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How Hall electric fields intrinsically chaotize and heat ions during collisionless magnetic reconnection[1]

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A longstanding conundrum in magnetic reconnection is its accompaniment by anomalous ion heating much faster than conventional collisional heating. It is well known that in-plane Hall electric fields that inherently develop during collisionless magnetic reconnection are associated with ion energization, but the exact mechanism behind the observed ion heating has not been clear. It is first shown via a zero-beta, two-fluid analysis that the Hall electric fields intrinsically satisfy the criterion for "stochastic heating" of ions — a process in which sufficiently strong electric fields chaotize particle orbits and effectively heat the particles. Second, a kinetic calculation is presented which illustrates that stochastic ion heating is also intrinsic to the Harris equilibrium. The spatial extent of the heating is found to decrease as the equilibrium thickness and/or the guide field increases, and above a threshold guide field, stochastic heating is not predicted. Third, the mechanism is verified by particle-in-cell simulations of collisionless reconnection. Extreme ion heating is observed at the regions where stochastic heating is predicted. In line with the kinetic calculation, both the predicted and the observed heating extent decreases as the guide field increases, and at a certain guide field strength, extreme ion heating disappears. Test-particle simulations show that ions that satisfy the stochastic heating criterion indeed undergo chaotic motion, as evidenced by finite Lyapunov exponents and violation of orbit adiabatic invariance. The present work shows that Hall electric fields intrinsic to collisionless reconnection intrinsically cause stochastic heating, thus establishing it as the generic ion heating mechanism.

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