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Relativistic Acceleration of Energetic Protons by Electromagnetic Ion cyclotron Waves in the Inner Jovian Magnetosphere

Yoshiharu Omura[1], Danny Summers[2], and Yi-Kai Hsieh[1]
[1] Research Institute for Sustainable Humanosphere, Kyoto University
[2] Memorial University of Newfoundland
e-mail (speaker):omura@rish.kyoto-u.ac.jp

We present a physical mechanism for generating GeV protons in the Inner Jovian Magnetosphere [1], which may contribute to formation of the proton radiation belts. The mechanism consists of two nonlinear processes called anomalous trapping and relativistic turning acceleration (RTA) and involves a special form of nonlinear wave trapping by electromagnetic ion cyclotron (EMIC) waves. Necessary conditions for anomalous trapping and RTA include a near-equatorial source of EMIC waves, strong wave amplitudes (of the order of a few percent of the background magnetic field strength), and a source of protons of sufficiently high energy. The anomalous trapping [2] occurs for energetic protons at low pitch angels, and it transports most of protons at low pitch angels to the energy and pitch angles satisfying the cyclotron resonance condition, while it is limited in the parameter space with a relatively large background magnetic field. Then the RTA occurs when the equator-ward moving protons encounter pole-ward moving EMIC waves, and they become entrapped and undergoes a turning motion due to increasing kinetic energy. The trapped ions then move poleward in the same direction as the waves and eventually become detrapped, but during the turning motion the ions undergo significant acceleration. We rigorously verify this process by providing the theory of nonlinear interactions between relativistic protons and coherent EMIC waves. The RTA process has been previously established for the analogous whistler mode wave-electron interaction [3]. We carry out test particle simulations for protons at $r = 2\ R_J$ (where R_J = Jovian radius) interacting with EMIC waves of amplitude B_w = 0.02 B_{0eq} where B_{0eq} = background magnetic field strength at the equator). We confirm that a large portion of test protons experience RTA and that some protons of critical energy 240 MeV can be accelerated to 10GeV in a period of 5 seconds.

We find that the RTA mechanism described above operates efficiently at Jupiter in particular for protons at low pitch-angles because of anomalous trapping, which guides nearly resonant protons at low pitch angles to a limited range of gyrophases where the particles are accelerated in the perpendicular direction. This mechanism was found previously in the interaction between whistler-mode chorus waves and electrons [2].

References

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