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Focused Transport of Solar Energetic Particles in the Interplanetary Space and the Formation of the Anisotropic Beam-like Distribution of Particles in the Onset Phase of Large Gradual Events

In the onset phase of large gradual solar energetic particle (SEP) events, the first particles of a given rigidity to arrive at Earth are accelerated in the low corona, focused into a narrow cone of pitch angles by the diverging magnetic field, and transported from near the Sun to 1 AU with minimal scattering. The effects of focused transport on the evolution of the beam-like SEPs are investigated analytically. The model assumes for simplicity constant focusing length and constant pitch angle diffusion coefficient for SEPs at small pitch angles. Cross-field transport is neglected. The analytical approximation provides a reasonable representation of the spatial and pitch angle distribution of the beam-like SEPs. Assuming an instantaneous injection of SEPs near the Sun, the model naturally reproduces several features of the SEP onset profiles observed at 1AU including the spike-like time-intensity profiles with rapid rising and declining edges, the highly anisotropic nature characterized by a Gaussian pitch-angle distribution with a width that increases with time, and the similar shape but dispersed onset times of the time-intensity profiles due to the late arrival of SEPs of lower rigidities. The dependence of some observable features on the magnetic path length (Lp) between SEP injection and observation is examined analytically. The model predicts a peak intensity in the anisotropic phase with a rise-time (Tr) from event onset that approximately satisfies Tr~Lp^(-2) and a width (Epsilon) of the Gaussian pitch-angle distribution at the peak that approximately satisfies Epsilon~Lp^(-1/2). Assuming that the SEPs that are observed after the beam-like structure in a large SEP event are nearly isotropic and governed by diffusive transport in interplanetary space, we perform an illustrative calculation to demonstrate the possible origin of the isotropic phase following the anisotropic onset as a natural result of interplanetary transport of SEPs.

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