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Ion Acceleration by Beating Electrostatic Waves: Theory, Experiments and Relevance to Spacecraft Propulsion

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After a brief overview of electrodeless plasma propulsion concepts, we will focus on a recently discovered ion acceleration mechanism, which appears to occur naturally in Earth's ionosphere, holds promise as an effective means to energize ions for applications in thermonuclear fusion and electrodeless space plasma propulsion. Unlike previously known mechanisms for energizing plasmas with electrostatic (ES) waves, and which accelerate only ions whose initial velocities are above a certain threshold (close to the wave's phase velocity), the new acceleration mechanism, involving pairs of beating ES waves, is non-resonant and can accelerate ions with arbitrarily small initial velocities, thus offering a more effective way to couple energy to plasmas. We will discuss the fundamentals of the nonlinear dynamics of a single magnetized ion interacting with a pair of beating ES waves and show that there exist necessary and sufficient conditions for the phenomenon to occur. We will see how these fundamental conditions are derived by analyzing the motion's Hamiltonian using a second-order perturbation technique in conjunction with Lie transformations. The analysis shows that when the Hamiltonian lies outside the energy barrier defined by the location of the elliptic and hyperbolic critical points of the motion, the electric field of the beating waves can accelerate ions regularly from low initial velocities, then stochastically, to high energies. We will then illustrate real plasma effects using Monte Carlo numerical simulation and discuss the recent results from a dedicated experiment in my lab in which laser-induced fluorescence (LIF) measurements of ion energies have provided the first laboratory observation of this acceleration mechanism. The talk will conclude with a few ideas on how the fundamental insight can be applied to develop novel plasma propulsion concepts.