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A new method of distinguishing among cosmogonic models of the Solar System

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Cosmogonic models

- describe the origin and evolution of planetary systems;
- should be consistent with the modern structure of the Solar System;
- different approaches, a lot of free parameters;
- “classical” (non-migrational) models: objects form on their current orbits;
- “dynamical” (migration-based) models: redistribution of matter due to planetary migrations.

Fig. 1. Artist's illustration of the protoplanetary disk (source: https://en.wikipedia.org/wiki/Formation_and_evolution_of_the_Solar_System)

Grand Tack model

(*Walsh et al., 2011*)

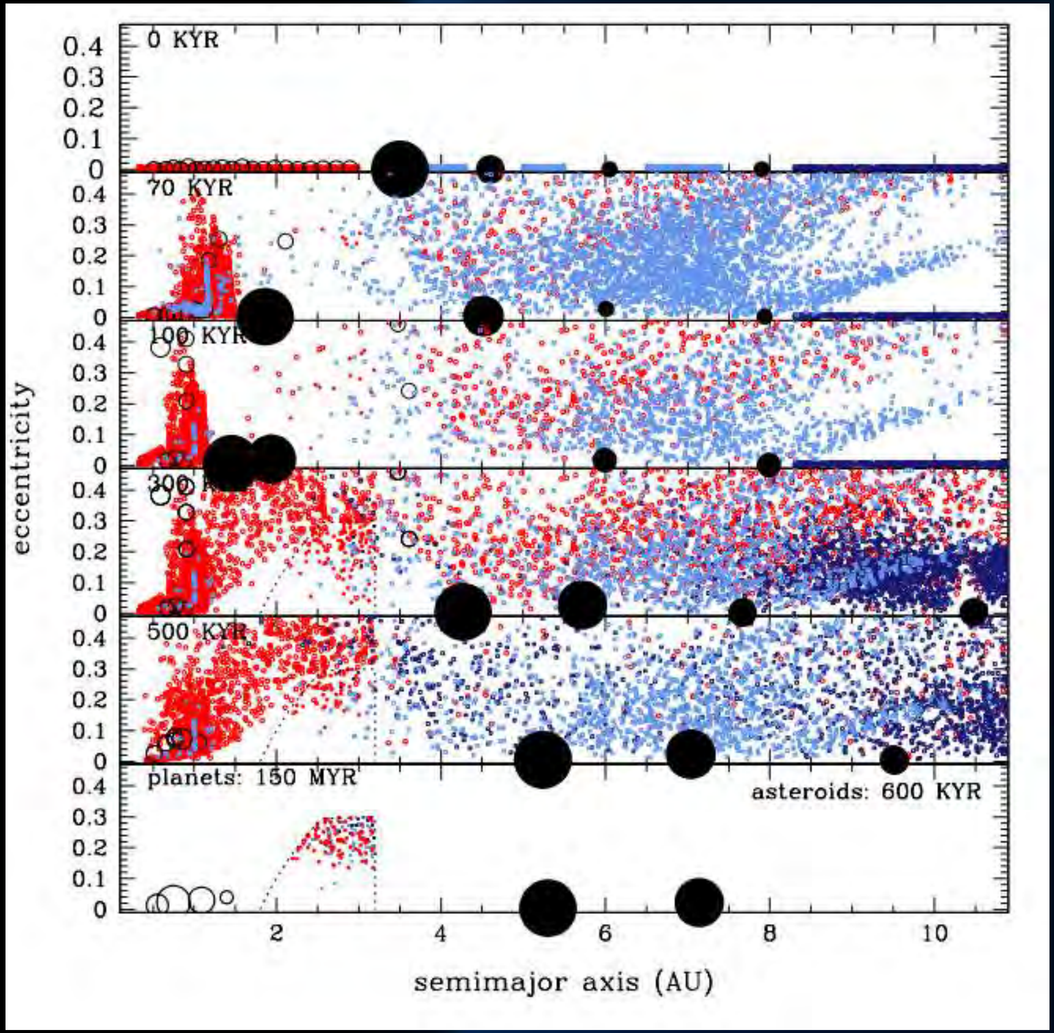

Fig. 2. Scenario of the model (source: Walsh et. al., 2011)

- covered in our bachelor thesis (2022);
- describes events before the dissipation of the protoplanetary disk;
- key role of gas-driven planetary migrations and mean-motion orbital resonances;
- migration of Jupiter (stopped and reversed by Saturn) provided a major redistribution of matter in the Solar System;
- explained the depletion of the initially massive asteroid belt.

Our simulation

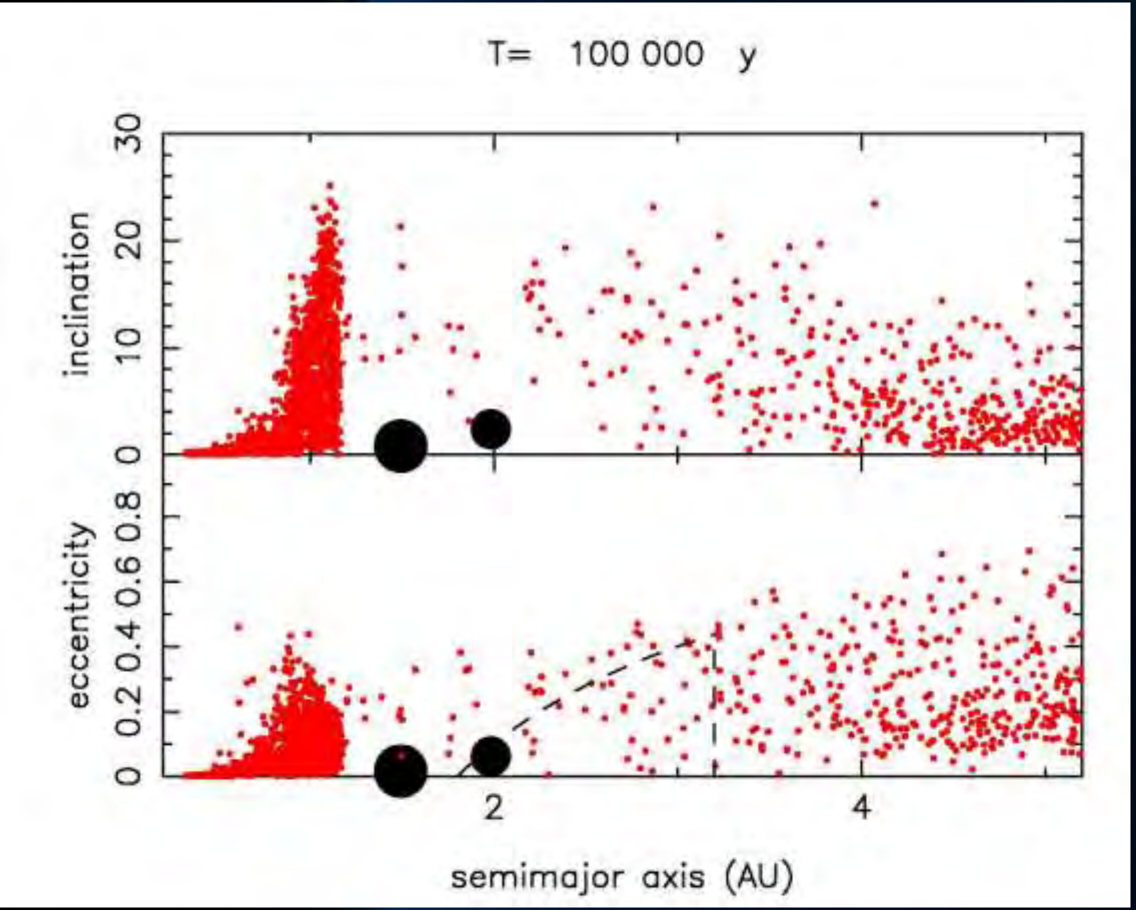

Fig. 3. Original distribution of bodies from the model (source: http://perso.astrophy.u-bordeaux.fr/~sraymond/movies_grandtack.html)

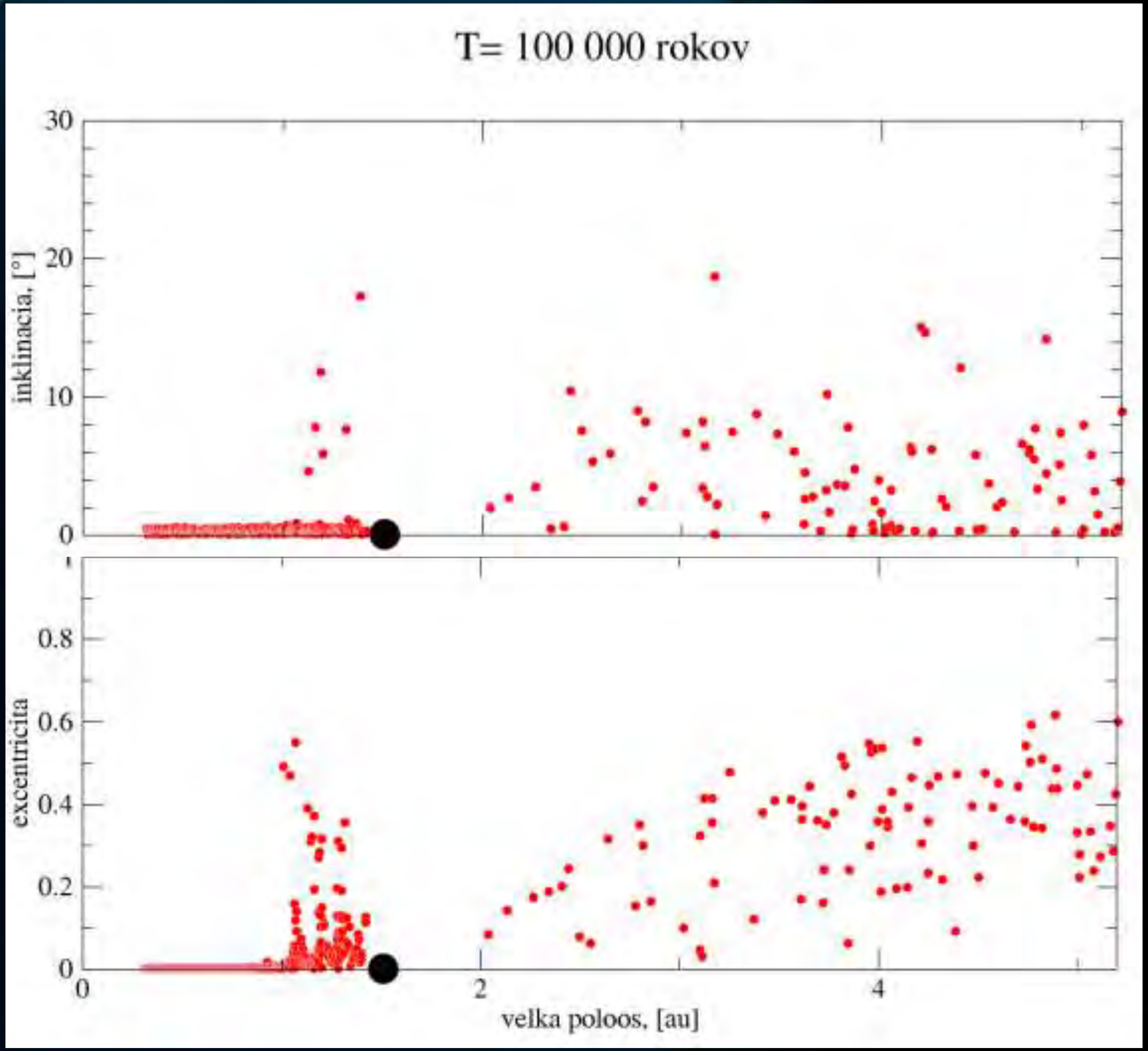

Fig. 4. Distribution of excentricities and inclinations at the end of the simulation

Pebble-accretion model

(Lambrechts and Johansen, 2012)

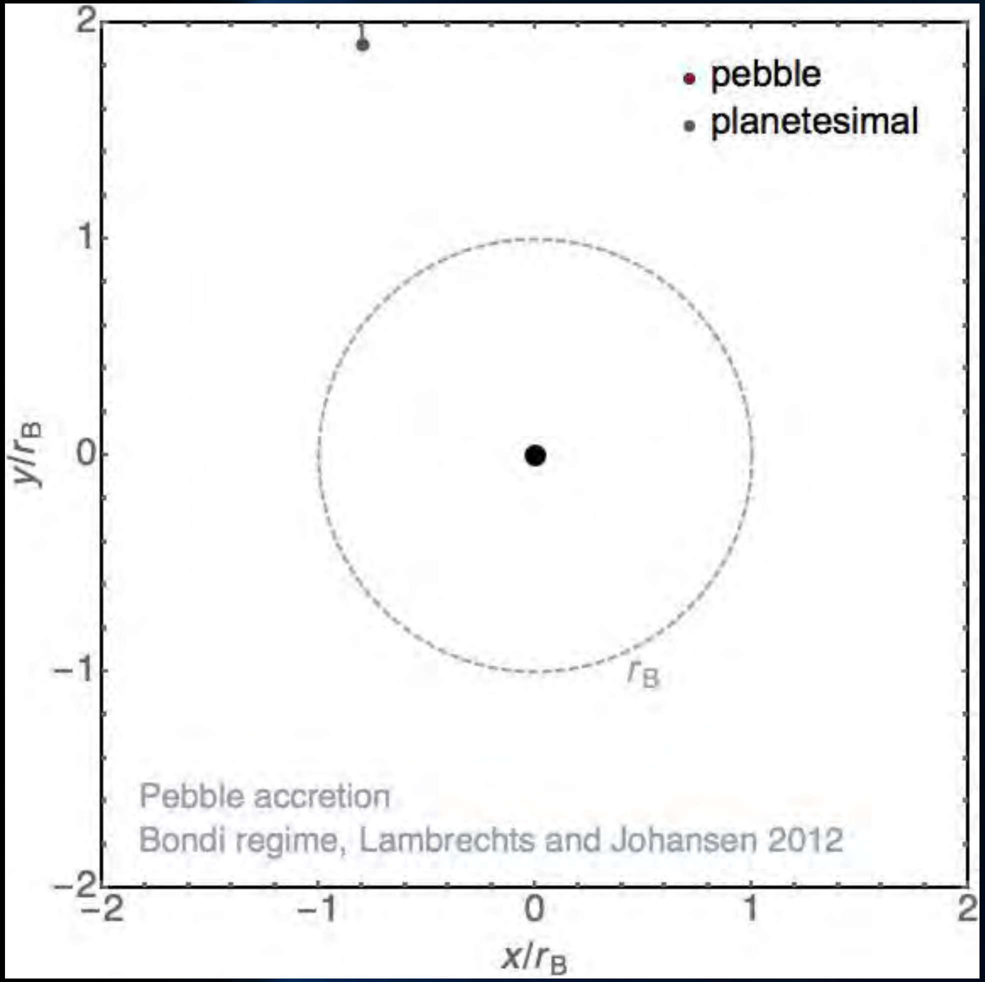

Fig. 5. Pebble vs planetesimal accretion (source: https://planetplanet.net/2022/06/26/from-planetesimals-to-planetary-embryos/)

- competing theory, does not involve migrations;
- key mechanisms: growth of planetary embryos due to the accretion of small pebbles (governed by gravity and gas drag);
- rapid formation of giant planets explained;
- low-mass asteroid belt from the start – no need for mass scattering.

Distinguishing among models

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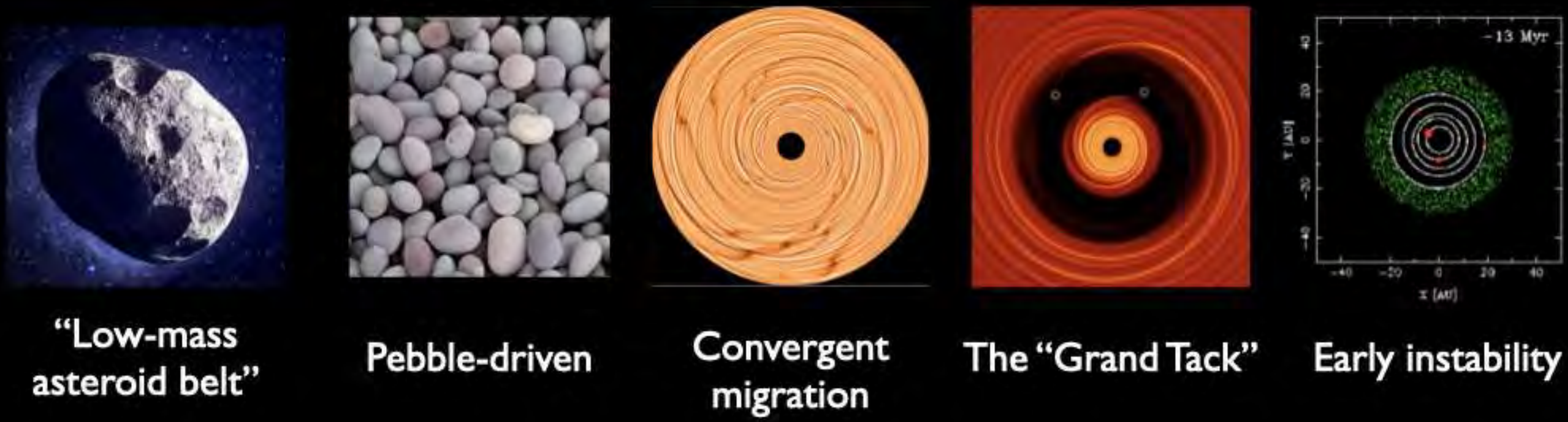

Fig. 6. Successful models (source: https://planetplanet.net/2022/06/29/formation-of-the-rocky-planets-choose-your-own-adventure/)

Manx comets

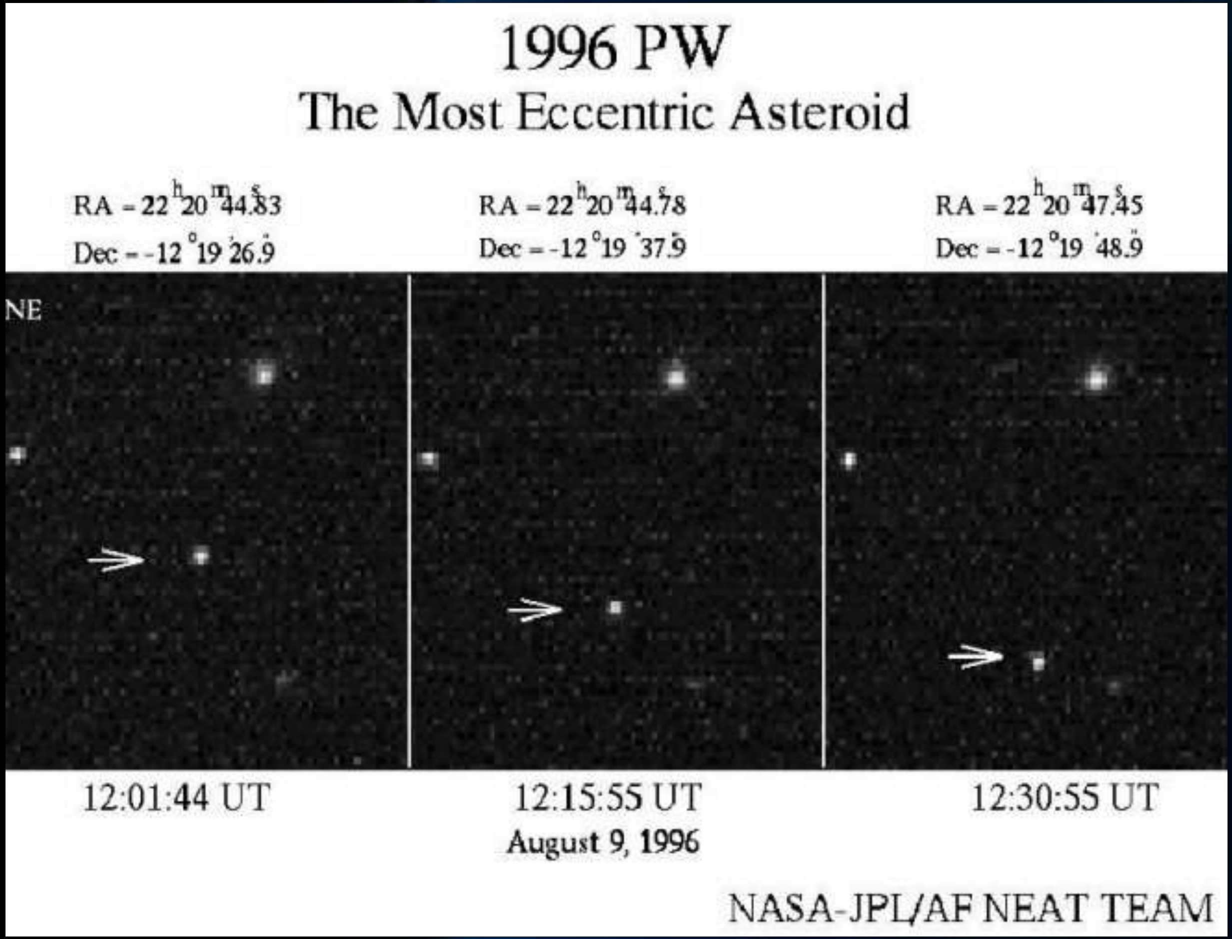

Fig. 7. Unusual object 1996 PW (source: https://hvezdaren-mi.sk/ /osem-miliard-asteroidov-v-oortovom-oblaku-komet/*)*

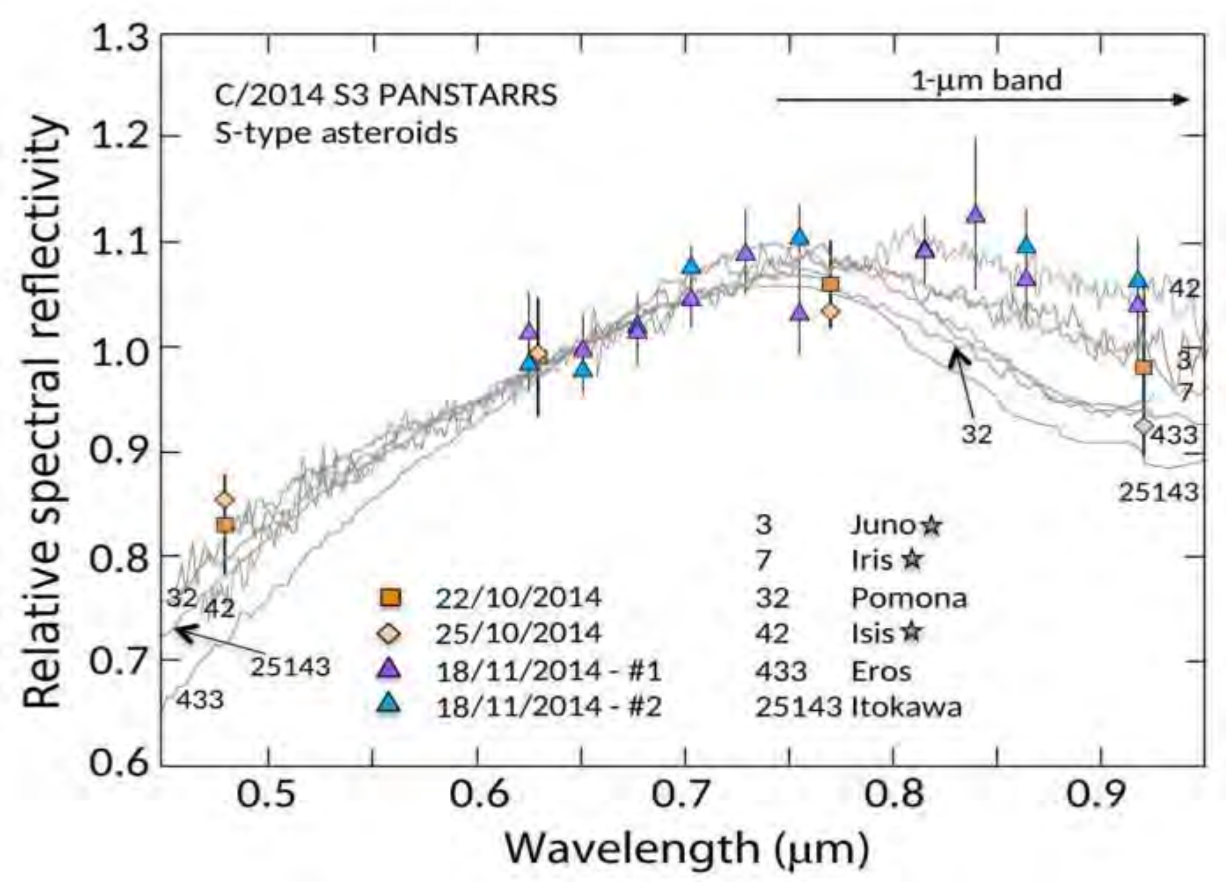

Fig. 8. Spectral reflectivity of C/2014 S3 (PANSTARRS) (source: Meech et al., 2016)

Meteoroid strength parameters

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$$K_B = \log[\rho_B] + 2.5\log[V_\infty] - 0.5\log[\cos Z] \quad (8)$$

where ρ_B is the air density at the start of the meteor (in g/cm^3), V_∞ is the initial speed (in cm/s^1) and Z is the local zenith angle of the radiant. Larger values of K_B indicate stronger/denser/less porous/higher specific heat/higher thermal conductivity of the meteoroid.

Meteoroid Strength Groups and Probable Material Associations.

Group	Strength Parameter	Probable Association
A:	$7.3 < K_B \leq 8$	Carbonaceous Chondrites/asteroidal/JFC
B:	$7.1 < K_B \leq 7.3$	Dense cometary material JFC/HTC
C:	$6.6 < K_B \leq 7.1$	Regular cometary material
D:	$6.6 > K_B$	Weak cometary material (JFC)

Fig. 9. K_B parameter (source: Flynn, 2018)

$$PE = \log(\rho_E) - 0.42\log(m_\infty) + 1.49\log(V_\infty) - 1.29\log(\cos Z_R) \quad (7)$$

where ρ_E is the atmospheric mass density (in g/cm^3) at the height of the fireball end point; m_∞ is the entry mass in grams, computed from the total light production; V_∞ is the entry speed in km/s, and Z_R is the entry angle from the zenith. Larger (i.e., less negative) PE values correspond to stronger material displaying less ablation.

Meteor Strength Classification (from Ceplecha et al., 1998).

Type.	PE Range.	Meteorite Association.
type I:	$PE > -4.60$	Ordinary Chondrite-like
type II:	$-5.25 < PE \leq -4.6$	Carbonaceous Chondrite (CI or CM)
type IIIa:	$-5.7 < PE \leq -5.25$	Short period cometary
type IIIb:	$PE \leq -5.7$	Weak cometary material

Fig. 10. PE-criterion (source: Flynn, 2018)

Rocky meteoroids on cometary orbits

	EN010697 "Karlštejn"
Date	1997 June 1
Time (UT)	$23^h 56^m 20^s \pm 3^s$
Beginning velocity (km s^{-1})	64.81±0.09
Beginning height (km)	92.96±0.01
Beginning geographic longitude (E)	14°.1965±0°.0001
Beginning geographic latitude (N)	49°.9176±0°.0001
Beginning angle to the vertical	65°.629±0°.012
Terminal velocity (km s^{-1})	61.1±0.9
Terminal height (km)	65.79±0.02
Terminal geographic longitude (E)	13°.3630±0°.0001
Terminal geographic latitude (N)	49°.9550±0°.0001
Terminal angle to the vertical	66°.165±0°.012
Length (km)	66.53
Duration (s)	1.03
Max. absolute magnitude	−7.4
Initial mass (kg)	0.2
Max. dyn. pressure (MPa)	0.66
PE coefficient	−4.52
Type	I

Fig. 11. Properties of the Karlštejn fireball (source: Spurný and Borovička, 1999)

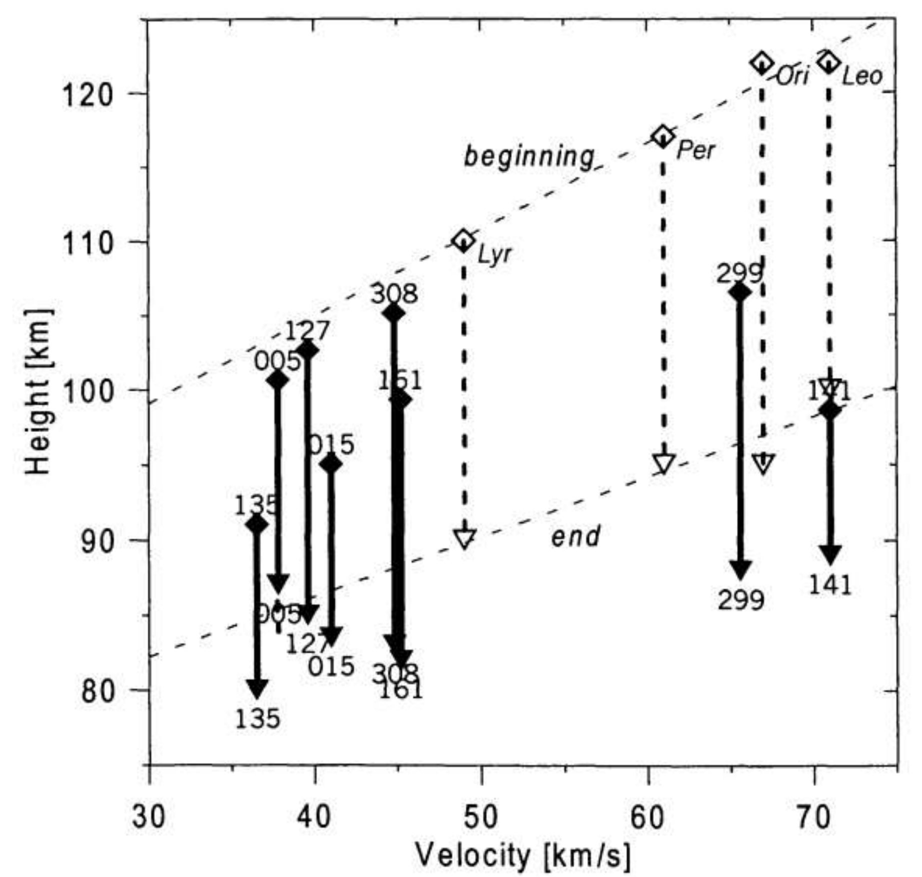

Fig. 12. Beginning and end heights of no-sodium and cometary meteors (source: Borovička et al., 2002)

Alberta fireball

(*Vida et. al., 2022*)

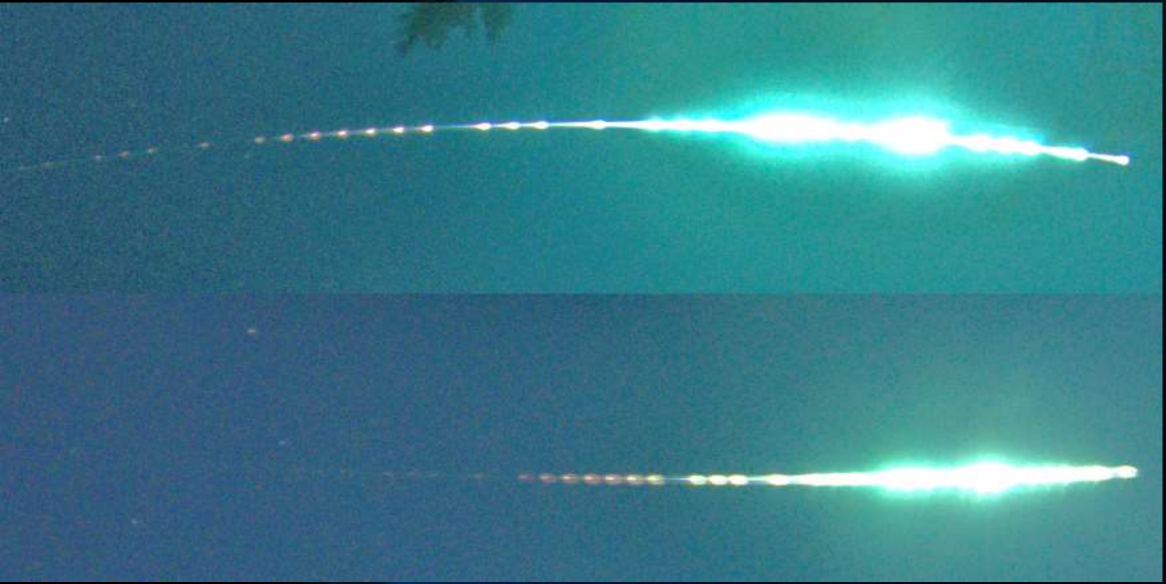

Fig. 13. Alberta fireball detected by two Global Fireball Observatory stations (source: Vida et. al., 2022)

- detected near Edmonton, Alberta, Canada on February 22, 2021 at 13:23:17 UTC;
- *PE = -4.49* → Type I (refractory material);
- retrograde long-period cometary orbit;
- end height 46.5 km with mass ~2 kg and speed 62 km/s;
- Vida et. al.: ~1–20% of the Oort cloud objects are rocky – proof for migration-based models.

Name	PE	T_J	Mass (kg)	a (au)	q (au)	e	i (deg)	ω (deg)	Ω (deg)
Alberta (this work)	$-4.49^{+0.12}_{-0.13}$	$-0.46^{+0.06}_{-0.02}$	$1.8^{+1.8}_{-0.9}$	104^{+126}_{-54}	$0.615^{+0.002}_{-0.002}$	$0.994^{+0.003}_{-0.006}$	$121.40^{+0.4}_{-0.4}$	$104.0^{+0.3}_{-0.4}$	333.86
Karlštejn[69]	$-4.53^{+0.42}_{-0.23}$	$0.64^{+0.12}_{-0.18}$	$0.20^{+0.50}_{-0.18}$	$3.5^{+0.18}_{-0.18}$	$1.012^{+0.0002}_{-0.0002}$	$0.710^{+0.016}_{-0.016}$	$137.90^{+0.10}_{-0.10}$	$174.60^{+0.14}_{-0.14}$	71.55
MORP #441[74]	-4.04	-0.78	0.020	24.7	0.765	0.969	159.7	56.7	103.8

Fig. 14. Set of Type I objects on cometary orbits used by Vida et. al.

Aims of our work

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Fig. 15. The All-sky Meteor Orbit System (AMOS) camera

- broaden the knowledge of cosmogonic models;
- investigate physical characteristics of meteoroids, concentrating on those limiting cosmogonic theories;
- prepare the database from AMOS cameras for analysis (*current stage: new software testing*);
- search in the database for refractory meteoroids on cometary orbits;
- investigate interesting cases trying to find patterns and limitations for cosmogonic models.

Thank you for attention!

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