7th Asia-Pacific Conference on Plasma Physics, 12-17 Nov, 2023 at Port Messe Nagoya

Direct observations of energy transfer from resonant electrons to whistler-mode waves in magnetosheath of Earth

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The interaction between electromagnetic fields and charged particles is central to collisionless plasma dynamics in space. Right-hand polarized electromagnetic whistler-mode waves have been the subject of many studies due to their efficient pitch-angle scattering and acceleration of electrons and play important roles in various regions (solar wind, shock waves, and planetary magnetospheres). A nonlinear wave-particle interaction theory for coherent large amplitude waves predicts that electrons around cyclotron resonance velocity exhibit nongyrotropy due to the phase trapping motion in the presence of an appropriate magnitude of spatial gradient of magnetic field intensity and/or temporal variation of the wave frequency [1]. The nongyrotropic electron velocity distribution functions can exchange energy and momentum with waves. Observational identification of such nongyrotropic electron velocity distribution functions, however, has been extremely difficult due to the short time scale of resonant electron dynamics. In this study, we show an observational result of nongyrotropic electron velocity distribution functions close to the cyclotron resonance velocity with ultra-high temporal resolution data obtained by the Magnetospheric Multiscale spacecraft (MMS) during large-amplitude whistler-mode wave events around the magnetosheath-side separatrix of the dayside magnetopause reconnection and the magnetosheath near the magnetopause. With measurements by the Fast Plasma Investigation Dual Electron Spectrometer (FPI-DES) and the search-coil magnetometer (SCM), we identified electron flux hole events that induce wave growth; a hole at an appropriate relative phase angle to the whistler-mode wave magnetic field appeared only close to the cyclotron resonance velocity. The Electron Drift Instrument also continuously detected modulation of electron flux near the cyclotron resonance velocity, which is consistent with the hole identified by FPI-DES measurements. During the time intervals, the magnitude of the gradient of magnetic field intensity along the magnetic field line, which was derived by four-spacecraft measurements, was consistent with an appropriate magnitude to cause phase trapping motion of resonant electrons. The nonlinear growth rate, which is calculated with observed resonant currents, became ~$0.005\Omega_{ce}$ (0.02–0.07ω), where ω is the angular frequency of the wave and Ω_{ce} is the electron cyclotron angular frequency. These results provide direct evidence of locally ongoing nonlinear wave-particle interaction between whistler-mode waves and cyclotron resonant electrons due to phase trapping motion [2]. Such nonlinear wave growth, which has been discussed mainly for wave growth in the magnetosphere, probably plays a role also around the magnetic reconnection and in the magnetosheath.

References

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