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Conditions for ion acceleration at collisionless shock waves

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Collisionless shock waves are highly efficient ion accelerators through diffusive shock acceleration (DSA). Shocks are found in simulations and spacecraft observations to be more efficient at quasi-parallel shock geometries, although quantitative experimental studies are lacking. We investigate the conditions for ion acceleration using 136 crossings of the Earth's bow shock by the four Magnetospheric Multiscale (MMS) satellites. We determine bow shock parameters like Mach numbers and shock angle by using upstream solar wind monitor spacecraft. Using MMS, we quantify ion acceleration efficiency of the shock and the dependence on shock parameters. We find that quasi-parallel shocks are more efficient at accelerating ions where up to 10% of the energy density is in energetic ions. Energetic ions are defined as having energies greater than 10 times the solar wind energy. Above a shock angle of $\sim 60^\circ$, essentially no energetic ions are observed in any of the events. We find that ion acceleration efficiency is significantly lower for low-Mach-number ($M_A < 6$) shocks while there is no Mach number dependence above this. 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. We also study in detail one of the shock crossing with a relatively high acceleration efficiency using the high-cadence plasma and field measurements of MMS. We find that short large amplitude magnetic structures (SLAMS) are important for the ion dynamics. Solar wind ions are reflected off the SLAMS, which causes an initial acceleration. Furthermore, the highest densities of energetic ions are observed at the SLAMS rather than the shock itself. This is because the SLAMS trap back-streaming energetic ions and convect them back toward the shock, which is important for the acceleration process since this increases the time the high-energy ions spend close to the shock.