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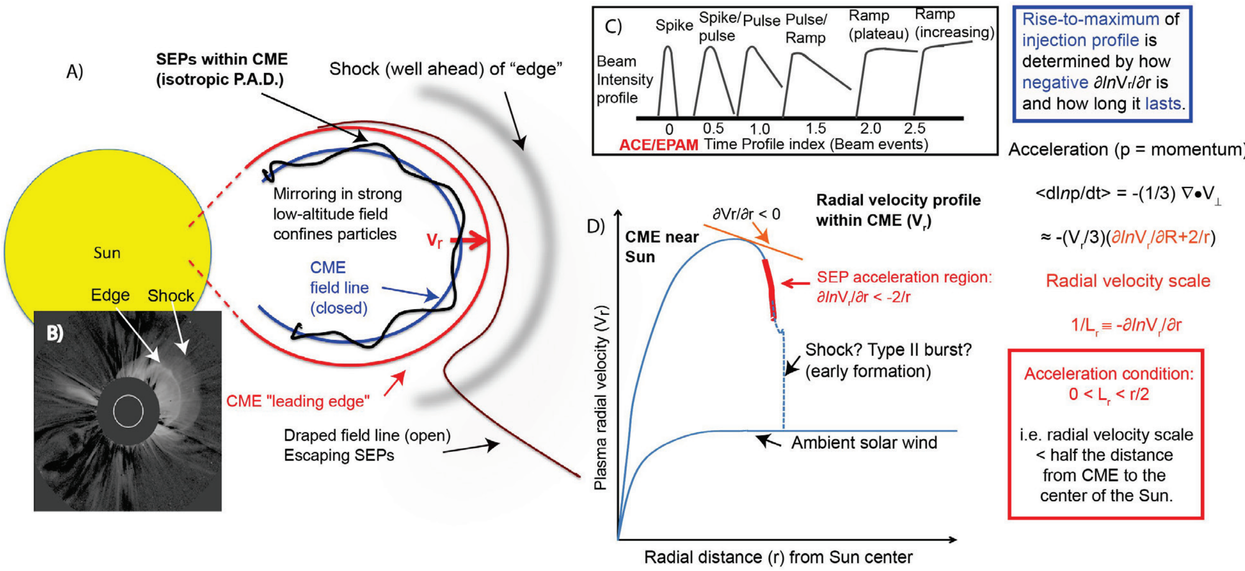
Compressive Acceleration of Solar Energetic Particles (SEPs) Within Coronal Mass Ejections (CMEs)



Analysis of the Solar Cycle 23 ACE/EPAM database revealed a continuous morphology (summarized in *Panel C*) of the injection history of ~200 magnetically well-connected SEP >40 keV electron events and associated CMEs [Haggerty and Roelof*, AIP Conf. Pro*c., **1183**, 3, 2009]. The explanation for this simple pattern may lie in a completely general expression [Roelof*, IOP J. Phys*. *Conf. Series* **642**, (2015) 012023] for the fractional time-rate-of-change of *any* individual charged particle's momentum (d*ln*p/dt), *independent* of *any* properties of the particle.

When the SEP velocity distribution is isotropic, the acceleration rate $\langle d\,ln\,p/dt\rangle = -(1/3)\nabla\cdot V_\perp$, averaged over pitch-cosine, involves only the compression (divergence) of the component of the plasma velocity *transverse* to the magnetic field ($\nabla\cdot V_\perp$). The isotropy condition is satisfied for SEPs on the closed magnetic field lines within the body of a CME, as sketched in Panel (A). There can be strong compression of the plasma behind the leading "edge" of the CME, well separated from the driven shock, as revealed in Panel B, a SOHO/LASCO white-light coronagraph image of a CME associated with an "SEP-rich" event [Kahler and Vourlidas, *JGR* **110**, A12S01, 2005]. As outlined in the equations at the right of the Figure, SEPs will be accelerated if there is a sufficiently *negative* radial gradient ($\partial V_r/\partial r < -2V_r/r$) in the radial plasma velocity. As illustrated by the generic sketch of V_r *vs.* r in Panel D, there will be a region within the nose of the CME where $\partial V_r/\partial r < 0$, because the pressure-driven velocity radial profile must always *steepen* Sunward of the CME leading edge. As to whether it steepens sufficiently for acceleration ($\nabla\cdot V_\perp < 0$), the equations reveal that the critical acceleration parameter is the radial scale ($1/L_r = -\partial\, ln V_r/\partial r$) of that radial velocity gradient.

Based on images such as Panel B, we expect small values of $L_r \sim 0.1\ R_S$ (expressed in solar radii) at the "edge". For a CME at $r=2R_S$, the formulas predict an e-folding time for momentum increase of 3.9 minutes, for *any* particle species at *any* energy (while it is in the compression region of the CME). Then the duration of the rise-to-maximum of the SEP injection profile (Panel C) will be ordered by how long the strong compression region lasts (where $\partial V_r/\partial r < -2V_r/r$). Brief compressions will produce brief "*Spikes*", longer ones will produce longer "*Pulses*", but when a strong shock forms ahead of the CME "edge", compression-accelerated particles will synergistically interact with the shock, thus extending the acceleration process well out into the solar wind, producing *"Ramps"*, the most intense and longest-lasting SEP injections observed.

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