Simultaneous observations of solar wind plasma entry from FAST and POLAR

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Abstract. On November 15, 1996, NASA FAST and POLAR satellites obtained data in the cusp/cleft region for extended intervals. POLAR sampled a narrow range of local times. FAST observed cusp/cleft plasma for more than 5 hours in local time. At 07:51 UT the satellites were in near magnetic conjunction, and the interplanetary magnetic field was steady for an extended interval before this time. We confirm prior observations that show solar wind plasma often enters the magnetosphere over extended regions of local time. For the one hour interval of steady solar wind conditions when POLAR encountered cusp/cleft plasma, irregularly spaced ion injections interspersed with intervals of nearly constant cusp/cleft ion fluxes were observed. The data are consistent with temporal variations in the reconnection rate. At the time of the near conjugate observations the data suggest that solar wind plasma entered the magnetosphere over an extended region of the magnetopause, i.e. not in small discontinuous patches.

Introduction

Investigations of mass transfer from the solar wind to the magnetosphere have been limited to mostly single point measurements. At ionospheric altitudes and above, particle detectors have identified the cusp/cleft region on the dayside of the magnetosphere. In this region intense fluxes of ions and electrons are found with thermal properties similar to those found in the shocked solar wind plasma of the magnetosheath. Newell and his colleagues (e.g. Newell and Meng, [1992]) have exploited the large data base of particle measurements from the Defense Meteorological Space Program (DMSP) satellites to infer much about the spatial variability of the injection of solar wind plasma. Nevertheless, there remain ambiguities about the spatial and temporal extent of the direct injection region. Crooker et al. [1991], Maynard et al. [1997], and Lockwood and Davis [1996,7] have suggested that solar wind plasma enters the magnetosphere coherently over a large fraction of the dayside magnetopause. Ambiguities in ground observations and limited spatial/temporal coverage from satellites have made it difficult to confirm these suggestions.

The state-of-the-art plasma instruments on the POLAR and FAST satellites provide higher temporal and spatial resolution of the energy, mass, and angle composition of solar wind plasma in the high and low altitude cusp/cleft regions of the magnetosphere than previously available. At 07:51 universal time (UT) on November 15, 1996, the two satellites were on magnetic field lines that mapped to within 200 km of each other at 100 km altitude. More importantly, ion mass spectrometers on both satellites observed the He^{++} component of the injected solar wind for extended intervals that included the time of near magnetic conjunction. Here we present the analysis of data acquired during this conjunction interval.

Observations

FAST was launched into a 4180 x 350 km, 82.9 degree inclination orbit in August, 1996. Figure 1 summarizes electron, ion and He^{++} data obtained on the FAST spacecraft from 07:44 to 08:02 on November 15, 1996. During this interval FAST crossed the high latitude northern polar cap in the dawn/dusk direction. At ~07:51 the magnetic footprint of FAST came within 200 km of the POLAR footprint.

Data from three FAST sensor packages are displayed in Figure 1: The electron electrostatic analyzers (EESA) and ion electrostatic analyzers (IESA), [Carlson et al., 1998] and the Time-of-flight Energy Angle Mass Spectrograph (TEAMS) [Klumpar et al, 1998]. Data from these sensor packages are displayed in two formats: Energy-time spectrograms and angle-time spectrograms. The electron data (top and 4th panels) and the ion data are acquired over the energy ranges 3 eV/e to 25 keV/e for ions and 4 eV/e to 30 keV/e for electrons. Data from restricted energy ranges are shown in Figure 1. Various time resolutions were used to sample the data but in no case were the IESA and EESA data acquired at a rate slower than 0.625 s per energy sweep. For these packages, complete pitch angle coverage with 11.25 degree resolution is available for every energy sweep. The TEAMS package was operated with 2 spin (10 s) resolution and sampled the energy range 5 -12,000 eV/e. The feature at 90 degrees in the electron angle time spectrogram is from photoelectrons locally produced on the spacecraft. The feature at ~270 degrees in the fifth panel is the signature of the rapid (~10 km/s) motion of the FAST spacecraft through a dense cold (~eV) plasma population. The <10 eV/e He^{++} population shown in the third panel is an instrumental artifact caused by the intense H^+ signal and incomplete mass resolution at low energies of the TEAMS sensor. Detailed examination of full mass spectra in discrete energy bands confirms that the energetic (>10 eV/e) He^{++} energy fluxes are not significantly contaminated by the tail of the more intense H^+ fluxes.

He^{++} fluxes at energies of several hundred eV and the intensities shown in Figure 1 can only come directly from the shocked solar wind plasma and are thus the clearest signature of the entry of solar wind plasma into the Earth's magnetosphere. The ion energies first decrease and then increase as FAST moves into the polar cap and returns to lower latitudes. The structured electron data observed from ~07:49:25 to ~07:55:12 shown in Figure 1 and complementary ion data meet the normal criteria used to identify cusp/cleft or boundary layer plasmas at low altitudes (Newell and Meng, [1992]). All three FAST sensor packages detected the changes expected after a crossing from closed to open field lines with the onset of injected magnetosheath plasma at ~ 07:49:25 on the morning side at about 09:38 MLT. Both the ion and electron components of cusp/boundary layer plasma are observed on FAST until ~07:53 and again from ~07:53:30 to 07:54. The electrons observed after 07:53 have characteristics typical of cusp or boundary layer plasmas so we infer FAST remained on open field lines until after about 07:56 when these electrons were no longer seen. Solar wind ion fluxes are missing after ~07:54 because poleward ion convection and finite ion velocities exclude newly injected solar wind ions from this region. The location of the open/closed field line boundary on the afternoon side is ambiguous. We place it at 07:55:12 (14:30 MLT), but it could be as late as 07:55:30 (14:40 MLT).

POLAR was launched into a 9 x 1.8 R_E, 90 degree inclination orbit in February 1996. During the interval of interest POLAR was located at ~ 11:00 MLT, and moved slowly Earthward and equatorward. Figure 2 shows electron and H^+ and He^{++} energy time spectrograms from the HYDRA [Scudder et al., 1995] and TIMAS [Shelley et al., 1995] instruments. Also in Figure 2 are two components of the plasma convection velocity inferred from the Electric Field Investigation (EFI) [Harvey, et al., 1995]. TIMAS provides mass-resolved ion spectra from ~98% of the full solid angle over the energy range from 15 eV/e to 33.3 keV/e. HYDRA sampled the ion and electron energy fluxes over the full solid angle covering the energy range from 12 eV/e to 18 keV/e every 1.15 seconds. The black line shown on the electron spectrum indicates the satellite potential. After 07:03, when POLAR first encountered cusp plasma, the spacecraft potential was less than 10 eV positive. The bottom two panels in Figure 2 present components of the ion convection velocity in despun spacecraft coordinates. The x-y and z (not shown) components are the two orthogonal spin plane components with the x-y direction approximately parallel to the solar ecliptic plane and having a positive sense away from the sun. The 56 component is aligned along the spacecraft spin axis and is positive duskward. Electric field measurements from the short (14 m) axial booms in the 56 direction are compromised by DC offsets arising from asymmetries of potential and density distributions of the sheaths around the spacecraft and differences in the contact potentials of the two sensors. For most of the interval a reasonable estimate for E_{56} has been derived by subtracting a constant term and a term proportional to density based on general agreement with the assumption E*B equal to zero. In the latter part of the interval B is too close to the spin plane to provide a check on the adjustments by calculating E*B. We have used the adjusted E_{56} to calculate the ion convection velocity, Vx-y.

The data presented in Figure 2 and high time resolution energy/angle spectra (not shown) reveal that POLAR encountered recently injected magnetosheath plasma almost continuously from ~07:07 to ~08:50 when it entered the dayside magnetosphere. The low energy component of H^+ seen intermittently after ~07:40 is upflowing and occurs on or near field lines with significant fluxes of upflowing O^+. The H^+ and He^{++} ion spectra are characterized by 5 clearly defined energy-time dispersions (07:07-07:15, 07:17-07:21, 07:21-07:32, 07:45-07:51, 07:53-08:00), and indeterminate regions with approximate constant or ambiguous energy-time behavior (07:15-07:17, 07:32-07:44, 07:51-07:53, 08:00-08:27). The ion drift determined from the EFI instrument is primarily tailward from ~06:30 to ~08:00. One energy-time dispersion (07:03-07:04) and several bursts of less than 20 seconds duration (07:05:30, 08:31, 08:34:30, 08:38, 08:41, and 08:49) were also observed before 7:07 and after 08:27.

Solar wind plasma entry is thought to be heavily influenced by the interplanetary magnetic field (IMF). At 07:51 the IMP8 and WIND spacecraft were at (-8.7, -31, -14.4) and (5.3, 20.6, 0.3) respectively in units of R_E in GSE coordinates. Magnetometer data show that WIND crossed the bow shock and entered the magnetosheath between 07:15 and 07:20. At IMP8, 30 R_E dawnward of the Earth-Sun line, the orientation and magnitude of the IMF was steady from ~06:40 to ~08:00 with the components in GSM coordinates (-7, +2, 0) nT. The IMF Bz component in GSM coordinates measured by WIND from ~06:00 to ~07:15 was also steady and near zero. At IMP8, after ~08:00, Bz became increasingly negative and By increasingly positive. The density, temperature, and velocity of the solar wind plasma observed well dawnward of the Earth-Sun line by IMP8 were similarly steady during the interval of interest.

Discussion

We focus our discussion on the interval when both the IMF conditions as well as magnetospheric convection are steady: from 07:07 to 08:00. Except for the large (at least 5 hours) extent in local time of injected solar wind plasma observed on FAST, the ion and electron observations reported in Figures 1 and 2 from POLAR and FAST are not inconsistent with the large body of cusp observations (e.g. Peterson [1985], Yamauchi and Lundin [1994], Newell and Meng, [1992], Smith and Lockwood, [1996]). What is unique about these observations is the collection of comprehensive plasma diagnostics obtained nearly simultaneously in both time and space that allow us to directly monitor the extent of solar wind plasma entry.

On the basis of the observations presented above and the work of Maynard et al., [1997] and Lockwood [1997], we conclude that solar wind plasma frequently enters the magnetosphere over extended regions of local time. Maynard et al., [1997] presented data from a unique DMSP crossing that showed injected magnetosheath plasma entering over 3.7 hours of local time. Maynard et al. noted that their observations were consistent with the recent theoretical work of Crooker et al. [1991] which suggests that solar wind plasma enters over extended regions of local time and that the extent in local time is related to the cross polar cap potential. Lockwood [1997] showed how entry of solar wind plasma over extended regions of local time is consistent with global reconnection. Grande et al. [1997] have also documented the large spatial extent of the solar wind injection region. In Figure 1 we showed that FAST detected injected solar wind plasma from ~07:49:25 to ~07:55:12, over 5 hours of local time. The solar wind conditions were not unusual and were steady. The large scale convection electric field monitored by POLAR, except for a brief excursion near 07:50, also shows a stable pattern. The analysis of Crooker et al. [1991] predicts that a cross polar cap potential greater than 50 kV is required to support solar wind entry over 5 or more hours of local time. The potential determined from the FAST electric field detector over a short segment of the orbit in the polar cap was ~ 21 kV. The potential inferred from a DMSP southern hemisphere pass slightly later (08:06 to 08:28) that cut across the night side from 21.2 to 2.8 hours MLT was 38.3 keV. This is well tailward of the MLT of the normal potential extremes. These observations are not inconsistent with the prediction made by Crooker et al.

The POLAR data presented in Figure 2 may be understood in terms of a varying reconnection rate. During the interval from 07:07 to 08:00, both the interplanetary magnetic field and large scale ion convection pattern over the polar caps were steady. We use He^{++} ions observed on a nearly stationary POLAR satellite to directly monitor transfer of solar wind plasma into the magnetosphere. Energy-time dispersions in the cusp/cleft region arise from restrictions in the spatial and/or temporal extent of solar wind injection, the finite energy width of intense magnetosheath plasma, the Earth's large scale convection electric field, and relatively slow ion velocities [Carlson and Tobert, 1980, Peterson, 1985]. Since POLAR was traveling slightly equatorward and convection was tailward, steady injection of solar wind plasma would appear at the POLAR location as a single dispersion with energy slowly increasing with time. Two types of He^{++} energy dispersions are seen in Figure 2: Nearly constant in time and decreasing with time. As noted above, intervals starting at 07:15, 07:32, 07:51 have no energy dispersion within the energy resolution of the TIMAS instrument. Because of finite instrumental energy band widths, this is consistent with a very slowly increasing He^{++} energy with time, and steady entry of solar wind plasma. However, intermixed with these intervals are five intervals with distinctive decreasing energy time dispersions. If there were no He^{++} ions observed before and after these dispersion events, the decreasing energy-time dispersions would be most simply explained as the result of solar wind plasma injections restricted in both space and time --i.e. isolated injection events. The observed H^+ and He^{++} ions, however, have nearly identical energy widths and energy-time dispersions which are not consistent with the transport of these ions from a localized patch on the magnetopause. The average time between the decreasing energy time dispersions is 10.6 minutes. Several ground observers, (e.g. Sandholt et al., [1992]) have observed features in the ionosphere near local noon with periods in the range 5 to 10 minutes. Smith and Lockwood [1996] and Lockwood and Davis [1996,7] have recently reviewed the observational and theoretical evidence addressing the temporal and spatial character of solar wind plasma entry into the magnetosphere. Among the mechanisms for plasma entry considered were an irregularly varying rate of reconnection of the solar wind and magnetospheric magnetic fields, irregular motions of the Earth's magnetic field, and variations in the physical location of reconnection on the magnetopause. The data presented here do not rule out any of these mechanisms. Because of the steady IMF and convection environment and the character of the H^+ and He^{++} ion distributions, we conclude that the POLAR observations on November 15 are consistent with an irregularly varying rate of reconnection.

Reports of a large local time extent of plasma entry and variations in the rate of plasma entry on 10 minute time scales are not new or unique. However, simultaneous information about the temporal and spatial extent of plasma entry is very limited [Lockwood and Davis, 1996,7]. The key observations presented above are the discontinuities or "steps" in the ion distribution that are detected at about 10 minute intervals on POLAR, and the detection of, at most, one discontinuity in the ion plasma encountered by FAST. Lockwood and Davis and others have shown that discontinuities or "steps" in the H^+ and He^{++} ion distributions are most simply interpreted as variations in the rate of reconnection or plasma entry. Lockwood and Davis argued that the regions of plasma entry must be extended in longitude (i.e. not "patchy" in local time) but did not have available near conjugate observations such as those presented in Figures 1 and 2.

We conclude that FAST observed steady solar wind entry over a large fraction of the dayside magnetopause, as suggested by Lockwood and Davis [1996,7] and Maynard et al. [1997]. The exact fraction of the magnetopause is, however, uncertain. If there were not a gap at about 07:53 in the FAST energetic ion data, then following the arguments of Lockwood and Davis, we could conclude that for the interval from 07:49:25 to ~ 07:54 that FAST observed steady solar wind entry with no intensifications over most of the dayside magnetopause. There are at least two possible causes of the gap in the FAST ion data at ~07:53: 1) The gap is actually the result of a variation in the reconnection rate that because of the dawn/dusk orientation of the orbit shows up as a ion plasma drop out rather than a "step"; 2) There is no "step" in the ion plasma because the geometry of plasma convection and the FAST orbit are such to take FAST briefly poleward of the region of the polar cap illuminated by magnetosheath plasma. In either case solar wind plasma entered over a large fraction of the magnetopause.

Our analysis does not rely on the two satellites being on the same field line. Instruments on the two satellites identify the locations of field lines at the time of near conjugacy when cusp plasma is encountered and the discontinuities or "steps" separate regions of quasi-steady plasma entry. FAST data show the longitudinal extent of plasma entry. POLAR data show the temporal variations at a fixed local time. The observed small variations in the IMF are not expected to significantly effect the location or rate of reconnection.
The near conjugate data acquired on November 15, 1996 presented here suggest that, during the interval of relatively steady solar wind conditions with a dominant Bx IMF component, solar wind plasma entered the magnetosphere over both extended longitudinal and latitudinal regions of the magnetopause with intensifications at about 10 minute intervals.

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Figure 1. Energy-time (first three panels) and angle-time (bottom two panels) of electrons (top and 4th panel), non mass-resolved ions (second and bottom panels) and mass-resolved He^{++} over the indicated

energy and angle ranges obtained from the FAST satellite on November 15, 1996. The particle energy fluxes are encoded on the color bars in units of keV/cm^2-s-sr-keV The FAST position in altitude (km), magnetic local time (hrs) is indicated on the bottom

Figure 2. Energy-time spectrograms of electrons (top panel) and mass-resolved H^+ and He^{++} ions over the energy ranges indicated. Electron energy-flux, and ion number fluxes are encoded using the color bars on the right. The bottom two panels present two components of the ion convection velocity as described in the text. The position of the POLAR spacecraft in geocentric distance (R/R_E), magnetic local time (MLT) and invariant latitude (INVL) is indicated at the bottom