URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Ion acceleration efficiency at the Earth's bow shock: observations and simulation results

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Collisionless shocks are some of the most energetic plasma phenomena in the universe and are abundant in astrophysical plasmas. Particles like galactic cosmic rays and solar energetic particles are accelerated at shocks in a process known as diffusive shock acceleration (DSA). The Earth's collisionless bow shock is despite its small size capable of accelerating ions through DSA and is often used as a plasma laboratory to study shock physics in space. Here we study and quantify ion acceleration at the bow shock with observations from NASA's Magnetospheric Multiscale (MMS) satellites and in a global hybrid-Vlasov Vlasiator simulation. From the MMS observations, we find that quasi-parallel shocks are more efficient at accelerating ions. There, up to 15% of the available energy goes to accelerating ions above 10 times their initial energy. Above a shock angle of $\sim 60^\circ$, essentially no energetic ions are observed downstream of the shock. We find that ion acceleration efficiency is significantly lower when the shock has a low Mach number ($M_A < 6$). There is little or no Mach number dependence for higher Mach numbers. We also find that ion acceleration is lower on the flanks of the bow shock than at the sub-solar point regardless of the Mach number. Using MMS's high cadence field and plasma measurements from one quasi-parallel bow shock crossing, we find that short large amplitude magnetic structures (SLAMS) are important for the dynamics of high-energy ions. The SLAMS trap backstreaming energetic ions and convect them back toward the shock. To complement the observations, we perform a global hybrid-Vlasov simulation with realistic solar wind parameters and shape and size of the bow shock. We find that the ion acceleration efficiency in the simulation shows good quantitative agreement with the MMS observations. The simulation shows that the acceleration efficiency decreases after a certain time a field line has been connected to the bow shock. This indicates that ions first undergo explosive and patchy acceleration and then settle into a more stable state with more moderate acceleration efficiency. The results presented here can help quantifying ion acceleration for a wide parameter range applicable for shocks in the heliosphere and in astrophysical settings.