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Proton aurora in the cusp

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[1] Frequently, the Far Ultraviolet Instrument (FUV) on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) spacecraft observes intense ultraviolet emission from a localized dayside region poleward of the general auroral oval location. This emission is especially distinct in the Doppler-shifted emission of hydrogen atoms produced by precipitating protons. We interpret this as a direct signature of proton precipitation into the cusp after reconnection of magnetospheric lobe field lines. This cusp signature appears only when the interplanetary magnetic field (IMF) has a positive northward B_z component. However, the intensity of the precipitation, and hence the intensity of UV emission, is not controlled by the magnitude of B_z but rather by the solar wind dynamic pressure. A statistical analysis of 18 cases observed in summer and fall 2000 shows good correlation between the UV intensity and the dynamic pressure and between the location in local time and the IMF B_y component. A quantitative analysis of observations from all three FUV subinstruments allows for an estimate of proton and electron energy fluxes during these times. In general, these estimates agree with results from in situ measurements by spacecraft and show that during these times, protons may contribute significantly to the overall energy deposition into the cusp. *INDEX TERMS:* 2704 Magnetospheric Physics: Auroral phenomena (2407); 2716 Magnetospheric Physics: Energetic particles, precipitating; 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; *KEYWORDS:* aurora, cusp, proton, precipitation, reconnection, interplanetary magnetic field (MLT)

1. Introduction

[2] The main objective of the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) mission is to improve the understanding of magnetospheric processes. One signature of the interaction between the magnetosphere and ionosphere is the occurrence of aurora. Observations of the global aurora can provide important context information supplementing the direct imaging of the magnetosphere. Previously flown satellites have demonstrated the suitability of far ultraviolet imaging for remote sensing observations of auroral precipitation [see, e.g., *Frank and Craven*, 1988]. The major objective of the Far Ultraviolet Instrument (FUV) on IMAGE is the observation of global changes in the aurora accompanying large-scale changes in the magnetosphere [*Mende et al.*, 2000]. The FUV consists of the imaging channel Wideband Imaging Camera (WIC) and the dual-channel Spectrographic imagers (SI-12 and SI-13). One feature of the FUV is the capability for simultaneous observation in three different wavelength regions. Previously flown imagers had to change filters between exposures, which introduced a temporal uncertainty when analysis involved comparison between distinct channels [*Torr et al.*, 1995].

[3] Since its discovery by low-altitude polar-orbiting satellites [*Burch*, 1968], the cusp has been known as the area where magnetosheath plasma could most easily access the lower altitude. Further statistical studies confirmed the localized nature of the cusp near local noon [see, e.g., *Newell and Meng*, 1994] and established our knowledge about the morphology, dynamics, particle, and optical signatures of the cusp [see, e.g., *Reiff et al.*, 1977; *Woch and Lundin*, 1992; *Sandholt*, 1997; *Dunlop et al.*, 2000]. There are three major models describing the cusp morphology and dependence on external solar wind conditions: the MHD model, the turbulence/diffusive entry model, and the direct flowing entry model [see *Yamauchi and Lundin*, 2001, and references therein]. These models describe many of the special cusp properties, but they are varyingly successful in describing the low-resolution and high-resolution observations, so that none of them describes everything (see *Yamauchi and Lundin* [2001] for a full discussion).

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[4] The magnetospheric cusp plays an important role as the region of most direct connection between the ionosphere and the interplanetary medium through reconnection [*Smith and Lockwood*, 1996]. Reconnection between magnetospheric and interplanetary magnetic field lines is likely to occur whenever their directions (or at least one component) are antiparallel [*Onsager and Fuselier*, 1994; *Fuselier et al.*, 1997]. During the southward interplanetary magnetic field (IMF) condition, magnetic field lines in the subsolar region can connect to the solar wind magnetic field and become open. During the northward IMF condition, reconnection can take place at the high-latitude magnetopause. During intermediate conditions with a small northward and dominating east-west component of the IMF, a mixed situation with reconnection at the high- and the low-latitude region may occur simultaneously [*Reiff and Burch*, 1985].

[5] Dayside auroral forms in the cusp region so far have mostly been classified from ground-based observations. During northward IMF conditions (clock angle $\theta < 45°$), bands of auroral emission dominate at high latitudes (78°–79°, type 2 cusp aurora); during intermediate conditions ($\theta \approx 45°-90°$), auroral bands are present at high and low (<75°) latitudes; and during southward IMF ($\theta > 90°$) the high-latitude aurora disappears, and only the low-latitude forms (type 1 cusp aurora) remain [*Sandholt et al.*, 1998]. These auroral forms show asymmetries depending on the IMF east-west B_y component and are related to reconnection processes at either high- or low-magnetopause latitudes [*Øieroset et al.*, 1997].

[6] In a recent paper, *Milan et al.* [2000] described an event study of an interval of northward IMF, where they observed luminosity near local noon poleward of the dayside auroral oval with the UVI instrument on the Polar satellite. They interpreted this emission as the signature of high-latitude reconnection and described its motion in response to IMF B_y changes in coordination with observations of the large-scale convection flow by the Co-operative UK Twin Auroral Sounding System (CUTLASS) Finland HF radar.

[7] In this paper we are going to perform a statistical analysis of the correlation of intense proton aurora emission in the dayside cusp region as observed by the IMAGE FUV with the corresponding solar wind parameters. After a brief summary of instrumentation and analysis techniques we will discuss individual observations and finally summarize 18 cases in a statistical way.

2. Estimate of Mean Energy and Energy Flux in the Cusp Aurora

[8] Auroral emissions can either be excited by precipitating electrons or protons [*Strickland et al.*, 1993]. Most emissions do not contain information about the identity of the exciting particle as they originate from oxygen and nitrogen atoms, molecules, or ions of the upper atmosphere. Many previous papers on aurora observations interpreted all emissions as being caused by electron precipitation. However, energetic protons are very efficient in producing secondary electrons that in turn are capable of creating aurora indistinguishable from pure "electron aurora" [*Hubert et al.*, 2001]. Generally, the flux of energetic protons is low, and the contribution of protons to the aurora is small, but occasionally, their contribution must be taken into account [*Frey et al.*, 2001].

[9] The auroral emission in a particular region depends on the local precipitation characteristics (spectrum and flux) of electrons and protons and the composition of the atmosphere. A full model calculation of the expected auroral signal requires a full description of the particle spectrum, for instance, by measurements from a low-altitude satellite as done by *Frey et al.* [2001]. This approach, however, is impossible on a global scale because there are simply not enough satellites orbiting Earth. A global approach has to rely on certain simplifications, and one reasonable way is the simplified description of the particle spectra by the mean energy and the total flux assuming a certain energy distribution function like Gaussian, Maxwellian, or kappa functions. This approach requires the determination of only five unknown parameters, the atmospheric composition (O/N_2 ratio) and the flux F and mean energies $\langle E \rangle$ of precipitating electrons e and protons p, respectively. The generalized simplified description of the signal in our instruments can then be given as

$$I(\mathrm{S12}) = F(p) b_{S12}(\langle E_p \rangle), \tag{1}$$

$$I(\mathrm{WIC}) = F(p) b_{\mathrm{WIC}}(\langle E_p \rangle) + F(e) a_{\mathrm{WIC}}(\langle E_e \rangle), \tag{2}$$

$$I(\mathrm{S13}) = F(p) b_{S13}(\langle E_p \rangle) + F(e) a_{S13}(\langle E_e \rangle). \tag{3}$$

[10] The measurements I(WIC), I(S12), and I(S13) provide three input parameters for solving the mathematical problem of simulating the global distribution of auroral emission. The parameters a and b with the subscripts for every instrument depend on the mean energy of the electrons and protons and on instrument parameters like the width and location of the passband, the gain, etc. For all our simulations we will assume a Maxwellian distribution for electrons and a kappa function for protons. Two of the unknown parameters (atmospheric composition and proton mean energy) will be eliminated in this approach. Here we use a single atmospheric composition altitude profile according to the Mass Spectrometer Incoherent Scatter (MSIS) model for high solar and moderate magnetic activity. The full description of this quantitative analysis of FUV observations is beyond the scope of this paper and will be published elsewhere. Here we will use it to estimate the precipitation characteristics in the cusp.

3. Instrumentation and Data Analysis

[11] The IMAGE satellite is in a highly elliptical orbit of 1000 × 45600 km altitude. The FUV consists of three imaging subinstruments and observes the aurora for 5–10 s during every 2 min spin period [*Mende et al.*, 2000]. The major properties like fields of view, spatial resolution, and spectral sensitivity were validated by in-flight calibrations with stars [*Gladstone et al.*, 2000]. The WIC has a passband of 140–180 nm. It measures emissions from the N_2 Lyman-Birge-Hopfield (LBH) band and atomic nitrogen N I lines, with small contributions from the atomic oxygen O I 135.6 nm line. The proton aurora imaging Spectrographic Imager channel (SI-12) is sensitive to the Doppler-shifted Lyman α emission around 121.8 nm from

Table 1. Summary of All Events Used for This Study[a]

Date and Time, UT	Density, cm^{-3}	B_y	B_z
2000, day-176, 0154–0545	6–42	−12 to + 10 (−4)	−6 to + 14 (+4)
2000, day-178, 1110–1212	2–18	−16 to −3 (−9)	−10 to + 33 (+1)
2000, day-183, 1913–2039	9–15	−3 to 0 (−2)	+4 to +4 (+5)
2000, day-195, 1524–1928	6–12	−2 to +11 (+5)	−1 to +10 (+4)
2000, day-210, 1114–1406	11–40	0 to +21 (+15)	−17 to +19 (+1)
2000, day-211, 1546–1902	10–21	−2 to +4 (+2)	−2 to +5 (+4)
2000, day-218, 0435–0955	1–12	−7 to +10 (+4)	−20 to +20 (+2)
2000, day-240, 1701–2122	6–17	−6 to +4 (−1)	−5 to +3 (+1)
2000, day-250, 1846–2241	3–26	−4 to +15 (+6)	−12 to +13 (+4)
2000, day-261, 1501–1933	5–27	−27 to +13 (−5)	−20 to +33 (+15)
2000, day-262, 0129–0943	2–35	−16 to +2 (−9)	+12 to +29 (+19)
2000, day-262, 1528–1842	2–23	−11 to +4 (−5)	−8 to +11 (+3)
2000, day-263, 0613–0951	1–12	−9 to +4 (−3)	−2 to +9 (+5)
2000, day-279, 0620–1110	14–74	−19 to +24 (0)	−26 to +21 (+7)
2000, day-309, 0202–0418	12–51	−22 to 0 (−12)	−9 to +15 (+2)
2000, day-311, 2149–2302	1–29	−1 to +9 (+5)	−13 to +9 (+1)
2000, day-313, 0233–0819	2–53	−10 to +10 (−1)	+3 to +18 (+15)
2000, day-331, 1116–1845	6–36	−14 to +16 (+2)	−14 to +19 (+9)

[a] The solar wind values are shifted for the propagation time. The magnetic field values show the range for the full time interval and the mean value, rounded to the nearest integer.

charge-exchanging precipitating protons. The instrument properties do not allow determination of the exact Doppler shift and the energy of the emitting hydrogen atom. However, as was confirmed by theoretical modeling, it is mostly sensitive to proton precipitation in the energy range of 2–8 keV, with very low sensitivity below 1 keV [*Gérard et al.*, 2000, 2001]. The oxygen imaging Spectrographic Imager channel (SI-13) has a passband of 5 nm around the 135.6 nm doublet of oxygen OI emission. The measured signal is a combination of OI and some contribution from lines in the N_2 LBH emission band (20–50% depending on electron energy).

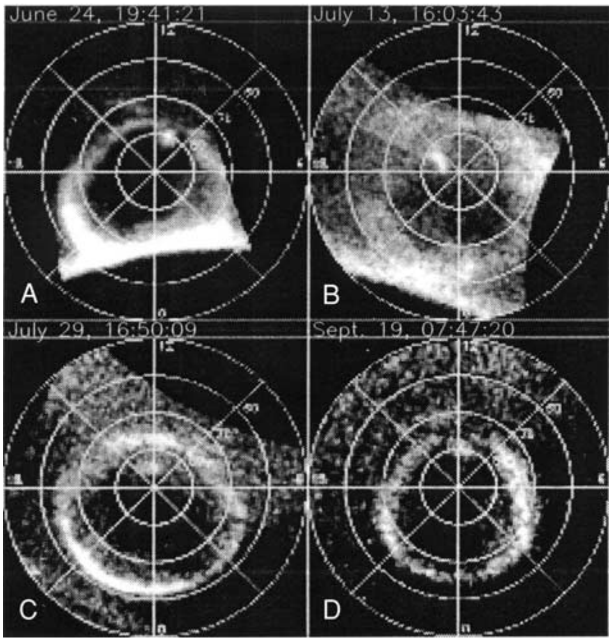


Figure 1. Examples of observations of the proton imager of the FUV on four different days in 2000. The original images were remapped into a MLT-latitude grid with local noon at the top, midnight at the bottom, and dawn to the right of each image. At some times the spacecraft was too close to the Earth to image the whole auroral oval.

[12] Solar wind parameters for this study were obtained through Coordinated Data Analysis Web (CDAWeb) from the Wind and Geotail spacecraft. Geotail can be about 30 *RE* in front of Earth, but it also moves through the magnetosphere, when measurements were discarded for this study. Wind changed from a location 40 *RE* in front of Earth to more than 200 *RE* at the dawn side. All solar wind properties were propagated to Earth using the instantaneous solar wind speed values.

[13] During the time period of 5 June to 26 November 2000 (days of year 157–331), 18 clear cases of a localized bright UV emission on the dayside were found (Table 1). Figure 1 shows examples from four different days, when the localized feature could be observed poleward of the dayside auroral oval location. These cases were especially pronounced in the images from the proton camera because this channel does not suffer from a dayglow background. However, after proper dayglow subtraction, similar features could be seen in the other FUV channels as well (Figure 2). The two selectrion criteria for the events were as follows: (1) a localized region of bright Doppler-shifted Lyman α emission had to be found poleward of the dayside auroral oval-, and (2) the localized region had to be observable for at least 30 min.

[14] The second criterion removed several short time periods from the original selection (for instance, 2000, day-268, 1735–1745 and 2000, day-315, 1238–1255). An image from another discarded time period (2000, day 160,

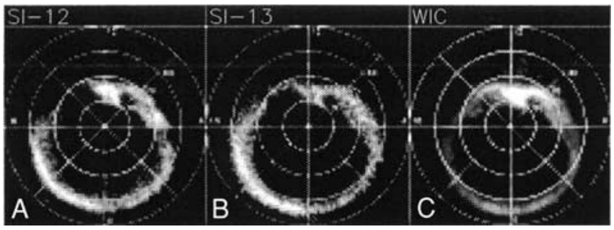


Figure 2. Observation of all three FUV on 18 September 2000 at 0402:01. The format of each image is the same as in Figure 1: (a) proton image, (b) the oxygen image, and (c) the wideband image.

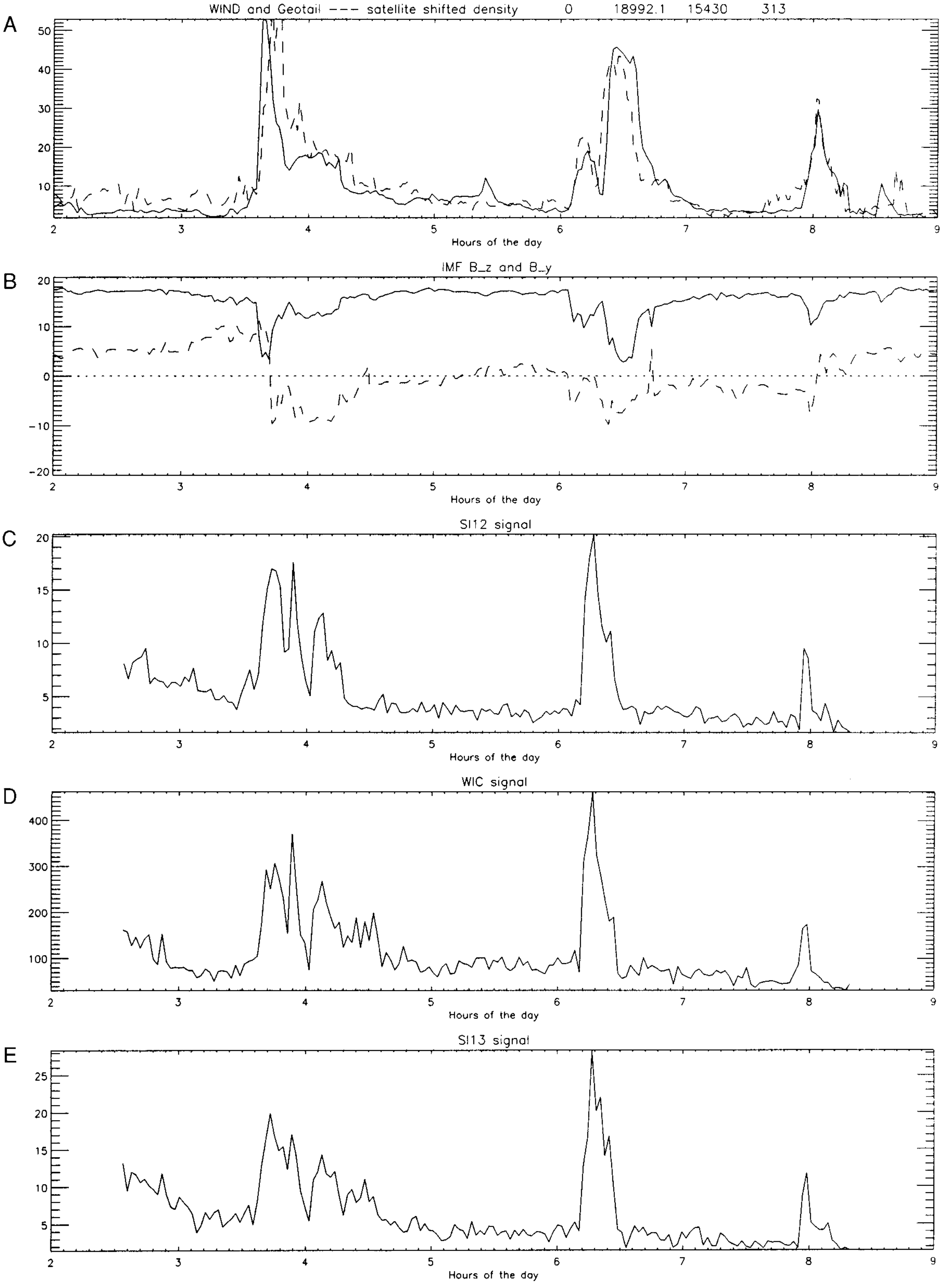


Figure 3. Summary of ultraviolet observations from the cusp and related solar wind parameters for 8 November 2000 (day 313): (a) the time-shifted solar wind proton density (Wind, solid line; Geotail, dashed line), (b) the Wind-measured IMF GSM B_z (solid line) and B_y (dashed line) components, (c) the brightest proton aurora emission (instrument counts), (d) the emission in the wideband imaging camera (instrument counts), and (e) the oxygen imager (instrument counts) in the corresponding regions.

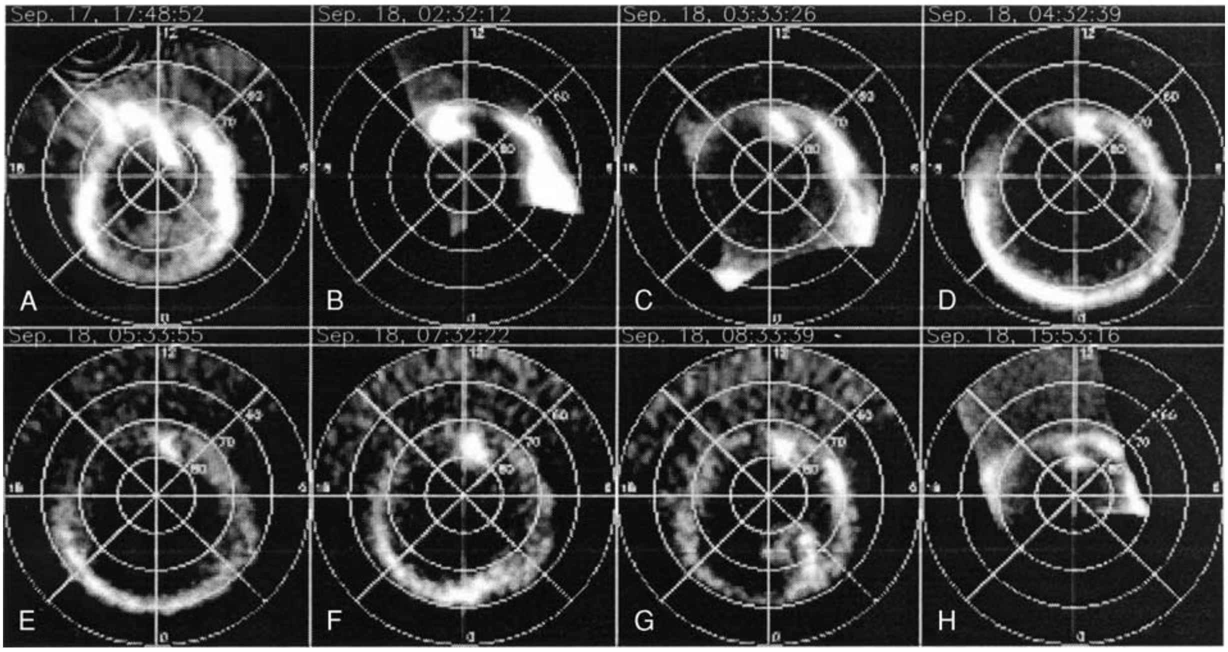


Figure 4. Examples of observations by the FUV proton imager on 17 and 18 September 2000. The format is the same as in Figure 1.

0912–0920) is given by *Fuselier et al.* [2001]. Each individual time sequence was then analyzed in the SI-12 images in the following way. Whenever the bright feature was seen in the SI-12 images, the mean count rate in a region of 3 × 3 pixels (about 300 × 300 km from apogee) around the brightest pixel was determined as well as the location in magnetic local time (MLT) and geomagnetic latitude. That location was then mapped into the images of SI-13 and WIC, where again, the mean image intensity in an area of 3 × 3 or 5 × 5 pixels, respectively, was determined. If the localized emission vanished below background level, the last location was tracked for another 30 min. If the emission appeared again within 30 min, the whole sequence was considered as one event. If the emission did not appear again, 15 min after the disappearance were still included in this study.

4. FUV Observations

4.1. Cusp Aurora on 8 November 2000

[15] FUV observations on 8 November 2000 (day 313) show most clearly the relationship between the auroral emission from the cusp and the solar wind parameters (Figure 3). Over the course of 5 hours the solar wind dynamic pressure increased three times for short periods, and the SI-12 signal closely followed these increases. The small differences in the arrival times of the shifted density pulses from Wind and Geotail are within the uncertainty range of 5 min. The IMF B_z component was almost steadily positive (northward) around 20 nT with short decreases during the times of pressure increases. All the other FUV instruments showed similar short increases in their output signal. How these changes are related to changes in the proton precipitation will be discussed later.

4.2. Cusp Aurora on 17–18 September 2000

[16] The FUV observations on 17–18 September 2000 (days 261–262) show the longest and clearest cusp signatures in this study. Figure 4 gives a summary of the observations between 17 September 1748 UT and 18 September 1553 UT. The signature of intense proton precipitation on the dayside appeared on 17 September after 1600 UT and was observable until 1953 UT, when the instrument was turned off before entering the radiation belt. When the FUV instrument turned on after leaving the radiation belt on 18 September at 0128 UT, an intense cusp signature could be observed, and it remained strong until 1013 UT when the instrument again was turned off before entering the radiation belt. See also Figure 2 for the signature in the other two FUV channels. At the beginning of the next orbit at 1528 UT the same feature was there again, but this time it disappeared after 1640 UT. There is good reason to believe that the intense cusp proton precipitation disappeared after 1300 UT and reappeared shortly before instrument turn on, and that it did not persist all the time when IMAGE was near perigee. The details of this will be discussed later.

[17] The solar wind conditions are summarized in Figure 5. The solar wind density increased dramatically on 17 September around 1600 UT (not shown) and remained high until 515 UT on 18 September. The drop in density is followed by a decreasing signal in the proton imager (Figure 5c). During this entire period the IMF remained strongly northward with a B_z always >10 nT and as high as 29 nT. The B_y component changed from positive values before 0130 UT to negative values later, and as a reaction, the cusp signature changed location from 1330 to 1030 MLT, which can also be seen in Figures 4b and 4c. Later, the cusp location remained in the prenoon region.

4.3. Cusp Aurora on 24 June 2000

[18] The observations on 24 June 2000 (day 176) are summarized in Figure 6. The solar wind density had already increased before FUV turned on after leaving the radiation belt. The cusp signal decreased together with the density, and

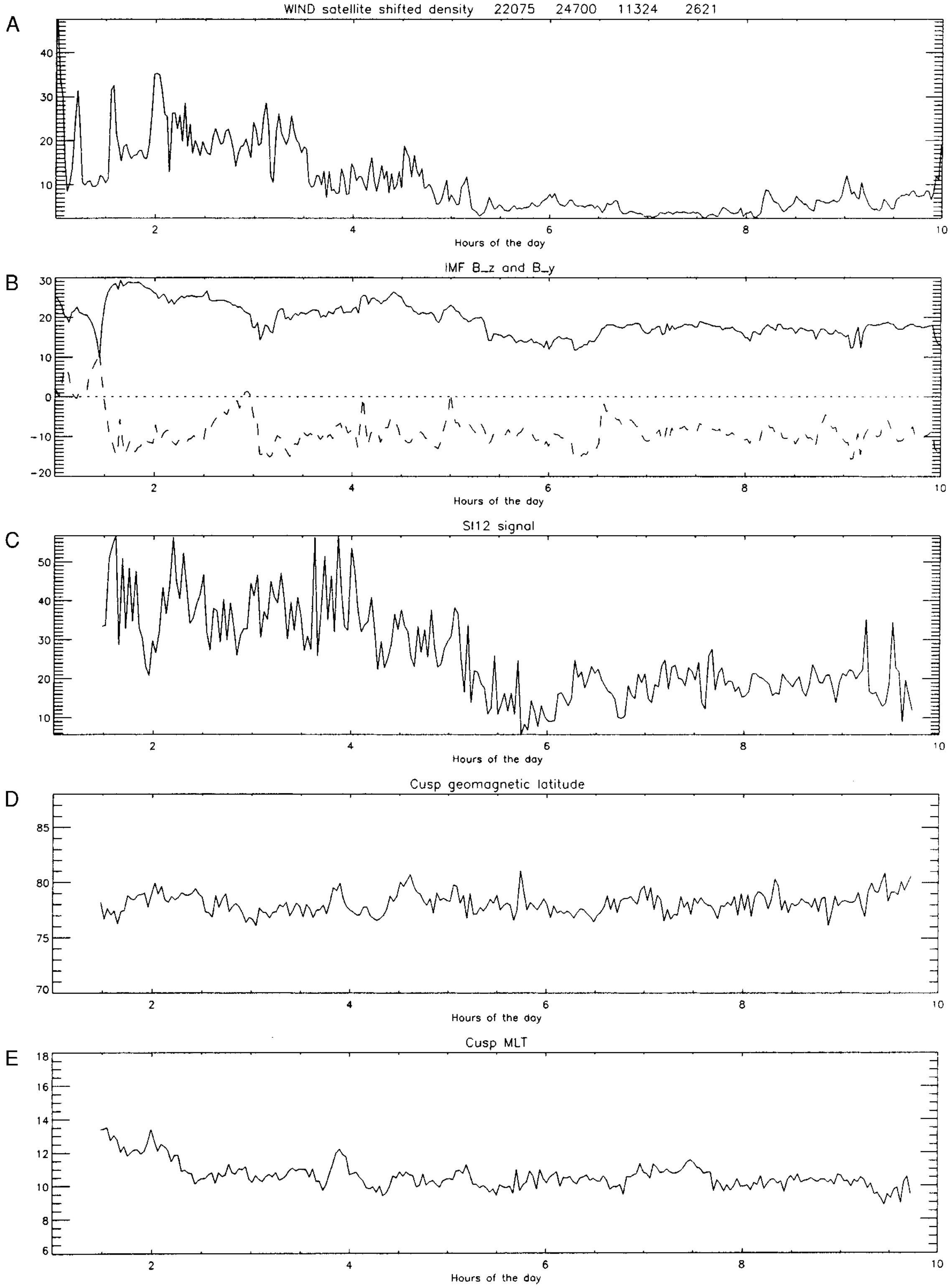


Figure 5. Summary of ultraviolet observations from the cusp and related solar wind parameters for 18 September 2000: (a) the time-shifted solar wind proton density measured by Wind, (b) the time-shifted IMF GSM B_z (solid line) and B_y (dashed line) components, (c) the proton imager signal in the cusp (instrument counts), and (d) the latitude and (e) the MLT location of the cusp.

it disappeared after 0530 UT when B_z turned negative. A short-lived increase appeared at 0625 UT, when B_z turned northward again, but the signal remained very small because the solar wind density was small, too. All data are shown in Figure 6; however, data after 0545 were not included in this study as they failed to fulfill criterion 2 from section 3. There is some indication that the latitude location increased with decreasing solar wind density (around 0300–0400 UT).

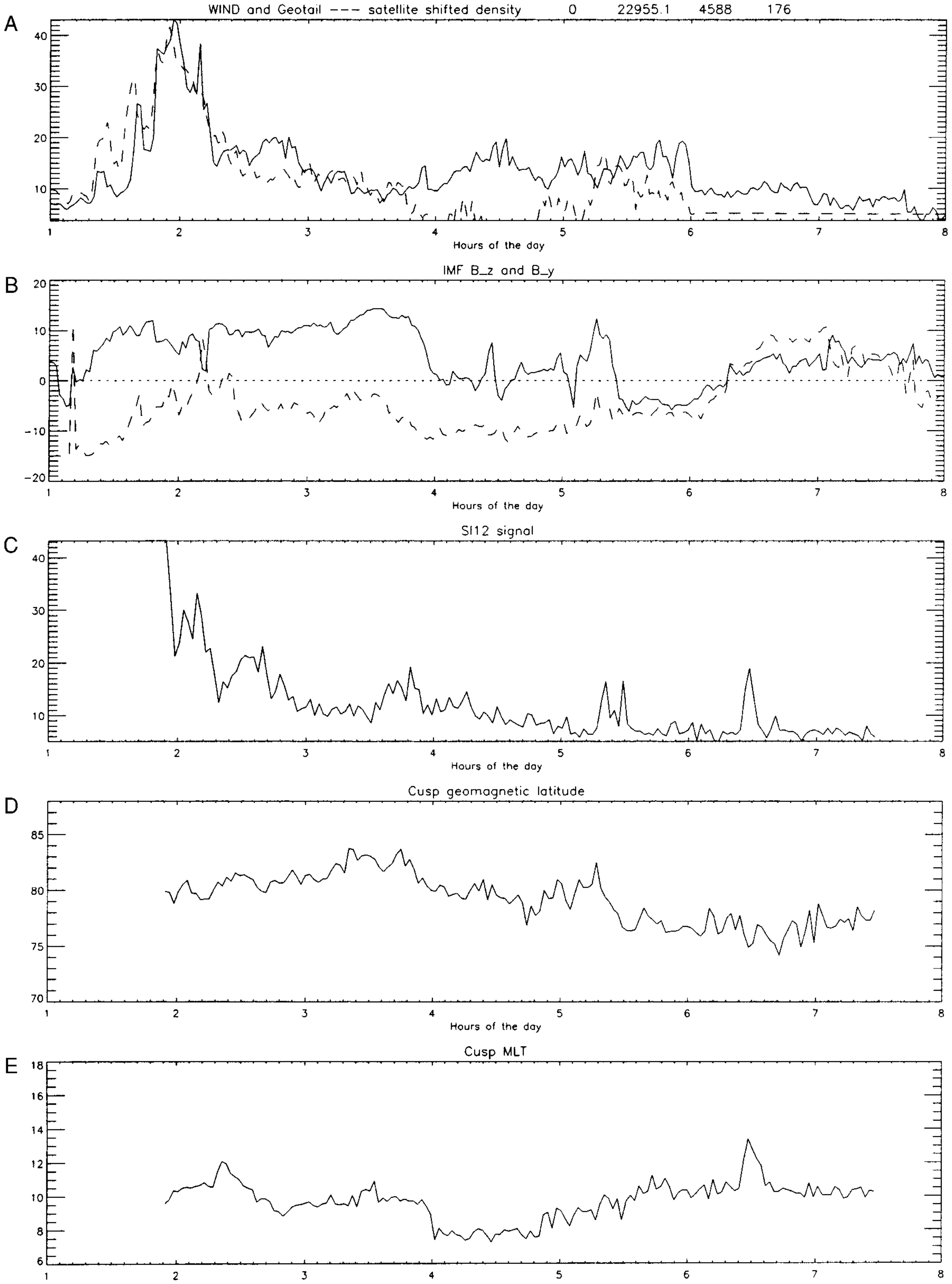


Figure 6. Summary of ultraviolet observations from the cusp and related solar wind parameters for 24 June 2000: (a) the time-shifted solar wind proton density measured by Wind (solid) and Geotail (dashed line), (b) the time-shifted IMF GSM B_z (solid line) and B_y (dashed line) components, (c) the proton imager signal in the cusp (instrument counts), and (d) the latitude and (e) the MLT location of the cusp.

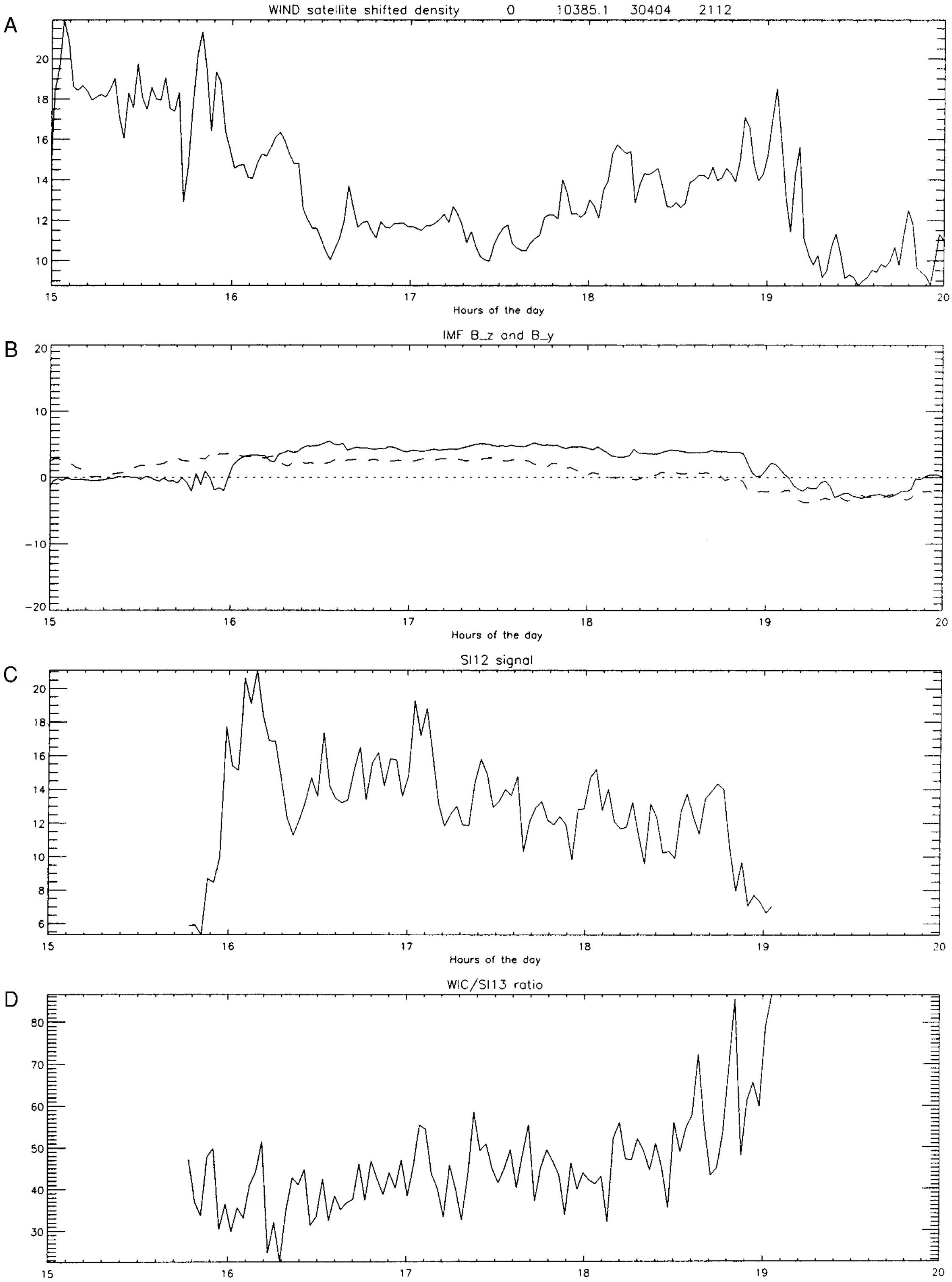


Figure 7. Summary of ultraviolet observations from the cusp and related solar wind parameters for 29 July 2000: (a) the time-shifted solar wind proton density measured by Wind, (b) the time-shifted IMF GSM B_z (solid line) and B_y (dashed line) components, (c) the proton imager signal in the cusp (instrument counts), and (d) the WIC/SI-13 signal ratio at the corresponding location.

A clear correspondence can again be seen between the MLT location of the cusp signature and the IMF B_y.

4.4. Cusp Aurora on 29 July 2000

[19] The observations on 29 July 2000 (day 211) are summarized in Figure 7. The solar wind density had already increased before FUV turned on after leaving the radiation belt; however, no cusp signal could be observed during the first 10 min of observation. It was only after 1600 UT that the change of B_z to positive values caused a strong increase in the cusp signal. Later, B_z remained very steady around 4 nT. The solar wind

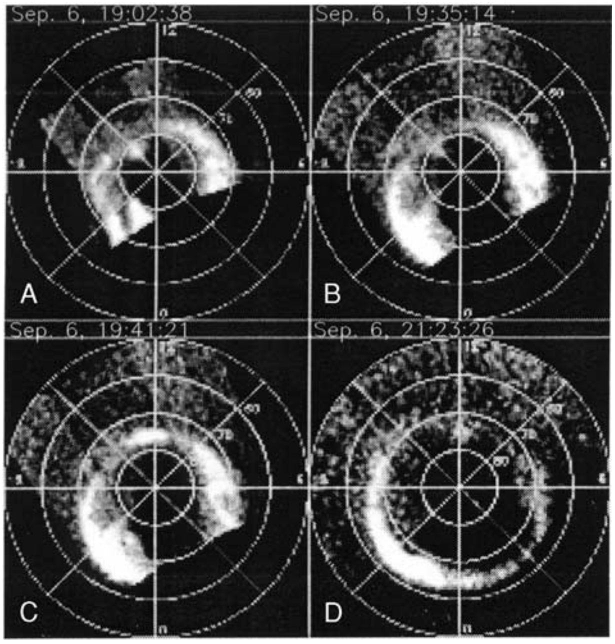


Figure 8. Examples of observations of the FUV proton imager on 6 September 2000. The format is the same as in Figure 1.

density increased after 1730 UT, but the cusp signal decreased with time.

4.5. Cusp Aurora on 6 September 2000

[20] Six September 2000 (day 250) was a period of repeated disappearance and appearance of the localized emission, and examples of proton observations are summarized in Figure 8. The solar wind density was high throughout the period, and a cusp signature could be observed at 1500 MLT because of the positive B_y component of 10 nT (solar wind data not shown). Suddenly, at 1940 UT, B_z changed from 12 to -9 nT, and the cusp signature, which could be seen around 1500 MLT and 80° latitude, disappeared. In response to this change the dayside auroral oval got bright between 1100 and 1400 MLT and around 76° latitude (Figure 8c). The localized emission appeared again briefly at 2000, 2020, and 2038–2107. Later, at 2130 UT, B_z changed from -8 to 11 nT, and the cusp signature appeared again at 1200 MLT when IMF B_y was close to 0 nT. These observations with the appearance and disappearance of the high- and low-latitude cusp aurora are the same as described from ground-based observations by *Øieroset et al.* [1997].

5. Discussion

5.1. Location of Cusp

[21] All cusp observations were localized between 70.8° and 85.6° geomagnetic latitude. Figure 9 gives a summary of the locations in histogram format. The latitude distribution is slightly asymmetric with more samples above 78° than below. The mean and median values are both 79.2°.

[22] The location of the cusp in magnetic local time and latitude is shown in Figure 10. All locations are distributed along the dayside between 6.6 and 16.0 hours MLT, and the median and mean times have the same values of 11.7 hours.

5.2. Dependence of Cusp Characteristics on Solar Wind Magnetic Field

[23] The propagated solar wind measurements were used to determine correlations between the proton precipitation location and intensity and the solar wind magnetic field and plasma parameters. The relationship between the IMF GSM B_z value and the cusp location and Lyman α emission is given in Figure 11. Cusp observations were performed during B_z periods between -21 and 34 nT, but there does not seem to be a clear dependence of the latitude location on B_z. The intensity of the proton precipitation is strongly biased toward positive values of B_z. However, there is no clear correlation between both quantities, as the correlation coefficient reaches only 0.41. There seem to be two subsets, one which contains small SI-12 signals for positive and negative values of B_z and one which seems to show an increasing SI-12 signal with increasing positive B_z. However, both subsets could not very easily be separated.

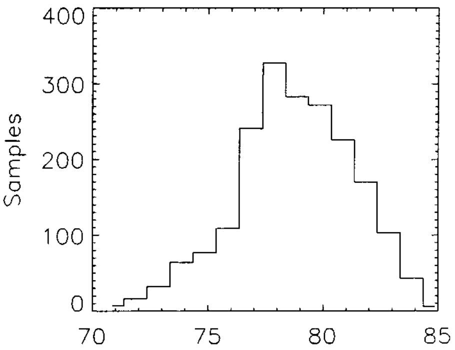


Figure 9. Histogram of the distribution of cusp observations in geomagnetic latitude.

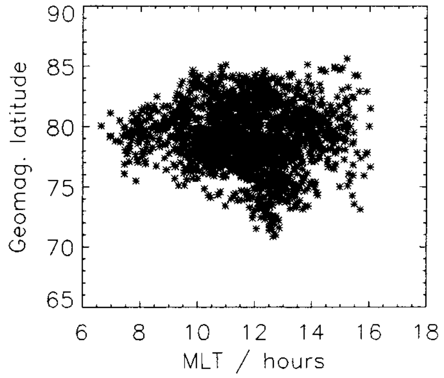


Figure 10. Distribution of cusp observations in MLT and geomagnetic latitude. The mean and median values are similar with 79.1° latitude and 11.7 hours MLT.

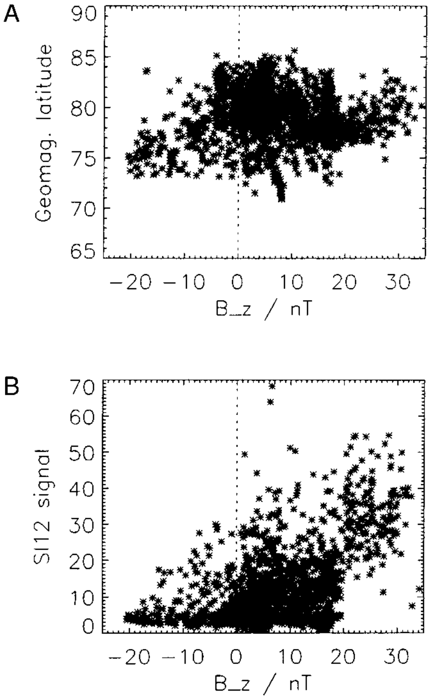


Figure 11. Dependence of the (a) cusp latitude location and (b) cusp proton precipitation on the value of the IMF B_z.

[24] Figure 12 summarizes the dependence of the cusp MLT location and proton precipitation on the value of IMF B_y. There is a clear correlation between the location and B_y with a prenoon location for negative B_y and a post-noon location for positive B_y. The least squares fit of all the data provided a result as

$$\mathrm{MLT} = 11.8 + 0.127B_y, \tag{4}$$

with B_y taken in nT and MLT given in hours.

[25] There is some indication that the response of the MLT location to IMF B_y changes is slower than, for instance, for emission changes in response to B_z changes (see, for instance, Figure 5). This finding is in agreement with *Milan et al.* [2000], who speculated about a dependence on the past history of the IMF.

5.3. Dependence of Cusp Characteristics on Solar Wind Dynamic Pressure

[26] Figure 13 summarizes the dependence of the cusp proton precipitation on the solar wind dynamic pressure. A good correlation of 0.66 was obtained for the relation between the cusp signal and the dynamic pressure. The least squares fit result is

$$\mathrm{SI12} = 2 + 1.2p_{\mathrm{dyn}} \tag{5}$$

with p_{dyn} in nPa and SI12 given here as instrument counts. Assuming a mean energy of 2 keV for the precipitating protons, this would translate into a Lyman α intensity in Rayleighs of

$$I(\mathrm{Ly}\ \alpha) = 500 + 300p_{\mathrm{dyn}} \tag{6}$$

5.4. Summary of All Correlations

[27] The data sets were then used to determine any possible correlation between 13 parameters, like IMF

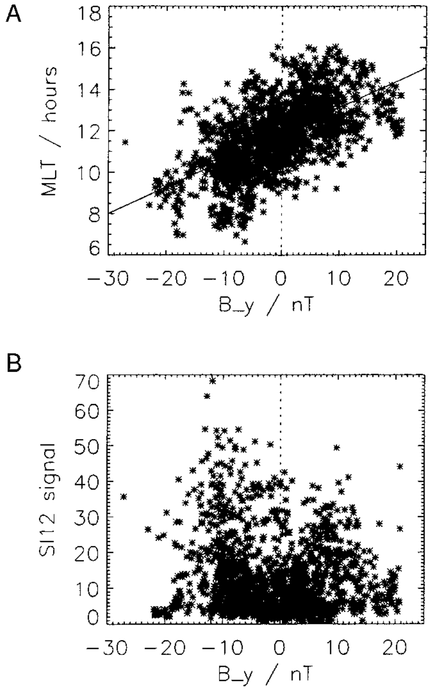


Figure 12. Dependence of the cusp local time location and cusp proton precipitation on the value of IMF B_y. Figure 12a also shows the least squares fitted linear relation of $\mathrm{MLT} = 11.8 + 0.127B_y$.

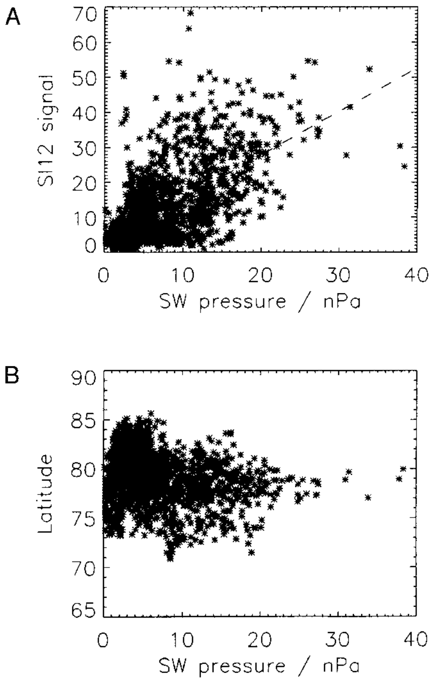
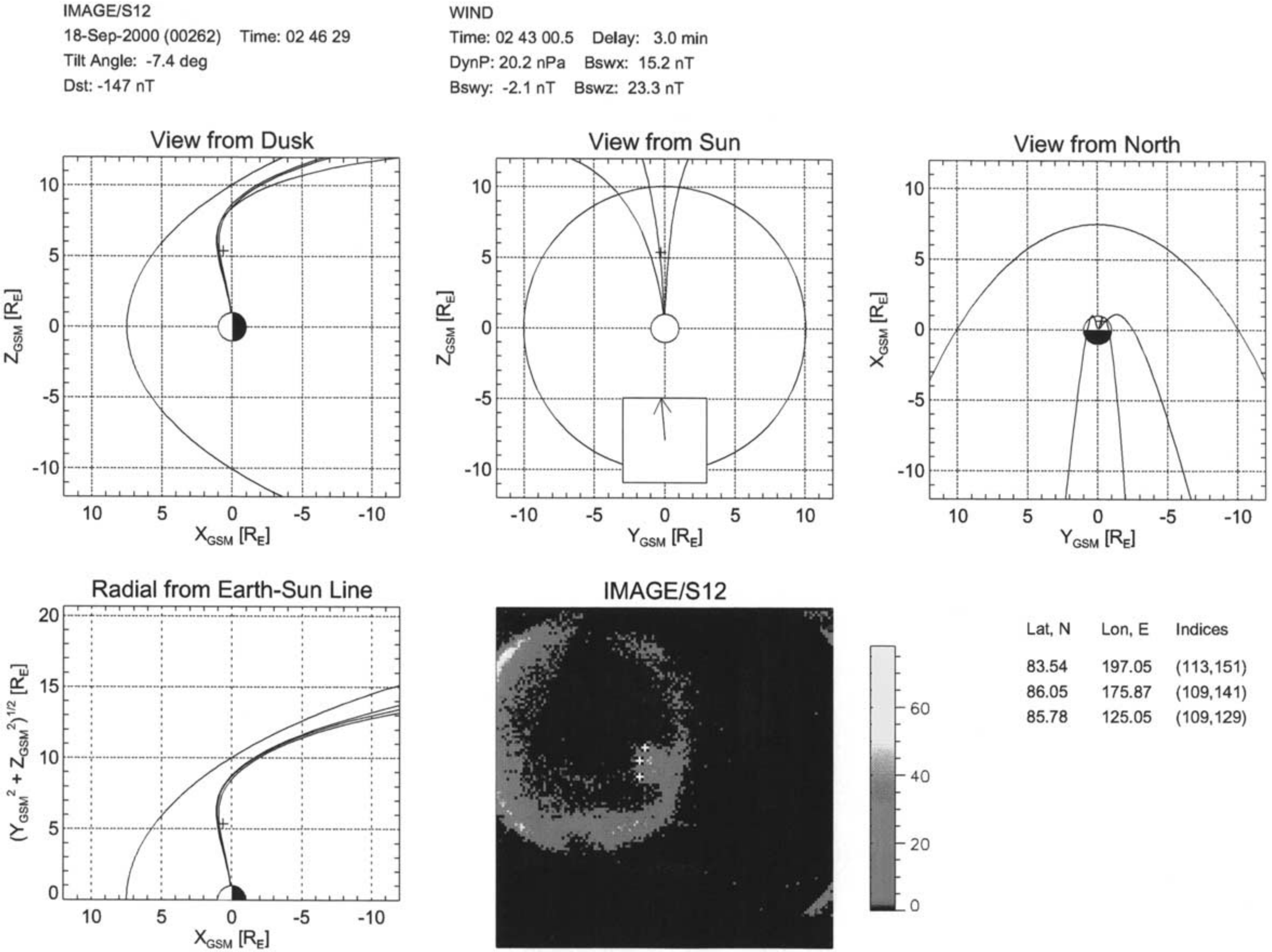
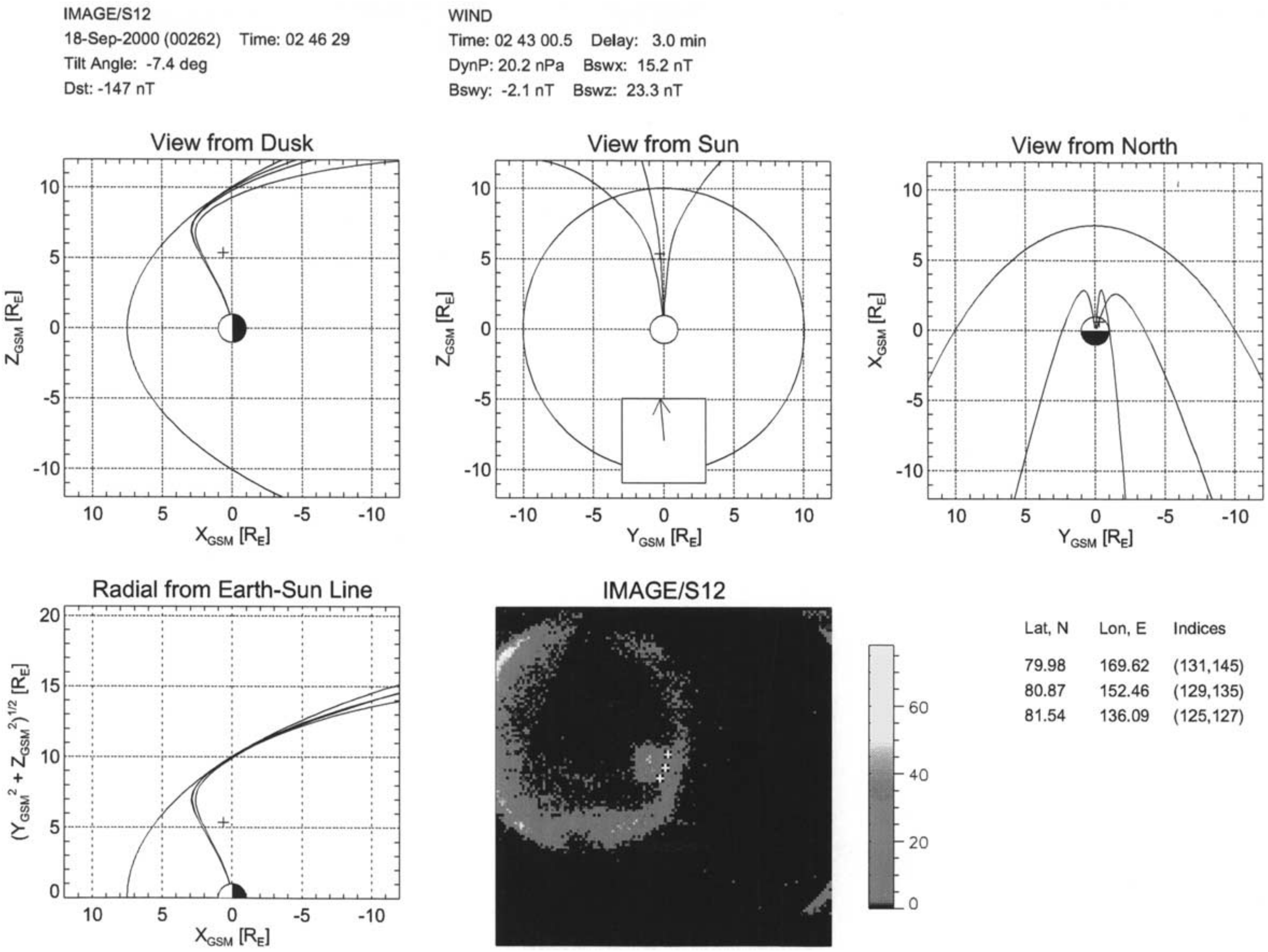


Figure 13. Dependence of the cusp latitude location and cusp proton precipitation on the solar wind dynamic pressure. Figure 13a also shows the least squares fitted linear relation of $\mathrm{SI\text{-}12} = 2 + 1.2\ p_{\mathrm{dyn}}$.



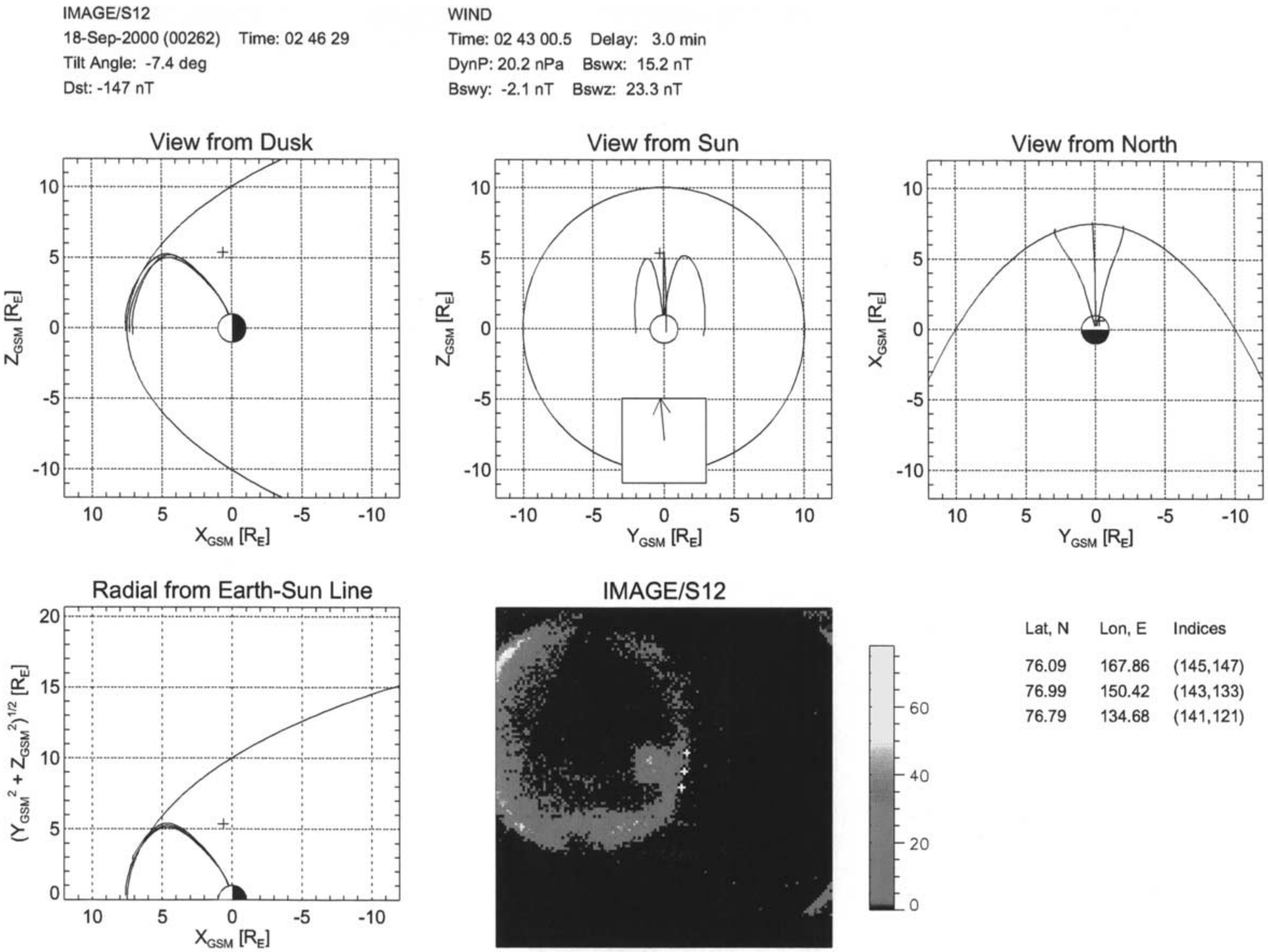
Lat, N	Lon, E	Indices
83.54	197.05	(113,151)
86.05	175.87	(109,141)
85.78	125.05	(109,129)

Figure 14. Result of field line mapping from the auroral region into the magnetosphere. (e) The original image taken by the proton camera at 0246:29 on 18 September 2000. Three points along the poleward border of the cusp signature were selected, and magnetic fields lines from those locations were mapped into the magnetosphere. These field lines looking (a) from dusk, (b) from the Sun, and (c) from above the North Pole. (d) These field lines in the rotated plane.



Lat, N	Lon, E	Indices
79.98	169.62	(131,145)
80.87	152.46	(129,135)
81.54	136.09	(125,127)

Figure 15. The same as Figure 14 but for three magnetic field lines passing through points along the line between the equatorward region of the cusp signature and the poleward border of the dayside auroral oval.



Lat, N	Lon, E	Indices
76.09	167.86	(145,147)
76.99	150.42	(143,133)
76.79	134.68	(141,121)

Figure 16. The same as Figure 14 but for three magnetic field lines passing through points along the equatorward border of the dayside auroral oval.

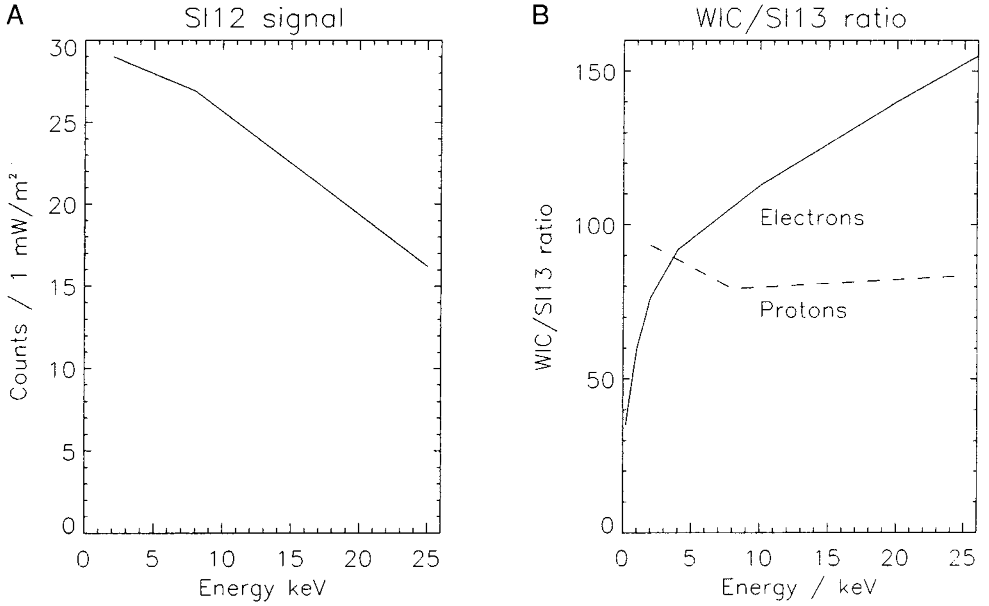


Figure 17. (a) Dependence of the SI12 signal on the mean proton energy for a unit flux of 1 mW m^{-2}. (b) The energy dependence of the ratio between the WIC and SI13 signal for a pure proton- or electron-produced UV emission.

components, solar wind density, pressure, velocity, and cusp signals and locations. A subset of the full 13 × 13 correlation matrix is given in equation (7):

$$\begin{array}{lrrrrrr} & n & B_y & B_z & \text{SI–12} & \mathit{Latitude} & LT \\ n & 1.00 & & & & & \\ B_y & 0.01 & 1.00 & & & & \\ B_z & -0.08 & -0.18 & 1.00 & & & \\ \text{SI–12} & 0.31 & -0.13 & 0.41 & 1.00 & & \\ \mathit{Latitude} & -0.40 & -0.15 & 0.08 & -0.26 & 1.00 & \\ LT & -0.01 & 0.59 & -0.20 & -0.03 & -0.06 & 1.00 \\ p_{sw} & 0.75 & -0.16 & 0.25 & 0.65 & -0.27 & -0.14 \end{array} \tag{7}$$

[28] The large correlation between the solar wind density n and the pressure p_{sw} is obvious as the pressure is calculated from the density. The matrix shows that the proton signal S12 correlates much better with pressure (0.65) than with density (0.31). Therefore the solar wind bulk speed is an additional factor for an increased signal and not just the solar wind density. However, this could be caused by the fact that the proton imager SI-12 is insensitive to Doppler-shifted Lyman α emission if the emitting hydrogen atom has <1 keV energy. The matrix also shows a reasonable correlation between the IMF B_y component and the MLT location of the cusp emission (0.59). The correlation between the IMF B_z and the proton signal is only 0.41, and reflects the fact that the cusp emission occurs with northward IMF, but its intensity is not related to the magnitude of B_z. There is some indication of an anticorrelation between the latitude location and the solar wind density and dynamic pressure; however, the correlation coefficients of −0.40 and −0.27 do not allow for a definitive determination.

5.5. Mapping of Cusp Location into Magnetosphere

[29] Now that the characteristics of the cusp proton precipitation have been investigated, the next question is where the protons come from. A mapping code was developed that maps any location in an FUV image into the magnetosphere [*Fuselier et al.*, 2002]. It uses external solar wind parameters (IMF and pressure) and maps along the Tsyganenko magnetic field model [*Tsyganenko*, 1995; *Tsyganenko and Stern*, 1996]. Figures 14, 15, and 16 show a representative example of this mapping for different locations in the proton camera image taken on 18 September 2000 at 0246:29 UT. During this time period the IMF B_z had been strongly northward and almost stable for several hours, and the time shifted value from the Wind-spacecraft for this particular time was 23.3 nT (see Figure 5). The solar wind dynamic pressure was slowly decreasing but still large at 20.2 nPa. These stable conditions allowed for a reliable use of IMF data because even a propagation uncertainty of 5–10 min would not have changed the external parameters. Furthermore, the magnetosphere should have had enough time to reach relatively stable conditions without sudden external changes.

[30] Figure 14 contains three magnetic field lines originating at the poleward border of the cusp. Those field lines map into the lobe region of the magnetotail. During this particular time the cusp signature was not clearly separated from the dayside auroral oval, and therefore Figure 15 shows the mapping of field lines from a line between the equatorward border of the cusp and the poleward border of the dayside auroral oval. Those magnetic field lines map directly to the high-latitude magnetopause. Finally, Figure 16 shows three mapped field lines from the equatorward border of the dayside auroral oval that map to the subsolar dayside magnetopause.

[31] According to the model calculations the magnetopause was pushed inward to <8 R_E, and it is very likely that pitch angle scattering in the subsolar magnetopause region is responsible for the intense proton precipitation into the dayside auroral oval region. The cusp signature, however, must have a different source. Under these northward IMF

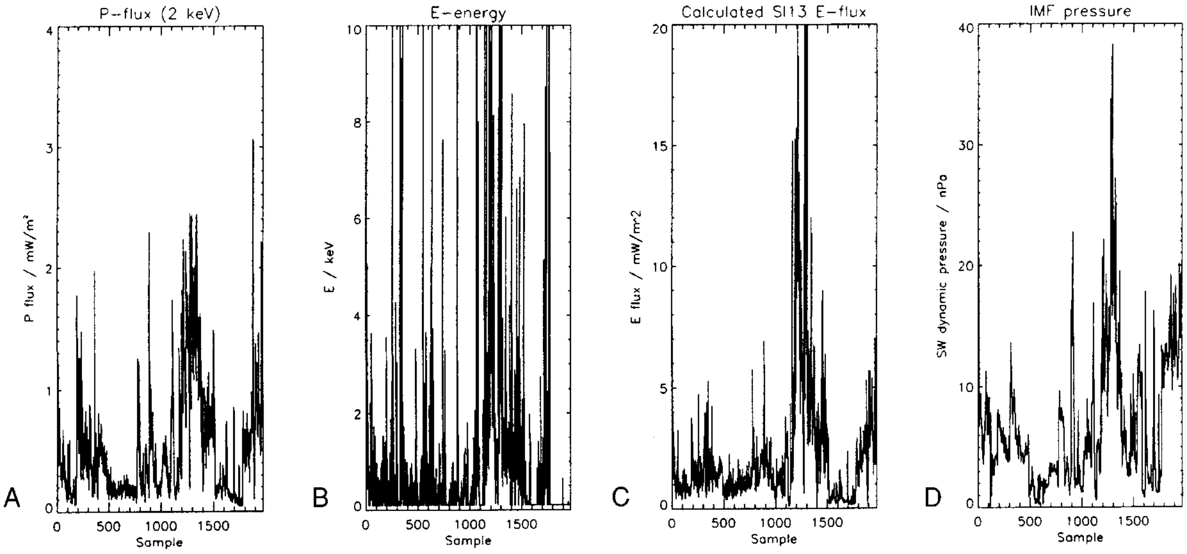


Figure 18. Result of flux estimates for all 18 events where all 2030 image sets are considered as individual samples: (a) the proton energy flux calculated from the SI12 signal assuming 2 keV proton precipitation, (b) the mean electron energy after correcting the WIC and SI13 signals for the proton contribution, (c) the estimated electron energy flux if the SI13 signal is analyzed using the mean electron energy from Figure 18b, and (d) the time-shifted solar wind dynamic pressure for the respective times of image sets.

conditions, direct magnetosheath precipitation after magnetic field reconnection in the high-latitude lobe region is the most likely candidate.

5.6. Flux Estimates

[32] The quantitative analysis of flux estimates as outlined in section 2 starts with a kappa distribution of the protons with $\kappa = 3.5$ [*Hubert et al.*, 2001] and an assumed mean proton energy in the cusp of 2 keV. This is a reasonable assumption according to statistical investigations of the average proton energy in the cusp [*Hardy et al.*, 1989, 1991].

[33] The SI-12 signal in the cusp is used to determine the proton flux according to Figure 17a and equation (1). The WIC and SI-13 signals are corrected for the proton-produced contribution (equations (2) and (3)), and the ratio is then used to determine the mean energy of the precipitating electrons according to Figure 17b. This ratio is energy-dependent because the SI-13 signal changes much more with energy of precipitating electrons then the WIC signal because of the deeper penetration of higher-energy electrons into the atmosphere and the effect of UV absorption by molecular oxygen. Therefore the proton-corrected WIC signal is finally used to determine the energy flux of electrons. The WIC/SI-13 ratio around 40 for most of the time in Figure 7, for instance, indicates a low energy of precipitating electrons.

[34] The results of flux estimates are given in Figure 18 where all 18 events are summarized and the simultaneous image sets are referred to as samples. The proton energy fluxes are, for most of the observations, between 0.05 and 1 mW m^{-2}, with a mean value of 0.5 mW m^{-2}, which are reasonable values compared to in situ measurements by satellites like FAST or DMSP. After correcting for the proton contribution the WIC/SI-13 ratio was used to calculate the mean energy of precipitating electrons, given in Figure 18b. Most of the time this energy is below 1 keV (mean value 910 eV), but there are several single data points with mean energies >10 keV. Such mean energies are unreasonable for cusp precipitation. Here it has to be kept in mind that the mean energy is estimated from the ratio of the WIC and SI-13 signals. Sometimes the SI-13 signal is very small (1–5 counts) on top of a dayglow signal of 20–40 counts. At such small count rates, statistical fluctuations and a slightly incorrect dayglow subtraction may very easily change the ratio by 50%. According to Figure 17 the WIC/SI-13 ratio is 60 for 1 keV electrons. A change of this ratio by 50% gives 40 eV for a ratio of 30 and 3.8 keV for a ratio of 90.

[35] The calculated electron energy fluxes (Figure 18c) are around 1 mW m^2 for most of the observations, which again, is a reasonable flux in the cusp. Large excursions from this value (samples 1200–1400) coincide with periods of very high solar wind dynamic pressure (Figure 18d). These deviations may indicate that the flux estimates may fail during periods of very large solar wind disturbances, when probably some of the simplifications outlined in section 2 may not be justified.

[36] Figure 19 summarizes the calculated ratio of proton energy flux to electron energy flux. Again, a large fluctuation can be seen. However, here the uncertainty in the proton energy flux is not as large as the uncertainty in the electron energy flux because the SI-12 signal does not suffer from dayglow background. The median of the whole data set is 0.26, and the mean is 0.30. This means that for this complete data set, generally, protons carry 26–30% of the energy flux that electrons do. This result is in very good agreement with a 27% estimate from model calculations for cusp precipitation using the statistical distribution of electron and proton precipitation [*Hardy et al.*, 1985, 1989] as input parameters [*Hubert et al.*, 2001].

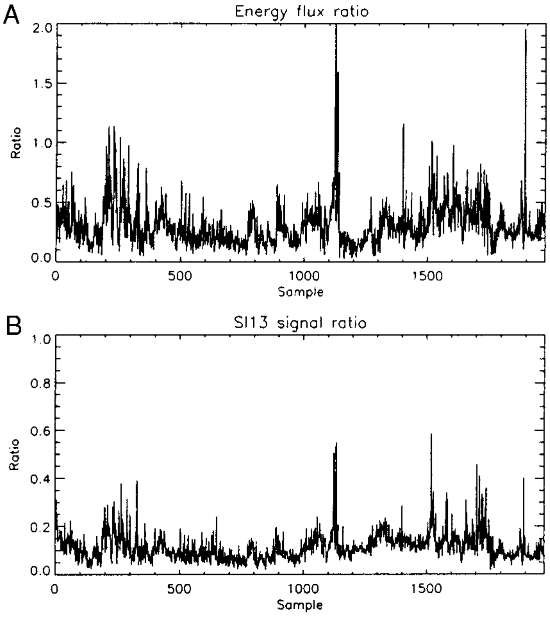


Figure 19. (a) Ratio between the estimated energy flux carried by protons and that carried by electrons into the cusp. (b) How much of the total SI-13 signal was produced by precipitating protons.

[37] Figure 19b shows the ratio of the proton-produced SI-13 signal to the total signal observed. The mean of this whole data set is 11%, but there are several cases where this ratio reaches 30%. The implication of this result is that groundbased observations of auroral emissions from the cusp may have overestimated the electron energy flux if the analysis assumed that all emission was produced by electrons. This could especially be the case for red line observations at 6300 nm because this emission is as unstructured as the proton precipitation and can be misinterpreted as the signature of soft electron precipitation.

[38] Equation (5) relates SI-12 counts to the solar wind dynamic pressure. After crossing the bow shock the solar wind is slowed down with a simultaneous increase in density and temperature [see, e.g., *Walker and Russell*, 1995]. Therefore the solar wind properties as measured by satellites will not be the same as properties for plasma entering the cusp. As a rough estimate, however, we want to check if the solar wind, in principle, is able to provide the plasma, which could produce the cusp signature as seen by the proton imager.

[39] From theoretical modeling we know that 36 SI-12 counts are produced by a flux of 1 mW m^{-2} of 2 keV protons, which requires a particle flux of 3.1×10^{12} protons m^{-2} s if we simply assume a monoenergetic beam. According to equation (5) this requires a solar wind dynamic pressure of 28 nPa (see also Figure 13). During many of our events a high solar wind density and bulk velocity produced such a high dynamic pressure. A 2 keV proton moves with a velocity of 619 km^{-1} s, which is not too high for many of our cases and will be used for further calculations. The dynamic pressure of 28 nPa would then be produced by a density of 4.4×10^7 protons m^{-3} (44 cm^{-3}), which moves with an average speed of 619 km^{-1} s. Such a solar wind would provide a flux of 2.7×10^{13} protons, which is an order of magnitude more than would be required for the production of the proton aurora if the solar wind could enter the cusp directly.

[40] Previous observations by *Øieroset et al.* [1997] showed particle data and discussed a proton acceleration by magnetic tension forces after high-latitude reconnection. Enhanced auroral green light emission was explained by electron acceleration at the magnetopause or at lower altitude. In another study, enhanced ionization in the cusp proper could be explained by either 1 keV electron or 3 keV proton precipitation and was considered as a result of additional acceleration in the cusp [*Nilsson et al.*, 1998]. Here we show that the solar wind provides enough energy and particle flux for our observations. Even after the interaction of the solar wind with the bow shock and in the magnetosheath, the high-energy tail of the Maxwellian solar wind proton distribution could account for our observations, and an additional acceleration of the protons is not necessary to produce the observed cusp signatures in the optical emission from precipitating protons.

6. Conclusions

[41] The major criterion for the case selection was a localized bright signal from proton precipitation poleward of the dayside auroral oval (section 3). It turned out that this cusp signature is observable whenever the IMF is northward and the solar wind density is at least slightly increased. The intensity of the proton precipitation is then primarily controlled by the solar wind dynamic pressure. This result is in agreement with previous findings by *Newell and Meng* [1994], who also found a much stronger correlation of the cusp area with the solar wind dynamic pressure than with the magnitude of $|B_z|$.

[42] A change of the IMF B_z component to southward causes the localized cusp emission to disappear [*Fuselier et al.*, 2002]. This is also the reason why we believe that the cusp signature disappeared during the perigee pass on 18 September 2000, when IMF B_z turned southward, and reappeared shortly before the FUV observations with the northward turn of B_z, as described in section 4.2. The event summaries in Table 1 and Figure 11 show several sampling points with negative B_z. This represents the fact that the original location of the cusp signature was tracked between repeated appearances and for 15 min more after it completely disappeared. A few of the B_z south points in Figure 11 may also be caused by the uncertainty in propagation time if the B_z suddenly turned southward. The mean values of B_z in Table 1 demonstrate the predominant occurrence during northward IMF.

[43] The location of the cusp in local time is controlled by the IMF B_y component, with prenoon locations for negative B_y and postnoon locations for positive B_y. The average location of all cases of this study was 79.1° geomagnetic latitude and 11.7 hours MLT. The brightest pixel method (see section 3) for the determination of the cusp location and the intensity of the Lyman α signal was not always unique. At closer distances between the spacecraft and aurora the cusp region extended over more than the 3×3 pixel area with many times more equally bright pixels. During weak UV emissions the statistical fluctuations sometimes moved the brightest pixel around. However, with our large data set

such fluctuations should have been averaged out. There is some indication that the response of the MLT location to IMF B_y changes is slower than, for instance, for emission changes in response to B_z changes. Other relations in this data set are not as obvious, though there are some indications of a correlation between latitude and solar wind dynamic pressure.

[44] The cusp is known as a highly dynamic region, and cusp crossings by satellites do not necessarily match with calculations of cusp locations [*Dunlop et al.*, 2000]. It cannot be expected that a particular field line model will exactly determine the cusp location. Our results in Figures 14–16 should therefore be considered as general results rather than exact representations. The mapping indicated that the region of proton precipitation is magnetically connected to the high-latitude magnetopause and the magnetospheric lobe region and that high-latitude reconnection is the most likely cause of this emission.

[45] A case study by *Milan et al.* [2000] found a similar dependence of a localized emission on B_z and B_y. They attributed the observed luminosity to the precipitation of accelerated electrons. The three independent imaging channels of the FUV enabled an estimate of the flux and energy of the precipitating protons and electrons. Though the whole process relies on certain assumptions and simplifications, the results were reasonable in comparison to particle measurements of other studies [see, e.g., *Newell and Meng*, 1994; *Øieroset et al.*, 1997]. These estimates confirm that under high solar wind dynamic pressure conditions, protons can carry a significant amount of energy flux into the cusp and that optical observations have to be corrected for this contribution before electron precipitation characteristics can be determined.

[46] **Acknowledgments.** We are grateful to the IMAGE-SMOC team who keep the spacecraft running. The IMAGE FUV investigation was supported by NASA through SwRI subcontract number 83820 at the University of California at Berkeley under contract number NAS5-96020. The solar wind measurements were obtained from CDAWeb. We acknowledge the following PIs: Wind Magnetic Fields Investigation: R. Lepping; Wind Solar Wind Experiment: K. Ogilvie; Geotail Magnetic Field Instrument: S. Kokubun; and Geotail Comprehensive Plasma Instrument: L. Frank. J. C. G. is supported by the Belgian National Fund for Scientific Research (FNRS). His work was funded by the PRODEX program of the European Space Agency (ESA) and the Belgian Fund for Collective Fundamental Research (grant FRFC 97–2.4569.97).

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