Multi-spacecraft Observations of Interplanetary Suprathermal Electrons in a Shock-ICME Interaction Region

Qianyi Ma[1] and Linghua Wang[1]

[1]School of Earth and Space Sciences, Peking University, Beijing, China

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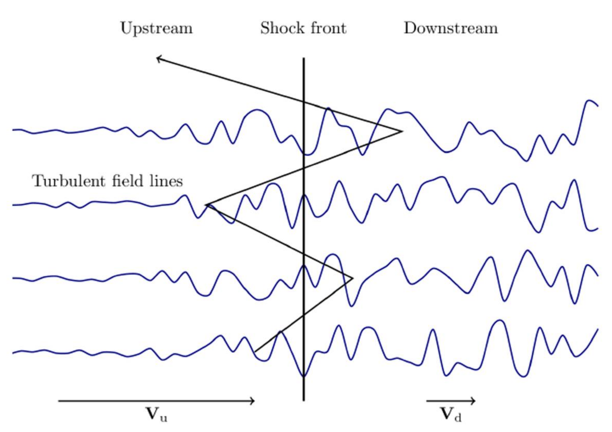
Abstract ID: EGU25-8856
E-mail: qianyima@pku.edu.cn

Abstract

Multiple interplanetary coronal mass ejections (ICMEs) and the shocks they drive sometimes form shock-ICME interaction regions, where suprathermal electrons can undergo complex and not yet fully understood physical processes. To enhance our understanding of electron acceleration and transportation in these regions, we will present a shock-ICME interaction case study based on multi-spacecraft observations. From November 30th to December 3nd, 2023, three ICMEs and two ICME-driven shocks were successively observed by SolO (0.84 AU), STEREO-A (0.97 AU), and Wind (0.99 AU), with a maximum longitudinal separation of ~17°. First, we use a R-H least-square shock fitting technique to obtain the shock parameters. Then, we self-consistently characterize the energy spectral features of these upstream and downstream suprathermal electrons using a recently proposed extended pan-spectrum fitting method (Li et al., 2025). Finally, we compare our results with the first-order Fermi acceleration and the shock drift acceleration mechanism, as well as the statistical results obtain by previous studies. We found that, although having the strongest drift electric field, the ICME-traversing shock 3 show weaker electron acceleration efficiency due to extremely slow drift velocity. The small V_{drift} at shock 3 is mainly due to its smaller r_B and thicker ramp. This suggests that during shock-ICME interactions, r_B and ramp thickness may have a greater impact on electron acceleration efficiency than E_{drift}.

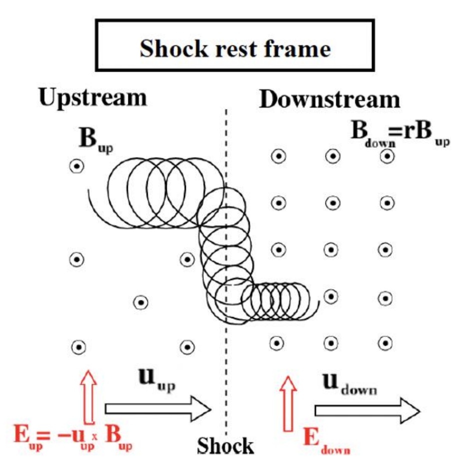
Introduction

First-order Fermi acceleration:

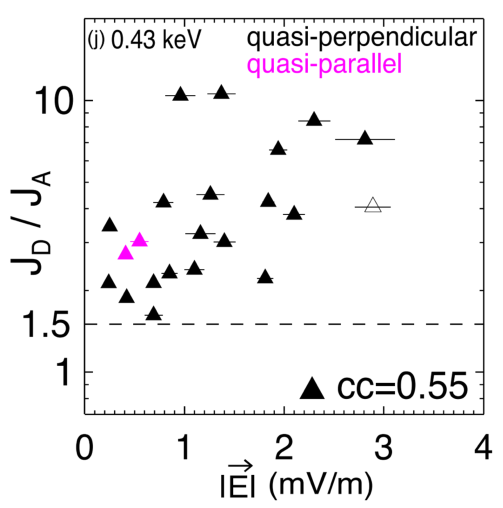


$$J \propto E^{-\frac{r+2}{2r-2}}$$

Shock drift acceleration:



$$\Delta\varepsilon = q \cdot \mathbf{E}_{\text{drift}} \cdot \mathbf{L}_{\text{drift}}$$
$$\mathbf{L}_{\text{drift}} = \mathbf{V}_{\text{drift}} \cdot T_{\text{drift}}$$

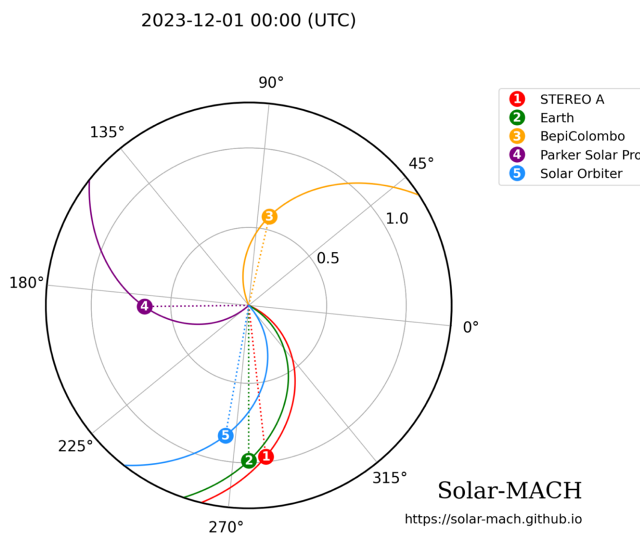


[Yang et al., 2019]

- SDA dominates electron acceleration in ICME-driven shocks
- Good correlation between acceleration efficiency J_d/J_u and drift electric field E_{drift}
- $T_{drift} \sim 1$s

Observations

Figure 1. Shock-ICME interaction event overview



- 2023 Nov 30 - 2023 Dec 3, a shock-ICME interaction event is observed by:
  SolO/EPD, Wind/3DP & ST-A/SEPT
- ICME 1 drives Shock 1 (S1), ICME 2 drives no shock, ICME 3 drives Shock 3 (S3), analyzed by [Chi et al., 2024]
- SolO/EPD: S3 inside ICME 2, no clear local acceleration
- Wind/3DP: S3 inside ICME 1, local acceleration at S1 & S3, reflected strahl electrons (with loss cone) at S3
- Contamination caused by penetrating protons noted

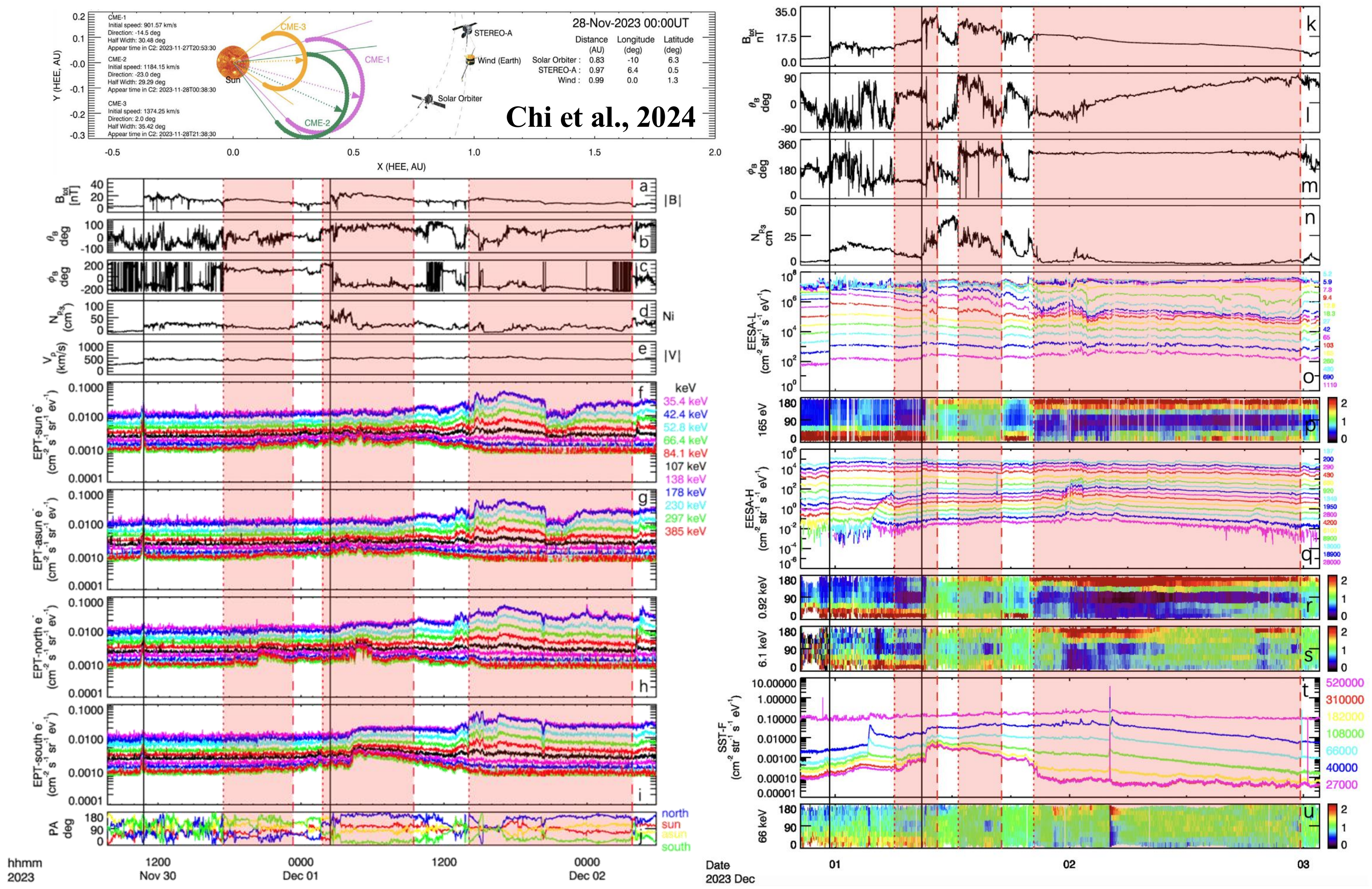


Table 1. Shock parameters of shock 1 and shock 3

	Shock 1		Shock 3	
	2023 November 30		2023 December 1	
	Solar Orbiter	Wind	Solar Orbiter	Wind
Time (UT)	10:47:28	23:26:24	02:26:40	08:51:06
Heliocentric distance (AU)	0.84	0.98	0.85	0.98
$\hat{n}$ **in RTN**	[0.933,0.286,0.219] ±[0.024,0.017,0.130]	[0.989,0.144,-0.038] ±[0.001,0.013,0.094]	[0.984,0.089,-0.152] ± [0.007, 0.005, 0.070]	[0.764,-0.004,0.645] ± [0.089, 0.001, 0.130]
V_{sh} **(km/s)**	496±18	496±11	562±3	536±42
θ_{Bn} **(°)**	77±11	49±9	61±4	66±7
M_f	2.5±0.4	2.5±0.3	1.8±0.1	1.3±0.1
r	1.9±0.2	3.0±0.2	2.1±0.2	1.5±0.1
r_B	2.0±0.1	2.5±0.1	1.8±0.1	1.5±0.1
D_{ramp} **(km)**	(5.7±0.6)×10³	(6.9±0.3)×10³	(5.3±0.4)×10³	**(1.2±0.1)×10⁴**
E_{drift} **(mV/m)**	0.6	0.5	1.3	**3.4**
Predicted β_{FFA}	2.1±0.3	1.8±0.1	1.9±0.3	3.3±0.7

- R-H least-square shock fitting: 2 min average in upstream & downstream
- $r_{S3}^{Wind} < r_{S3}^{SolO} \sim r_{S1}^{SolO} < r_{S1}^{Wind}$
- D_{ramp}: $D_{S3}^{Wind} > D_{S1}^{Wind} \sim D_{S1}^{SolO} \sim D_{S3}^{SolO}$
- E_{drift}: $E_{S3}^{Wind} > E_{S3}^{SolO} > E_{S1}^{SolO} \sim E_{S1}^{Wind}$

Will S3 at Wind have a stronger local acceleration than S1 at Wind?

Figure 2. Suprathermal electrons near shock 1 and 3 measured by Wind

- 10-min average electron flux
- Acceleration efficiency J_d/J_u peak at 90° PA **(SDA)**
- Perpendicular flux vs. energy spectra self-consistently fit to power-laws (β_1, β_2, β_3) with break energies (E_1, E_2) [Li et al., 2025]
- Shock 1: $J_d(E_d) \sim J_u(E_u)$ but J_d higher at $E < 0.5$ keV
- Shock 3: enhanced upstream flux with an upward double power-law shape
  $E_{1,d} < E_{1,u}$
- SolO: no observable local electron acceleration,
  $\beta_d \sim \beta_u \sim 1.5$

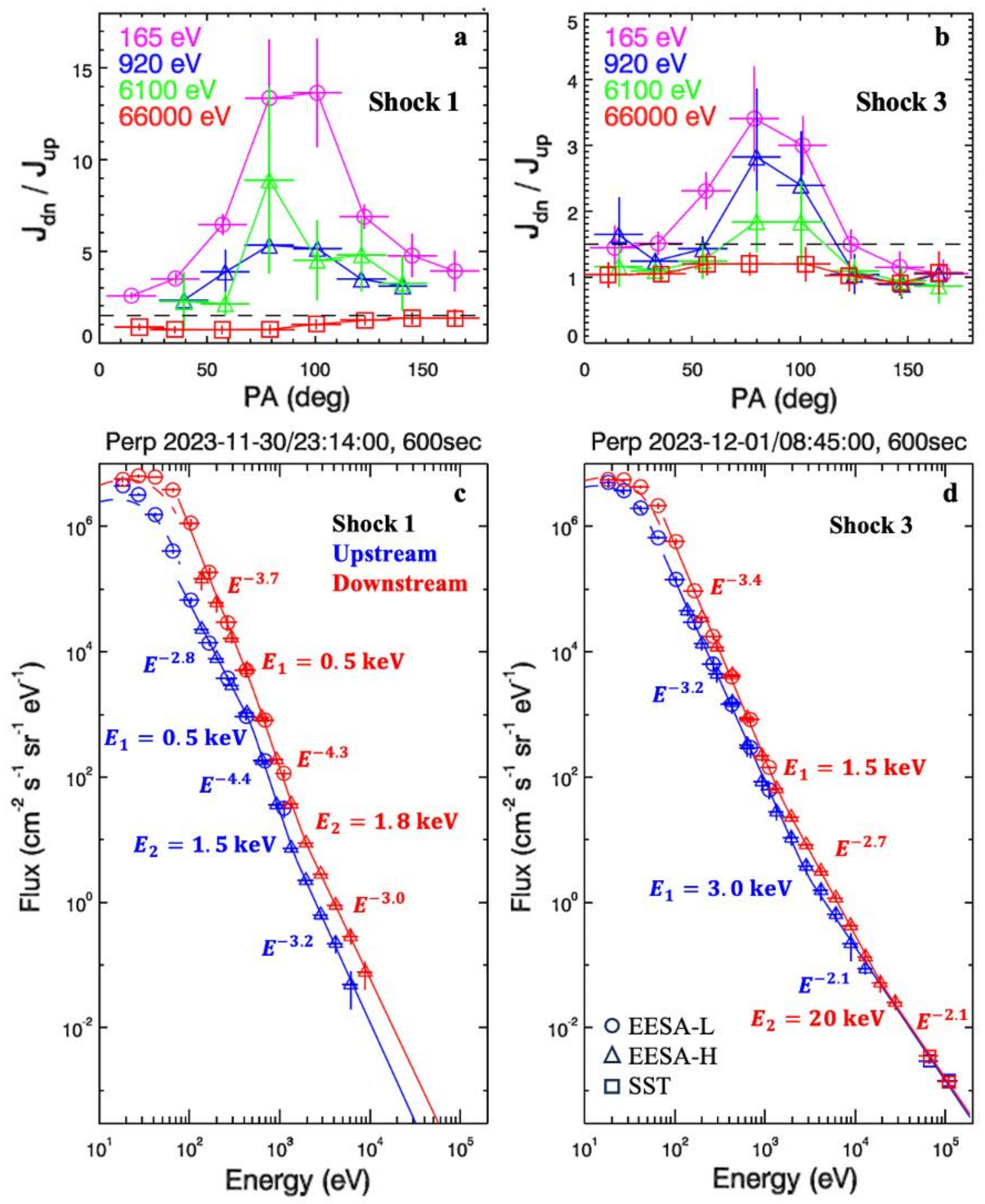
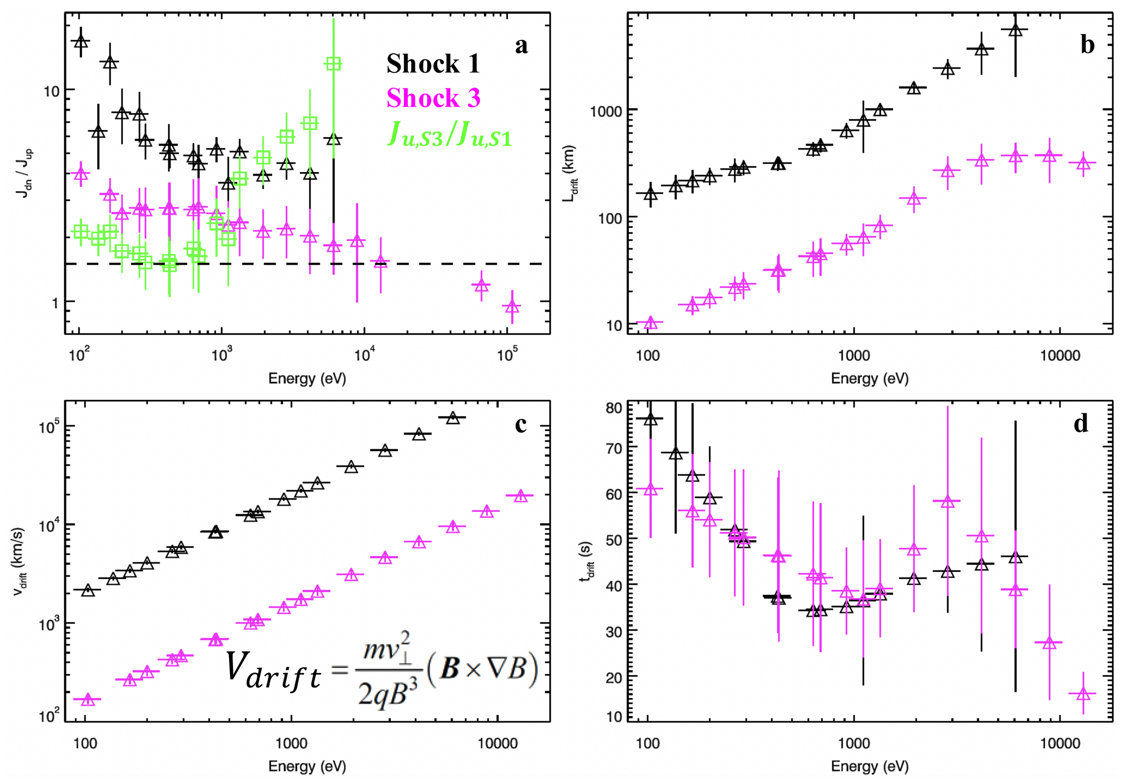


Figure 3: J_d/J_u of shocked electrons and SDA estimations



- $\left(\frac{J_d}{J_u}\right)_{S1} > \left(\frac{J_d}{J_u}\right)_{S3}$
- $J_{u,S3} > J_{u,S1}$, $J_{u,S3}$ larger at high energies
- $L_{drift} \propto E$
- V_{drift} estimated:
  $$V_{drift} = \frac{mv_\perp^2}{2qB^3}(\boldsymbol{B}\times\nabla B)$$
- Very slow V_{drift} of S3 at Wind
- Extremely long $T_{drift} \sim$ 50s

Summaries

We present a case study of suprathermal electron acceleration in a shock-ICME interaction region observed by Wind/3DP and SolO/EPD and find that:

- Compared to shock 1, shock 3 (traversing a pre-ICME) exhibits a smaller r_B, a thicker ramp, and a larger E_{drift}. Upstream electrons at shock 3 have a higher flux than shock 1 and show a harder energy spectrum at $E >$1 keV.
- Wind/3DP observed local electron acceleration at both shocks, with J_d/J_u peaking at 90° PA, consistent with SDA. The energy spectra of shocked electrons show triple power-laws with two break energies, inconsistent with the predicted β_{FFA}. SolO/EPD did not observe significant local electron acceleration at either shock.
- Shock 3 have a larger E_{drift} but weaker electron acceleration (J_d/J_u) than shock 1, contradicting the statistical results of Yang et al., 2019. V_{drift} of shock 3 is one magnitude slower than shock 1. $T_{drift} \sim$ 50s for both shocks.

The small V_{drift} at shock 3 is mainly due to its smaller r_B and thicker ramp. This suggests that during shock-ICME interactions, r_B and ramp thickness may have a greater impact on electron acceleration efficiency than E_{drift}.