Observational evidence for local particle acceleration associated with magnetically confined magnetic islands in the heliosphere – a review

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Abstract. The occurrence of unusual energetic particle enhancements up to several MeV/nuc at leading edges of corotating interaction regions (CIRs), near the heliospheric current sheet and downstream of interplanetary shocks at 1AU has puzzled observers for a long time. Commonly accepted mechanisms of particle energization, such as a classical diffusive shock acceleration mechanism or magnetic reconnection at current sheets, are unable to explain these phenomena. We present a review of recently obtained observational results that attribute these atypical energetic particle events to local acceleration of particles in regions filled with small-scale magnetic islands confined by currents sheets of various origins. The observations are in very good accordance with the theory of stochastic particle energization in the supersonic solar wind via a sea of small-scale flux-ropes interacting dynamically (Zank et al., 2014, 2015; le Roux et al., 2015, 2016).

Keywords: magnetic islands, particle acceleration, current sheets, interplanetary shocks, magnetic reconnection

Introduction

Case studies of particle acceleration up to several MeV/nuc throughout the heliosphere show that some energetic particle (ion and electron) flux enhancements are not associated with standard mechanisms of particle acceleration (Mazur et al., 2000; Al-Sawad et al., 2009; Leske et al., 1999; Mulligan et al., 2008; Chollet and Giacalone, 2008; Chollet et al., 2010; Malandraki et al., 2005, 2008; von Rosenvinge et al., 2009; Foullon et al., 2011; Stasiewicz et al., 2013; Zharkova and Khabarova, 2015; Khabarova et al., 2015a,b, 2016). Atypical energetic particle events (AEPEs) represent increases in energetic particle flux observed at timescales from ~1/2 hour to several hours, sometimes, against the background of classical solar energetic particle (SEP) events, but mostly in the relatively quiet solar wind. The AEPEs are observed by different spacecraft with a time delay, corresponding to propagation of the solar wind from one spacecraft to another, therefore they cannot be classified as solar energetic particle events (SEPs) related to flares or ICMEs. They do not represent energetic particle enhancements associated with CIRs either. Very likely, they are associated with a local particle acceleration region embedded in the background solar wind (see Khabarova et al. (2015a,b) and references therein).

Khabarova et al. (2015a,b, 2016) found that AEPEs at 1 AU are observed in magnetically confined areas that contain magnetic islands with a typical width of ~0.01 AU or less. Either the heliospheric current sheet (the HCS) or current sheets of various origins that have equally strong background magnetic fields provide the magnetic confinement of flux ropes/plasmoids that experience dynamical merging or contraction. The results are in a very good agreement with predictions based on a theory of stochastic particle energization in the supersonic solar wind via numerous dynamically interacting small-scale flux-ropes (Zank et al., 2014, 2015b,a; le Roux et al., 2015, 2016). According to an emerging paradigm, electrons and ions can be accelerated stochastically by magnetic reconnection processes in solar wind regions filled with magnetic islands or flux ropes. Particle energization occurs as a result of several potential mechanisms, including via the so-called anti-reconnection electric fields that form from the merging of magnetic plasmoids, and when trapped particles experience multiple reflections from the strongly curved field lines at the ends of elongated contracting islands.

Small-scale magnetic islands are crossed by spacecraft at 1 AU for several minutes, typically, for ~1/2 hour. However, larger flux ropes associated with energetic particle enhancements may be detected too, for example, inside atypical ICMEs, detached from the Sun. During the quiet periods, magnetic islands are generated by magnetic reconnection at strong current sheets in the solar wind, as discussed in Retinò et al. (2007), Huang et al. (2011), Huang and Bhattacharjee (2013), Eastwood et al. (2002), Eriksson et al. (2014). Particle energization associated with magnetic islands near reconnecting current sheets is also observed in the terrestrial magnetosphere (Chasapis et al., 2015; Wang et al., 2016). This effect is sometimes discussed in terms of fractional acceleration (Zelenyi and Milovanov, 2004; Pavlos, 2013). In the solar wind, magnetic islands predominantly occur in the vicinity of the HCS, as shown by Cartwright and Moldwin (2010).

Conditions favorable for the formation of regions containing dynamically evolving magnetic islands may occur in the solar wind very often, for example,
(i) near the reconnecting HCS, especially during time periods when its shape is rippled;
(ii) at edges of solar wind streams (ICMEs or CIRs), interacting with the HCS or with each other;
(iii) between strong current sheets within CIRs or ICMEs;
(iv) in the turbulent wake of interplanetary shocks (that can interact with the HCS).

Khabarova et al. (2015a, 2016) have used both in situ measurements of the interplanetary magnetic field (IMF) and plasma parameters and the IMF profile restorations based on measurements of interplanetary scintillations to show that the HCS often possesses a plisse-like form with numerous ripples which contain magnetic islands within them. Observations of such conglomerates are well-correlated with the occurrence of AEPEs. It is shown that some part of the AEPEs is associated with magnetic islands merging near the HCS.

A shock formed in the solar corona in front of a propagating CME is usually thought to be a source of all ICME-associated particles possessing MeV energies that are observed at 1 AU. However, particles can obtain such energies near ICMEs due to an alternative mechanism. Interaction between an ICME and the HCS at both the leading and trailing edges of the stream leads to effective confinement and compression of magnetic islands, experiencing contraction in the region between the HCS and the ICME. An increased magnetic reconnection rate at the HCS, which is stressed by the ICME, results in the production of more small-scale magnetic islands that contribute to local particle acceleration via the mechanism proposed by Zank et al. (2014), as shown in Khabarova et al. (2015a,b, 2016).

Another example is the HCS-CIR interaction, which is quite similar to the previous case because of the formation of a region filled with magnetic islands compressed between the high-density leading edge of a CIR and the HCS. This is frequently observed several hours before the passage of CIRs. When fast solar wind streams catch up with slow solar wind, Stream Interaction Regions (SIRs) of compressed heated plasma or more regular CIRs are created at the leading edge of the high-speed stream (Pizzo, 1978; Balogh et al., 1999). Since coronal holes are often long-lived structures, the same CIR re-appears often for several consecutive solar rotations. At low heliographic latitudes, such CIRs are typically bounded by forward and reverse waves on their leading and trailing edges, respectively, that steepen into shocks at heliocentric distances beyond 1 AU (e.g. Smith and Wolf, 1976; Forsyth and Gosling, 2001). Energetic ion increases have been frequently observed in association with CIRs, and these shocks to be believed to accelerate ions up to several MeV per nucleon. (See Richardson, 2004 and references therein for a review of the effects of CIRs on energetic particles). In this paradigm particle acceleration is commonly believed to occur mainly at the well-formed reverse shock at 2-3 AU with particles streaming back from the shocks from the outer heliosphere to 1 AU (Malandraki et al., 2007).

However, this paradigm demands specific timing and ion/electron flux features which are not always observed. Furthermore, previous works have shown that statistical acceleration in the vicinity of CIRs could also contribute to particle acceleration (e.g. Scholer et al., 1999), and recent multi-spacecraft observations illustrated the importance of local phenomena for the acceleration of low energy particles in the vicinity of CIRs (Gomez-Herrero et al., 2011). Comparison of elemental abundances in Solar Energetic Particles, thought to be accelerated from the ambient material in the corona or solar wind by shock waves driven by large coronal mass ejections (CMEs) and CIR-Associated events at 1 AU shows that the latter exhibit significant enrichments of helium and carbon relative to SEP events (e.g. Mason and Sanderson, 1999). Composition signatures during CIRs have been used to understand the origin of the seed particle population accelerated in association with CIRs (Malandraki et al., 2008).

The behavior of energetic particles near interplanetary shocks is often inconsistent with predictions of classical diffusive shock acceleration theory. Zank et al. (2015b) find that a combination of classical diffusive shock acceleration and acceleration in a downstream sea of dynamical magnetic islands can explain the observed energetic ion flux profiles.

In this work, we illustrate some of the above discussed results and stress the role of magnetic islands in the atypical suprathermal particle enhancements observed at 1 AU. Based on the observations, we suggest that local particle acceleration may take place directly in the solar wind and be determined by the occurrence of induced electric fields in merging/contracting magnetic islands and local reconnecting current sheets in the turbulent plasma (Zank et al., 2014, 2015a,b; le Roux et al., 2015, 2016).

Reconnecting HCS and merging magnetic islands associated with accelerated particles

The existence of small-scale ripples of the HCS is confirmed both by modeling (Merkin et al., 2011) and observations (Arnold et al., 2013; Khabarova et al., 2015a). The left panel in Figure 1 illustrates the results of modeling the HCS shape based on the real position of the solar equator. The HCS shape in the left panel shows both large-scale waves and much smaller-scale ripples, which is in agreement with in situ observations. Such ripples can be identified in the IMF data as relatively fast changes in clock and cone IMF angles that occur several hours before the final change of the IMF direction (sector crossing). STEL measurements of interplanetary scintillations help to restore not only the velocity, but also the IMF profiles, confirming the complex form of the HCS, as shown in right panel of Figure 1 (see detailed explanations how to interpret STEL plots in Khabarova et al. (2015b)). In situ observations allow us to conclude that ripples confine magnetic islands that may experience merging, seen in Figure 2.

Figure 2 is adapted from Khabarova et al. (2015a). It illustrates AEPEs associated with the HCS crossing (thick vertical line). The largest magnetic islands are merging and smaller ones disappear and "swallow" each other, as follows from the comparison of measurements from the ACE and the WIND spacecraft that were 150 Earth radii apart. Remarkably, since the area filled with dynamical magnetic islands that trap and accelerate particles occurs somewhere nearby the HCS, the associated increase in the energetic particle flux never has a maximum exactly at the HCS position. However, the HCS provides seed particles into the region of secondary acceleration due to the magnetic reconnection. The rotation of the IMF vector inside the islands traced by both spacecraft is clearly seen in the hodograms presented in Figure 1c.

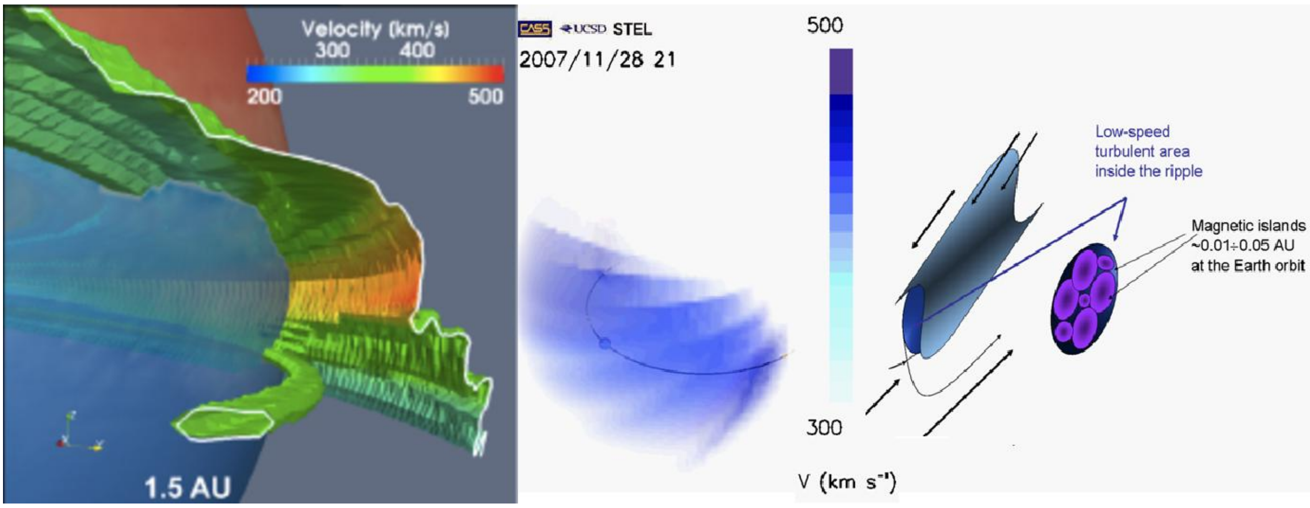

Figure 1: Illustration of the occurrence of small-scale magnetic islands inside ripples of the HCS. Adapted from Merkin et al. (2011) - left panel, and Khabarova et al. (2015a) - right panel. A plisse-like form of the HCS is seen both from modeling (left panel) and STEL observations (right panel).

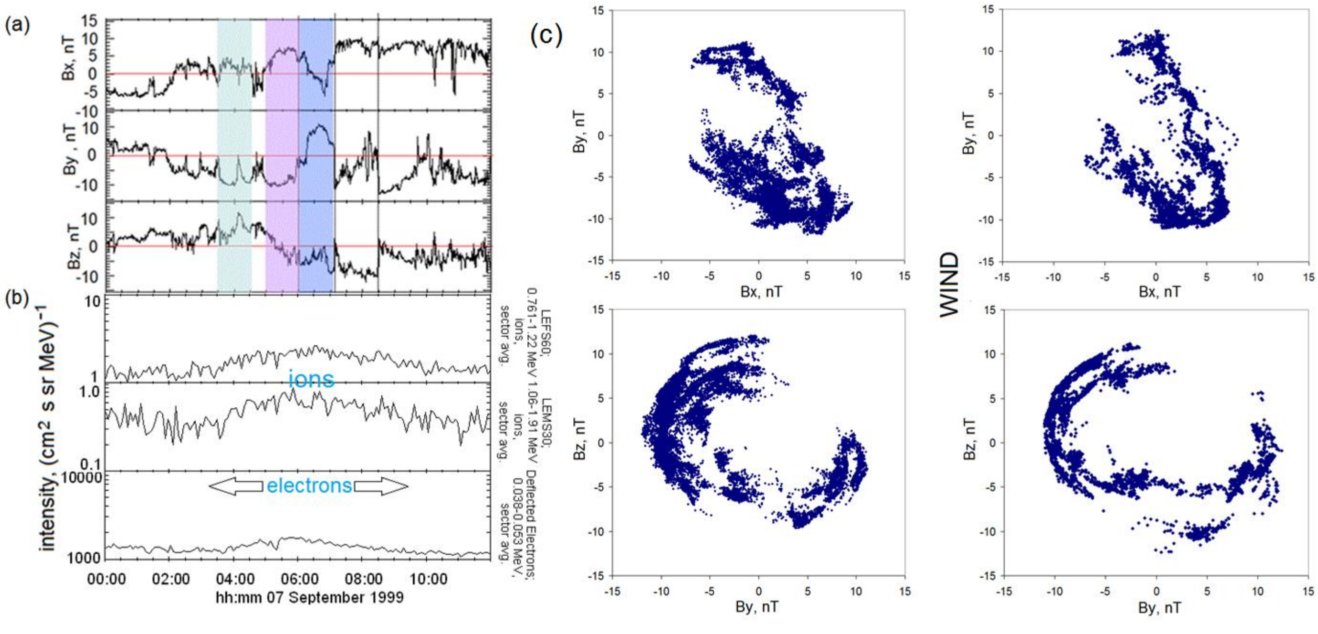

Figure 2: The IMF components (a) and energetic particle flux enhancements (b) associated with the crossing of an area filled with merging magnetic islands from ACE measurements. (c) Rotation of the IMF vector inside the islands (indicated by blue and purple stripes), experiencing merging as found through comparison of ACE and WIND measurements.

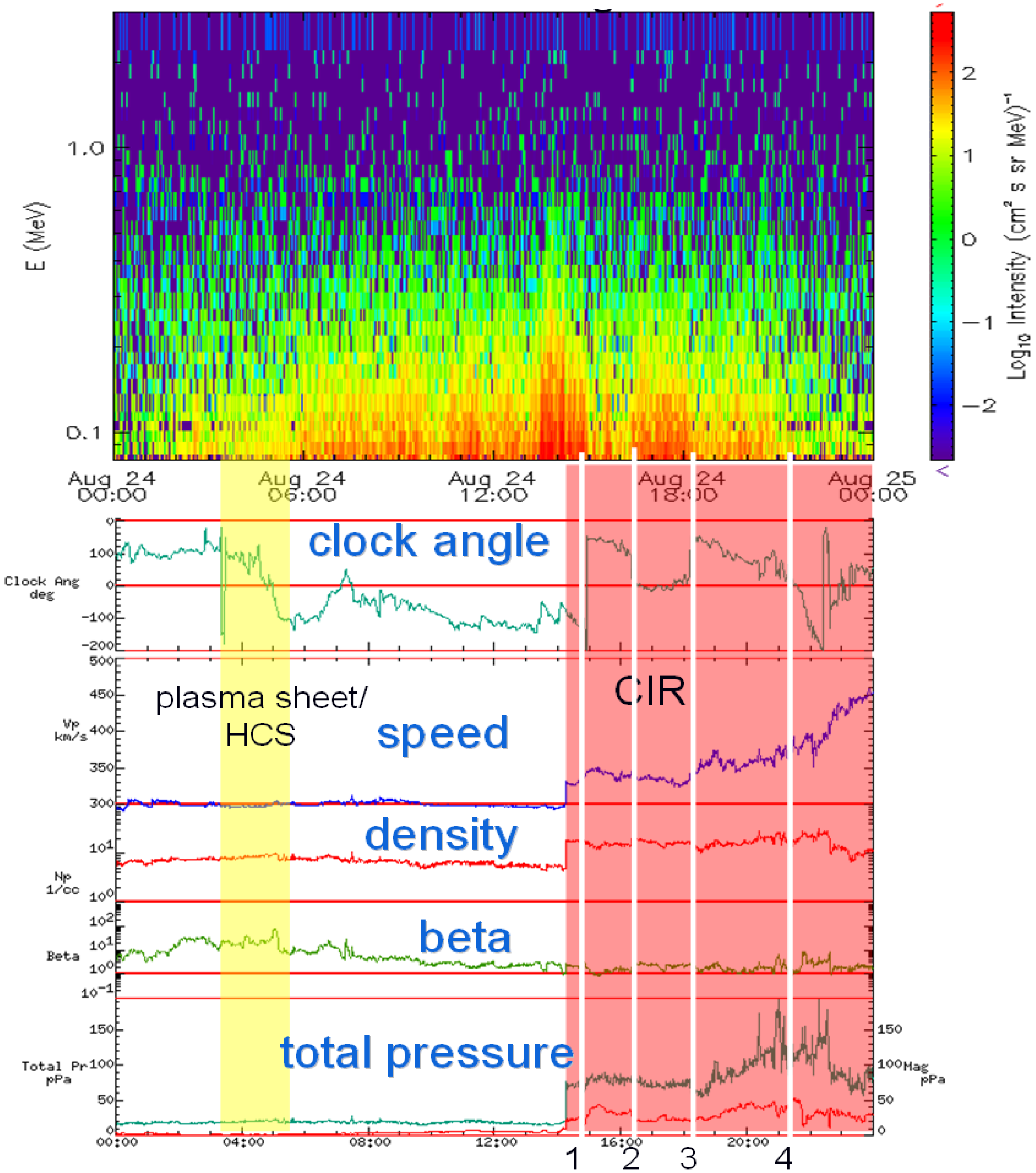

Figure 3: AEPEs observed by STEREO B over a wide range of energies between the HCS and the strongest current sheet at the CIR leading edge (indicated by white line no.1) on August 25, 2007. Some smaller intensity AEPEs are seen between other strong current sheets within the CIR. The secondary current sheets are indicated by vertical white lines no.2-4.

AEPEs associated with HCS-CIR interaction. Local acceleration of particles within a CIR

The HCS crossing that occurred on August 25, 2007 before the crossing of the CIR's leading front was traced by several spacecraft. The detailed picture of the ion energetic spectrum (the upper panel in Figure 3) shows the energetic particle flux increase that is observed from the moment of crossing of the heliospheric plasma sheet containing the HCS (the yellow stripe).

The largest variations in energetic particle flux occurred not between the HCS and the CIR's forward shock, as seen from plasma data (the left edge of the red stripe), but between the CIR- associated leading current sheet (the vertical black line no.1 in Figure 3) and the heliospheric current sheet. The same behavior in the energetic particles can be seen in Figure 4, which shows LEMS120 ACE/EPAM measurements of energetic ions (two upper panels) compared with the IMF variations. WIND measurements confirm the result obtained from the analysis of ACE and STEREO observations, that particle acceleration may occur between strong current sheets independently of their origin if there are small-scale magnetic islands in the area between them (Figure 5 and 6).

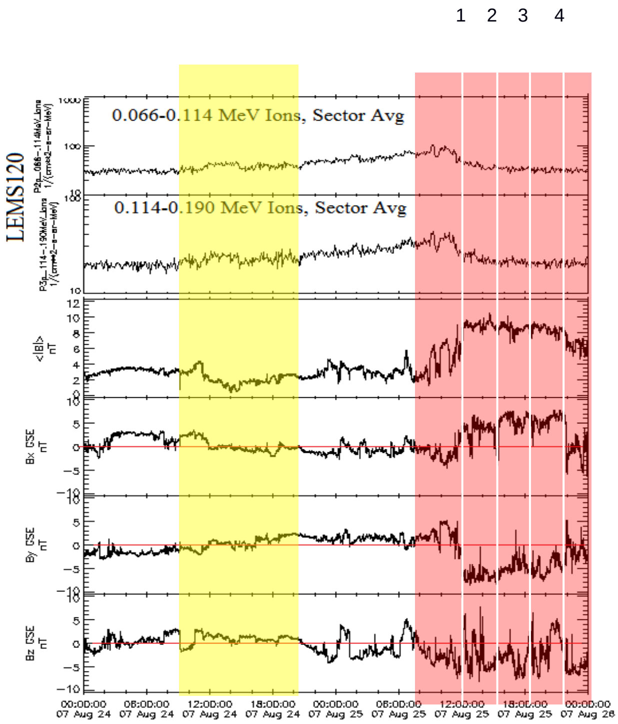

Figure 4: The same event observed by ACE. LEMS120 energetic ion flux measurements (two upper panels) and the IMF components.

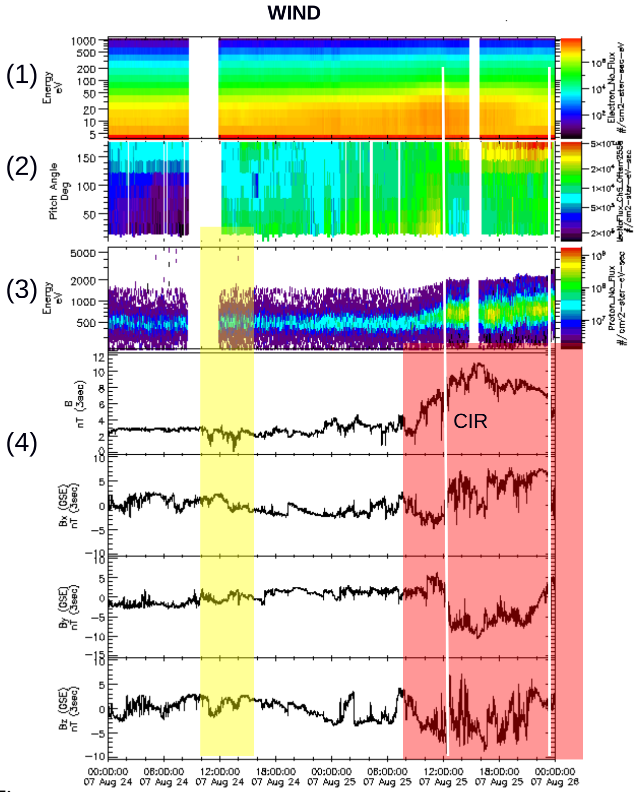

Figure 5: WIND observations of the event shown in Figures 3-5. (1) electron flux spectrogram, (2) pitch angle distribution at 255eV, (3) ion flux spectrogram, (4) the IMF components.

In Figure 5, the change in the IMF direction at the HCS is clearly seen in panels (2) and (4). The increases in both energetic electron flux and ion flux are observed before the CIR arrival, shown by the red stripe. Pearl-like variations in energetic particle flux can be seen in the area between the current sheets inside the CIR, which is full of magnetic islands separated by smaller-scale current sheets.

Figure 6 illustrates detail from subsequent crossings of CIR-associated current sheets (shown by vertical lines in Fugure 5) associated with energetic particle flux increases in detail and shows the IMF rotation inside numerous magnetic islands occurring in this region. This confirms the idea that the mechanism of particle acceleration in the presence of magnetic islands is quite universal. Magnetic islands located between the leading CIR current sheet and the HCS trap and additionally accelerate ions. The same occurs between the current sheets located behind the CIR leading edge in the presence of magnetic islands between them (Figure 5 and Figure 6).

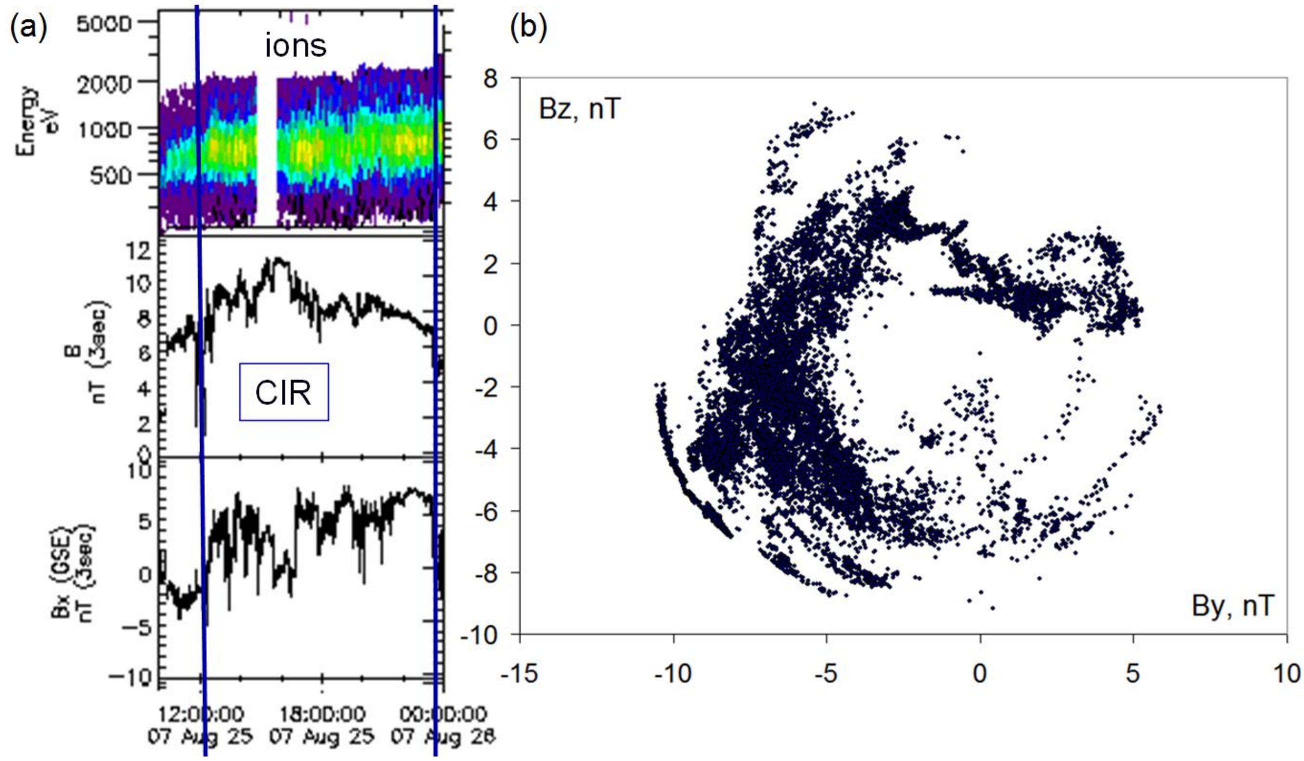

Figure 6: (a) WIND observations of ions in the low-energy range and the IMF components, corresponding to the region between current sheets shown by vertical lines (see also Figures 3, 4 and 5). (b) The hodogram shows distinct rotation of the IMF vector inside magnetic islands located between the current sheets. 3 second resolution WIND data.

AEPEs associated with interplanetary shocks

Crossings of interplanetary shocks are often associated with unexpected behavior of energetic particles. Classical diffusive shock acceleration (DSA) predicts peaking of the particle intensity of a given energy at the shock, after which constant particle intensity is predicted. Therefore, the amplification rate should be 1 after the shock crossing. However, it is often observed to be larger than 1, which means that particles are accelerated in some other way, perhaps, in the turbulent wake of the shock.

Zank et al. (2015b) showed that a combination of classical diffusive shock acceleration and acceleration in dynamical magnetic islands behind the shock can explain the energetic ion flux profiles observed downstream of the heliospheric termination shock. It was found that the ordering of the amplification factor obtained from Voyager 2 data corresponds to theoretical predictions very well.

Another important result obtained for the first time in Zank et al. (2015a) is the observation of a threshold between higher and lower energy ion flux profiles.

Figure 7 illustrates this effect, showing the flux amplification calculated for different energies observed during the crossing of the interplanetary shock that occurred on March 1st 2006 by Voyager 2, when it was at 78.9 AU (see additional information in the Appendix of (Zank et al., 2015b)). There is a clear distinction in the behavior of the lower energy (<0.54 MeV) and higher energy (>0.54 MeV) accelerated particles. For higher energy particles, the amplification is ordered by increasing energy, which is the opposite for the lower energy particles. The threshold level varies with plasma properties and with heliocentric distance. At the heliospheric termination shock, the threshold is approximately at 2 MeV. The origin of the phenomenon is still unclear, although it was suggested that particle trapping in magnetic islands that advect away from the HTS may be responsible for this effect (Zank et al., 2015b).

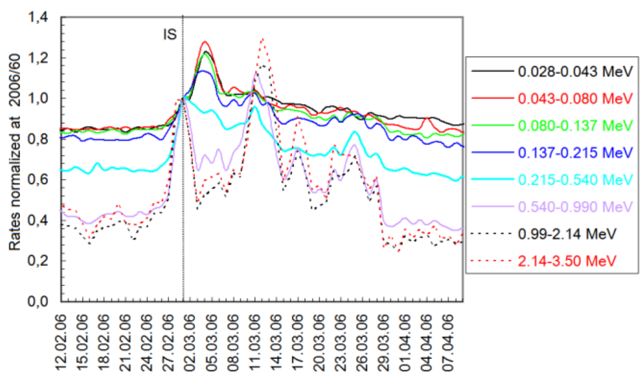

Figure 7: The flux amplification factor obtained from LECP Voyager 2 measurements during an interplanetary shock crossing on March 1st, 2006. Correspondence between colors and energies is shown on the right. Proton flux intensities are normalized at the shock (shown by the vertical line). The amplification factor for energies higher than 0.54 MeV is in accord with the predictions of Zank et al., 2015b, and is the inverse for low energies as was first found in (Zank et al., 2015b).

Summary and discussion

Theoretical results (Zank et al., 2014, 2015a,b; le Roux et al., 2015, 2016) on particle acceleration associated with dynamical processes in small-scale magnetic islands in the solar wind are confirmed by observations of AEPEs associated with various plasma configurations that confine magnetic islands by strong current sheets. Current sheets play a critical role in the creation of AEPEs not only because they represent magnetic walls for magnetic islands and allow particle trapping and re-acceleration for a prolonged time period, but also because of the constant creation of magnetic islands due to magnetic reconnection. The mechanism proposed by Zank et al. (2014) has broad applicability, since it can be combined with other classical mechanisms of particle acceleration. If there is an additional source of particle energization, such as a current sheet (Kirsch, Pavlos and Sarris, 1984; Pavlos and Sarris, 1984a, b, 1989; Zharkova and Khabarova, 2012, 2015;) or an interplanetary shock (see Verkhoglyadova et al., 2010; Matsumoto et al., 2015; Tessein et al., 2015; Zank et al., 2015b and references therein), the maximum reachable energy depends on energies of pre-existing (seed) particles that experience re-acceleration in the sea of magnetic islands. As shown in Zank et al. (2015a, b), the combined mechanism accelerates particles more effectively.

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