Electron Heating Within the Earth's Bow Shock

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(Received 26 March 1982)

High-temporal-resolution measurements of electron velocity distributions, $f(\vec{v})$, have been obtained for many transits through the Earth's bow shock. Within all oblique shocks studied, the maximum of $f(\vec{v})$ is offset with respect to the ion rest frame parallel to $\vec{B}$ and directed downstream. These observations indicate that electron thermalization within the bow shock consists first of a downstream acceleration parallel to $\vec{B}$ by the macroscopic shock electric field, followed by beam-driven plasma instabilities.

PACS numbers: 52.35.+c

Much work has been done to understand the physical mechanisms which convert free-streaming ion kinetic energy to electron and ion thermal energy within collisionless shocks.[1,2] In quasiperpendicular shocks, attention has centered on instabilities driven by currents perpendicular to the magnetic field $\vec{B}$.[3] This Letter reports the results of an experimental study which demonstrates the importance of instabilities driven by field-aligned electron beams. Data from the fast plasma[4] and magnetic field[5] experiments on ISEE-2 have been used to study the evolution of electron velocity distributions, $f(\vec{v})$, as the spacecraft transits the Earth's bow shock. Cuts through $f(\vec{v})$ parallel to $\vec{B}$ within the bow shock often show maxima shifted downstream from the ion reference frame by amounts comparable to the upstream parallel electron thermal speed. Preliminary calculations indicate that some of these distributions are linearly unstable to ion acoustic and Buneman waves.

The orbit of ISEE-2 is elliptical with apogee of $22.2R_e$ and inclination of 28.8°. As such, shock crossings occur (generally more than twice per orbit because of the motion of the shock) when apogee is located in the noon hemisphere. The present study concentrates on those crossings where the orientation of the magnetic field, $\vec{B}$, was within ~± 30° of the scanning plane of the plasma analyzer. This latter criterion was imposed to reduce projection effects inherent in a two-dimensional measurement. (The analyzer integrates over ± 55° in polar angle about the scanning plane.) Further, the study was restricted to shock crossings when the satellite was operated in its high data-rate mode. In this mode 16 azimuthal scans through $f(\vec{v})$ at each of 16 energies are obtained every 3 sec. Details of the instrument and a description of operational modes are given elsewhere.[4] Cuts through $f(\vec{v})$ parallel to $\vec{B}$ were constructed for each of the selected shock transits and overlayed.

Fifteen shock crossings meeting the above criteria occurred on eight different days between October 1977 and December 1978. Sample cuts through $f(\vec{v})$ parallel to $\vec{B}$ measured during two of these crossings are presented in Fig. 1. These examples were chosen because they show the important features of all fifteen crossings and represent widely separated portions of the forward hemisphere of the bow shock. Whereas the crossing on 13 December 1977 occurred in the dawn sector ($\Phi \sim -60°$), that on 23 July 1978 occurred in the dusk sector ($\Phi \sim +65°$). Here Φ is the azimuth of the ISEE spacecraft with $\Phi = 0°$ at noon and increasing counterclockwise when viewed from the north.

The velocity distributions measured across each of the sample shocks are very similar. Upstream in the solar wind the distributions have relatively narrow maxima centered on a speed near zero in the solar-wind rest frame. As the shock is approached from the upstream side, the widths of $f(v_{\parallel})$ near their maxima narrow and the maxima move away from their velocities in the solar wind and decrease in amplitude. In each of

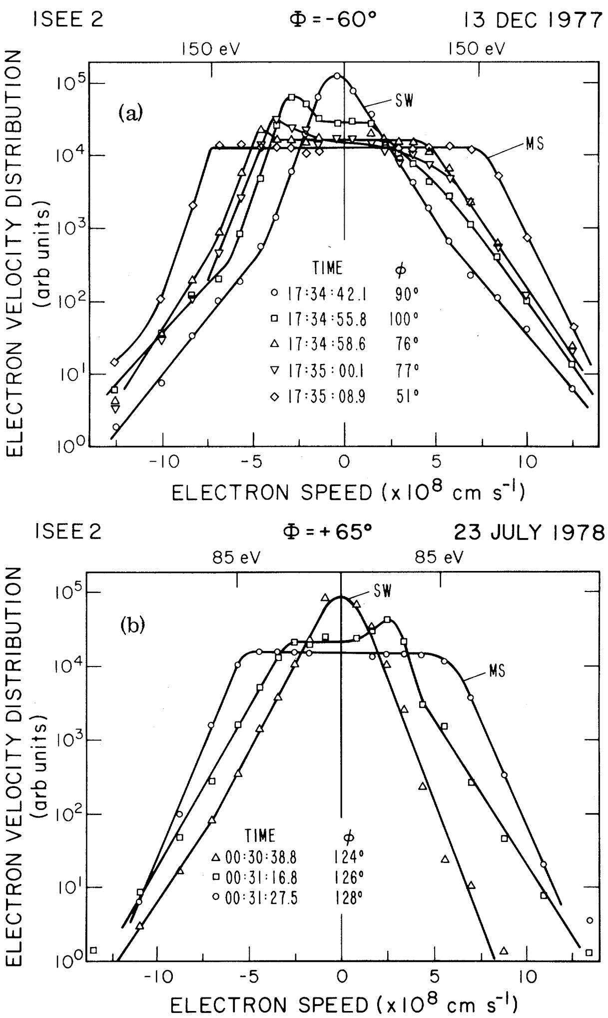

FIG. 1. Cuts, parallel to $\vec{B}$, of electron velocity distributions measured during two separate shock crossings. The significant part of each cut was measured in less than 100 msec. Counting statistics near the peaks are generally close to 5% and are less than the size of the symbols. SW and MS refer to solar wind and magnetosheath, respectively.

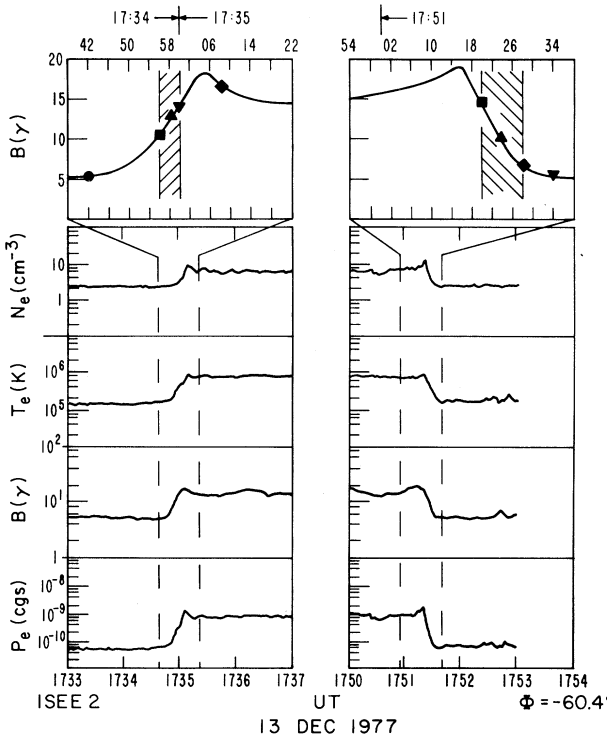

FIG. 2. Profiles of electron number density, N_E, electron temperature, T_E, magnetic field magnitude, B, and electron thermal pressure, P_E, for two of the shock crossings observed on 13 December 1977. The symbols superimposed on the expanded plots give the times when measurements of $f(v_{\parallel})$ in Fig. 1 labeled with the same symbols were measured.

the cases studied, the associated drift velocities are always directed toward the downstream side of the shock. This is demonstrated in Fig. 1 since both plots are oriented such that positive speeds refer to directions along $\vec{B}$ toward the dawn sector. Thus during the crossing on 13 December 1977 when ISEE-2 was in the dawn sector the maximum is offset to the left, or into the shock. In contrast, during the crossing on 23 July 1978 when ISEE-2 was in the dusk sector, the maximum is offset to the right, again into the shock.

During the more extended shock crossings such as those on 13 December 1977, progressions of maxima are observed. As the maxima become more offset they become more attenuated in amplitude and finally merge into the nearly flat-topped distributions characteristic of the magnetosheath.[6,7] Simultaneously with the development of offset maxima, a flat ledge develops in the opposite direction. In each case the magnitude of the speed of the outer edge of the ledge is close to that of the oppositely directed downstream maximum, and is no larger than that of the outer edge of the neighboring magnetosheath flat-topped distributions. The energies corresponding to these speeds ranged between 30 and 150 eV.

Comparisons of plots of the magnetic field strength and the electron number density and temperature for each of the crossings show that the offset maxima in $f(v_{\parallel})$ are often observed to occur near the center of the shock transitions where all gradients are largest. This is illustrated in Fig. 2 for two shock crossings on 13

December 1977. The shaded areas in the upper expanded traces of the magnetic shock profiles correspond to the times during which offset maxima in $f(v_{\parallel})$ were observed. As can be seen, times when offset maxima in $f(v_{\parallel})$ are observed bracket the center of the shocks where the slopes of the magnetic field profiles are maximum. The lower three traces in Fig. 2 show that this location also corresponds to maxima in the slopes of the number density, electron temperature, and electron pressure.[8] However, crossings have also been observed where prominent offset maxima occurred in the upstream "foot" of the shock.

The important features of electron velocity distributions measured during transits of the Earth's bow shock can be summarized as follows: Far upstream, the distributions have relatively Maxwellian shapes at low energy which peak near the proton rest frame. Within the shock, $f(v_{\parallel})$ often has an offset maximum shifted towards the downstream side by a speed comparable to, but larger than, the upstream parallel electron thermal speed. On the upstream sides of the distributions within the shock, $f(v_{\parallel})$ has a flat ledge extending to a speed close to that of the oppositely directed offset maximum of the shock. Downstream the $f(v_{\parallel})$ has a flat top extending to energies which range between approximately 30 and 150 eV. The heights of the flat tops measured downstream are typically an order of magnitude less than the peaks of the Maxwellians measured upstream.

The electron velocity distributions observed within the Earth's bow shock appear very similar to those generated in electrostatic double layers with two-dimensional numerical simulations.[9] These simulations also exhibit low-frequency electrostatic turbulence generated by instabilities driven by maxima in $f(v_{\parallel})$ offset from the ion rest frame. Such turbulence has characteristics very similar to that reported within the Earth's bow shock.[10,11] We interpret these similarities to indicate that the primary mechanisms which thermalize electrons within the bow shock are instabilities driven by field-aligned electron beams accelerated by the electric field component parallel to $\vec{B}$. Indeed, preliminary calculations show that some of the velocity distributions such as shown in Fig. 1 are unstable to ion acoustic and Buneman waves. Wave vectors at maximum growth rate are aligned with $\vec{B}$ in accord with characteristics of the electrostatic turbulence observed within the Earth's bow shock.[11]

We wish to thank D. Forslund, K. Lee, and K. Quest for many useful conversations. We are also very grateful to R. Anderson for his help, patience, and good humor which were essential for the completion of this study. This work was supported in part by the National Aeronautics and Space Administration and the branch of the Institute of Geophysics and Planetary Physics at Los Alamos and was carried out under the auspices of the U. S. Department of Energy. This work was supported in part by the National Aeronautics and Space Administration under Contract No. NAS5-25772, and in part by the Bundesministerium für Forschung und Technologie under Grant No. 01 0 I 027-ZA/WF/WRK 275:4.

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