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Multiple spacecraft observations of energetic ions during a high solar wind pressure event

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[1] On 28 June 1999 the Wind spacecraft (near the forward libration point) observed a large solar wind pressure spike from 0445 UT to 0600 UT. The Polar satellite at 7 hours magnetic local time detected an energetic particle event in the high-altitude region associated with turbulent diamagnetic cavities from 0512 UT to 0627 UT. The particles and cavities are very similar to those that were previously found in the high-altitude dayside cusp region. They are independent of both the solar wind velocity and the interplanetary magnetic field (IMF) vectors. The enhancements of the magnetic field fluctuations in the ultra-low frequency range measured by the Wind were also observed by the Polar. Most of the time, during the event period, the IMF had a duskward component, suggesting that cusp diamagnetic cavities also existed in the postnoon sector in the Northern Hemisphere. Energetic ions of both ionospheric origin and solar wind origin were observed by the Polar spacecraft during this event period. The He^{++}/H^+ ratio in the diamagnetic cavities was a factor of four higher than in the quasi-trapping region before the event onset, while the He^+/He^{++} ratio in the cavities was more than one order of the magnitude lower. In this event, the measured cusp ions had energies up to 4 MeV. No clear relationship between the cusp energetic ion flux and the IMF cone angle was found. The Interball 1 spacecraft located just upstream of the bow shock in the prenoon sector measured an upstream ion event from about 0516 UT to 0600 UT. The onset of the energetic ions observed by Interball 1 in the upstream event was the same for different energies; the ion energy spectra were independent of the solar wind velocity and their intensities were independent of the bow shock geometry and the solar wind density. The energetic ion event onset was first detected in the cusp by Polar at 0512 UT, then near the bow shock in the prenoon by Interball 1 at 0516 UT, and then in the far upstream by Wind at 0523 UT. The measured energetic ion intensity decreased with increasing distance from the cusp diamagnetic cavities. These observational facts together with the IMF directions suggest that (1) this large solar wind pressure event produced an extremely large diamagnetic cavity (>10 R_E) within the magnetosphere, (2) the bow shock was not the main source of both the cusp and upstream energetic ions, and (3) the upstream energetic ions most likely came from the cusp.

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1. Introduction

[2] It is well known that variations in the solar wind pressure move the magnetopause position [*Chapman and Ferraro*, 1931]. Magnetic merging of the interplanetary magnetic field (IMF) with the geomagnetic field (GMF) causes the magnetosphere to open and to permit the solar wind plasma direct entry into the cusp [*Dungey*, 1961], while viscous interaction at the magnetopause boundary allows diffusive plasma entry to the magnetosphere [*Axford and Hines*, 1961]. In 1996, the Polar spacecraft observed the initial cusp energetic particle (CEP) events [*Chen et al.*, 1997, 1998; *Sheldon et al.*, 1998; *Fritz et al.*, 1999a]. They are defined as a decrease in magnetic field magnitude in the dayside cusp, a more than one order of magnitude increase in intensity for the 1–10 keV ions, and a more than three sigma increase above background for >40 keV ion intensity. Many times multiple CEPs or multiple cusps were observed in the high-altitude and high-latitude dayside region [*Chen et al.*, 1997, 1998; *Chen and Fritz*, 1998]. In addition to the energetic O^{+6} and He^{++} of solar wind origin, energetic O^+

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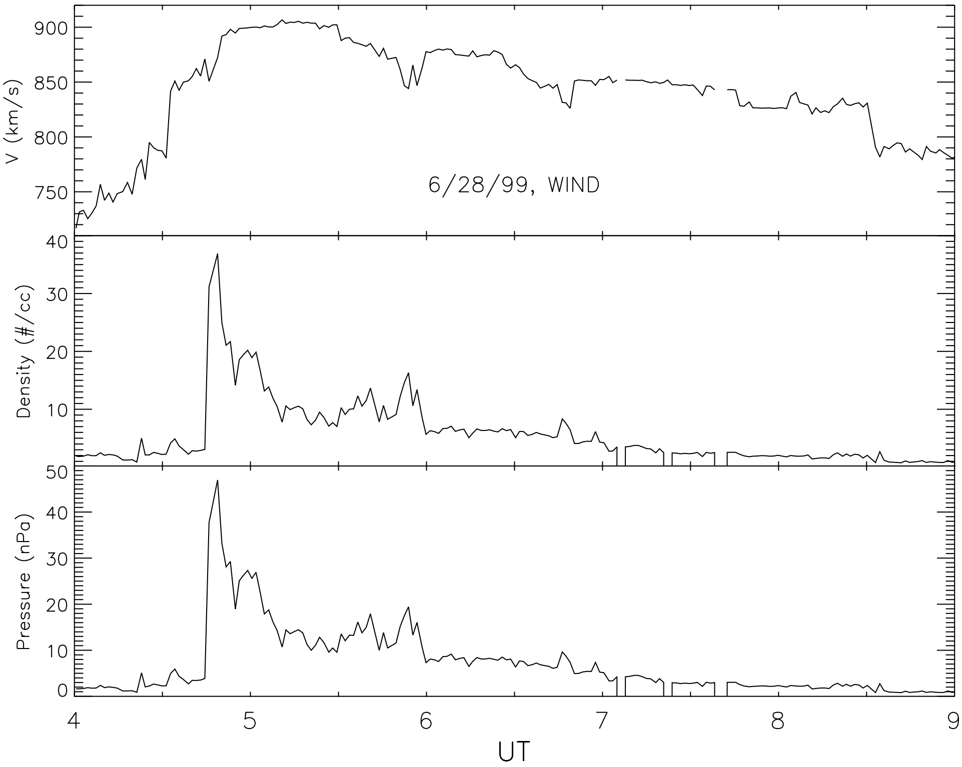

Figure 1. The solar wind speed (top panel), the solar wind density (middle panel), and solar wind dynamic pressure (bottom panel) versus time, measured by the Wind spacecraft at 0400–0900 UT on 28 June 1999.

ions of ionospheric origin were also observed in the high-altitude dayside cusp region [*Chen and Fritz*, 2001]. The CEPs had energies from 40 keV up to 8 MeV and were associated with strong magnetic field turbulence; the intensities of the CEPs were observed to increase by as large as four orders of the magnitude during the cusp crossings, indicating that the dayside high-altitude cusp is a key region for transferring the solar wind energy, mass, and momentum into the Earth's magnetosphere [*Chen and Fritz*, 2002]. Understanding the dependence of the CEPs on the solar wind conditions is an important scientific issue.

[3] Another important scientific issue is the origin of >40 keV/e ions in upstream particle events, which has remained unresolved and controversial. There are three possible source regions for the upstream energetic ions: (1) the bow shock, (2) leakage from the outer radiation belt, and (3) the high-altitude dayside cusp. In the case of the first source, energetic ions could be energized by the shock drift acceleration at the quasi-perpendicular bow shock or by the Fermi mechanism at the quasi-parallel bow shock [e.g., *Lin et al.*, 1974; *West and Buck*, 1976; *Gosling et al.*, 1978; *Anderson*, 1981; *Terasawa*, 1981; *Lee et al.*, 1981; *Lee*, 1982]. The energetic ions could also be energized by the dipolization process in the geomagnetic tail during magnetic storms and substorms [*Lezniak and Winckler*, 1970; *Quinn and Southwood*, 1982; *Aggson et al.*, 1983; *Delcourt et al.*, 1990; *Lopez et al.*, 1990; *Hesse and Birn*, 1991]. These ions then drift westward to form the outer radiation belt. Those energetic ions in the outer radiation belt may encounter the magnetopause and escape through a tangential discontinuity or a rotational discontinuity [e.g., *Speiser et al.*, 1981; *Sibeck et al.*, 1987; *Paschalidis et al.*, 1994; *Karanikola et al.*, 1999; *Kudela et al.*, 2002]. The energetic ions could also be energized in the cusp diamagnetic cavities (CDC) by the interactions of these ions with the turbulent ultra-low frequency (ULF) electromagnetic power [*Chen and Fritz*, 1998]. Some of the cusp energetic ions may escape into the upstream through open field lines [*Chen and Fritz*, 2002, 2003].

[4] To determine which is the dominant source region for the upstream energetic ions, particle and field data from multiple spacecraft are used. The energetic ions measured simultaneously by the Polar, the Interball 1, and the Wind spacecraft showed different onset times and intensities at different locations during the 28 June 1999 high solar wind pressure period, providing important information on the origin of the upstream energetic ions.

[5] The energetic ion data were obtained from ion detectors on board the various spacecraft. The Imaging Proton Sensor (IPS) on board Polar was designed to measure three-dimensional proton angular distributions over the energy range of 20 keV to 10 MeV [*Blake et al.*, 1995]. The Charge and Mass Magnetospheric Ion Composition Experiment (CAMMICE) on board Polar was designed to measure the charge and mass composition over the energy range of 1 keV/e to 60 MeV, to determine the fluxes of various ion species and their relative abundances and to determine the incident charge state of these ions [*Chen et al.*, 1997]. Earlier versions of the CAMMICE instruments have been described in detail by *Fritz et al.* [1985] and *Wilken et al.* [1992]. The energetic particle experiment DOK-2 on board Interball 1 was designed to measure ions over the energy

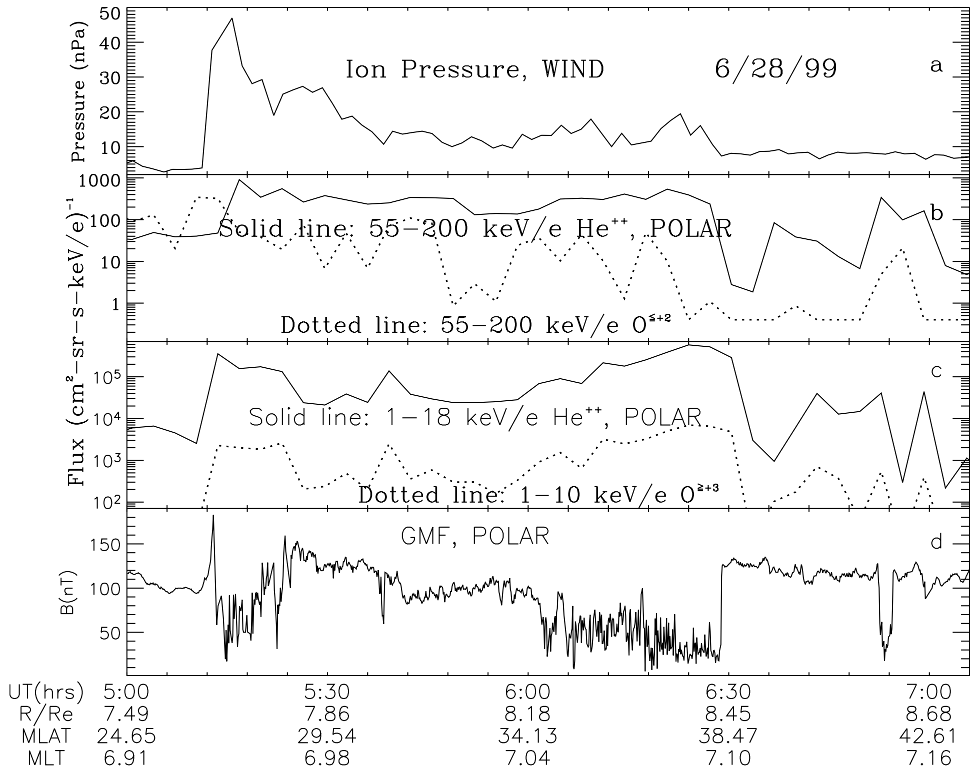

Figure 2. Wind observation. (a) The solar wind pressure, together with Polar observations, (b) the 55–200 keV/e He^{++} (solid line) and the 55–200 keV/e $O^{\leq +2}$ (dotted line) fluxes, (c) the 1–18 keV/e He^{++} (solid line) and the 1–10 keV/e $O^{\geq +3}$ (dotted line) fluxes, and (d) the magnitude of the local magnetic field, during the 28 June 1999 high solar wind pressure period. The distance of Polar from the Earth (in R_E), the magnetic latitude (MLAT), and the magnetic local time (MLT) are shown at the bottom of the figure. Corrections have been made for the propagation time from Wind to Polar.

range of 25–850 keV [*Kudela et al.*, 1995; *Lutsenko et al.*, 1998]. The Three-Dimensional Plasma and Energetic Particle (3DP) instrument on board Wind was designed to make measurements of full three-dimensional distribution of ions from 20 keV to 11 MeV [*Lin et al.*, 1995].

2. High Solar Wind Pressure Event Observed by Wind

[6] On 28 June 1999, the Wind spacecraft, near the forward libration point, observed a sudden increase (by more than one order of magnitude) of the solar wind dynamic pressure at about 0445 UT as shown in the bottom panel of Figure 1. This high solar wind pressure event, measured by the Solar Wind Experiment (SWE) [*Ogilvie et al.*, 1995] on Wind, had a duration of about 1.25 hours (0445 UT to 0600 UT) during which the pressure remained larger than 9 nPa and had a peak value of about 47 nPa. This peak value is more than one order of magnitude higher than the normal one. The top panel of Figure 1 is the solar wind speed measured by Wind and indicates that the solar wind speed had a value of about 850–900 km/s during this 1.25 hour period. The middle panel plots the solar wind ion density observed by Wind from 0400 to 0900 UT, and it shows that the time profile of the solar wind density was very similar to that of the solar wind dynamic pressure shown in the bottom panel. The solar wind density had a peak value of about 37 particles/cc, a very large number.

3. Polar Observations

[7] Figure 2 replots the solar wind dynamic pressure measured by Wind and displays the measurements made by Polar from 0500 UT to 0706 UT on 28 June 1999, where the Wind data are displaced by about 27 min from Wind local observations to match in time the location of the Polar observations. This time delay was estimated by taking into account the solar wind propagation time (with V_x) from Wind to the bow shock in upstream plus the propagation time (with $V_x/2$) from the bow shock to the Polar position in downstream. The composition of the ions measured by Polar show that the energetic (55–200 keV/e) He^{++} of solar wind origin (solid line in Figure 2b) increased significantly during this event period. Furthermore, a significant flux level of the energetic (55–200 keV/e) $O^{\leq +2}$ of ionospheric origin (dotted line in Figure 2b) was observed by Polar during this period as well, where the $O^{\leq +2}$ fluxes were dominated by singly ionized oxygen ions. Polar also detected about one to two orders of magnitude enhancements of 1–18 keV/e He^{++} and 1–10 keV/e $O^{\geq +3}$ fluxes (Figure 2c) throughout the period of 0512–0630 UT when the local GMF strength measured by Polar showed diamagnetic cavities with large variations (Figure 2d).

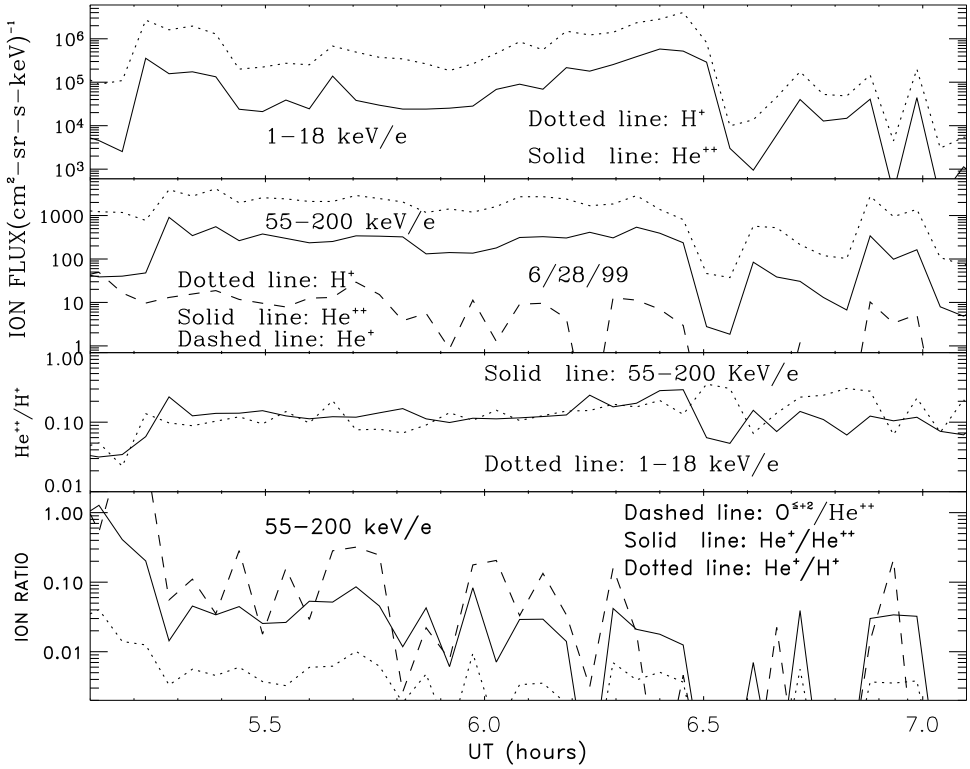

Figure 3. The time profiles of (top panel) the 1–18 keV/e He^{++} (solid line) and H^+ (dotted line), (panel 2 from top) the 55–200 keV/e He^{++} (solid line), H^+ (dotted line), and He^+ (dashed line), (panel 3 from top) the He^{++}/H^+ ratios over 55–200 keV/e (solid line) and 1–18 keV/e (dotted line), and (bottom panel) the $O^{\leq +2}/He^{++}$ (dashed line), He^+/He^{++} (solid line), and He^+/H^+ (dotted line) over 55–200 keV/e at 0506–0706 UT on 28 June 1999.

[8] At about 0512 UT the GMF strength (Figure 2d) increased from about 100 nT to 180 nT and then decreased to about 18 nT, corresponding to the significant increase of the solar wind pressure (Figure 2a). An inspection on Figure 2 indicates that the event period (0512–0630 UT) observed by Polar (bottom three panels) corresponded to the high solar wind pressure period observed by Wind, but the flux level of the charged particles did not one to one correspond to changes of the solar wind pressure.

[9] Both the ion and field data in Figure 2 showed three basic features similar to the cusp energetic particle (CEP) events reported previously in the normal cusp [*Chen et al.*, 1997, 1998; *Fritz et al.*, 1999a]; the three basic features are (1) the diamagnetic cavities with large field fluctuations, (2) the more than one order of magnitude increase in intensity for lower energy solar wind plasma, and (3) the significant increase of higher-energy charged particles. Figure 2 thus suggests that Polar observed a CEP event during the high solar wind pressure period.

[10] The top two panels of Figure 3 are plots of ion flux measured by Polar versus time over two energy ranges of 1–18 keV/e (top panel) and 55–200 keV/e (panel 2 from the top) from 0506 UT to 0706 UT on 28 June 1999. In panel 2 of Figure 3, He^+ ions are predominantly ionospheric origin, while He^{++} ions are predominantly solar origin. The bottom two panels of Figure 3 show the ratios of the ion charge composition. The He^{++}/H^+ ratios are shown in panel 3 from the top over the energy ranges of 1–18 keV/e (dotted line) and 55–200 keV/e (solid line), while the $O^{\leq +2}/He^{++}$ (dashed line), He^+/He^{++} (solid line), and He^+/H^+ (dotted line) over the energy range of 55–200 keV/e are shown in the bottom panel. There are three interesting features: (1) Solar origin ions dominated over the period of 0515–0630 UT (bottom panel); (2) the He^{++} to H^+ ratio at 0512–0630 UT in the diamagnetic cavities was about 0.1–0.2, higher than before 0512 UT in the quasi-trapping region (panel 3); (3) the He^+/He^{++} and He^+/H^+ ratios decreased by more than one order of the magnitude and by a factor of about 5, respectively, from the quasi-trapping region before 0512 UT to the diamagnetic cavities after 0512 UT (bottom panel).

[11] Figure 4 plots the energy spectrum of the 6/28/99 CEP event, where the IPS (open squares) and Heavy Ion Telescope (HIT) (solid circles) are two different ion sensors on board Polar. In Figure 4, the cusp energetic ions have an energy up to 4 MeV.

4. Solar Wind Conditions and Diamagnetic Cavities

[12] The time profiles of the three components of the solar wind velocity measured by Wind in GSE coordinates during the high solar wind pressure period are plotted in the top three panels of Figure 5. Corrections have been made for the propagation time from Wind to Polar. The clock angles calculated from Wind (dotted line) and Polar (solid line) magnetic field data are showed in panel 4 from top of Figure 5. It indicates that the clock angle obtained from

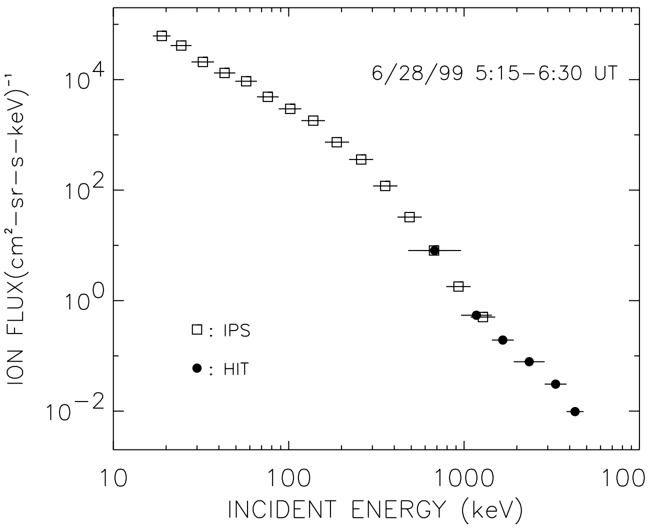

Figure 4. The measured cusp energetic particle (CEP) ion energy spectrum at 0515–0630 UT on 28 June 1999, where the Imaging Proton Sensor (IPS) (open squares) and Heavy Ion Telescope (HIT) (solid circles) are two sensors on board Polar.

Wind was different from that obtained from Polar except at around 0514 UT when Polar was close to the magnetopause boundary layer. The bottom panel of Figure 5 plots the distance of Polar from the magnetopause, where a positive value indicates Polar was inside the magnetopause in the magnetosphere and a negative value indicates Polar was outside the magnetopause in the magnetosheath. The magnetopause position is obtained from the model of *Shue et al.* [1998] after taking into account the solar wind pressure and the IMF z-component. This panel suggests that Polar was about one to two R_E from the magnetopause inside the magnetosphere during the event. Figure 5 further shows that the CDC location observed by Polar is independent of the solar wind velocity, which is consistent with what reported by *Sheldon et al.* [2003] on 9/22/96 CEP events.

[13] Figure 6 compares the three components of the IMF (top two panels) measured by Wind with the cusp diamagnetic cavities (bottom panel) observed by Polar during 28 June 1999 high solar wind pressure period, where the corrections for the solar wind time delay from Wind (27 min) to Polar have been made. The big change of the GMF in the first 3 min (0512–0515 UT) of the event (increased from about 100 nT to 180 nT and then decreased to 18 nT, bottom panel) occurred when the IMF changed its direction. However, for the entire event period no obvious dependence of the CDC position on the IMF components are found. One interesting point of Figure 6 is that at 0515–0542 UT and after 0612 UT the IMF B_y component was positive, while the CDC were observed at 7 hours magnetic local time (prenoon) in the northern hemisphere (see bottom of Figure 6). According to the prediction of the current MHD models, a positive IMF B_y would move the dayside northern cusp duskward into postnoon and southern cusp dawnward into prenoon [e.g., *Cowley et al.*, 1991; *Crooker et al.*, 1998], so that under the positive IMF B_y conditions the observation of the CDC in the prenoon in the northern hemisphere is unexpected and not predicted by the existing MHD models. This is a newly recognized property of the high-altitude dayside cusp region, something for which there is as yet no quantitative model. Since this prediction of the current MHD models is believed to be correct, one would expect that the northern (southern) CDC should also exist in the postnoon (prenoon) under the positive IMF B_y conditions on 28 June 1999.

[14] Figure 7 further compares the fluctuations of the IMF components (top two panels) measured by Wind with that of the GMF components measured by Polar (bottom two panels), where $dB = B_{i+1} - B_i$. The time delay corrections from Wind to Polar have been made. Even though Wind was in the far upstream region and Polar was inside the magnetosphere, the enhanced fluctuations in the ULF (ultra-low frequency) range observed by Wind were also detected by Polar at the similar time intervals. It is significant that the ULF fluctuations seem to pass right through the magnetopause from solar wind into the CDC.

5. Cone Angle and Cusp Energetic Ion Fluxes

[15] The cone angle is the angle between the IMF direction and the Sun-Earth line and is an indication of the bow shock geometry at the subsolar point. At the subsolar point, the bow shock is called quasi-parallel if the cone angle is less than 45°, and quasi-perpendicular if

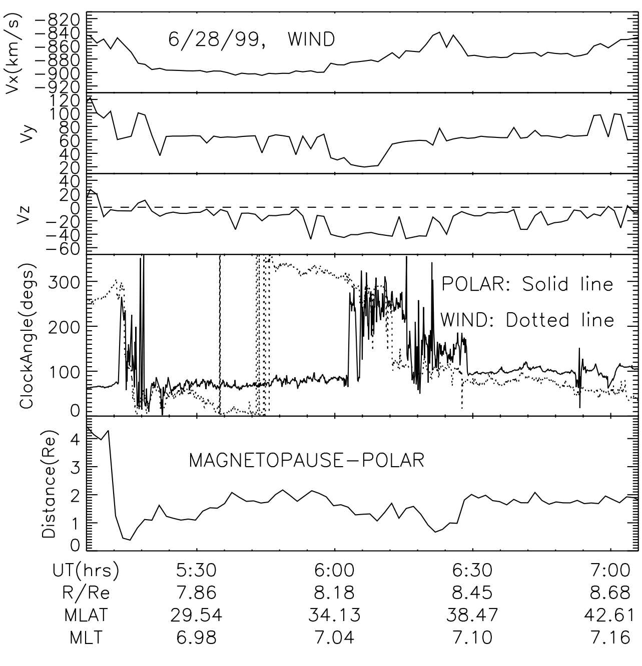

Figure 5. The time profiles of the three components of the solar wind velocity measured by Wind in GSE coordinates (top three panels), the clock angles calculated from Wind (dotted line) and Polar (solid line) magnetic field data (panel 4 from top), and Polar distance from the magnetopause (bottom panel) during the 28 June 1999 high solar wind pressure period. The distance of Polar from the Earth (in R_E), the magnetic latitude (MLAT), and the magnetic local time (MLT) are shown at the bottom of the figure. Corrections have been made for the propagation time from Wind to Polar.

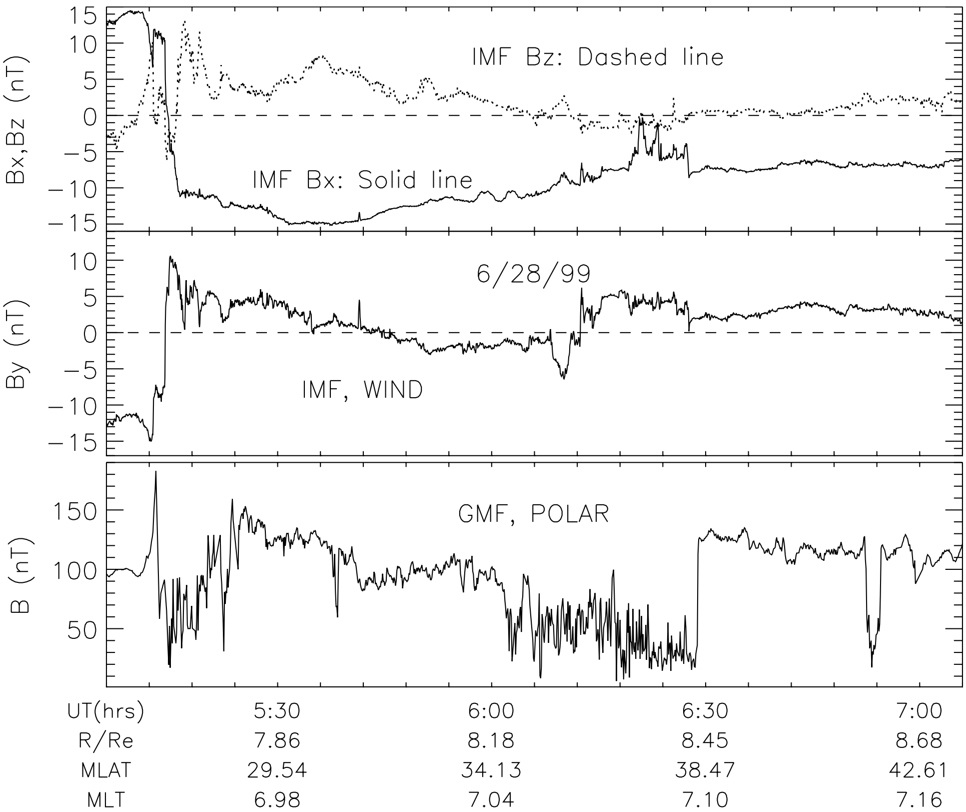

Figure 6. Comparison of the cusp diamagnetic cavities observed by Polar (bottom panel) with the three interplanetary magnetic field (IMF) components measured by Wind (top two panels) during 28 June 1999 high solar wind pressure period. Corrections have been made for the propagation time from Wind to Polar. The distance of Polar from the Earth (in R_E), the magnetic latitude (MLAT), and the magnetic local time (MLT) are shown at the bottom.

this angle is larger than 45°. Figure 8 plots the time profiles of the cone angle determined from the Wind IMF data (top panel) and the cusp energetic ion fluxes measured by Polar over four different energy ranges (bottom panel) during the high solar wind pressure period on 28 June 1999. In Figure 8, for most of the time from 0506–0706 UT the cone angle was less than 45°, indicating that the bow shock was quasi-parallel at the subsolar point. However, there were two short time intervals about 0512–0518 UT and 0620–0624 UT when the cone angle was around and above 45°, indicating a quasi-perpendicular bow shock geometry at the subsolar point in these two time intervals. Enhanced energetic ion fluxes were also present in these two intervals. Another feature in Figure 8 is that the onset of the CEP event was the same for different energies; that is, no velocity dispersion was found (see bottom panel).

6. Interball 1 Observations

[16] During the high solar wind pressure period on 28 June 1999, the Interball 1 spacecraft was upstream near the bow shock in the prenoon located at ~ (X = 22.4, Y = −15.7, Z = −6.25 in R_E) in GSE coordinates, and the Wind was near the forward libration point at ~ (209, −22.5, −2.6 in R_E). Figure 9 compares the IMF components measured by both the Interball 1 (solid lines) and the Wind (dotted lines), where the corrections for the solar wind time delay

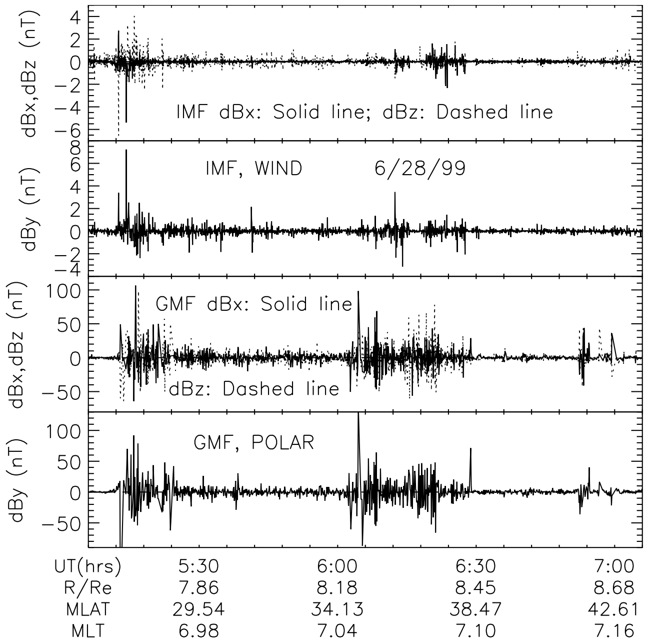

Figure 7. Comparison of the fluctuations of the IMF components (top two panels) measured by WIND with that of the GMF components measured by Polar (bottom two panels). The distance of Polar from the Earth (in R_E), the magnetic latitude (MLAT), and the magnetic local time (MLT) are shown at the bottom.

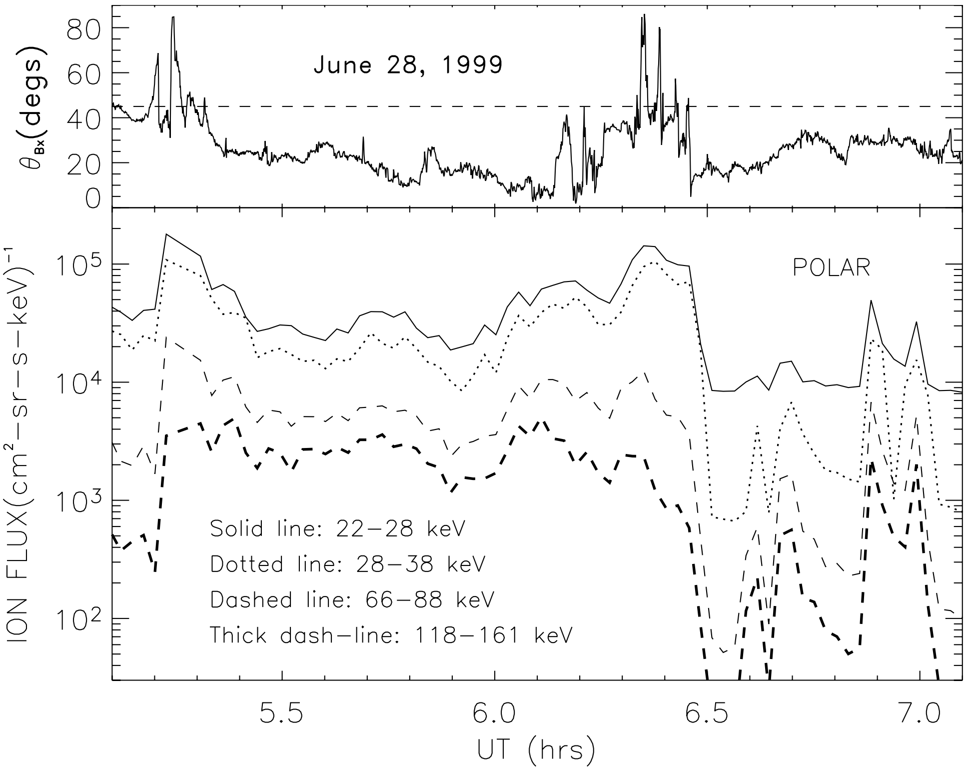

Figure 8. The cone angle determined from the Wind IMF data (top panel) and the cusp energetic ion fluxes measured by Polar over four different energy intervals (bottom panel) during the high solar wind pressure period on 28 June 1999.

from Wind (~26 min) to Interball 1 have been made. In spite of about 200 R_E difference in distance between Interball 1 and Wind, the IMF conditions measured by the two spacecraft were similar. At about 0515:30 UT, the IMF changed its direction and then its x-component became dominant.

[17] Figure 10 compares the upstream ion energy spectra observed by Interball 1 before 0515:30 UT (0513:13–0515:25 UT, open squares) and after 0515:30 UT (0515:39–0515:41 UT, solid circles). Compared to the ion flux at 0513:13–0515:25 UT, the upstream ion intensities at 0515:39–0515:41 UT increased over all energy ranges shown in Figure 10, indicating Interball 1 observed an upstream ion event onset at 0515:39 UT. Three peaks were observed in the 2-s ion flux (0515:39–0515:41).

[18] Figure 11 displays the time-intensity profiles of the upstream ion event observed by Interball 1 over three different energy intervals (61–65 keV, 198–212 keV, and 339–363 keV; bottom panel) with the solar wind ion density measured by Wind (top panel), the solar wind speed measured by Wind (panel 2 from top), the local magnetic field measured by Interball 1 (panel 3 from top), and the Θ_{Bn} for Interball 1 (panel 4 from top) versus time. The Θ_{Bn} is the angle between the IMF direction and the bow shock normal, where the bow shock normal is determined from the model of *Formisano* [1979]. The bow shock is called quasi-parallel if the Θ_{Bn} is less than 45° and quasi-perpendicular if this angle is larger than 45°. It is noticed that during this upstream event period (~0515:39–0600 UT) the solar wind speed was rather stable with a value of about 900 km/s (panel 2), while there was a two to three orders of magnitude change of the energetic ion flux measured by Interball 1 (bottom panel). Panel 4 shows that on 28 June 1999, Interball 1 was magnetically connected with the quasi-parallel bow shock before the onset (0515:39 UT) of this

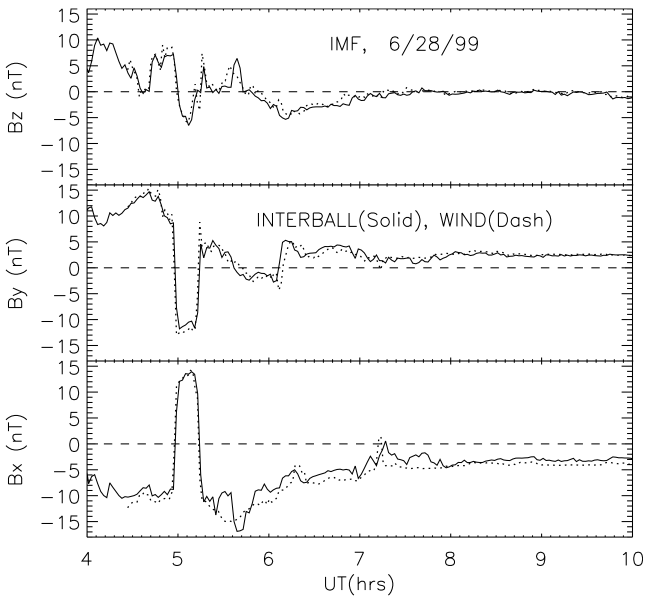

Figure 9. Comparison of the IMF components measured by Wind (dotted lines) in the far upstream region and by Interball 1 (solid lines) near the bow shock on 28 June 1999, where the corrections for the solar wind time delay from Wind to Interball 1 have been made.

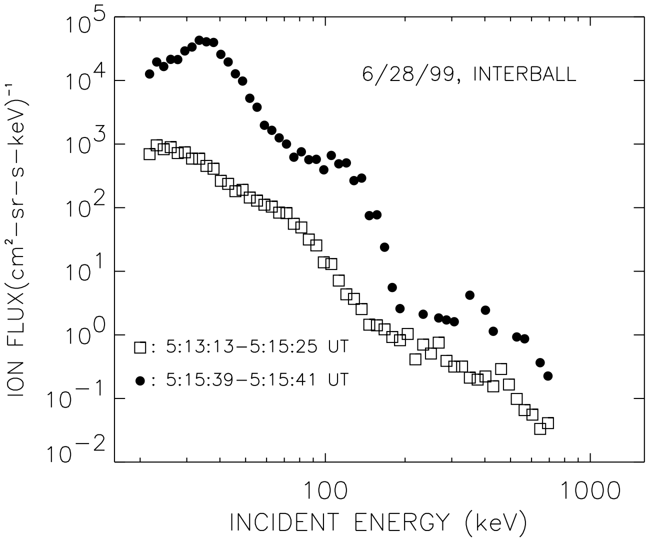

Figure 10. Interball 1 observations of the ion energy spectra before the upstream ion event onset at 0513:13–0515:25 UT (open squares) and after the onset at 0515:39–0515:41 UT (solid circles) on 28 June 1999.

upstream event until 0537 UT and was magnetically connected with the quasi-perpendicular bow shock after 0537 UT. Such magnetic connections with the bow shock can also be seen from the direct IMF measurement by Interball 1 shown in panel 3. Before 0537 UT the ULF waves were present with larger fluctuations (panel 3 of Figure 11), indicating that Interball 1 was magnetically connected with the quasi-parallel bow shock at the time; in contrast, after 0537 UT the fluctuations were much smaller and Interball 1 was either magnetically connected with the quasi-perpendicular bow shock or not magnetically connected with the bow shock. At 0537–0600 UT, Interball 1 still observed significant energetic ion fluxes even though it was in the quasi-perpendicular bow shock geometry.

7. Discussions

[19] The observations shown in sections 3 and 4 suggest that the high solar wind pressure event on 6/28/99 created the CDC observed by Polar at about 7 hours MLT, 30° MLAT, and 8 R_E from Earth (Figure 2) at a location that such a CDC should not be expected there under normal solar wind conditions. A statistical study of the CDCs (CEPs) observed by Polar in 1996 indicated that the CDCs are located from 45° to 80° MLAT with a peak number at about 65° MLAT and from 7 to 9 R_E in geocentric distance with a peak at about 8.8 R_E [*Chen et al.*, 1998]. Figure 6 shows that at the time the IMF was mainly in the radial direction toward the Earth, which should move the CDC poleward in the north and equatorward in the south due to magnetic mergings; in other words, one would expect the CDC also to exist in the north at >65° MLAT. The NOAA-12 satellite in a Sun-synchronous orbit at about 70° MLAT and 10 hours MLT observed a more than one order of magnitude increase of the 250–800 keV proton flux and more than four orders of magnitude increase of the 30–80 keV proton flux at about 0512 UT on 28 June 1999. If these energetic protons

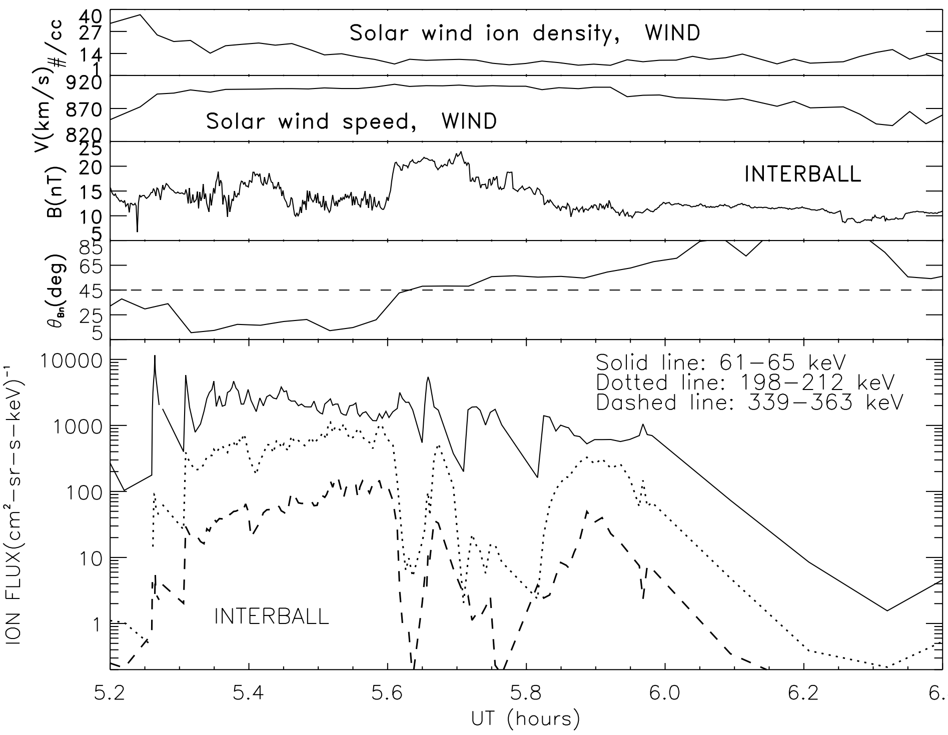

Figure 11. The solar wind ion density (top panel) and the solar wind speed (panel 2 from top) measured by Wind, the local IMF measured by Interball 1 (panel 3 from top), the Θ_{Bn} for Interball 1 (panel 4 from top), and the upstream ion fluxes observed by Interball 1 over three different energy intervals (61–65 keV, 198–212 keV, and 339–363 keV; bottom panel) versus time at 0512–0624 UT on 28 June 1999.

were part of the CEP event, then it suggests a large northern cusp existed in both the radial and latitudinal directions under such a high solar wind pressure condition. From the middle panel of Figure 6, the positive IMF y-component should move the northern cusp duskward into the postnoon sector according to MHD simulations [e.g., *Cowley et al.*, 1991; *Crooker et al.*, 1998], and the CDC should also exist in the postnoon sector in the Northern Hemisphere. Therefore one would expect to observe a CDC region crossing over an interval of more than 5 hours (>12–7) of local time. If one uses 8 R_E as the geocentric distance for this CDC as observed by Polar along with a 5 hour extent in local time, a simple calculation suggests an extremely large (>10.47 R_E) CDC in the longitudinal direction under the high solar wind pressure condition on 6/28/99. This is the largest CDC known so far.

[20] The facts that (1) energetic (55–200 keV/e) oxygen ions of ionospheric origin were observed in the CDC (panel 2 of Figure 2), (2) the CEP energy spectrum extended up to 4 MeV (Figure 4), and (3) the CEP ion fluxes were independent of the solar wind velocity (Figure 5) and the IMF cone angle (Figure 8) indicate that most of these energetic ions measured by Polar were not energized at the bow shock. The AE index was very small before 0512 UT. At about 0512 UT, the AE index increased from about 100 nT to 800 nT, suggesting an offset of magnetic activity at this time. Since Polar also observed the enhancement of the energetic ion flux at about 0512 UT, any associated substorm should not be the main source of these energetic ions in the CDC.

[21] An important long-standing unsolved question is the origin of upstream energetic ions. The Interball 1 spacecraft started to connect magnetically to the quasi-perpendicular bow shock at 0538 UT on 6/28/99 (Figure 11). The energetic ions detected by Interball 1 after 0538 UT may be explained by the drift acceleration ($V_yB_z - V_zB_y$) (Figures 5 and 6); however, the decrease of the upstream energetic ion flux after 0600 UT in a more perpendicular bow shock geometry and the increase of the upstream energetic ion flux at 0516–0537 UT (Figure 11) in the quasi-parallel bow shock geometry cannot be explained by the shock drift acceleration. Therefore the quasi-perpendicular bow shock should not be the main source of the upstream energetic ions observed by Interball 1.

[22] On the other hand, in order for there ions to be accelerated at a quasi-parallel bow shock, they need to interact with the bow shock many times and to stay there for an extended period. The higher the energy obtained, the longer the time required. By analyzing 33 diffuse ion events upstream from the bow shock, *Ipavich et al.* [1981] found an inverse velocity dispersion signature in every event. The onset time in the upstream ion event measured by Interball 1 for different energy ranges were almost the same (not any obvious inverse velocity dispersion) (bottom panel of Figure 11). Furthermore, at the upstream event onset (0515:39 UT), the ion energy spectrum accumulated in 2 s showed three distinct peaks at around 34 keV, 120 keV, and 340 keV. Such a feature has been called "almost monoenergetic ions" (AMI) and was first reported by *Lutsenko and Kudela* [1999] from Interball 1 energetic ion measurements. The energetic ion detectors on board Interball 1 have much higher-energy resolutions than those on board Polar. *Lutsenko and Kudela* [1999] reported that more than 200 cases of energetic ion beams have an energy spectrum with 1–3 narrow peaks in the region upstream of the bow shock and in the magnetosheath. The AMI feature is unexpected from the bow shock acceleration. The AMI may come from the CEPs. Some of the CEPs that are energized by a cusp resonant acceleration mechanism may escape into the solar wind through open field lines when the CDCs collapse, and an ion detector with high energy and time resolutions will observe resonant peaks in the ion energy spectra in the magnetosheath and upstream of the bow shock.

[23] If the quasi-parallel bow shock was the source of the measured ions, the resulting spectral index of the ion energy spectrum should depend only on the solar wind velocity, and the spectral amplitude should be anticorrelated with the bow shock geometry and should be linearly related to the solar wind density [e.g., *Trattner et al.*, 2003; *Sheldon et al.*, 2003]. Figure 12 compares the ion energy spectrum at 0518–0521 UT (F_1) with that at 0530–0533 UT (F_2) (top panel) and their ratio (bottom panel) on 6/28/99. The solar wind ion density, the solar wind speed, and the Θ_{Bn} have an averaged value of 17.9 (#/cc), 896 (km/s), and 11.5°, respectively, at 0518–0521 UT, and of 13.5 (#/cc), 900 (km/s), and 13.4°, respectively, at 0530–0533 UT. For a power law spectrum, $F = A * E^i$ with A being the spectral amplitude (a constant) and i the spectral index (a constant), since the solar wind speed is almost the same at 0518–0521 UT and at 0530–0533 UT, one would expect the same spectral index for these two time periods; i.e., $i_1 = i_2$, and the ion flux ratio, $F_2/F_1 = A_2/A_1 =$ constant, if the measured upstream energetic ions were energized at the quasi-parallel bow shock. The Interball 1 energetic ion data in bottom panel of Figure 12 show that over 20–30 keV, the ion flux ratio was almost the same; however, at energy >30 keV, the ratio starts to increase. The key point is that during these two periods, the upstream solar wind velocities were almost the same, but the ion flux ratio (at >30 keV) changed by as large as one order of magnitude (bottom panel of Figure 12). The solar wind density was about 33% higher at 0518–0521 UT than at 0530–0533 UT, which may explain the higher ion flux over 20–30 keV at 0518–0521 UT if the quasi-parallel bow shock was the main source; however, it cannot explain the observation at >30 keV shown in Figure 12. Similarly, the connection efficiency to the bow shock cannot explain the ion measurement at >30 keV shown in Figure 12 due to a lack of an anticorrelation between the upstream energetic ion flux and the bow shock geometry. Thus in this case, the quasi-parallel bow shock may be the main source for the upstream ions only up to 30 keV and should not be the main acceleration source for the upstream ions >30 keV.

[24] From 0500 to 0630 UT on 6/28/99, the 50–400 keV ion fluxes, measured by the LANL1994_084 (near local noon), the LANL1991_080 (near dawn), and the LANL1989_046 (near dusk) geostationary satellites, were rather stable except for near 0512 UT when the LANL1994_084 near local noon observed a decrease of the 50–400 keV ion fluxes. At the time, Interball 1 was in the prenoon upstream from the bow shock and was 6.25 R_E below the equatorial GSE plane ($X = 22.4$, $Y = -15.7$, $Z = -6.25$ in R_E), and the IMF measured by Interball 1 was

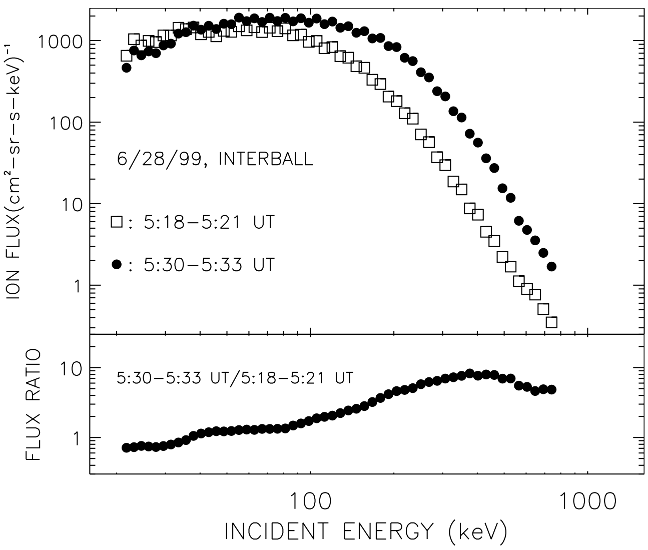

Figure 12. Comparison of the ion energy spectrum at 0518–0521 UT with that at 0530–0533 UT (top panel) and their ratio (bottom panel) on 6/28/99.

dominated by its B_x component. Under these conditions Interball 1 would not observe outer radiation belt energetic ions leaked from the duskside magnetopause near the equatorial plane. In other words, the leakage from the equatorial outer radiation belt was also not the main source of energetic ions in this upstream event observed by Interball 1.

[25] One possible source is the production of energetic ions in the cusp. *Sheldon et al.* [1998] reported one kind of orbit, in which the charged particles are mirroring around the minimum magnetic field near the cusp center and are drifting in closed drift shells around the cusp. The cusp has a locally outward magnetic gradient in contrast to the typical inward gradient in the radiation belt. The energetic ions could be energized in the cusps by the resonant interactions of these ions with the turbulent ultra-low frequency (ULF) electromagnetic power, since the ULF range covers all of the ion drift, bounce, and gyrofrequencies in the cusp [*Chen and Fritz*, 1998]. The left-hand polarization of the cusp electric field could be resonant with the ion gyroperiod, the right-hand polarization could be resonant with the ion drift period, and the fluctuation of the cusp parallel electric field could be resonant with the ion bounce period. Recently, *Chen et al.* [2004] reported that (1) turbulent cusp electric field with an amplitude of about 100 mV/m has been detected by Polar; (2) dominated by its perpendicular components, the cusp electric field spectral density for fluctuations in the ULF range shows orders of magnitude increases; and (3) both left- and right-hand polarizations have been measured. The CEPs could also be energized in the CDC by an adiabatic compression [*Sheldon et al.*, 2005] or in the outer cusp by a large

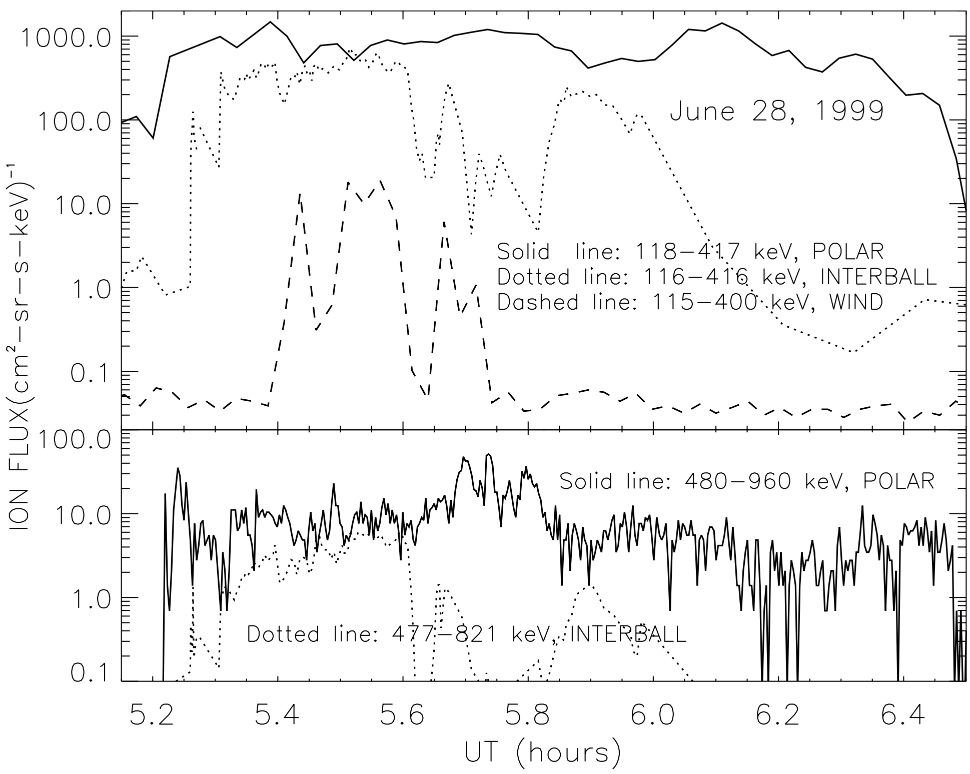

Figure 13. The simultaneous energetic ion observations by Wind (dashed line), Interball 1 (dotted line), and Polar (solid line) over an energy range of about 110–400 keV (top panel) and by Interball 1 (dotted line) and Polar (solid line) over about 480–900 keV (bottom panel) from 0509 to 0630 UT on 28 June 1999, where no time delay corrections were made for the energetic ions transported from the Wind and Interball 1 to the Polar.

transient electric field associated with violation of adiabatic invariants [*Delcourt et al.*, 2005].

[26] The simultaneous energetic ion observations by the three spacecraft (Wind, dashed line; Interball 1, dotted line; Polar, solid line) over an energy range of about 110–400 keV (top panel) and by two spacecraft (Interball 1, dotted line; Polar, solid line) over about 480–900 keV (bottom panel) from 0509 to 0630 UT are compared in Figure 13 during the 28 June 1999 high solar wind pressure period, where no time delay corrections were made for the energetic ions transported from Wind and Interball 1 to Polar. During this period, the Interball 1 spacecraft was upstream from the bow shock in the prenoon sector located at (X = 22.4, Y = −15.7, Z = −6.25 in R_E) in GSE coordinates, and Wind was near the forward libration point at ~ (209, −22.5, −2.6 in R_E). As shown in Figure 13, three observational facts are obvious: (1) the event onset (increase of energetic ion intensity) was observed first by Polar in the cusp at 0512 UT, then by Interball 1 upstream near the bow shock at 0516 UT, and then by Wind far upstream at 0523 UT; (2) the time interval from onset of the energetic ion fluxes to their decrease (i.e., the duration of the event) increased from far upstream (Wind) to near the bow shock (Interball 1) and to the cusp (Polar); and (3) the intensity of the energetic ion flux decreased from the cusp (Polar) to near the bow shock (Interball 1) and to far upstream (Wind). The onset time delay (7 min) from Interball 1 (0516 UT) to Wind (0523 UT) was not due to the IMF connection to the bow shock because the IMF measured by WIND was very similar from 0519 to 0536 UT and was dominated by its B_x component (Figure 9). In fact, an 115 keV proton takes about 4.24 min from Interball 1 (22.4 R_E) to reach Wind (209 R_E) for a simple time of flight, and 7 min is expected if taking into account the proton spiral movement along the IMF field line.

[27] In fact, the CEP events are very common in the high-altitude dayside cusp regions and are always there day after day. Around solar minimum at the time of Polar launch through the end of 1997, there were about 300 cusp crossings, in which 279 or 93% of the crossings were identified as CEP events [*Fritz et al.*, 1999b]. In April 1999 when closer to solar maximum, there were 40 cusp crossings and all of them were identified as CEP events [*Fritz et al.*, 2003a]; in May 1999, there were 35 cusp crossings and again all of them were CEP events [*Chen and Fritz*, 2005]. These CEP events were associated with diamagnetic cavities and strong magnetic field turbulence. The intensities of the cusp energetic ions were observed to increase by as large as four orders of the magnitude, and their seed populations were a mixture of ionospheric and solar wind particles [*Chen and Fritz*, 2001; *Fritz et al.*, 2003a, 2003b]. Recent research shows that the time series and the fluctuations of the solar wind density were highly correlated with the GMF observations for intervals ranging from a few to 12 hours [*Kepko and Spence*, 2003]. Figure 3 shows that the H^+ and He^{++} ions track each other exactly, and over large energy ranges, even though their gyrotimes and their bounce times are very different and should interact with waves differently, which suggests an adiabatic heating, a global compression, not just a wave-particle interaction. One would expect the cusp magnetic field to increase in a compression (such as in a cyclotron or betatron). However, no, the cusp magnetic field decreased! This puzzle is the key to understanding the behavior. The energetic particles are acting as if they are demagnetized, like a simple gas in this case. The CDC expels the magnetic field, and then the plasma inside it acts like a neutral gas. The increase in Chapman-Ferraro currents decreases the volume of the CDC by a factor of 10 (or conversely, increases the pressure by a factor of 10), which increases the work (energy of particles) by a factor of 10. Since this is a multiplication (not an addition), it does not change the spectral form (as plotted on log-log scale). This is precisely what Interball 1 is showing. However, the compression is perpendicular to the local magnetic field direction. This is a magnetic bottle geometry, not a Fermi-like parallel compression. When CEPs scatter (due to turbulence), they leak out of the bottle and race upstream to be observed by Interball 1. Any energy dispersion is purely due to TOF effects (on the order of minutes), not due to the exponential rise in time with energy due to stochastic acceleration. The observational facts (extremely large CDC, event onsets of energetic ion intensities, and radial IMF) suggest that the upstream energetic ions measured by Interball 1 and Wind may be interpreted as leakage of the cusp energetic ions along open field lines.

8. Conclusions

[28] On 28 June 1999, the high solar wind dynamic pressure compressed both the bow shock and the magnetosphere. At 0506–0630 UT, the Wind spacecraft was close to the forward libration point, the Interball 1 spacecraft was upstream and near the bow shock in the pre-noon sector south of the GSE X, Y plane, and the Polar satellite was in the high-altitude dayside region. Our principal conclusions from the simultaneous multiple spacecraft observations are the following:

[29] 1. The solar wind pressure produced an energetic ion event 1 to 2 R_E inside the magnetopause.

[30] 2. Both particle and field features suggest that the ion event detected by Polar was a CEP event even though Polar was at 7 hours magnetic local time. The measured cusp ions had energies up to 4 MeV.

[31] 3. Energetic ions of both ionospheric origin and solar wind origin were observed by the Polar during this event period. The He^{++}/H^+ ratio in the diamagnetic cavities was higher by a factor of about four than in the quasi-trapping region before the event onset, while the He^+/He^{++} in the cavities was lower by more than one order of the magnitude.

[32] 4. The cusp energetic ions were independent of the solar wind velocity, the IMF vector, and the cone angle.

[33] 5. The enhancements of the magnetic field fluctuations in the ultra-low frequency range measure by the Wind spacecraft were also observed by the Polar satellite.

[34] 6. The Interball 1 spacecraft located just upstream of the bow shock in the prenoon sector measured an upstream ion event from about 0516 UT to 0600 UT. The onset of the upstream event observed by Interball 1 was the same for different energies.

[35] 7. The upstream ion energy spectra measured by Interball 1 were independent of the solar wind velocity, and their intensities were independent of both the bow shock geometry and the solar wind density.

[36] 8. The energetic ion event was observed by Polar at 0512–0630 UT, by Interball 1 at 0516–0600 UT, and by Wind at 0523–0545 UT.

[37] 9. The event onset was first detected in the cusp, then near the bow shock on the prenoon, and then in the far upstream region; and the measured energetic ion intensity decreased with increasing distance from the cusp.

[38] 10. These observational facts together with the IMF directions suggest that (1) this high solar wind pressure event produced an extremely large diamagnetic cavity (>10 R_E) within the magnetosphere, (2) the bow shock was not the main source of the cusp energetic ions, (3) the bow shock was also not the main source of the upstream energetic ions, and (4) the upstream energetic ions most likely came from the cusp.

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