Electron-Beam Instabilities in the Foreshock of High-Mach-Number Oblique Shocks

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Motivated by simulations of non-relativistic high-Mach-number shocks in supernova remnants, we investigate the evolution of relativistic electron beams in the extended foreshock of oblique shocks. Starting with the PIC simulation of a shock with $M_A = 30$ and $\vartheta_{Bn} = 60°$, we analyse the waves and phase-space distributions in two regions of the electron foreshock, where shock-reflected electrons interact with the incoming background electrons and excite characteristic instabilities.

Far from the shock front, the upstream plasma is dominated largely by electrostatic waves. But in the near-upstream region of the foreshock, in which the beam of shock-reflected electrons is denser by an order of magnitude, oblique electromagnetic waves dominate the plasma.

In order to isolate the excitation processes of these waves and determine where in the foreshock they are generated, we study which instabilities are driven unstable in periodic simulations with electron distributions as we observe them in the two foreshock regions. A comparison with a linear dispersion analysis proves that the electrostatic waves in the far upstream result from the electron-acoustic instability, which also operates in the near-upstream region.

On the other hand, the electromagnetic fluctuations with a typical propagation angle of around 55° are only visible in the simulation with near-upstream conditions. The linear dispersion relation of this system predicts the growth of a mode with the same characteristics: oblique whistler waves with a large electrostatic component and a small electromagnetic component with right-hand circular polarisation and left-handed helicity of the magnetic fieldlines. This mode is gyroresonant with electrons and is expected to scatter them rapidly perpendicular to the background magnetic field, but it saturates too early to significantly heat the electrons in our simulation.