Particle re-acceleration in 3D current sheets in the heliosphere and their diagnostics from observations

V.V. Zharkova, Q. Xu, O.V. Khabarova, O. Malandrin

University of Northumbria, UK; *CfAham Space Centre, UK; **IZMIRAN, Russia; *Observatory of Athens, Greece

Summary

This research aims to explore variations of electron pitch-angle distribution (PAD) during spacecraft cross reconnecting current sheets (RCSs) with magnetic islands. The results can benchmark the sampled characteristic features with realistic PADS derived from in situ observations.

Particle motion is simulated in 2.5D Harris-type RCSs using particle-in-cell (PIC) method considering the plasma feedback to electromagnetic fields. We evaluate Harris-type PADS and PADs in different locations and under different directions of passing the current sheet by a virtual spacecraft. The RCS parameters are comparable to heliospheric and solar wind conditions.

- The energy gains and the PADs of particles would change depending on the specific topology of magnetic fields.
- Besides, the observed PADS also depend on the crossing paths of the spacecraft. When the guiding field is weak, the bi-directional electron beams (strahls) are mainly present inside the islands and located close above/below the X-nullpoints in the upper layers.
- The magnetic field relaxation near X-nullpoint converts the PADs towards 90°.
- Meanwhile, the high-energy electrons confined inside magnetic islands create PADs about 90°.

It is evident that electrons of different energies behave differently. Electrons of low-energy 11 channel closely follow the magnetic topology of smallest and dynamical MIs (see the up-and-down variations occurring in accordance with most intense variations in the IMF).

- It is known that usually PAD patterns vary rather slowly from channel to channel, depending on the strength of the IMF at the entry points. The PAD patterns may vary depending on variations of pitch angles with respect to the plasma seen in higher-energy channels and 5.

- Furthermore, the most intense flux follows the position of the most intensely reconnecting MIs in the middle of Figure 2 (compare the bird-like red PAD pattern and large-scale variations in Bel).

- The channel 5 PAD indicates unimpaired/smooth strahl flowing in the downstream regions (the central part of the SIR from the side of the Parker spiral, normally it is observed by STEREO B first [Gomez-Herrero et al. 2011]. The M-null region observed on 2007 May 25. The electron PADs from dispersionless to completely defocused. Lower-energy electrons do not leave MIs showing the most intense PAD profiles at their half length in the island, d the current sheet half-thickness. Both counterstreaming strahls and dropsouts may be observed in such a configuration.

3. Simulations

In order to understand the PAD features discussed above and to test the idea about the PAD patterns dependence on the key results of simulation, we model the PADs of particles accelerated in typical RCS and MIs configurations, considering the ambient plasma feedback to the presence of accelerated particles discussed in Xia and Zharova (2020).

- We trace particles in the vicinity of a 3D current sheet with a half-width of one gyroradius (∼1.6π along X) extended along Z. It is the static magnetic field induced by the PADs of electric field by accelerating particles is perpendicular to the reconnection plane.
- Particles from the ambient neutral plasma are dragged into the reconnection region from both sides by the magnetic diffusion process, leaving the RCS only after passing the magnetic trapping region. This is the PAD pattern obtained in typical magnetic field topology shown in Figure 4a (see details in Zharova & Gordovskyy 2005; Xia & Zharova 2018, 2020).
- After that, particles with opposite charges (electrons versus protons/ions) are ejected into the magnetosheath plasma.
- Particles of the same charge form two distinct groups ("transit" and "bounced") with different energies and trajectories (Figure 4a). The maximal energy reaches 20 keV (higher-energy electrons, upper panels in Figure 4b).
- The PADs of electrons accelerated in MIs without the guide field By/B0 = 0 are quite symmetric with respect to the midplane, while when By/B0 varies from 0 to 1, bounced electrons (lower-energy electrons, bottom panels in Figure 4b) are intensified. B is the static magnetic field induced by the acceleration of solar wind electrons to keV energies at the 3D RCS. a) Topology of magnetic field lines in the vicinity of the single X-nullpoint of the RCS on the left, and example of 2.5D particle-in-cell simulations (3D by velocity V and 2D by coordinate) of particle trajectories for the strong guide field, By/B0 = 0.5 (right).

4. Interpretation of observations

The electrons in the upper left PAD of Figure 4b are ejected mainly along 0°-180°, and the RCS midplane is clearly visible as a vertical stripe. This PAD pattern is often observed in the solar wind (see Figures 2 and 3) but has always been interpreted in terms of crossing of the RCS or a similar current connected to the solar source. This study shows that such a pattern just reflects a crossing of a single thin current sheet reconnecting in a weak guiding field.

References


Fig. 1. Three panels in (a) and (b) from top to bottom are the solar wind density, the solar wind speed, and the IMF strength obtained from the L1 (ACE) and WIND spacecraft (a) and the STEREO A and STEREO B spacecrafts.

Fig. 2. The electron PADs of different energies, the IMF, and the density in the region filled with MIs of variable size as observed by the WIND spacecraft on 2007 May 25. From top to bottom: PADs of electrons measured with −24 Δ in the resolution following the channels: Channel 3 (often ∼50 eV), Channel 5 (often ∼255 eV), Channel 7 (often ∼121 eV), Channel 9 (∼50 eV). Channel 11. Often ∼25 eV is MS strength; the three IMF components in the GSE system; and the solar wind density. Crossings of CIS separating MIs are shown by vertical dashed purple lines.

Fig. 3. Analogies to Figure 2, but for STEREO A (left) and STEREO B (right). Upper PAD panels are for the 6507, 246, and 713-194 eV energy channels.

Fig. 4. Modeling of acceleration of solar wind electrons to keV energies at the 3D RCS. The top plot presents the magnetic field topology (black lines) and the paths of a spacecraft (purple line). Middle and bottom panels present the PADs of mid-energy (center) and lower-energy (bottom) energy electrons accelerated in the system of the islands and MIs.

Fig. 5. PADs observed when a hypothetical spacecraft crosses two coalescent MIs. The top plot presents the magnetic field topology (black lines) and the paths of a spacecraft (purple line). Middle and bottom panels present the PADs of mid-energy (center) and lower-energy (bottom) energy electrons accelerated in the system of the islands and MIs. Parameters of the islands employed are B0 = 10-9T, E0 = 0.100m V/m, B = 0.035T, α = 1.1, δ = 0.2, 1/2, l = 1, 4, 0.035T, l is the half length of the island, d is the current sheet half-thickness. Both counterstreaming strahls and dropsouts may be observed in such a configuration.

It shows signatures of intermittent bi-directionality, the location of MIs and CISs, very similar to the lower-energy PADs and correlated in Figure 3, especially in the region with the largest MIs and the local density increase (see Figure 3b).

The behavior of suprathermal electrons in both the lower PAD 73-194 eV panels in Figures 3c) (STEREO A and B) (Fig. 4a) generally reflects the PAD features seen in the 58-121 eV WIND energy channels in Figure 2 with a corresponding short time shift. STEREO PAD patterns in the 246-446 eV channel (the middle panels of Figure 3c) are consistent with WIND 255 eV PAD in Figure 2 in which the fast acceleration of lower-energy PADs is completely different from the other PADs.

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