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Re-Acceleration of Energetic Particles in Large-Scale Heliospheric Magnetic Cavities

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Abstract. Case studies show that some energetic particle flux enhancements up to MeV/nuc. observed at 1 AU cannot be treated as a consequence of particle acceleration at shocks or during flares. Atypical energetic particle events (AEPEs) are often detected during crossings of magnetic cavities formed by strong current sheets of various origins in the solar wind. Such cavities confine small-scale magnetic islands (SMIs) produced by magnetic reconnection. SMIs, in turn, trap and re-accelerate energetic particles according to predictions based on the theory of Zank *et al.* describing stochastic particle energization in the supersonic solar wind via numerous dynamically interacting SMIs. AEPEs possess energies that overlap SEP events and can be an important component in understanding space weather.

Keywords. Solar wind, particle acceleration, magnetic islands, current sheets

1. Introduction

Energetic particle flux enhancements (EPFEs) observed at 1 AU in the keV-MeV energy range are predominantly treated as a phenomenon that has a distant origin. Some EPFEs are classical solar energetic particle (SEP) events, produced by particle acceleration near the Sun, which result from either solar flares or diffusive particle acceleration at shocks associated with interplanetary coronal mass ejections (ICMEs). The same diffusive shock acceleration (DSA) mechanism is usually considered to be responsible for 1 AU EPFEs observed in quiet (non-flare) times and associated with long-lived corotating interaction regions (CIRs) or randomly occurring stream interaction regions (SIRs). In this case, interplanetary shocks are formed at CIR/SIR edges further from the Earth's orbit, with energetic particles reaching the Earth from 2–3 AU as they stream towards the Sun. In both cases, the source of accelerated particles is located far from the point of observation, and so it has long been thought that the processes in the solar wind that could accelerate particles locally to substantial energies do not exist. However, an increasing number of EPFEs detected at 1 AU cannot be explained by the dominant paradigm of nonlocal particle acceleration, suggesting instead that local particle acceleration or modulation of EPFE time-intensity profiles by local structures should be considered. The problem that observers typically face, for the interpretation of such events, is the observation of a time shift in variations of EPFE time-intensity profiles that corresponds to the propagation of the thermal solar wind, and not energetic particles from a distant source (Khabarova *et al.* 2015, 2016; Khabarova & Zank, 2017; Khabarova *et al.* 2017). These energetic particle flux enhancements, called "atypical energetic particle events"

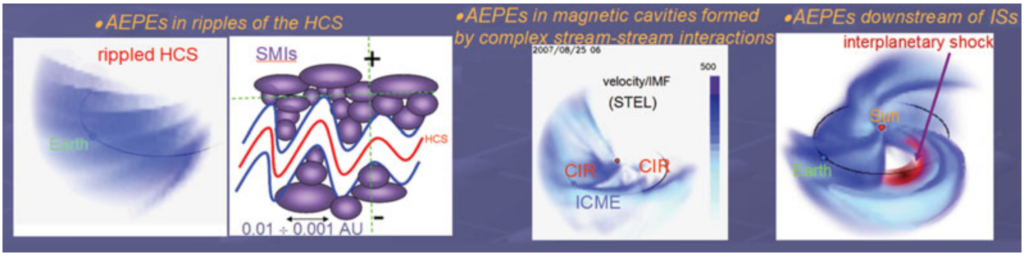

Figure 1. The three most common situations for the formation of magnetic cavities bounded by strong current sheets in the solar wind. The cavities are filled with small-scale magnetic islands (SMIs) created by magnetic reconnection. SMIs confine SMIs and trap and re-accelerate energetic particles up to several MeV, depending on the initial energy of seed particles. Left: magnetic cavities formed in ripples of the HCS. Middle: magnetic cavities produced by the interaction of CIRs and an ICME. Right: magnetic cavities formed by the interaction of an interplanetary shock with the HCS.

(AEPEs), are associated with additional mechanisms of particle acceleration that occur locally. In this paper we present examples of AEPEs that result from local particle acceleration in the solar wind, with up to MeV energies. Consequently, AEPEs should be regarded as another, if underestimated, hazardous factor in terms of the space radiation environment for space weather.

2. Atypical energetic particle events observed at 1 AU

Formation of magnetic cavities in the solar wind Recent studies of particle acceleration mechanisms in the heliosphere reveal the importance of stream-stream interactions and heliospheric current sheet (HCS) – stream interactions that often occur in the solar wind. These interactions can produce huge magnetic cavities that are bounded by strong current sheets. The cavities are usually filled with small-scale magnetic islands produced by magnetic reconnection (Wei *et al.* 2000; Khabarova *et al.* 2015, 2016). The entire system confines small scale magnetic islands and traps and re-accelerates energetic particles via a stochastic mechanism proposed by Zank *et al.* (2014, 2015) and le Roux *et al.* (2015, 2016). The mechanism of repeated particle interactions with dynamically interacting, reconnecting, merging, and contracting magnetic islands or flux ropes has been confirmed by numerous in situ observations (Khabarova *et al.* 2015, 2016, 2017). Stochastic particle acceleration by small-scale magnetic islands can yield significant particle energization, particularly when the seed particle population is initially energized by another mechanism such as, for example, DSA. As a result, crossings of magnetic cavity regions are often associated with unusual variations in the energetic particle flux up to several MeV/nuc. near the Earth's orbit.

Figure 1 illustrates some typical situations that are favourable for local particle acceleration and re-acceleration during the propagation of the solar wind from the corona to the Earth's orbit. Velocity and IMF plots reconstructed from interplanetary scintillation data (Jackson *et al.* 2013) show that the HCS often possesses a rippled form (left panel of Figure 1), and in situ observations confirm the occurrence of small-scale magnetic islands (SMIs) that fill the HCS ripples. Observations show that the heliospheric plasma sheet (HPS) region and its vicinity contain not only the embedded HCS, but also numerous small-scale structures, namely, SMIs and secondary current sheets produced presumably by magnetic reconnection. The rippled form of the HCS effectively confines SMIs and

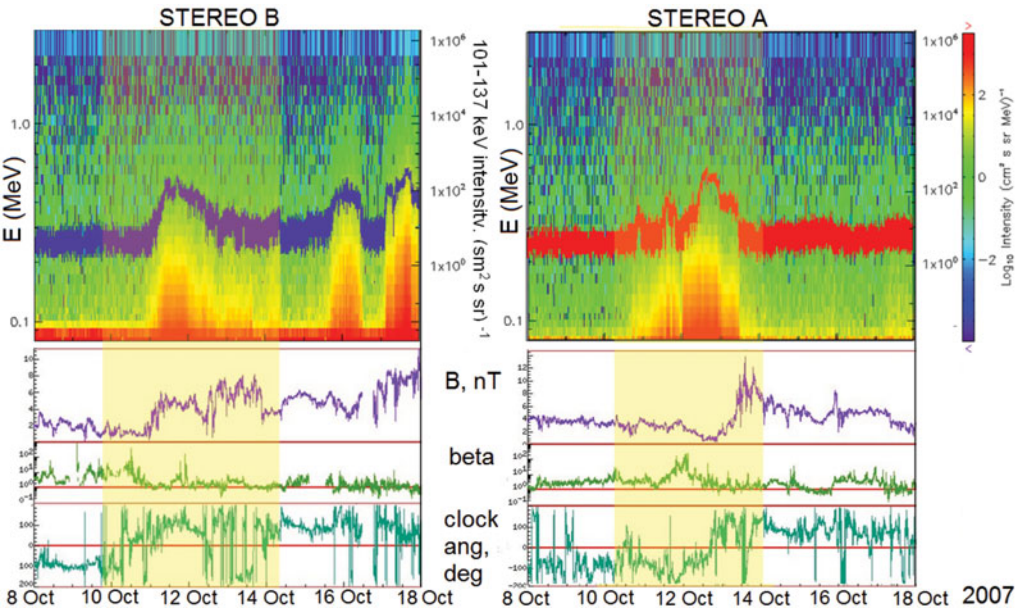

Figure 2. Crossing of the rippled HPS and associated AEPEs observed by STEREO B (left) and STEREO A (right). The separation angle is 36°. From top to bottom: energy flux of ions (omni-directional flux spectrogram) and variations in the 101–137 keV energy channel of the anti-Sun telescope; the IMF strength, the plasma beta and the IMF clock angle. The latter varies quickly back and forth many times as the spacecraft crosses numerous SMIs within the HCS ripples, and its more-or-less regular change across zero angle suggests an IMF sector crossing. The yellow stripes identify a region filled with SMIs within and around the HPS. HPS crossings are characterized by a very large plasma beta.

allows for additional particle acceleration. Magnetic cavities can also form through CIR-ICME interactions or by CIR-HCS interactions. The middle panel of Figure 1 shows the case of a CIR-ICME-CIR interaction that lead to the formation of a large magnetic cavity (Khabarova *et al.* 2016). Another example that creates magnetic cavities is interplanetary shocks (ISs). The right panel of Figure 1 illustrates an IS interacting with the HCS, which is transparent to the shocks, but is deformed. It has been shown that IS-HCS interaction intensifies magnetic reconnection and SMI production (Khabarova *et al.* 2016). The turbulent sheath region downstream of ISs may also be filled with SMIs (Zank *et al.* 2015).

AEPEs in ripples of the HCS Even non-disturbed current sheets in the solar wind represent multi-layer structures that have a tendency to reconnect and form magnetic islands (Wei *et al.* 2000; Lazarian et al, 2012; Malova *et al.* 2017). This characteristic makes it difficult to find signatures of simple Petschek-like magnetic reconnection near strong current sheets, including the HCS. However, the occurrence of reconnecting current sheets can be revealed by plasma and IMF signatures as well as particle behaviour, all of which are typical for multi-X-point magnetic reconnection (Zharkova & Khabarova, 2015; Khabarova *et al.* 2015, 2016).

Figure 2 shows STEREO multi-spacecraft observations of AEPEs during the crossing of a highly disturbed, rippled HPS filled with SMIs during October 2007. The HPS shape was slightly different when observed by STEREO Behind than at the STEREO Ahead spacecraft, which were separated by 35°. The upper panels of Figure 2 show omni-directional flux and energetic ion flux of 103–137 keV from the anti-Sun STEREO

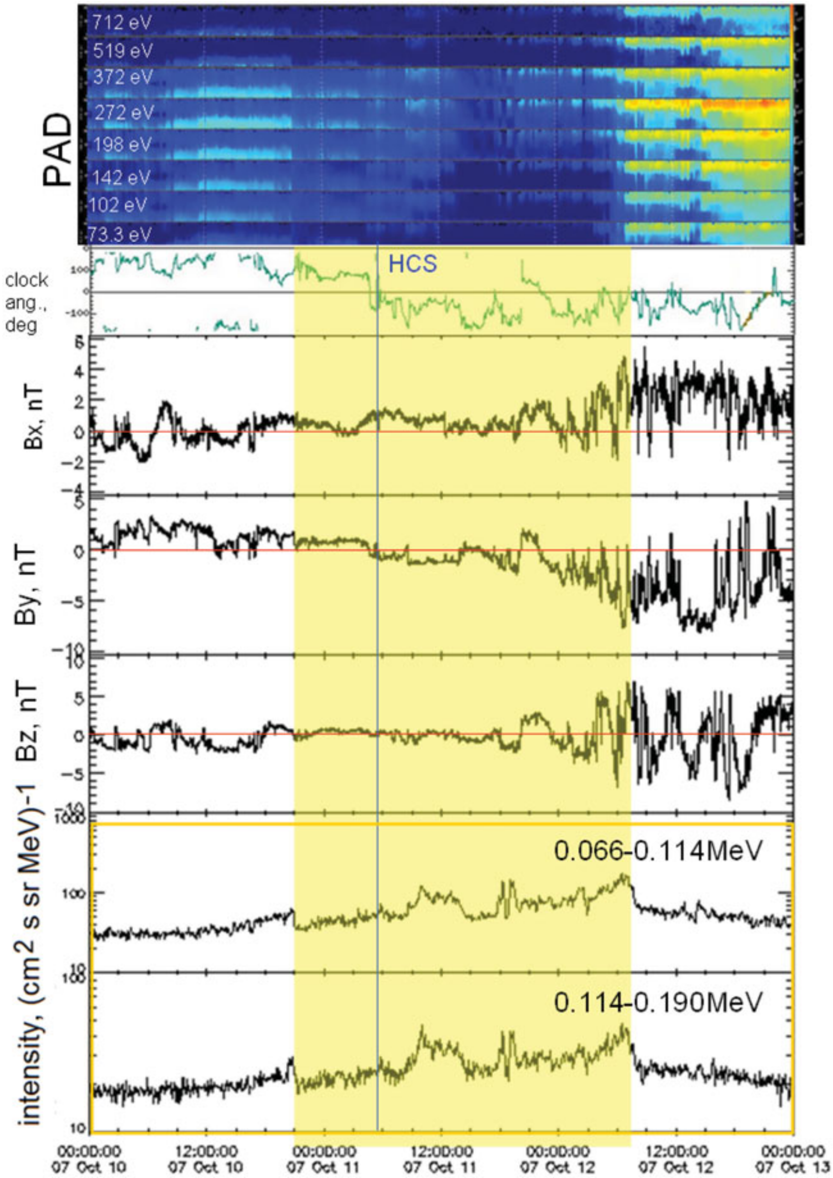

Figure 3. The heliospheric plasma sheet crossed by ACE. The yellow strip indicates both the HPS location and the occurrence of an energetic ion flux enhancement. A typical disorganized PAD (pitch-angle distribution) histogram of suprathermal electrons is seen during the HPS crossing. This can be explained by the rippled profile of the HCS/HPS and the occurrence of small- scale magnetic islands produced by magnetic reconnection in the region (see Figure 1). A corresponding energetic particle flux enhancement is shown in the bottom two panels. The vertical line shows the position of the HCS within the HPS.

telescopes. The time-intensity ion flux profiles are shifted with respect to each other, which corresponds to the peculiarities of the HPS rippled profile observed by the two spacecraft. The energetic ion flux demonstrates a clear anisotropy during the October 2007 AEPE event, i.e. time-intensity profiles were different for different viewing directions. Besides the main maximum of energetic ion flux indicated in Figure 2, additional

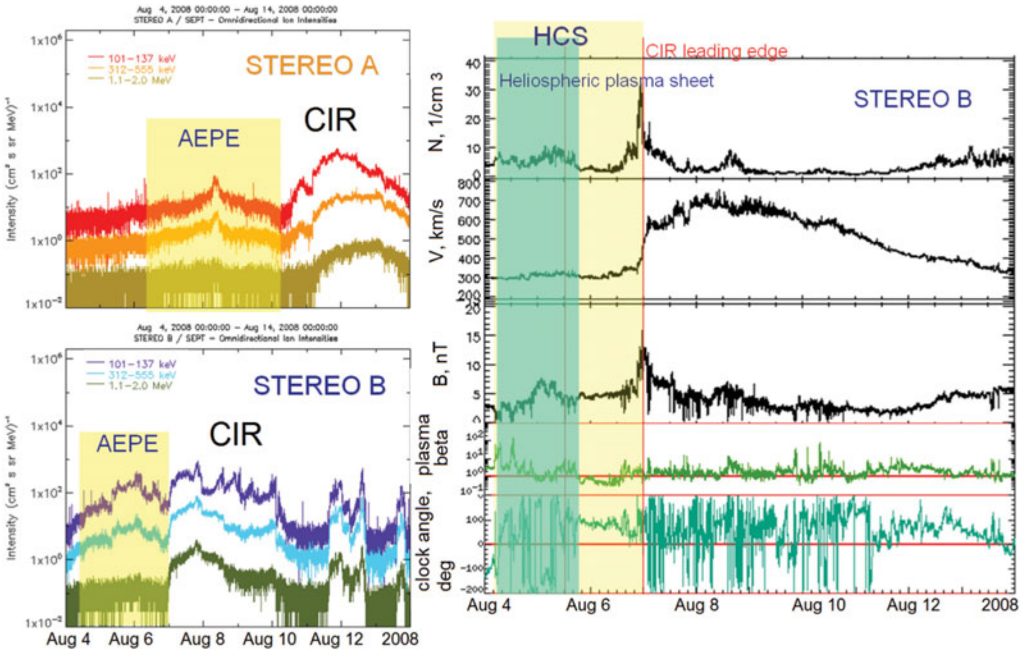

Figure 4. STEREO observations of a typical CIR (see Papaioannou *et al.* 2014), preceded by an AEPE (left panel). The separation angle between STEREO B and STEREO A was 65.5°. The AEPE is associated with a magnetic cavity formed by the heliospheric plasma sheet (HPS) (the green vertical stripe) and the leading CIR current sheet (right panel).

energetic ion flux enhancements related to pre-CIR deformation of the HCS and particle acceleration in the region filled with SMIs were detected by STEREO B after the main crossing of the HCS/HPS. However, the enhancements were not so pronounced in the STEREO A observations.

Details of the HCS crossing and corresponding AEPE observed by STEREO A in October 2007 were discussed in Zharkova & Khabarova (2015) in terms of confirmation of ongoing magnetic reconnection at the HCS embedded into the HPS. It was noted that the region filled with accelerated particles was much wider than expected from PIC modelling, which might be a signature of additional acceleration by dynamical magnetic islands surrounding the structure. Magnetic islands can be identified by the rotation of the IMF during the period of interest (not shown).

This particular crossing of the HCS was detected by the L1 spacecraft (WIND and ACE) on October 11, 2007 with a corresponding time shift (i.e., see Leif Svalgaard's list of sector boundary crossings: http://www.leif.org/research/sblist.txt). It is often thought that the behaviour of suprathermal electrons identifies the HCS as a boundary at which suprathermal elections change direction abruptly. However, there are some crossings that do not follow the dominant paradigm that suggests all energetic electrons are produced in the solar corona. Observations show that local processes can affect PADs dramatically (see the yellow strip in Figure 3). The occurrence of corresponding energetic flux enhancements associated with HPS crossings confirms the idea that SMIs bounded by strong current sheets can accelerate particles to at least 0.5 MeV.

AEPEs in magnetic cavities formed by a complex stream-stream interaction AEPEs are often observed before the arrival of regular CIRs or irregular stream interaction regions

(SIRs) SIRs to the Earth's orbit. EPFEs observed well before the leading edge of a CIR without a well-formed forward shock cannot be explained within the framework of particle acceleration via DSA at a distant propagating interplanetary shock (Zank *et al.* 2000). We have found that pre-CIR AEPEs occur mainly within confined regions filled with magnetic islands being compressed between the high-density leading edge of a CIR and the HPS (Khabarova *et al.* ApJ, 2016). Indeed, any complicated stream-CIR interactions can yield the same effect by the formation of magnetic cavities ahead of CIRs. An example is shown in Figure 4. The yellow stripes in Figure 4 identify AEPEs observed before a CIR-produced EPFE, which was subsequently detected by the well-separated STEREO B and STEREO A spacecraft (the left panel of Figure 4). The CIR can be considered typical e.g., Papaioannou *et al.* 2014. The AEPE was associated with a crossing of the magnetic cavity formed between the HPS and the CIR-leading current sheet. The HPS is identified by a green stripe in the right panel of Figure 4. The AEPE is stable and almost as large as a CIR-associated EPFE. This illustrates the idea that AEPEs can be as dangerous as EPFEs of e.g., interplanetary shock origin.

AEPEs downstream of interplanetary shocks A combination of particle acceleration via magnetic reconnection at current sheets and stochastic acceleration in dynamical small- and medium-scale magnetic islands may energize particles even more efficiently than an IS (Zank *et al.* 2015; Khabarova & Zank, 2017). Initial particle acceleration may occur in different ways, including particles accelerated via DSA at ISs combined with particle acceleration via magnetic reconnection at current sheets. During an IS interaction with the HCS (i) the IS pushes the HCS, so it is typically observed both before and after the passage of the IS, and (ii) it intensifies magnetic reconnection in the HPS. As a result, AEPEs are sometimes observed far beyond the turbulent wake of an IS, simultaneously with the HPS crossing (Khabarova *et al.* 2016). We have found observationally that particle energization at ISs ahead of an ICME can be much weaker than that of combined particle acceleration near reconnecting current sheets at the edges of a fragmented magnetic cloud within the ICME (Khabarova & Zank, 2017).

3. Summary and conclusions

This study emphasizes the need for a comprehensive systematic investigation of AEPEs produced by local particle acceleration in the solar wind. Observations show that AEPEs are not rare since magnetic cavities filled with dynamical magnetic islands are almost inevitably formed by the HCS on one side and current sheets at the edge of an ICME or CIR on the other. Energetic particles can be efficiently accelerated up to energies of several MeV within magnetic cavities that are filled with magnetic islands. AEPEs may themselves be as intense as ordinary EPFEs produced by DSA or flares. Therefore, AEPEs represent a serious and currently poorly recognized danger for spacecraft and astronauts.

The analysis of in situ multi-spacecraft data often shows that streams propagate and interact with current sheets in a very complicated fashion. This interaction frequently leads to the formation of magnetic cavities. In the presence of complicated interacting large-scale dynamical structures, relating data from distant spacecraft may offer little insight into understanding the large-scale topology of the region in which particle acceleration may occur, because even multi-point measurements cannot reconstruct the current form of a magnetic cavity, nor its origin and prior evolution. One approach that is useful utilizes interplanetary scintillation tomographic data to reconstruct the solar wind speed, density and interplanetary magnetic field, thereby providing some understanding of the 3-D structure of stream interactions that lead eventually to AEPEs.

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