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Evidence of autogenous first-order Fermi acceleration of energetic ions upstream of Earth's bow shock

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Earth's magnetosphere serves as an obstacle to the surrounding supersonic solar wind that fills interplanetary space, and as the solar wind slows and deflects to flow around the magnetosphere, it results in the formation of Earth's bow shock and magnetosheath. Under almost all solar wind conditions, the bow shock is a supercritical shock in collisionless plasma, and thus, an ion foreshock typically forms consisting of supra-thermal ions back-streaming into the incident solar wind along interplanetary magnetic field (IMF) lines that are quasi-parallel to the local bow shock normal direction. Various plasma instabilities from such a system result in a variety of nonlinear wave and ion kinetic activity in the foreshock. This activity includes the formation of large-scale transient ion foreshock phenomena such as hot flow anomalies (HFAs). HFAs are concentrations of super-heated foreshock plasma that form around IMF discontinuities and expand explosively into the surrounding solar wind. As they evolve, HFAs often develop their own shocks on their upstream edges in the solar wind, and it has been hypothesized that such systems may enable first-order Fermi acceleration between the converging the HFA shock and the bow shock. Here, we present detailed analysis of an HFA observed by NASA's Magnetospheric Multiscale (MMS) mission. The HFA was associated with energetic ion signatures up to $\sim$1 MeV. With the capabilities afforded by MMS' instrumentation and multipoint nature, we show that: 1) the acceleration mechanism was dependent on ion mass and charge-state and was consistent with the theory of first-order Fermi acceleration; 2) the rate of energy gain of these ions was also mass dependent and consistent with the theory of first-order Fermi acceleration; 3) the accelerated ions were observed streaming away from the HFA after it passed over the MMS spacecraft and continued to evolve; and 4) the ions accelerated in this system were of solar wind origin with initial energy on the order of 1 keV. These results have important implications for particle acceleration at supercritical, collisionless plasma shocks throughout the Universe. The bow shock itself is responsible for the HFA's formation, and thus, the Fermi acceleration of ions observed here occurred autogenously, independent of any interaction with some external system. This offers a solution to the "injection problem" of Fermi acceleration and implies that foreshock transients, like HFAs, may play an important role in the generation of cosmic rays at other astrophysical shocks throughout the Universe.