

Mach number dependence of ion-scale kinetic instabilities at collisionless perpendicular shocks

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We investigate kinetic plasma instabilities at the collisionless shock using linear theory and nonlinear Particle-in-Cell (PIC) simulations. We focus on the Alfvén-ion-cyclotron (AIC), mirror, and Weibel instabilities, which are all driven unstable by the effective temperature anisotropy caused by the shock-reflected ions within the transition layer of a strictly perpendicular shock, in which the upstream magnetic field is perpendicular to the shock normal. We conduct linear dispersion analysis with a homogeneous plasma model to mimic the shock transition layer by adopting a ring distribution with a finite thermal spread for the velocity distribution of the reflected ion component. We find that, for the propagation parallel to the ambient magnetic field, the AIC instability at low to modest Alfvén Mach numbers tends to transition to the Weibel instability at high Mach numbers. The instability property is, however, also strongly affected by the sonic Mach number. We conclude that the instability at a strong shock with Alfvén and sonic Mach numbers both in excess of 20-40 may be considered Weibel-like in the sense that the growth rate is much larger than the ion gyrofrequency. Two-dimensional PIC simulations find that the oblique mirror instability is not the dominant instability at high Mach numbers and confirm the linear theory predictions for the parallel mode. We find that the saturation level of the Weibel-like instability is consistent with a limit imposed by the particle trapping rather than the Alfvén current limit. However, the large growth rate and the short wavelength of the instability suggest that the homogeneous model with the gyrotropic reflected ion distribution may not necessarily be a quantitatively correct model for the realistic shock transition layer.

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