Direct measurements of energy transfer from hot protons to EMIC waves in ULF waves at the outer magnetosphere

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We report the temporal variation of energy transfer from hot anisotropic protons to electromagnetic ion cyclotron (EMIC) waves during a compressional ULF wave event using the data obtained by the four MMS (Magnetospheric Multiscale) spacecraft traversing the duskside outer magnetosphere. For the ULF wave, the period was about 2-5 minutes (Pc5 frequency range), and the magnetic and ion pressures were in antiphase, such that the total pressure remained almost constant. To derive the propagation velocity of the ULF wave, we applied timing method to the filtered (0.001-0.05 Hz) magnetic field data from the four spacecraft. The derived phase velocity was ~40 km/s that was comparable to $\mathbf{E} \times \mathbf{B}$ drift velocities. Thus, they were mirror mode type structures that have zero frequency in the plasma rest flame and we can therefore investigate the spatial size of the structure from the period and the velocity. The burst ion data from Fast Plasma Investigation Dual Ion Spectrometer (FPI-DIS) with a time resolution of 150 ms are available for two of the EMIC wave events during the ULF wave. To directly detect energy transfer from hot protons to EMIC waves, we apply the Wave-Particle Interaction Analyzer (WPIA) method to the data. The energy transfer rate by cyclotron resonance was calculated as the dot product of the wave component of the perpendicular electric fields and ion current perpendicular to the magnetic field around the resonance velocity which is called the resonant current. The energy transfer rate peaked at the local minima of magnetic field intensity, which corresponds to the maxima of the ion pressure in the compressional ULF wave. This result indicates that the spontaneous EMIC wave generation is affected by ULF waves, and preferential locations for the cyclotron resonant energy transfer are magnetic field intensity troughs with the spatial size of only ~3 times of hot proton gyro-radius. In these troughs, the relatively low resonance velocity owing to small magnetic field intensities and the enhanced hot proton flux can contribute to the enhanced energy transfer from hot protons to EMIC waves by cyclotron resonance.

Keywords: MMS spacecraft, EMIC wave, Wave-particle interaction

