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Turbulent Magnetic Reconnection in Earth's Magnetotail: Secondary Reconnection, Wave Modes and Electron Energization

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Magnetic reconnection and turbulence are the two most important energy conversion phenomena in plasma physics. Magnetic reconnection and turbulence are often intertwined. For example, reconnection occurs in thin current layers formed during cascades of turbulence, while reconnection in large-scale current sheet also evolves into a turbulent state. How the magnetic energy is dissipated and how particles are accelerated in turbulent magnetic reconnection are outstanding questions in the plasma physics community. Here we report MMS observations of a turbulent reconnection in Earth's magnetotail. We found sub-ion-scale filamentary currents in high-speed outflows that evolved into turbulent states. Some of these filamentary currents were reconnecting, thereby further dissipating the magnetic energy far from the X line. We notice that turbulent reconnection is more efficient in energizing electrons than laminar reconnection. Electrons were primarily accelerated around the X-line rather than in the outflow region. Coherent structures composed of filaments are important in accelerating electrons during turbulent reconnection. The hardest electron spectra were primarily produced by betatron acceleration. Applying the K-filtering technique to multi-spacecraft measurements, we are able to resolve the wave mode with wavelength below the ion Larmor radius in turbulent reconnection for the first time. Our results are essential for clarifying the role of turbulence in magnetic reconnection.