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Whistler wave generation and its role for electron acceleration at quasi-perpendicular shock

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Observations suggest that supernova remnant shocks (SNRs) are the primary accelerators generating galactic cosmic rays. The standard frame- work for understanding how SNRs accelerate cosmic rays is known as diffusive shock acceleration (DSA), which can naturally produce a power-law energy spectrum of nonthermal particles in SNR shocks from synchrotron X-ray observation. However, DSA faces challenges with efficiently accelerating low-energy particles, known as the injection problem. Stochastic shock drift acceleration (SSDA) presents a promising solution, suggesting that the high-frequency whistler waves in the shock transition region can scatter and accelerate low-energy electrons, aligning well with observations [1]. However, the origins of these waves in transition regions remain elusive. Understanding the mechanisms behind high-frequency wave generation is critical to resolving the electron injection problem.

In this work, we aim to investigate the generation mechanisms of waves, particularly whistler waves, in shock transition regions by conducting a linear instability analysis using advanced models of electron velocity distributions.

The first step is to model the electron velocity distribution in the shock transition region. Previous studies [2,3] typically used simplified models, such as the superposition of Maxwellian distributions, to analyze wave generation. However, as suggested by recent simulations and observations, the electron velocity distribution is more complex. In our approach, we apply Liouville mapping to model the distribution better. We first assume the upstream and downstream electron distributions under a steady magnetic field profile. The local distribution in the shock is derived from these upstream and downstream distributions through Liouville mapping. We also consider partial pitch-angle diffusion to take into account the non-adiabatic effect. This distribution captures key local features, such as mirror-reflected electrons and temperature anisotropy due to magnetic field compression, which serve as important sources of free energy that drive instabilities and wave generation in the shock environment. This approach gives a more sophisticated distribution model that achieved better agreement with observations [4] compared to traditional models.

Then the next step is to perform a linear analysis based on the derived distribution. Previous studies often preferred simplified distributions because the standard method for solving dispersion relation is typically applicable only to relatively simple distribution like the bi-Maxwellian distribution. In our case, the standard way is no longer suitable. Therefore, we conduct a linear analysis using the semi-analytical method [5], which is applicable to an arbitrary distribution, to calculate wave growth/damping rates. Applying Earth's bow shock parameters [6], our model observed multiple instabilities in both upstream and shock transition regions. The transition region exhibited stronger instabilities due to its complex electron distribution, driving whistler wave generation in quasi-parallel propagation. Predicted dominant frequencies ranged from tens to hundreds of Hz, consistent with spacecraft observations (~300 Hz), validating our model. These high-frequency waves play a critical role in confining electrons within the shock region, enabling their pre-acceleration.

This framework establishes a valid model linking shock parameters to wave generation. Future studies will focus on incorporating simulation and observational data to refine our model and get a deeper understanding of the mechanisms responsible for electron acceleration in shock environments. On the other hand, electron acceleration and wave power are influenced by key shock parameters, such as the Alfvén Mach number in the de Hoffmann-Teller frame (HTF) [1]. Therefore, we plan to conduct a thorough investigation into wave growth rates within shock regions, analyzing how frequency and amplitude vary with these parameters. By integrating wave generation dependencies with SSDA, we aim to predict which shocks can sufficiently accelerate low-energy particles into DSA cycles.

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