Determining the Density Of Southern Delta Aquariid Meteors

Insights From the Canadian Automated Meteor Observatory

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Overview of the Southern Delta Aquariids (SDA) Shower

Introduction to SDA:

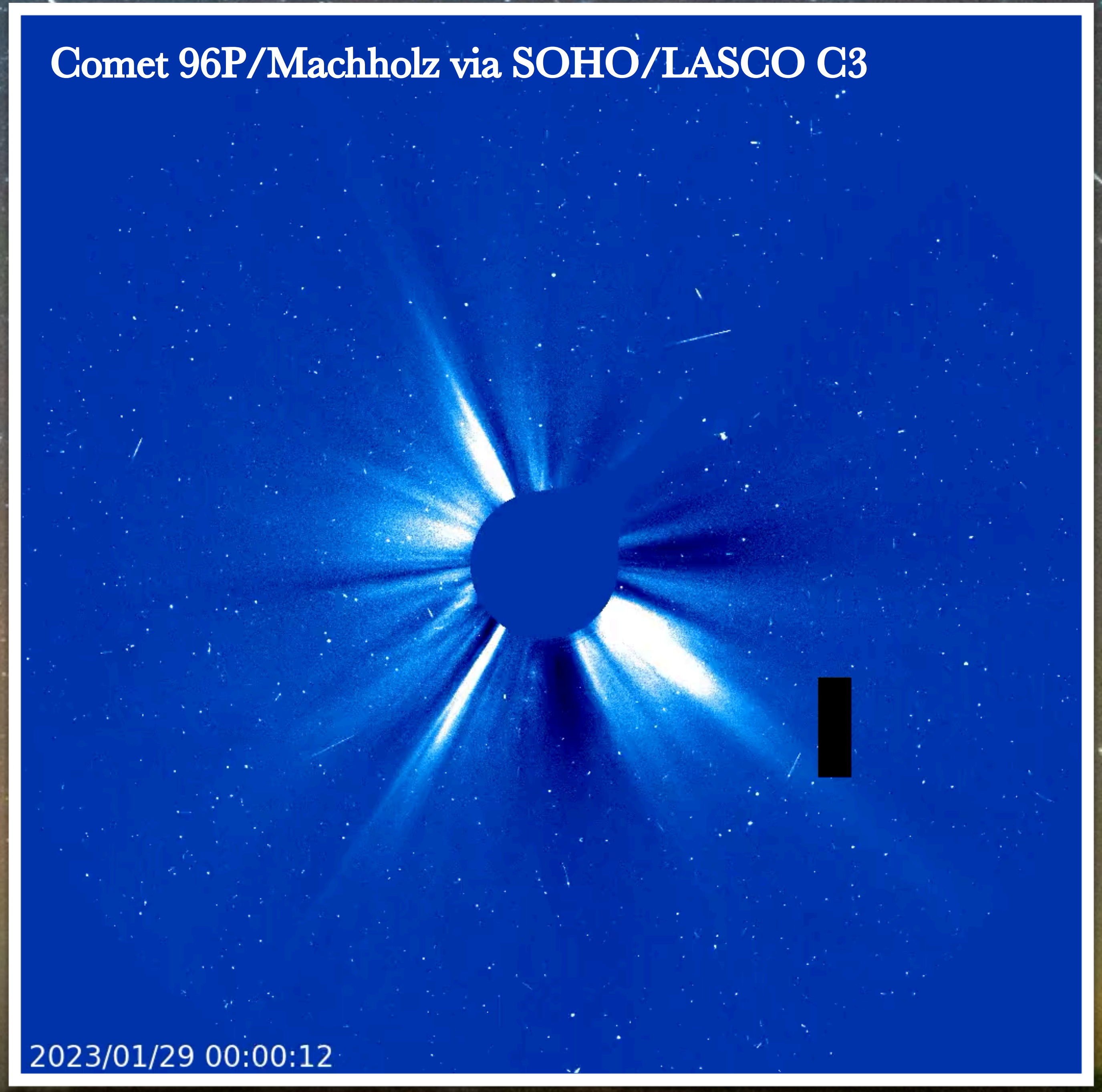
- Peak Activity: July 30th (Miskotte 2018)
- Zenithal Hourly Rate (ZHR): Around 20 meteors per hour (Jenniskens 2006)
- Geocentric Velocity: ~41 km/s (Jenniskens 2006)

Unique Characteristics:

- Perihelion Distance: ~0.1 AU (Abedin et al. 2018)
- Activity Period: Over a month (Abedin et al. 2018)
- Small Particle Richness: Strongest shower detected by the Advanced Meteor Orbit Radar (AMOR) to a radar limiting magnitude of +14 (Galligan 2000), and the second strongest annual shower detected by the Canadian Meteor Orbit Radar (CMOR) to a radar limiting magnitude of +8 (Brown et al. 2008)

Observational Highlights:

- Fragmentation: Strongest among all showers (Jacchia et al. 1967)
- Material Refractivity: k_B proxy strength parameter found to be the largest (Joiret & Koschny 2023) or second largest (next to Geminids) among all major showers (Matlovič et al. 2019)
- Potential Linkage: Comet 96P/Machholz (McIntosh 1990; Abedin et al. 2018)



Credit: ESA/NASA/USNRL/K.Battams.

Why Investigate the SDAs?

Most meteor showers with ZHRs above ten (QUA, LYR, ETA, PER, ORI, LEO, and GEM) have numerous studies providing bulk density estimates.

In contrast, the SDA shower has only a couple such attempts. This knowledge gap in the properties of SDA meteors is significant for the scientific community and is recognized on NASA's 2024 monitoring agenda (Moorhead 2023), since it has a more than 20 percent flux enhancement relative to the sporadic meteoroid flux. Addressing this informational void is worthy for comparative characterization studies of meteor showers.

Review of Previous Research on SDA Meteors

1. **Super-Schmidt Records (1967):**
   - **Researcher:** Verniani
   - **Bulk Density Estimate:** 300 kg/m³ (from 5 meteors)
   - **Method:** Single body ablation assumption, luminous efficiency values now considered too low
2. **Photographic Measurements (2009):**
   - **Researcher:** Babadzhanov
   - **Bulk Density Estimate:** 2,400 ± 600 kg/m³
   - **Method:** Quasi-fragmentation model, fits to light curves (no fits to deceleration and wake profiles)
3. **Proxy Metrics:**
   - **Researchers:** Matlovič et al. 2019 and Joiret & Koschny 2023
   - **Focus:** k_B proxy strength parameter, material refractivity
   - **Findings:** High k_B values similar to the Geminids (7.34 ± 0.11): 7.59 ± 0.13 & 7.61, respectively.

Goals

Quantify Bulk Density: To determine the average bulk density of Southern Delta Aquariid meteoroids using observations from the Canadian Automated Meteor Observatory.

Characterize Ablation Process: To model the ablation and fragmentation stages of SDA meteoroids, identifying differences in density and structural composition during their atmospheric entry.

Compare with Other Showers: To compare the bulk density and material properties of SDA meteoroids with other major meteor showers, exploring the implications of their low perihelion distances and potential thermal processing effects.

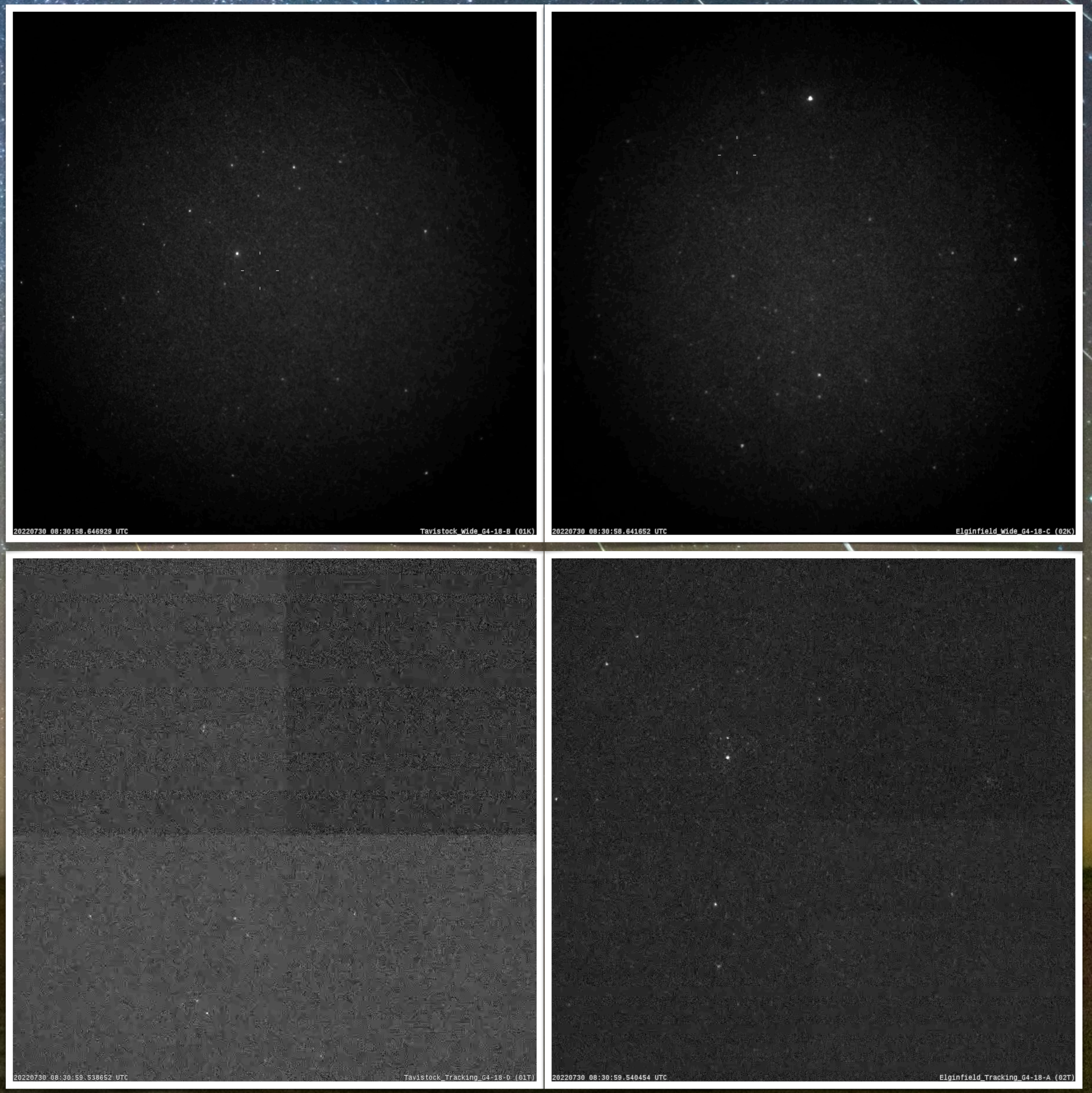
Observations

1. **Data Collection:**

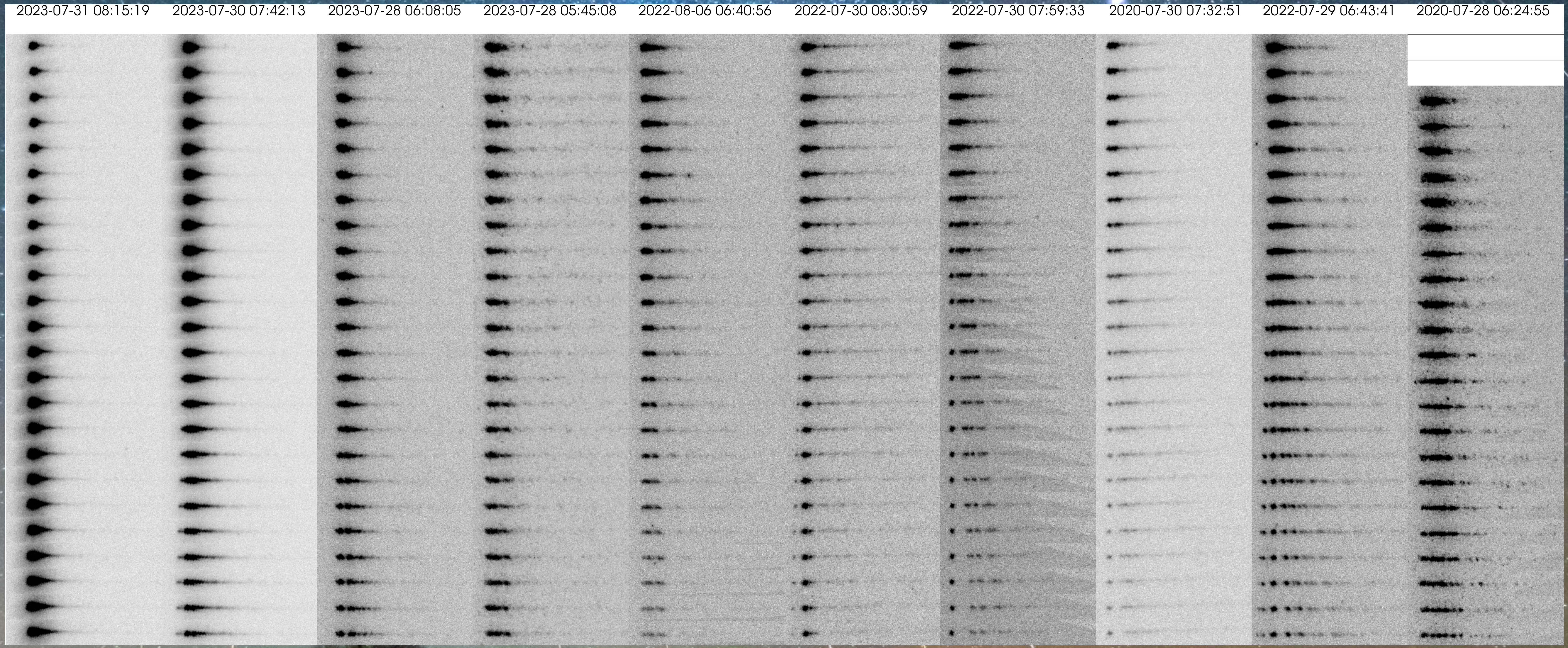
- **Observation Period:**
  - Collected data from 2020 to 2023.
- **Instruments Used:**
  - Optical cameras & EMCCD cameras (for 4/10 events).

2. **Methodology:**

- **Data Analysis:**
  - Manual reduction of optical observations.
  - Measurement of lightcurve, deceleration, and wake profile.
- **Event Selection:**
  - Ten SDA meteors selected for detailed analysis.
  - Criteria based on visibility and data quality (e.g, $Q_* > 15$, highly perpendicular).



Ten SDA Meteors



Meteor Morphology:

- **Two distinct erosion stages observed:**

- **Early Phase:**
  - Meteors generally exhibit a smooth tadpole-shaped morphology.
  - Features a bright head with a clearly defined wake.
  - Images capture the progressive fragmentation of the meteor.

- **Later Phase:**
  - Several fragments become visible as the meteor travels.
  - Leading fragment governs light production.

Ablation and Erosion Modeling

1. METSIM Tool:

- **Graphical User Interface:**
  - Designed for numerical modeling of meteoroid ablation and erosion.
  - Based on the erosion model proposed by Borovička et al. (2007).
- **Model Assumptions:**
  - Meteoroids fragment in the atmosphere through the loss of μm-sized grains.
  - No progressive fragmentation once grains are released.
  - Each grain ablates separately as a single body.

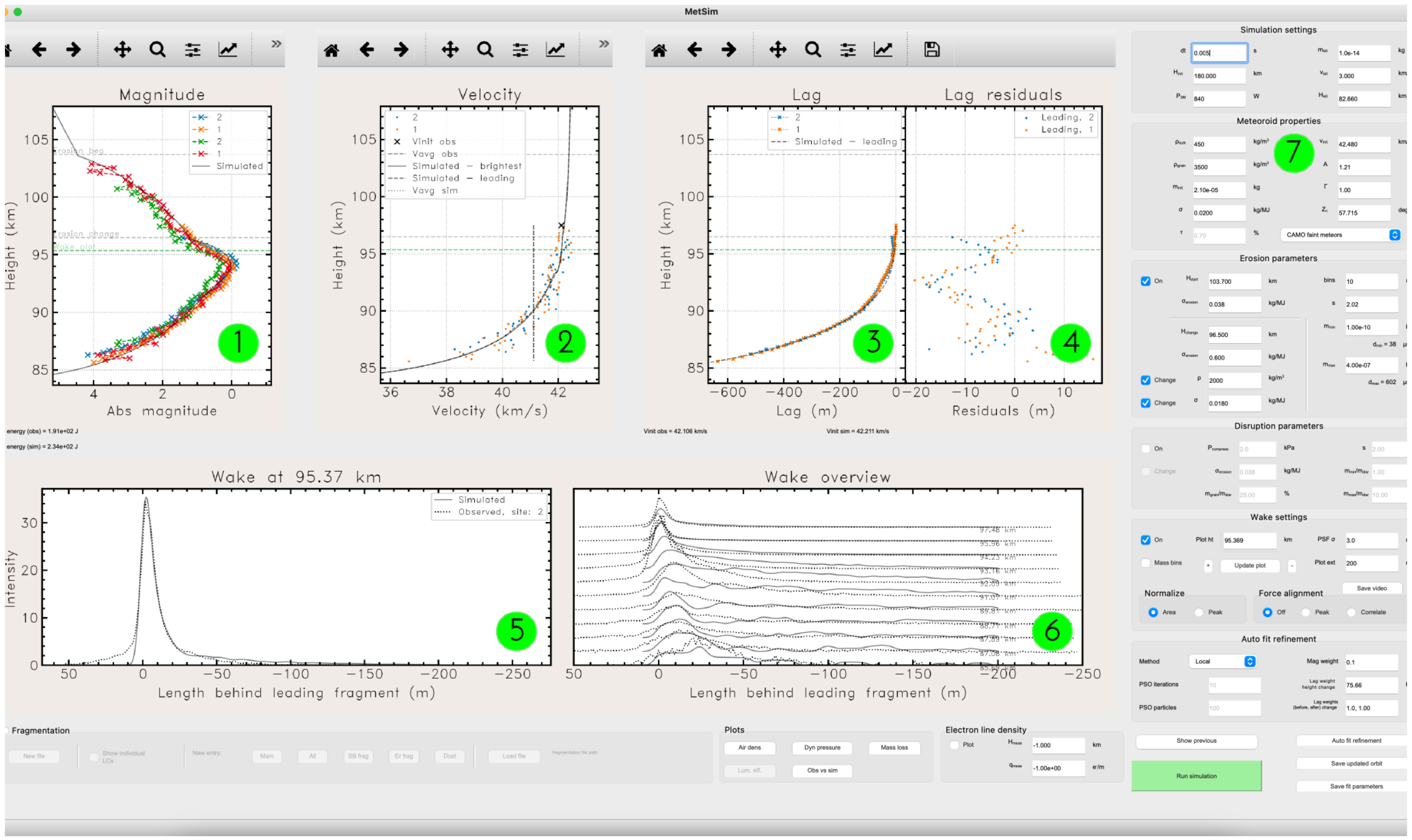
2. Modeling Process:

- **Erosion and Ablation:**
  - Separate mass loss into ablative and erosive components.
  - Compute erosion using an erosion coefficient.
  - Fit model to observed data using simulated lightcurve, velocity, deceleration, and wake profiles.

Model Free Parameters for SDA Meteor Analysis

Parameter	Description	Range
v_∞	Meteoroid Initial Velocity	$12 - 72$ km s^{-1}
m_∞	Meteoroid Initial Mass	$10^{-9} - 1$ kg
ρ_m	Meteoroid Bulk Density	$100 - 3,500$ kg m^{-3}
σ	Ablation Coefficient	$0.001 - 0.3$ kg MJ^{-1}
η	Erosion Coefficient	$0.001 - 2$ kg MJ^{-1}
m_l	Smallest Grain Mass	$10^{-12} - m_u$ kg
m_u	Largest Grain Mass	$m_l - \frac{m_\infty}{2}$ kg
s	Grain Mass Index	$1.4 - 2.5$
H_e	Erosion Start Height	$70 - 120$ km
H_{ec}	Erosion Change Height	$70 - 120$ km
η_c	Erosion Change Coefficient	$0.001 - 2$ kg MJ^{-1}
σ_c	Ablation Change Coefficient	$0.001 - 0.3$ kg MJ^{-1}
ρ_{mc}	Meteoroid Bulk Density Change	$100 - 3,500$ kg m^{-3}

METSIM Graphical User Interface



Light Curves and Lag Profile Fits for Meteor 1

- Wide field observations occur initially, followed by the narrow field systems which lock onto the meteor to provide subsequent data until the fadeout altitude.
- The lag refers to the difference in position between the observed meteor and a hypothetical meteor moving at a constant speed equal to the initial velocity.

$\rho_m = 1{,}460$ kg m^{-3}

$\sigma = 0.02$ kg MJ^{-1}

$H_e = 103.7$ km

$\eta_e = 0.038$ kg MJ^{-1}

$m_u = 6 \times 10^{-7}$ kg

$m_l = 10^{-10}$ kg

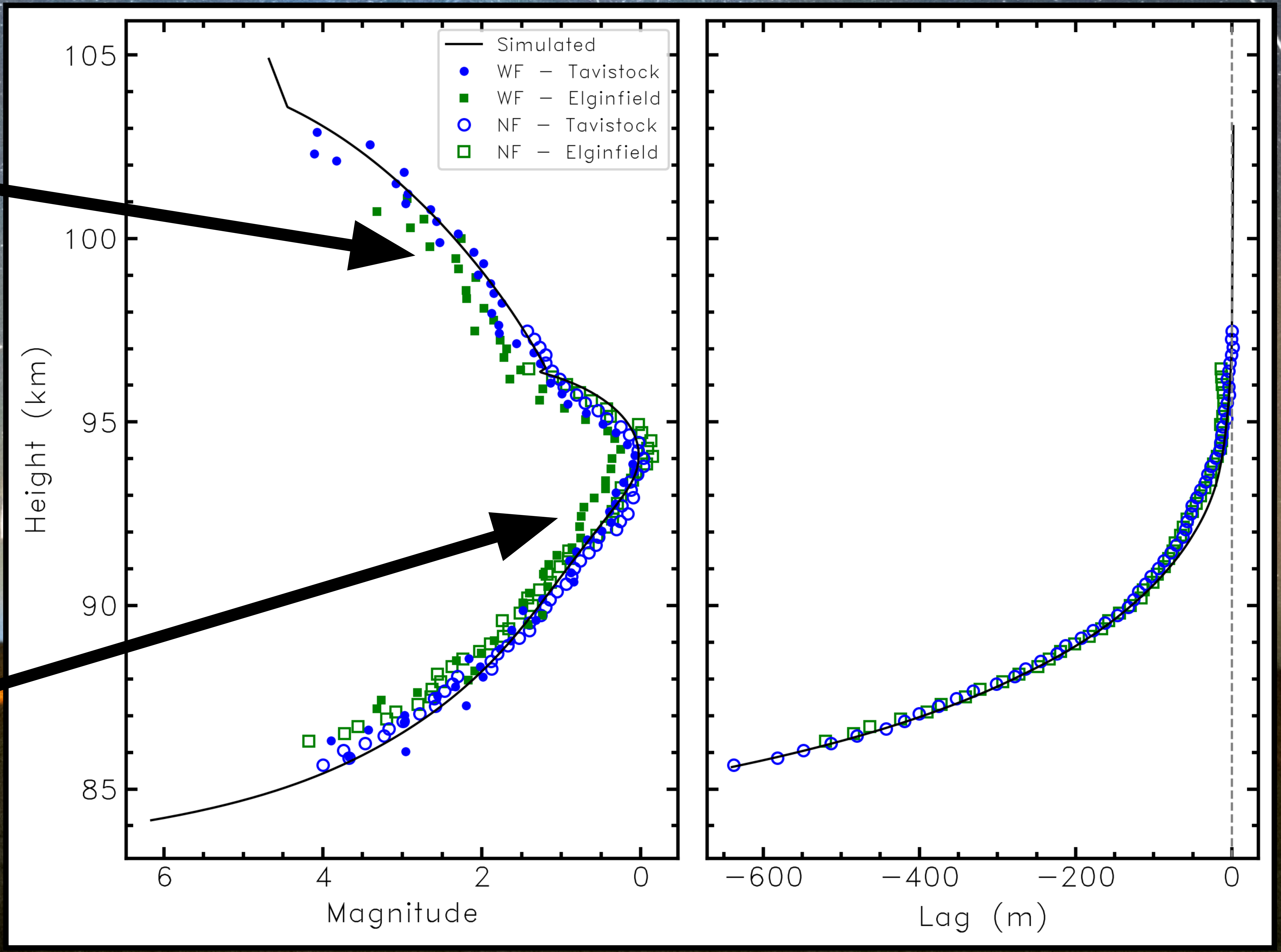
$s = 2.02$

$\sigma_c = 0.018$ kg MJ^{-1}

$H_{ec} = 96.5$ km

$\eta_{ec} = 0.6$ kg MJ^{-1}

$\rho_{mc} = 2{,}000$ kg m^{-3}

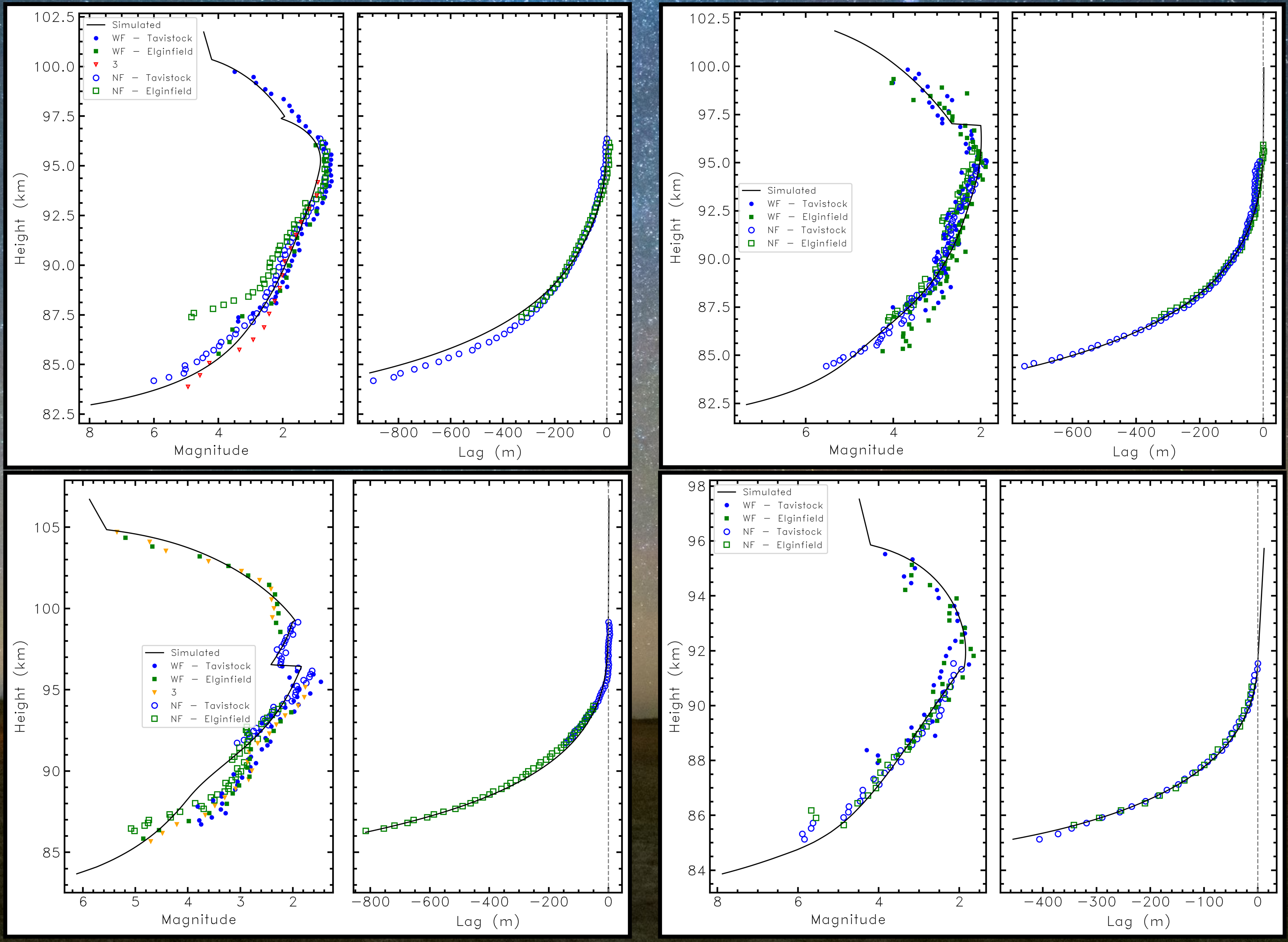


Light Curves and Lag Profile Fits for Meteors 2-5

The Value of EMCCD Data

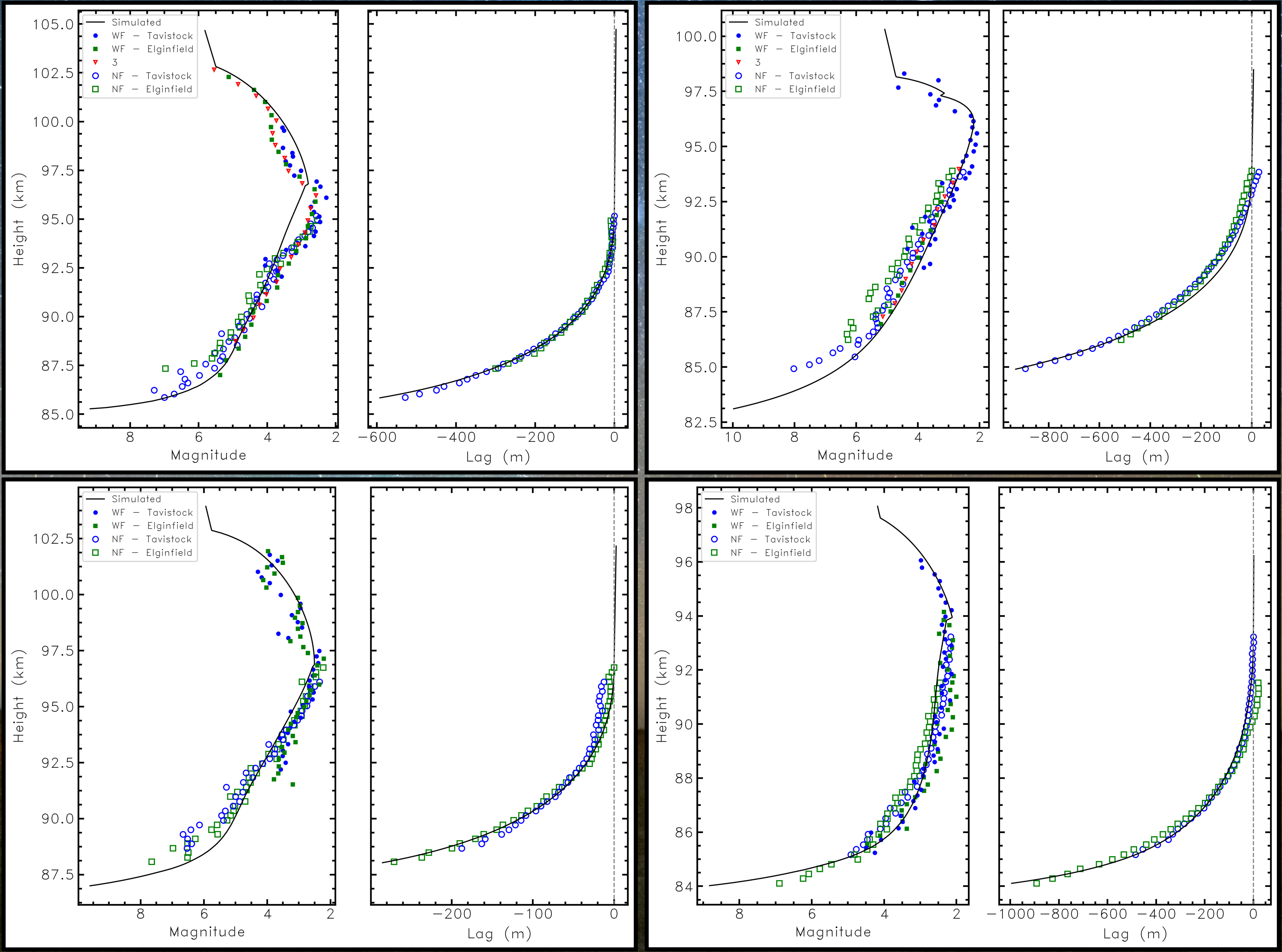
The EMCCD observations help decipher between a reduction offset in the narrow-field system.

The EMCCD system helps corroborate the entire light profile.



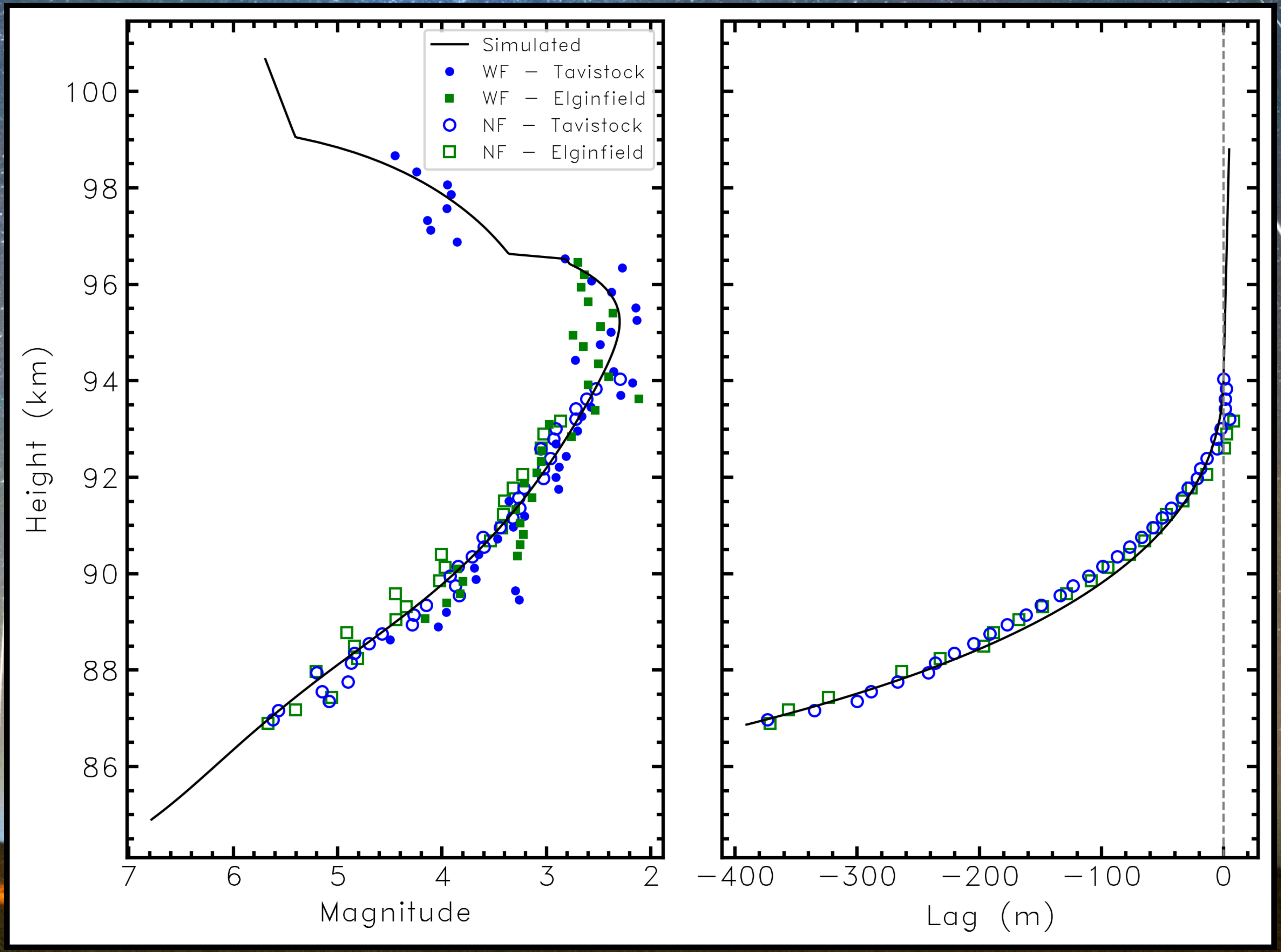
Light Curves and Lag Profile Fits for Meteors 6-9

The EMCCD observations help corroborate nearly the entire light profile.

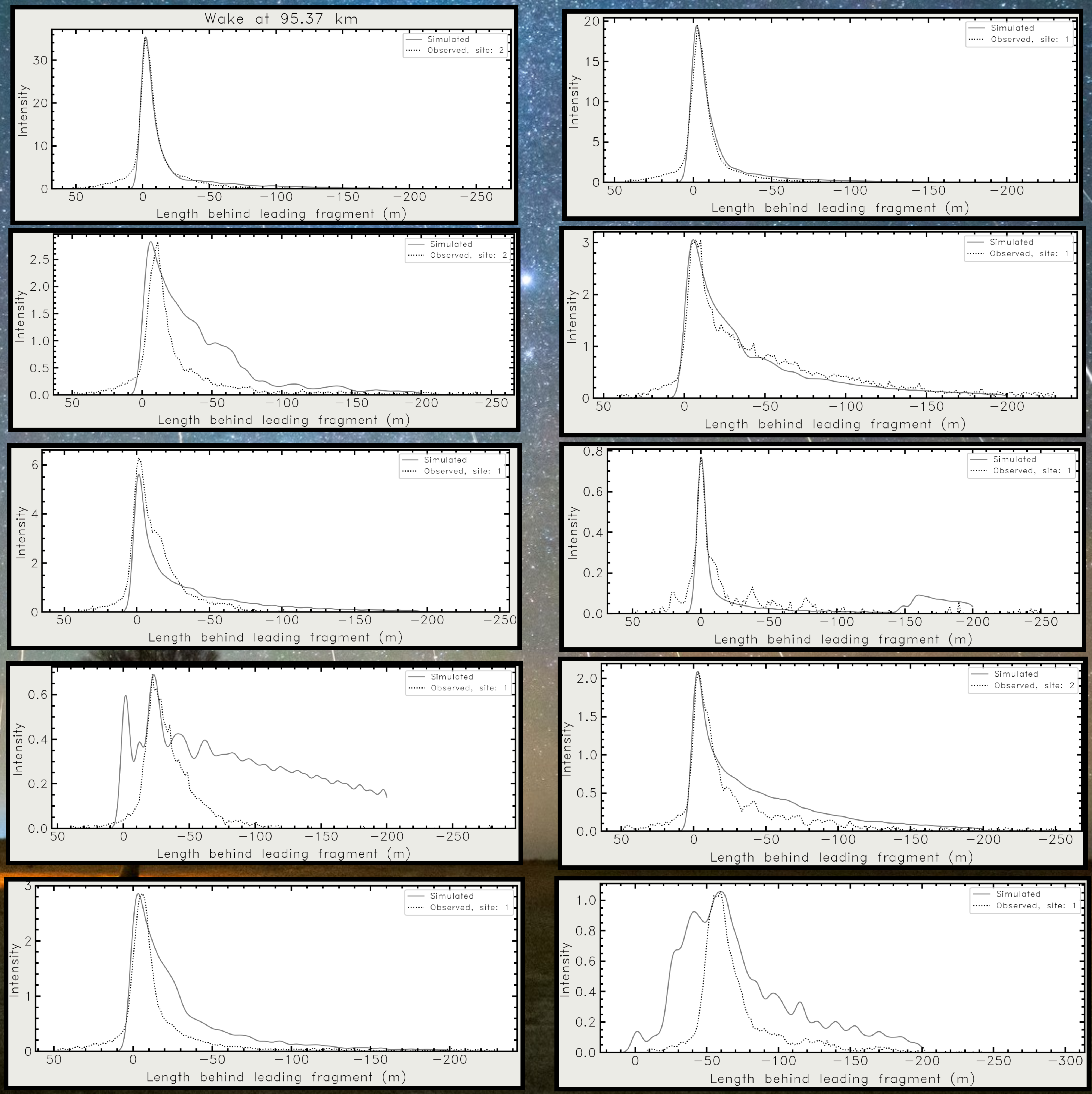


The EMCCD observations help corroborate half of the CAMO observations.

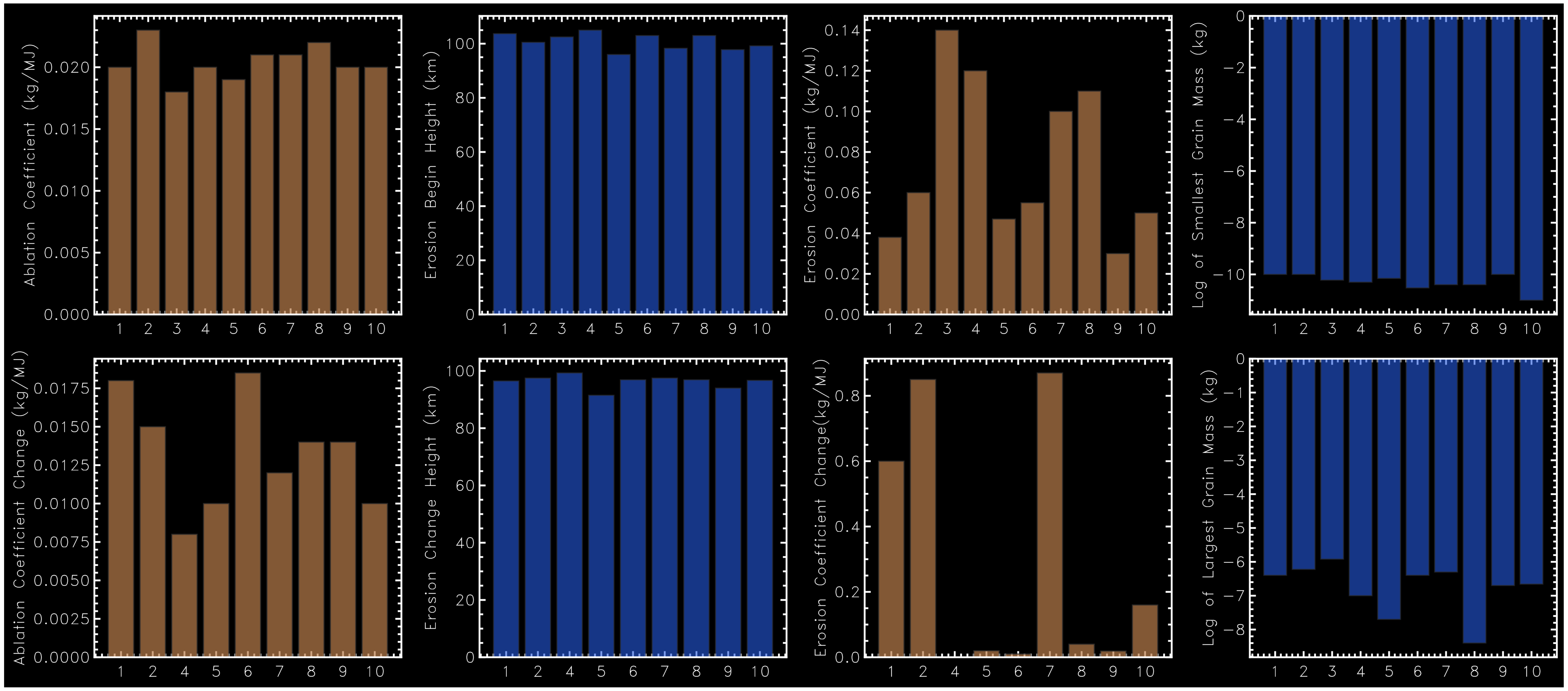
Light Curves and Lag Profile Fits for Meteor 10



Narrowfield Onset Wake Profiles for Meteors 1-10

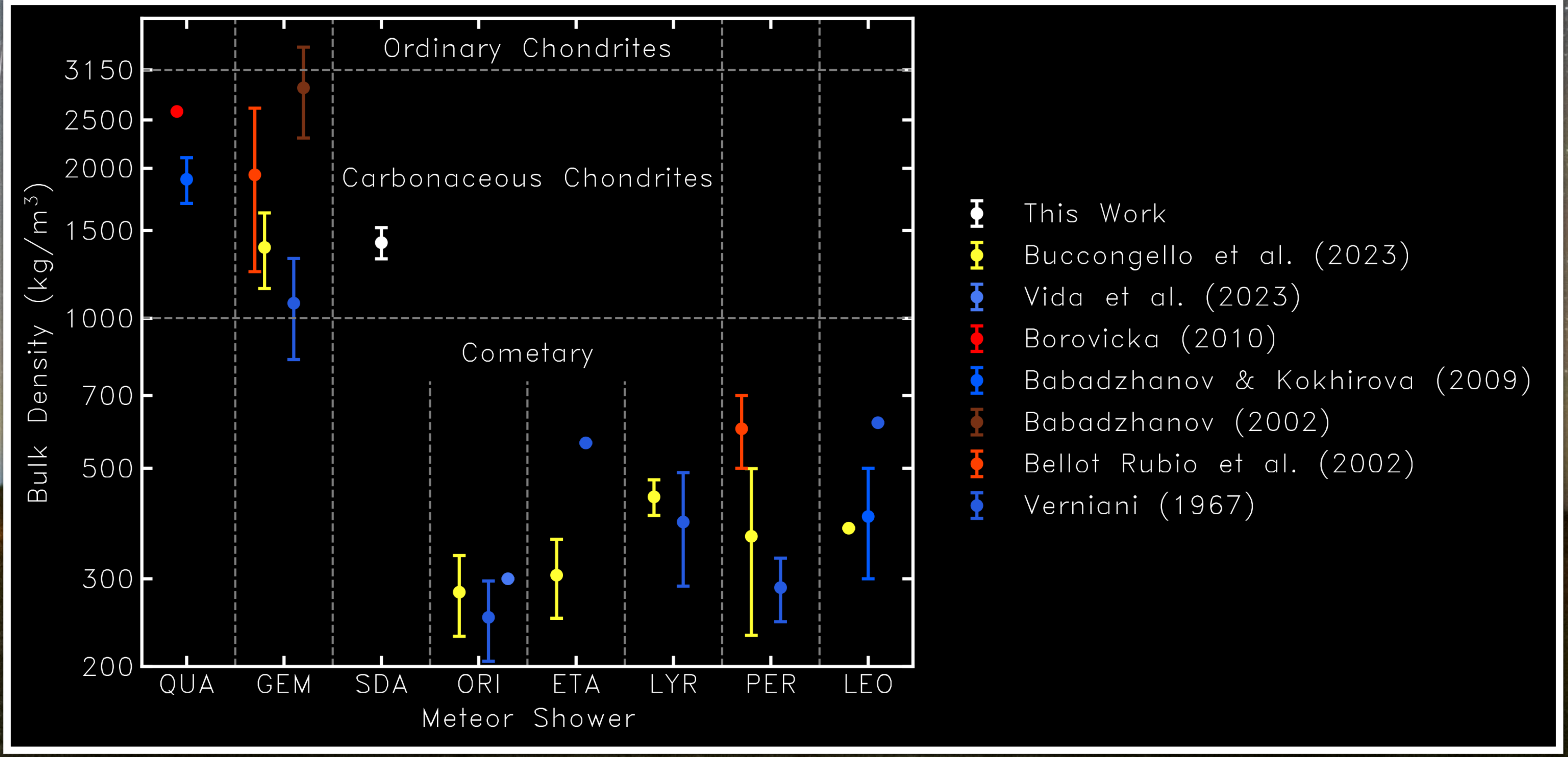


Comparison of METSIM Free Parameters



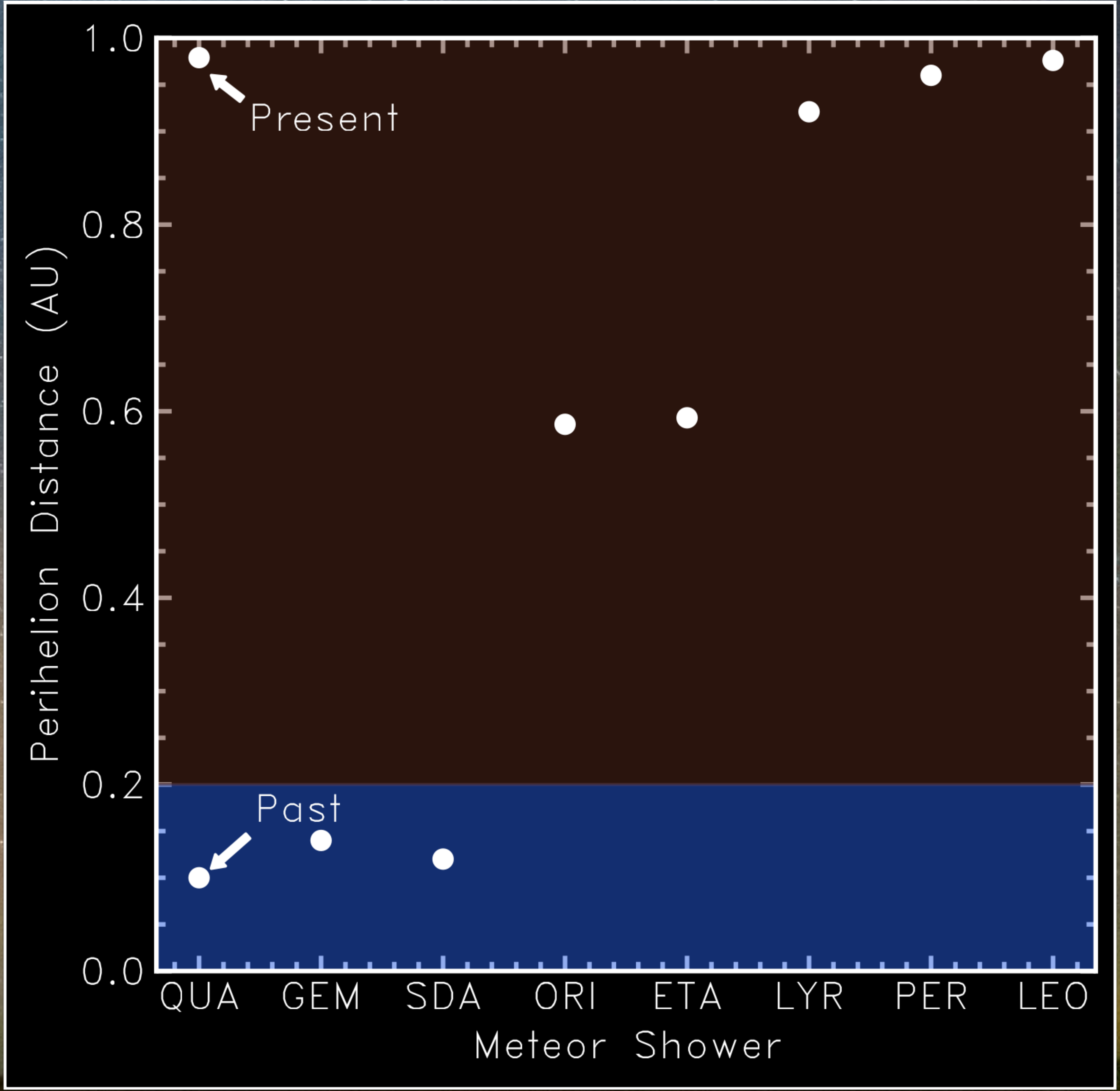
Results Overview

- **Average Bulk Density:**
  - Observation:
    - The average bulk density for the ten SDA meteors analyzed is 1,420 ± 100 kg/m³.
  - Comparison:
    - This density is comparable to other high-density meteor showers like the Quadrantids and Geminids.

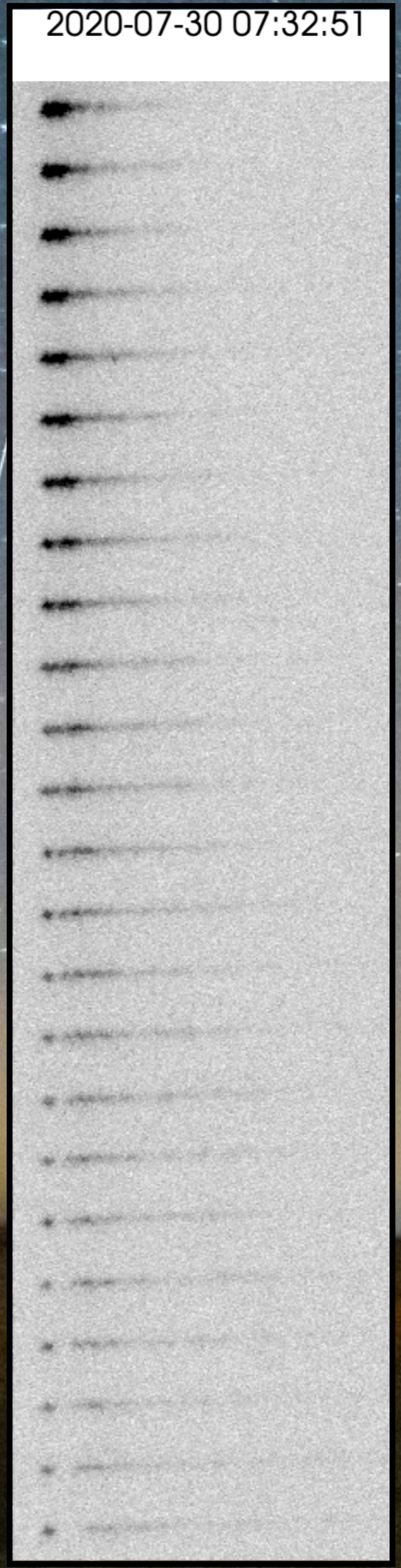


The Impact of Thermal Desorption on Bulk Density

1. Introduction to Thermal Desorption:
   - Thermal desorption is the process where volatile compounds are released from a material due to heating.
   - Meteoroids approaching the Sun undergo heating, causing volatile components to desorb.
2. Figure Description:
   - Graph comparing perihelion distances of various meteor showers.
   - Showers with low perihelion distances, like SDA, QUA, and GEM, exhibit higher bulk densities, which is attributed to thermal desorption, suggesting a correlation between perihelion distance and bulk density.
   - Borovička et al. 2005 suggests that small sporadic meteoroids with perihelia <0.2 AU are depleted in volatile sodium (Na) and compacted.
   - SDA meteoroids are Na-free and compacted at perihelion temperatures ~1,000 K (Borovička 2010; Matlovič et al. 2019).
   - The age of SDA stream: 10,000 to 20,000 years (Abedin et al., 2018), implying a long action time for thermal desorption.
   - Geminids (GEM) have highly depleted Na and other volatiles at 0.14 AU, heated to ~700 K (Borovička, 2010).
   - High densities observed in SDA, QUA, and GEM are likely due to small perihelia.



Thermal Desorption Leads to Elevated Densities



- **Dual Erosion Stages:**
  - Initial Stage:
    - Characterized by a low bulk density (~700 ± 110 kg/m³).
    - High erosion rates with smaller grain loss.
  - Later Stage:
    - Dominated by a higher density fragment (~2,310 ± 160 kg/m³).
    - Lower erosion rates, indicating more refractory material.
  - **Implications for Meteoroid Structure:**
    - Bimodal Composition:
      - Meteoroids consist of a porous outer layer and a compact inner core.

Date and Time (UTC)	ρ_{eff} (kg m^{-3})	ϕ_{eff} (%)	ρ_∞ (kg m^{-3})	ϕ_∞ (%)	f_{m_∞} (%)	ρ_s (kg m^{-3})	ϕ_s (%)	f_{m_s} (%)	m_∞ (kg)	K_B
2023-07-31 08:15:19 (1)	1,460	58.3	450	87.1	34.8	2,000	42.9	65.2	2.1×10^{-5}	7.10
2023-07-30 07:42:13 (2)	1,680	52	600	82.9	30	2,150	38.6	70	1.2×10^{-5}	7.40
2023-07-28 06:08:05 (3)	1,500	57.1	1,500	57.1	100	—	—	—	6.0×10^{-6}	7.27
2023-07-28 05:45:08 (4)	1,650	52.9	650	81.4	45.8	2,500	28.6	54.2	6.0×10^{-6}	7.07
2022-08-06 06:40:56 (5)	820	76.7	500	85.7	81.2	2,200	48.6	18.8	4.60×10^{-6}	7.68
2022-07-30 08:30:59 (6)	1,210	65.4	500	85.7	61.5	2,350	32.9	38.5	2.3×10^{-6}	7.14
2022-07-30 07:59:33 (7)	1,700	56.3	550	84.3	34.6	2,300	34.3	65.4	2.6×10^{-6}	7.46
2020-07-30 07:32:51 (8)	1,410	58	700	80	74.5	3,500	0	25.5	2.1×10^{-6}	7.45
2020-07-28 06:24:55 (9)	970	72.3	450	87.1	58.7	1,700	51.4	41.3	5.55×10^{-6}	7.16
2022-07-29 06:43:41 (10)	1,780	52.6	1,100	68.6	32	2,100	40	68	2.25×10^{-6}	7.72

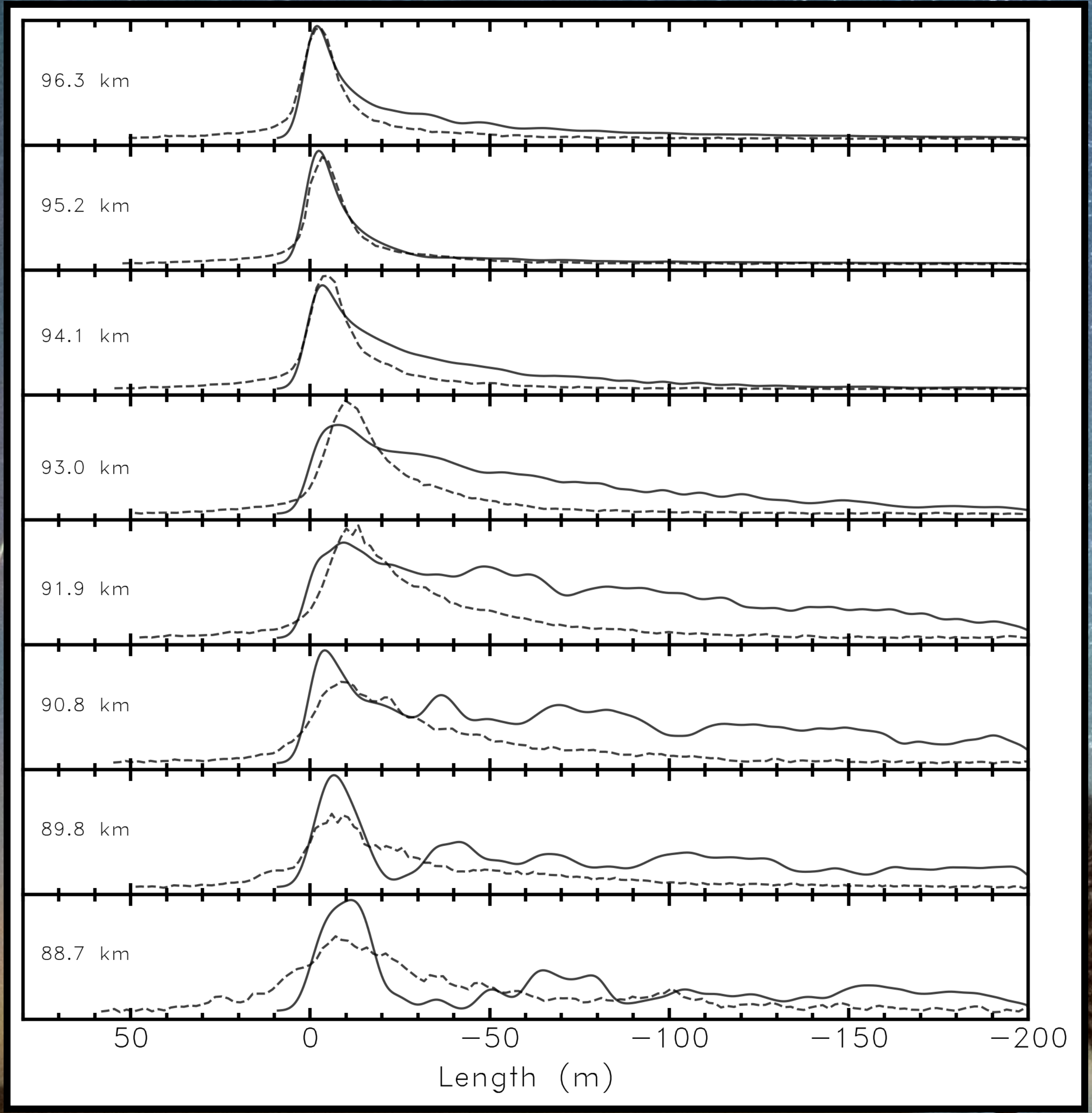
Conclusions

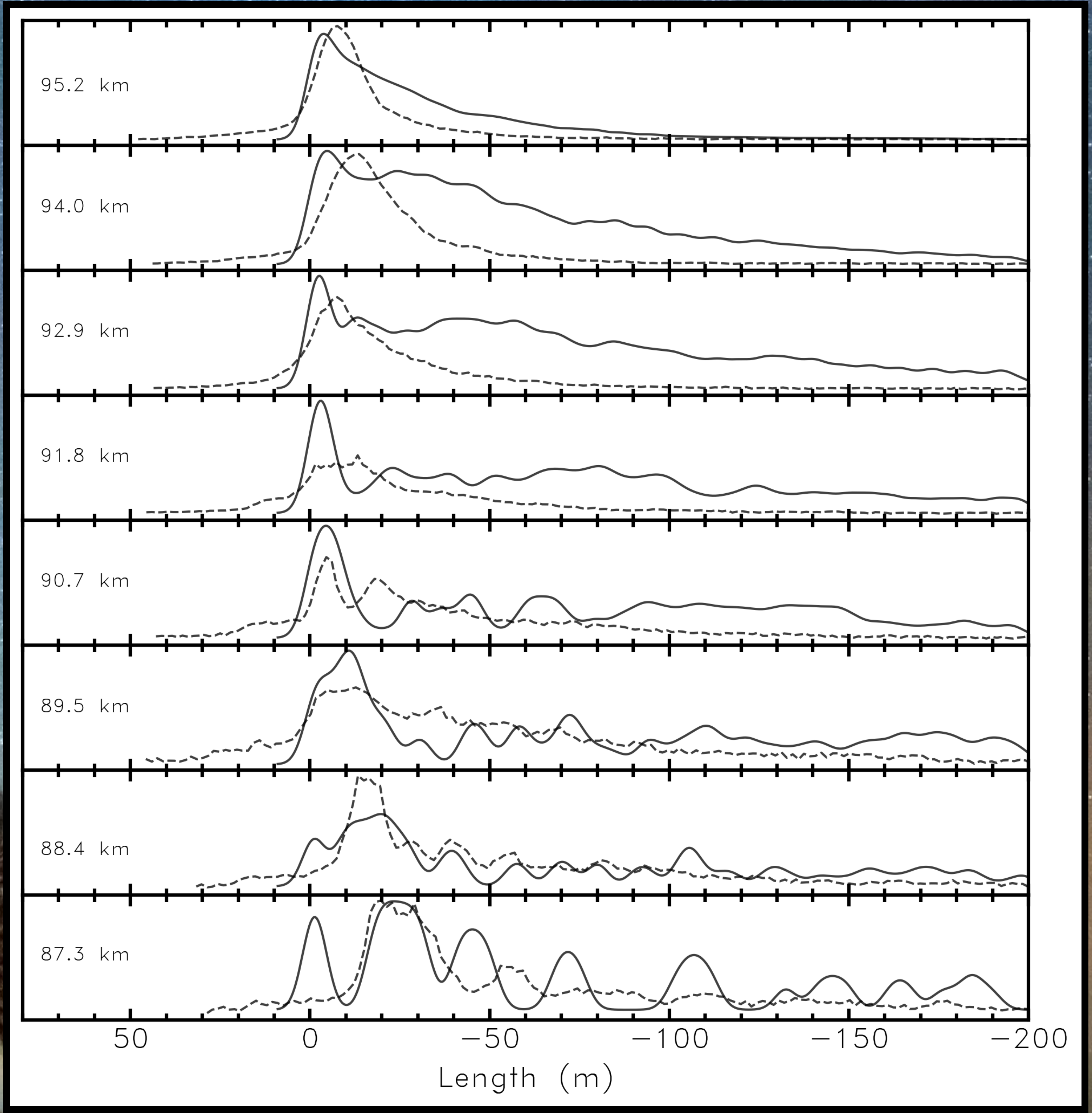
1. High Bulk Density:
    - The average bulk density for ten SDA meteoroids in the 1-3 mm diameter range is 1,420 ± 100 kg/m³, placing them in the carbonaceous chondrite class.
2. Dual Erosion Stages:
    - Initial Stage:
        - Characterized by relatively low bulk density (700 ± 110 kg/m³).
    - Later Stage:
        - Dominated by a high-density leading single-body fragment (2,310 ± 160 kg/m³).
3. Bimodal Structure:
    - Component Analysis:
        - SDA meteoroids consist of a low-density, porous component and an embedded compact component.
    - Ablation Coefficients:
        - Similar for both components, indicating they are made from the same fundamental grains.
4. Thermal Processing:
    - Perihelion Distance:
        - Small perihelia (~0.1 AU) result in high temperatures (~1,000 K).
    - Volatile Loss:
        - Significant loss of volatile elements such as sodium.
5. Comparisons with Other Showers:
    - Similar Densities:
        - QUA and GEM showers also have high bulk densities due to similar thermal desorption processes.SDA is now third shower that has relatively high densities.
    - Shared Characteristics:
        - Thermal desorption and compaction at low perihelion distances are common.

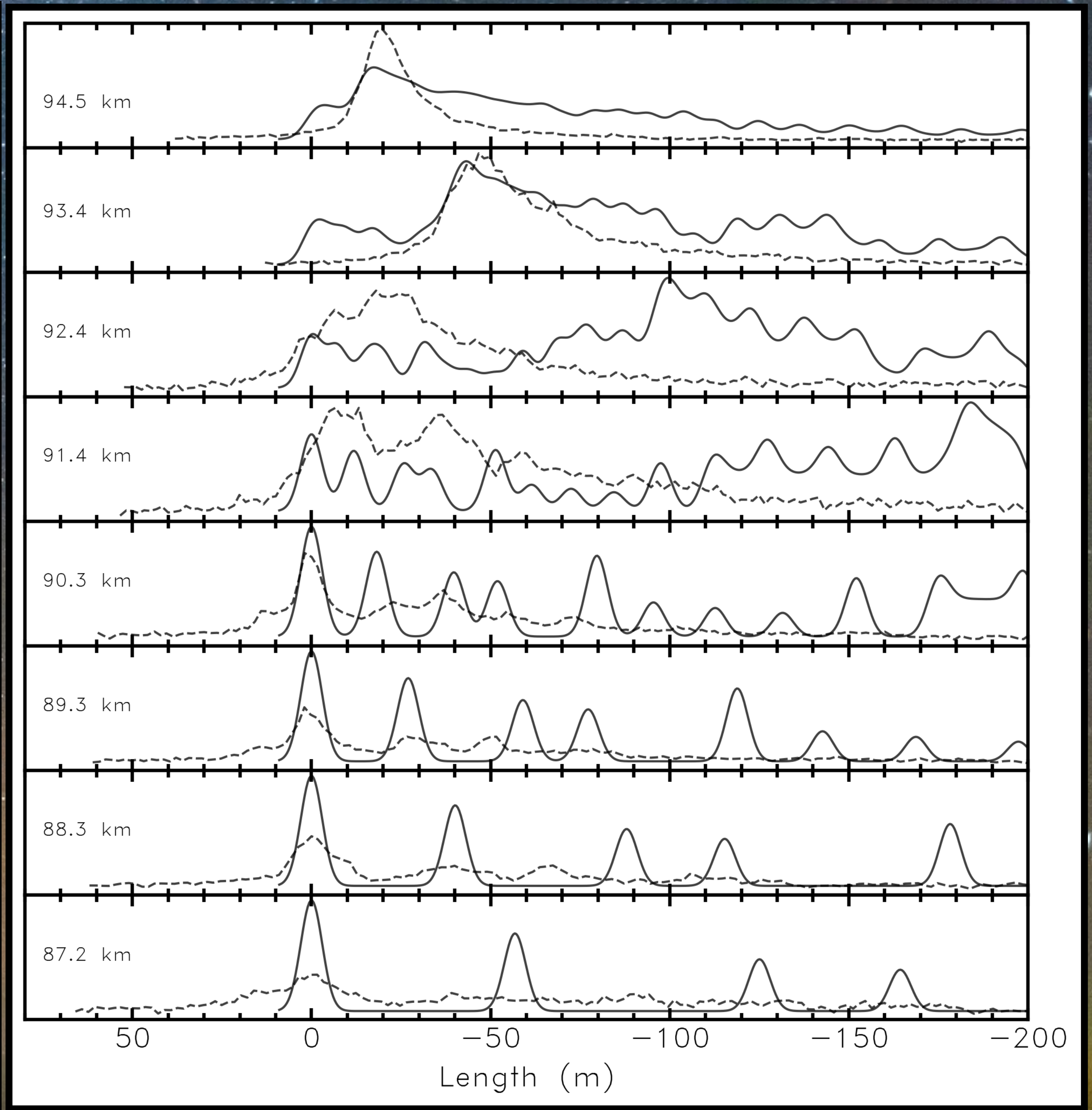

Questions?
Thank you for your attention.
Are there any questions?

Backup Slides

Wake Profiles for Meteors 1-3

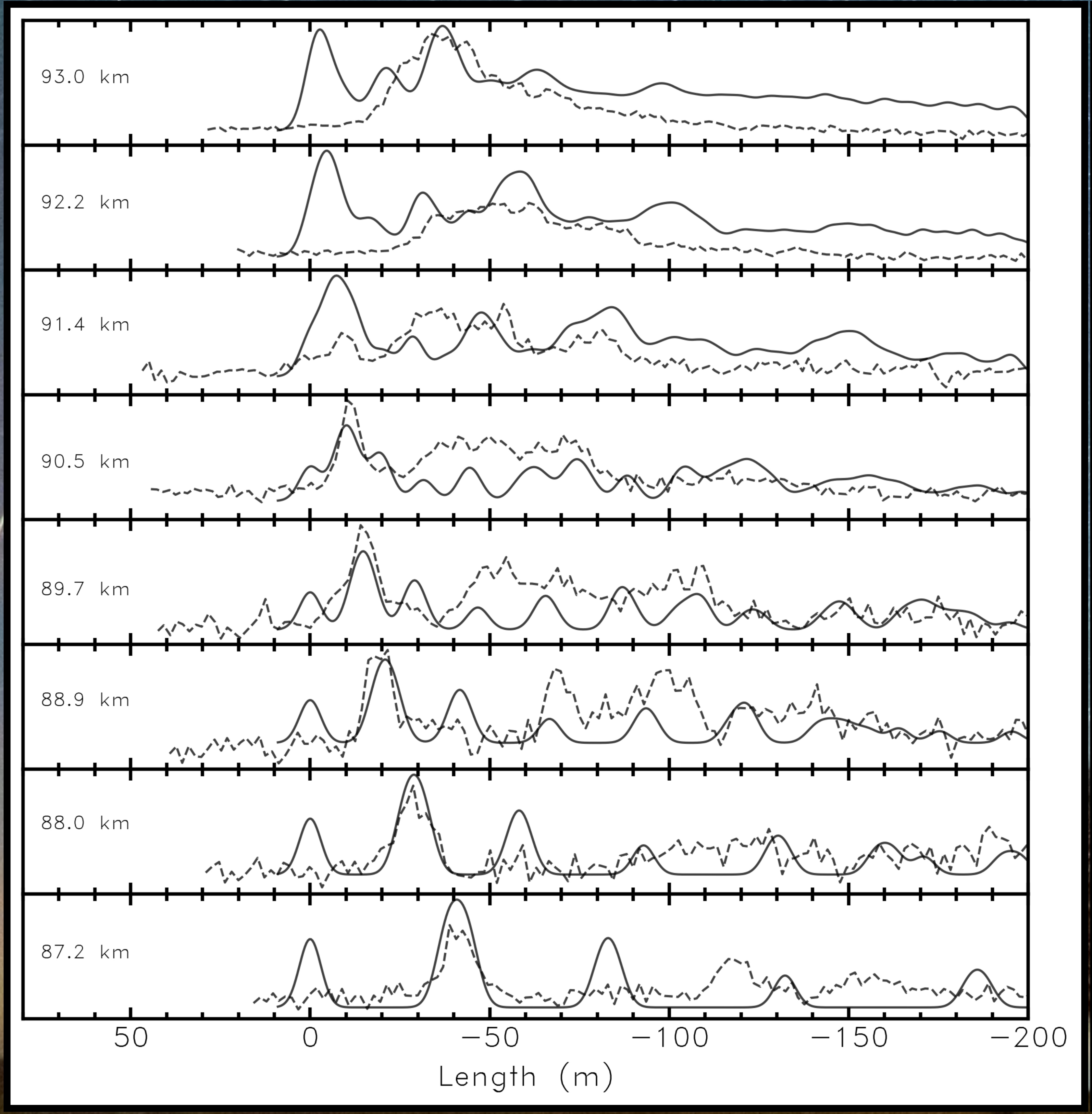


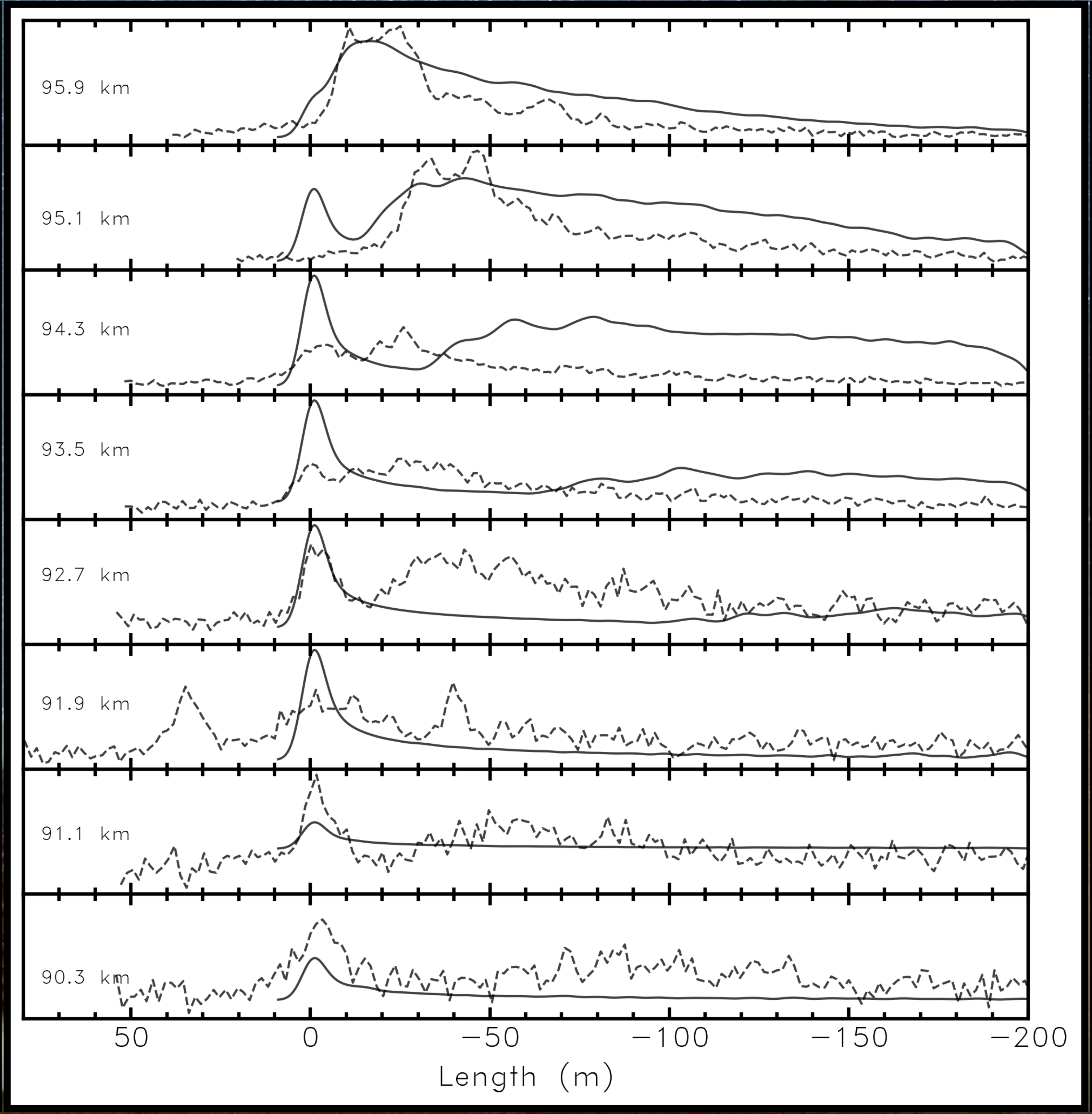


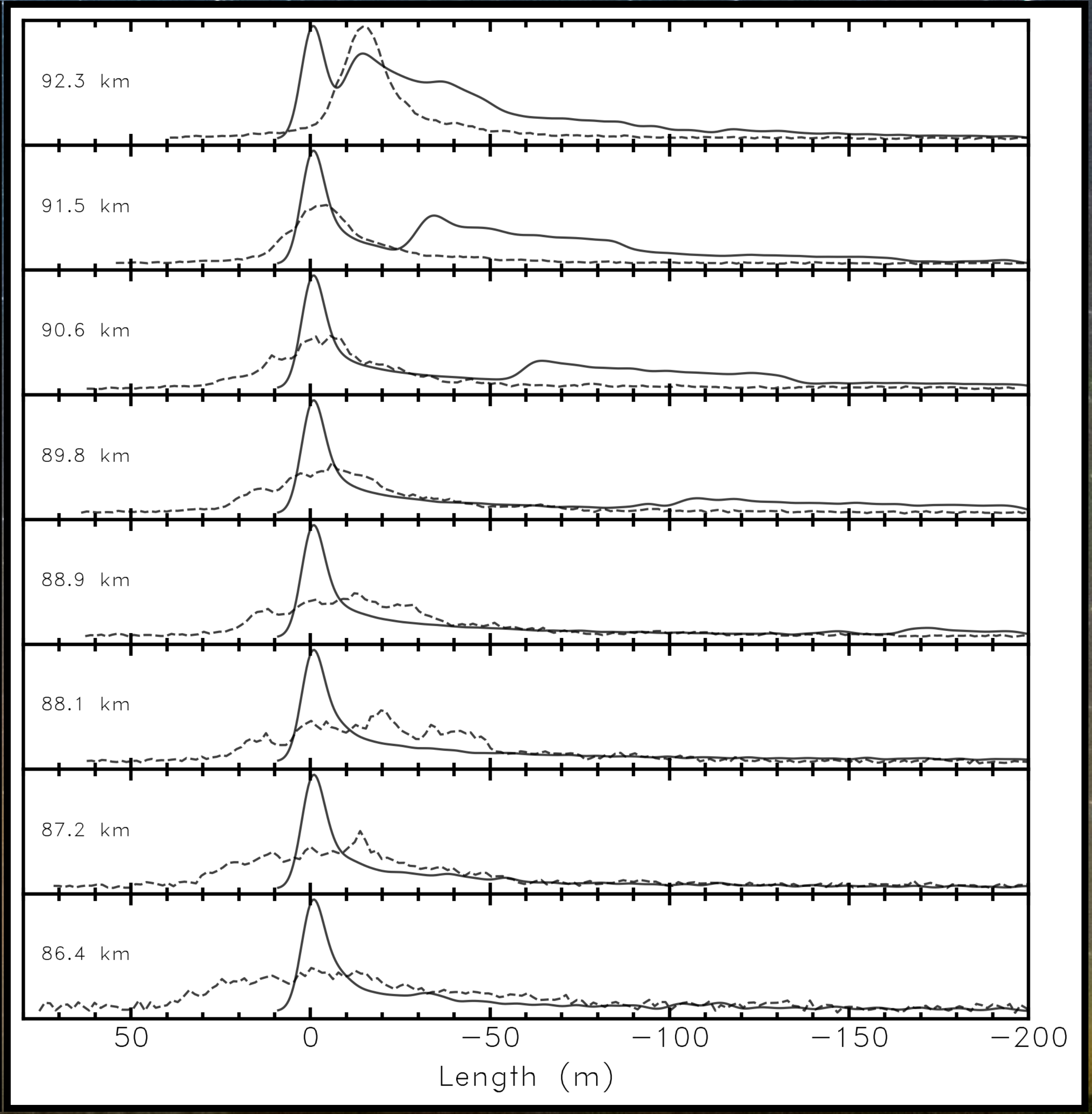


Wake Profiles for Meteors 4-6

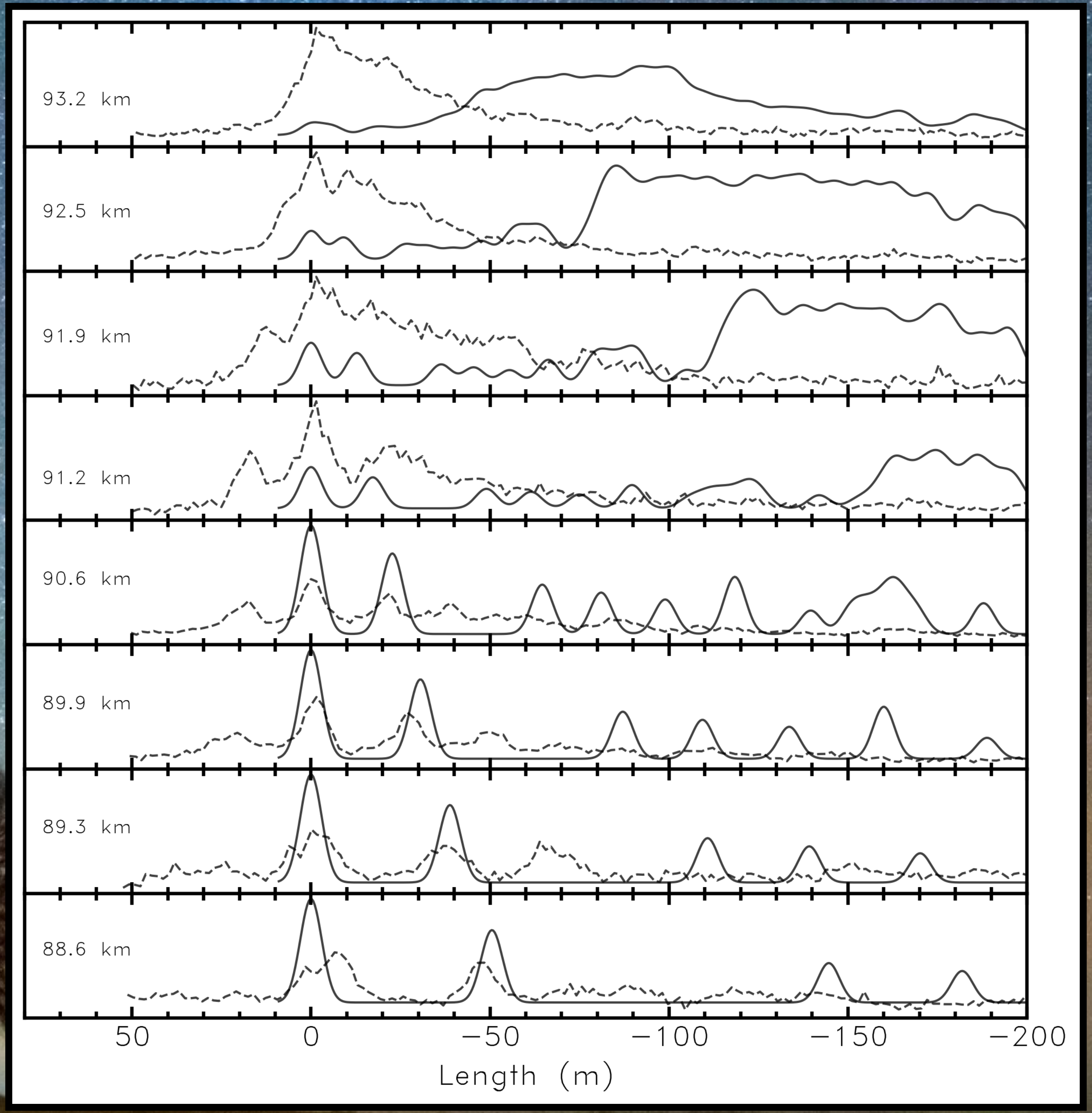
Wake Profiles for Meteors 7-9







Wake Profiles for Meteors 10



Best-fit Model Parameters

Identifier	σ (kg MJ^{-1})	H_e (km)	η (kg MJ^{-1})	m_u (kg)	m_l (kg)	s	H_{ec} (km)	η_{ec} (kg MJ^{-1})	σ_c (kg MJ^{-1})	ρ_{mc} (kg m^{-3})
1	0.02	103.7	0.038	4×10^{-7}	1×10^{-10}	2.02	96.5	0.6	0.018	2,000
2	0.023	100.5	0.06	6×10^{-7}	1×10^{-10}	1.98	97.5	0.85	0.015	2,150
3	0.018	102.5	0.14	1.2×10^{-6}	6×10^{-11}	1.85	—	—	—	—
4	0.02	105.0	0.12	1×10^{-7}	5×10^{-11}	2	99.3	0.001	0.008	2,500
5	0.019	96.0	0.047	2×10^{-8}	7×10^{-11}	1.9	91.5	0.02	0.01	2,200
6	0.021	103.0	0.055	4×10^{-7}	3×10^{-11}	2.05	96.9	0.01	0.0185	2,350
7	0.021	98.3	0.1	5×10^{-7}	4×10^{-11}	2.15	97.5	0.87	0.012	2,300
8	0.022	103.0	0.11	4×10^{-9}	4×10^{-11}	1.9	96.9	0.04	0.014	3,500
9	0.02	97.8	0.03	2×10^{-7}	1×10^{-10}	1.9	94	0.019	0.014	1,700
10	0.02	99.2	0.05	2.2×10^{-7}	1×10^{-11}	1.9	96.7	0.16	0.01	2,100

Table 3. Best-fit model parameter values for the ensemble of SDA meteors. These include the ablation coefficient, erosion start height, erosion coefficient, largest grain mass, smallest grain mass, grain mass index, erosion change height, erosion change coefficient, ablation change coefficient and meteoroid bulk density change.

Fundamental Equations of Meteor Physics

$$\frac{dm}{dt} = -K\sigma m^{2/3}\rho_a v^3$$

$$\frac{dv}{dt} = -Km^{-1/3}\rho_a v^2$$

$$I = -\tau\frac{v^2}{2}\frac{dm}{dt}$$

$$\frac{dh}{dt} = v\cos(z)$$

$$K = C_D S m^{-2/3}$$

Shape-density coefficient

$$\sigma = \frac{C_H}{2Q_a C_D}$$

Ablation coefficient

Quasi-Continuous Fragmentation

$$\frac{dm}{dt} = \left(\frac{dm}{dt}\right)_{\text{ablation}} + \left(\frac{dm}{dt}\right)_{\text{fragmentation}}$$

$$\left(\frac{dm}{dt}\right)_{\text{fragmentation}} = -K\eta m^{2/3}\rho_a v^3$$

$$n(m) \propto m^{-s} \qquad m_l < m < m_u$$