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Solar Protons above 500 MeV in the Sun's Atmosphere and in Interplanetary Space

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At least two distinct acceleration mechanisms produce energetic particles at or near the Sun: (1) acceleration at coronal sites of magnetic reconnection, generally associated with flares and (2) acceleration at shocks driven by fast coronal mass ejections (CMEs). Both mechanisms can accelerate protons to well beyond 500 MeV. Moreover, when a very large solar energetic particle (SEP) event is observed in interplanetary space, both a large flare and the launch of a fast CME are observed nearly simultaneously (unless the flare occurs behind a limb). Numerous studies have tried to sort out how these two phenomena contribute to the energetic particle population. To date, there is no consensus on this issue, particularly at the highest energies, where the release of particles from the neighborhood of the Sun generally persists for only a short period of time. Although the maximum of Cycle 24 has been notably deficient in producing high-energy SEPs, new instrumentation has provided powerful new insights into these questions. Fermi provides routine measurements of solar gamma-rays above 100 MeV, from which the number of >500 MeV protons interacting in the solar-atmosphere can be deduced, separately in the impulsive phase of the flare (lasting minutes and coincident with hard x-ray emission) and in the frequently observed extended phase (which can persist for many hours and whose origin is under debate). Simultaneously, other satellites and ground-based neutron monitors provide measurements of these high-energy protons in interplanetary space, the modeling of which is greatly strengthened by the STEREO's observations of the large-scale heliospheric distribution of SEPs. We report results for seven events in which the time-integrated number of >500 MeV protons at the Sun and in interplanetary space have been independently extracted. We find that >500 MeV protons in the impulsive phase of the flare typically constitute a percent or less of the protons in IP space, without any clear correlation to the number of >500 MeV protons in interplanetary space. By contrast, the number of >500 MeV protons in the extended phase of the flare is typically $\sim$5-10% of the number in interplanetary space and is well correlated with it. These results suggest that (1) the impulsive phase of the flare does not make a significant contribution to the interplanetary population at these very high energies and (2) the extended-phase gamma-ray emissions are likely due to shock-accelerated protons precipitating down onto the solar atmosphere.