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Semi-transparent shock model for major solar energetic particle events

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Production of solar energetic particles in major events typically comprises two stages: (i) the initial stage associated with shocks and magnetic reconnection in solar corona and (ii) the main stage associated with the CME-bow shock in solar wind. The coronal emission of energetic particles from behind the interplanetary shock wave continues for about one hour , being not shielded by the CME shock in solar wind and having the prompt access to particle detectors at 1 AU.

On occasion of two well-separated solar eruptions from the same active region, the newly accelerated solar particles may be emitted well behind the previous CME, and those solar particles may penetrate through the interplanetary shock of the previous CME to arrive at the Earth's orbit without significant delay, which is another evidence that high-energy particles from the solar corona can penetrate through travelling interplanetary shocks.

Diffusive shock acceleration is fast only if the particle mean free path near the shock is small. The small mean free path (high turbulence level), however, implies that energetic particles from coronal sources could not penetrate through the interplanetary shock, and even the particles accelerated by the interplanetary shock itself could not escape to its far upstream region. If so, they could not be promptly observed at 1 AU. However, high-energy particles in major solar events are detected well before the shock arrival at 1 AU. The theoretical difficulty can be obviated in the framework of the proposed model of a "semitransparent" shock.

As in situ plasma observations indicate, the turbulence energy levels in neighboring magnetic tubes of solar wind may differ from each other by more than one order of magnitude. Such an intermittence of coronal and solar wind plasmas can affect energetic particle acceleration in coronal and interplanetary shocks. The new modeling incorporates particle acceleration in the shock front and the particle transport both in parallel to the magnetic field and in perpendicular to the magnetic field directions. The modeling suggests that the perpendicular diffusion is always essential for the energetic particle production, because particles can be accelerated in tubes with a high turbulence level and then escape to far upstream of the shock via neighboring, less turbulent tubes.

We have modeled both the transmission of high-energy (>50 MeV) protons from coronal sources through the interplanetary shock wave and the interplanetary shock acceleration of $\sim$1-10 MeV protons with subsequent transport to far upstream of the shock. The modeling results imply that presence of the fast transport channels penetrating the shock and the cross-field transport of accelerated particles to those channels may play a key role in the high-energy particle emission from distant shocks and can explain the prompt onset of major solar energetic particle events observed near the Earth's orbit.