ACE News #194 – October 9, 2017
MMS Observation of Inverse Energy Dispersion in Shock Drift Accelerated Ions

The four Magnetospheric Multiscale (MMS) spacecraft observed a ~1 min burst of energetic ions (50–1000 keV) in the region upstream from the bow shock on 6 December 2015. The event was detected by MMS-2 with the Energetic Ion Spectrometer (EIS) that measures ion composition. EIS measured the inverse energy-time dispersed event (i.e. lower energy particles reach their maximum intensities before the higher energy particles) from 08:18:10 UT to 08:19:30 UT in the region just upstream from the subsolar quasi-perpendicular bow shock.

Energy-time dispersed ion structures are often attributed to the leakage of substorm injected ion dispersions in the magnetosphere or Fermi acceleration upstream from the quasi-parallel bow shock [1,2,3,4]. Ipavich *et al*. [3] interpreted the inverse dispersion patterns as evidence for Fermi acceleration, which prescribes the relationship between the particle energies and acceleration time. The higher-energy particles require more time to reach their equilibrium intensities since the diffusion coefficient depends linearly on energy.

If the energetic ions observed upstream from the quasi-perpendicular bow shock are of solar origin, then the seed solar ions must be directly energized via shock-drift acceleration. We compared the differential intensities for the ion species observed by the ACE-EPAM, ACE-ULEIS, and MMS-EIS. The ion energy spectrum obtained by ACE exhibits a different slope and intensities from that of the upstream ions observed by MMS, and the He/O ratio at ACE (~262.4) differs by an order of magnitude from that at MMS (~22.6). This indicates that the source of the energetic ions observed by MMS in the region upstream from the quasi-perpendicular bow shock is not ambient solar material.

However, the event can't be explained solely by leakage from the magnetosphere. The strongly southward orientation of the interplanetary magnetic field (IMF) lines at the time of the event precludes any connection to the magnetosphere [5]. We suggest that the ions detected by MMS gradient drifted out of the nearby quasi-parallel foreshock and into the quasi-perpendicular bow shock.

Figure 1b illustrates how energetic magneto-spheric ions within the foreshock region upstream from the quasi-parallel bow shock (right of Figure 1b) might gradient drift across the foreshock boundary region of enhanced magnetic field strengths. They would then be convected into the region upstream from the quasi-perpendicular bow shock (left of Figure 1b) and perhaps further energized by shock-drift acceleration. The gyroradius of the convected energetic ion in the upstream from the quasi-perpendicular bow shock would be increased by the electric field during the gradient drift. Each of the ion species exhibited inverse energy dispersion. As predicted by models for shock drift acceleration, the energies of the ions increased as θ_{Bn}, the angle between the IMF and the shock normal, increased. Additional details can be found in Lee *et al.* (2017) [5].

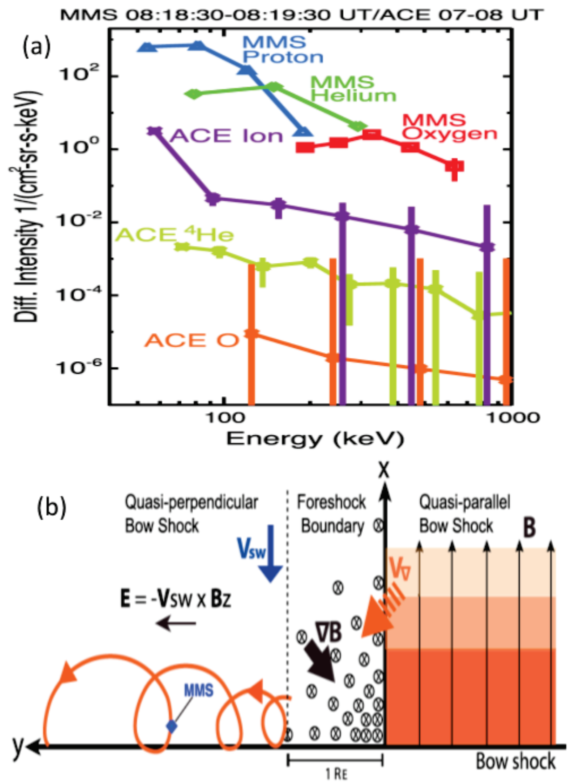

Figure 1a: *Comparison of time-averaged MMS (1 min) and ACE (1 hour) ion composition energy spectra. MMS was located immediately outside the Earth's bow shock at the subsolar point, and ACE was at the L1 Lagrange point.* ***Figure 1b:*** *A sketch of the shock geometry indicating how the energetic ions reach the quasi-perpendicular region of the bow shock. Magnetospheric ions Fermi-accelerated within the foreshock upstream from the quasi-parallel bow shock may gradient drift across the edges of the foreshock and then be convected into the bow shock where further shock-drift acceleration may occur. Energization by the electric field increases the gyroradius of the convecting ion as it gradient drifts in the region upstream from the quasi-perpendicular bow shock. The sequence of events enables spacecraft upstream from the quasi-perpendicular bow shock to observe ions escaping from the magnetosphere.*

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