

A Numerical Simulation of Charged Particle Interactions with Interplanetary Shock Waves

Robert B. Decker, January 1979
John Hopkins/Applied Physics Lab Maryland

Significant intensity enhancements of low energy (0.10–10.0 MeV) solar ions are sometimes observed several hours prior to the passage of solar flare generated shock waves by satellites located in interplanetary space. The intimate temporal association between these energetic storm particle (ESP) events and the propagating shock strongly suggests that ambient particles are accelerated locally at the shock front. A computer model has been developed to numerically simulate the combined effects of a charged particle's energization at the shock and propagation to a satellite-borne particle detector at the observation point.

A charged particle's adiabatic motion is assumed to be scatter-free along the laminar spiral interplanetary magnetic field (IMF). The interplanetary shock wave is taken as a sun-centered spherical surface that expands radially outward. The plasma and field changes across the shock obey the jump conditions for a fast mode MHD shock wave.

For a chosen shock model, a particle of specified observed kinetic energy and pitch angle at a given observation time and fixed observation point is followed numerically backward in time through the IMF and shock wave. The shock interaction is treated by solving the particle's exact orbit equations through the locally planar MHD shock discontinuity. The resultant trajectory relates the particle's phase space coordinates at the time of observation to those at a time immediately before shock interaction. The application of Liouville's theorem of the constancy of the single-particle distribution function along a dynamical phase space trajectory enables one to construct particle fluxes at the observation point by using an ensemble of numerically generated trajectories and a model of the ambient particle distribution.

The numerical trajectory results reveal that particles either reflect from or penetrate through the shock, with the reflecting particles undergoing the greatest energy increase. As seen from the shock's rest frame, the principle mechanism for particle acceleration is the particle's drift along the induced electric field as the particle crosses and recrosses the shock discontinuity. Charged particle energization at the shock increases with increasing shock speed and strength and also increases as the angle ψ_1 between the shock surface and the upstream magnetic field vector decreases.

Constant velocity spherical shocks that propagate through the nominal spiral IMF produce enhancements in the low energy proton total fluxes at 1 AU that are characterized by: (a) long (~ 4 –8 hrs from half-maximum to

maximum), steady pre-shock rises to a peak followed by an abrupt decrease at the shock passage; (b) highly field-aligned pre-shock flux anisotropies directed away from the approaching shock; (c) weak post-shock anisotropies nearly perpendicular to the the magnetic field and directed away from the receding shock; (d) a steadily softening pre-shock energy spectrum that is steepest just before the shock passage and is slightly softer than the ambient distribution after the shock passage.

Spherical shocks that move through the nominal spiral IMF and decelerate between 0.1 and 1.0 AU produce pre-shock flux enhancements that are larger and more rounded than those due to constant velocity shocks. Nonspherical shocks or spherical shocks that pass through a fluctuating IMF are extremely effective particle accelerators when the angle ψ_1 is relatively small. This situation can produce large pre-shock flux enhancements or isolated spike-like enhancements several hours prior to the shock arrival. Both the duration and the magnitude of the pre-shock flux enhancement increase as the radial location of the observation point is increased beyond 1 AU.