Exploring Shocks in the Heliosphere for the SEP-producing CMEs with SoloHI Observations: *Preliminary study*

Shaheda Begum Shaik[1]*, Robin Colaninno[2], Phillip Hess[2] and Mark Linton[2]

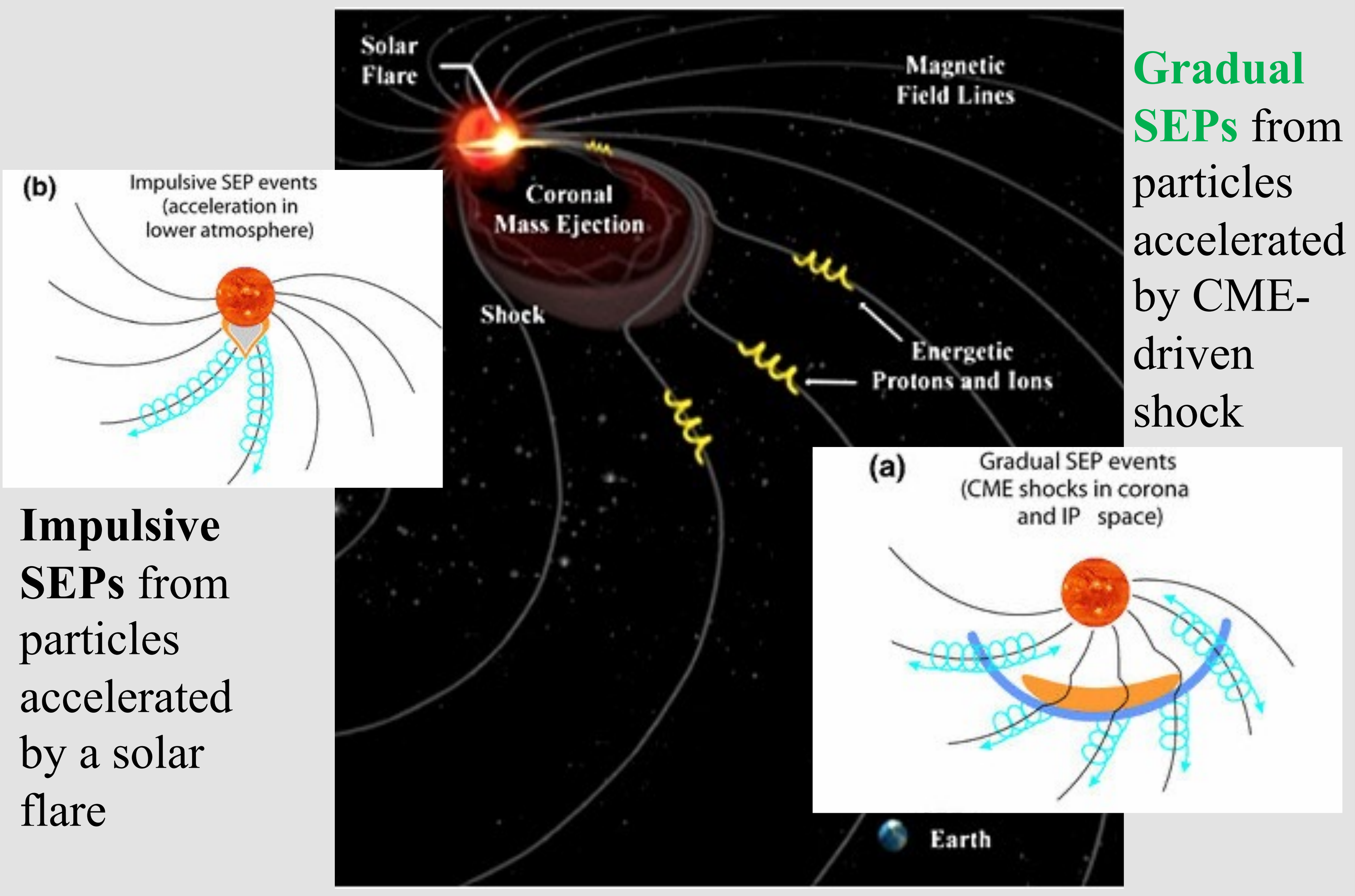
[1]George Mason University, Fairfax, VA, USA, [2]Naval Research Laboratory, Washington, DC, USA

Abstract

The shocks driven by Coronal Mass Ejections (CMEs) and the associated particle acceleration are important phenomena for studying solar energetic particle (SEP) events, which hold significant implications on space weather and forecasting. Recent white-light observations of CMEs from the **Solar Orbiter Heliospheric Imager (SoloHI)** onboard the Solar Orbiter mission have demonstrated **sharp double-front features and unique substructures of the CME-driven shocks**. We present the preliminary analysis from an initial small set of the SEP-producing CMEs observed by SoloHI during March and April, 2022. We aim to make an event-to-event comparison of the CME and **shock characteristics** with the associated in-situ particle data of these SEP events. We also discuss the **reconstruction of the three-dimensional geometry of the shock** using the third viewpoint of SoloHI in conjunction with STEREO and SOHO observations of these CME-driven shocks. We present the **excess density measure** on one of the SEP events, which is the primary step to determine the shock strength from its density jump.

Background

Two-class picture of SEP Events



Gradual SEPs from particles accelerated by CME-driven shock

Impulsive SEPs from particles accelerated by a solar flare

Label: Schematic of interplanetary magnetic field and energetic particles propagating in the heliosphere. Two classes of particle acceleration in SEP events from solar flares and from CME-driven shocks.

For the CME-driven shocks observed from the close proximity and from the high resolution images of SoloHI, we aim to investigate various physical parameters of shock such as **shock strength (density jump/compression ratio), shock speed**, **shock Mach number** that can influence the level of SEP particle enhancement.

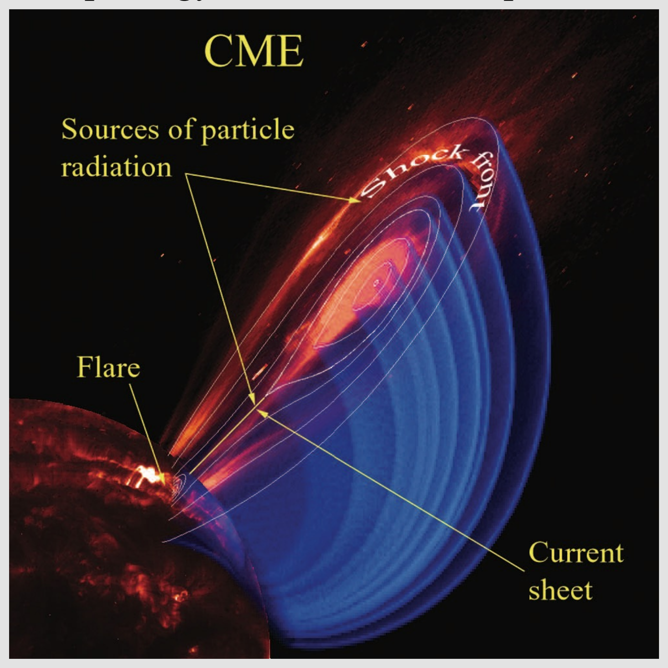
Solar Orbiter Heliospheric Imager (SoloHI)

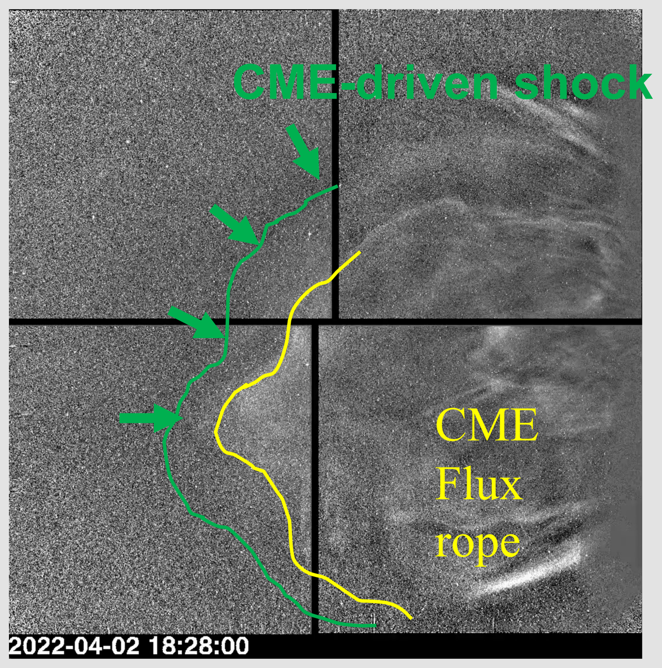
- SoloHI is a white-light heliospheric imager onboard Solar Orbiter spacecraft
- One of the six remote-sensing instruments on Solar Orbiter, along with four in-situ instruments.
- Field of view of 40° with an offset from the Sun center by about 22.5°. FOV spans over the elongations of 5.4° to 44.9° to the east of the Sun in the anti-ram direction.
- From the start of its observation in 2021, SoloHI has detected more than over 200 CME events.

SoloHI CME Observations

Event	CME Speed (km/s)	Flare Class	Active Region	Particle Flux At Earth	Particle Flux At SO	Shock in SoloHI images	Halo in LASCO
28-Mar-22	700	M4.0	AR12975	Yes	Yes	Yes	Yes
28-Mar-22	900	M1.1	AR12975	No	No	No	Yes
30-Mar-22	640	X1.3	AR12975	Yes	Yes	Yes	Yes
2-Apr-22	1400	M3.9	AR12976	Yes	Yes	Yes	Yes

Label: CME events observed by SoloHI from the same active region (AR) & the adjacently connected AR. All are SEP events, expect the one highlighted in gray. SoloHI images of CME and shock morphology observed on 02 April 2022 is shown below along with a flare-CME-SEP cartoon.



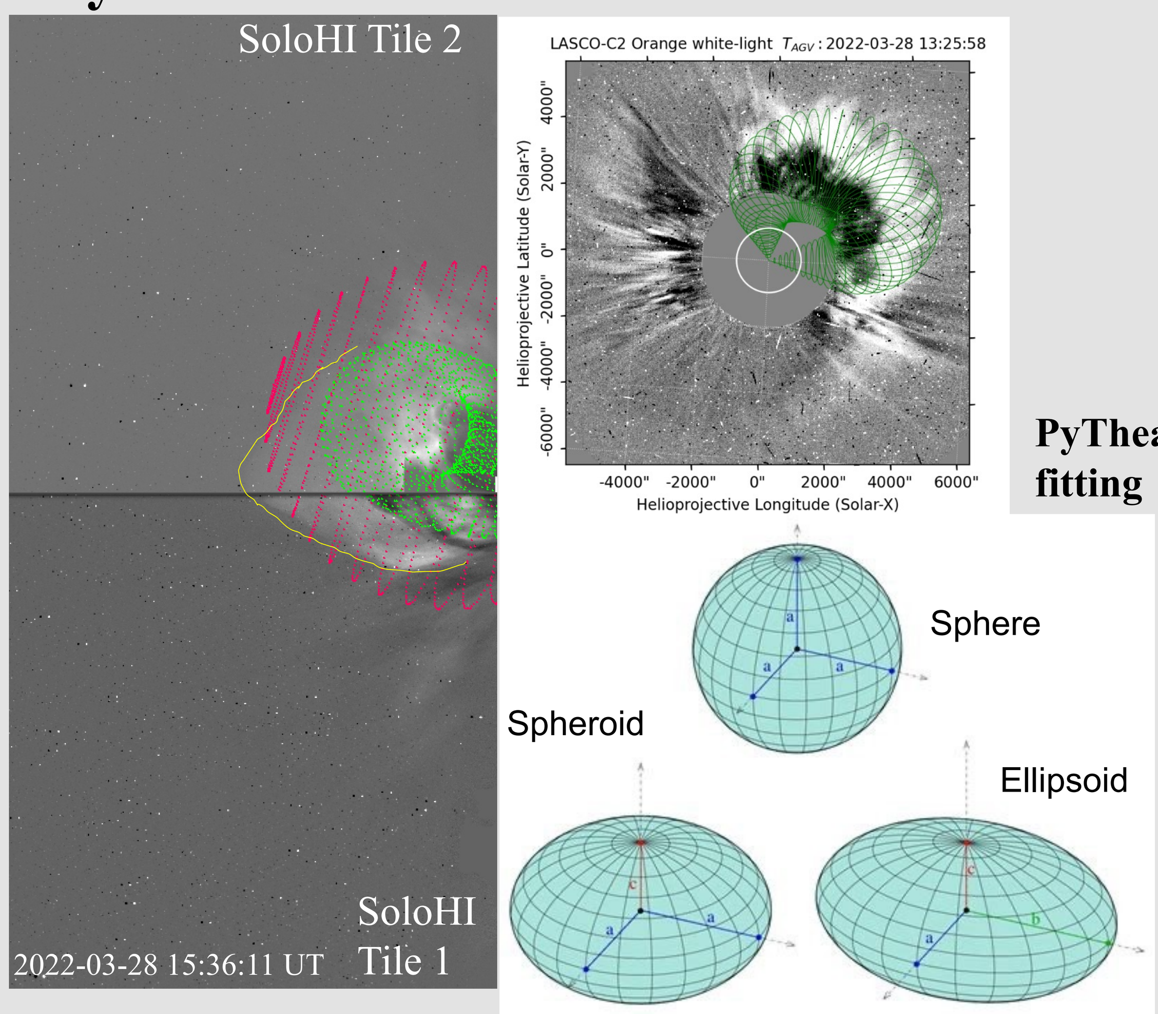


Observations in SoloHI images:

- **'Double front' morphology** of the shocks with a fainter front leading the CME flux rope front and a faint emission in between.
- Steamer deflection in the wake of the CME and the CME evolution restricted between a couple of steamers - constrains the shape of the CME fronts and shows **anisotropic propagation of shocks**.
- Shocks in SoloHI can provide physical characteristics of shocks early in their evolution before reaching the in-situ spacecraft.

Shock Morphology Analysis: GCS & PyThea 3D reconstruction of CME and Shock

GCS shock fitting



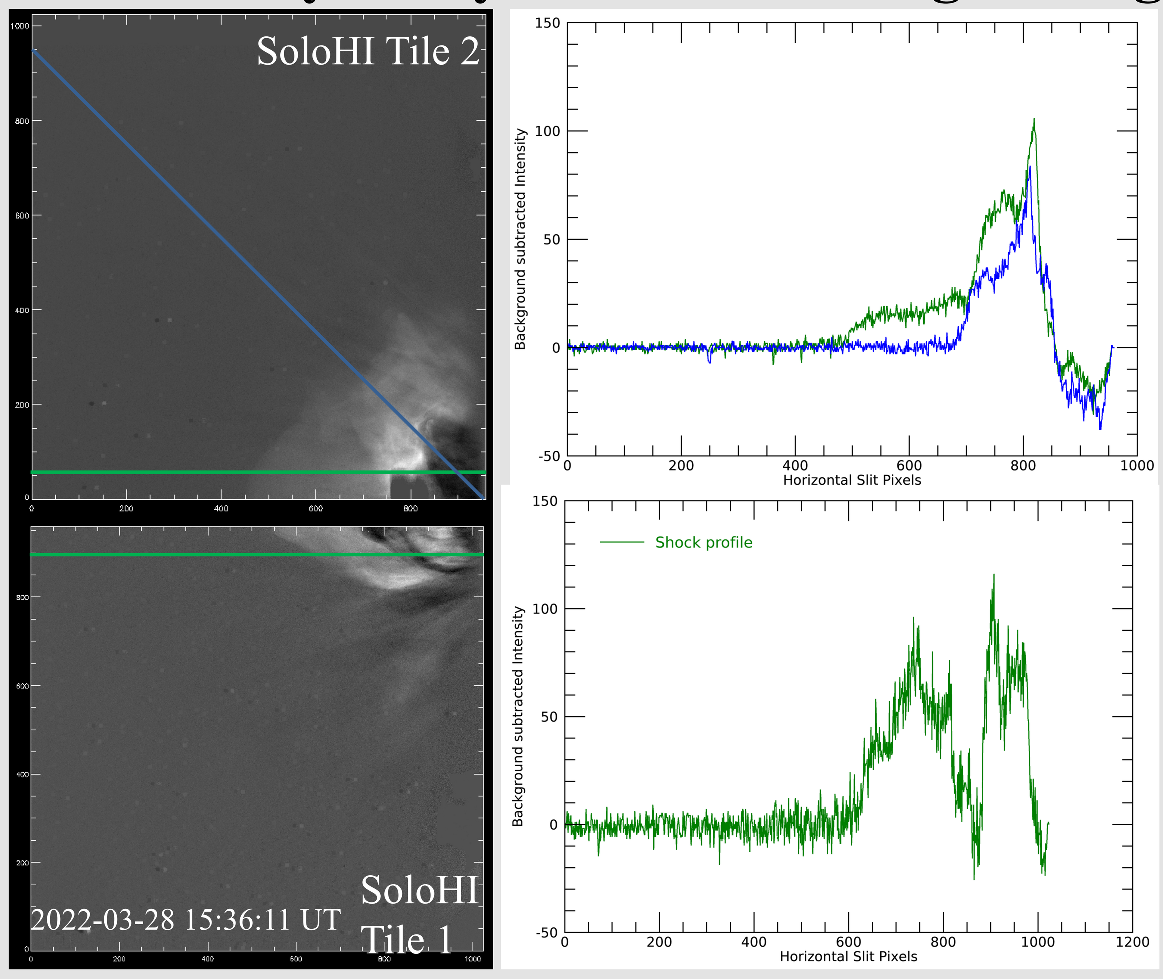
PyThea shock fitting

Label: Reconstruction of shock and its various morphologies – anisotropic shock front fitting.

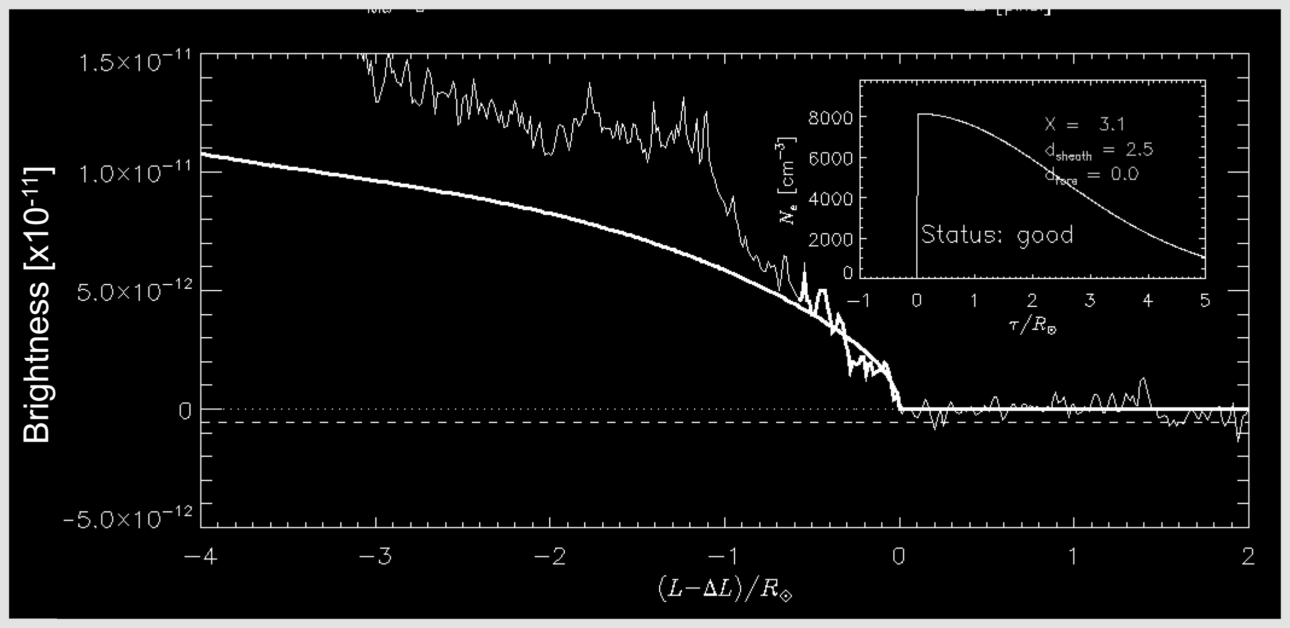
- Geometrical parameters: heliocentric distance, latitude (ϕ), and longitude (θ), the tilt angle (γ) of the ellipsoid center
- Positional parameters: heliocentric height of the ellipsoid at the apex (h), length of the other two semi-axis (κ), aspect ratio (α), and eccentricity (ε) ➔ **shock geometry, speed, and direction**

Future work: Shock parameters to determine the **shock Mach number** from the MAST model (Magneto-Hydrodynamic Around a Sphere Thermodynamic) (Lionello et al., 2009, Kouloumvakos et al., 2019)

Shock Density Analysis from white-light images



Label: Intensity profiles of CME flux rope and the associated shock showing asymmetrical latitudinal extent.



Label: Excess brightness profiles from a position angle cut taken on COR2 image along the shock normal. The thick white line shows the modeled excess brightness profile. Electron density profile is shown in the inlet panel.

- Asymmetric Gaussian function for modeling electron density
- τ' is the full width half maximum of d_{front} Gaussian function

$$N_e(\tau) = \rho_e \exp - \frac{(\tau - \tau\prime)^2}{2d^2},$$

$$d = \begin{cases} d_{front}, \text{ if } \tau < \tau\prime, \\ d_{sheath}, \text{ if } \tau \geq \tau\prime, \end{cases}$$

$$\text{with } \tau\prime = 2 d_{front} \sqrt{2\ln 2},$$

- Excess density along the shock normal for 28 March 2022 event from COR2 images is derived as 8 x 10^3 cm^{-3}.
- *Future work:* Determine the density jump by removing the background density using density models (as discussed in Kwon and Vourlidas, 2018). ➔ **Shock strength**

Discussion

- All the SEP events studied here show a clear double front shock morphology and anisotropic shock propagation.
- The corresponding particle data observed at various spacecraft show distinct profiles, indicating different CME and shock structures and particle transport.
- *Future work:* Obtain Speed of the shock – Shock strength - Event-to-event comparison – Correlation with the observed in-situ particle data – Comparison with a high speed CME non-SEP event (highlighted in the table) from the same AR.

References

- Kouloumvakos et al., ApJ 876:80 (18pp), 2019
- Kwon and Vourlidas, J. Space Weather Space Clim., 8, A08, 2018
- Lionello et al., ApJ, 690, 902, 2009

Contact Information

Shaheda Begum Shaik, sshaik7@gmu.edu