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Relativistic electrons produced by foreshock disturbances observed upstream of the Earth's bow shock

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It has been known for years that charged particles can be accelerated by high Mach number collisionless shock waves. The accelerated particles can stream away upstream to form a foreshock region in communication with the shock. Due to differences in gyroradii, ions are more readily accelerated than electrons by collisionless shocks. These energetic, suprathermal ions stream against the incident flow providing free energy that can generate foreshock disturbances – large-scale (i.e. tens to thousands of thermal ion gyroradii), transient (∼5-10 per day) structures. They have recently been found to accelerate ions to energies of several keV [e.g., Wilson et al., 2013] and even produce their own mini foreshocks [e.g., Liu et al., 2016]. While the high Mach number (M > 40) Kronian bow shock can generate ∼MeV electrons [e.g., Masters et al., 2013], the much weaker Earth's bow shock (1 ≤ M < 20) cannot generate electrons beyond a few 10s of keV [e.g., Wu, 1984]. All previous observations of energetic foreshock electrons were attributed to geomagnetic and/or solar activity but we observe no geomagnetic or solar activity associated with these enhancements. Further, given that electrons generally have much smaller gyroradii than shock ramp widths and thermal speeds that greatly exceed shock speeds, no known shock acceleration mechanism can explain the energization of thermal electrons up to these relativistic energies. These observations could provide a new paradigm for electron injection in astrophysical shocks and resolve several unanswered questions in heliospheric and astrophysical plasmas.