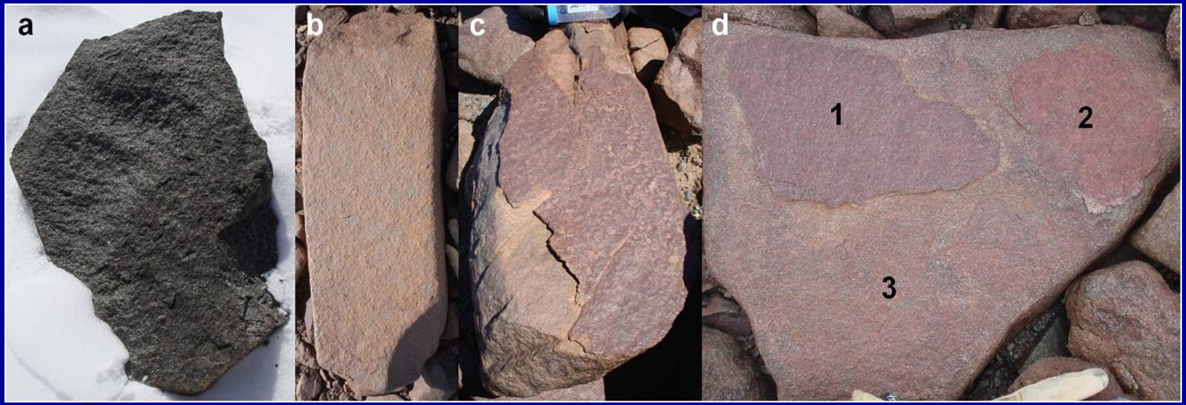
sufficient to exceed the material strength

consistent ejection velocities

Koten et al. (2024) A&A, 683, A5

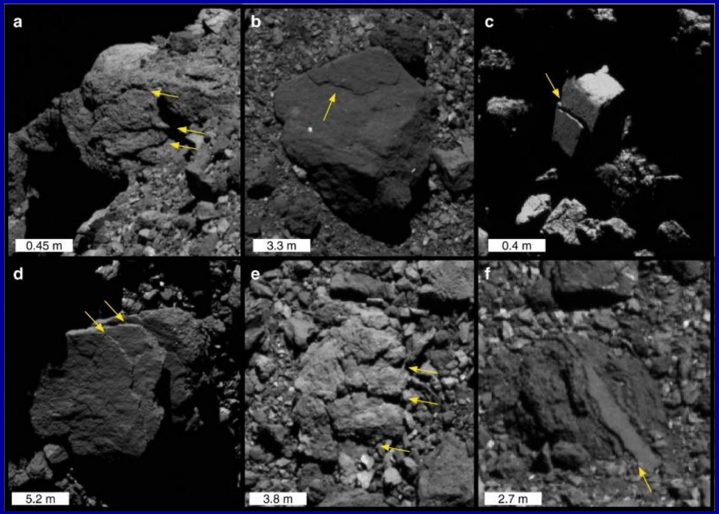
Thermal stress

- Thermal fatigue => formation, growth and fusion of cracks
- Cyclic load not exceeding the strength
- Observed on Earth:



(Lamp et al. JGR, 2017)

- On Bennu:



(Molaro et al., Nature, 2020)

Hawaii cluster 11 July 2024

- 15 meteors within 3,8 seconds: bright fireball + faint meteors
- Subaru- Asahi StarCam, Mauna Kea
- Third cluster by this

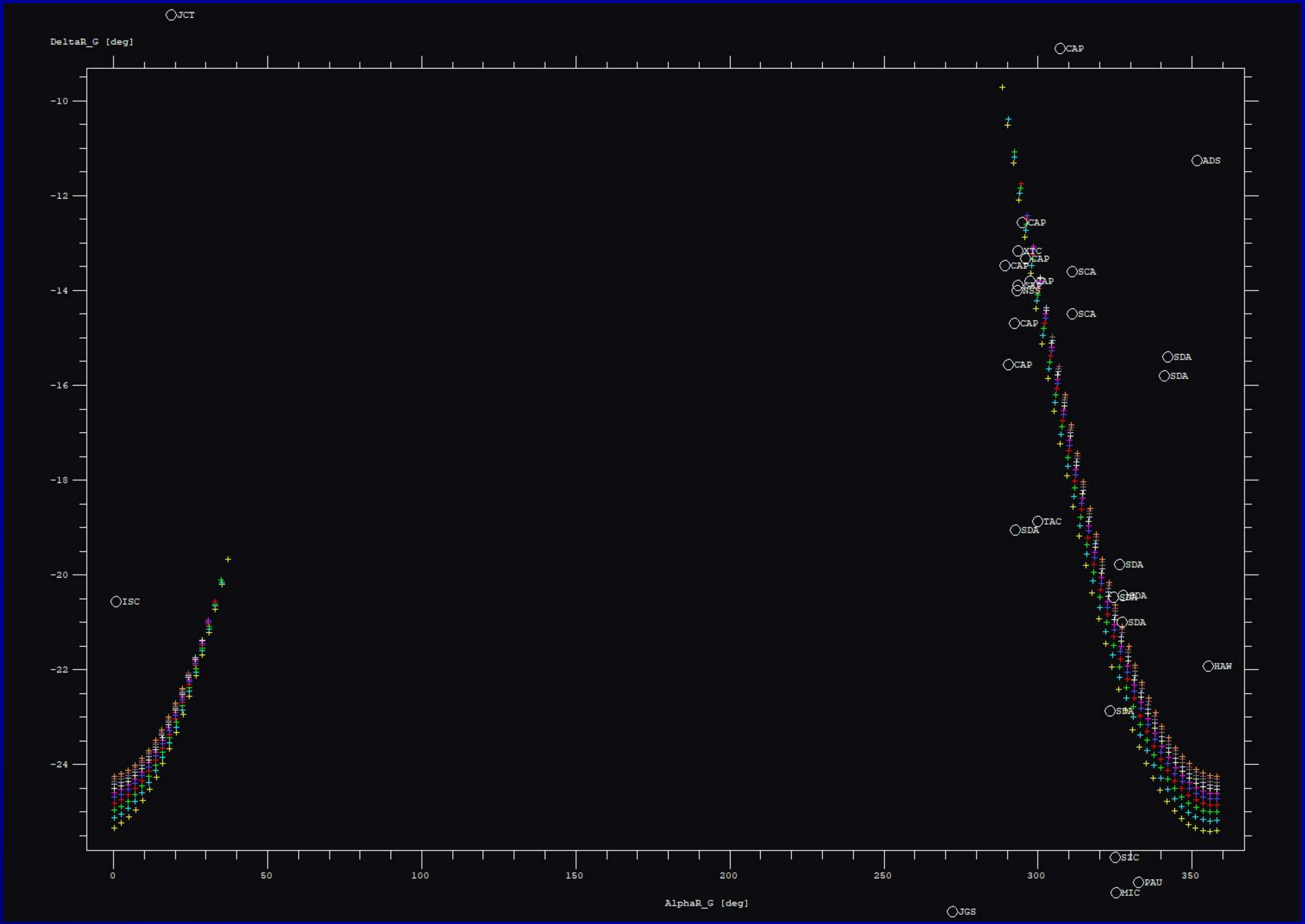
camera in three years (!)

11 July 2024

14:05:33 UT

single station observation

Single station solutions

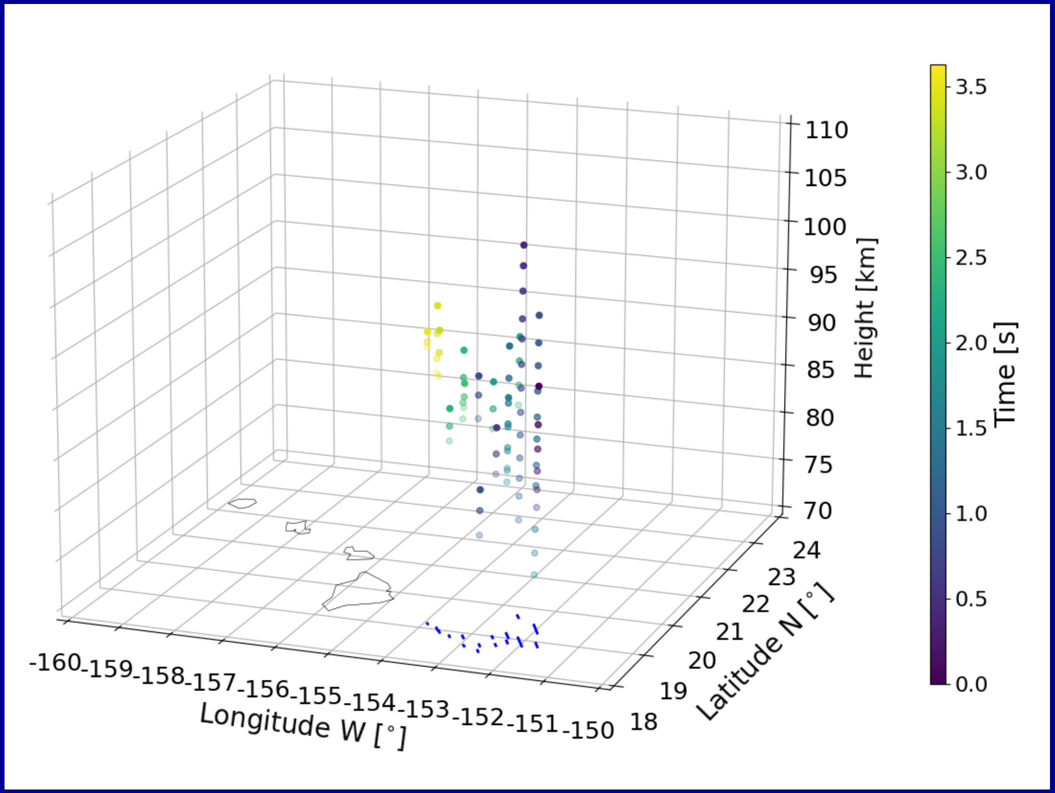


3D trajectories

- radiant: α_G = 22.2º; δ_G = -22.5º, V_G = 55.5 km/s
- east of Hawaii island
- 426 – 374 km from Mauna Kea camera (the brightest meteor)
- H_{BEG} = 110 - 87 km

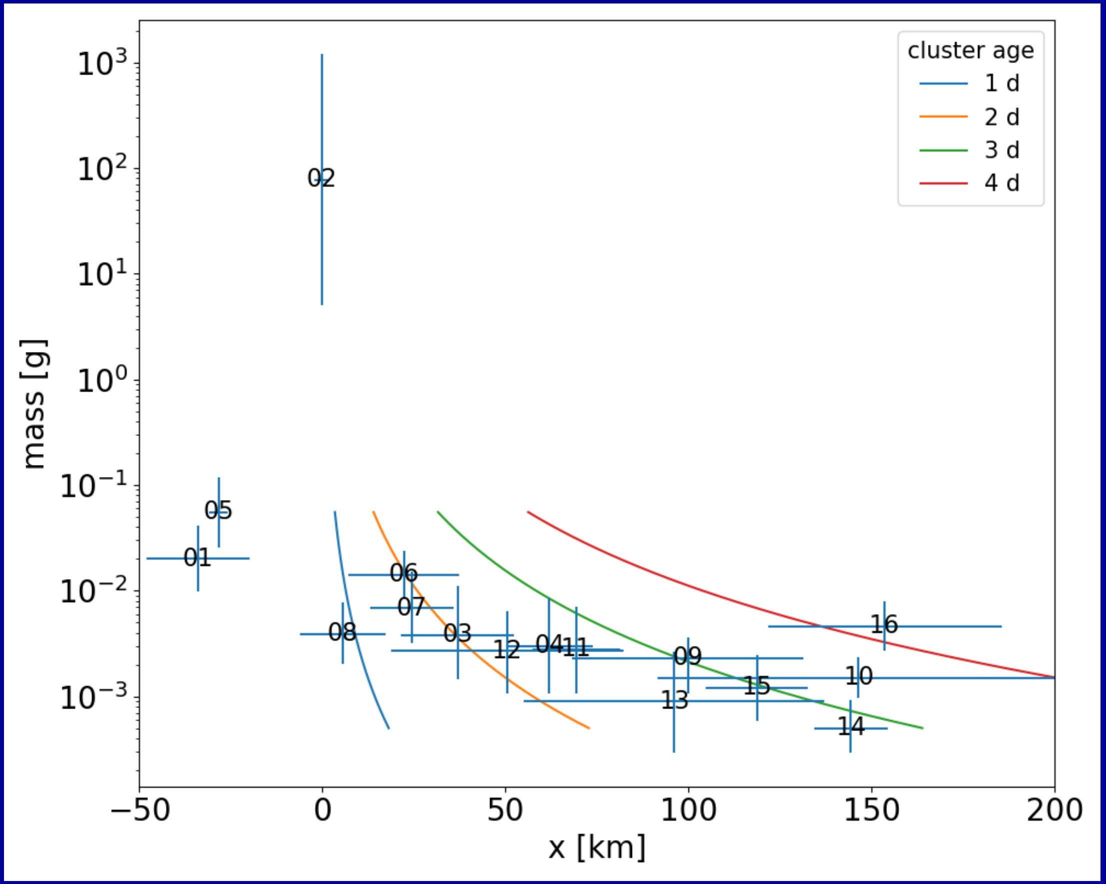
meteoroid type A

$T_J > 3$



Mass separation of fragments

Relatively good mass separation = lower mass, larger shift in antisolar direction



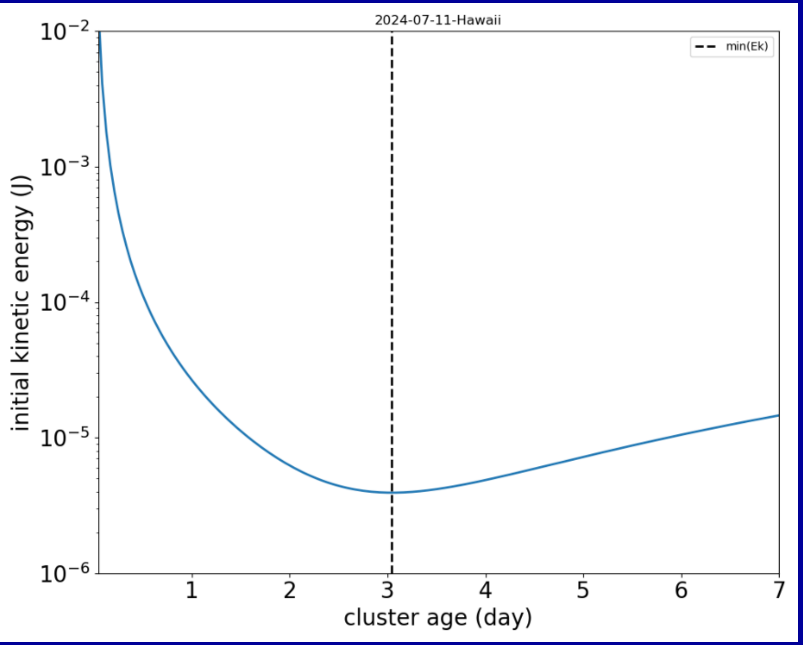
bulk density 2500 kg/m^3

(expected positions with zero ejection velocity)

Age of cluster

- age calculated as minimum of:

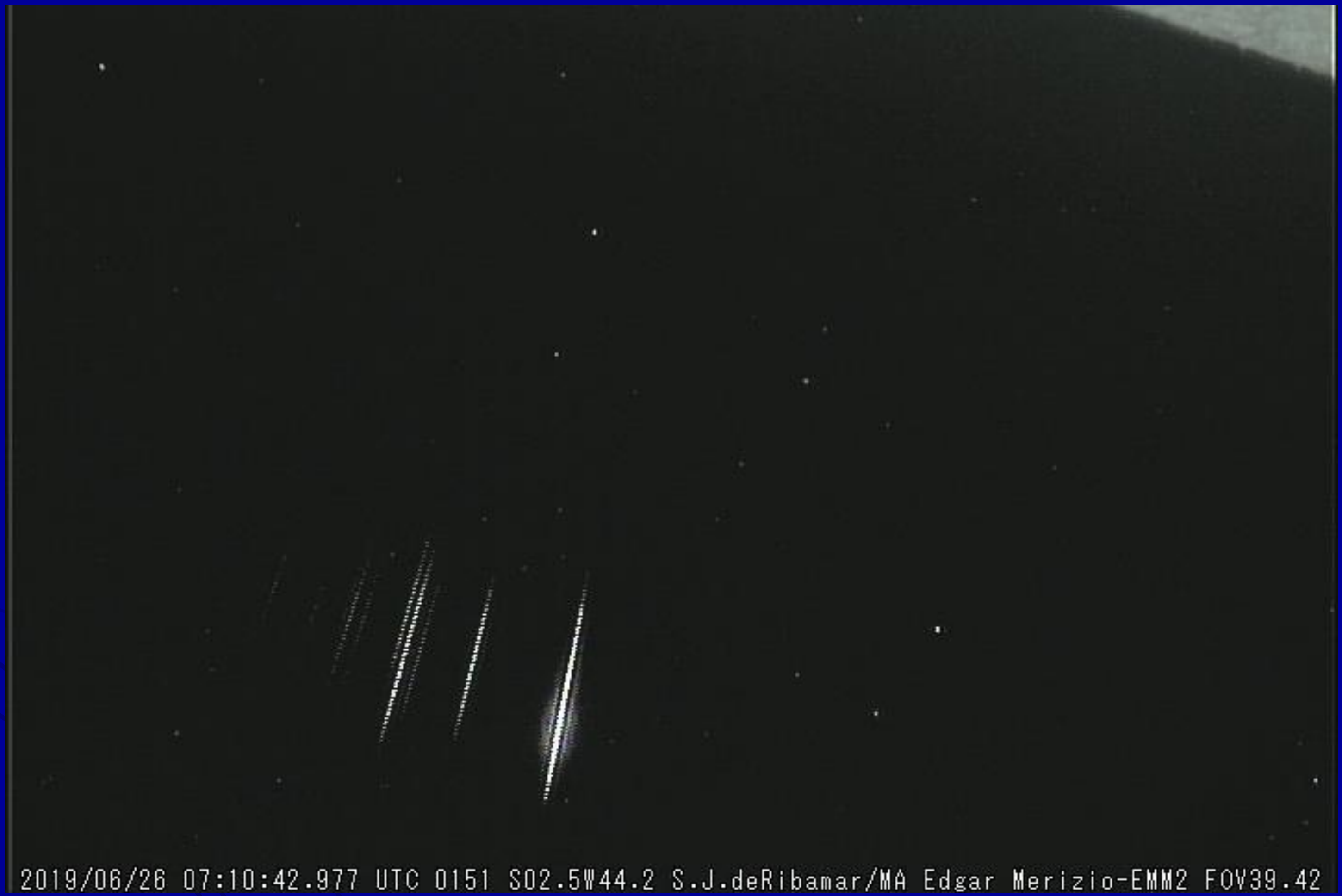
- initial kinetic energy: 3.04 d
- mean x-component of v_{ej}: 2.54 d
- mean v_{ej}: 2.96 d
- median v_{ej}: 2.62 d
- maximal v_{ej}: 3.00 d



- Ejection velocities up to 0.5 m/s
- Thermal stress as the most probable mechanism

sufficient to exceed the material strength, consistent ejection velocities

26 June 2019 Brazil meteor cluster



26 June 2019 at 7:10:43 UT
10 meteors within 0.5 second
São Luís (northern Brazil) – only single station

Single station, unknown radiant

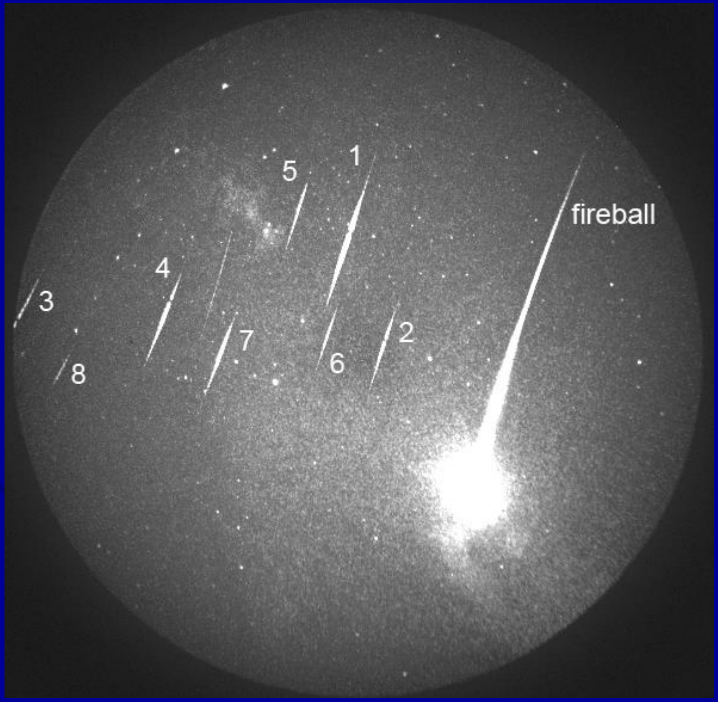
- Different solutions for radiant and velocity – „mini“ meteor shower
- Single station data on meteor cluster can provide us with very realistic atmospheric trajectories
- Similar atmospheric trajectories – age of the cluster, ejection velocities, kinetic energy => origin

- Brazil cluster:

1. Very compact – 350 km^2, 0.5 s
2. Very young – 1.1 day
3. Low ejection velocities < 0.4 m/s

More meteor clusters

- September ϵ Perseid 2016 – fireball + 9 faint meteors
- Croatia 2021 – two main fragments (multi station)
- Hawaii 2021 – double-cluster (?) (single/double station)
- Hawaii 2023 – R Lyrae shower (single)



Summary of analysed clusters

	SPE	Scan.	TAH	Brazil	Croatia	Hawaii 2021	Hawaii 2023	Hawaii 2024	Leo 2002
fragments	10	22	51	10	5	15	7	15	9
area [1000 km^2]	11.5	110	9.6	0.35	2.65	145	5	32	0.83
time [s]	1.5	10	8.5	0.5	1.15	10.9	2.8	3.8	0.48
mass separation	YES	YES	NO	YES	YES	YES	NO	YES	NO
main body mass / total [%]	> 99.9	98.5	48	82.7	81 (2 pcs)	78.5	58	> 99.9	33
age [days]	2.28 ± 0.44	10.6 ± 1.7	0.3 – 9.0	1.1	1.5	4.6	0.1-4	3	< 1.5
ejection velocity [m/s]	0.1-0.8	0.1-0.6	< 1.0	< 0.4	0.1-0.2	< 0.5	> 0.1	< 0.5	< 0.2 if age > 8h
mechanism	thermal	thermal	thermal/?	thermal	thermal	thermal	thermal/?	thermal	thermal/?

Observed findings

- Absolutely mass dominant body – better mass separation
- Mass separated clusters – reliable age and ejection velocities
- Low ejection velocities => thermal stress
- Age of the clusters up to 10 days – relatively close to the Earth

- Non-mass separated events – uncertain age, ejection velocities => other possible formation mechanisms (collisions, rotational bursting)

Selection effects

- Limited FOV of camera/network – only relatively close meteoroids in space
- Higher ejection velocities (collisional origin) – higher distances between fragments – no detection as a cluster
- Global meteor networks search?
- Ashimbekova et al. (2025) – promising results, 16 candidates

- We will be happy if anybody can share data on the meteor clusters even single station ones!

Acknowledgments

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Praemium Academiae

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Thank you for your attention!