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Atypical energetic particle events observed prior energetic particle enhancements associated with corotating interaction regions

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Recent studies of mechanisms of particle acceleration in the heliosphere have revealed the importance of the comprehensive analysis of stream-stream interactions as well as the heliospheric current sheet (HCS) – stream interactions that often occur in the solar wind, producing huge magnetic cavities bounded by strong current sheets. Such cavities are usually filled with small-scale magnetic islands that trap and re-accelerate energetic particles (Zank et al. ApJ, 2014, 2015; le Roux et al. ApJ, 2015, 2016; Khabarova et al. ApJ, 2015, 2016). Crossings of these regions are associated with unusual variations in the energetic particle flux up to several MeV/nuc near the Earth's orbit. These energetic particle flux enhancements called "atypical energetic particle events" (AEPEs) are not associated with standard mechanisms of particle acceleration. The analysis of multi-spacecraft measurements of energetic particle flux, plasma and the interplanetary magnetic field shows that AEPEs have a local origin as they are observed by different spacecraft with a time delay corresponding to the solar wind propagation from one spacecraft to another, which is a signature of local particle acceleration in the region embedded in expanding and rotating background solar wind.

AEPEs are often observed before the arrival of corotating interaction regions (CIRs) or stream interaction regions (SIRs) to the Earth's orbit. When fast solar wind streams catch up with slow solar wind, SIRs of compressed heated plasma or more regular CIRs are created at the leading edge of the high-speed stream. 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. Energetic ion increases have been frequently observed in association with CIR's shocks, and these shocks to be believed to accelerate ions up to several MeV per nucleon. 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, AEPEs observed for many hours before the crossing of the forward shock (or even before the leading edge of a CIR without well-formed forward shock) cannot be explained within the framework of this paradigm.

We have recently found that the effect of pre-CIR AEPEs occurs mainly as a result of the formation of a region filled with magnetic islands compressed between the high-density leading edge of a CIR and the HCS (Khabarova et al. ApJ, 2016). We show here that any kind of complicated stream-CIR interactions may lead to the same effect due to the formation of magnetic cavities in front of CIRs.

The analysis of in situ multi-spacecraft measurements often suggests very complicated ways of propagation of streams and current sheets that form magnetic cavities. In the case of multiple stream-stream interaction, comparisons of data from distant spacecraft may be puzzling and even useless for understanding the large-scale topology of the region of particle acceleration, because even several point measurements cannot reconstruct approximate forms of the magnetic cavities and shed light on the pre-history of their origin and evolution. We employ interplanetary scintillation tomographic data for reconstructions of the solar wind speed, density and interplanetary magnetic field profiles to understand a 3-D picture of stream interactions responsible for pre-CIR AEPEs.

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