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Simultaneous imaging of the reconnection spot in the opposite hemispheres during northward IMF

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[1] Cusp aurora associated with high latitude lobe reconnection was imaged simultaneously by IMAGE and Polar in the opposite hemispheres for a short time interval on September 18, 2000. These very rare images taken during strongly northward IMF and high solar wind pressure give a unique opportunity to examine the IMF and dipole tilt control of the cusp aurora and theta aurora. As suggested by theory and observations from one hemisphere, the longitudinal location of the cusp aurora is controlled by the IMF B_y component, whereas the >5° poleward shift of the southern cusp aurora is attributed to the effects of the dipole tilt angle. The appearance of a non-conjugate theta aurora can be explained by the more efficient reconnection process in the southern hemisphere due to IMF $B_x > 0$. Imaging of auroral signatures of magnetic reconnection also demonstrates the potential to examine differences in reconnection rate in the opposite hemispheres. **Citation:** Østgaard, N., S. B. Mende, H. U. Frey, and J. B. Sigwarth (2005), Simultaneous imaging of the reconnection spot in the opposite hemispheres during northward IMF, *Geophys. Res. Lett.*, *32*, L21104, doi:10.1029/2005GL024491.

1. Introduction

[2] During periods of sustained northward IMF and high solar wind pressure, high latitude lobe reconnection can be very efficient. At the footpoint of the merging field lines a bright auroral spot can be seen for hours, indicating a "quasi" continuous reconnection process. The first observations from space of this spot by UVI on Polar were interpreted by *Milan et al.* [2000] to be the type 2 cusp aurora classified by *Sandholt et al.* [1998], and to be the optical manifestation of high-latitude reconnection suggested by models [*Reiff and Burch*, 1985]. Using the Spectrographic Imager on IMAGE, which has the ability to separate electron and proton precipitation, *Frey et al.* [2002] found that protons on average contribute 30% to the total energy flux precipitated within the cusp spot. Combined imaging from space of proton precipitation and in situ observations of high latitude reconnection by the Cluster satellites [*Phan et al.*, 2003] indicate that reconnection under these conditions is a varying but continuous process [*Frey et al.*, 2003b]. The azimuthal location of the high-latitude reconnection spot is thought to be controlled by IMF B_y, as suggested by ground measurements [*Sandholt et al.*, 1998], in situ particle measurement [*Newell et al.*, 1989] and confirmed by global imaging from space [*Milan et al.*, 2000; *Fuselier et al.*, 2002; *Frey et al.*, 2002]. The latitudinal location of this spot has been found to have a dipole tilt dependence [*Newell and Meng*, 1989; *Bobra et al.*, 2004], but no conclusive evidence of a predicted IMF B_x dependence [*Cowley*, 1981] of the latitudinal location has so far been found [*Newell et al.*, 1989]. Under the same conditions, i.e., sustained northward IMF, theta aurora is commonly observed. *Craven et al.* [1991] found theta to be a conjugate phenomenon, while *Østgaard et al.* [2003] found two cases where theta aurora was only seen in one hemisphere.

[3] In this paper we report the very first observations of the cusp spot simultaneously in the opposite hemisphere, giving a unique opportunity to verify the reconnection geometry and predicted spot locations. Appearance of a non-conjugate theta aurora also enables us to further investigate what controls the non-conjugacy of this phenomenon.

2. Observations

[4] Our simultaneous conjugate images are provided by the imagers on IMAGE and Polar. Both the VIS Earth camera [*Frank et al.*, 1995] and the IMAGE-FUV SI13 [*Mende et al.*, 2000] are detecting OI emission lines from the aurora, 130.4 nm and 135.6 nm, respectively. As these emissions lines are produced mainly by secondary electrons, their intensities are proportional to the total energy flux (protons and electrons). Usually, this means that they are mainly produced by electrons, unless the energy flux of protons is comparable to the energy flux of electrons. In addition, the IMAGE-FUV SI12 channel, by blocking out the geocorona and measuring the Doppler-shifted Lyman-α makes images of energetic proton precipitation only [*Mende et al.*, 2000]. Thus, the IMAGE-FUV system enables a determination of the relative importance of proton and electron precipitation. Exposure times (cadences) are 10 s ($\sim$2 min) and 32.5 s ($\sim$1 min) for IMAGE SI12/13 and VIS Earth camera, respectively. For the mapping to apex magnetic coordinates [*Richmond*, 1995] we assume production altitude of 130 km. Although, the orbits of the two spacecrafts were such that, from 2000 to 2003, imaging of the conjugate hemisphere simultaneously were possible, we have only found 15 min of data, where the bright spot from high-latitude reconnection could be identified simultaneously in both hemispheres. The reason for this is that we need sustained northward IMF, high solar wind pressure and the two spacecrafts in right locations and that the signal from the spot must be distinguishable from day-glow in both hemispheres. Nevertheless, on September 18, 2000, the conditions for seeing the bright spot first from the same

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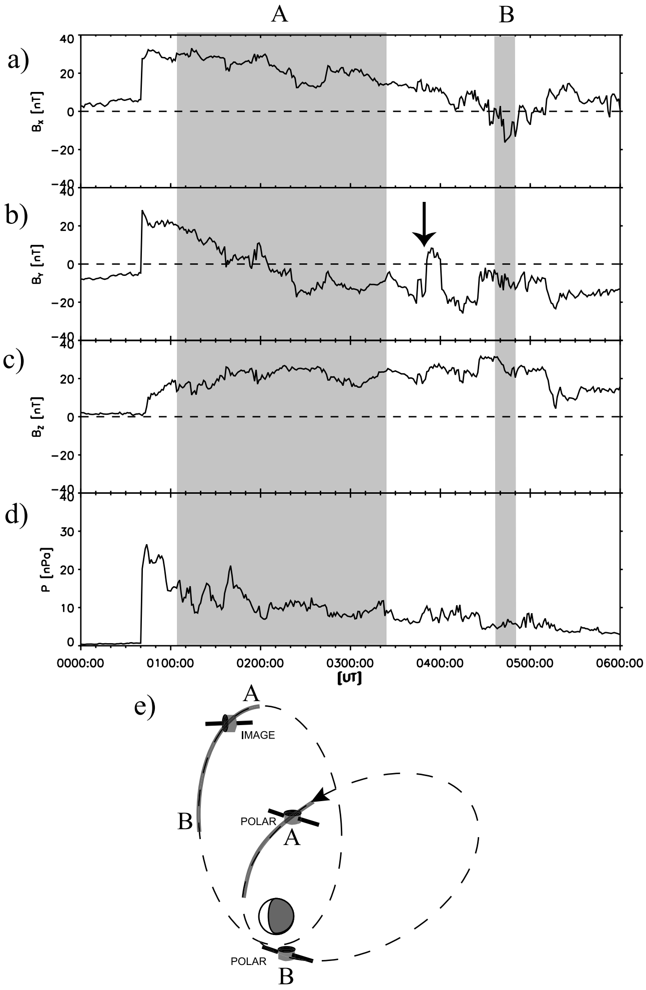

Figure 1. Solar wind conditions on September 18, 2000 from ACE [231,−35,18] R_E GSM. (a)–(c) IMF B_x, B_y and B_z, (d) Solar wind dynamic pressure. (e) Sketch of the orbits of IMAGE and Polar in the XZ plane. Thick gray lines indicate the time intervals A and B. A time shift of 31 minutes has been applied assuming planar propagation of the solar wind from ACE to X = 0.

hemisphere for 1.5 hours and then for a short interval simultaneously in the opposite hemispheres were fulfilled.

[5] In Figure 1 the solar wind conditions measured by ACE (Wind was too far off the Sun-Earth axis at GSM Y: −227 R_E) show northward IMF and a high solar wind pressure (>10 nPa) after 0030 UT. The time shift of 31 minutes is confirmed by the short eastward IMF B_y around 0350 UT, resulting in a postnoon excursion of the cusp spot seen in the SI12 images (not shown). Figure 1e shows the spacecraft locations during the long interval when both satellites were in the northern hemisphere (interval A) and during the short interval of simultaneous conjugate observation (interval B).

[6] The simultaneous observations at 0133 UT from the northern hemisphere can be seen in Figure 2a. The spot is clearly seen in the SI12 (protons only) and also clear and bright in the SI13 and VIS Earth camera. Figure 2b, left panel, shows that the two imagers are seeing similar variations in the spot average intensities within a 10° (longitude) × 10° (latitude) box centered around the peak intensity, except toward the end when VIS-Earth cameras slant viewing angle results in slightly higher intensities. In Figure 2b, right panel, we have used the scheme of calculating the proton and electron contribution in the SI13 images described by *Frey et al.* [2003a], assuming an proton mean energy of 8 keV, consistent with the DMSP measurements (Figure 2c). For the entire interval, the protons contribute on average ∼60% of the signal in SI13. In Figure 2c we show the in situ measurements by DMSP F12 through the spot at 0230 UT. The DMSP track is indicated by the arrow in Figure 2a. The opposite calculation, using the DMSP electron and proton spectra at 0230 UT (black vertical line in Figure 2c) to estimate the SI13 signal, confirms this large proton contribution of 60%. As the VIS Earth camera signal is mainly produced by secondary electrons, we believe that most of the cusp spot seen by Polar is also produced by protons. The DMSP measurements indicate that the cusp aurora, under these conditions, is produced by 8 keV protons and 0.5–1 keV electrons. We should notice that, due to the high ion

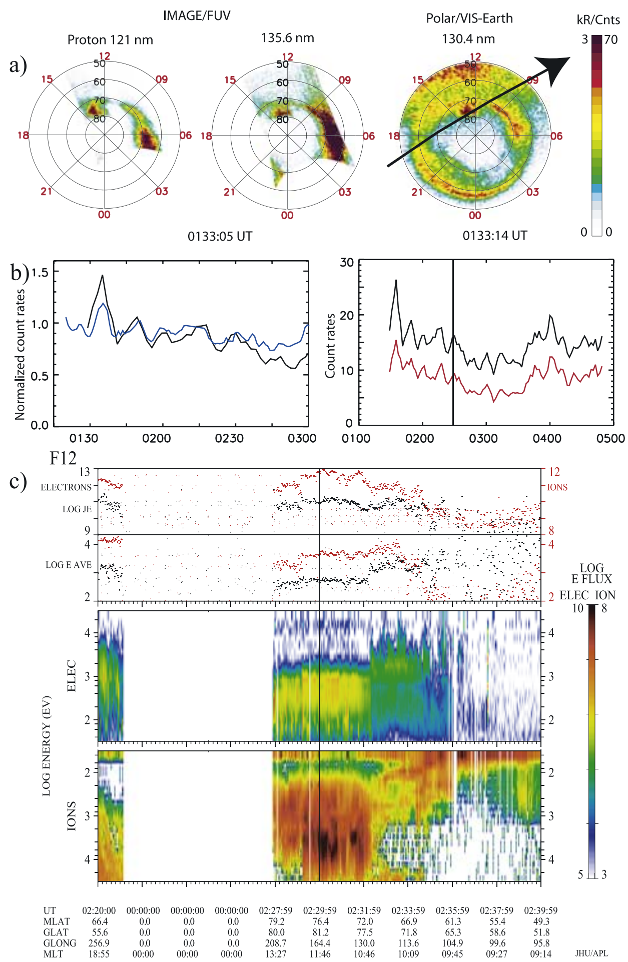

Figure 2. (a) IMAGE-FUV SI12 [kR] and SI13 [kR] and VIS Earth camera [Cnts] see the reconnection spot from the same hemisphere, interval A in Figure 1. (b) Left: average intensity of the cusp spot, within a 10° × 10° box centered around the peak intensity, seen by SI13 (black line) and VIS Earth camera (blue line); right: average (in a 10° × 10° box) counts produced by electrons (red) compared to the average of the total (black) counts in the SI13 images. (c) DMSP electron and ion measurements.

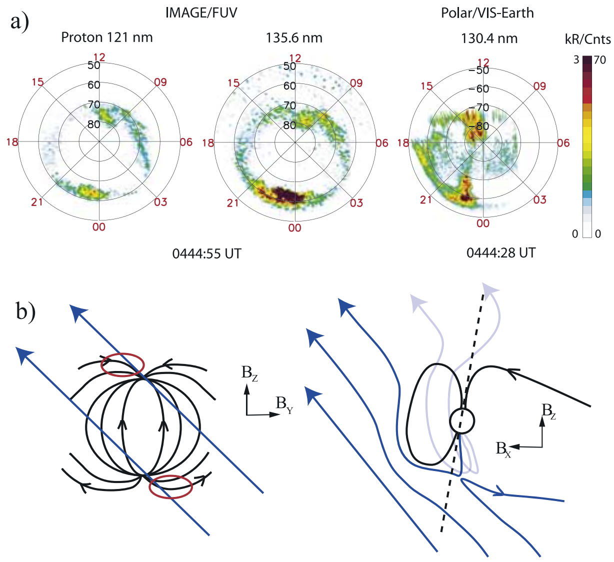

Figure 3. (a) IMAGE-FUV SI12 and SI13 and VIS Earth camera see the reconnection spot in the opposite hemispheres, interval B in Figure 1. (b) The reconnection geometry.

and electron mean energies, this cusp aurora would not have been identified as cusp precipitation by the automatic algorithm developed by *Newell et al.* [1989].

[7] Around 0440 UT (see Figure 1 interval B) Polar had moved to the southern hemisphere and for ~15 minutes we observed the cusp precipitation in the opposite hemispheres simultaneously. IMF was still strongly northward (20 nT), B_x had been large and positive for four hours and solar wind pressure was still >5 nPa. Comparing the images of the cusp spot in both hemispheres at 0444 UT seen in Figure 3a we will emphasize the following: The cusp spot in the northern hemisphere is located at 10–12 MLT and 74°–80° latitude, while the southern cusp spot is at 12–17 MLT and 80°–87° latitude and a theta aurora is only seen in the southern hemisphere.

3. Discussion

[8] Following the anti-parallel reconnection paradigm the longitudinal shift of 1–2 MLT is consistent with the negative IMF B_y component, as sketched in the left panel of Figure 3b. This supports the IMF B_y, or more correctly the IMF clock angle [*Bobra et al.*, 2004], control of the longitudinal shift of the high latitude cusp aurora inferred from observations in one hemisphere [*Newell et al.*, 1989; *Sandholt et al.*, 1998; *Milan et al.*, 2000; *Fuselier et al.*, 2002].

[9] Uncertainties in the mapping due to the slant viewing angle of Polar could account for 1° or 2° in latitude, but not 5°–6°, as observed. Seasonal effects due to the actual dipole angle of −11° (as depicted in Figure 3b, right panel) is expected to give a poleward shift in the sunlit (i.e., southern) hemisphere. *Newell and Meng* [1989] found a statistical displacement of the cusp of about 0.7° latitude per 10° dipole tilt angle, while *Bobra et al.* [2004] found a 1.9° (1.2°) shift per 10° dipole angle for the observed (modeled) high-latitude cusp location. Our findings are in the same range as found by *Bobra et al.* [2004], i.e., 2 × 1.9° ~ 4° ± 2° ~ 5–6°, who identified the cusp in a similar way as we do. Our data do not support the predicted poleward shift of the northern cusp (relative to the southern cusp) for IMF $B_x > 0$ predicted by *Cowley* [1981]. We find the opposite and the shift can entirely be explained as a dipole tilt angle effect.

[10] From the cusp observations around 0440 UT it is clear that a theta aurora is seen in the southern hemisphere but not in the northern hemisphere. As suggested by *Østgaard et al.* [2003] the occurrence of theta in only one hemisphere may be attributed to the sign of the IMF B_x. *Østgaard et al.* [2003] found that the theta arcs were located at the convection reversal boundary of the lobe convection cell and argued that the associated flow shears could produce electric fields that easily accelerate electrons to ~1 keV. By assuming that the driver of the convection cells is the lobe reconnection process, they suggested that the sign of the B_x component could explain why the flow shears (despite the signatures of lobe reconnection and sunward flows they observed) were large enough in one hemisphere but not in the other to generate the electric fields to produce theta aurora. Although IMF B_x turns negative a few minutes before our observations, our interpretation is based on the assumption that it is the strongly northward IMF with a large positive B_x prior to the observations that sets the stage and determines in which hemisphere the reconnection process is most efficient. In our case the positive B_x may cause reconnection to occur first and more efficiently in the southern lobe, as depicted by the darker blue field lines in Figure 3b, right panel. The more efficient reconnection in the southern hemisphere is what we suggest is responsible for driving flow shears with sufficient strength to generate electric fields to produce theta aurora in only one hemisphere. We also notice that the theta occurs in the sunlit hemisphere (see the actual dipole tilt angle in Figure 3b), excluding the alternative argument given by *Østgaard et al.* [2003] that the theta aurora is suppressed in the summer hemisphere due to the larger exposure to solar EUV radiation. Theta aurora is thought to be triggered by large polarity changes in IMF B_y. Although theta aurora is not present in the northern hemisphere during the several hours of observations, we did see a very weak and transient signature of theta aurora (not shown) just as the polarity changes occur, around 0320 UT (indicated by arrow in Figure 1b).

[11] Although the non-conjugate theta aurora may indicate significant differences in reconnection rate in the opposite hemispheres, a time interval of 15 minutes is too short to extract quantitative information about the relative reconnection rate. Nevertheless, our observations (see e.g., Figure 2b, left panel) demonstrate that conjugate imaging holds the promise of determining the relative strength and variations of reconnection rates in the opposite hemispheres.

4. Conclusions

[12] We have presented the first simultaneous optical observations of cusp aurora in both hemispheres. Due to a strong and sustained northward IMF and high solar wind pressure (for many hours) the cusp spot is seen as the ionospheric footprint of high latitude lobe reconnection, giving a unique opportunity to examine IMF and dipole tilt angle effects on the cusp location and polar cap precipitation. From this study we conclude that (1) The longitudinal

shift is controlled by the IMF B_y, (2) the latitudinal shift is consistent with dipole tilt angle effects, and (3) non-conjugate theta aurora is consistent with a strong positive IMF B_x, resulting in more efficient reconnection in the southern hemisphere.

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References

Bobra, M. G., S. M. Petrinec, S. A. Fuselier, E. S. Claflin, and H. E. Spence (2004), On the solar wind control of cusp aurora during northward IMF, *Geophys. Res. Lett.*, *31*, L04805, doi:10.1029/2003GL018417.

Cowley, S. W. H. (1981), Asymmetry effects associated with the X-component of the IMF in a magnettically open magnetosphere, *Planet. Space Sci.*, *29*, 809–818.

Craven, J. D., J. S. Murphree, L. A. Frank, and L. L. Cogger (1991), Simultaneous optical observations of transpolar arcs in the two polar caps, *Geophys. Res. Lett.*, *18*, 2297–2300.

Frank, L. A., J. B. Sigwarth, J. D. Craven, J. P. Cravens, J. S. Dolan, M. R. Dvorsky, P. K. Hardebeck, J. D. Harvey, and D. W. Muller (1995), The visible imaging system (VIS) for the Polar spacecraft, *Space Sci. Rev.*, *71*, 297–328.

Frey, H. U., S. B. Mende, T. J. Immel, S. A. Fuselier, E. S. Claflin, J.-C. Grard, and B. Hubert (2002), Proton aurora in the cusp, *J. Geophys. Res.*, *107*(A7), 1091, doi:10.1029/2001JA900161.

Frey, H. U., S. B. Mende, T. J. Immel, J. C. Gérard, B. Hubert, J. Spann, G. R. Gladstone, D. V. Bisikalo, and V. I. Shematovich (2003a), Summary of quantitative interpretation of IMAGE ultraviolet auroral data, *Space Sci. Rev.*, *109*, 255–283.

Frey, H. U., T. D. Phan, S. B. Mende, and S. A. Fuselier (2003b), Continuous magnetic reconnection at Earth's magnetopause, *Nature*, *426*, 533–537.

Fuselier, S. A., H. U. Frey, K. J. Trattner, S. B. Mende, and J. L. Burch (2002), Cusp aurora dependence on interplanetary magnetic field Bz, *J. Geophys. Res.*, *107*(A7), 1111, doi:10.1029/2001JA900165.

Mende, S. B., et al. (2000), Far ultraviolet imaging from the IMAGE spacecraft.3. Spectral imaging of Lyman-α and OI 135.6 nm, *Space Sci. Rev.*, *91*, 287–318.

Milan, S. E., M. Lester, S. W. H. Cowley, and M. Brittnacher (2000), Dayside convection and auroral morphology during an interval of northward interplanetary magnetic field, *Ann. Geophys.*, *18*, 436–444.

Newell, P. T., and C.-I. Meng (1989), Dipole tilt angle effects on the latitude of the cusp and cleft/low-latitude boundary layer, *J. Geophys. Res.*, *94*, 6949–6953.

Newell, P. T., C.-I. Meng, D. G. Sibeck, and R. Lepping (1989), Some low-altitude cusp dependencies on the interplanetary magnetic field, *J. Geophys. Res.*, *94*, 8921–8927.

Østgaard, N., S. B. Mende, H. U. Frey, L. A. Frank, and J. B. Sigwarth (2003), Observations of non-conjugate theta aurora, *Geophys. Res. Lett.*, *30*(21), 2125, doi:10.1029/2003GL017914.

Phan, T., et al. (2003), Simultaneous Cluster and IMAGE observations of cusp reconnection and auroral proton spot for northward IMF, *Geophys. Res. Lett.*, *30*(10), 1509, doi:10.1029/2003GL016885.

Reiff, P. H., and J. L. Burch (1985), IMF B_y-dependent plasma flow and Birkeland currents in the dayside magnetosphere, 2. A global model for northward and southward IMF, *J. Geophys. Res.*, *90*, 1595–1609.

Richmond, A. D. (1995), Ionospheric electrodynamics using magnetic apex coordinates, *J. Geomagn. Geoelectr.*, *47*, 191–212.

Sandholt, P. E., C. J. Farrugia, J. Moen, O. Noraberg, B. Lybekk, T. Sten, and T. Hansen (1998), A classification of dayside auroral forms and activities as a function of interplanetary magnetic field orientation, *J. Geophys. Res.*, *103*, 23,325–23,345.

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