Field-Aligned Currents and Flow Bursts in the Earth’s Magnetotail

BACHELOR THESIS

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Abstract

We use electric and magnetic field data from MMS spacecraft between 2016 and 2017 to statistically investigate earthward propagating plasma flow bursts and field-aligned currents (FACs) inside the plasma sheet of the geomagnetic tail. We observe that the occurrence rate of flow burst peaks around the midnight region with decreasing trend towards Earth and the plasma sheet flanks. Further, we distinguish between long and short FACs. Long FACs last on average 6 sec and have a magnitude of 5-20 nA/m². Short FACs last on average 10 times shorter and have an magnitude of 10-50 nA/m². Both, long and short FACs occur on average one time per flow burst, on minimum 0 times and on maximum 4 times per flow burst. In total, 43 % of the observed FACs are located in a flow burst, 40 % before and 17 % right after a flow burst.

Wir verwenden elektrische und magnetische Felddaten von 2016 und 2017 aus der MMS-Raumfahrtmission, um erdärts propagierende Plasmaflüsse mit explodierender Eigenschaft (engl. flow bursts) und Ströme entlang des magnetischen Feldes (engl. field-aligned currents, FAC) innerhalb der Plasmaschicht der sonnenabgewandten Seite statistisch auszuwerten. Wir beobachten, dass die Häufigkeit der propagierenden Plasmaflüsse in der Mitternachtsregion ihr Maximum erreicht und in Richtung der Erde und der Plasmaschichtflanken deutlich abnimmt. Weiterhin unterscheiden wir zwischen langen und kurzen Strömern. Lange Ströme dauern im Durchschnitt 6 Sekunden an und haben eine Größenordnung von 5 bis 20 nA/m², während kurze Ströme im Durchschnitt 10 mal kürzer andauern und eine Größenordnung von 10 bis 50 nA/m² aufweisen. Sowohl lange als auch kurze Ströme treten durchschnittlich ein mal pro Plasmafluss auf und weisen eine maximale Rate von 4 auf. Im Gesamten treten die Ströme in 43 % der Fälle innerhalb eines Plasmastromes auf, in 40 % der Fälle bevor und in 17 % der Fälle nach dem Plasmstrom.
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# Contents

Abstract ................................................................. ii  
Acknowledgment ....................................................... iii  

1 Introduction .......................................................... 1  

2 Theory ................................................................. 3  
2.1 Basic Space Plasma Physics ..................................... 3  
   2.1.1 Single particle motion ..................................... 4  
   2.1.2 Magnetohydrodynamics and Frozen-In theorem ............. 5  
2.2 Spatial Environment of Earth .................................... 7  
   2.2.1 GSE Coordinate System ................................... 7  
   2.2.2 Interplanetary Magnetic Field ............................. 7  
   2.2.3 Earth's Magnetosphere .................................... 8  
   2.2.4 Magnetotail and Plasma Sheet ............................ 8  
2.3 Magnetic Reconnection ........................................... 9  
   2.3.1 X-Line Model of Magnetic Reconnection .................. 10  
2.4 Propagation of a Earthward Flow Burst .......................... 10  
2.5 Field-Aligned Currents .......................................... 12  

3 Data ................................................................. 13  
3.1 About MMS ....................................................... 13  
3.2 Orbit .......................................................... 13  
3.3 Data and Instruments ........................................... 14  
   3.3.1 EDP instrument ........................................... 15  
   3.3.2 FGM instrument .......................................... 15  
3.4 Curlometer Technique .......................................... 15  

4 Data Processing ................................................... 17  
4.1 Selection of Flow Bursts ...................................... 17  
4.2 Selection of FACs .............................................. 17  
4.3 Selection of DFs associated to FACs ............................ 18  

5 Observations and Results .......................................... 20  
5.1 Illustrative Events ............................................. 20  
   5.1.1 Flow Bursts .............................................. 20  
   5.1.2 FACs .................................................. 21  
   5.1.3 Flow Burst with FACs ................................... 22  
   5.1.4 FACs Appearance ....................................... 24  
5.2 Statistical Investigations ...................................... 24  
   5.2.1 Probing Time of MMS1 ................................... 25  
   5.2.2 Occurrence Distributions ................................. 25  
   5.2.3 Properties of FACs associated to Flow Bursts .......... 28  

iv
6 Discussion
   6.1 Improvements and Suggestions for Further Studies

7 Summary

Bibliography
1 | Introduction

Earth’s magnetosphere exhibits a vast amount of physical phenomena by interacting with the solar wind. Many of them are still not explored or fully understood. Fortunately, the increasing accessibility of in-situ measurements with high accuracy improves the possibility to investigate those. In order to do this, it is necessary to combine theoretical work with analyses of satellite data, ground-base data and computer modeling.

The presence of charged particles together with electric and magnetic fields provides interesting phenomena to explore. Due to interactions between Earth’s magnetic field and the solar wind, a stream of charged particles pulling sun’s magnetic field with it, a cavity surrounding Earth known as the magnetosphere is created. It partially shields Earth from the solar wind.

Earth’s magnetosphere is topological separated in different regions enclosed by current systems. It connects the interplanetary magnetic field down to earth’s upper atmosphere, the ionosphere. Two of them are of higher interest: The dayside magnetopause and nightside magnetotail. The magnetopause is a current sheet emerging through the pressure equilibrium of earth’s magnetosphere and the solar wind. In the magnetotail, the magnetic fields get stretched out by the solar wind. This region contains oppositely aligned magnetic fields, separated by a cross-tail current sheet.

The ”Dungey Convection Cycle” shows the energy and momentum transfer from the solar wind to the magnetosphere-ionosphere system. It proposes that magnetic “reconnection”, a change in topology of magnetic fields, drive plasma convection described by the ”E×B”-drift in the magnetosphere and magnetotail. Through magnetic reconnection, magnetic field lines (magnetic flux) ”opens” at the magnetopause region, flow toward magnetotail embedded by the solar wind and reclose in the cross-tail current sheet. This enables the magnetic flux to flow back to the dayside magnetopause and close the cycle. The merging of magnetic flux in the magnetotail results in a transformation of energy saved in the magnetic fields to kinetic energy in the plasma (Zhang et al., 2015).

The increase of the kinetic energy in the plasma results in the acceleration of plasma particles towards earth and tail, defined as flow bursts. While flowing earthward, currents along the magnetic field (Field-Aligned Currents, FACs) arise at the leading edge of flow bursts. At the leading edge, magnetic fields get pushed together, similar to a snow plow, resulting in a sharp gradient of the field, called dipolarization front. The magnetic fields, with which FACs are flowing, map the dynamics of the magnetotail to the earth’s upper atmosphere, the ionosphere.

Many features of magnetic reconnection, such as what initiates the transformation of magnetic field energy into kinetic energy of plasma particles and how this energy is transported to Earth’s ionosphere, are not fully understood. As well as effects of earthward flow bursts to ionospheric phenomena, such as auroras, are not fully solved. This thesis is a statistical investigation of earthwards flowing flow bursts and FACs in the magnetotail region.
Basic space plasma physics, the environment of earth's magnetosphere and the physics behind magnetic "reconnection" are introduced in chapter 2. The analyzed data are obtained from NASA's Magnetospheric Multiscale mission (MMS) consisting of four spacecraft. The mission was primarily initiated to reveal the origin of magnetic reconnection. Spacecraft and instrumentation are explained in chapter 3. The data procedure to statistical analyze flow bursts and FACs is shown in chapter 4. Finally, results are presented in chapter 5 followed by a discussion and suggestion for further research in chapter 6. A short summary and conclusion completes the findings in chapter 7.
2 | Theory

2.1 Basic Space Plasma Physics

Most of the measurable matter in the universe exists in a state, called plasma. Plasma is the fourth state of matter in form of a quasineutral gas consisting of charged and neutral particles. These particles exhibit collective flow and interaction behavior like a fluid rather than single particle collisions. Space plasma is nearly fully ionized in regions of the solar wind, magnetosheath, geomagnetic tail-lobes and the plasma sheet. The plasma is partly ionized in the ionosphere (Chen, 2016).

Electric fields $E$ and magnetic fields $B$ are everywhere present in space surrounding Earth. They dictate the dynamics of charged particles in the plasma. Therefore, plasma cannot be treated as free particles. Often in space, plasma are quasineutral, i.e. the charge densities of ions and electrons are on average equal. By introducing a positive test charge into a plasma, rapidly moving electrons will rearrange around the test charge in order to isolate it. This introduces the well-known Debye-length $\lambda_D$, the distance for which the test charge potential decreases with the factor $1/e$. Therefore, no net-charge exists on large spatial scales $L \gg \lambda_D$.

There exist three different approaches to describe a plasma: Single particle motion, kinetic theory and fluid approach. The single particle motion describes the motion of single particles and the fields each particle creates. In this approach, rapidly varying fields and collective behaviour of plasma particles are neglected. It is the most precise approach of describing plasma without any major simplifications. Unfortunately, it is impossible to implement the theory for practical uses because of the vast amounts of particles, even in space.

The kinetic theory is a statistical approach. It describes the plasma as a phase-space density by using distribution functions in 7 dimensions (space, momentum and time dimensions). In contrast to the description of every particle in the single particle motion, the distribution function describes the distribution of momentum and particle density for a group of particles in an infinitesimal time, momentum and space-volume.

By using the distribution function of the kinetic theory, the multi-fluid description can be derived. In the fluid approach, each plasma species, mostly electrons and ions, can be described as a fluid. Each fluid follows a collective behaviour and can be described by macroscopic variables, such as number density of particles $n$, average (bulk) velocity $\mathbf{u} = \langle \mathbf{v} \rangle$, charge density $\rho_i = n_i e$, with elementary charge $e$ and species $i$ and current densities $\mathbf{j} = n_i \mathbf{v}_i$ (Baumjohann and Treumann, 2012).

Maxwell’s Equations describe how the electric and magnetic field are related to particle motion. By combining the behaviour of the ion and the electron fluid with Maxwell’s Equations, the Magnetohydrodynamics (MHD) can be derived. It treats all plasma species as a single fluid influenced by the $E$ and $B$ fields. By combining all fluids, the single fluid MHD can be
derived which introduces a single charge density $\rho$, center of mass (bulk) velocity $\mathbf{u}$ and current density $\mathbf{J}$ (Cravens, 1997).

### 2.1.1 Single particle motion

Since the plasma particles are charged, they react to both magnetic and electrical fields. Their dynamics is dictated by the Lorentz force

$$F = q(E + \mathbf{v} \times \mathbf{B}),$$

(2.1)

with charge $q$, velocity $\mathbf{v}$, electrical field $\mathbf{E}$ and a magnetic field $\mathbf{B}$.

For $\mathbf{B} = 0$ the force on the particle is parallel to $\mathbf{E}$ with $F = qE$. For $\mathbf{E} = 0$ and $\mathbf{v}$ with a component perpendicular to a constant magnetic field $\mathbf{B}_0$, the particle gyrates around the magnetic field lines with gyrofrequency $\Omega_g = \frac{qB}{m}$ and gyroradius $r_g = \frac{mv}{|q|B}$.

If both electrical and magnetic fields are present, the particle will experience the $\mathbf{E} \times \mathbf{B}$-drift

$$v_{\perp} = \frac{E \times B}{B^2},$$

(2.2)

perpendicular to both fields.

![Figure 2.1: Charged particle drift in a magnetic and electric field. Adapted from Stannered and Maschen (2007).](image)

Figure 2.1 illustrates the perpendicular motion of positively and negatively charged particles. Although differently charged particles gyrate oppositely, the $\mathbf{E} \times \mathbf{B}$-drift direction remains the same and therefore do not generate any currents.

In additions to the $\mathbf{E} \times \mathbf{B}$-drift, a particle in a nonuniform magnetic field (non-zero gradient and curvature) will experience a complex drift perpendicular to the magnetic field and its gradient. (Cravens, 1997).
2.1.2 Magnetohydrodynamics and Frozen-In theorem

Single fluid magnetohydrodynamics (MHD) is one way of modelling the macroscopic behaviour of space plasma. It is an approximation of the kinetic theory, which statistically describes plasma in a 7-dimensional phase-space. Hereby, it is possible to calculate density, velocity, energy, pressure and temperature of the plasma. It holds only for spatial scales bigger than particle scales, e.g. Debye-length and Gyroradius and for time scales bigger than microscopic particle motion, e.g. Gyrofrequency (Cravens, 1997).

The motion of the plasma in an electro-magnetic field is described by Maxwell’s equations

$$\nabla \cdot \mathbf{E} = \rho / \varepsilon_0 \quad \text{Poisson's equation}$$

$$\nabla \cdot \mathbf{B} = 0 \quad \text{Faraday's law}$$

$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E} \quad \text{Faraday's law} \quad (2.3)$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \varepsilon_0 \partial_t \mathbf{E} \quad \text{Ampere's law} \quad (2.4)$$

with electric field $\mathbf{E}$, magnetic field $\mathbf{B}$, net-charge density $\rho \approx 0$, vacuum permeability $\mu_0$ and vacuum permittivity $\varepsilon_0$. The second term of Ampere’s law (2.4) can be neglected in space as the electric field slowly varies.

The electric field cannot be obtained by Poisson’s equation, as we assume quasi neutrality ($\rho = 0$). Instead the electric field is obtained from the generalized Ohm’s law

$$\mathbf{E} = -(\mathbf{u} \times \mathbf{B}) + \eta \mathbf{j} + \frac{1}{n_e} \left( \frac{m_e}{n_e} (\partial_t \mathbf{j} + \nabla (\mathbf{J} \mathbf{u} + \mathbf{u} \mathbf{J})) \right), \quad (2.5)$$

with number density $n$, elementary charge $e$, plasma pressure $p_e$, resistivity $\eta$ and electron mass $m_e$. Term (1) describes motional $\mathbf{E}$ and ohmic term. Term (2) describes Hall-term, ambipolar polarization and Electron inertial term. It originates from the multiple-fluid approximation of the kinetic theory by subtracting the ion and electron momentum equation, which in turn hold due to the momentum conservation of particle interactions (Chen, 2016).

Term (2), containing time variations, electron inertia, pressure gradient and hall term in (2.5), can be neglected for most regions in space. Combining Term (1) with Faraday’s law (2.3) and Ampere’s law (2.4) gives the convective-diffusion equation

$$\partial_t \mathbf{B} = \nabla \times \left( \mathbf{u} \times \mathbf{B} \right) + D_B \nabla^2 \mathbf{B}, \quad (2.6)$$

with magnetic diffusion coefficient $D_B = \frac{\eta}{\mu_0 \sigma} = \frac{1}{\mu_0 \sigma}$, resistivity coefficient $\eta$ and conductivity $\sigma$. Term (3) describes magnetic convection and term (4) magnetic diffusion.

For highly diffusive plasma (term (4) dominates), magnetic fields act independently to the motion of the plasma. For dominantly convective plasma (term (3) dominates), the time
evolution of the magnetic field is determined by the motion of the plasma. The relative contribution of convective and diffusive term determines the behaviour of the plasma and is described by Reynold's number

\[ R_m = \frac{\nabla \times (u \times B)}{D_B \nabla^2 B}, \]  

(2.7)

in which a large Reynolds's number indicates convective plasma and a small number a diffusive plasma.

In the ideal MHD approximation (often assumed in space physics), plasma is highly conductive. Therefore, the resistivity \( \eta \) can be neglected, the magnetic diffusion coefficient \( D_B \) becomes 0 and the Reynolds number infinitely large. This leads to a highly convective plasma. Consequently, eq. (2.6) becomes

\[ \partial_t B = \nabla \times (u \times B) \]  

(2.8)

This implies that the magnetic flux is frozen in to the plasma fluid. In other words, the magnetic flux through a closed loop within an infinitely conductive fluid is conserved over time \( (d\Phi = B \cdot dA = \text{constant}, \text{with flux } \Phi \text{ and area } A \text{ inside the loop}). \) The magnetic field and plasma flow together in so called "flux tubes". If the plasma moves, the magnetic field will follow and vice versa. This is known as the "frozen-in"-theorem.

The assumption of a highly conductive plasma leads to the ideal Ohm's law

\[ E = -u \times B \]  

(2.9)

and the corresponding ideal bulk velocity

\[ u = \frac{E \times B}{B^2}, \]  

(2.10)

which corresponds to the \( E \times B \)-drift perpendicular to both fields. This implies that the electric field component parallel to the magnetic field is completely neglected. If the ideal MHD conditions hold, the bulk velocity of plasma particles in space can be determined with provided electric and magnetic fields (Cravens, 1997; Chen, 2016).
2.2 Spatial Environment of Earth

The motion of a plasma is highly connected to the magnetic field and vice versa. Therefore, the knowledge of basic magnetic field geometry in Earth's magnetosphere and the interaction of Earth's magnetic field with the solar wind are crucial for understanding physical events in the geomagnetic field.

2.2.1 GSE Coordinate System

The geocentric solar ecliptic (GSE) coordinate system is used throughout the study to determine the position of the spacecraft and determine all vector quantities of the electric and magnetic field while observing events of interest and relate them to certain regions in Earth's magnetosphere. This system has its x-axis towards the Sun and its z-axis perpendicular to the plane of Earth's orbit around the Sun. The y axis completes the right-handed orthogonal basis (Hapgood, 1997). This system is fixed relative to the Earth-Sun line, which makes it convenient for studying the interaction of sun and earth.

2.2.2 Interplanetary Magnetic Field

In addition to emitting light, sun emits plasma, charged particles and magnetic fields. The magnetic field is called the interplanetary magnetic field (IMF) and exceeds from sun in a spiral pattern. Earth's magnetic field is enclosed and its dynamics are connected to the IMF. While \( B_x \) and \( B_y \) are oriented parallel to the ecliptic, \( B_z \) is oriented perpendicular, which is created by disturbances in the solar wind. The interaction of the Sun with Earth's magnetic field give rise to phenomena and dynamics (pluto.space.swri.edu, 1999b).
2.2.3 Earth's Magnetosphere

Figure 2.3: Earth's magnetosphere with the sun to the left, diffusion regions marked in green. Retrieved 2018-04-10, from https://www.nasa.gov/mission_pages/sunearth/science/magnetosphere2.html

Figure 2.3 shows the geometry of earth's magnetosphere, labeling the most essential regions: Bow shock, magnetosheath, magnetopause, magnetotail and plasma sheet.

The bow shock is a shock formed at the dayside front. In this region the supersonic solar wind decreases its velocity to subsonic, gets compressed and heated, in order to avoid Earth's magnetosphere (pluto.space.swri.edu, 1999a).

The magnetosheath is located between the bow shock and the magnetopause. The average particle density and magnetic field strength are considerably higher than in the solar wind due to the shock. The plasma flows around the blunt magnetosphere in the sheath, while its velocity is subsonic and therefore smaller than the supersonic speed of the solar wind (Heikkila, 2011).

The magnetopause is a boundary current layer, which separates Earth's magnetosphere and the magnetosheath. Its location is determined by the pressure balance between the Earth magnetospheric pressure and the solar wind pressure \( p_B = p_K \) (Russell and Elphic, 1978).

2.2.4 Magnetotail and Plasma Sheet

The magnetotail, or geomagnetic tail, is located at the nightside of earth. The dipole configuration of the inner magnetosphere does not hold due to interaction with the solar wind...
compressing the dayside and stretching the nightside. Large topological changes take place via magnetic "reconnection".

The magnetic configuration consists of a north and south lobe, where magnetic field lines are directed earthwards and tailwards, respectively. The magnetic fields in the tail lobes are connected to the solar wind.

The plasma sheet lies between the lobes and contains a (cross-tail) current sheet in its center. It contains denser plasma regions and its magnetic field is relatively weak. It is located near the equatorial plane and has a typical thickness of 2-6 $R_E$.

The current sheet originates from the orientation of the magnetic field. The magnetic field contains a rotation term, which leads to a current orthogonal to the field orientations due to Ampere's law (2.4). The current sheet goes from dawn to dusk in the magnetotail. The plasma sheet current closes a circuit with the magnetopause current around the lobes (Stern, 2006).

Table 2.1 summarizes the typical values of particle density and magnetic field in the solar wind, tail lobes and plasma sheet.

Table 2.1: Typical values for particle density and magnetic field in the solar wind and magnetotail (Cravens, 1997).

<table>
<thead>
<tr>
<th>Solar Wind</th>
<th>Tail lobe</th>
<th>Plasma Sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$ [cm$^{-3}$]</td>
<td>7</td>
<td>0.01</td>
</tr>
<tr>
<td>$</td>
<td>B</td>
<td>[nT]$</td>
</tr>
</tbody>
</table>

2.3 Magnetic Reconnection

Magnetic "reconnection" is a local microscopic process. Macroscopic changes in the magnetic topology and rearrangement of plasma regions are possible, i.e. initially oppositely oriented magnetic fields get connected. During the reconnection, magnetic energy is converted to kinetic energy via acceleration of plasma.

The diffusion region caused by reconnection is correlated to some anomalous resistivity, located at current layers between opposite aligned magnetic fields. For reconnection, the magnetic diffusion term (4) dominates in (2.6). The Reynolds number

$$R_m \sim \frac{uB/a}{D_B B/a^2} \sim \frac{La}{D_B},$$

with $L$ length of the diffusion region, $u$ plasma flow and $a$ corresponding to a very thin current layer, gets relatively small. As a result, the magnetic field is no longer frozen-in to the plasma (Gonzalez and Parker, 2016). Therefore, the assumption of a highly conductive plasma and conditions for the ideal MHD is violated. Reconnection are highly time-varying (turbulent), leading to bursty particle outflows.
Earth’s magnetosphere contains two main diffusion regions, at the dayside magnetopause and at the plasma sheet in the magnetotail. Those regions are marked with green circles in Figure 2.3.

### 2.3.1 X-Line Model of Magnetic Reconnection

The X-line model illustrates the basic physics behind magnetic reconnection at diffusion regions. It assumes the diffusion region in xz-plane and infinite in y.

![X-line model of magnetic reconnection](image)

Figure 2.4: X-line model of magnetic reconnection. Magnetic fields located outside the xy-plane, electric fields aligned towards y. Diffusion region located in the blue box with length $2L > >$ thickness $2a$. Particle flows marked with thick arrows. X-line defines region with magnetic field equal to zero. Retrieved from Doc. Maria Hamrin (Umeå University).

Figure 2.4 shows the X-line model. The current sheet is located at the xy-plane. Magnetic fields are aligned in +x and -x direction above and below the xy-plane outside the diffusion region. The electric field outside the diffusion region is aligned in +y-direction. The magnetic field lines deform towards the xy-plane, lose their frozen-in identity and annihilate each other due to magnetic pressure and particle flow $u_0 \approx E \times B / B^2$ towards the current sheet. After reconnecting, the resulting field lines are transported in x and are again frozen-in to the plasma. This causes a flow burst propagation $u_e \approx E \times B / B^2$ (Cravens, 1997).

### 2.4 Propagation of a Earthward Flow Burst

Focusing on the magnetic reconnection in the magnetotail, the oppositely aligned magnetic field of the northern and southern lobes may reconnect in the plasma sheet, causing high-speed plasma flows towards earth and tail. Earthward flow bursts subsequently arrive at the more dipolar geomagnetic field closer to earth and come either to a full stop at about $10R_E$ or deviate around the Earth. The earthward component of the flow burst velocity $v_x$ usually dominates, but a non-zero velocity component in dawn and dusk direction $v_y$ occur fre-
quently due to flaring effects outside the midnight plane (xz-plane). Flow bursts compress
the magnetic fields ahead of them similar to a snow plow effect. This results in a sharp mag-
netic field gradient, mostly in $B_z$, called dipolarization front (DF) (Sharma et al., 2008). Inves-
tigations of Sun et al. (2013) observed small dips of $B_z$ just before the sharp gradient.

The perpendicular velocity of the flow burst, determined by the $E \times B$-drift (2.2), significantly
dominates outside the diffusion region and dipolar configuration of the near earth magneto-
sphere.

Statistical investigation of flow bursts by Angelopoulos et al. (1994, 1992) have shown that
those flow burst are more frequently earthwards and located at the plasma sheet. They used
AMPTE/IRM data from 1985 and ISEE2 data from 1978/1979 with probing regions in the
plasma sheet and $x = [-22, -10] R_E$. They are mostly located close to the neutral sheet re-
region. The length of the flow burst towards earth is around 1-4 $R_E$ with high variations. Its
thickness is around 1-3 $R_E$. Flows with earthward velocities over 300 km/s were observed
only in 5% of active hours (strong solar winds and geomagnetic substorms) and only 3% of
them last over two minutes.

Although they occur infrequently ($\sim 5 - 6\%$ of the spacecrafts probing time), they are re-
sponsible for half of the mass and energy transport and around 70-80 % of the magnetic flux
transport towards earth (Sharma et al., 2008; Angelopoulos et al., 1994).

Figure 2.5: Schematic picture of a high-speed flow burst (plasma "bubble") propagating towards
Earth. The flux and plasma pileup region in front of the bubble is in yellow, the bubble itself grey
and field-aligned current regions green. Flow velocities are marked by red arrows. Retrieved from
Walsh et al. (2009).

Figure 2.5 shows a model of a flow burst propagating towards earth. The flow burst corre-
sponds to the grey region (plasma "bubble"). The magnetic flux pileup is at the leading edge
of the bubble shown in yellow. The regions around the bubble, in which field-aligned cur-
rents emerge, are labeled in green. The red arrows illustrate the direction of plasma flows in
and around the bubble.

The presence of a non-zero $B_y$ component in the geomagnetic tail influences the properties
and motion of the plasma bubble by influencing the direction of the magnetic field draping around the edges of the flow burst. In the presence of $B_y$, the motion of the bubble will have a dusk- or dawnward component (Walsh et al., 2009).

### 2.5 Field-Aligned Currents

Field-aligned currents (FACs) are associated with the DF of earthwards moving flow bursts in the geomagnetic tail, connecting it with the ionosphere. These currents close the current system between neutral sheet and ionosphere. In the northern and southern hemisphere, FACs move towards the flow burst on the dusk-side and towards the ionosphere on the dawn-side of the flow burst.

Such FACs can be generated by flow vortices suggested by investigations of Keiling et al. (2009), but also by pressure gradients due to deceleration of the flow burst (Sun et al., 2013).

![Figure 2.6: Model of FAC associated with DF structure. Black arrows show the magnetic field direction. Green arrows show directions of the DF normal. Red and blue arrows indicate FAC’s corresponding to region-1 and region-2 sense, respectively. Retrieved from Sun et al. (2013).](image)

An analyze of Sun et al. (2013) investigate most FACs corresponding to DFs between 15 and 20 $R_E$ at the nightside of Earth. DFs have a thickness of 1000-2000 km and the associated current density is between 5 – 20 nA/m$^2$. They observed two different types of FACs, illustrated in Figure 2.6. Relative strong region-1 FACs (red arrows) flowing inside the duskflank of the DF and outside the dawnflank of the DF with current densities 10 – 20 nA/m$^2$. Region-2 FACs (blue arrows) are oppositely aligned to their related region-1 FAC with current densities 5 – 10 nA/m$^2$. They are located in front of the DF and are associated with the dip in $B_z$ just before its sharp gradient.
3 | Data and Instrumentation

3.1 About MMS

The Magnetospheric Multiscale mission MMS (NASA) is constructed primarily to reveal the 3D-structure and dynamics of the extremely thin electron diffusion region of the reconnection zone to understand how the magnetic field reconnects. Therefore the main investigation zones of the spacecraft are the dayside and nightside diffusion regions of earth’s magnetosphere. To optimize chances of observing magnetic reconnection, the orbit of the mission is in the equatorial plane.

![MMS spacecraft instruments](https://mms.gsfc.nasa.gov/spacecraft.html)

The mission consists of four identical spacecraft, orbiting earth in a tetrahedral shape in order to distinguish between space and time variation and provide several measurement techniques, e.g. the curlometer technique used for this project. Each spacecraft holds 11 instruments to measure particle and field data, shown in Figure 3.1 (NASA, 2018).

3.2 Orbit

The orbit of MMS during 2016 and 2017 is roughly divided in two phases to probe all reconnection regions. Phase 1 focuses on the low-latitude magnetopause and near-earth magne-
totail, phase 2 on the distant magnetotail and high-latitude magnetopause (Fuselier et al., 2016). Further phases are afterwards added with the extension of the MMS mission.

Figure 3.2: Four samples of the orbit of MMS1. For months in phase 1 over three selected days and for July 2017 over seven days; green corresponds to February 2016, red to July 2016, pink to February 2017, blue to July 2017.

Figure 3.2 shows four orbital samples of the MMS spacecraft. For each month in phase 1, every third day from the 2. to the 8. is shown. For July 2017 (phase 2), all days from the 2. to the 8. are shown due to the longer time duration for one orbit. It has been observed that the spacecraft orbited earth in phase 1 during the whole year of 2016 and started with phase 2 in the beginning of 2017. The mission mostly probed magnetotail regions of interest for this project from mid of May until beginning of September 2017.

3.3 Data and Instruments

Magnetotail data for this study are provided by four MMS spacecrafts. The data are accessible through the homepage of "MMS Science Data Center" (https://lasp.colorado.edu/mms/sdc/public/). In total 2 years (2016 and 2017) of MMS data are used in this study. Further, only GSE coordinates have been used through the project and all results are given in GSE coordinates.

Particle data are not continuously provided, as the Fast Plasma Instrument (FPI) is not always taking measurements. Therefore, only fluxgate-magnetometer (FGM), electric field double probe instrument (EDP) and position data measured by the GPS instrument are used. In
3.3.1 EDP instrument

The EDP consists of the Spin-Plane Double Probe (SDP) and Axial Double Probe (ADP) instruments. The SDP consists of 4 biased spherical probes extended on 60 m long wire booms, close to the unperturbed plasma, 90° apart in the spin plane. The ADP consists of 2 biased cylindrical probes extended on 12 m booms along the spacecraft rotation. Combined, they measure the 3-D electric field with an accuracy of 0.5 mV/m. The time-resolution of the instrument is 1 ms, downsampled to 32 samples per second in the fast survey data used through this project.

In general the double probe instrument measures the voltage difference between spherical probes by a use of a chosen bias current on the spin plane of the spacecraft (Khotyaintsev et al., 2017).

The EDP is not continuously measuring data, e.g. in magnetospheric regions not of interest, to prevent redundant deterioration of the instrument which would later result in measuring errors.

3.3.2 FGM instrument

The FGM provides magnetic field data. Each spacecraft consists of two tri-axial FGM mounted on the end of two 5 m booms to avoid interference from the spacecraft. The essential component of the sensors are two magnetic ring cores. One set of wire windings are wrapped around the ring cores to drive them into saturation. Another set of windings measures the time varying magnetic flux in the cores and cancels the ambient field out by driving a current into the coils. The used current gives an estimation for the magnetic field.

The time resolution of the instrument is of the order of milliseconds and downsampled to 16 samples per second for the survey data used through this project. The FGM is a very fault-tolerant and stable instrument with measurement errors below 0.5 nT (Leinweber et al., 2016).

3.4 Curlometer Technique

The curlometer technique calculates the electric current density from the measured magnetic field data from four spacecraft, which orbit in a tetrahedral shape. The spacecraft position is converted from GSE to barycentric coordinates, to express their relative position to each other in a basis of an tetrahedron. The estimated 3D current in barycentric coordinates is then converted back to GSE coordinates.
The technique is based on Ampere’s law (2.4). Expressed in integral form, it gives
\[ \mu_0 \int j \, ds = \oint B \, dl, \]
with current \( j \) perpendicular to each tetrahedron face and magnetic field \( B \) along the three edges of each tetrahedron face. For practical estimations, a homogeneous current density profile is assumed inside the tetrahedral faces which enables the usage of linear interpolation. With this, the equation can be rewritten as
\[ \mu_0 j_{av} \cdot (r_{1\alpha} \times r_{1\beta}) = \Delta B_{1\alpha} \cdot r_{1\beta} - \Delta B_{1\beta} \cdot r_{1\alpha}, \] (3.1)
with \( j_{av} \) mean current over the tetrahedron volume. The indices 1 and \( \alpha, \beta, \gamma = 2, 3, 4 \) refer to the apexes of the tetrahedron. \( \Delta B_{ij} \) is the difference of measured magnetic field between two spacecraft \( i, j \). \( r_{ij} \) is the spatial distance between two spacecraft \( i, j \).

![Figure 3.3: Illustration of the curlometer technique. Currents normal to each tetrahedral shape is given by thick arrows. Retrieved from Dunlop et al. (2002).](image)

**Figure 3.3** illustrates the measured current related to three edges of the tetrahedron and three spacecraft on each corner. Therefore, four spacecraft give a full 3D current density (Dunlop et al., 2002).

Four main error estimation enter here, such as measurement uncertainty of the magnetic field, linear interpolation used on a not-homogeneous current density profile, a missing proper tetrahedral shape and simultaneity of measurements. Especially in geomagnetic regions with low magnetic field (< 50 nT) and high activity, high estimation errors occur frequently.

The error can be estimated by the ratio of the magnetic field divergence to the rotation of the magnetic field \( \nabla \cdot B / \nabla \times B \) and the structure of the tetrahedral configuration. The tetrahedral shape can be determined by the elongation and the planetary respectively representing how stretched and flat the shape is. High values of elongation and planetary (\( \approx 1 \)) indicate a highly stretched and flat tetrahedron and low values (\( \approx 0 \)) indicate a symmetrical and well-shaped tetrahedron (Robert et al., 1998).
4  |  Data Processing

The observed data are statistically analyzed through three sub-routines in Mathwork’s Matlab software, corresponding to the selection of flow bursts, FACs and DFs. At first, flow bursts and FACs are analyzed separately. Afterwards, FACs and flow bursts are analyzed together in order to find a possible correlation between them. In the end FACs are analyzed with DFs.

In order to provide comparable results to earlier publications using spacecraft data of Cluster (ESA), magnetic and electric field data are downsampled to 0.25 samples per sec for analyzing flow bursts and 5 samples per sec for analyzing FACs and DFs. A similar procedure was done by Schmid et al. (2016) who compared DFs between Cluster and MMS.

First, the considered regions in the geomagnetic tail are limited from -9 to +9 $R_E$ in the $y$-direction and below -10 $R_E$ in x-direction, related to the event selection by the publication of Pitkänen et al. (2013). The limit in x roughly excludes high $E \times B$-drifts from flow events with high azimuthal flows for $x > -10 R_E$. The y limit includes only flow and current events far from the magnetopause. Moreover, we remove the lobes and part of the boundary layer between plasma sheet and lobes by requiring $|B_x| < 25$ nT.

To statistically map the observed flow burst and FAC events in the geomagnetic tail, the considered region is partitioned in $1 \times 1 R_E^2$ bins. These are the typical size scales of earthward propagating flow bursts. Each bin represents the occurrence rate of the observed events. Except for sec. 5.2.2, the occurrence is calculated by dividing the total time each event has been observed in each bin with the time the spacecraft has covered this bin.

Finally, the dependence of the FAC magnitude is compared to the mean perpendicular velocity in xy-plane of the flow burst $v_{\perp x y}$ and the DF strength ($\max(B_z) - \min(B_z)$).

4.1 Selection of Flow Bursts

To classify a fast flow event, the lower limit of the measured $E \times B$-drift perpendicular to the magnetic and electric field in xy plane $v_{\perp x y} = \sqrt{v_{\perp x}^2 + v_{\perp y}^2}$ is set to 200 km/s for at least 30 seconds. Simultaneously the drift is set to be earthward with $v_x > 0$. Single samples not matching to these conditions are neglected. Therefore, $v_{\perp x y}$ may be below 200 km/s for around 4 seconds. This selection is similar to the study of Pitkänen et al. (2013) except that we compute $v$ from the $E \times B$-drift.

4.2 Selection of FACs

Further, significant rises in the measured current density projected to the magnetic field $j_{||}$ are defined as FAC events. For an accurate estimation of the currents we require that $|\nabla \cdot$
\( B/\nabla \times B \mid < 0.5 \). The threshold for the Planetary and Elongation of the tetrahedral shape is set to 0.6.

To classify FAC events, \( j_j \mid = j_{0.2} \) was resampled over time intervals of 1 sec \( j_1 \) and 50 sec \( j_{50} \). The resampled time-series \( j_{50} \) represents the average current density and includes that the current density does not fluctuate around 0 due to cross-calibration error. Further, the standard deviation \( \sigma \) was estimated for each point in the time-series \( j_{0.2} \) by taking a time window of 1 min before and after that point and calculating the standard deviation of all measured \( j_{0.2} \) inside this window. Selected FACs fulfill at least one of the following conditions:

\[
\begin{align*}
|j_{0.2}| &> |j_{50}| + 8.5\sigma \quad \text{for at least 0.2 sec.} \quad (4.1) \\
|j_{0.2}| &> |j_{50}| + 4.5\sigma \text{ and } |j_{0.2}| > |j_1| + 1 \text{nA/m}^2 \quad \text{for at least 0.6 sec.} \quad (4.2) \\
|j_{0.2}| &> |j_{50}| + 2.5\sigma, \sigma > 2 \text{nA/m}^2 \text{ and } |j_1| > |j_{50}| + 4 \text{nA/m}^2 \quad \text{for at least 2 sec.} \quad (4.3) \\
|j_{0.2}| &> |j_{50}| + 1.5\sigma, \sigma > 1.5 \text{nA/m}^2 \text{ and } |j_1| > |j_{50}| + 3 \text{nA/m}^2 \quad \text{for at least 5 sec.} \quad (4.4)
\end{align*}
\]

The numeric conditions to \( \sigma \) in (4.3) and (4.4) and the difference between \( j_{0.2}, j_1 \) and \( j_{50} \) in (4.2)-(4.4) have been made to exclude small fluctuations of \( j_1 \). FAC events matching the conditions of (4.1) and (4.2) are combined and defined as short FACs (< 1 sec). The combination of FAC events from (4.3) and (4.4) are defined as long FACs (> 1 sec). To my knowledge, no studies have been found with a selection method for FAC events to compare to.

**FACs Associated to Flow Bursts**

FAC events, which occur three minutes before a flow burst is selected, are correlated to these flow burst in this project. This approach is in accordance to the event study of DF and FACs on the leading edge of flow bursts by Sun et al. (2013), who examined on the strong magnetic field gradient in front of flow bursts.

Further statistical observations have shown the majority of FACs inside the flow burst event and a non-neglectable amount of FACs after flow burst events, shown in Figure 5.9. Therefore, these FACs have also been classified to correlate with the flow bursts. FACs beyond these time intervals are set to originate from other physical phenomena and are not considered here.

### 4.3 Selection of DFs associated to FACs

To classify DFs by an significant increase in \( B_z \), only the time intervals 15 sec before and 8 sec after selected FAC events are considered for the magnetic field as statistical investigations have shown that FACs and DFs occurred likely simultaneous. The criteria for \( B_z \) is set to \( \max(B_z) - \min(B_z) \geq 4 \text{nT} \). The limit for the inclination angle \( \Theta = \arctan(B_z/\sqrt{B_x^2 + B_y^2}) \) of the magnetic field is set to \( \max(\Theta) \geq 45^\circ \) and a change of \( \Theta_{\max(B_z)} - \Theta_{\min(B_z)} \geq 10^\circ \) between the maximum and minimum of \( B_z \). The limits to \( B_z \) and the inclination angle are according
to the study of Fu et al. (2012) who used Cluster data. The significant reduction of the time interval compared to his study (3 minutes before the DF and 1 minute after) is due to the strong variance of the magnetic field in MMS data.
5 Observations and Results

The results of this project are structured as follows: First, examples of the selected flow bursts, FACs and FACs related to a flow burst are shown. Second, we superpose all FACs to present the typical appearance of FACs. Third, the occurrence rate of each event in xy and xz planes is given. This enables to find regions with higher occurrence of flow bursts and FACs and point out a (theoretical) possible correlation between them. Finally, a statistical analysis of the time lag between FACs and flow burst and the dependence of FACs magnitude to the flow burst velocity and DF strength is shown.

5.1 Illustrative Events

5.1.1 Flow Bursts

Flow bursts selected by the algorithm appear as strong increase of the perpendicular ion velocity in the xy plane. A simultaneous change in the electric and magnetic field is observable due to calculation of $v_{\perp xy}$ as $v_{\perp xy} = (E \times B / B^2)_{xy}$.

Figure 5.1a shows the perpendicular velocity in the xy plane in black, the velocity in the x-direction in blue and the velocity in y direction in red. Figure 5.1b shows the x, y and z components of the measured magnetic field $B_x, B_y, B_z$. Highlighted in blue are the fast flows selected by the algorithm.

The first fast flow event at 04:10 shows a strong increase of $v_{\perp xy}$ and a positive $v_x$. The event has a peak velocity of 450 km/s and lasts around one minute until $v_{\perp xy}$ reaches below 200 km/s. Furthermore, $v_{\perp xy}$ increases much stronger than $v_x$, indicating that most of it is due to $v_y$. The magnetic field components $B_x$ and $B_y$ change slightly with stronger increase in $B_y$. Only $B_z$ remains almost constant. After 10 minutes four strong flow bursts are observable. They contain peak velocities from 600 to 1200 km/s and last for around 5 to 8 minutes with time intervals of 30 seconds between them in which $v_{\perp xy}$ decreases below 200 km/s. Ahead of each flow burst, $B_x$ decreases and is almost zero for the first two flow bursts. The other two components $B_y$ and $B_z$ strongly fluctuate during the flow burst events. Before 04:10 and after 04:40, in which no flow bursts are observed, $B_y$ and $B_z$ are approximately 0 and $B_x$ constant. This indicates that the tail was in a stretched configuration. The ions velocity is significantly high compared to the dominantly observed velocity below 100 km/s in the geomagnetic tail (Juusola et al., 2011).

Compared to a study of Angelopoulos et al. (1994), a small value of $B_z$ indicates the small distance to the cross-tail current sheet. The flow bursts causes a high magnetic flux transport observable through a rapid change of $B_y$ and $B_z$. A high $v_{\perp xy}$ accompanied with positive $v_x$ shows a large transport of particles towards earth.
CHAPTER 5. OBSERVATIONS AND RESULTS

5.1.2 FACs

In addition to study fast flows, we investigate field aligned currents (FACs) which appear as significant increase of the current density aligned to the magnetic field $j$. A simultaneous change in the magnetic field is observable corresponding to the usage of Ampere's law (2.4) for the Curlometer technique. Strong changes in the magnetic field give a significant rise of the current density perpendicular to the change.

Figure 5.2a shows the calculated current density projected along the instantaneous magnetic field. Figure 5.2b shows the components of the magnetic field. Highlighted in cyan and red are respectively the times long and short FACs selected by the algorithm.

The first two FAC events are similar in magnitude (~ 40 nA/m$^2$) and duration (~ 1 s). They are oppositely aligned to the magnetic field and separated by a relatively calm current density lasting 10 sec. With the FACs an increase of all magnetic field components is observable. Four minutes later a long positive FAC appears. It has a magnitude of 30 nA/m$^2$ and lasts about
CHAPTER 5. OBSERVATIONS AND RESULTS

Figure 5.2: Data of FACs from 2017-07-01. (a) Current density aligned to the magnetic field and (b) magnetic field components. Cyan and red marked area indicate the time where the selection for the long and short FACs holds, respectively.

2-3 sec. A simultaneous decrease in all magnetic field components is observable.

5.1.3 Flow Burst with FACs

Investigations have shown that FACs and flow bursts can be seen about the same time.

Figure 5.3 a,b,c show respectively the perpendicular ions velocity in the xy plane and velocity in the x direction, the current density aligned to the magnetic field and the components of the magnetic field. Blue and red marks the times in which a fast flows and short FACs are selected.

First, \( v_{\perp xy} \) gradually increases for about 15 sec until it reaches its peak of about 1000 km/s. Afterwards, \( v_{\perp xy} \) decreases for 15 sec down to 100 km/s. Finally another small increase of \( v_{\perp xy} \) up to 200 km/s is observable. The flow burst lasts 35 seconds and has a mean speed of 400 km/s. From the duration and average speed, we can estimate the size of the flow burst to \( 2 R_E \).
Two strong FACs appear at the leading edge of the flow burst. The first reaches a magnitude of -50 nA/m² and the second a magnitude of +80 nA/m². They are oppositely aligned and both last for about a second. The first FAC is accompanied by a small dip in all components of the magnetic field. The second FAC is accompanied by an increase in $B_x$ and $B_z$ whereas $B_y$ keeps decreasing. The third and fourth FACs show similar pattern, but the positive FAC appears firstly and is followed by a negative FAC. The fifth FAC is negative and appears alone. It lasts much longer (even outside the selected time). Simultaneous, $B_z$ dips while $B_x$ and $B_y$ increase.

The first four FACs appear in pairs. The first pair has a negative and then positive FAC. The second pair has a positive and then negative FAC. For each pair, the first FAC occurs with
a small dip in $B_z$ and the second with an increase in $B_z$. Further observations and studies of FACs related to flow bursts by Sharma et al. (2008); Sun et al. (2013); Snekvik et al. (2007) have shown a similar pattern of FACs, which occur in pairs. These studies investigated DF on the leading edge of a flow burst and show how the magnetic field and current density varies before an observed flow burst.

### 5.1.4 FACs Appearance

![Figure 5.4: Superposed epoch analysis for (a) long and (b) short, positive FACs. Average FAC is shown in black, the standard deviation in grey.](image)

The superposed epoch analysis is used to show the average appearance of long and short FACs selected by the algorithm. Figure 5.4 shows the selected (a) long and (b) short, positive FACs. The average appearance of an FAC event is shown in black and its upper and lower standard deviation in grey. The typical duration of FACs is set to be the full width at half maximum (FWHM) of the average FAC. The upper and lower standard deviation indicates the maximum and minimum magnitude of the majority of FACs. Long FACs last 6 sec with a long peak (2 sec) and a typical current density below 20 nA/m$^2$. Short FACs appear roughly 10 times shorter than long FACs ($\sim 0.6$ sec) with a short peak (0.2 sec) and a magnitude between 10 and 50 nA/m$^2$.

### 5.2 Statistical Investigations

Table 5.1 shows the number of selected events in 2016 and 2017. In total 310 earthward flow bursts and 2908 FACs were observed. Among the 2908 FACs, 704 were observed in association with flow bursts. It appears that long and short FACs are equally likely to occur. On average two FACs are observed for each flow burst.
Table 5.1: Number of events observed by MMS in 2016 and 2017 (FBs - flow bursts).

<table>
<thead>
<tr>
<th>Event</th>
<th>FBs</th>
<th>FACs</th>
<th>FACs rel. to FBs</th>
<th>DF rel. to FBs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1784 (long)</td>
<td>369 (long)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1124 (short)</td>
<td>335 (short)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>310</td>
<td>2908</td>
<td>704</td>
<td>186</td>
</tr>
</tbody>
</table>

5.2.1 Probing Time of MMS1

Figure 5.5: Probing time of MMS1 in (a) the xy-plane and (b) the xz-plane. In both planes, a high probing time between -10 and -12 \( R_E \) in \( R_E \) is observable. This undermines that the spacecraft mostly were in phase 1 of the mission (2016 and beginning of 2017). The spacecraft covered the magnetotail region rather uniformly in dusk-dawn direction. The coverage increases in -x direction.

5.2.2 Occurrence Distributions

Flow Bursts

Figure 5.6 shows the occurrence rates of observed earthward flow bursts in the (a) xy- and (b) xz-plane. The occurrences in each bin reaches from 0 % to around 30 % with an average of 3 %, white bins point out regions that the spacecraft have not covered. The occurrence rate of flow bursts increases around \( y = 0 \) and \( y = 2 R_E \) and between -20 and -25 \( R_E \) in \( x \). The occurrence rate decreases rapidly for \( x \geq -17 R_E \) until almost no flow burst with the required selection criteria are observed above -12 \( R_E \) in \( x \). This indicates that an earthward
propagating flow burst slows down closer to earth. A strong dusk-dawn asymmetry with high concentration on the dusk is perceptible.

The study of Kiehas et al. (2018) using ARTEMIS mission between 2011 and 2015 also shows a higher occurrence of flow burst with \( v \geq 400 \) km/s on the dusk. However, flow bursts with a perpendicular velocity over 200 km/s occur relatively symmetric. The study relates the asymmetry to the preferable occurrence of magnetic reconnection on the duskside for high activities. This may be caused by strong solar winds shifting the neutral sheet duskward.

**FACs**

Figure 5.7 shows the occurrence rate of long FACs in the (a) xy- and (b) xz-plane. Short FACs are shown in (c) xy and (d) xz plane. Long FACs occur on average 10 times more frequently than short FACs, even though long and short FACs have been equally selected. This is due to the fact that long FACs appear roughly 10 times longer on average (see sec. 5.1.4). Both types rarely occurred in the region close to earth \((x \in [-12, -10] R_E)\) even though the spacecraft regularly covered this region during phase 1. Therefore, FACs might not occur closer to earth.

The occurrence rate of long FACs is between 0.005 and 1 percent, on average 0.6 percent. They appear uniformly in \(-x\) direction in the xz-plane with a slightly higher preference to the dawnside on the xy-plane.

Short FACs have a rate between 0.005 and 0.2 percent, on average 0.05 percent. They appear more frequently on the duskside with a similar pattern as the occurrence of flow bursts.
CHAPTER 5. OBSERVATIONS AND RESULTS

Figure 5.7: Occurrence rate of FACs. Long FACs in (a) xy- and (b) xz-plane. Short FACs in (c) xy- and (d) xz-plane.

FACs Associated with Flow Bursts

In contrast to previous occurrence rates, Figure 5.7 shows the number of occurring FACs associated to flow bursts per flow burst. Long FACs are shown in (a) xy- and (b) xz-plane and short FACs are shown in (c) xy- and (d) xz-plane. White bins point out regions in which no flow bursts are observed. Long FACs in correlation to flow bursts occur 0 to 4 times per flow burst with an average of 1 time. Short FACs in correlation to flow bursts appear roughly the same amount per flow burst.

FACs related to flow bursts occurred more frequently near \( y = 0 \) with a slightly higher rate on the dawnside. On average one long and one short FAC are observed per flow burst. This
matches the assumption that FACs mostly occur in pairs with a flow burst.

5.2.3 Properties of FACs associated to Flow Bursts

Time Lag

Figure 5.9 shows the relative occurrence of FACs correlated to flow burst against time difference. FACs occurring before and after flow burst are shown respectively by positive and negative time differences. For $t = 0$, FACs are observed inside a flow burst event.
FACs occur almost evenly distributed three minutes before and one minute after a flow burst with a slight increase 15 seconds before and 10 seconds after the event. Most often, FACs have been selected inside the flow burst (~0.42), followed by preceding FACs (~0.4). But FACs also occur frequently after the event (~0.18).

FACs during and after flow bursts are not covered by DF and FACs studies of Sun et al. (2013) and Sharma et al. (2008). To my knowledge, no studies of FACs during these times have been published. Due to the high occurrence, there might be a potential correlation.

**Magnitude**

![Figure 5.10: Magnitude of FACs against mean \( v_{\perp xy} \) of flow bursts. Mean value and standard deviation represented in a 50 km/s interval.](image)
Figure 5.10 shows the magnitude of FACs associated to flow bursts against the mean value of $v_{\perp xy}$ of the flow burst they are associated to. The mean value and standard deviation show a slight increase of FACs strength for $v_{\perp xy} \in [200, 400] \, km/s$ and stays roughly constant for higher velocities.

Figure 5.11: Magnitude of FACs against DF. Red dots represents samples of FACs related to DF. Black line and grey region respectively represent mean value and standard deviation of the FACs magnitude inside a 4 nT interval.

Figure 5.11 shows the magnitude of the FACs correlated to the DFs at the leading-edge of a flow burst against the difference between maximum and minimum of $B_z$ of the DFs. Red dots show all samples. Black line and grey region respectively represent the mean value and standard deviation of the FAC magnitudes inside an 4 nT interval.

A small trend of increasing mean value and standard deviation is perceptible with stronger DFs giving rise to a small dependence of the FACs magnitude to the DF. However, strong FACs ($> 20 \, nA/m^2$) already occur with weak DFs ($< 10 \, nT$) and the samples are highly spread. It appears that the magnitude of the FACs is higher dependent to the DFs than on the perpendicular velocity in xy-plane of the flow burst, but other conditions also strongly influence the strength.

Furthermore, the amount of samples for strong DFs ($> 10 \, nT$) and flow bursts ($v_{\perp xy} > 400 \, km/s$) decrease rapidly undermining a significant low occurrence of strong events. Mean values and standard deviations do not give a high accuracy for stronger DFs and flow bursts due to the less amount of observations.
Comparing the occurrence rate in Figure 5.6 with Plate 6 of the study of Angelopoulos et al. (1994) for earthward propagating flow bursts indicates some deviations. Angelopoulos defines flow bursts as bursty bulk flows (BBFs) due to their bursty property. The occurrence rate of BBFs using ISEE2 has a dawnward asymmetry instead of a duskward asymmetry observed from the IRM mission and this project. Moreover, the occurrence rate is on average 2 times higher in Angelopoulos et al. (1994) observations (5-6 % instead of 3 %) whereas the occurrence rate for \( x > -17 R_E \) deviates significantly between this project and their observations. Only the decreasing trend of the occurrence rate towards earth and dusk-dawn direction has a similar pattern to the one in Figure 5.6. Figure 5.6 shows many gaps and strong differences between nearby bins while the occurrence rate in Angelopoulos et al. (1994) shows a more consistent pattern.

There are several possible reasons for this. First, the selection method is different. Angelopoulos et al. (1994) selected flow bursts by using the measured bulk velocity of the particle data from ISEE2 during 1978/79 and from IRM during 1985. Continuous ion velocities with \( v_i > 100 \) km/s and at least one sample \( v_i > 400 \) km/s with earthward component \( v_{ix} > 0 \) are classified as BBFs. Samples with \( v_i > 400 \) km/s 10 min tops apart were considered as one BBF event. Moreover, they use GSM coordinates (a rotation in yz-plane along the x axis compared to GSE) and ISEE2 covers a smaller region \( x > -22 R_E \).

The differences in the dawn-dusk asymmetry between ISEE and MMS may result from the different coordinate systems. The preferred location of the neutral sheet during different years may also shift the regions of observed flow bursts, as the study of Kiehas et al. (2018) using more recent ARTEMIS data from 2011-2015, has also shown a duskward asymmetry. The different occurrence rate and fragmentary pattern in Figure 5.6 emphasizes the strong differences of selection methods between this project and Angelopoulos et al. (1994). It seems that in general the perpendicular component of the E\( \times \)B-drift in xy-plane deviates slightly from the actual ion velocity in the geomagnetic tail. Closer to earth \( (x > -12 R_E) \), azimuthal velocity components contribute to the ion velocity, while close to the diffusion regions in the neutral sheet the frozen-in theorem no longer holds. The different limits for \( v_i \) and \( v_{\perp x y} \) may also shift the occurrence rates. Further, the limit \( |B_x| < 25 nT \) excludes potential flow burst events at the boundary layer between the plasma sheet and tail lobes which gives deviations of the occurrence rate for higher \( |z| \) values.

The dawn-dusk asymmetry of flow burst occurrence can be related to the used coordinate system GSE. It does not consider the direction of the solar wind deviating from the earth-sun line due to aberration effects. The solar wind may change the orientation of the tail preferably in dawn or dusk direction. This in turn might change the location of the diffusion region to the duskside, which lead to a higher occurrence of earthward flow bursts on this side.

The observed field aligned current densities from MMS data show variations in the current density profile in greater detail compared to studies of Sun et al. (2013) and Snekvik et al.
Even small-scale events influencing the current densities are observable. Sun and Snevniks observed FACs last from 5 to 20 sec, which is significantly longer than the mean duration of short FACs (0.6 sec) shown in this project. The duration of long FACs covers only the lower limit of Sun and Snevniks observed FACs.

A reason for the high difference in the duration of FACs may be the higher sampling rate of MMS data reducing averaging of magnetic field data. Furthermore, the MMS spacecrafts are considerably closer to each other (∼6-8 km) compared to Cluster (∼200-19000 km (Kramer, 2002)). Through the small distance of the MMS spacecrafts, the curlometer technique gets more precise in detecting even small current fluctuations caused by small scale events. The large tetrahedral shape of Cluster averages over these small fluctuations due to linear interpolation.

The superposed epoch analysis gives long FACs with 5-20 nA/m² and short FACs with 10-50 nA/m², whereas in the study of Sun et al. (2013) he distinguishes between FACs inside the DFs with 10-20 nA/m² and FACs in front of the DFs with 5-10 nA/m². The magnitude of the long FACs match with the values given by Sun’s study, while the mean value for short FACs is considerably higher.

The high total number of FACs compared to FACs associated to flow bursts as well as the occurrence rate of FACs in Figure 5.7 showing FACs all around the considered regions give rise that the current system is usual not continuous and even strong fluctuations may occur due to small scale phenomena. The difference in magnitude and duration of observed FACs between this project and studies using Cluster might lead to different statistical results. To my knowledge, no comparable statistical investigations of FACs have been made using MMS data.

The dependence between FACs and DFs is surprisingly small. A stronger dependence was expected as studies by (Sun et al., 2013) suggest a model, in which FACs flow in and out the DF, as illustrated in Figure 2.6. This shows that the magnitude of FACs is also dependent on many other physical conditions in space.

The deviating results in statistical investigations of flow bursts and FACs show some ambiguities and limitations to consider. First, the spacecrafts were orbiting Earth inside the considered region only between May and September 2017, whereas during 2016 they orbited closer to Earth (x > −12 R_E). Therefore, the amount of observable events is limited and statistical investigations are fragmentary. Moreover, most measurement devices were only activated during certain times to prevent deterioration. Therefore, no particle data could be used. In combination, the amount of data which are useful for this project is highly limited compared to the abovementioned studies. Alternatively, a distribution of occurrence separated in 2 × 2R_E² bins would be more conform under these circumstances.

The given example in Figure 5.3 is conform with the given models of the plasma "bubble" in section 2.4. The increase of the B_z component just ahead of the flow burst correlates with the dipolarization front at the leading edge of the plasma "bubble". The steady increase and
decrease of $\nu_{\perp x y}$ correlate with the plasma flow inside the bubble, illustrated by red arrows in section 2.4. The decreasing occurrence of selected high speed flows close to earth shown in Figure 5.6 propose that the earthward propagating flow burst subsequently arrive at the more dipolar geomagnetic field ($x \sim -12 R_E$) and rapidly decreases its earthward velocity and do not fulfill the selection method.

The given example in Figure 5.3 and the average number of occurring FACs per flow burst (Figure 5.8) are comparable to the model of FACs flowing out and in the dipolarization front at the leading edge of the flow burst (section 2.5). The first FAC of an occurring pair is accompanied by a small $B_z$ dip, indicating its position at the leading edge of the dipolarization front followed by the study of Sun et al. (2013). The second FAC follows with a strong $B_z$ increase, indicating its position inside the dipolarization front. The order of positive and negative FAC is assumed to depend on the position relative to the dipolarization front of the flow burst.

6.1 Improvements and Suggestions for Further Studies

Improvements for the statistical study are practicable by including data of spacecraft missions (4 spacecraft orbiting in a tetrahedral shape) with bigger amount of data from the magnetotail, e.g. Cluster.

Especially continuously provided particle data give the opportunity to determine the bulk velocity more precisely and exclude velocity estimation errors from the $E \times B$-drift. This also enables a more precise determination of the plasma sheet region given by ion temperature and particle densities. MMS data does not continuously provide particle data, but if particle data are provided, they are even precise enough to estimate the current density without using the curlometer technique.

In order to reduce the observed dusk-dawn asymmetry, Geocentric Solar Wind (GSW) coordinates are a physical more useful alternative to GSE. GSW coordinates consider the deviation of the solar wind from the earth-sun line shifting the neutral sheet from the midnight plane. The X-line points out the location of the neutral sheet instead of the midnight plane. The implication of this coordinate system has high processing demands and solar wind data are required.

For further studies the precise relative location of FACs at the DFs and their direction are of interest, similar to the study of Sun et al. (2013). Simultaneous mapping of FACs in the ionosphere around the northern and southern pole may enable to associate these to the FACs emerging from the DFs at the leading edge of the flow burst. This would undermine the theoretically assumed coherence between earthward propagating flow bursts caused by magnetic reconnection and excitation of particles in the ionosphere appearing as Auroras (MI-Coupling). In addition, further investigations of FACs occurring inside and just after flow bursts are of interest to reveal their source of existence.
Summary and Conclusion

In this project, earthward flow bursts and field-aligned currents inside the plasma sheet of the geomagnetic tail have been studied. In total, two years (2016, 2017) of magnetic and electric field obtained by MMS have been used to study field-aligned currents (FACs) and flow bursts. Further, the average appearance of FACs, the chronological order between FACs and flow bursts, and the dependence of the FAC magnitude to the DF and flow burst velocity have been investigated. We compare some of our results to other studies using the Cluster, ARTEMIS, ISEE2 and IRM missions. Summarized, the findings are:

1. An event example show a pair of oppositely FACs in front of the flow burst and another pair inside. One single FAC occurs at the end of the flow burst event. Regarding the occurring pair of FACs, the first FAC is accompanied by a dip in $B_z$ and the second with a strong rise in $B_z$.

2. Observed FACs were separated into long FACs lasting on average 6 sec with magnitude of 5-20 nA/m$^2$ and short FACs lasting on average 0.6 sec with a magnitude of 10-50 nA/m$^2$. The values for long FACs agree with the FACs observed by the study of Sun et al. (2013) and Snekvik et al. (2007) using Cluster data from 2003 and 2007, whereas short FACs show significant different properties. The significant higher precision of MMS data and close distance between the spacecraft compared to previous missions (Cluster, ARTEMIS, ISEE2, IRM) gives the possibility to observe more small-scale phenomena.


4. FACs occurred rather uniformly in x direction. Long FACs have a slight dawnward asymmetry, whereas short FACs have a slight duskward asymmetry similar to the asymmetry found in the occurrence rate of flow bursts. A high amount of FACs is associated to flow burst events.

5. Long FACs occurred 0 to 4 times per flow burst, on average 1 time. Short FACs also occurred 0 to 4 times and on average 1 time. Therefore, 2 FACs occurred per flow burst on average.

6. FACs most often occurred inside a flow burst event. They occurred slightly less frequent before a flow burst was observed and occurred in 1 of 6 times after the flow burst event. FACs occurring in front of the flow burst are also found in studies by Sun et al. (2013) and Snekvik et al. (2007). The relative high amount of FACs inside and after the flow burst event suggest a correlation between them.

7. The magnitude of FACs appeared to have only a small dependence on the DF strength and a even weaker dependence to the velocity of the flow bursts.
Bibliography


