National Observatory of Athens (NOA)

IAASARS

INSTITUTE FOR ASTRONOMY, ASTROPHYSICS, SPACE APPLICATIONS & REMOTE SENSING
(formerly INSTITUTE OF ASTRONOMY & ASTROPHYSICS)
National Observatory of Athens

Working Group 6, WG6: ‘Solar Energetic Particles (SEPs)’ – Summary Report

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Solar Energetic Particles: Origin, Acceleration and Transport

Christina M.S. Cohen

Caltech

What We Know *& Don't*

- Origin is the suprathermals
  - *Composition, spectrum, variability*
- Acceleration is mostly by CME-driven shocks
  - *Location on the shock, orientation*
  - *Seed population*
  - *Magnetic connection, IPM conditions*
- Transport is governed by rigidity

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- Transport is ~~governed by rigidity~~ complicated
  - *Dependence on energy*
  - *Longitudinal distribution*
- Parker Solar Probe & Solar Orbiter will help

There will be new surprises

XVIth Hvar Astrophysical Colloquium

International Study of Earth-affecting Solar Transients

ISEST 2018 Workshop

THE FEATURES OF PLASMA TURBULENCE ASSOCIATED WITH SOLAR TRANSIENTS

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Main objectives:

The turbulence in the solar wind is traditionally considered as freely developing in space, however actually its development is limited by natural boundaries created by different large scale dynamic structures associated with Solar transients. Velocity shear near these boundaries can play a critical role on the formation of turbulent cascade, especially at the dissipation scale and in the region of transition between inertial and dissipation scale.

The main goal of the study:

To reveal the relation between the type of large scale solar wind structures and the characteristics of plasma turbulence observed inside them.

We present:

- The analysis of the ion flux fluctuation spectra at scales 0.01-10 Hz on the basis of high resolution plasma measurements by the BMSW instrument onboard the SPECTR-R astrophysical mission during 2011-2015.
- The selection of large scale solar wind types such as EJECTA(Interplanetary Coronal Mass Ejection), MC (Magnetic Clouds), SHEATHs(compression region before EJECTA or MC), CIR (compression region before high-speed streams) and the pristine solar wind using catalogue of Yermolaev (Yermolaev et al., 2009) during the investigated period.
- Collection of a large statistical sample (more than 3000 spectra) evenly distributed in the selected large-scale solar wind structures.
- Comparison of the properties of plasma turbulence in different large-scale solar wind streams especially associated with Solar transients.

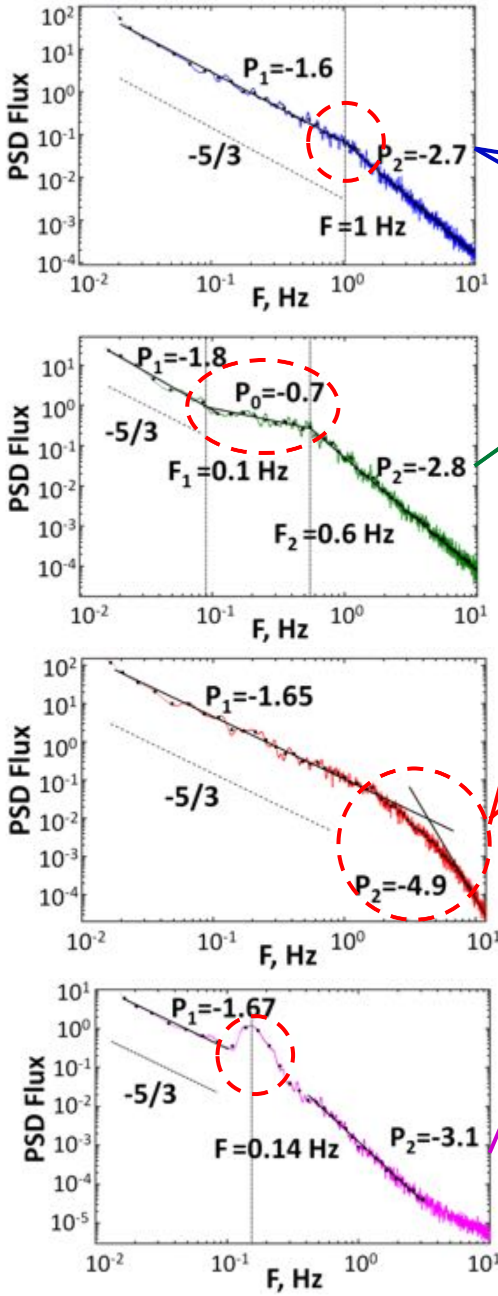
The shapes of turbulent spectra in different large scale SW structures.

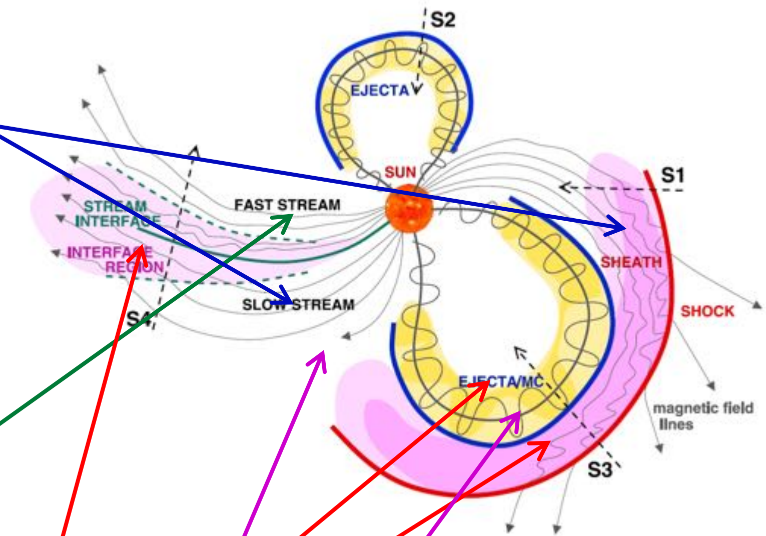
Spectra with two slopes and one break (classical framework):
in the pristine slow solar wind and inside SHEATH regions.

Spectra with flattening in the vicinity of the break
(predicted by Chandran et al. 2009 as a superposition of Alfvénic turbulence and Kinetic Alfvénic turbulence for low level of fluctuations):
in the not disturbed fast solar wind.

Spectra with fast nonlinear decay in the kinetic range, the slope up to -5!
(stronger damping, leading to sharper cutoff at ion scales):
in magnetic clouds, SHEATHs preceeding them, corotating interaction regions between fast and slow solar wind.

Spectra with bump in the vicinity of the break
(signature of instabilities or localized coherent structure):
in the slow solar wind, inside magnetic clouds but the statistics are poor.





(Riazantseva et al. JPP 2017, Rakhmanova et al. JGR 2018)

Conclusions:

- The spectra with two slopes and one break and spectra with flattening in the vicinity of the break are the most popular spectral shapes in the solar wind. However the spectra with two slopes and one break are more frequent in pristine slow SW and in SHEATH regions, whereas the spectra with flattening in the vicinity of the break are more frequent in the non disturbed fast solar wind.

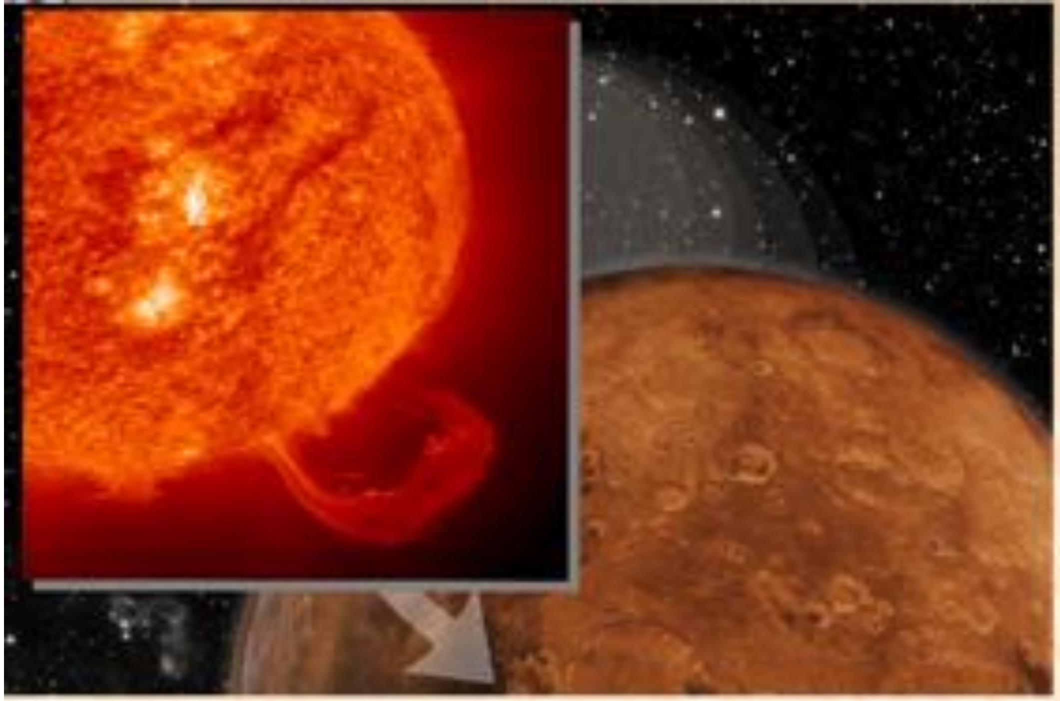
- The distribution of the shapes of the ion flux fluctuation spectra for MC and SHEATH before MC strongly differ from the distributions for other large scale SW streams. The abnormaly large amount of the spectra with nonlinear steepening at the kinetic scale is observed. The steepening can be also observed in the CIR region, but the statistics show the rather wide range of the slopes.

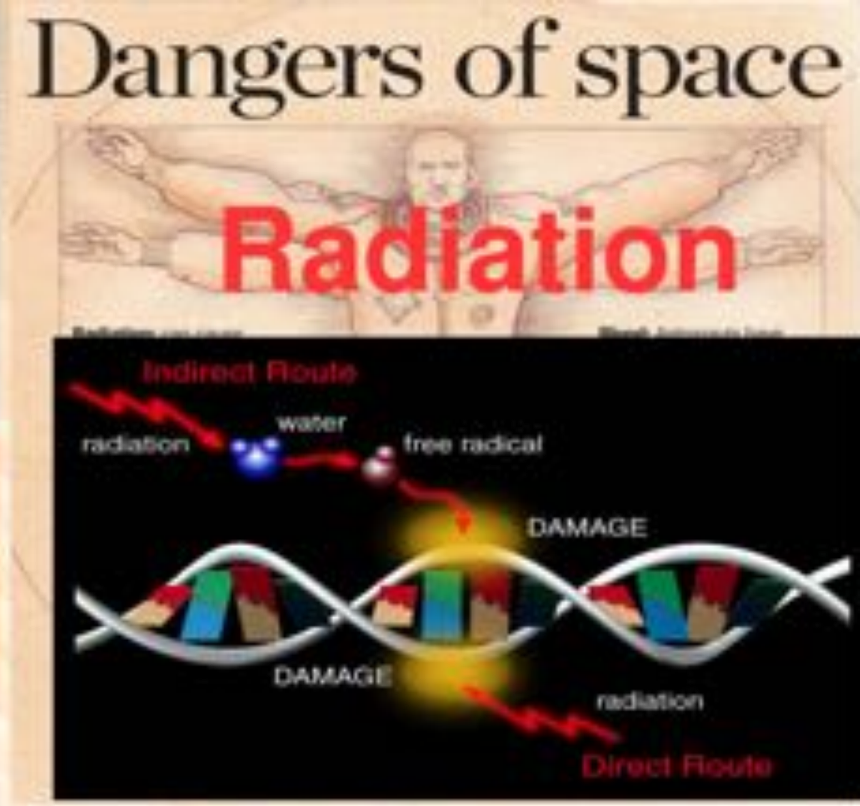
- The spectral steepening is rarely observed in the pristine slow solar wind, in EJECTA and in the SHEATH before EJECTA.

- The spectral steepening is rarely observed in high speed streams not associated with dynamic events of Solar corona, so the value of velocity doesn't play the key role play, but the velocity shear near the boundaries of different large scale solar wind structures.

- The spectra with slope -5/3 (the slope following from Kolmogorov model of fully developed isotropic turbulence) is typically observed at the MHD scale in the solar wind, however the flatter slopes can be observed also in slow pristine solar wind and SHEATH before EJECTA;

- The spectral slope closest to the theoretical model predictions at the kinetic scale ($P_2 \approx -2.67$) is observed only in the slow pristine solar wind. The spectral slope at the kinetic scale in high speed streams and in EJECTA is steeper $P_2 \approx -(2.7-2.8)$. This value is close to the typical slope of the interplanetary magnetic field fluctuation spectra published in literature. The steepest spectral slope at the kinetic scale $P_2 \approx -(2.8-3)$ is observed inside the MC and also inside the compression regions of SHEATHs and CIRs.





Challenges of space weather and space radiation predictions for human explorations to Mars

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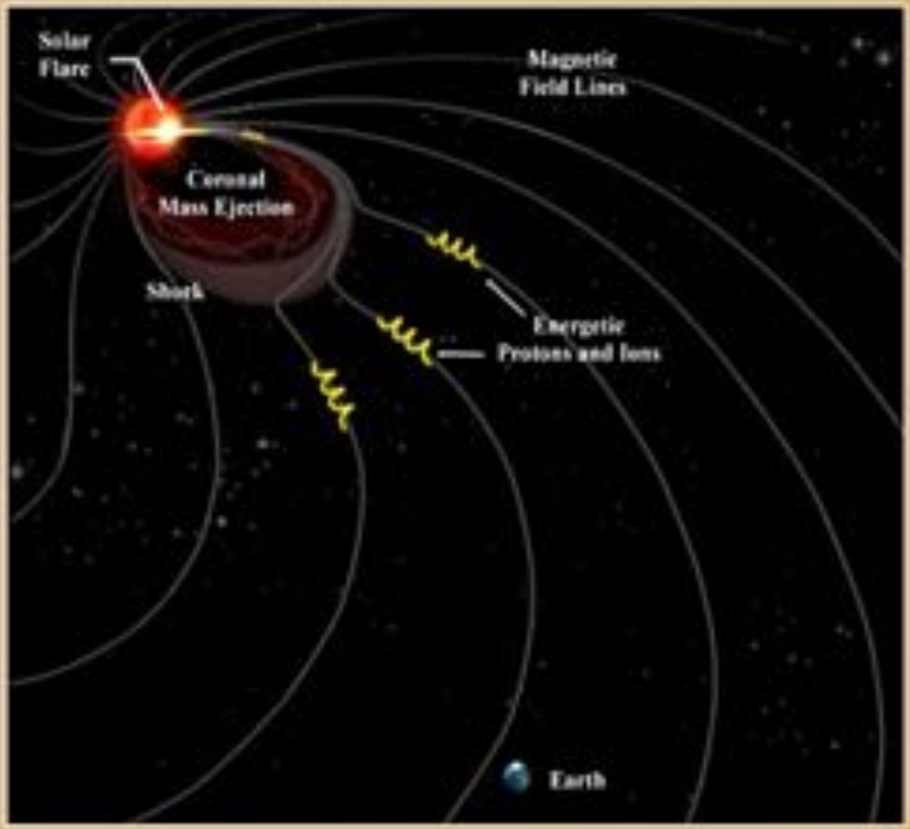
ISEST 2018 Workshop
Hvar, Croatia
September 2018

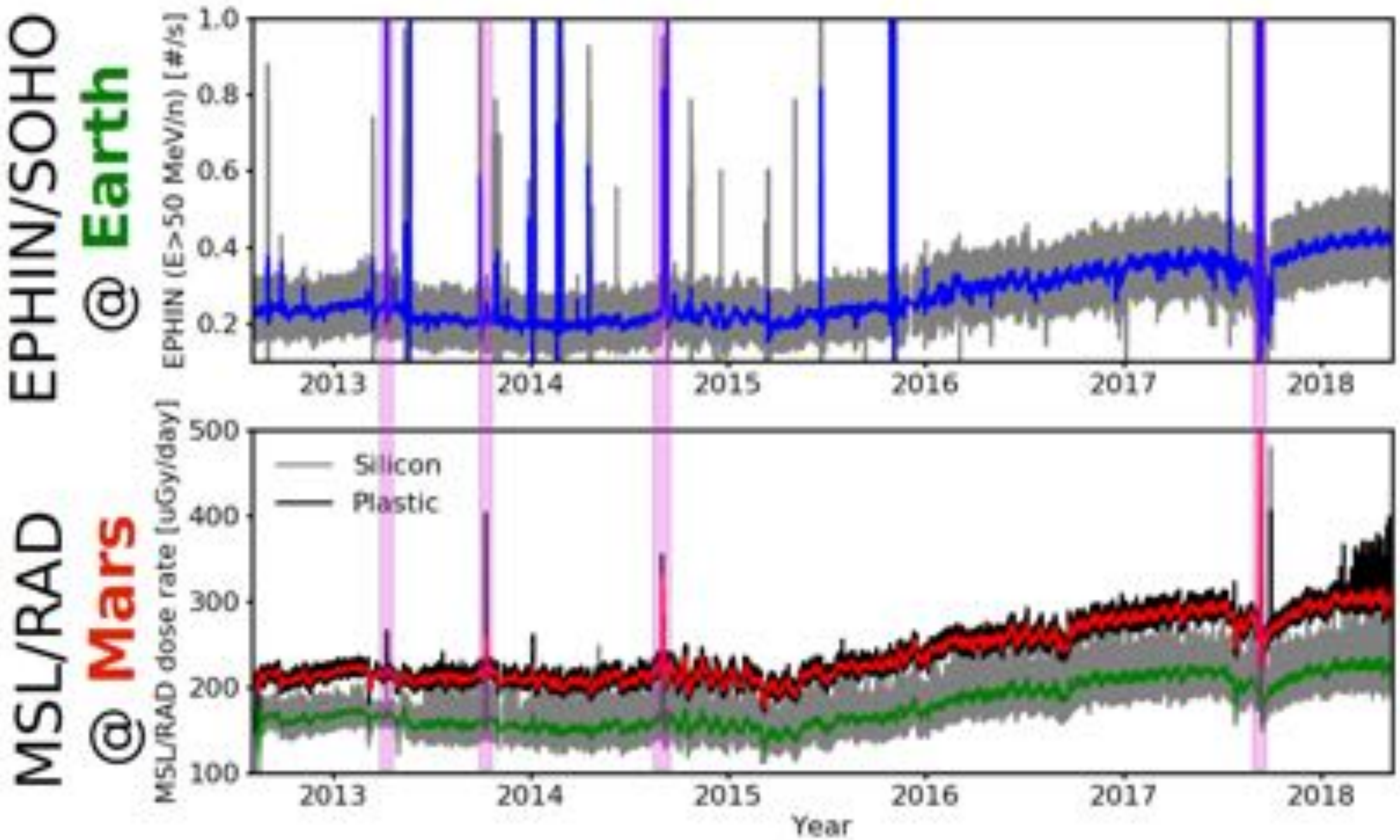
SEP measurement at Mars

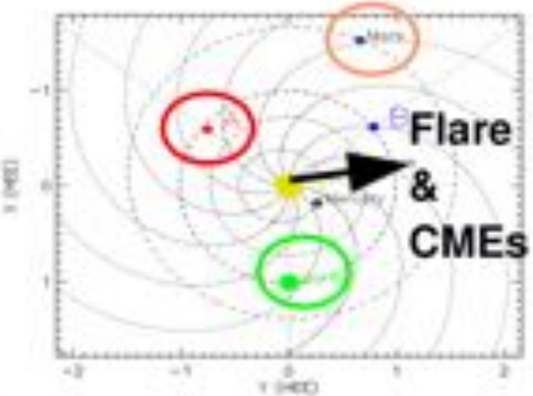
RAD observed several solar particle events (**SPEs**) during the cruise phase and on the surface of Mars. Their onset times and spectra are different from those observed at near Earth due to:

- the atomic and nuclear **interaction** of particles with the Martian **atmosphere**
  - which has been extensively modeled (e.g., Guo et al 2018 AJ)
- different **magnetic connection** to the particle acceleration sites (flares, and/or CMEs and shocks)
- **Cross-field transportation effects** on particles as they propagate through the heliosphere

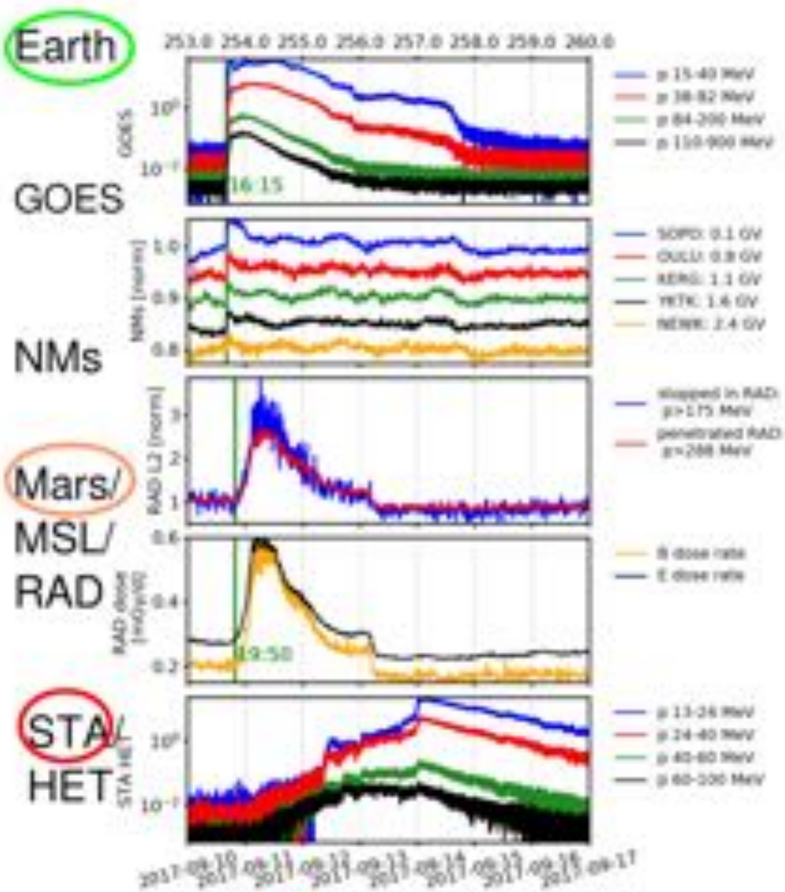


The same SEP events are seen with different flux and spectra at Earth and at Mars





E.g, the last (also the biggest seen by RAD) event on 2017-09-10 with SEPs (>100 MeV) arriving at Earth, Mars and STEREO-A



Earth

- The onset of protons > 100 MeV seen by GOES at Earth is at about **16:15** on 2017-09-10.
- SEPs were also registered as a ground level enhancement (GLE) seen by multiple neutron monitors with cutoff rigidities up to about 3 GV (~2 GeV protons)

Mars

- Mars magnetic foot point is ~150 degrees from the flare.
- The earliest onset at Mars is about **19:50** and this has been the biggest GLE at Mars seen by the Radiation Assessment Detector (RAD) since the landing of the Curiosity rover.
- Considering the atmospheric cutoff and the RAD detector response function, particles with > ~300 MeV arrived at Mars. *We are working on retrieving the SEP spectra at Mars on top of the atmosphere from surface measurement.*

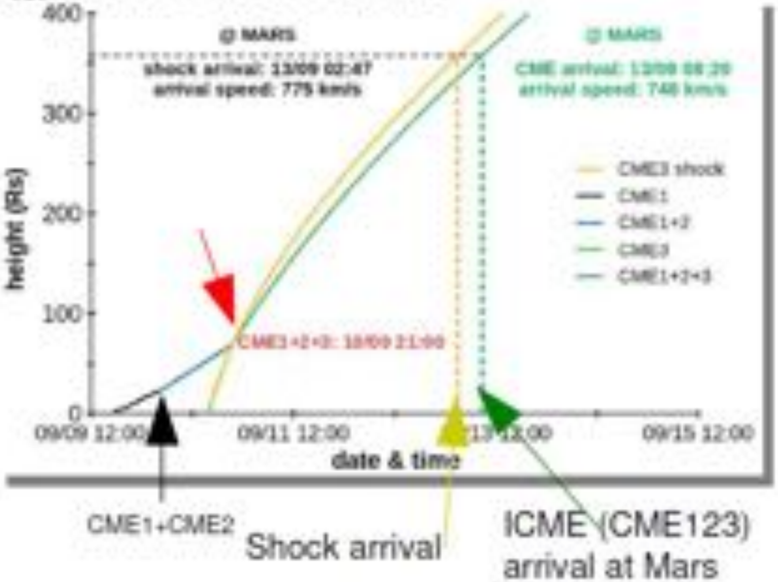
STEREO-A

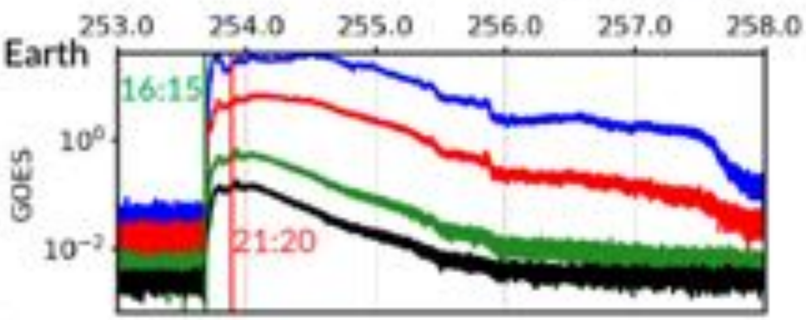
- STA foot point is >~200 degrees away from flare and still detected particles ~ 100 MeV.
- The SEPs arriving at STA are likely transported there across Interplanetary Magnetic Field (IMF) lines via diffusion and scattering as STA was at the back side of the flare and CME shock.

Guo et al 2018, Space Weather, 16, 1156

Also see Hassler et al 2018, Ehresmann 2018 & Zeitlin 2018

Modeling results of the propagation and interaction of the 3 CMEs

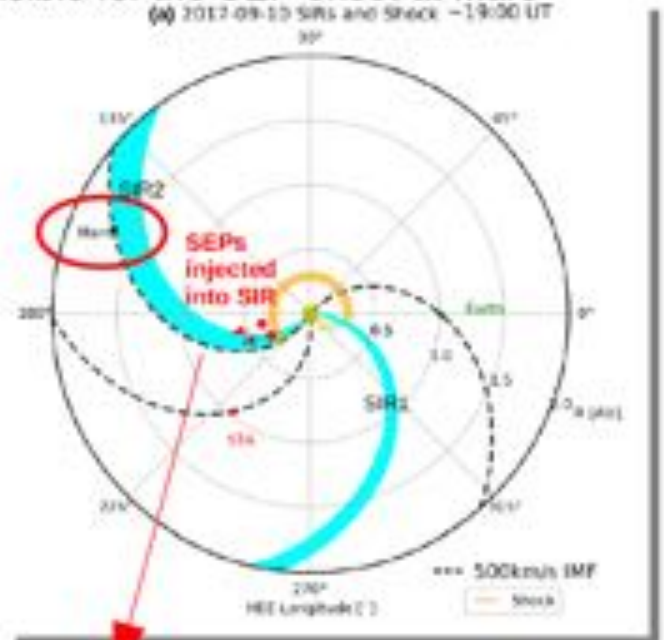


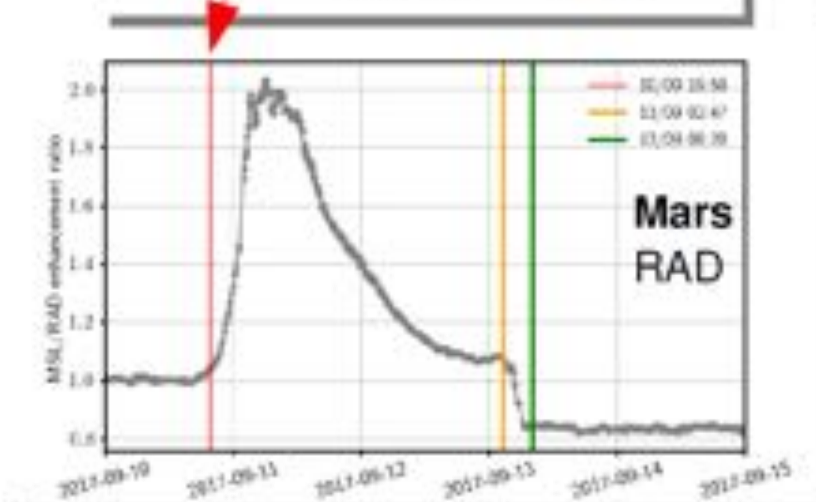


- During the collision, CME mass merged as an entity and the two colliding bodies continued their propagation further with the momentum conserved [Temmer et al., 2012]
- Merging of 3 CMEs may be contributing to the particle injection ~21:20 as observed insitu at Earth.

Upon the SEP onset at Mars, the modeled shock front is close to the Parker spiral connecting to Mars.

A Streaming Interaction Region (SIR) may also be responsible for the SEP onset at Mars





Outlook for space weather and space radiation predictions for human explorations to Mars

GCR radiation is anti-correlated with the heliospheric activity and needs to be better measured and quantified under different shielding environment under different modulation conditions.

SEP events are difficult to predict. However, **synergistic** analysis of the remote-sensing and in-situ measurements combined with modeling tools is helping us to better forecast extreme space weather conditions for human explorations in space.

To forecast SEP events, it is important and necessary to consider:

- The **acceleration and injection** of the particles at the Sun and the continuous acceleration by the ICME driven shock in the interplanetary (IP) space.
- The heliospheric position of the spacecraft and its **magnetic connection** to the injection site (flare and/or shock front).
- Scattering and cross-field **transport** of particles in the IP space.
- The **shielding** configuration of the local environment, e.g., the spacecraft material or the planet atmosphere shielding.

Particle acceleration in 3D RCSs with coalescent and squashed magnetic islands: TP and PIC approach

Valentina Zharkova and Qian Xia

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Zharkova and Gordovskyy, 2004,ApJ; 2005a,

MNRAS; 2005b, SSRv; Zharkova et al, 2011, SSRv; Siversky and Zharkova, 2009, JPP; Zharkova and Agapitov, 2009, JPP;

Zharkova and Khabarova, 2012, 2015

Xia and Zharkova, 2018

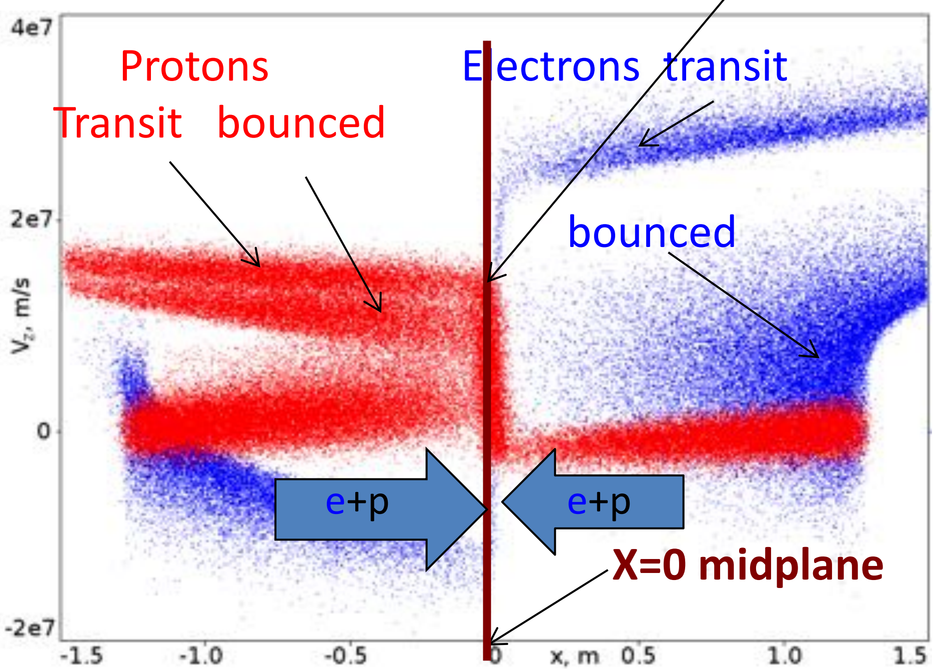
In a current sheet with single X-nullpoint

Electrons and protons are separated with respect to RCS midplane

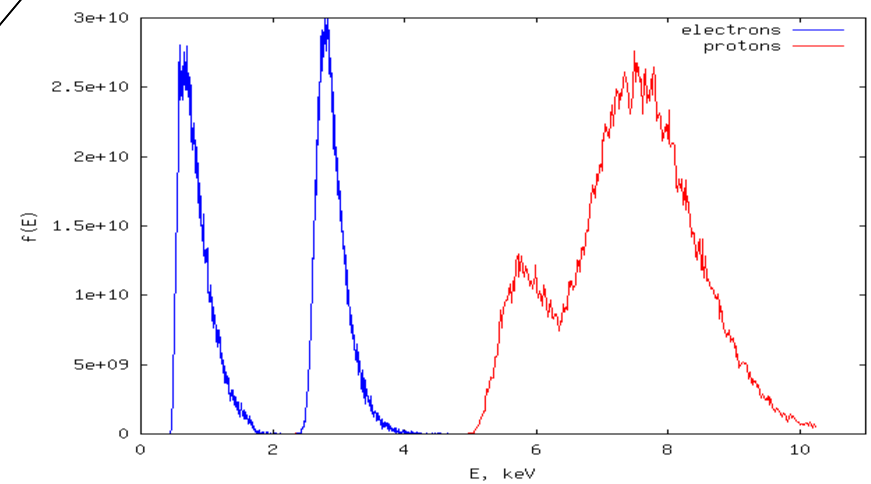
$$B_0 = 100\text{G} \qquad B_y = 1\text{G}$$

$$B_x = 0.4\text{G} \qquad \frac{m_p}{m_e} = 10$$

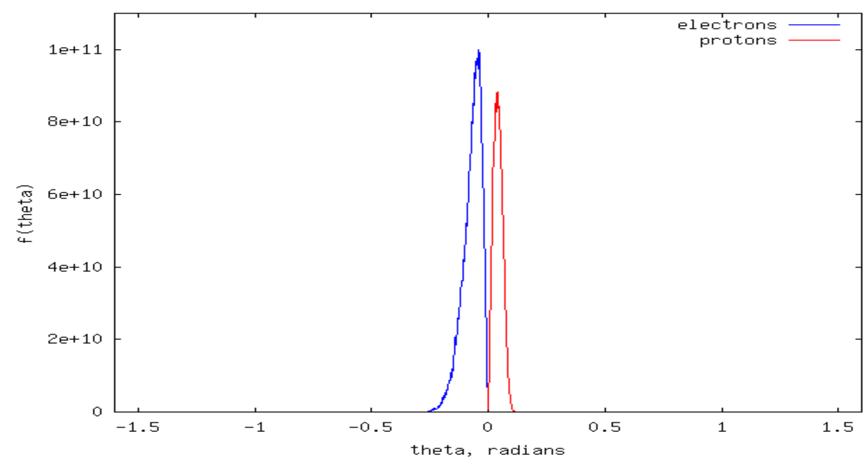
x-V_z phase space



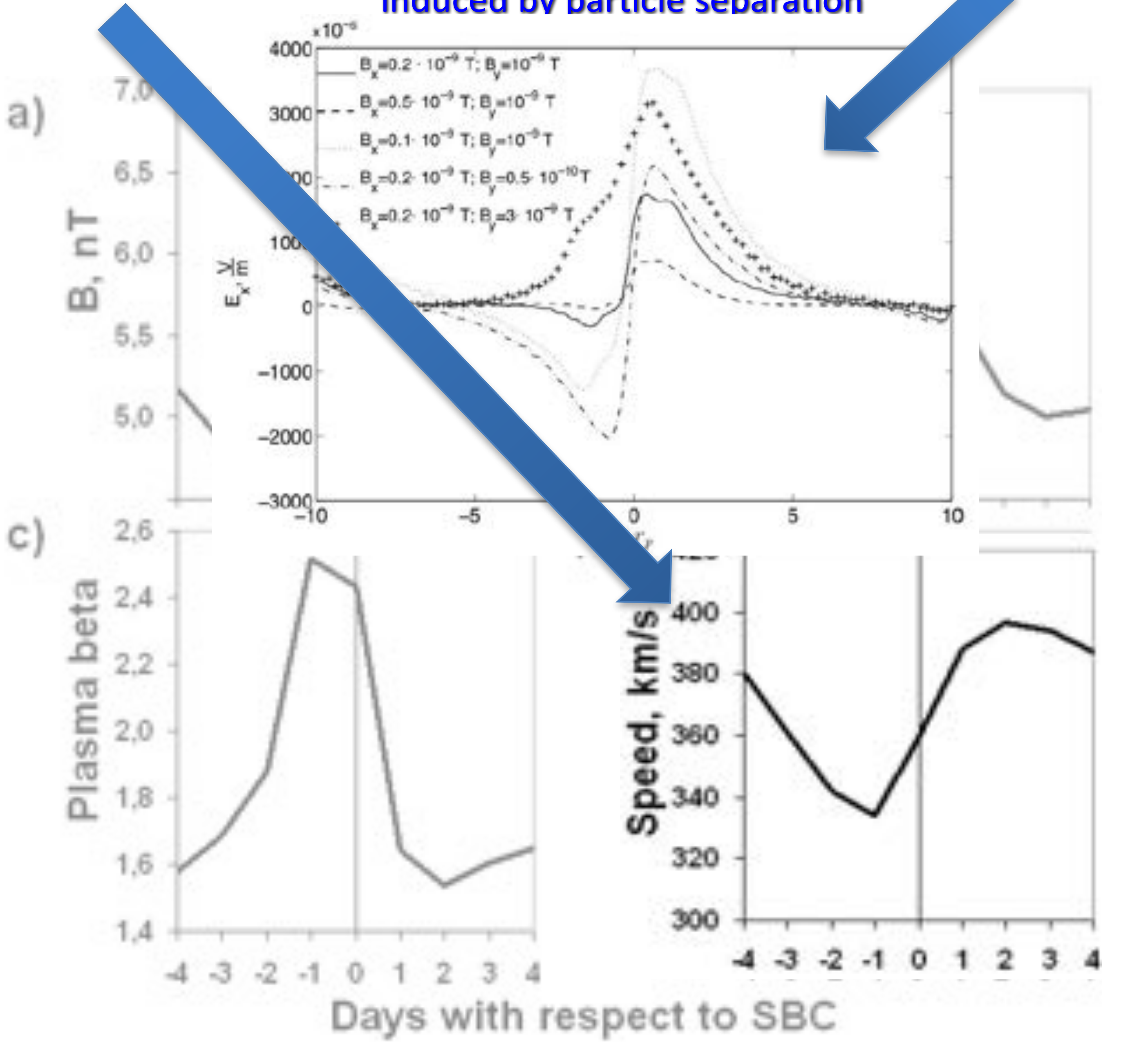
Energy distributions of ejected particles



Pitch angle distributions

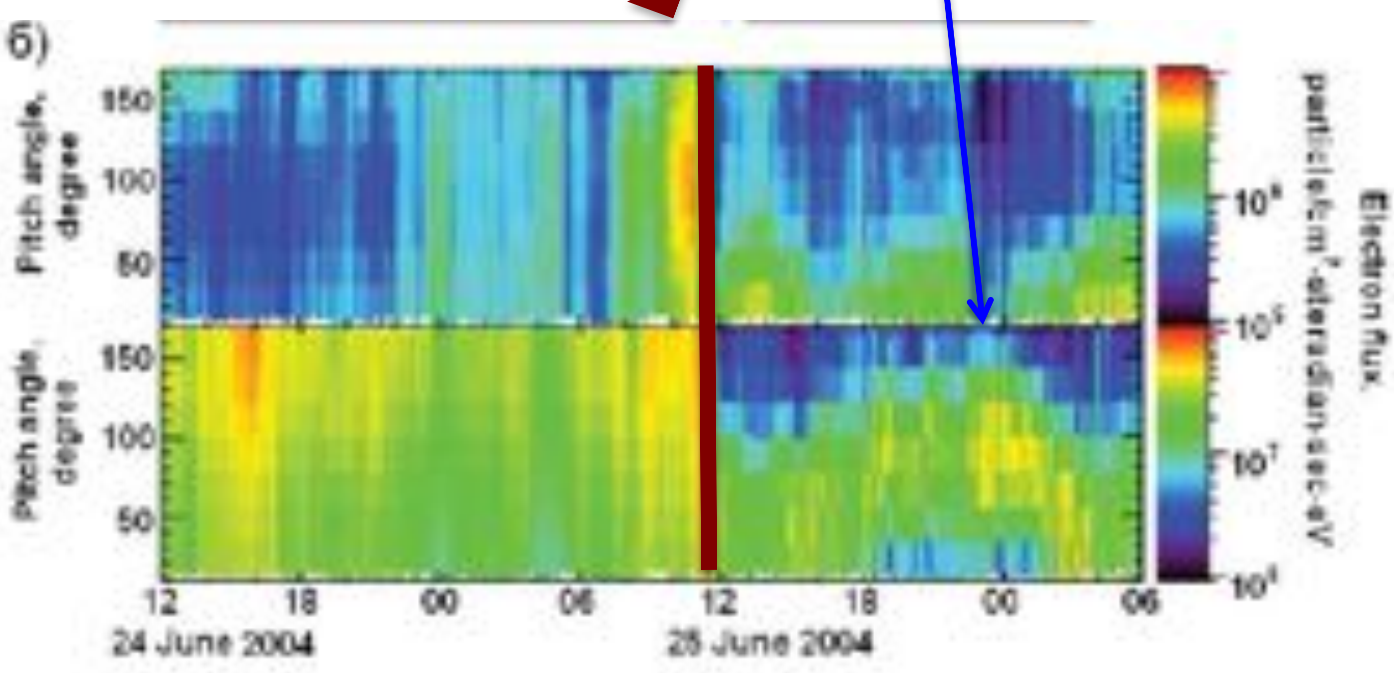


Motion of ions crossing the HCS guided by polarisation electric field induced by particle separation



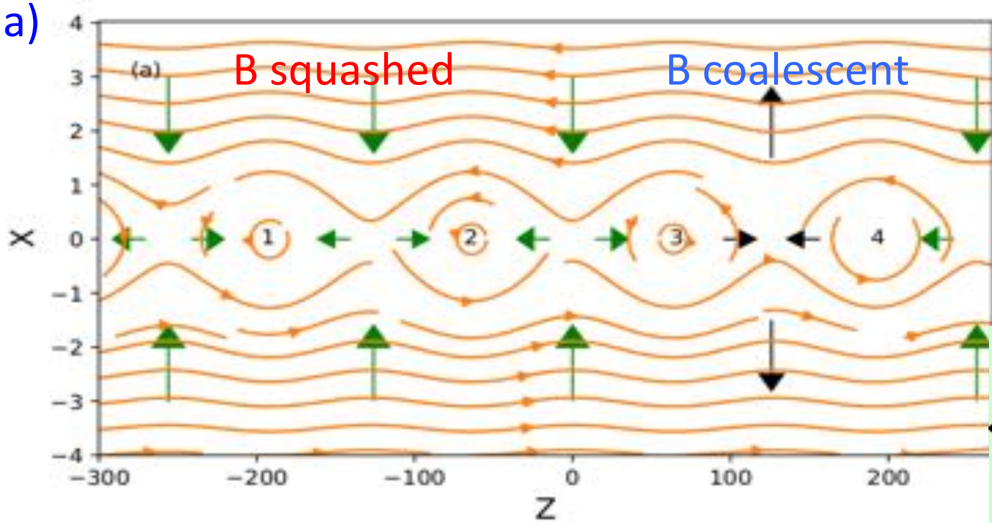
Separation of HCS Sector Boundary (midplane) and electron turn by 180° (electron cloud) depends on magnitude of a guiding field magnitude Bz

No	Event	Distance D from the main SB, km	Density, cm^{-3}	B_z, nT GSE
1	24-26 June 2004	$4.0 \cdot 10^6$	11	3.5
2	10-13 July 2010	$5.8 \cdot 10^7$	22	6.0
3	28-31 May 1995	$4.0 \cdot 10^7$	36	8.0



Current sheet is subject to tearing instability → magnetic islands multiple X and O-nullpoints

a)

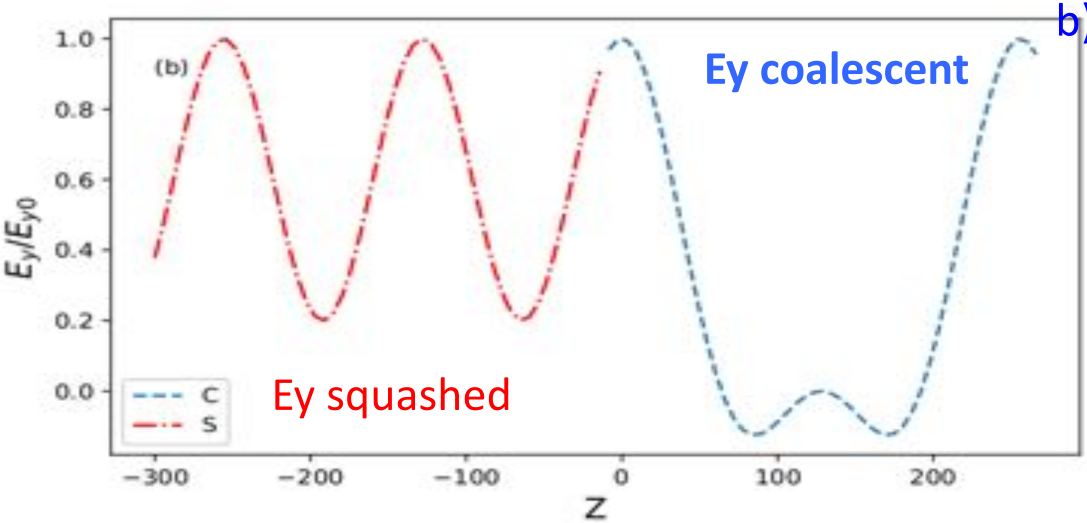


a) The plasma inflow (green arrows) and outflow (black arrows) directions in a coalescent magnetic island chain.

The solid orange lines show the magnetic field in the X–Z plane [Fadeev et al. 1965].

$$\begin{cases} B_z = -\dfrac{\sinh(x/d)}{\cosh(x/d)+\epsilon\cos(kz/d)}B_0, \\ B_x = -\dfrac{\epsilon\sin(kz/d)}{\cosh(x/d)+\epsilon\cos(kz/d)}B_0, \end{cases}$$

b)



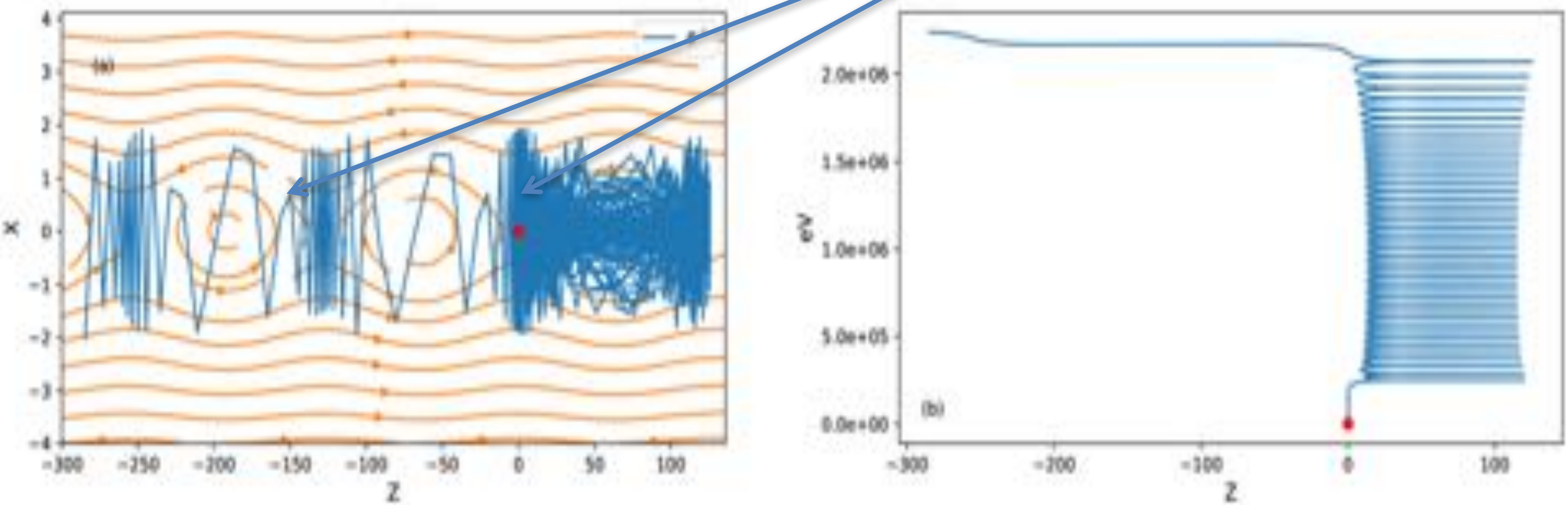
b) The blue dash line and red dash-dot line show the E_y from coalescent and squashed islands on the midplane.

$$C : E_y = E_{y0}\cos(\frac{kz}{2d})\cos^2(\frac{kz}{4d}),$$

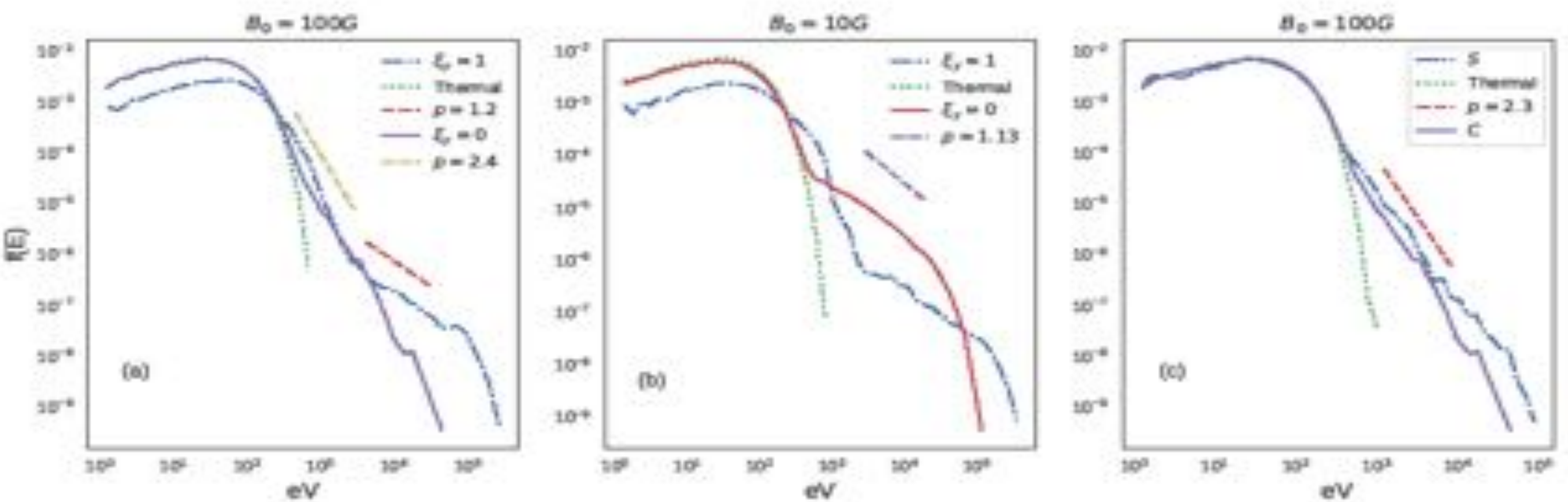
$$S : E_y = E_{y0}[0.6 + 0.4\cos(z/d)],$$

Xia & Zharkova, 2018, A&A

Particles accelerated in magnetic islands in X-nullpoints and form clouds between O-nullpoints



Higher energy gains in squashed islands. Energy spectra – power laws Xia&Zharkova, 2018, A&A



Conclusions

- A strong guiding field leads to separation of electrons from protons with respect to the midplane
- 3D RCSs with multiple O-nullpoints (magnetic islands still reveal the separation of electrons from protons to the opposite X-semiplanes)
- This separation leads to formation of polarisation electric field across the current sheet with 2 orders of magnitude larger than the reconnection electric field
- Magnetic field imposes different pitch-angle distributions and energy spectra of particles entering a current sheet from the opposite (transit) and the same side (bounced).
- Electron beams are often injected well directed at 30-40^{o} to the Bz while protons have wider pitch angle distributions
- In some conditions previously injected electrons are accelerated to subrelativistic energies in a single magnetic island, in other they pass through a few islands while forming clouds about neighbouring X-nullpoints.
- Particle energy gains in coalescent islands are lower than in squashed ones; the higher the squashed island aspect ratio the higher is the gained energy.

Numerous Posters on SEP research

- Bruedern et al.
- Galsdorf et al.
- Heber et al.
- Kirin
- Koeberle et al.
- Kollhoff et al.
- Kuehl et al.,
- Tsvetkov et al.