Understanding the Thermal Properties of Fast CMEs by Integrating White-light Observations and Analytical Modeling

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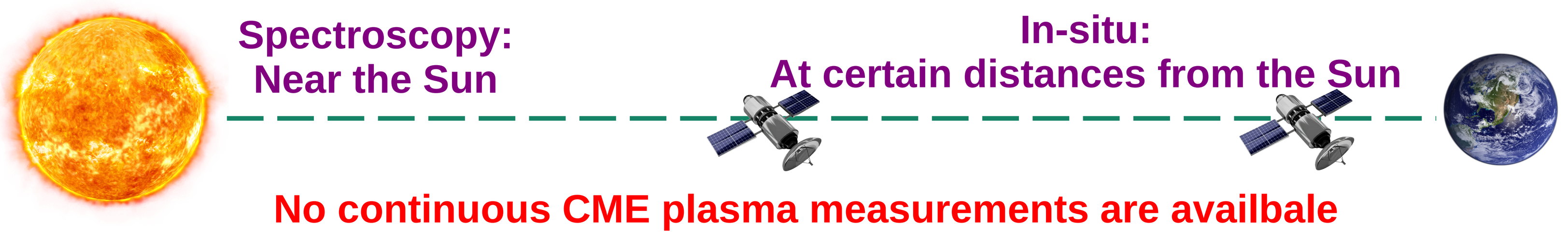
1. ABSTRACT

This study investigates the diverse kinematic profiles and associated thermodynamic changes of nine fast coronal mass ejections (CMEs). We estimated distance-dependent evolution in various internal parameters using the improved **Flux Rope Internal State (FRIS)** model. The model incorporates inputs of 3D kinematics obtained from the graduated cylindrical shell (GCS) model. Our findings disclose the evolution thermal state and the dominant forces fo the radial expansion of CME during it's propagation phase. This study enriches our understanding of the internal properties of CMEs, offering valuable insights for refining assumptions in the polytropic index value for better projections of CME property.

2. CONTEXT

Coronal Mass Ejections (CMEs) are episodic solar eruptions containing huge magnetized plasma that can cause prolonged geomagnetic storm and severely impact the planetary environment, making their prediction crucial to space weather.



No continuous CME plasma measurements are availbale

Comprehending the heating and acceleration of CMEs remains a challenge

- The aim is to probe the complete evolution profile for the internal thermal properties of CMEs using both analytical models and all sorts of available observations.

3. METHODOLOGY

- **Flux Rope Internal State (FRIS) model:** An analytical model to measure the internal properties of CMEs by considering the **kinematics as input**.
- **Graduated Cylindrical Shell (GCS) model:** To estimate the **3D kinematics** using white-light coronagraphic data at multiple vantage points.

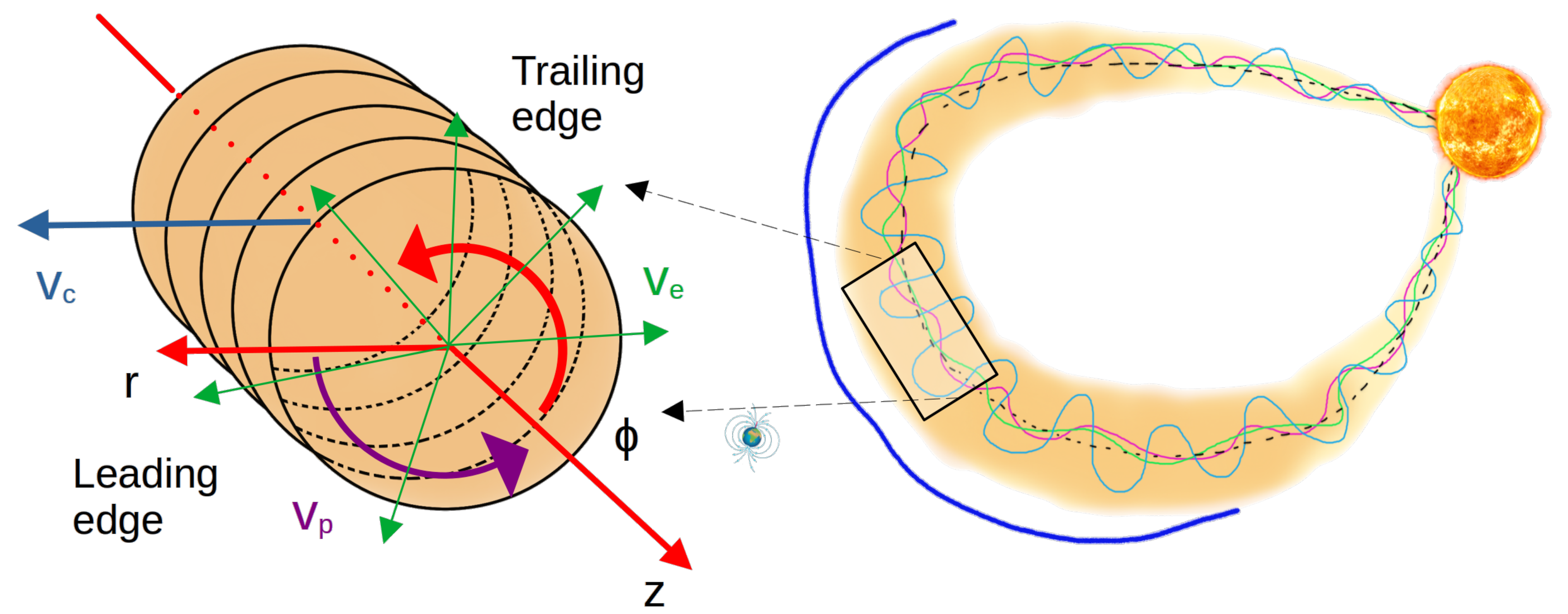


Figure 1: **Schematic of the cylindrical flux rope CME in the FRIS model (Khuntia et al., 2023, ApJ)**

FRIS model flow & considerations

- CMEs are axisymmetric cylindrical Flux-rope on a local scale
- Conservation of Mass and Angular momentum
- Ideal MHD equation for Single magnetic fluid
- Laws of Thermodynamics
- The involved thermodynamic process is polytropic in nature,

  $PV^{\Gamma(t)}$ = constant
- Conservation of magnetic flux
- Solve the radial equation of motion for the CME expansion in terms of measurable kinematic parameters

4. RESULTS: MEASURED 3D KINEMATICS

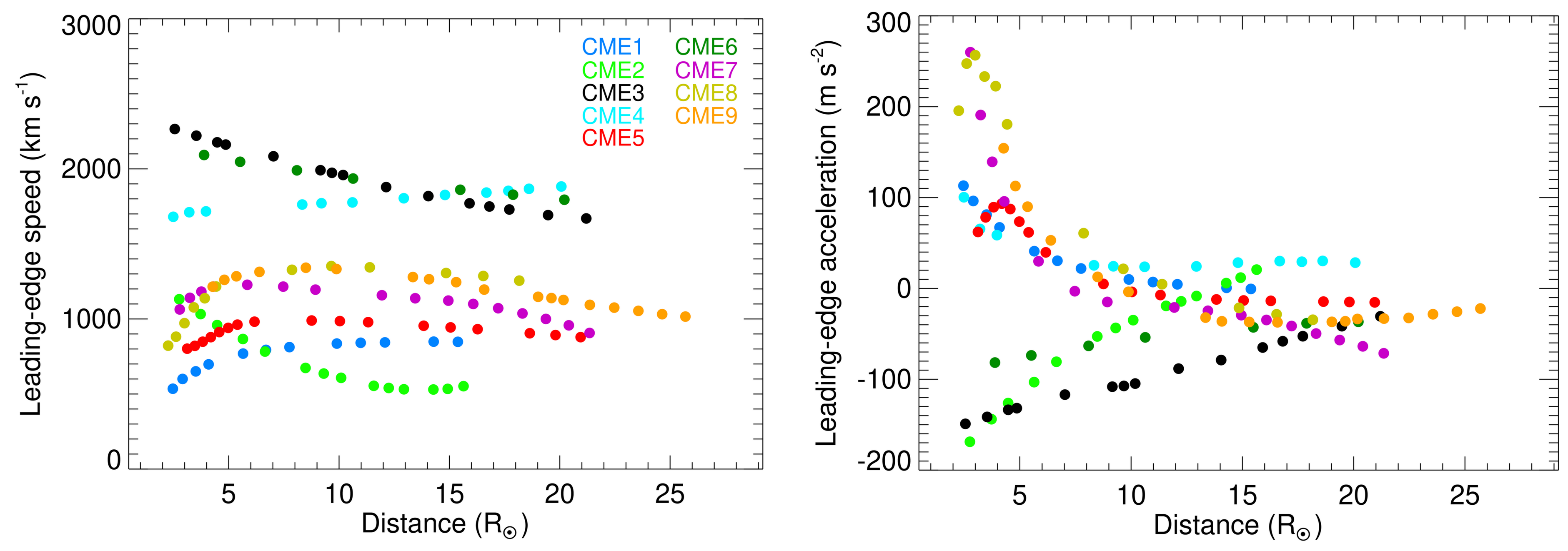


Figure 2: **Varied 3D kinematics of the selected fast CMEs, leading-edge speed (left) and acceleration (right) with distance away from the sun.**

5. RESULTS: MODEL DERIVED THERMODYNAMICS

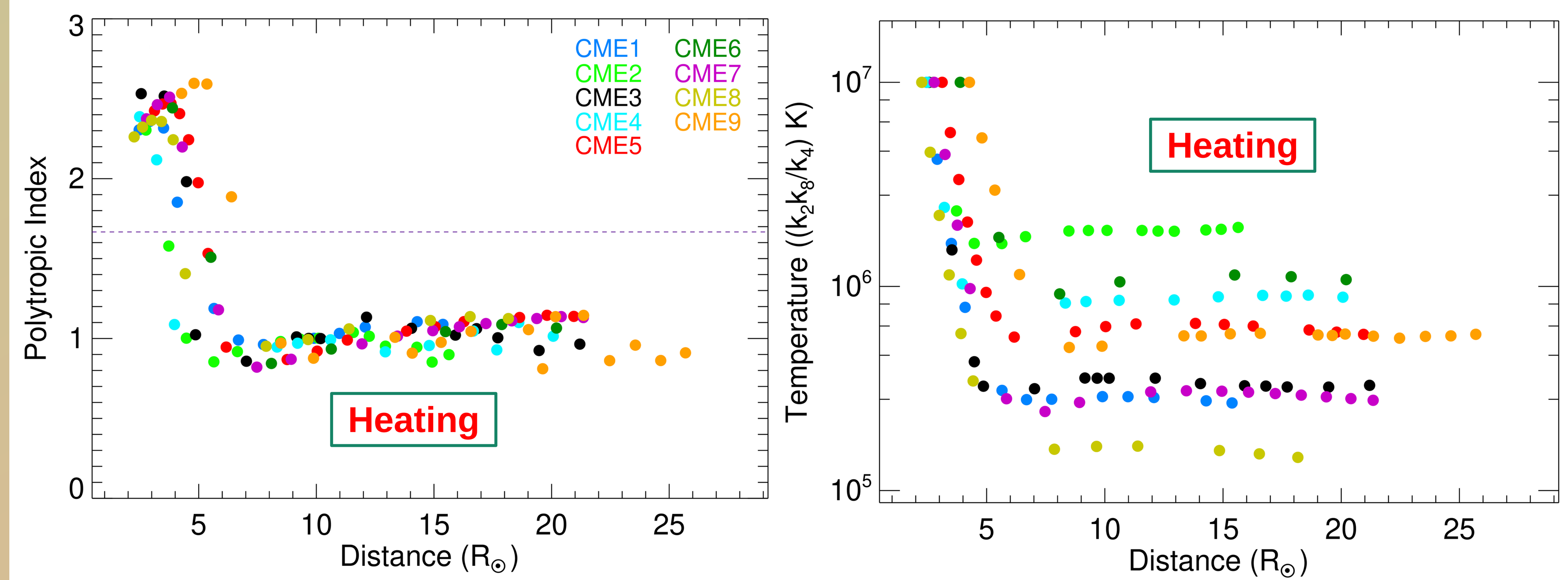


Figure 3: **The FRIS model-derived Polytropic index (left) and temperature (right) evolution for the selected fast CME show rapid heat release and temeperature decrease at intial heights after which heating at higher heights during their propagation.**

FRIS MODEL-DERIVED QUANTITIES

Internal plasma parameters:
Polytropic Index
Heating rate
Rate of change in entropy
Temperature
Thermal pressure
Proton number density

Internal forces:
Lorentz force
Thermal pressure force
Centrifugal force

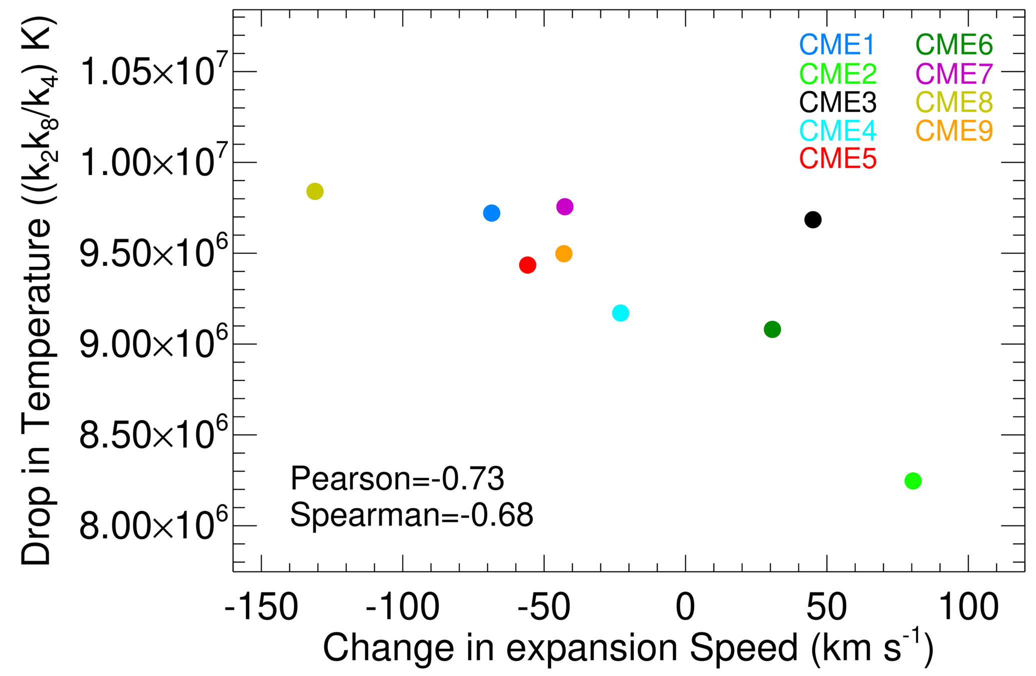
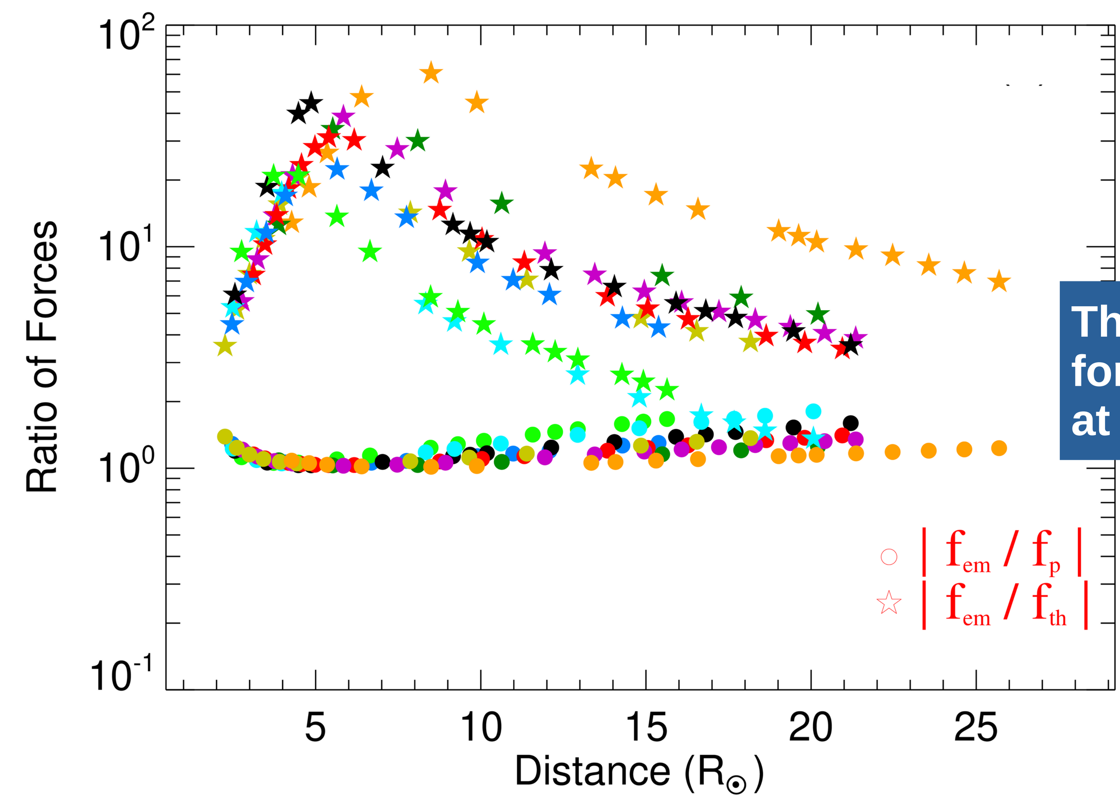


Figure 4: **A correlation plot showing that CME with a greater increase or lesser decrease in expansion speed at lower coronal heights will experience a larger drop in the initial temperature.**

6. RESULTS: MODEL DERIVED INTERNAL FORCES



Thermal pressure force dominates at higher heights

Figure 5: **The FRIS model-derived internal forces, such as Lorentz force(f_{em}), thermal pressure force (f_{th}) and centrifugal force (f_p) that are responsible for the radial expansion of the CME flux rope.**

7. RESULTS: DIFFERENTIAL EMISSION MEASURE (DEM) ANALYSIS

Release of heat and drop in temperature at initial propagation heights

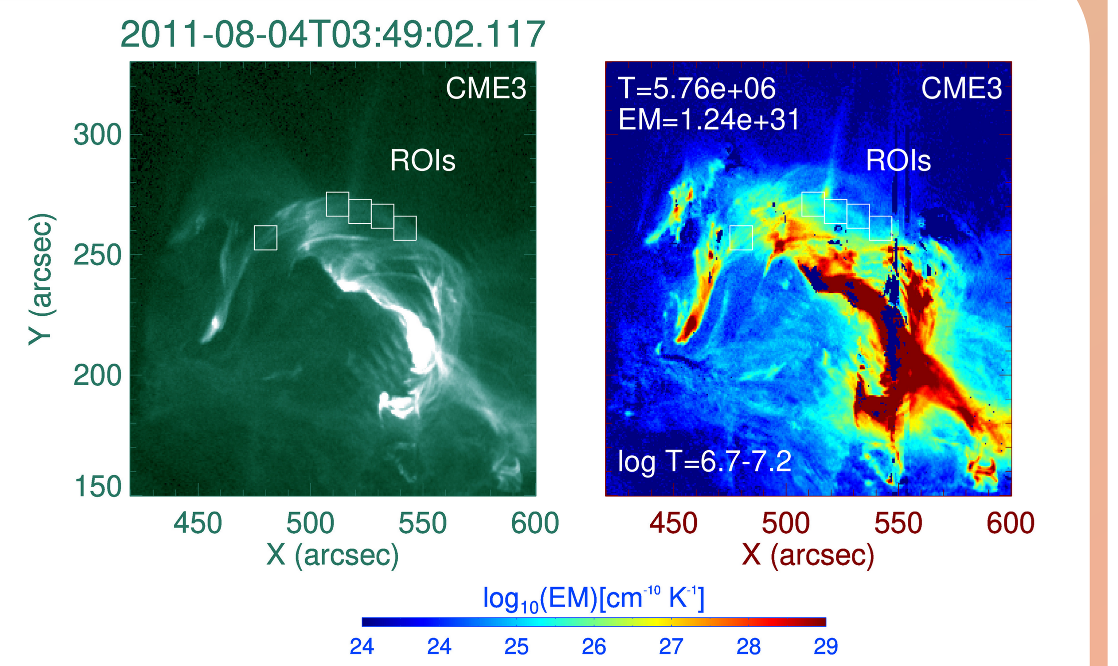


Figure 6: **Erupting CME associated hot-flux rope in SDO/AIA 94 Å (left) and the corresponding DEM plot (right) showing the temperature of the flux rope to be above the ambient coronal temperature.**

8. TAKE HOME POINTS

- Need for the **refinement in polytropic index value** in MHD models.
- CMEs undergo multiple heat transfers during their interplanetary journey.
- Despite the expansion, the temperature doesn't drop as much as expected from adiabatic cooling.
- CMEs follow a **near-isothermal state** during their propgation phase at higher heights.
- The internal thermal pressure and centrifugal force contributes, while the Lorentz force inhibits the radial expansion.
- The **thermal pressure force** can solely drive the radial expansion of CME at higher heights.

Reference & more details