# Direct measurements of energy exchange between EMIC waves and ions observed by the MMS spacecraft in the magnetosphere

*Naritoshi Kitamura[1], Masahiro Kitahara[2], Masafumi Shoji[3], Yoshizumi Miyoshi[3], Yuto Katoh[2], Satoko Nakamura[4], Hiroshi Hasegawa[1], Yoshifumi Saito[1], Shoichiro Yokota[1], Barbara L Giles[5], Thomas E Moore[5], Daniel J Gershman[5,6], Craig J Pollock[7], Adolfo F Vinas[5], Christopher T Russell[8], Robert J Strangeway[8], Stephen A Fuselier[9], James L Burch[9]

1. Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 2. Department of Geophysics, Graduate school of Science, Tohoku University, 3. Institute for Space-Earth Environmental Research, Nagoya University, 4. Research Institute for Sustainable Humanosphere, Kyoto University, 5. NASA Goddard Space Flight Center, 6. University of Maryland, 7. Denali Scientific, 8. Institute of Geophysics and Planetary Physics, University of California, Los Angeles, 9. Southwest Research Institute

Wave particle interactions, which cause particle acceleration and pitch-angle scattering, are a fundamental energy exchange process in collisionless space plasma. The four MMS (Magnetospheric Multiscale) spacecraft traversing the duskside magnetosphere measured electromagnetic ion cyclotron (EMIC) waves from ~12:18 to 12:22 UT on 1 September 2015. In this period, the burst ion data from Fast Plasma Investigation Dual Ion Spectrometer (FPI-DIS) with a time resolution of 150 ms are available. Although electric field data from probes were not usable to analyze the wave electric field due to the fluctuation with a frequency of ~0.1 Hz likely caused by ion beams from Active Spacecraft Potential Control (ASPOC) neutralizes, cold ions with energies less than 300 eV are detected by FPI-DIS due to the large magnitude of the electric field drift caused by the wave electric fields under weak background magnetic fields (~22-40 nT). Since the frequency of the EMIC waves were lower than ~1/5 of the proton gyro frequency, perpendicular electric fields were derived from the cross product of the negative cold ion velocity and the magnetic field. Using these data, we investigate energy exchange rates between EMIC waves and ions. To directly detect energy exchange between EMIC waves and energetic ions, we apply the method of Wave-Particle Interaction Analyzer (WPIA) that that is to calculate the Joule heat from dot product between the wave electric field (perpendicular component in the frequency range of 0.05-0.15 Hz in the present case) and ion resonant currents [*Fukuhara et al.*, 2009; *Katoh et al.*, 2013]. Near the beginning of the wave event, 15-second averages of the dot product reached -0.4 $pW/m^3$ for ions with pitch angles of 33.25-78.75 degrees and energies of 14-30 keV. The negative value of the power in this pitch angle range indicates that the perpendicular energy of ions was being transferred to the EMIC waves propagating toward higher latitudes at the MMS location by cyclotron resonance. Ion data show non-gyrotropic distributions around the resonance velocity, and that is consistent with the nonlinear trapping of protons by the wave and formation of an electromagnetic proton hole [e.g., *Omura et al.*, 2010]. Near the beginning of the same wave event, strongly phase bunched $He^+$ ions up to ~2 keV with pitch angles slightly larger than 90 degrees were also detected. The dot product of the wave electric fields and $He^+$ ion currents showed a positive value. This indicates that the $He^+$ ions were being accelerated by the electric field of the EMIC waves. The observed feature of $He^+$ ions is consistent with non-resonant interaction with the wave but is inconsistent with cyclotron resonance. In this event, we could measure energy transfer from hot ions to the EMIC wave and from the wave to $He^+$ ions for the first time.

Keywords: wave particle interaction, EMIC wave, MMS spacecraft, WPIA, heavy ion, particle acceleration

 