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Resonant and nonresonant wave-particle interactions in the mirror and firehose instabilities

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In space plasmas, it is common to observe thermal pressure anisotropies, where the particle temperature—and thus the thermal pressure—measured perpendicular to the local magnetic field differs significantly from that measured parallel to it. Such temperature anisotropies can drive various plasma instabilities[1-5]. For example, when the perpendicular temperature exceeds the parallel temperature, this condition can excite electromagnetic ion cyclotron and mirror instabilities. Conversely, when the parallel temperature is greater than the perpendicular temperature, it can generate parallel and oblique firehose instabilities. Among these instabilities, the mirror and oblique firehose instabilities are widely believed to act as dominant regulatory mechanisms[6-7], constraining the temperature distribution in space plasma environments such as the solar wind.

However, a long-standing debate persists regarding the primary source of free energy responsible for exciting these instabilities, particularly the relative contributions of nonresonant versus resonant particles. For example, both MHD and kinetic plasma models can predict the excitation of the mirror instability: MHD models attribute the excitation to nonresonant particle behavior, whereas kinetic models highlight the role of resonant particles.

To clarify the respective roles of nonresonant and resonant particles in instability excitation, we apply a recently developed energy transfer rate method[8-9]. This approach can quantitatively evaluate the contributions of resonant and nonresonant wave–particle interactions to the growth of mirror and firehose instabilities.

Our analysis provides a clearer understanding of the mechanisms driving these instabilities. In particular, we show that nonresonant particles supply the free energy to excite the mirror instability. We also show the comprehensive wave-particle interaction scenario in the oblique firehose instability. These findings improve our understanding of the origins of these instabilities and establish a theoretical framework for investigating wave–particle interaction processes using in-situ satellite measurements in space plasma environments.

References

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