Magnetic field line random walk and solar energetic particle path lengths: Stochastic theory and PSP/ISOIS observations

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Context. In 2020 May-June, six solar energetic ion events were observed by the Parker Solar Probe/ISOIS instrument suite at ≈0.35 AU from the Sun. From standard velocity-dispersion analysis, the apparent ion path length is ≈0.625 AU at the onset of each event.
Aims. We develop a formalism for estimating the path length of random-walking magnetic field lines to explain why the apparent ion path length at an event onset greatly exceeds the radial distance from the Sun for these events.
Methods. We developed analytical estimates of the average increase in path length of random-walking magnetic field lines, relative to the unperturbed mean field. Monte Carlo simulations of field line and particle trajectories in a model of solar wind turbulence were used to validate the formalism and study the path lengths of particle guiding-center and full-orbital trajectories. The formalism was implemented in a global solar wind model, and the results are compared with ion path lengths inferred from IS IS observations.
Results. Both a simple estimate and a rigorous theoretical formulation are obtained for field-lines' path length increase as a function of path length along the large-scale field. From simulated field line and particle trajectories, we find that particle guiding centers can have path lengths somewhat shorter than the average field line path length, while particle orbits can have substantially longer path lengths due to their gyromotion with a nonzero effective pitch angle.

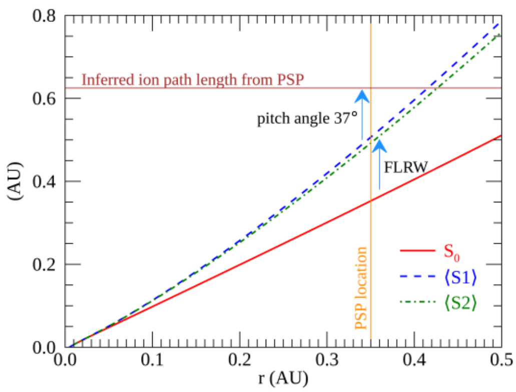

Figure: Path length S_0 for a large-scale field line from the global solar wind simulation is compared with two computations of path length of random-walking field lines. The orange vertical line indicates the approximate radial position of PSP at the time of several solar storms, and the brown horizontal line depicts the path length derived from the dispersion analysis of these events.

Conclusions. The long apparent path length during these solar energetic ion events can be explained by (1) a magnetic field line path length increase due to the field line random walk and (2) particle transport about the guiding center with a nonzero effective pitch angle due to pitch angle scattering. Our formalism for computing the magnetic field line path length, accounting for turbulent fluctuations, may be useful for application to solar particle transport in general.