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Magnetospheric Model Performance During Conjugate Aurora

by

William Longley

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APPROVED, THESIS COMMITTEE

Patricia Reiff, Chair
Professor of Physics and Astronomy; Associate Director of Outreach Programs, Rice Space Institute

Anthony Chan
Professor of Physics and Astronomy

Frank Geurts
Assistant Professor of Physics and Astronomy

HOUSTON, TEXAS
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Abstract

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On August 17th, 2001, the IMAGE satellite viewed the Northern aurora, while the POLAR satellite observed the Southern aurora. Unlike typical cases where the aurora is conjugate, the large Y-component of Interplanetary Magnetic Field (IMF) makes the polar cap shift towards the dusk in one hemisphere and towards the dawn in the other. Using the satellite images, we identified the Polar Cap Boundary in both hemispheres, and determined the Dawn-Dusk Offset, ∆L, which ranged from 0° to 15° latitude. We found correlations of 0.90 in the North and 0.83 in the South between ∆L and IMF By. We then computed Polar Cap Boundaries using four MHD models. None of the models accurately reproduced the observations, with BATSRUS producing boundaries that are too symmetric, OpenGGCM producing boundaries that are too distorted, and the LFM-MIX model giving the best average offset but did not match the observed variation with solar wind parameters.
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Introduction

1.1 The Event and Space Weather

A coronal mass ejection (CME) hit the Earth at 11:00 UT on August 17th, 2001, indicated by a jump in the solar wind’s flow speed from 340 km/s up to 480 km/s. The CME carried with it a strong magnetic field, with a y-component (By) averaging around 25 nT for nearly 12 hours, and a z-component (Bz) varying from 0 nT to -20 nT. By 16:00 UT the Kp index was measured as 5, and it would increase up to 7 by 19:00 UT. During this 16:00 to 19:00 UT window, aurora were simultaneously observed by the IMAGE satellite in the northern hemisphere, and by the POLAR satellite in the southern hemisphere.

The above description of the auroral event this paper focuses on, and the field of Space Weather can be summarized as follows. The Sun is constantly ejecting a low density plasma, primarily composed of protons and electrons, radially outward at a typical speed of 350-400 km/s into interplanetary space; this is the solar wind. Embedded in the solar wind is a weak Interplanetary Magnetic Field (IMF), which follows an Archimedean spiral outward from the Sun. This shape of the IMF is known as the Parker spiral, and under normal conditions the magnetic field intersects the Earth’s orbit at 45 degree angle, where the radial and tangential components of the magnetic field are equal [Parker, 1963]. The average strength of the magnetic field at Earth is about 6 nT. This means the By component alone in this event (See Section 1.4 for definition of the x-y-z axes) is more than 4 times larger than the average value of the IMF. When the solar wind’s velocity jumps up 100 km/s within an hour, and carries a magnetic field significantly stronger than average, a magnetospheric storm will occur.
The severity of the magnetospheric storm is characterized by the Kp index, a number ranging from 0 to 9 derived from ground based magnetometer stations. A scale showing the effects of a solar storm based on the observed Kp index can be found at [http://www.swpc.noaa.gov/NOAAscales]. A Kp index of 5 indicates a minor geomagnetic storm, with minimal impacts on power grids and spacecraft, and the occurrence of aurora at high latitudes. The event we are examining has a peak Kp value of 7, which can induce large currents in high latitude power grids, cause surface charging on satellites, expand the Earth’s atmosphere to increase drag on satellites, and cause intense aurora at mid to high latitudes. A very large geomagnetic storm of Kp = 9 can destroy transformers in power grids, leading to regional blackouts. Additionally, spacecraft can build up a charge on their surface, which can potentially discharge through the spacecraft’s electronics causing them to fail. Large currents will also build up in pipelines; radio communications and satellite navigation can be degraded or knocked out; and intense aurora can be observed at mid latitudes. National Research Council [2008] estimated a severe geomagnetic storm can cost over $1 trillion, and at least 4 years to recover from. Improving our understanding of the aurora also improves our understanding of the whole geomagnetic storm, allowing us to better mitigate the potential economic effects of a severe storm.

1.2 The Magnetosphere and Magnetic Reconnection

The basic picture of the Earth’s magnetosphere is that of a dipole magnetic field compressed by the solar wind on the sunward side, and with an extended tail pointing away from the Sun (Figure 1.1). This model has two fundamentally different areas of
magnetic field lines. At mid and low latitudes we see closed field lines, which are field lines with both ends connected to the Earth. At high latitudes we see open field lines, which are field lines with one end connected to the Earth and one end connected to the IMF. The area defined by the open field lines is called the Polar Cap, and the boundary between open and closed field lines is called the Polar Cap Boundary. The footpoints of the magnetic field lines will convect (move) around the polar cap, typically in a 2, 3 or 4 cell pattern (Figure 1.2) dictated by the direction and strength of the IMF [Reiff et al., 1985; Hesse et al., 1997]. As the field lines reach the noon-midnight region they can reconnect, allowing a partial penetration of the IMF into the magnetosphere [Komar et al., 2013].

Figure 1.1: The Earth’s Magnetosphere viewed from dusk at the equator. The blue magnetic field lines are from the IMF, the green magnetic field lines are the Earth’s closed field lines, and the red magnetic field lines are the Earth’s open field lines. Magnetic reconnection occurs at the two grey areas. Figure from https://perswww.kuleuven.be/~u0052182/weather/les3/node8.html.
Bright aurora occur during periods of heightened solar activity, with the most intense and lowest-latitude occurring in response to a CME from the Sun. The higher energy particles from the CME get trapped in the Earth’s magnetic field, where they eventually precipitate into the Earth’s upper atmosphere. In the Earth’s upper atmosphere the higher energy particles collide and react with Oxygen and Nitrogen, emitting a green or red color from Oxygen, and a blue or crimson color from Nitrogen. The pattern of the aurora that one sees from the ground can either be in vibrant, discernable features called the discrete aurora, or it can be a large featureless glow called the diffuse aurora. It is important to note that the aurora is never seen in just one location on the Earth. It is generally observed as a nearly-complete ring centered on the magnetic pole. Typically when an aurora is occurring in one hemisphere, it will also occur simultaneously in the opposite hemisphere, but the intensity and location may differ, depending on the time of year and solar activity [Newell et al., 2010].

The aurora is caused by electrons precipitating from the Earth’s magnetosphere; thus similar fluxes at both ends of a magnetic field line is a reasonable assumption, since the electrons can rapidly bounce from one end of the field line to the other [Störmer,
Magnetic reconnection allows both energy and particles to be transferred from the solar wind to the magnetosphere, but reconnection is not the mechanism responsible for accelerating particles into the aurora [Østgaard et al., 2009; Reiff, 2013]. The high degree of North/South symmetry in this basic model allows one to define magnetically conjugate points as a pair of points that share the same longitude, and are equidistant from the equator. Basic plasma dynamics dictates that the trapped particles in the Earth’s magnetic field will follow the magnetic field and bounce between the north and south hemispheres, eventually precipitating into the atmosphere when either the particles scatter into the “loss cone” (the diffuse aurora) or parallel electric fields accelerate electrons into the loss cone [Reiff et al., 1988]. The fact that particles follow the same field line between hemispheres led to conjectures that the aurora in each hemisphere would look the same at magnetically conjugate points [Vestine and Sibley, 1960].

1.3 Observations of Conjugate Aurora

These conjugate auroras have been observed as far back as 1958 using all-sky cameras positioned at conjugate points in Alaska and the South Pacific during the International Geophysical Year [DeWitt, 1962]. The method of using all-sky cameras at conjugate auroral points is still being used since the high spatial resolution of the cameras allow the discrete auroral forms to be studied and compared in each hemisphere. Sato et al. [2005] traced similar points in the discrete aurora to show the conjugate points moving 200 km in longitude and 50 km in latitude during an hour long auroral event. However, a lot of luck is required in obtaining clear weather conditions at both locations of the all-sky cameras, and this has led to observations of the aurora from above the cloud.
level. A series of simultaneous aircraft flights along the College, AK meridian was carried out between 1967 and 1970. Stenbaek-Nielsen et al. [1972] examined the images taken from these flights to observe discrete equator-oriented auroral arcs that showed a high degree of conjugacy, as well as a separate system of discrete poleward arcs that were displaced as much as 300 km from their conjugate points. Stenbaek-Nielsen concluded that the diffuse aurora are conjugate, but the discrete aurora are non-conjugate but on closed field lines. A revisit of the conjugate flight data by Stenbaek-Nielsen and Otto [1997] concluded that the spatial shifts in discrete aurora assumed to be conjugate are too large to be explained by any perturbations in Earth’s magnetic field, and are thus created by independent processes in each hemisphere.

More recently satellites have been used to view the auroral oval with large scale, unobstructed views from space. The Defense Meteorological Satellite Program (DMSP) series of satellites have been in circular low Earth orbits (~800 km altitude, varies by satellite) since 1962 [Hall, 2001]. While the DMSP satellites were initially used for meteorological and military purposes, they soon evolved into covering a wide range of scientific tasks, including narrow field views (roughly as wide as the border between the U.S.A. and Canada) of the aurora. Then in 1971 the Canadian satellite ISIS II was launched into a circular orbit at 1400 km altitude, providing the first views of the entire auroral oval until it was decommissioned in 1990 [http://www.asc-csa.gc.ca/eng/satellites/isis.asp]. Using the ISIS images, Lui and Anger [1973] observed the diffuse aurora occurring in a continuous oval around the poles, even when no discrete aurora are observed. The data from DMSP and ISIS were used for some of the earliest studies of large scale auroral morphology by Siren [1975] and Kamide and Akasofu.
Whalen et al. [1977] was able to compile all-sky images, airplane based images, DMSP images, and ISIS II images to examine a 12 hour period of continuous aurora. Dynamics Explorer 1 was launched in 1981 (decommissioned in 1991) into a highly elliptical polar orbit, while carrying an auroral imaging camera [Hoffman, 1980]. The highly elliptical polar orbit is used because it keeps the satellite high above one hemisphere for more than 70% of the satellite’s orbit, maximizing the amount of time the satellite is able to view one hemisphere (Figure 1.4). On February 1986 the Swedish Viking satellite was also launched into an elliptical polar orbit over the northern hemisphere with an auroral imager, until it was decommissioned in May 1987 [Viking Science Team, 1986].

The next satellite launched with auroral imaging capabilities was POLAR in 1996. POLAR was launched in a highly elliptical polar orbit with an 18 hour period, spending more than 13 hours of the orbit high above one hemisphere [Frank et. al, 1995].

Figure 1.3: Plot of POLAR’s orbit during the event, showing how the apogee is close enough to the equator to give POLAR a view of the southern hemisphere from 16:40 UT (indicated by the green arrows) to 19:00 UT (indicated by the red arrows), though the view is incomplete towards later times.
The apogee of the orbit was initially in the northern hemisphere, but precesses southward by 16 degrees every year, causing the apogee to be near the equator starting in 2001 and allowing POLAR to start observing the aurora in the southern hemisphere for several hours at a time. While POLAR was in orbit, the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite was launched in early 2000. IMAGE was also placed into a highly elliptical polar orbit, spending more than 10 hours of its 14.2 hour orbital period high above one hemisphere [Burch, 2000]. IMAGE’s apogee also precesses at a rate of 50 degrees each year, starting at 40 degrees north in 2000, going over the pole and back to 40 degrees north in 2002, and finally into the southern hemisphere from 2003 until the satellite’s operations ceased at the end of 2005. In 2001 POLAR’s orbit had shifted from high in the northern hemisphere to near the equator, able to partially observe the southern hemisphere when IMAGE was launched high into the northern hemisphere.
However, starting in 2003 both spacecraft had their apogees in the southern hemisphere, giving us only the brief window of 2001-2002 where each satellite was able to primarily observe a different hemisphere. Unfortunately, since IMAGE ceased operations in 2005 and Polar in 2008, there has been no routine auroral monitoring spacecraft; however, a network of ground-based auroral all-sky imagers is being used now to support the equatorially orbiting THEMIS mission [Angelopoulos, 2008].

The launch of WIND in 1994 and the launch of ACE in 1997 allowed continuous, high temporal resolutions of the solar wind and IMF for the first time. The availability of high quality IMF data has led to several studies of the IMF’s effect on auroral conjugacy. Østgaard et al. [2004] used simultaneous observations of five conjugate aurora events observed by POLAR and IMAGE to identify shared features of the aurora in each hemisphere. The distinct features were found to be shifted in longitude, with the amount of shift correlating weakly with IMF clock angle ($\theta_c = \arctan(By/Bz)$) and the By component. Østgaard et al., [2005] strengthened the statistics in the 2004 paper by adding four more events to the study. The 2005 paper also applied the same methods to outputs from the Tsyganenko 96 and 02 models to find the longitudinal shifts to be present in the models, but to a lesser effect. Liou and Newell, [2010] used POLAR to determine the longitude of 2539 auroral breakups. The longitude of the auroral breakups was found to correlate well with the By component of the IMF and the dipole tilt angle, but not the IMF clock angle. Østgaard et al., [2011b] expanded this study to over 6600 events, and concluded that the longitude of the auroral breakup correlated well with both IMF clock angle and the By component. Five hours of an auroral event on October 22nd, 2001 was simultaneously imaged from POLAR and IMAGE in opposite hemispheres.
and examined by Østgaard et al., [2011a].

1.4 Coordinate Systems

Our examination of aurora requires two different coordinate systems; one three-axis cartesian system to measure components of the IMF, and one latitude and longitude system to create polar plots of the aurora. To measure the IMF we use the Geocentric Solar Magnetospheric (GSM) coordinate system defined by the $x$-axis lying along the Sun-Earth line, the $z$-axis containing the projection of the magnetic dipole orthogonal to the $x$-axis, and the $y$-axis completing the right handed orthogonal triad [Hapgood, 1992]. This coordinate system is favored simply because the $B_z$ component of the IMF will align with magnetic noon, and the $B_y$ component will align with the magnetic equator at the magnetopause.

The raw data from IMAGE and POLAR capture whatever the camera is pointing at. To make this data comparable between satellites, or even between successive time steps of the same satellite, we map it to a latitude and longitude based polar map. Since the aurora occur centered on the magnetic poles, we need to use a coordinate system based on the magnetic field. This is further complicated by the 100 km or higher altitude the aurora occur at, necessitating a coordinate system that follows the magnetic field lines above the Earth’s surface. The Apex coordinate system fills these needs perfectly. The Apex coordinate system is based on magnetic shells, where each magnetic shell has an apex of a given height above the Earth’s surface. The latitude and longitude mappings in Apex coordinates are particularly suited for mapping the ionosphere, where the aurora happen to occur [VanZandt et al., 1972].
Data

2.1 IMAGE and POLAR Data

The IMAGE satellite was in position to capture the August 17th, 2001 event in the Northern Hemisphere from 16:41 UT to 19:01 UT. The FUV-WIC instrument is used to view the aurora in the 140 nm to 160 nm ultraviolet band, capturing several Nitrogen emission lines in the Lyman-Birge-Hopfield band [Mende et al., 2000]. WIC has a spatial resolution of less than 0.1 degrees, and a temporal resolution of 120 seconds [Burch, 2000].

The POLAR satellite was able to fully capture the event in the Southern Hemisphere from 17:00 UT to 18:13 UT, and partially capture the event from 16:41 UT to 17:00 UT, and 18:13 UT to 19:01 UT. The VIS instrument is used to view the 130.4 nm Oxygen emission line with a spatial resolution of 0.12 degrees [Frank et. al, 1995]. POLAR-VIS has a temporal resolution of 54 seconds, but the ~2 minute temporal resolution of IMAGE is used instead, matched to the closest VIS image.

The raw data from both satellites are then mapped to Apex coordinates (Figure 2.1) courtesy of Jone Reistad and Nikolai Østgaard from the University of Bergen, Norway. We then identify the Polar Cap Boundary (PCB) by using an operational definition of a 2.0 kR (1300 counts on the detector) precipitation threshold for IMAGE data, and a 6.0 kR (27 counts on the detector) precipitation threshold for POLAR data. The Dawn-Dusk offset, ΔL, is then computed by subtracting the colatitude of the PCB at 6:00 MLT from the colatitude of the PCB at 18:00 MLT. Positive ΔL values signify a polar cap that is shifted to the dusk, and negative ΔL values signify a polar cap shifted to the dawn. For instances where a satellite does not completely capture the aurora at 6:00
or 18:00 MLT, we estimate the location of the polar cap boundary and place an appropriately sized error bar on that point. For all points a minimum error of ±0.3 degrees latitude is used to account for the pixel width of the data. For the 67 image frames we use, 1 of the frames from IMAGE does not capture the 18:00 MLT boundary, 3 of the frames from POLAR fail to capture both the 6:00 MLT boundary and the 18:00 MLT boundary, and 24 of the POLAR frames only capture the 6:00 boundary. All of these frames are used in the study, with missing data being extrapolated from boundary points known at other MLTs.

Figure 2.1: The aurora observed by IMAGE in the northern hemisphere (left) and by POLAR in the southern hemisphere (right) at 17:34 UT. The northern polar cap shows a clear shift towards dawn, and the southern hemisphere shows a clear shift towards dusk. In these images looking down on the Apex pole, noon is at the top, midnight at the bottom, dawn at the right and dusk at the left.

2.2 Models

The results from the IMAGE and POLAR observations will be compared to the outputs of the SWMF/BATS-R-US model both with and without the Comprehensive Ring Current Model (referred to as BATSRUS and BATS-CRCM from here on) [Tóth et
al., 2005], the OpenGGCM model [Raeder et al., 2001; Fuller-Rowell et al., 1996], and the CMIT/LFM-MIX model (referred to as LFM) [Lyon et al., 2004; Merkin and Lyon, 2010]. We ran all of these models from the NASA Community Coordinated Modeling Center (CCMC) website with the assistance of Masha Kuznetsova. All three of these models use as inputs the measured solar wind plasma and magnetic field, and solve 3-dimensional MHD equations. Each model approximates the Earth’s magnetic field as a dipole, with the BATSRUS models allowing the dipole tilt angle to update throughout the simulation, and the OpenGGCM and LFM models keeping a fixed dipole tilt angle for the duration of the run. The BATSRUS, BATS-CRCM and OpenGGCM used the 5.4 nT average Bx over the course of the model run, while the LFM model only allows 0 Bx. The models were only run from 16:15 to 19:15 UT to minimize the effects of a fixed dipole tilt in the OpenGGCM and LFM models.

The output of importance for each model is the Polar Cap Boundary that is plotted on the Ionosphere map, which can be seen for each model in Figures 2.2-2.5. For each frame of the ionosphere, for each model, the colatitude of the PCB at 6:00 MLT is subtracted from the colatitude of the PCB at 18:00 MLT to produce the Dawn-Dusk offset, ΔL, in the same way we computed ΔL for the IMAGE and POLAR data. Some of the outputs of the OpenGGCM and LFM models have multi-valued PCBs at a fixed MLT, possibly as a result of lobe cells (see Section 4). We handle this in two ways: the first way is to locate and record each distinct value of the PCB at the desired MLT, and to then to independently examine each point’s evolution in time. The second way, we deal with multi-valued PCBs is to average all the locations together, compute the standard deviation, and then use that standard deviation as an error bar for our analysis.
Figure 2.2: BATSRUS Ionosphere and polar cap boundary at 18:41 UT. In these images the color bar indicates the ionospheric potential and the solid circle the indicates the polar cap boundary (which can be very distorted for some of the models at certain times). A blue area is convection flowing clockwise and a red area is convection flowing counterclockwise. In steady state, flow lines are equipotentials.

Figure 2.3: BATS-CRCM Ionosphere and polar cap boundary at 18:41 UT.
2.3 Solar Wind Data

We use the “OMNI Combined, Definitive, 1AU 1 minute IMF and Plasma data” dataset from CDAWeb for our IMF and solar wind data. The IMF and solar wind data are already time shifted to account for propagation to the Earth’s bowshock, and are averaged over 1 minute intervals. The key parameters used for correlation against $\Delta L$ are the IMF $B_y$ and $B_z$ components in GSM coordinates; the IMF Clock Angle, $\theta_C = \arctan(B_y/B_z)$; and the Epsilon parameter, $\epsilon = vB^2\sin(\theta_C/2)$. Figure 2.6 shows $B_y$, $B_z$, $\theta_C$, and $\epsilon$ parameters during the event, as well as one hour prior to the event.
Figure 2.6: IMF By, Bz, Clock Angle, and Epsilon parameter on August 17th, 2001.
Results

3.1 IMAGE and POLAR results

The computed Dawn-Dusk Offset, $\Delta L$, observed by the IMAGE and POLAR satellites is plotted against the solar wind parameters $B_y$, $\Theta_C$, and $\epsilon$. We perform a least squares fit to minimize the equation $\chi^2 = \sum_i ((\Delta L_i - yfit_i)/\sigma_i)^2$ where $yfit$ is the computed fit line, and $\sigma$ is the error bar associated with each point $\Delta L$. We then compute $r^2 = 1 - (\sum_i (\Delta L_i - yfit_i)^2)/\sum_i (\Delta L_i - \overline{\Delta L})^2$, and take the square root to arrive at the standard correlation coefficient $r$. We use the $\Delta L$ and $\sigma$ values from each frame of data to calculate the fit; therefore a $\Delta L$ value with a large $\sigma$ will be unimportant to the fit line. However, when calculating the correlation coefficient, we only include $\Delta L$ values where $\sigma$ is less than 2 degrees of latitude.

Taking the 1 minute averaged solar wind parameters, we find that $\Delta L$ correlates well with $B_y$ in both hemispheres, with $r = 0.84$ in the Northern Hemisphere, and $r = 0.81$ in the Southern Hemisphere. $\Delta L$ correlates fairly well with the 1 minute averaged IMF clock angle, $\Theta_C$, yielding a correlation of $r = 0.79$ in the Northern Hemisphere, and $r = 0.68$ in the Southern Hemisphere. The $\epsilon$ parameter correlates only weakly with $\Delta L$, with $r = 0.73$ in the Northern Hemisphere, and $r = 0.56$ in the Southern Hemisphere.

The Earth’s magnetosphere has been shown to reconfigure itself over a 30-60 minute time window in response to changes in the solar wind. To explore this expectation we try different time averages of $B_y$, $\Theta_C$, and $\epsilon$, and even try using a simple time delay of these parameters. The simple time delay involves correlating $\Delta L$ against a solar wind parameter measured $t$ minutes ago. With $t$ in the range of 15 to 45 minutes, we find that $\Delta L$ correlates poorly against all three solar wind parameters, indicating that the
magnetosphere is also influenced by immediate changes in solar wind conditions. We then try a simple constant weighted average of the parameters over the previous $t$ minutes. This works well, and by trying different values of $t$ we can improve the correlations of $\Delta L$ against each of the three solar wind parameters. For $B_y$, we find a 30 minute constant average produces the best correlations, with $r = 0.90$ in the Northern Hemisphere, and $r = 0.83$ in the Southern Hemisphere (Figure 3.1). Averaging $\Theta_C$ over 45 minutes yields $r = 0.88$ in the Northern Hemisphere, and $r = 0.85$ in the Southern Hemisphere (Figure 3.2). Finally, a 50 minute time average of $\epsilon$ produces correlations of $r = 0.85$ in the Northern Hemisphere, and 0.87 in the Southern Hemisphere (Figure 3.3). Using a linearly or exponentially weighted average of the solar wind parameters at best improves correlations by 0.1%, but typically produces correlations well below what we obtained with constant averages. Table 3.1 shows all of these correlations together.

![Dawn Dusk Offset: Polar/IMAGE](image)

Figure 3.1: Dawn-dusk offset measured by IMAGE (northern hemisphere) and POLAR (southern hemisphere) vs. 30 minute averaged IMF $B_y$ component.
Figure 3.2: Dawn-dusk offset measured by IMAGE and POLAR vs. 45 minute averaged IMF Clock Angle.

Figure 3.3: Dawn-dusk offset measured by IMAGE and POLAR vs. 50 minute averaged Epsilon parameter.
Table 3.1: Correlations (r) of various solar wind parameters against the observed Dawn-Dusk offset from the IMAGE and POLAR satellites.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1 min By</th>
<th>30 min &lt;By&gt;</th>
<th>1 min $\Theta_C$</th>
<th>45 min $\Theta_C$</th>
<th>1 min $\epsilon$</th>
<th>50 min $\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta L$ in North</td>
<td>r = 0.84</td>
<td>r = 0.90</td>
<td>r = -0.79</td>
<td>r = -0.88</td>
<td>r = 0.73</td>
<td>r = -0.85</td>
</tr>
<tr>
<td>$\Delta L$ in South</td>
<td>r = 0.81</td>
<td>r = 0.83</td>
<td>r = -0.68</td>
<td>r = -0.85</td>
<td>r = 0.56</td>
<td>r = -0.87</td>
</tr>
<tr>
<td>PCW in North</td>
<td>r = 0.20</td>
<td>r = 0.13</td>
<td>r = -0.05</td>
<td>r = -0.15</td>
<td>r = -0.09</td>
<td>r = -0.25</td>
</tr>
<tr>
<td>PCW in South</td>
<td>r = 0.67</td>
<td>r = -0.76</td>
<td>r = 0.77</td>
<td>r = 0.71</td>
<td>r = 0.72</td>
<td>r = 0.60</td>
</tr>
</tbody>
</table>

One thing that should be noted is that this event had a relatively small range of By values actually observed. Plotting the polar cap width versus time, we see that in the data, the polar cap begins to shrink significantly after 18:20 UT. This shrinkage is related to the onset of reconnection in the magnetotail, which reduces the flux in the polar cap. Evidence for such reconnection is seen in the imagery as both a brightening of the aurora at midnight and its motion poleward. Thus simple correlations of observed parameters, e.g. width and offset, versus By are strongly influenced by the time variations inherent in this event. For example, the imaging data show that the change in offset as a function of By is not expected, that is, for larger By the northern offset becomes more positive (less negative) whereas the southern offset also becomes more positive (Figure 3.4), whereas a simple interpretation would expect that both would become more extreme with more extreme values of By. All of the models agree in that sense, that is, larger offsets for larger By’s, but the data do not.

We also computed the Polar Cap Width by taking the colatitude of the PCB at 6:00 MLT and adding it to the colatitude of the PCB at 18:00 MLT. Correlating the Polar Cap Width against the 1 minute averaged By yields correlations of $r = 0.09$ in the Northern Hemisphere, and $r = 0.78$ in the Southern Hemisphere. The IMF Clock Angle,
produces correlations of $r = 0.27$ in the Northern Hemisphere and $r = 0.64$ in the Southern Hemisphere. Finally, performing a regression of the Polar Cap Width against $\epsilon$ gives us correlations of $r = 0.41$ in the Northern Hemisphere and $r = 0.48$ in the Southern Hemisphere. Neither time averaging the solar wind parameters nor using a time delay improved the correlations of the Polar Cap Width against any of these parameters; many of the Polar Cap Width plots look decidedly non-linear (similar to Figure 3.4).

Figure 3.4: Time series of the polar cap width measured by IMAGE and POLAR. The event showed decided time variations caused by internal magnetospheric instabilities, despite a relatively steady input. The polar cap width grew from 17:20 to 18:20, then shrank as a major geomagnetic storm released the energy stored in the magnetotail, reducing its flux and therefore the polar cap size.

3.2 Model results

Using the same methods from section 3.1 we plot $\Delta L$ and the Polar Cap Width as calculated by the various MHD models against the solar wind parameters $B_y$, $\Theta_C$, and $\epsilon$. The correlation coefficients from these plots are listed in Tables 3.2-3.4. While the table
lists many moderate to strong correlations, none of the models have fits to $\Delta L$ as strong as the data from POLAR and IMAGE. Since the Open-GGCM and LFM models have polar cap boundaries that are often multivalued along a given meridian, we have tracked the polar cap at both the lowest (listed as Eqw, since this is the most Equatorward boundary) and highest (listed as Pol, as this is the most Poleward boundary) latitudes that it crosses the dawn-dusk meridian.

Table 3.2: Correlations ($r$) of a 30 minute averaged By against the Dawn-Dusk offset ($\Delta L$) and Polar Cap Width (PCW) as determined by each of the models.

<table>
<thead>
<tr>
<th>30 min. $&lt;\text{By}&gt;$</th>
<th>BATS-RUS</th>
<th>BATS-CRCM</th>
<th>OpenGGCM Pol</th>
<th>OpenGGCM Eqw</th>
<th>LFM Pol</th>
<th>LFM Eqw</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta L$ in North</td>
<td>$r = -0.75$</td>
<td>$r = -0.91$</td>
<td>$r = -0.42$</td>
<td>$r = 0.44$</td>
<td>$r = -0.29$</td>
<td>$r = -0.30$</td>
</tr>
<tr>
<td>$\Delta L$ in South</td>
<td>$r = 0.11$</td>
<td>$r = 0.31$</td>
<td>$r = 0$</td>
<td>$r = 0.24$</td>
<td>$r = 0.48$</td>
<td>$r = 0.11$</td>
</tr>
<tr>
<td>PCW - North</td>
<td>$r = -0.88$</td>
<td>$r = -0.86$</td>
<td>$r = -0.10$</td>
<td>$r = -0.22$</td>
<td>$r = 0$</td>
<td>$r = -0.60$</td>
</tr>
<tr>
<td>PCW - South</td>
<td>$r = -0.92$</td>
<td>$r = -0.88$</td>
<td>$r = -0.23$</td>
<td>$r = -0.13$</td>
<td>$r = -0.28$</td>
<td>$r = -0.70$</td>
</tr>
</tbody>
</table>

Table 3.3: Correlations ($r$) of a 45 minute averaged $\Theta_C$ against $\Delta L$ and PCW.

<table>
<thead>
<tr>
<th>45 min. $&lt;\Theta_C&gt;$</th>
<th>BATS-RUS</th>
<th>BATS-CRCM</th>
<th>OpenGGCM Pol</th>
<th>OpenGGCM Eqw</th>
<th>LFM Pol</th>
<th>LFM Eqw</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta L$ in North</td>
<td>$r = 0.753$</td>
<td>$r = 0.916$</td>
<td>$r = 0.45$</td>
<td>$r = -0.43$</td>
<td>$r = 0.21$</td>
<td>$r = -0.35$</td>
</tr>
<tr>
<td>$\Delta L$ in South</td>
<td>$r = -0.112$</td>
<td>$r = -0.318$</td>
<td>$r = 0$</td>
<td>$r = -0.27$</td>
<td>$r = -0.49$</td>
<td>$r = -0.05$</td>
</tr>
<tr>
<td>PCW - North</td>
<td>$r = 0.896$</td>
<td>$r = 0.838$</td>
<td>$r = 0.16$</td>
<td>$r = 0.17$</td>
<td>$r = 0$</td>
<td>$r = 0.62$</td>
</tr>
<tr>
<td>PCW - South</td>
<td>$r = 0.910$</td>
<td>$r = 0.860$</td>
<td>$r = 0.25$</td>
<td>$r = 0.17$</td>
<td>$r = 0.25$</td>
<td>$r = 0.71$</td>
</tr>
</tbody>
</table>

Table 3.4: Correlations ($r$) of a 50 minute averaged $\epsilon$ against $\Delta L$ and PCW.

<table>
<thead>
<tr>
<th>50 min. $&lt;\epsilon&gt;$</th>
<th>BATS-RUS</th>
<th>BATS-CRCM</th>
<th>OpenGGCM Pol</th>
<th>OpenGGCM Eqw</th>
<th>LFM Pol</th>
<th>LFM Eqw</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta L$ in North</td>
<td>$r = 0.761$</td>
<td>$r = 0.906$</td>
<td>$r = 0.42$</td>
<td>$r = -0.38$</td>
<td>$r = 0.21$</td>
<td>$r = -0.33$</td>
</tr>
<tr>
<td>$\Delta L$ in South</td>
<td>$r = -0.131$</td>
<td>$r = -0.313$</td>
<td>$r = 0$</td>
<td>$r = -0.25$</td>
<td>$r = -0.51$</td>
<td>$r = 0$</td>
</tr>
<tr>
<td>PCW - North</td>
<td>$r = 0.886$</td>
<td>$r = 0.835$</td>
<td>$r = 0.23$</td>
<td>$r = 0.16$</td>
<td>$r = 0$</td>
<td>$r = 0.61$</td>
</tr>
<tr>
<td>PCW - South</td>
<td>$r = 0.895$</td>
<td>$r = 0.859$</td>
<td>$r = 0.27$</td>
<td>$r = 0.14$</td>
<td>$r = 0.18$</td>
<td>$r = 0.70$</td>
</tr>
</tbody>
</table>
What is more useful, and more interesting, is comparing the plot trends between each model. Table 3.5 lists the ranges and average of ∆L in each hemisphere for all the models and the satellite data. Both BATSRUS models have very small dawn-dusk offsets, whereas the POLAR/IMAGE data, the LFM model, and the OpenGGCM model all have abs(∆L) > 10 at times, and a large range of ∆L over the course of the event. Finally, the slope of the fit lines to ∆L varies between the data, with the Northern Hemisphere ∆L vs By plots having a positive slope for the satellite data and the max Open-GGCM boundary, but a negative slope for all of the other models. The slopes of the ∆L vs By plots in the Southern Hemisphere are positive for all models and the satellite data (but with 0 correlation for OpenGGCM Pol). Further complicating the point is that the Polar Cap Boundary in the Northern Hemisphere of the LFM model is multivalued at 18:00 MLT for every time step during the event.

Table 3.5: Minimum and maximum Dawn-Dusk offsets measured from every satellite and model (in degrees of latitude).

<table>
<thead>
<tr>
<th>Northern Hemisphere</th>
<th>IMAGE</th>
<th>BATSRUS</th>
<th>BATS-CRCM</th>
<th>OpenGGCM Pol</th>
<th>OpenGGCM Eqw</th>
<th>LFM Pol</th>
<th>LFM Eqw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max ∆L</td>
<td>0 deg</td>
<td>-1 deg</td>
<td>1 deg</td>
<td>12 deg</td>
<td>20 deg</td>
<td>-5 deg</td>
<td>8 deg</td>
</tr>
<tr>
<td>Avg ∆L</td>
<td>-7.6 deg</td>
<td>-2.2 deg</td>
<td>-0.6 deg</td>
<td>-6.1 deg</td>
<td>-4.4 deg</td>
<td>-10.4 deg</td>
<td>1.7 deg</td>
</tr>
<tr>
<td>Min ∆L</td>
<td>-15 deg</td>
<td>-4 deg</td>
<td>-4 deg</td>
<td>-15 deg</td>
<td>-18 deg</td>
<td>-21 deg</td>
<td>-2 deg</td>
</tr>
<tr>
<td>Southern Hemisphere</td>
<td>POLAR</td>
<td>BATSRUS</td>
<td>BATS-CRCM</td>
<td>OpenGGCM Pol</td>
<td>OpenGGCM Eqw</td>
<td>LFM Pol</td>
<td>LFM Eqw</td>
</tr>
<tr>
<td>Max ∆L</td>
<td>14 deg</td>
<td>3 deg</td>
<td>7 deg</td>
<td>21 deg</td>
<td>31 deg</td>
<td>19 deg</td>
<td>19 deg</td>
</tr>
<tr>
<td>Avg ∆L</td>
<td>10.2 deg</td>
<td>2.5 deg</td>
<td>5 deg</td>
<td>3.7 deg</td>
<td>14.4 deg</td>
<td>14.5 deg</td>
<td>15.3 deg</td>
</tr>
<tr>
<td>Min ∆L</td>
<td>5 deg</td>
<td>2 deg</td>
<td>4 deg</td>
<td>-10 deg</td>
<td>2 deg</td>
<td>8 deg</td>
<td>13 deg</td>
</tr>
</tbody>
</table>
Discussion and Summary

4.1 Magnetospheric Response to Solar Wind Changes

$\Delta L$ measured from POLAR and IMAGE correlated best with a 30 min average of $B_y$, a 45 minute average of $\Theta_C$, and a 50 minute average of $\epsilon$. One might jump to conclusions and think the magnetosphere responds to each of these variables on those time scales, but a deeper look into the solar wind data shows that this is not the case. The first thing to note is how pathologically high the $B_y$ component is, ranging from 22 nT to 32 nT, with an average of 27.6 nT over the course of the event. In comparison, the only other studies of conjugate aurora captured by POLAR and IMAGE occurred during events with $B_y$ between -10 nT and 10 nT [Reistad et al., 2013]. This abnormally high $B_y$, coupled with the fact that we only examined 67 images taken over a 2 hour and 20 minute interval means we do not have a firm basis for drawing broad conclusions. All we can say is that our data supports the general theory that the magnetosphere takes upwards of an hour to reconfigure itself in response to solar wind changes.

We also do not have evidence to support $\Delta L$ responding specifically to one parameter. When looking at 45 minute averaged solar wind parameters, we find $B_y$, $B_z$, $\Theta_C$, and the $\epsilon$ parameter all show high correlations ($0.8 < r < 0.9$) with $\Delta L$. However, a quick look at the collinearity of the variables shows another abnormality in our data set. Table 6 shows the correlations of the 1 minute averaged parameters with themselves, Table 7 shows the same for 45 minute averages. For the 1 minute averaged parameters we see that $B_z$, $\Theta_C$, and $\epsilon$ are all highly correlated and collinear, but $B_y$ is only weakly correlated with the other parameters. When averaged over 45 minutes all of the parameters are highly correlated and collinear.
Table 4.1. Cross-correlations of 1 minute averaged solar wind parameters.

<table>
<thead>
<tr>
<th></th>
<th>Bz</th>
<th>Θ_C</th>
<th>ϵ</th>
</tr>
</thead>
<tbody>
<tr>
<td>By</td>
<td>r = 0.77</td>
<td></td>
<td>r = 0.68</td>
</tr>
<tr>
<td>Bz</td>
<td>----</td>
<td>r = 0.99</td>
<td>----</td>
</tr>
<tr>
<td>Θ_C</td>
<td>----</td>
<td>----</td>
<td>r = 0.93</td>
</tr>
<tr>
<td>ϵ</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
</tbody>
</table>

Table 4.2. Cross-correlations of 45 minute averaged solar wind parameters.

<table>
<thead>
<tr>
<th></th>
<th>Bz</th>
<th>Θ_C</th>
<th>ϵ</th>
</tr>
</thead>
<tbody>
<tr>
<td>By</td>
<td>r = 0.96</td>
<td>r = 0.97</td>
<td>r = 0.93</td>
</tr>
<tr>
<td>Bz</td>
<td>----</td>
<td>r = 1.00</td>
<td>r = 0.99</td>
</tr>
<tr>
<td>Θ_C</td>
<td>----</td>
<td>----</td>
<td>r = 0.98</td>
</tr>
<tr>
<td>ϵ</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
</tbody>
</table>

We expect correlations between Bz and the derived parameter ϵ, and correlations between By and Bz with Θ_C, but these high correlations above 0.95 are surprising, and a result of the very limited parameter range explored in this event. To draw any conclusions about which solar wind parameter has the strongest effect on the dawn-dusk offset we would need to add to our study another event where the solar wind data have a larger range of values. Additionally, the dipole tilt angle has been shown to affect auroral symmetry, but these effects are not observable during a single two and a half hour long window [Østgaard, 2005; Liou and Newell, 2010]. Future studies would greatly benefit from a larger parameter space, which is best accomplished by examining several events.

4.2 Lobe Cells

The largest source of error in locating the satellite imaged polar cap boundary occurs at dusk in the northern hemisphere near the end of the event (Figure 4.1). The
difficulty arises from weak precipitation occurring well inside the typical auroral oval. The location of the precipitation in the summer hemisphere along with a large By is suggestive that this is a High Latitude Dayside Aurora (HiLDA), indicating a dominant dusk convection cell. HiLDA tend to occur with an IMF clock angle between 50 and 90 degrees, a negative Bx component, and a solar wind density less than 4 cm⁻³ [Frey et al., 2004]. However, this event occurred with a clock angle ranging from 90 to 140 degrees, an average Bx of 6 nT, and a solar wind density ranging from 12 cm⁻³ to 20 cm⁻³, indicating that something else is occurring within the dusk convection cell.

Figure 4.1: Aurora observed in the northern hemisphere (left) by IMAGE, and in the southern hemisphere (right) by POLAR at 18:42 UT.

If we look at the ionosphere computed by BATS-CRCM (Figure 2.3), we see a southern hemisphere with two convection cells of comparable strength, and the polar cap boundary running through the middle of each cell. However, in the northern hemisphere we see a dominant (both in size and potential) dusk convection cell sitting inside the polar cap boundary. BATSRUS has the same ionospheric convection as BATS-CRCM, and the LFM and OpenGGCM models also show dominant dusk convection cells sitting
largely inside the polar cap boundary. Crooker and Rich, [1993] found that a convection pattern like this in the summer hemisphere during a strong +By period is best explained by a lobe cell circulating within the dusk convection cell [Reiff et al., 1985; Burch et al., 1985].

A lobe cell arises when the IMF merges not with a dayside closed magnetic field line but with a field line in the tail which is already open, leading to a “stirring” of open field lines [Reiff et al., 1985]. A lobe cell can be completely open, or partially open and partially closed, depending on the tilt of the dipole and the x-component of the IMF [Crooker and Rich, 1993]. This process may be fundamentally unstable, thus the difficulty in these models in successfully tracing the open/closed boundary, and the variable positions, are directly related to the existence of these lobe cells. It is not unlikely that reconnection of fields with extreme By components can be very spotty in the magnetotail, leading to “islands” of closed (or open) flux inside the polar cap, and the extremely perturbed polar cap boundaries predicted by OpenGGCM (Figure 2.4).

4.3 Model Validity

The unusually high By during this event allows us to really test the robustness of the magnetospheric models we used. While ∆L measured by IMAGE and POLAR correlated well with all the time averaged solar wind parameters, only the northern hemispheres of the BATS-RUS and BATS-CRCM models showed comparable correlations. For the polar cap width, the LFM and OpenGGCM models matched IMAGE and POLAR’s lack of correlation with any solar wind parameter. The LFM model was also the only model to calculate ∆L values in the same range as IMAGE and POLAR,
with the ranges of BATSRUS and BATS-CRCM being too narrow, and the range of OpenGGCM running completely wild.

The unusually high By was handled well by the BATSRUS and BATS-CRCM models, however, their outputs are too symmetric compared to the satellite observations. The LFM model generated polar cap boundaries that are distorted and asymmetric, but generally in line with the observed polar cap measurement. The OpenGGCM model responded with highly irregular polar cap boundaries, showing no dependency on the solar wind conditions. The most critical zero-level predictions are the average dawn-dusk offset during the event and the range of the offsets, which clearly show the LFM model producing an average polar cap offset closest to the observed polar cap offset.

4.4 Summary

Using the dawn-dusk offset as a proxy measurement of auroral conjugacy we have found each hemisphere responds differently to changes in the solar wind. The northern hemisphere develops a lobe cell within the dusk convection cell, creating a moderate amount of precipitation not seen in the southern hemisphere. Even before the lobe cell occurs we see a trend where the dawn-dusk offset decreases with time in each hemisphere, causing the southern hemisphere to become more symmetric about the pole, but leading to a greater asymmetry of the northern polar cap. Our observations were compared to several MHD model outputs, with no model yielding an accurate depiction of the event. Most of the disagreement between the models and the satellite data, and even between the models themselves, results from the way each model depicted a lobe cell developing throughout the event.
Acknowledgements

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