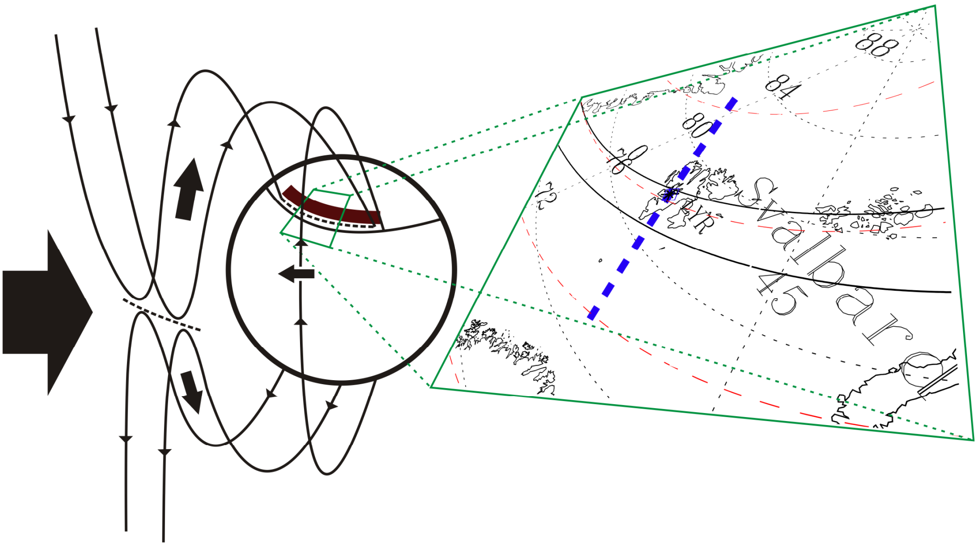
UNIVERSITY OF TROMSØ UIT

FACULTY OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF PHYSICS AND TECHNOLOGY

The Dayside Open/Closed Field line Boundary

Ground-based optical determination and examination



Magnar Gullikstad Johnsen

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Abstract

The Open/Closed field line Boundary (OCB) is the most important boundary in the magnetospheric system. On the dayside, the equatorward edge of the 6300 Å[OI] cusp aurora can be used as a proxy for the OCB. This work, which is a dissertation for the degree of Philosophiæ Doctor consists of three scientific papers focusing on the latitude of the optical cusp OCB and one paper focusing on polar cap patch generation mechanisms in the vicinity of the OCB.

In Paper I we use modeling to demonstrate the variability of the cusp aurora with respect to vertical volume emission rate profiles and horizontal modulation owing to neutral wind. A meridian scanning photometer (MSP) simulator has been developed in order to study the manifestation of the cusp aurora in the MSP data from Svalbard. A method for obtaining the OCB location and finding the correct mapping altitude in order to transform the OCB location from MSP scan angle to magnetic latitude is found by simulating the horizontal movement of a reference cusp aurora. The reference cusp aurora, which is based on expected ionospheric and atmospheric conditions and electron precipitation characteristics, is defined from the modeling results. Uncertainties in the scan angle to magnetic latitude transformation are found by simulating a wide range of realistic cusp auroras deviating from the reference cusp aurora. In Paper II the method of Paper I for finding the OCB is tested on real MSP data and compared with the OCB as obtained by satellite energetic particle measurements with very successful results.

In Paper III the method of Paper I is used on 15 years of MSP data from Svalbard in order to study the statistical behavior of the cusp OCB. A possible relationship between the OCB latitude in the cusp and the solar cycle is revealed, and a possible expansion is briefly discussed. By comparing the OCB latitude with solar wind parameters, solar wind-magnetosphere coupling functions and geomagnetic indices, good correlations are found, which are in concurrence with previous satellite based, statistical studies. We find a relationship between the OCB latitude and the ring current density (SYM/H), demonstrating great complexity in the physics behind the OCB location. We argue that the balance between reconnection dynamics on the dayside and nightside as well as the history or integral of previous events in the magnetospheric system are important factors for governing the cusp OCB latitude.

Paper IV gives an overview of the solar wind and ionospheric conditions as measured during the Investigation of Cusp Irregularities 2 sounding rocket campaign. The rocket was launched through a newly produced polar cap patch. Based on the measurements performed in-situ by the rocket instrumentation and with groundbased optics and radars, a new creation mechanism, which partly involves ionization by both particle precipitation and solar irradiation and upwelling from sub F-layer altitudes, is suggested.

Preface

I started working on my PhD in the spring of 2007. When I got the position, I was the happiest person ever! Now, four years later, I am about to reach my goal of getting the degree, and it feels good. For me, being part of the tradition of auroral research at the Auroral Observatory in Tromsø, has meant a lot. Working out of my office in the old, historic observatory building I have thought about this great tradition which I have been a part of, and it has made me proud. My supervisors during these four years deserves thanks, Professor Unni Pia Løvhaug here at the Auroral Observatory and Professor Dag A. Lorentzen at UNIS. I realize that Unni and Dag have played important roles for the benefit of my career so far, and I look forward to our cooperation in the future. Several excellent and helpful persons deserves my appreciation for various professional and scientific interactions: Professors Asgeir Brekke, Jøran Moen, Kjellmar Oksavik, Ulf-Peter Hoppe and Dr. Bjørn Gustavsson. From August 2009 to July 2010 I was a visiting scholar at Boston University in the USA, it was a memorable year and I have fond memories from Boston. I thank professor Joshua Semeter for hosting me at Boston University.

Although not very apparent from this thesis, I have been involved in several measurement campaigns. I participated in the launch assessment of the SCIFER-2 and ICI-2 sounding rockets. I have also planned and performed two multi instrument campaigns in order to study polar cap patch morphology, one where a total of 5 incoherent scatter radars were running simultaneously. Through this I have had quite a lot to do with incoherent scatter radars and mainly EISCAT. I have, indeed, spent a lot of time analyzing data from both the mainland systems and ESR. Therefore, I would like to thank Dr. Ingemar Häggström at EISCAT HQ in Kiruna, he is invaluable when it comes to understanding GUISDAP and to make it work. I also thank the staff at the radar sites in Tromsø and in Longyearbyen for being very helpful during experiments.

Most important, my partner and very good friend Hanne Sigrun Byhring, what should I have done without you? I do not think I would have managed to get happily through this without you! It has been important to have you as my close friend, fellow PhD student and physicist, thank you.

My good friend Jeff Holmes has been good to have both in Svalbard and the US, he takes over for Hanne Sigrun when she falls asleep owing to too technical dayside aurora and polar cap patch discussions! My mother and father I thank for being supportive and proud of me and my accomplishments. My brother, Sverre, thank you for our nice semi-annual hunting trips to Revsjøen and for being a good academic role model. Tanja and Jon Are, thank you for making my and Hanne Sigruns social lives more interesting.

Last I would like to thank the administrative staff at the Auroral Observatory for being kind and helpful!

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Contents

Chapter 1

The Open/Closed Field Line Boundary

The most important boundary in the magnetospheric system is the Open/Closed field line Boundary (OCB). This boundary marks where the high latitude geomagnetic field maps into the solar wind rather than to the opposite hemisphere, thus it represents the demarcation of the Polar Cap. In the Dungey Cycle (*Dungey*, 1961) paradigm, for the simplest case where the interplanetary magnetic field (IMF) is anti-parallel to the geomagnetic field at the sub-solar point, the solar wind drives an anti-sunward convection inside the polar cap and a sunward return flow on lower latitudes. The convection is reversed by magnetic reconnection in the magnetotail and at the magnetopause. E-fields mapping along the magnetic field lines into the high latitude ionosphere results in the well known ($E \times B$-driven) two-cell ionospheric convection pattern. The Dungey Cycle is illustrated in Figure 1.1 a). The solar wind is flowing towards the magnetosphere from the left, carrying the IMF. Magnetopause reconnection occurs at the sub-solar point of the magnetopause (blue field line marked 1). The opened magnetic field lines are pulled across the polar cap (green lines marked 2, 3 and 4) and reconnected in the magnetotail (blue line marked 5). The northern and southern OCBs are indicated by red, solid lines. Newly closed field lines (marked 6) convects sunward along lower latitudes to the dayside where they are ready to reconnect with the IMF (marked 7). In Figure 1.1 b) the resulting ionospheric convection is illustrated, the numbered dots corresponds to the footpoints of the numbered field lines in Figure 1.1 a). The auroral oval is indicated by the green band and the OCB by a red dotted line. As can be seen, magnetic reconnection happens at the OCB (points 1 and 5), the anti-sunward flow inside the polar cap corresponds to open field lines (i.e. the polar cap maps to the solar wind) and the closed field lines (points 6 and 7) exist on lower latitudes in the sunward return flow.

Since the field lines inside the polar caps are the only field lines with direct access to the solar wind, the area of the polar cap is a direct measure of how much open flux there is in the magnetosphere (cf. *Milan et al.*, 2003, 2007). One may use the area of the polar cap as a measure of the amount of energy stored in the magnetosphere owing to the interaction between the interplanetary medium and the geomagnetic field. The amount of open flux is governed by the balance of flux erosion on the magnetopause through magnetic reconnection (merging) and open flux destruction through magnetic reconnection in the magnetotail. In a case of unbalanced reconnection where the reconnection on the magnetopause is higher than in the tail, the amount of open flux will increase and consequently the size of the polar cap will increase moving the OCB equatorwards. In the other case where reconnection is more efficient in the magnetotail, the polar cap will shrink moving the OCB polewards. By monitoring the polar cap area and the change in it, it is possible to assess the balance between opening and closure of magnetic flux and to derive total reconnection rate in the magnetospheric system (*Milan et al.*, 2003); this is important in the study of magnetic storms and substorm processes. Furthermore, by monitoring the instantaneous change in the size and shape of the polar cap, by identifying the OCB and its movements, the temporal and spatial nature and variations of reconnection at the magnetopause and in the magnetotail may be studied. On a global scale, the shape of the OCB may reveal the topography and nature of the magnetopause reconnection x-line and effects on the magnetosphere from solar wind parameters such as the dynamic pressure and IMF orientation (e.g. *Elphinstone et al.*, 1990; *Kabin et al.*, 2004; *Rae et al.*, 2010). It is also of great importance to know the location and shape of the OCB if one wishes to study plasma convection processes in the magnetosphere (e.g. *Lockwood*, 1998; *Watanabe et al.*, 2005).

Locally, if the OCB is successfully identified and its horizontal orientation with respect to the L-shell is found, it is possible to assess if it is mapping to an active reconnection site by determining if there is plasma flow across it or not. The flow component perpendicular to the OCB may be measured in order to derive the reconnection electrical field at the reconnection site (e.g. *Vasyliunas*, 1984; *de La Beaujardiere et al.*, 1991; *Lockwood et al.*, 2005a). This was successfully done by *Lockwood et al.* (2005b) in order to study the role of magnetic reconnection in relation to the production of polar cap patches (see Chapter 3). More generally, knowing the location and orientation of the

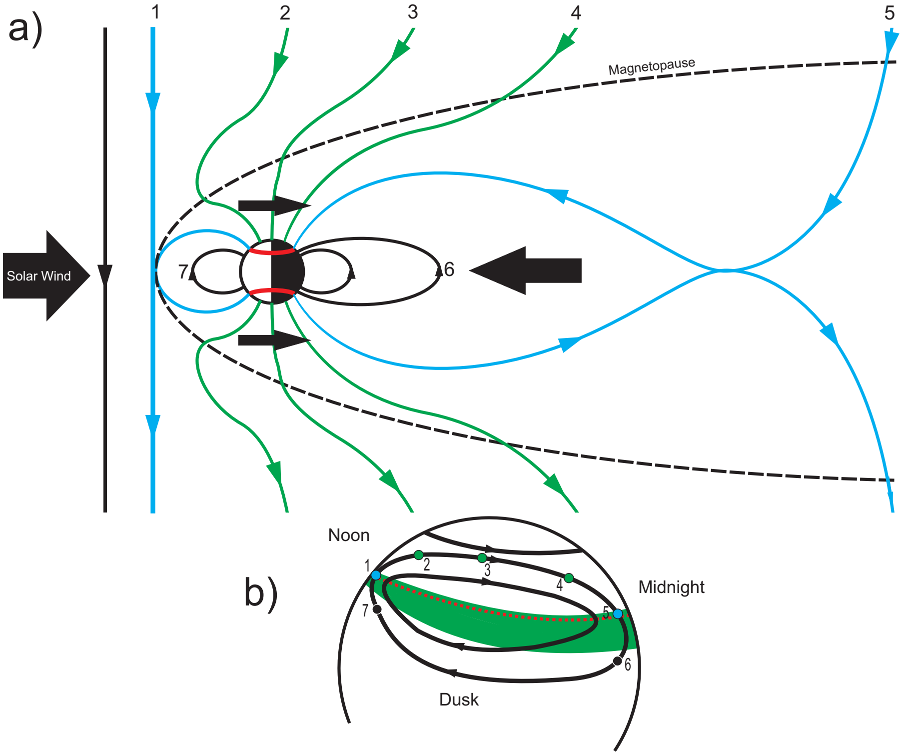

Figure 1.1: a) Illustration of the Dungey Cycle in the Earth's noon-midnight meridian plane. The sun is to the left. The IMF reconnects to the Earth's Dipole field at 1, the opened field lines are pealed back (2-4) and reconnected in the magnetotail (5). Closed flux is returned to the dayside (6-7). The magnetopause is indicated by a black dashed line. The northern and southern polar caps are north and south of the red lines indicating the OCB, respectively. b) The resulting two-cell ionospheric convection with dots corresponding to numbered field lines seen in a). The auroral oval is represented by the green band and the OCB by the red, dotted line. (Inspired by figure on page 227 in *Kivelson and Russell* (1995).)

OCB is of importance in any observational studies since the interpretation of physical phenomena often depends heavily on where the magnetic field lines map, i.e. if the physical process is occurring on open or closed field lines (cf. *Lockwood*, 1998).

The work collected in this PhD thesis mainly focuses on the determination of the dayside OCB latitude by the means of a ground-based optical instrument situated beneath the ionospheric footprint of the cusp. A short review of other techniques for obtaining the OCB is given in Chapter 2. A smaller part of the thesis focuses on the production of polar cap patches in the vicinity of the cusp OCB. An introduction to polar cap patches, which are "islands" of high density plasma originating near the dayside cusp and drifting with the ionospheric convection across the polar cap, is given in Chapter 3. The motivation behind the PhD work will be presented in Chapter 4 and the work, which consists of three papers submitted to a peer-reviewed journal (Journal of Geophysical Research - Space Physics) and one published paper, is summarized in Chapter 5. Prospects for future studies are briefly discussed in Chapter 6.

Chapter 2

Determining the Open/Closed Field Line Boundary

A wide range of experimental techniques are being used to obtain the OCB, or rather a proxy of it. They may be divided into space- and ground based techniques. The majority of the techniques actually measure the ionospheric signatures of particle precipitation or momentum transfer from the solar wind; the main assumption is that the polar cap contains very little precipitation (low energies with low fluxes), ie. polar rain, and that the majority of precipitation (electron energies $\gtrsim 1$ keV) occurs on closed field lines within the auroral oval. Thus, a transition from polar rain to precipitation with higher energies and fluxes, manifested as a transition from no aurora inside the oval to aurora, is normally considered to be a crossing of the OCB. Extra caution is needed in the cusp, since the higher fluxes here create aurora on open field lines. Given the above assumption, precipitation boundaries measured by in-situ particle instrumentation will always represent the blueprint for the OCB location. A thorough discussion of different techniques for obtaining the OCB, with their different strengths and weaknesses, and the physical interpretation behind is outside the scope of this work. However, a short presentation of different techniques and concepts is given below.

2.1 Space-based techniques

The technique which is considered (e.g. *Boakes et al.*, 2008; *Longden et al.*, 2010) to be most accurate for obtaining the OCB is by measuring particle precipitation boundaries with the help of particle detectors onboard low-altitude satellites such as the Defense Meteorological Satellite Program (DMSP) spacecraft. This technique is based on a-priori knowledge about the (energy) spectral characteristics and signatures of the precipitating electrons and protons and the related source regions. Different source regions are identified by different spectral characteristic of the precipitation, and hence, the transitions between different precipitation regimes are identified as the boundaries between different magnetospheric regions. There is a long history of measurements of identifying the dayside OCB in this way and numerous studies exists using satellites such as DMSP (*Carbary and Meng*, 1986; *Newell and Meng*, 1988, 1992; *Wing et al.*, 2001; *Newell et al.*, 2006, 2007), NOAA POES (e.g. *Oksavik et al.*, 2005), Akebono (e.g. *Asai et al.*, 2005), Polar (e.g. *Zhou et al.*, 2000; *Palmroth et al.*, 2001) and Cluster (e.g. *Pitout et al.*, 2006). The same measurements as are mentioned here can naturally also be performed by the use of rockets (cf. *Lorentzen et al.*, 1996). In the cusp, elevated electron temperatures are often observed owing to heating of the ambient electron gas from soft electron precipitation of magnetosheath origin (*Kofman and Wickwar*, 1984; *Doe et al.*, 2001). Using data from the langmuir probe onboard the Dynamic Explorer 2 satellite, *Prölss* (2006) performed a statistical study where he identified the equatorward boundary of this temperature enhancement, and thus the cusp OCB. Downward pointing photometers such as the SSUSI instrument (http://sd-www.jhuapl.edu/SSUSI/, downloaded July 2011) which has been carried by the DMSP satellites since number 16, are ideal for obtaining the OCB optically in conjunction with the onboard particle detectors. However, there are no studies that have done this so far.

Common to the above mentioned techniques is that the satellite/spacecraft only gets one or two "snap-shots" of the OCB per hemisphere per orbit which normally takes 90 minutes or more - or for a sounding rocket, only one boundary passing per launch - and thus it is not possible to continuously monitor the OCB. This is the main weakness of satellite techniques where measurements are performed in-situ or close to the measurement object, although it is very powerful in case studies as an auxiliary technique or in large, statistical studies.

Ultra-violet imagers onboard satellites such as Viking, Polar and IMAGE have proved successfully in monitoring the OCB globally over long time intervals (e.g. *Elphinstone et al.*, 1990; *Milan et al.*, 2003; *Østgaard et al.*, 2005;

Boakes et al., 2008; *Longden et al.*, 2010). Here the satellites are in high enough orbits so that the entire auroral oval ideally may be imaged at once. As the emissions monitored by such imagers are considered to come from precipitation by particles of higher energies than what is normally seen on open field lines, the poleward boundary of the observed auroral oval is chosen as the OCB. This is normally a good approximation within several degrees (*Boakes et al.*, 2008).

2.2 Ground- based techniques

A large variety of instruments and experimental techniques exists for obtaining the OCB from the ground. *Rodger* (2000) presents a short review of the different techniques on both the dayside and nightside, and their strengths and weaknesses.

Since it measures the most comprehensive set of physical parameters, the incoherent scatter radar (ISR) technique provides the widest range of potential ways to obtain the OCB. By measuring the electron density and identifying the increase in the E-layer ionization owing to the transition from polar rain to plasma sheet boundary layer precipitation on the nightside, *de La Beaujardiere et al.* (1991) and *Blanchard et al.* (1996) obtained the OCB in order to calculate reconnection rates. Their method was adapted by *Blanchard et al.* (2001) for the dayside using modeling in order to subtract photoionization. On the nightside, owing to the softness of polar rain and its minimal effect on the ionosphere, there is an expected electron temperature increase when crossing from open to closed field lines, and thus into plasma sheet boundary layer precipitation. This temperature increase has been used successfully in several studies in order to obtain the OCB (*Østgaard et al.*, 2005; *Aikio et al.*, 2006). An electron temperature increase is also expected in the dayside associated with soft cusp precipitation (*Doe et al.*, 2001), and its equatorward edge may be used to obtain the OCB. However, problems may arise owing to other heating sources than the soft electrons on open field lines or rapid electron cooling owing to high electron densities (*Moen et al.*, 2004). Another popular proxy for the OCB has been the convection reversal between sunward and anti-sunward flow in the ionospheric convection. As a result of frictional heating from neutral-ion collisions there is an ion temperature increase associated with north-south expansion or contraction of the convection reversal boundaries (*Lockwood et al.*, 1989; *Moen et al.*, 2004; *Lockwood et al.*, 2005b,a). *Moen et al.* (2004) compared electron and ion temperature boundaries in the pre-noon sector and found good correspondence but pointed out problems with the use of the electron temperature boundary (see above). They concluded that the convection reversal was somewhat north of the real OCB and represents the arrival of the rotational discontinuity from the reconnection site on the magnetopause. It should be noted that this finding applies to the dayside OCB when it maps to an active reconnection site.

Optically, the 6300 Å [OI] emission is being used when determining the OCB. This emission is preferred mostly because it is caused by relatively low energy electron precipitation, it comes from the F-layer and the excitation threshold for the O^1D-state is only ~ 1.96 eV, which means that it is easily excited. Thus, it is visible even under very quiet conditions. On the nightside, *Blanchard et al.* (1995) successfully obtained the OCB from the poleward boundary of the 6300 Å [OI] emission, they also found good correspondence between their optical OCB and satellite passes. Furthermore, comparing the OCB as obtained by ISR measurements with the poleward edge of the 6300 Å [OI] emission, *Blanchard et al.* (1996) found good correspondence. On the dayside, typical cusp aurora is almost totally dominated by the 6300 Å [OI] emission. This aurora is caused by soft electron precipitation on open field lines and thus, the equatorward boundary of it corresponds with the OCB. *Lorentzen et al.* (1996) showed this by comparing particle measurements from the SCIFER rocket with measurements made with the meridian scanning photometer in Longyearbyen. Using optics for the determination of the OCB has advantages in that very high spatial and temporal resolution is achieved and under ideal tropospheric conditions the OCB morphology may be monitored for long time-spans. Owing to the offset between the magnetic and geographic poles not many places in the northern hemisphere are suitable for optical, dayside observations, either owing to the cusp being too far south (geographic) or inhospitable climate. Several stations in the arctic have been used, but Svalbard ($78°N, 15°E$) is the only location where routine based measurements have been performed and for which long time series of data exist. Several good locations for cusp studies exist in Antarctica, such as the South Pole and McMurdo. However, for logistical reasons these locations have not been extensively used.

Using the SuperDARN network of HF-radars, it is possible to locate the OCB by identifying the equatorward boundary of broad Doppler spectral width regions on the dayside (*Baker et al.*, 1995) and nightside (*Lester et al.*, 2001).

The poleward boundary of the eastward and westward electrojets may be found using magnetometers in order to identify the (magnetic) convection reversal boundary and thus sometimes the OCB (*Ridley and Clauer*, 1996; *Amm et al.*, 2003), however, not many studies have tried this. The results of *Hubert et al.* (2010) indicate that the magnetometer technique might be equally reliable as other techniques, at least when the observations are performed away from the Harang discontinuity.

A wide range of studies exist where different techniques for obtaining the OCB have been compared, and most show an overall good agreement within their respective measurement errors although there may be deviations in certain MLT sectors. Some examples, doubtfully all, are listed below:

- Ground-based optics - in-situ particle measurements: (*Lorentzen et al.*, 1996; *Moen et al.*, 1996; *Blanchard et al.*, 1997; *Oksavik et al.*, 2000)
- Ground-based optics - HF radars: (*Rodger et al.*, 1995; *Milan et al.*, 1999; *Lester et al.*, 2001; *Moen et al.*, 2001)
- HF radars - satellite particle measurements: (*Baker et al.*, 1995)
- ISR - ground-based optics: (*Blanchard et al.*, 1996)
- ISR - space-based optics: (*Østgaard et al.*, 2005; *Aikio et al.*, 2006; *Hubert et al.*, 2010)
- ISR - satellite particle measurements: (*Blanchard et al.*, 2001; *Doe et al.*, 2001; *Moen et al.*, 2004; *Lockwood et al.*, 2005a)

Chapter 3

Polar Cap Patches

Half of the time, i.e. when the interplanetary magnetic field (IMF) Bz component is negative (southward), the polar cap is populated by F-layer patches (*McEwen and Harris*, 1996). These are islands of high density plasma on a lower background density, drifting with the ionospheric convection from the dayside towards the nightside. Similar density enhancements in the auroral and subauroral zones are referred to as "blobs". Patches contain highly structured plasma and are known to disturb radio signals used by satellite based communications, navigation and imaging (*Buchau et al.*, 1985; *Basu and Valladares*, 1999; *Carlson et al.*, 2008). A well established definition for patches (*Crowley*, 1996) is that their density is at least twice as high as the background plasma density. Their horizontal scale sizes are in the order of 100s to 1000s of kilometers. Patches are observable by means of a wide range of instruments and methods, such as radars (*Carlson et al.*, 2002; *Lockwood et al.*, 2005c; *Oksavik et al.*, 2006), optics (*McEwen and Harris*, 1996; *Lorentzen et al.*, 2004), ionosondes (*MacDougall et al.*, 1996; *McEwen et al.*, 2004) and satellite scintillation techniques (*Buchau et al.*, 1985; *Dandekar and Bullett*, 1999). Detailed studies of patches started in the beginning of the 1980s with the works of *Buchau et al.* (1983) and *Weber et al.* (1984). It was early established by satellite measurements that the patches observed inside the polar cap are not locally produced by particle precipitation, and that they enter the polar cap in the vicinity of the cusp by means of ionospheric convection (*Weber et al.*, 1984).

The plasma source for patches has been under debate with two main candidates both considered by *Weber et al.* (1984). The first is soft-particle precipitation in the cusp. The second source may be plasma produced from solar EUV photoionization at sub polar latitudes (*Foster*, 1984, 1993; *Foster et al.*, 2005), and which is transported by convection as a continuous tongue of ionization (TOI) to cusp latitudes were it is divided into patches. In a case-study, using satellite tomography and ground-based optical instruments from Svalbard, *Walker et al.* (1999) showed how a patch may be created from particle impact ionization in the cusp if the energy of the auroral precipitation is sufficiently soft, so that the majority of ionization occurs in the upper F-region (above 250 km) where the loss of electrons due to recombination is small. *Oksavik et al.* (2006) attributed a patch reported on a lobe convection cell to particle impact ionization. These observations were both found consistent with modeling work by *Millward et al.* (1999) who show that typical cusp electron precipitation of around 100 eV will produce the highest ionization at altitudes around 300 km. In another case-study performed by *Pryse et al.* (2004), the authors ruled out particle impact ionization as the source for a plasma density enhancement observed immediately equatorward of the cusp. Using satellite tomography they further showed that the source of this density enhancement is a latitudinally restricted region of ionization upstream in the evening convection cell, and thus they illustrated how the TOI reaches cusp latitudes and may serve as a plasma source for patches. *Moen et al.* (2006) reported discrete horizontal electron density structures in the TOI immediately south of the dayside OCB. Thus, they were the first to report electron density patches at subauroral latitudes in the dayside ionosphere. Convection bursts associated with downward Birkeland currents were proposed as a possible segmentation mechanism for the TOI. *MacDougall and Jayachandran* (2007) proposed a new source for patches, namely particle impact ionization from soft precipitation in the sunward return flow in the dawn sector. Taking corotation into account, they argued that the dawn convection cell is responsible for most of the plasma transport through the midday cusp and that sunlight exposure of the plasma is mainly involved in increasing the average plasma density. *Moen et al.* (2007) showed in a statistical study of MSP data from Svalbard, that patches populate both convection cells when leaving the polar cap around local magnetic midnight, thus contradicting *MacDougall and Jayachandran* (2007).

Since the origin and fate of polar cap patches is determined through auroral and thus magnetosphere-ionosphere interconnection processes, it is in the vicinity of the OCB that they must be studied in order to be understood. This is also why the majority of patch studies has been performed in either the dayside or nightside auroral zone. Many studies exist where patches are observed to leave the polar cap across the OCB, entering the nightside auroral oval. *Lorentzen et al.* (2004) showed, using the Longyearbyen MSP, how the increased convection velocity during substorms increase the exit speed of patches. *Semeter et al.* (2003) showed how the upward particle flux increased as a polar cap patch crossed the nightside OCB entering a region of discrete auroral rays with associated, strong ion upflow. In their works both *Crowley et al.* (2000) and *Pryse et al.* (2006) illustrated how polar cap patches are reconfigured in the Harang discontinuity and transformed into longitudinally elongated auroral boundary blobs and subauroral blobs, and thus confirming the modeling results of *Robinson et al.* (1985).

In the dayside, where the patches enter the polar cap there has been great controversy on their structuring mechanism. As mentioned above, there are several candidates for the plasma source of patches. In particular, if the TOI or solar EUV ionized plasma is the source, physical structuring mechanisms are needed in order to explain the segmentation into discrete patches. *Lockwood and Carlson* (1992) suggested that transient equatorward leaps of the dayside OCB owing to flux transfer events or pulsed reconnection will bring segments of high density plasma from the TOI or sunlit ionosphere onto open field lines and consequently convect into the polar cap. Another possible mechanism is time varying convection, where the intake from the sub-cusp ionosphere is shifted between high and low density plasma regions by the changing size (*Anderson et al.*, 1988) and (IMF By determined) shape (*Sojka et al.*, 1993, 1994) of the convection pattern. A third mechanism proposed is structuring of plasma enhancements through plasma depletion owing to enhanced recombination rates. These enhanced recombination rates are reached because of Joule heating in the vicinity of flow channel events or traveling convection vortices in the cusp (*Rodger et al.*, 1994; *Valladares et al.*, 1994). In the model of *Rodger et al.* (1994) a combination of such a plasma density depletion in a flow channel event and modulation of the convection by the IMF By component, is used to structure patches where the source plasma is locally produced by particle impact ionization. In their modeling work *Valladares et al.* (1996) used traveling convection vortices in the cusp to illustrate how low density plasma could be transported from earlier local times to create depletions in the TOI.

Several thorough reviews on polar cap patch observations and theories have been written by eg. *Tsunoda* (1988); *Crowley* (1996); *Basu and Valladares* (1999).

Chapter 4

Motivation

The primary motivation for this PhD-work was to use the wealth of data from the Longyearbyen Meridian Scanning Photometer (MSP) in order to study the statistical location of the Open/Closed field line Boundary (OCB) in the cusp. The data set used, spans the auroral seasons from 1994/95 to 2008/09. The MSP has been in operation in Longyearbyen since 1984, but the data prior to 1994 has not been easily accessible. Also the lack of continuous solar wind measurements by satellites before January 1995 have made the early data less useful for this work.

It is well established that the equatorward boundary of the cusp aurora may be used as a proxy for the OCB (cf. *Lorentzen et al.*, 1996; *Sandholt et al.*, 1998). The cusp aurora is characterized by emissions caused by soft electron precipitation near magnetic noon. Owing to the low energies, emissions from excited states with low excitation thresholds, such as the O^1D state of atomic oxygen, dominates in the ionospheric cusp. Hence, the cusp aurora is normally "blood red" and may be identified by high red to green intensity ratios ($\frac{I6300}{I5577} \gg 1$).

During southward interplanetary magnetic field (IMF) the OCB maps along the geomagnetic field to the reconnection x-line on the magnetopause. Studying the location of the dayside OCB is important for several reasons: By measuring the plasma flow across the OCB, the magnetopause reconnection rate may be inferred (e.g. *Lockwood et al.*, 2005a), this provides information about the nature of magnetopause reconnection. The latitudinal location and movement of the OCB is of importance as it reflects the balance of magnetic reconnection on the magnetopause and in the magnetotail, and thus, reveals information about the total amount of open magnetic flux in the magnetosphere (e.g. *Milan et al.*, 2003, 2007).

The data from an MSP is given as the light intensity integrated along a line of sight as function of time and scan angle. In Figure 4.1 keograms (Keogram = Auroral Diagram, from Inuktitut for the aurora shining during the period before there was any daylight - Keoeeit (*Petrie*, 1963)) in the 6300 Å [OI] (top) and 5577 Å [OI] (bottom) emissions, are shown for a typical cusp aurora. It is clearly seen that the red emission is dominating over the green emission, also the north-south movement of the aurora is easy to follow. From the data, as presented in Figure 4.1, the OCB is obtainable by identifying the equatorward edge of the red aurora. The OCB is marked with a white on black, solid line in the figure.

As is seen in Figure 4.1, the spatial information given by the MSP is the scan angle, which is the elevation angle of the instrument line of sight where 0, 90 and 180 degrees are the northern horizon, zenith and southern horizon, respectively. Thus, obtaining the exact horizontal location in a global coordinate system of any observed feature in the data, depends on knowing or successfully obtaining its altitude. Since the scan angle is an instrument-centered coordinate, it is fairly useless if one wishes to compare the information contained in the MSP data with results from other studies, put the MSP data into a global framework consisting of other instruments such as satellites or radars or wish to understand the features studied by the MSP in relation to physical processes that are global or occurring somewhere outside the reference frame of the instrument. This is the case for a statistical treatment of the OCB location as obtained by an MSP. The OCB is only comparable to other physical parameters in the near Earth geospace if it is presented in magnetic latitude. As stated above, if the obtained OCB is to be mapped into a global coordinate system (in this case to obtain the magnetic latitude), we need to know its altitude.

The altitude of the obtained OCB (i.e. the altitude where the line of sight intersects the OCB) will depend on the volume emission rate altitude profile and overall shape of the 6300 Å [OI] red aurora. It has long been known that the latitudinal width of the particle cusp varies (*Newell and Meng*, 1987; *Carbary and Meng*, 1988), and thus the latitudinal width of the cusp aurora. The vertical volume emission rate profile of the cusp aurora will also vary considerably. The shape and characteristic energy of the precipitating cusp particles will vary and shift the aurora in altitude. Over the solar cycle the neutral atmosphere will contract and expand further causing altitude shifts in the aurora. The ionospheric density altitude profile and precipitating energy flux will affect heating and cooling rates in the ambient electron gas; a heated electron gas ($T_e \gtrsim 3000$ K) will contribute to excitation of atomic oxygen into

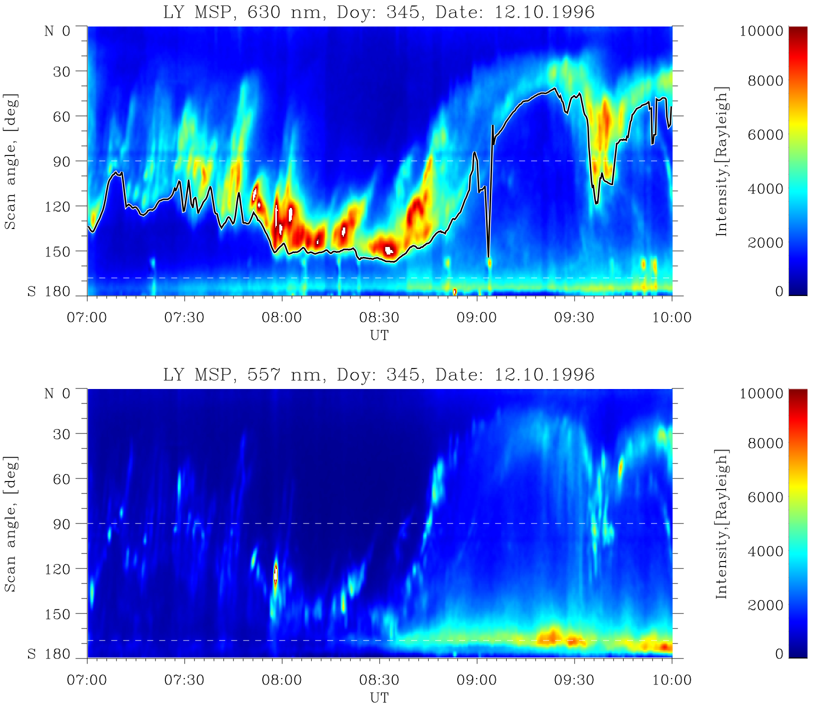

Figure 4.1: Keograms showing the cusp aurora in the 6300 Å [OI] red (top) and 5577 Å [OI] green (bottom) channels. Line of sight intensities are given as colors according to the right hand color bars, intensity ranges are identical in both panels. Time is given along the x-axis. The MSP pointing direction is given as scan angle, where 0 is the northern horizon, 90 is zenith and 180 is the southern horizon, along the y-axis.

the O^1D state. This effect may cause the aurora to change in height from altitudes near the F-layer peak (when the cooling is efficient) to very high altitudes (when the cooling is less efficient) (e.g. *Lockwood et al.*, 1993). All these aspects of cusp aurora height variations are well known within the space physics community. However, there are, to my knowledge, no papers that thoroughly address the problem of choosing the correct mapping altitude for optical emissions in the cusp. Furthermore, very few papers thoroughly discuss the errors or uncertainties introduced by the choice of a single mapping height. It was therefore necessary to examine the variations in emission altitude profiles and the overall shape of the cusp aurora, before we could proceed with the statistical treatment of the optical cusp OCB location. Thus, a qualitative and thorough assessment of these variations in the cusp aurora, choice of OCB mapping altitudes, determination of uncertainties introduced by these specific mapping altitudes and verification of the results, became major motivation factors in this work.

Height determination of the aurora is an old field of study. The pioneer in height determination of the aurora is without doubt Carl Størmer. Using the technique of paralactic photography he and his collaborators made an impressive amount of measurements during the first half of the 1900s (*Størmer*, 1955). In order to determine the volume emission rate profiles of aurora from two ground stations, one may use triangulation. Using a combination of paralactic photographs and photometer measurements Harang was able to determine the volume emission rate profiles of auorae (*Harang*, 1946a,b). Using measured maximum intensities, half values and background levels in order to draw parallelogram boundaries for the auroral forms under the "thin sheet approximation", it is possible to get volume emission rate profiles as well as the horizontal location of the aurora (*Belon et al.*, 1966; *Romick and Belon*, 1967a,b). This technique has been used on dayside aurora in only a few studies (*Sandholt*, 1982; *Sandholt et al.*, 1983; *Egeland et al.*, 1992; *Sigernes et al.*, 1996). However, depending on whether one is studying transient cusp features like poleward moving auroral forms (PMAFs) or not, it is likely that the "thin sheet approximation" is not always valid for cusp auroras since they may be wide and asymmetrical. Often the only reliable result from applying triangulation may be the determination of the emission peak altitude. *Lockwood et al.* (1993) were able to determine the altitude of the cusp 6300 Å[OI] emission peak by comparing its latitudinal velocity with the velocity of the 5577 Å[OI] emission peak. A result which is common for all the studies of cusp aurora altitudes mentioned above, is that a great variability in the emission peak height is observed, and it may vary by more than 100 km over the course of minutes. Another, more superior, technique for examining the multi-dimensional structure of the the aurora is optical tomography. Many tomographic studies on aurora have been performed (i.e. *Solomon et al.*, 1988; *Semeter et al.*, 1999; *Doe et al.*, 1997; *Gustavsson et al.*, 2001), however, no attempts have been made on the dayside aurora. The closest is the study of *Doe et al.* (1997), which is on polar cap aurora, a common phenomenon inside the polar cap during northward IMF conditions. In many cases the polar cap aurora is similar to the cusp aurora with respect to particle precipitation softness and ionospheric conditions.

Owing to the lack of systematic studies discussing the volume emission rate profiles and shape of the cusp aurora, it became clear that we needed to use modeling in order to obtain relevant volume emission rate profiles. Since it is easy to use and easily accessible, the open source airglow / electron transport model of Stan Solomon, the GLOW model (*Solomon et al.*, 1988), was chosen in order to calculate the volume emission rate of the 6300 Å [OI] emission. The GLOW model needs as input a neutral atmosphere and at least an electron density profile. We used the Mass Spectrometer Incoherent Scatter (MSIS-90) model (*Hedin et al.*, 1991) to provide the neutral atmosphere.

Since studies of the dayside OCB and physical processes associated with the cusp are closely related, a natural part of this PhD-work was to participate in larger measurement campaigns such as the Investigation of Cusp Irregularities 2 (ICI-2) sounding rocket launch. This participation consisted mainly of assisting in observations and data acquisition from the EISCAT Svalbard radar or the Kjell Henriksen Observatory and taking part in the discussions related to the assessment of the scientific conditions during the launch window. The ICI-2 rocket was launched southward from Ny-Ålesund into a newly created polar cap patch which was emerging from the cusp aurora. The measurement situation was excellent and a wide range of data was acquired. One published result from the campaign is the proposal for a new patch creation mechanism (*Lorentzen et al.*, 2010).

In the next chapter, we will give a summary of the papers which are a part of this PhD work.

Chapter 5

Summary of Papers

The first three papers presented here discuss the optical, latitudinal location of the dayside OCB. Paper I and II present and validate a model-based method for obtaining the optical dayside OCB in MSP data from Svalbard. Paper III applies this method on 15 years of data in a statistical analysis and compares the obtained OCB latitude with solar wind parameters, the solar cycle and geomagnetic indices. The last paper (Paper IV), which is a result from the ICI-2 sounding rocket campaign, discuss the creation of polar cap patches in the vicinity of the cusp OCB. Paper I, II and III have been submitted to the Journal of Geophysical Research. Paper IV has been published in the Journal of Geophysical Research.

Paper I: A model based method for obtaining the open/closed field line boundary from the cusp auroral 6300 Å [OI] red line, *by M. G. Johnsen, D. A. Lorentzen, J. M. Holmes and U. P. Løvhaug.*

In this paper we present a method for obtaining the dayside OCB from the 6300 Å [OI] emission in MSP data from Svalbard and how to map it into a geomagnetic reference frame. The great variations in volume emission rate profiles of cusp aurora, obtained using the GLOW model, are illustrated and discussed. The effect of a poleward neutral wind on the cusp auroral 6300 Å [OI] emission is also quantified and illustrated. Based on parameters that are considered to be common in the cusp, a reference cusp aurora is defined, and using an MSP simulator, functions describing proper mapping altitude (as function of scan angle) which should be used for converting the scan angle of the OCB into magnetic latitude are found. Using a wide range of other realistic cusp aurora shapes, width and volume emission rate profiles, the uncertainties/errors introduced by the choice of mapping altitudes are quantified (also using the MSP simulator) and presented as a set of parabolic functions.

Paper II: The dayside open/closed field line boundary as seen from space- and ground-based instrumentation, *by M. G. Johnsen and D. A. Lorentzen.*

The results of Paper I were entirely based on modeling, and in Paper II the framework of Paper I was applied to authentic MSP data. Hence we tested the method by comparing the OCB as obtained by the MSP with in-situ measurements performed by a satellite. Three different days of MSP data where the cusp aurora was observed in the south (IMF $B_z < 0$), zenith (IMF $B_y > B_z$) and north (IMF $B_z > 0$), respectively, were chosen. All three days had passes of the NOAA-16 satellite along or very close to the MSP meridian plane in the relevant time interval close to magnetic noon. Thus, the OCB as obtained by the onboard energetic particle detectors could be used to verify the OCB as determined by the MSP technique presented in Paper I. Very good correspondence between the two instruments was found in all three cases with the satellite OCB always staying within the error boundaries of the MSP OCB, thereby validating the method of Paper I.

Paper III: A statistical analysis of the optical dayside open/closed field line boundary, *by M. G. Johnsen and D. A. Lorentzen.*

With a method for obtaining the latitudinal location of the dayside OCB from MSP data within a set of uncertainties from Paper I, and it being validated in Paper II, we applied this technique in Paper III. 15 years of MSP data was examined and the OCB was obtained from a total of 155 days of usable data. A semi automatic method was used in order to extract the OCB from the data. However, as evidenced by the spike seen just after UT 09.00 in Figure 4.1, this method was not perfect, and the results needed to be examined manually afterwards in order to secure their quality.

The OCB latitude was treated statistically and compared to the solar cycle variations from one auroral season to the next, to different solar wind parameters and solar wind - magnetosphere coupling functions and geomagnetic indices. The results were discussed in relation to earlier satellite-based statistical studies. An interesting relationship between the solar cycle and seasonal median OCB latitude was found. Coupling functions that includes both the IMF strength, direction and solar wind velocity correlates well with the OCB latitude. However, geomagnetic indices known to be related to magnetotail processes also correlated well, indicating a greater complexity of the factors governing the OCB latitude than pure magnetopause coupling.

Paper IV: In situ measurement of a newly created polar cap patch, *by D. A. Lorentzen, J. Moen, K. Oksavik, F. Sigernes, Y. Saito, and M. G. Johnsen.*
The ICI-2 sounding rocket was launched from Svalbard into a newly created polar cap patch on December 5. 2008. In this paper the relationship between Poleward Moving Auroral Forms (PMAFs) and the production of polar cap patches is investigated. Throughout the rocket launch window a series of PMAFs with recurrence rates of $\sim 15-27$ minutes were observed. Associated with each PMAF the airglow signature of a polar cap patch was seen to emerge and drift into the polar cap. Using groundbased optics and radars as well as the in-situ measurements performed by the ICI-2 rocket, the ionospheric conditions in the vicinity of such a polar cap patch were analyzed. A conceptual model for polar cap patch creation, which partly involves ionization by both particle precipitation and solar irradiation and upwelling from sub F-layer altitudes due to Joule heating, was proposed.

Chapter 6

Future Work

As shown in Paper I, the secondary effect of atomic oxygen excited by thermal, ambient electrons, is an important contributing factor to the shape and altitude of the cusp auroral volume emission rate profiles. Inside the cusp aurora the electron temperature profile is governed by the balance between heating in the form of columb collisions between ambient and precipitating electrons and cooling by downward heat conduction and collisions between electrons and ions. From this it becomes clear that, as both the ionospheric conditions in the cusp F-layer and the properties of the cusp precipitation may vary considerably, the contribution by thermally excited oxygen to the aurora is highly variable. By modeling, light could be shed on how this contribution varies over the solar cycle, as function of magnetic local time, latitude of the cusp and also cusp local time sector, and expected as well as extreme case electron temperature profiles could be defined. Furthermore, results from modeling efforts will be easily comparable to measurements performed by the Longyearbyen MSP in conjunction with the EISCAT Svalbard radar and satellites such as NOAA and DMSP in order to verify the results.

Since there is a great lack of observational information of the multi-dimensional nature of the cusp aurora, it would be desirable to develop a optical tomographic network similar to ALIS (*Steen et al.*, 1997) for Svalbard.

It should also be investigated if the MSP simulator presented in Paper I, together with modeling, may be used in order to reproduce the cusp large scale dynamics as observed above Svalbard. Using coupling functions and particularly the relationship between the OCB latitude and the PCN index as described in Paper III, a real-time (to one hour advance - from satellite data) forecasting software might be feasible as a tool during measuring campaigns such as rocket launches through the cusp aurora.

The development of a technique for obtaining the dayside OCB latitude within a set of uncertainties opens up for a wide range of applications. Using MSPs in the nightside to obtain the OCB mapping into the magnetotail together with simultaneous measurements of the dayside OCB will perhaps shed more light on the balance between reconnection on the magnetopause and in the magnetotail and how it affects the shape and size of the auroral oval.

The MSP statistics of Paper III should be extended to cover the whole MSP data set back to 1984, it could even possibly be extended to 1978 if data from the early MSPs in Svalbard still exists. This would in particular be of importance for further investigating the causal relationship between the solar cycle and dayside OCB latitude. Finally, the data set does not include only the OCB, statistics could be applied to the emission intensities of the different channels measured by the instrument.

The measurements made during the ICI-2 sounding rocket campaign, which are presented in Paper IV, were performed during quiet geomagnetic conditions close to solar minimum. As solar cycle 24 is increasing in strength disturbed conditions will become more common and the overall background plasma density is expected rise. Furthermore, at high (cusp) latitudes in the European sector, a more pronounced tongue of ionization stretching from lower latitudes, will be observed more often. It would be of interest, through future sounding rocket campaigns, to further investigate the patch creation mechanism proposed in Paper IV in context of these changing background conditions.

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Paper I

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Submitted to Journal of Geophysical Research

Paper II

The dayside open/closed field line boundary as seen from space- and ground-based instrumentation

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Paper III

A statistical analysis of the optical dayside open/closed field line boundary

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