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Acceleration of Suprathermal protons near an Interplanetary Shock

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Context. Interplanetary collisionless shocks are known to be sources of energetic charged particles up to hundreds of MeV. However, the underlying acceleration mechanisms are still under debate.
Aims. We determine the properties of suprathermal protons accelerated by the interplanetary shock on 2021 November 3 with the unprecedented high-resolution measurements by the SupraThermal Electron Proton sensor of the Energetic Particle Detector onboard the Solar Orbiter spacecraft, in order to constrain the potential shock acceleration mechanisms.
Methods. We first reconstruct the pitch-angle distributions (PADs) of suprathermal protons in the solar wind frame. Then, we study the evolution of the PADs, flux temporal profile and velocity distribution function of this proton population close to the shock and compare the observations to theoretical predictions.
Results. We find that the suprathermal proton fluxes peak ∼12 to ∼24 seconds before the shock in the upstream region. The proton fluxes rapidly decrease by ∼50% in a thin layer (∼8000 km) adjacent to the shock in the downstream region and become constant further downstream. Furthermore, the proton velocity distribution functions in the upstream (downstream) region fit to a double power law, $f(v) \propto v^{-\gamma}$, at ∼1000 − 3600 km s^{-1}, with a γ of ∼3.4 ± 0.2 (∼4.3 ± 0.7) at velocities (v) below a break at ∼1800 ± 100 km s^{-1} (∼1600 ± 200 km s^{-1}) and a γ of ∼5.8 ± 0.3 (∼5.8 ± 0.2) at velocities above. These indices are all smaller than predicted by first-order Fermi acceleration. In addition, the proton PADs show anisotropies in the direction away from the shock in the close upstream region and become nearly isotropic further upstream, while downstream of the shock, they show a clear tendency of anisotropies towards 90° PA.
Conclusions. These results suggest that the acceleration of suprathermal protons at interplanetary shocks are dynamic on a time scale of ∼10 seconds, i.e., few proton gyro-periods. Furthermore, shock drift acceleration likely plays an important role in accelerating these suprathermal protons.