Observations of non-conjugate theta aurora

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[1] Based on simultaneous imaging data from IMAGE FUV and Polar VIS Earth camera and DMSP particle measurements we report two events where a theta aurora was observed in one hemisphere but not in the other. IMF control and hemispherical conductivity differences are suggested as possible explanations for the occurrence of non-conjugate theta aurora. *INDEX TERMS:* 2475 Ionosphere: Polar cap ionosphere; 2704 Magnetospheric Physics: Auroral phenomena (2407); 2776 Magnetospheric Physics: Polar cap phenomena; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions. **Citation:** Østgaard, N., S. B. Mende, H. U. Frey, L. A. Frank, and J. B. Sigwarth, Observations of non-conjugate theta aurora, *Geophys. Res. Lett.*, *30*(21), 2125, doi:10.1029/2003GL017914, 2003.

1. Introduction

[2] Since Dynamic Explorer 1 (DE1) provided the first images of a transpolar arc extending all across the polar cap [*Frank et al.*, 1982], imaging from space combined with solar wind monitoring have revealed a strong solar wind control on its triggering, motion and intensity. Theta auroras are associated with northward IMF [*Lassen and Danielsen*, 1978; *Kullen et al.*, 2002] and lobe reconnection, and are located in the region of sunward flow in a 4 cell ionospheric convection pattern [*Reiff and Burch*, 1985; *Frank et al.*, 1986; *Cumnock et al.*, 2002]. The precipitating electrons in the theta arcs are accelerated by electric fields [*Frank et al.*, 1986] probably resulting from shear flows at the convection reversal boundary [*Cumnock et al.*, 2002]. Particle characteristics (spectra and ion composition) observed in the arcs indicate that theta auroras are created on closed field lines [*Peterson and Shelley*, 1984; *Frank et al.*, 1986] as predicted by models [*Reiff and Burch*, 1985; *Chang et al.*, 1998]. Some studies have reported a clear causative effect between polarity changes of B_y and formation of theta aurora [*Cumnock et al.*, 1997, 2002] while others attribute their creation to polarity changes in B_z [*Newell and Meng*, 1995] or polarity changes in either of them [*Chang et al.*, 1998; *Kullen et al.*, 2002]. In any case, the polarity change has to be large enough to change the merging location significantly [*Chang et al.*, 1998]. Not so much attention has been paid to the IMF B_x component influence on the theta aurora. However, statistical studies have shown that both theta events and small scale Sun-aligned arcs in the northern hemisphere (NH) are strongly correlated with a negative B_x [*Lassen and Danielsen*, 1978; *Kullen et al.*, 2002]. Similarly, *Iijima et al.* [1984] reported a strong correlation between field-aligned current densities in the southern polar cap and positive B_x. *Cumnock et al.* [2002] found that the moving theta auroras in the NH tend to fade after crossing the noon-midnight meridian when B_x is positive, but crossed the entire polar region when B_x is negative. The *Reiff and Burch* [1985] model predicts a larger lobe convection cell in the hemisphere where lobe reconnection is favored. The theta aurora may also be affected by conductivity differences in the polar caps due to solar EUV radiation. Statistical studies have shown that discrete arcs in the auroral oval are suppressed in the sunlit hemisphere [*Newell et al.*, 1996]. The only simultaneous optical observations of theta aurora in both hemispheres are images from DE 1 and the Viking spacecraft [*Craven et al.*, 1991]. The theta observations coincided with abrupt changes in all IMF components. The two polar arcs were found to be parallel with a 180° counterclockwise rotation and they moved in opposite directions. Here we present two events where both polar caps were observed and a theta aurora was seen in one hemisphere, but not in the other.

2. Observations

[3] On November 5, 2001, a bright theta aurora was observed by the IMAGE FUV system in the NH from ~1800 UT to ~2000 UT. From 1915 UT to 2000 UT the VIS Earth camera (Polar) provided global images from the southern hemisphere (SH). The two upper panels of Figure 1 display the simultaneous unsmoothed images from (a) IMAGE FUV SI13 (135.6 nm) and (b) VIS Earth camera (130.4 nm), where the SI13 images from NH are mapped to the same viewing geometry as the VIS Earth images in the SH. Although the auroral 130.4 nm emissions are 4 times brighter and more scattered than the 135.6 nm emission [*Frey et al.*, 2003], both emissions are produced by electron impact on O, and the differences should not affect comparison of large scale features like the theta aurora. In the NH, the SI13 images show that the intensity of the theta is comparable to that of the auroral oval. In the SH, however, although particle contamination produces some noise in the VIS Earth images no theta aurora with intensity comparable to the auroral oval is observed. In Figure 1c three DMSP passes are mapped onto SI13 images that correspond exactly to the crossing through the theta aurora observed in the NH. F14 (solid line) passed the NH while F12 and F15 (dashed lines) passed the SH. Spectrograms from the SSJ/4 instrument on F14 in the NH (Figure 1d - left panel) show that the theta aurora is produced by 0.4–1 keV electrons while the 1–10 keV ions indicate that the theta precipitation is on closed field lines with open field lines on both sides. If the SH-theta is a 180° counterclockwise rotation of the NH-theta [*Craven et al.*, 1991] one would not expect F15 to see the theta, but F12, with its track closer to the dawn-dusk meridian should be

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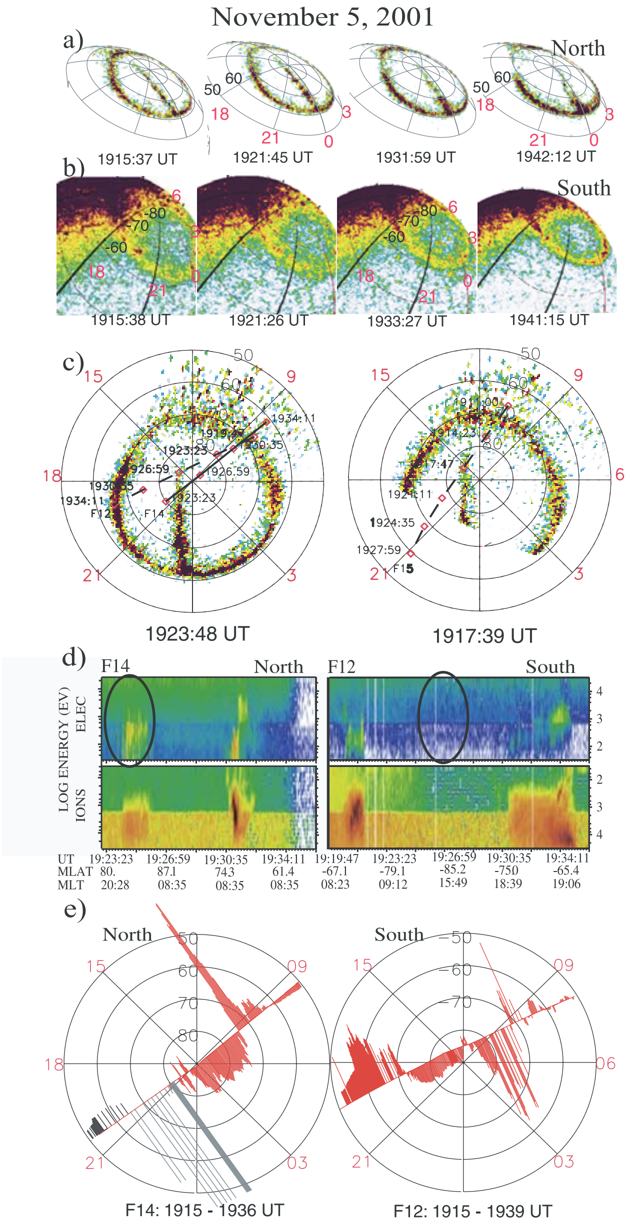

Figure 1. November 5, 2001. (a) SI13 images from the NH. (b) VIS Earth images from the SH. (c) Trajectories of DMSP passes (solid: NH, dashed: SH) mapped onto simultaneous SI13 images from the NH. (d) Spectrograms from DMSP, electrons and ions, where the ovals signify the expected location of the theta auroral precipitation (if any). (e) Cross track plasma drift data from DMSP. Grey color indicate data where the amplitude is not correct. All images are presented in apex magnetic coordinates.

able to observe the theta, if any. However, SSJ/4 data from F12 (Figure 1d - right panel) and F15 (not shown) in the SH show no signatures of theta precipitation, but polar rain signifying open field lines. In Figure 1e the cross track plasma drift data from the two hemispheres are shown. In the NH, F14 data (Figure 1e - left panel) show two narrow regions of sunward flows separated by an anti-sunward flow at ~85° magnetic latitude, just where the theta is observed. This 4-cell convection pattern is further supported by a high latitude bright proton auroral spot measured by FUV SI12 (not shown) in the NH. A small region of weaker sunward flow is seen in the F12 data from the SH (Figure 1e - right panel), dawnward to the sunward flow in the NH. However, the sunward flow is not associated with any particle precipitation (Figure 1d) or auroral signatures. The theta auroral precipitation appears as a non-conjugate phenomenon, despite similarities in convection pattern in the two hemispheres.

[4] On April 18, 2001, the VIS Earth camera observed a theta aurora in the SH from 1128 UT (first available image) until 1150 UT, when the theta disappeared. SI13 provided images from 0900 UT to 1200 UT from the NH. As this theta aurora as well as the auroral oval was fainter than observed on November 5 and the theta is a relatively stationary feature, we have added 6 VIS Earth images and 3 SI13 images to obtain comparable ~4.5 min resolution images with higher counting statistics from both hemispheres (Figures 2a and 2b). A clear theta aurora, even brighter than the auroral oval (e.g., 1139:20–1143:51 UT), is seen in the SH, while images from the NH show no theta. Figure 2c displays the trajectories of two DMSP passes in the SH plotted onto the VIS Earth image closest in time to the passes. F12 and F14 traversed the theta at ~1124 UT and ~1119 UT, respectively. Spectrograms from

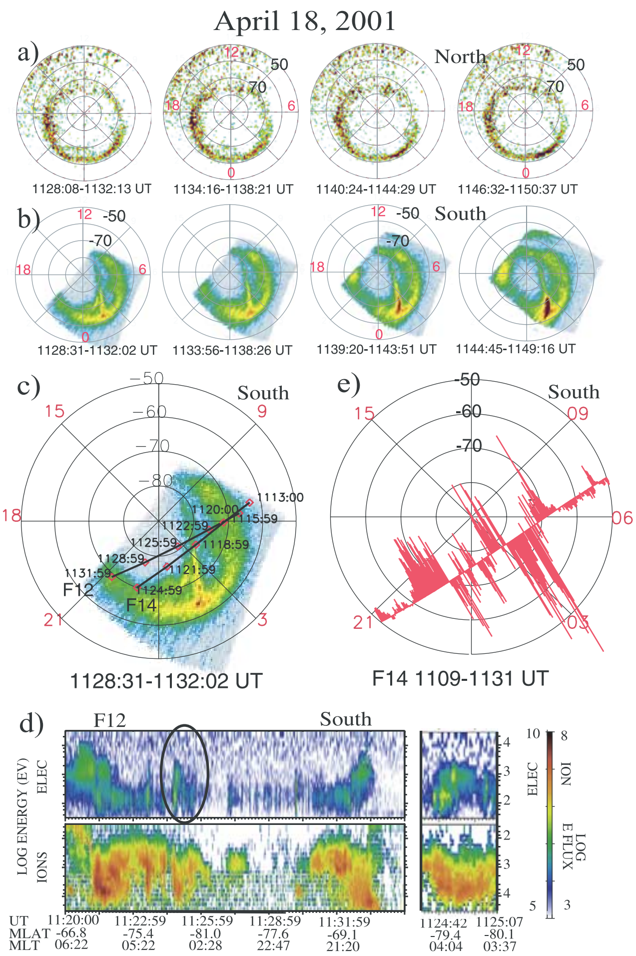

Figure 2. Same as Figure 1, but for April 18, 2001, except for the less dynamic color bars used to visualize the fainter (than Nov 5) theta aurora. DMSP passes are from the SH.

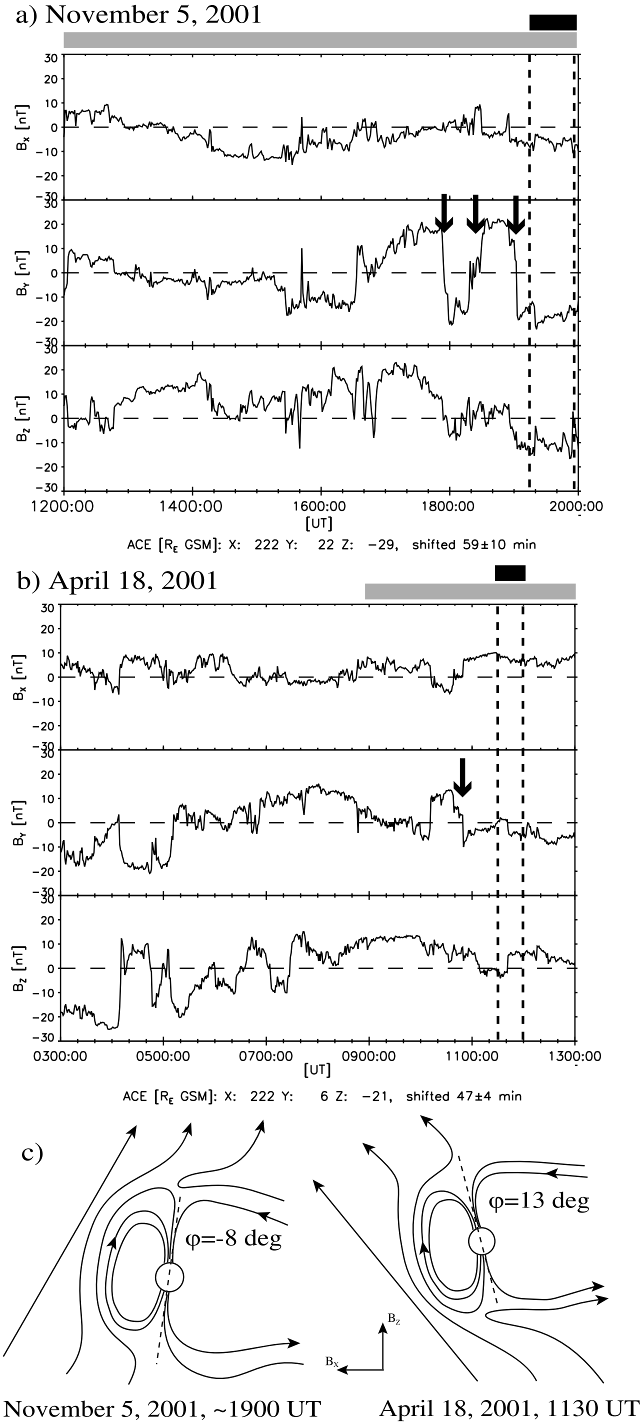

Figure 3. (a) The three components of IMF (in GSM) on November 5, 2001 time shifted to X = 0. Grey (black) horizontal bar indicate when SI13 (VIS Earth) data were available. The dashed lines indicate times of joint observations. (b) Same parameters on April 18, 2001. (c) Sketches to illustrate tilt angles (dashed line - φ) defining sunlit and dark hemispheres as well as where lobe reconnection is favored.

F12 (Figure 2d) and F14 (not shown) demonstrate that the theta is produced by $\sim$1 keV electrons while the 1–10 keV ions indicate closed field lines. The 1–10 keV ions dawnward of the theta indicate a region of closed field lines, while the polar rain (electrons) signifies open field lines duskward of the theta. The cross track plasma drift data from F14 (Figure 2e - SH) and F12 (not shown) indicate a 4 cell lobe reconnection convection pattern with very strong sunward flows adjacent to the theta aurora. Unfortunately no low-altitude satellite passes were available from the NH. However, the high latitude proton spot in the SI12 images (data not shown) associated with lobe reconnection was seen with various intensity from $\sim$0900 UT to $\sim$1140 UT, indicating that lobe reconnection occurred in the NH as well, but without being able to cause any theta aurora.

3. Discussion and Summary

[5] Figures 3a and 3b contain the time-shifted ACE IMF data. Similar IMF conditions were observed by Wind (not shown). We first notice that both events occurred after many hours of northward IMF. The bright theta aurora on November 5, that first appeared at $\sim$1800 UT (in the NH), was associated with three large polarity changes in B_y (arrows), moving the lobe reconnection site from dusk to dawn to dusk and finally to dawn again, resulting in open field lines on either side of a narrow region of closed field lines associated with the theta aurora [*Chang et al.*, 1998; *Cumnock et al.*, 2002]. The fainter theta observed on April 18 may have been triggered by the smaller B_y polarity change prior to 1050 UT (arrow). Both events are also associated with smaller polarity changes in B_z [*Newell and Meng*, 1995; *Chang et al.*, 1998], although only the B_y changes are large enough to change the merging location significantly [*Chang et al.*, 1998]. Although both events occurred during relatively high solar wind pressure conditions (data not shown), the difference in solar wind pressure ($\sim$10 nPa on November 5 versus $\sim$5 nPa on April 18) may also be important to explain the different theta intensities [*Kullen et al.*, 2002]. The high solar wind pressure on November 5 can also explain the wide oval, non-typical for IMF northward conditions. One possible candidate to explain why theta aurora can occur in one hemisphere but not in the other is the sign of IMF B_x. During the time intervals of simultaneous observations (see dashed lines in Figure 3a and 3b) IMF B_x was ≤ -3 nT on November 5 (1915–2000 UT) and ≥ 5 nT on April 18 (1130–1150 UT). In Figure 3c, we have illustrated the IMF orientation (in XZ plane) downstream of the bow shock on November 5 just before 19 UT (with $B_x = -3$ nT and $B_z = 5$ nT) and on April 18 at 1130 UT (with B_x = 5 nT and B_z = 5 nT). Although the dipole tilt-angle tends to decrease the effect of B_x during both events, the negative B_x on November 5 favors lobe reconnection in the NH, while the positive B_x on April 18 favors lobe reconnection in the SH. This explanation implies that the B_x effect dominates the dipole tilt-angle effect, contrary to what was suggested by *Crooker and Rich* [1993]. Both theta arcs are observed at the convection reversal boundary of the lobe convection cell [*Cumnock et al.*, 2002] and the associated flow shears can produce electric fields that easily accelerate electrons to $\sim$1 keV. The driver of the convection cells is the lobe reconnection and the sign of the B_x component can explain why the flow shears, despite signatures of lobe reconnection and sunward flows [*Eriksson et al.*, 2003], are large enough in one hemisphere but not in the other to produce these electric fields. This is consistent with

the *Chang et al.* [1998] model for theta triggered by polarity changes in B_y and the results from *Kullen et al.* [2002], who found no midnight arcs in the NH for positive B_x. As the theta aurora is also a proton auroral phenomenon, steady scattering of plasma sheet ions into the loss cone must also be present in this region of flow shear and upward current. *Reiff and Burch* [1985] predict that the sunward flow on closed field lines must be a conjugate phenomenon, while the sheet current along the convection reversal may not be conjugate, in nice agreement with our results. It may be argued against this explanation and especially in the November 5 case, that the sign of B_x is not consistent for the hour or two prior to the simultaneous observations and that the lobe reconnection may be totally dominated by the large B_y component. An alternative explanation is that conductivity differences lead to a suppression of theta aurora in one hemisphere. Although both events occurred close to equinox, the dipole tilt-angles of $-8°$ and $13°$ for November 5 and April 18, respectively (Figure 3c), leave one polar cap more exposed to solar EUV radiation than the other. Consequently, the conductivity is larger in the sunlit polar cap, which allows currents to flow without any potential drop and electron acceleration [*Newell et al.*, 1996]. However, the small tilt-angle on November 5 ($-8°$ at 1900 UT) leaves both polar caps exposed to solar EUV (confirmed by images, not shown) and the conductivity differences should be small. DMSP (12 and 14) particle data indicate weaker precipitation in the southern hemisphere at ~0830 MLT/70° Mlat but it does not disappear as the transpolar precipitation does. Moreover, the theta aurora appears in the nightside polar cap, which is in the dark even in the southern hemisphere. The observations of theta aurora in both hemispheres reported by *Craven et al.* [1991] were obtained when the dipole tilt angle was large (28°). Consequently, in the reference frame of the Earth's dipole, B_x was close to zero (as pointed out by *Chang et al.* [1998]) and there would be no preference for lobe reconnection in a specific hemisphere. On the other hand, if the conductivity differences due to solar EUV is the controlling factor, the large dipole tilt-angle (28°) should effectively have suppressed theta aurora in the northern hemisphere, contrary to what they observed.

[6] We have presented two events where a theta aurora was observed in one hemisphere but not in the other. The imaging observations are supported by particle data from low altitude satellites. The occurrence of non-conjugate theta aurora may be explained by the IMF B_x, which controls where lobe reconnection is most efficient and consequently in which hemisphere a 4-cell convection pattern can drive flow shears, with sufficient strength to generate electric fields to produce theta aurora. Alternatively or as an additional effect, the theta aurora may be suppressed in one hemisphere due to different exposure to solar EUV radiation.

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