Monitoring the dayside and nightside reconnection rates during various auroral events using IMAGE-FUV and SuperDARN data

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Abstract: The Imager for Magnetopause to Aurora Global Exploration (IMAGE) spacecraft was launched in 2000 with several imaging instruments onboard. The Far UltraViolet (FUV) experiment was devoted to the imaging of the N2 LBH (Wideband Imaging Camera - WIC-), OI 135.6 nm (Spectrographic Imager -SI13-) and Doppler-shifted Lyman-alpha auroral emission (SI12). The Doppler-shifted Lyman-alpha emission is solely due to proton precipitation and is not contaminated by dayglow, allowing to monitor the auroral oval at dayside as well as at nightside. Remote sensing of the polar aurora can be advantageously completed by ground based data of the Super Dual Auroral Radar Network (SuperDARN) that monitors the ionospheric convection flow pattern in the polar region. In the present study, the SI12 images are used to determine the open/closed (o/c) field line boundary, and monitor its movement. The SuperDARN data are used to compute the electric field of the polar cap at the location of the o/c boundary. The total electric field is then computed along the boundary accounting for its movement applying Faraday's law, so that the dayside and nightside reconnection voltages can be retrieved. This procedure is applied to monitor the dayside and nightside reconnection voltages during several events. The phases of the substorm cycle can be identified: the growth phase characterised by intense dayside flux opening and occasionally pseudobreakups, the onset which is immediately followed by a maximum intensity of the flux closure rate, and the recovery phase during which the flux closure voltage slowly returns to undisturbed values, with occasional poleward boundary intensifications which appear along with a slight intensification of the closure voltage. The transient response to an interplanetary shock is also monitored and reveals a sharp intensification of the closure rate, despite a low open flux value for the studied case. A case of auroral streamer event has also been studied, presenting a remarkably large flux closure rate. This feature is related with a bursty enhancement of the ionospheric convection. Bursty bulk flow events can thus be associated as well with enhanced flux closure. The tool that we developed can also be used to study the relations between the topology of the magnetotail and the flux closure rate as well as to set up proxies relating the solar wind conditions with the dayside reconnection voltage. The monitoring of dayside and nightside reconnection rates can thus be considered as an investigation tool for nearly all types of auroral features.

Key words: Reconnection, Substrom, Shock.

1. Introduction

The solar wind plasma outflow from the Sun carries the interplanetary magnetic field. Interaction between the solar wind plasma and the Earth magnetosphere on the dayside of the planet causes the production of open magnetic flux. Opened field lines, that map from the polar cap into the solar wind, are carried antisunward by the solar wind flow and are stretched into a long magnetic tail, in which the field lines eventually reconnect and return to the Earth [6]. The auroral substorm cycle classically consists of a growth phase, a substorm onset, an expansion phase and finally a recovery phase [1, 11]. During the growth phase, the interplanetary magnetic field (IMF) carried by the solar wind is usually oriented southward so that it efficiently reconnects with the geomagnetic field, producing new open flux. This phase ends in a substorm onset characterized by a sudden localized brightening of the polar aurora near midnight, which announces the expansion phase during which accumulated openflux is closed by intense magnetic reconnection in the magnetotail [14] (and references therein). The system then returns to a quiet state during the recovery phase.

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We have developed a method combining space-based measurements of the proton aurora and ground-based measurements of the ionospheric flow to compute the global rates at which flux is opened and closed in the Earth's magnetosphere [8]. These rates are expressed as voltages, with 1 V being equivalent to 1 Wb s 1 from Faraday's law. The images of the proton aurora are from the Spectrographic Imager at 121.8 nm (SI12) instrument of the Far UltraViolet (FUV) experiment onboard the Imager for Magnetopause to Aurora Global Exploration (IMAGE) satellite [12]. They allow us to estimate the location of the boundary between open and closed field lines, as well as its latitudinal motion [8]. The ionospheric flow velocity $\vec{v}_i$ is measured with the Super Dual Auroral Radar Network (SuperDARN) radar system and is used to retrieve the ionospheric electric field $\vec{E}_i$ given by $\vec{E}_i = -\vec{v}_i \times \vec{B}$ where $\vec{B}$ is the Earth's magnetic field [15]. The electric field in the reference frame of the open-closed field boundary can then be obtained, and integrated along the boundary to compute the voltages associated with flux opening and closure [4] (and references therein). This method is applied to the study of the substorm cycle [8] and of interplanetary shocks [9]. The IMAGE-FUV instrument captures an image of the planet every 2 min, though the filtering process that is applied in our method to denoise our results and allow time derivative computation reduces the time resolution to 12 min, thus slightly smearing rapidly varying signals.

2. Reconnection voltages during the substorm cycle

2.1. Open-close boundary identification with SI12

We summarize here the results extensively discussed in [8]. The location of the open-close field line boundary is estimated using the polar boundary of the proton aurora observed with the SI12 instrument of the IMAGE-FUV experiment. The method is calibrated using a comparison between the open-close boundary deduced from in situ measurement of the precipitating particles from the DMSP satellites. This comparison shows that the polar boundary of the proton aurora that we determine with SI12 images is on average 0.55 equatorward of that deduced from DMSP observations. This shift is thus accounted for in the open-close field line boundary location that we determine. Note that particles can diffuse across the separatrix as they travel between the tail and the ionosphere. This is a source of uncertainty that affects both methods used in the calibration. This process would actually affect any method based on auroral observations in the vicinity of the boundary. The detailed structure of the cusp is not accounted for. This approximation only affects the opening voltage through the contribution associated with the motion of the boundary, which is not dominant in the cusp sector [8].

Images of the proton aurora are preferred for the absence of significant dayglow contamination. This allows the determination of the boundary over the whole oval at any time of the year and for any diameter of the polar cap. The boundary is fitted with Fourier series, which allows an easy computation of its velocity using several consecutive snapshots of the proton aurora. The motional component of the electric field can thus be retrieved and combined with the ionospheric electric field deduced from SuperDARN radar data to retrieve the total reconnection electric field, as explained in the introduction.

2.2. Flux closure during substorm intervals

Fig. 1 shows the location of the open-close boundary estimated with SI12 images of the proton aurora on 29 December 2000. Pseudobreakups are observed at 0241, 0320 and 0341 UT. An expansion phase onset takes place at 0359 UT, and poleward boundary intensifications (PBI's) are seen between 0650 and 1000 UT, with a maximum brightness around 0800 UT. Although these PBI's do not clearly appear in the proton aurora, they better show up in images of the electron aurora obtained with the Wide band Imaging Camera (WIC) of the IMAGE-FUV experiment.

The open flux and reconnection voltages that we deduce from the SI12 and SuperDARN observations during this interval are presented in Fig. 2. The open flux increases between 0230 and 0400 UT, an interval during which the IMF was northward (Fig. 3). During this growth phase, the magnetosphere accumulates open flux up to 0.78 GWb. Magnetic flux closure is seen to intensify at the time of the pseudobreakups, but the time resolution of the method does not allow to discriminate between a progressive or a transient intensification.

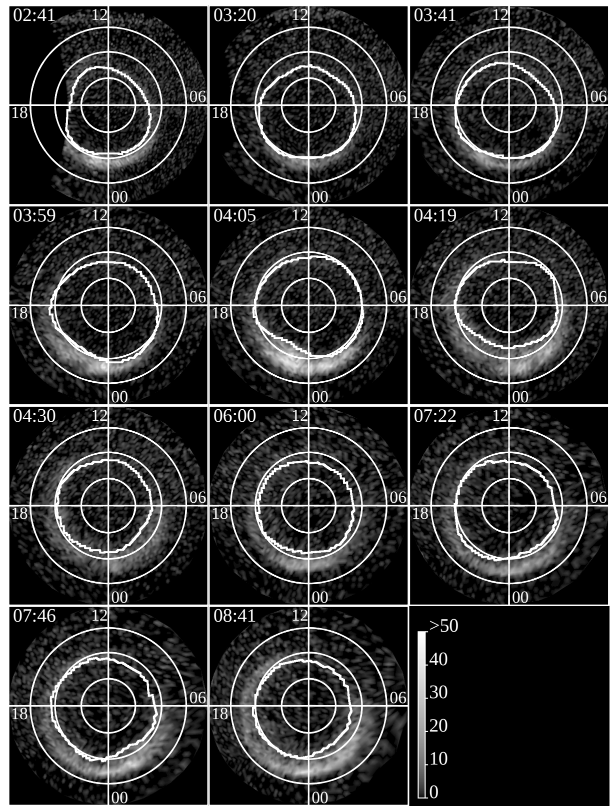

Fig. 1. Sample of polar views of the proton aurora obtained with IMAGE-FUV SI12 between 0235 and 1120 UT on 29 December 2000. The fitted open/closed field line boundary is overlaid in white. The colour scale is expressed in SI12 counts.

The closure voltage reaches its maximum intensity shortly after substorm onset (140 kV), which is in favour of the near earth neutral line paradigm. These trends have been found in other substorms as well, although exceptions exist, for complicate events having multiple onsets, for example. At the time of the PBI's, during the recovery phase, the closure voltage intensifies as well, suggesting a relation between PBI's and magnetic flux closure. The quiet times closure voltage is found to be 30 kV.

2.3. Flux opening during substorm intervals

As already outlined above, intense production of open magnetic flux has been observed during the substorm growth phase between 0230 and 0400 UT on 9 December 2000. Dayside reconnection is favoured during intervals of southward IMF, and proxies based on the solar wind properties can be set up to estimate the electric field responsible for magnetic reconnection along the dayside neutral line, where magnetospheric and interplanetary field lines merge. This electric field must

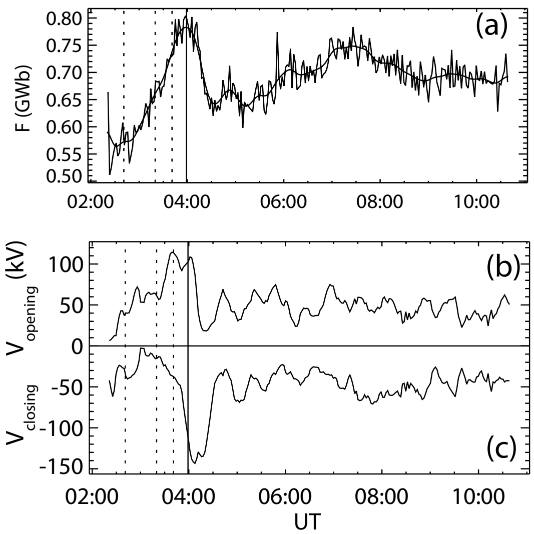

Fig. 2. Open magnetic flux (a), flux opening voltage (b) and flux closure voltage (c) derived from SI12 and SuperDARN data on 9 December 2000.

then be multiplied by an effective length in order to retrieve the reconnection voltage inferred from the solar wind properties. Conversely, the ratio of the opening voltage that we deduce and the solar wind electric field gives an estimate of the effective length of the reconnection site. This length is typically of a few Earth radii. Fig. 4 presents the effective length obtained comparing the opening voltage of Fig. 2 and the proxy for the reconnection electric field proposed by [16], i.e. $E = v_{sw} B_T sin^4 (\theta/2)$ where v_{sw} is the solar wind velocity, B_T is the transverse magnetic field and θ is the clock angle.

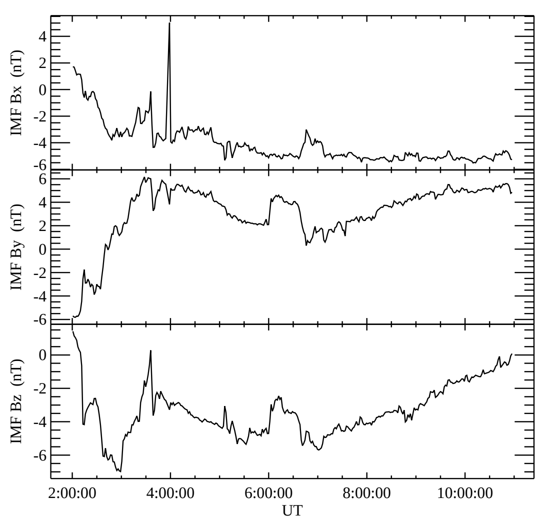

Fig. 3. Interplanetary magnetic field components measured by the WIND satellite on 9 December 2000.

The computed effective length of the merging site is of reasonable order of magnitude, and relatively stable versus time in the present case, during which the IMF was nearly always southward as indicated by the shading. However, during other intervals presenting a northward IMF, the computed effective length can be off by several orders of magnitude. This suggests that proxies of the reconnection field are valid during southward IMF, i.e. when reconnection is large, whereas they should be considered with caution during northward IMF intervals.

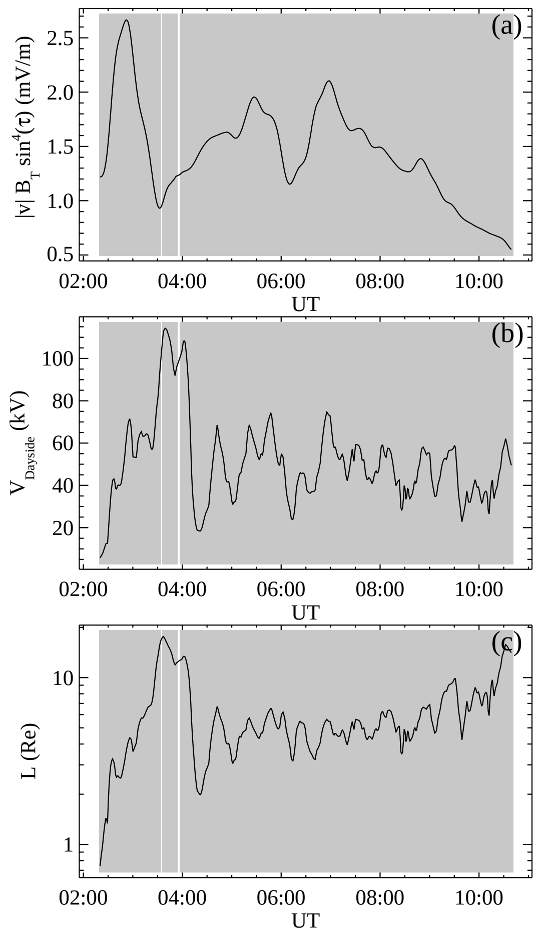

Fig. 4. Proxy for the reconnection electric field at the dayside merging site, based on solar wind properties (a), flux opening voltage obtained from SI12 and SuperDARN observations (b), and effective reconnection length deduced from curves a and b on 9 December 2000. Shadings indicate southward IMF.

3. Shock-induced flux closure

We summarize here the results presented in [9]. It is well known that, among other disturbances, interplanetary shocks can trigger flux closure and the development of an expansion phase [5] (and references therein), [13, 14]. Flux closure induced by the interaction of IP shocks and the magnetosphere is presented and analyzed in the light of an MHD simulation of the space environment with GUMICS-4.

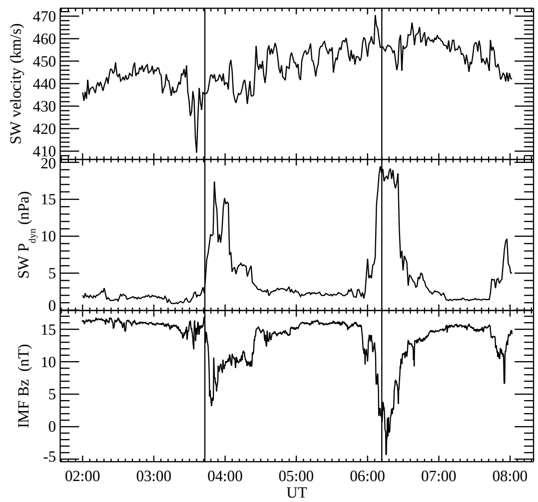

Fig. 5. Solar wind properties measured with the ACE spacecraft on 8 November 2000. The vertical solid lines indicate the ramp of the solar wind pressure pulse.

3.1. Observational analysis

On 8 November 2000 between 0300 and 0700 UT, two interplanetary shocks (Fig. 5) impinged on the Earth during a prolonged interval of northward IMF. The magnetosphere did not accumulate large amounts of open flux during that interval and no substorm expansion phase could develop at all. The open flux and reconnection voltages deduced from SI12 and SuperDARN observations are shown in Fig. 6. A transpolar arc was observed between 0400 and 0530 UT that disturbed our algorithms and impaired their reliability, although the presence of a transpolar arc is not of crucial importance in this study because these structures evolve only slowly whereas we are studying transient phenomena. Both shocks triggered a dayside subauroral proton flash (DSPF) when they reached the dayside magnetosphere [7]. The flux closure rate intensified shortly after the interaction of each shock and the magnetosphere, reaching up to 130 kV despite the low value of the open flux and the absence of substorm expansion activity. The flux closure, confirmed by the dipolarization detected with the GOES-8 satellite, is clearly induced by the interaction of both solar wind high pressure fronts and the magnetosphere. A simulation of the space environment representing the interaction between an IP shock and the magnetosphere during a northward IMF interval was conducted to clarify the mechanism responsible for the flux closure.

3.2. MHD simulation

The GUMICS-4 model was used to solve the equations of ideal MHD in the case of an IP shock impinging on the Earth magnetosphere during an interval of northward IMF. Magnetic reconnection is not explicitly included in GUMICS-4 [10], but a phenomenon of numerical diffusion mimics resistive processes, so that magnetic flux is nevertheless closed in the modelled magnetotail. The computed plasma flow and density maps can be used to analyze how the compression of the tail leads to flux closure. As the IP shock sweeps along the magnetotail, it compresses the magnetospheric plasma. The compression extends all the way down to the central plasmasheet, where a

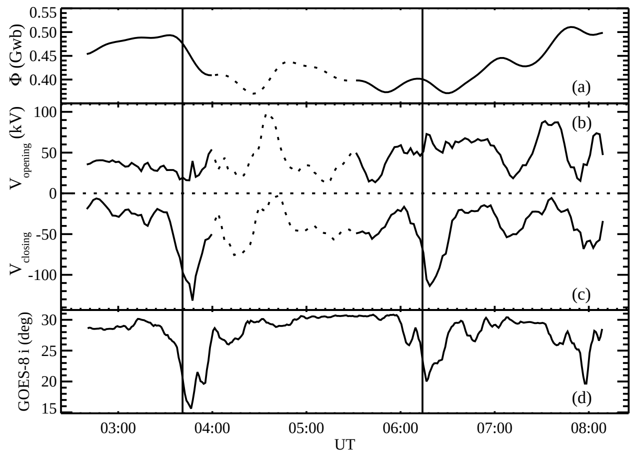

Fig. 6. Open magnetic flux of the magnetosphere (a), flux opening rate at the dayside (b) and flux closure rate in the magnetotail (c), 8 November 2000, deduced from combined ground-based and global remote sensing observations. Inclination angle of the magnetic field deduced from measurements of the GOES-8 satellite at geosynchronous altitude (d). Vertical lines indicate the arrival time of the main ramp of each interplanetary shock at the Earth magnetopause. A transpolar arc was observed between 0400 and 0530 UT that disturbed our algorithms and impaired their reliability (dotted lines in panels a, b and c).

thinning of the plasma sheet takes place, leading to the formation of an X line where magnetic flux is closed, and to the formation of a plasmode expelled downtail. A detailed analysis of the computed magnetic field reveals that the flux closure is due to the compression of the tail.

4. Flux closure during an auroral streamer event

An auroral streamer is a north-south aligned bright arc. It has an upward (downward) field-aligned current on its dusk (dawn) side, and it is surrounded by two vortices. It has been shown that the magnetic field lines threading auroral streamers map to the magnetotail into plasma bubbles forming bursty bulk flows (BBF). It has also been shown that the magnetic field of these plasma bubbles is dipolarized [3, 2]. A preliminary study has been undertaken on a streamer event observed on 7 December 2000 around 2200 UT that shows that intense flux closure takes place at the time of the observed streamer, especially along magnetic field lines threading the polar edge of the streamer.

5. Summary

A method that combines FUV imaging of the proton aurora and radar observations of the ionospheric convection has been developed to estimate the open flux threading the polar cap as well as the flux opening and closure voltages. Application of that method to substorm intervals reveals that 1. magnetic flux closure can intensify prior to substorm onset, producing pseudobreakups. 2. The flux closure voltage generally reaches a maximum value shortly after onset. 3. The closure voltage progressively returns to the quiet times value of 30 kV during the recovery phase. 4. PBI's sometimes occurring during the recovery phase are associated with an intensification of the closure rate. 5. Proxies used to estimate the reconnection electric field responsible for field line merging between the solar wind and the magnetosphere are valid during southward IMF intervals, but should only be used with caution when the IMF is northward.An application to an interval presenting the interaction of IP shocks in the absence of substorm expansion, analyzed in the light of an MHD simulation, showed how the compression of the tail leads to the formation of a neutral line in the plasmasheet. This process causes magnetic flux to be closed at a rate that can reach 130 kV, despite the absence of substorm expansion activity.

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