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Multi-Fluid Nature of the Termination Shock and the Slow Bow Shock: Implications for Particle Acceleration

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First, we give a brief overview of the theory of shocks and critical surfaces in hot multi-component plasmas in the multi-fluid Hall MHD formalism. The mode-splitting of fast magnetosonic waves gives rise to particle acceleration at discontinuities, where the minority ion species are accelerated by the shock electric field of the majority species. The mode-coupling between different magnetosonic modes results in nonlinear quasi-stationary waves, solitons or oscillitons, where the phase and group velocities coincide. The solar wind is a typical example of multi-ion plasmas where thermal solar wind ions and hot pickup ions comprise two separate particle populations. The two ion fluids are fully coupled through the magnetic field upstream of the termination shock, where the solar wind bulk flow is quasi-perpendicular to the Parker spiral-like heliospheric magnetic field. However, in the heliosheath, where the ion flows start to divert from the radial direction, pickup ions and thermal solar wind ions become decoupled in the parallel direction, resulting in different ion flow velocities. This multi-fluid nature of the solar wind cannot be captured in current single-fluid MHD models of the heliosphere. Our new multi-ion Hall MHD model of the heliospheric interface treats pickup ions, thermal solar wind ions and electrons as separate fluids.
Next, we present a multi-fluid Hall MHD simulation of the termination shock, which is able to capture even finite gyroradius effects on ion scales due to the additional terms in the momentum and energy equation. Our simulation confirms the theoretically predicted quasi-stationary oscilliton wave mode downstream of the termination shock, which is in reasonable agreement with Voyager 2 observations. We suggest that the suprathermal tail of the ion distribution downstream of the termination shock is due to the nonlinear growth of the oscilliton mode, which can create a kappa distribution out of a two-temperature bi-Maxwellian distribution through the dissipation of wave energy into thermal energy.
We also discuss the possible existence of a slow magnetosonic bow shock ahead of the heliosphere [Zieger et al., GRL, 2013], provided that the interstellar wind is subfast and superslow, as suggested by recent IBEX measurements [McComas et al., Science, 2012], and the angle between the interstellar bulk flow velocity and the interstellar magnetic field is less than 45 degrees [Opher et al., Nature, 2009]. The spatially localized quasi-parallel slow bow shock creates a magnetic trapping region in the outer heliosheath, which could accelerate trapped high-energy cosmic ray particles through cross field diffusion.
Finally, we point out the similarities between shocks and plasma boundaries in different multi-component space plasma environments like the heliosheath, cometosheaths, and the magnetic pileup region ahead of non-magnetized planets (e.g. Mars).