Dissipation at the Earth's Quasi-Parallel Bow Shock

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Abstract

The Earth's bow shock is a boundary where the solar wind becomes decelerated from supersonic to subsonic speed before being deflected around the Earth. This thesis presents measurements by the Cluster spacecraft upstream and at the Earth's quasi-parallel bow shock where the angle between the upstream magnetic field and the bow shock normal is less than 45 degrees. An intrinsic feature of quasi-parallel shocks is the ability of ions, that are reflected off the shock in a specular manner, to propagate far upstream and to interact with the incident solar wind. This leads to the generation of a variety of plasma waves, e.g., Ultra-Low Frequency (ULF) waves, which in their turn interact with the different ion populations. Some of the ULF waves are thought to steep into so-called Short Large-Amplitude Magnetic Structures (SLAMS).

This thesis studies the impact of SLAMS on the incident solar wind. SLAMS are thought to play an important role in terms of 1) returning shock-reflected ions back to the shock where they can eventually contribute to downstream thermalisation and 2) local pre-dissipation of the solar wind.

The first electric field measurements of SLAMS showed a strong electric field rotation over SLAMS in association with the rotation of the magnetic field. This often leads to a local change from quasi-parallel to quasi-perpendicular conditions. In addition, short-scale electric field features were observed, e.g., spiky electric field structures associated with the leading edge of SLAMS and solitary electric field structures on Debye length scales, which are suggested to represent ion phase space holes.

Using the ability of the four Cluster satellites to obtain propagation vectors of SLAMS and the high-resolution electric field measurements, the electric potential over SLAMS was studied. These structures are associated with a significant potential on the order of a few hundred to thousand Volt. Comparing these findings with data from the ion spectrometer, it was found that the bulk flow is locally significantly decelerated and moderately deflected and heated. In addition, SLAMS reflect incident ions on both the leading and trailing edge. The flux of so-called gyrating ions show a clear maximum in association with SLAMS. This indicates that SLAMS indeed play an important role for pre-dissipation of the solar wind upstream of the shock.

Keywords: collisionless shocks, wave-particle interactions, nonlinear phenomena, cross-shock potential, Cluster spacecraft

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List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Multi-point electric field measurements of Short Large-Amplitude Magnetic Structures (SLAMS) at the Earth’s quasi-parallel bow shock,
R. Behlke, M. André, S. C. Buchert, A. Vaivads, A. I. Eriksson, E. A. Lucek, and A. Balogh,

II Solitary structures associated with Short Large-Amplitude Magnetic Structures (SLAMS) upstream of the Earth’s quasi-parallel bow shock,
R. Behlke, M. André, S. D. Bale, J. S. Pickett, C. A. Cattell, E. A. Lucek, and A. Balogh,

III The electric potential at the Earth’s quasi-parallel bow shock: Initial Cluster results.
R. Behlke, H. Kucharek, S. D. Bale, M. André, and E. A. Lucek,

IV Cluster observations of the electric potential at the Earth’s quasi-parallel bow shock.
R. Behlke, H. Kucharek, S. D. Bale, M. André, and E. A. Lucek,

V Dissipation properties of SLAMS upstream of the Earth’s quasi-parallel bow shock.
R. Behlke, H. Kucharek, M. André, and E. A. Lucek,

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List of papers not included in the thesis

1. Multi-spacecraft observations of broadband waves near the lower hybrid frequency at the Earthward edge of the magnetopause.

2. Coordinated ground-based, low altitude satellite and Cluster observations on global and local scales during a transient post-noon sector excursion of the magnetospheric cusp.

3. Coordinated Cluster, ground-based instrumentation and low-altitude satellite observations of transient poleward-moving events in the ionosphere and in the tail lobe.
4. Coordinated Cluster and ground-based instrument observations of transient changes in the magnetopause boundary layer during an interval of predominantly northward IMF: relation to reconnection pulses and FTE signatures,
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1. Introduction

The Earth’s magnetic field is embedded in a particle flow from the Sun, the solar wind. The interaction between the geomagnetic field and the magnetised solar wind leads to the creation of the magnetosphere, a finite region of space in which the geomagnetic field is confined and which is shielded from direct access of the solar wind (in a simplified picture).

The magnetopause is the discontinuity separating the magnetosphere from the solar wind, thus forming a cavity in the solar wind. In front of the magnetopause, a standing shock wave, the bow shock develops over which the supersonic solar wind flow is decelerated to subsonic speeds, see Section 2.1. In the anti-sunward direction, the otherwise dipole-like geomagnetic field is stretched into a comet-like tail by the solar wind, forming the magnetotail. Figure 1.1 shows a sketch of the configuration of the magnetosphere and the main boundary layers.

Particles and energy enter the magnetosphere from different sources, e.g.,
- Penetration of the solar wind into the magnetosphere due to magnetic reconnection at the dayside,
- Escape of ionospheric plasma, originating in the neutral atmosphere, into the magnetosphere,
- Penetration of cosmic rays and solar electromagnetic radiation down to ground level.

The bow shock is the first boundary layer which the solar winds encounters in front of the Earth. This thesis deals with detailed observations of the Earth’s bow shock by the four Cluster satellites. Also, other planets with magnetospheres are known to have similar boundaries. Shocks are also believed to play an important role for the acceleration of solar flare energetic particles, which then propagate outwards to fill the heliosphere (analogically, this is the region filled by the expanding solar wind). Interstellar shocks are believed to create cosmic rays, which can be observed within the heliosphere.

Observations of fields and particles near interplanetary shocks and the Earth’s bow shock allow us to study the important processes in-situ. Particle acceleration at collisionless shocks can be best observed at planetary bow shocks and travelling interplanetary shocks. The Earth’s bow shock is the most studied example of a collisionless shock and has been the subject of extensive observational and theoretical investigations [47, 53, 54]. This gives
Figure 1.1: Overview of the Earth’s magnetosphere. Adapted from [4].

us first-hand knowledge of processes within shocks. This knowledge can be used to understand shocks far beyond our heliosphere.

This thesis concentrates on one part of the Earth’s bow shock, the so-called quasi-parallel bow shock, see Section 2.3. It is one region associated with the Earth’s magnetosphere that is not well-investigated, but needs to be studied in order to understand the overall Sun-Earth interaction and to improve our understanding of general shock physics.
2. The physics of collisionless shocks

2.1 Why is there a shock in front of the Earth?

If we consider the general problem of a flow past an obstacle, a variety of possible scenarios emerge. For a sub-sonic flow, sound waves or pressure waves travel upstream against the flow and “inform” the upstream regions about the obstacle. Thus the flow responds to this information and is deflected around the obstacle.

In the case of a super-sonic flow, signals “informing” about the obstacle get swept downstream faster than they propagate. The upstream flow cannot react to the presence of the obstacle. If the obstacle is absorbing, the flow simply impinges on the object and is absorbed by it. If the obstacle cannot absorb the flow, a shock is created which is located in the upstream flow. The shock then leads to a super-sonic to sub-sonic transition of the flow. This sub-sonic flow is then deflected around the obstacle.

A typical distance from the Earth to the subsolar point of the bow shock is \( \sim 14 R_E \) (\( R_E = \text{Earth radii} \)). However, the location of the bow shock is strongly dependent on the solar wind speed and density.

In this chapter, an overview of general characteristics of collisionless shocks, the characteristics of the Earth’s bow shock in general and its quasi-parallel part in particular are given. See [47, 53, 54] for a review on quasi-parallel shocks.

2.2 The Rankine-Hugoniot equations for shocks

The plasma properties in the downstream and upstream region of a shock can be described by parameters such as bulk flow \( \mathbf{v} \), magnetic field \( \mathbf{B} \), plasma density \( \rho \) and pressure \( p \). Let \( \mathbf{n} \) be the unit vector along the shock normal and \( \mu_0 \) the permeability in free space. The relation between parameters on the two sides of the shock is then given by basic conservation laws, known as the Rankine-Hugoniot relations. For a magnetohydrodynamic (MHD) shock, they read under stationary conditions (the abbreviation \([X] = X_u - X_d\) gives the difference of a quantity \( X \) between the upstream and downstream region):
- conservation of mass

\[ [\rho \mathbf{v} \cdot \mathbf{n}] = 0, \quad (2.1) \]

- conservation of momentum

\[ \left[ \rho \mathbf{v} (\mathbf{v} \cdot \mathbf{n}) + \left( p + \frac{\mathbf{B}^2}{2\mu_0} \right) \mathbf{n} - \frac{(\mathbf{B} \cdot \mathbf{n})\mathbf{B}}{\mu_0} \right] = 0, \quad (2.2) \]

- conservation of energy

\[ \left[ (\mathbf{v} \cdot \mathbf{n}) \left( \frac{\rho \mathbf{v}^2}{2} + \frac{\gamma - 1}{\gamma} p + \frac{\mathbf{B}^2}{\mu_0} \right) \frac{(\mathbf{B} \cdot \mathbf{n})(\mathbf{B} \cdot \mathbf{v})}{\mu_0} \right] = 0, \quad (2.3) \]

where \( \gamma \) is the specific heat ratio,

- Maxwell’s equations

\[ [\mathbf{B} \cdot \mathbf{n}] = 0, \quad (2.4) \]

which states that the normal component of the magnetic field is continuous \((B_n = \text{const.})\),

\[ [\mathbf{n} \times \mathbf{E}] = 0, \quad (2.5) \]

which states that the tangential component of the electric field is continuous \((E_t = \text{const.})\).

Hence, the Rankine-Hugoniot relations resemble a set of five equations for the five unknown quantities \( \rho, \mathbf{v}, p, B_n \) and \( E_t \). Note that all quantities for Equations (2.1)-(2.5) are considered in the shock rest frame. It is worth noting that the Rankine-Hugoniot relations are obtained independent of the structure within the shock itself [51].

### 2.3 Shock geometries, shock modes and Mach numbers

The physics of collisionless shocks is strongly dependent on the angle \( \theta_{B_n} \) between the (upstream) magnetic field and the shock normal. The following classification according to \( \theta_{B_n} \) is generally used:

- **perpendicular** shocks: \( \theta_{B_n} = 90^\circ \),
- **parallel** shocks: \( \theta_{B_n} = 0^\circ \),
- **oblique** shocks: \( 0^\circ < \theta_{B_n} < 90^\circ \), which can be subdivided into
  - **quasi-parallel** shocks: \( 0^\circ < \theta_{B_n} < 45^\circ \),
  - **quasi-perpendicular** shocks: \( 45^\circ < \theta_{B_n} < 90^\circ \).

Generally, the normal vector is defined so that it points into the unshocked medium. In a shock rest frame, this normal points **upstream**. The **downstream**
Another classification can be made in terms of different modes of MHD waves, which can steepen into shocks: fast, slow and intermediate waves. Intermediate shocks exist only in anisotropic media. The phase speed of the fast and slow mode $v_{ph}$ is defined by

$$2v_{ph}^2 = (c_s^2 + v_A^2) \pm \sqrt{(c_s^2 + v_A^2)^2 - 4c_s^2v_A^2\cos^2\theta}, \quad (2.6)$$

where $c_s$ is the sound speed, $v_A$ the Alfvén speed and the $\,'+$' sign refers to the fast and the $\,'-$' sign to the slow mode. The Alfvén speed is defined as

$$v_A = \frac{B}{\sqrt{\mu_0\rho}}. \quad (2.7)$$

Note that the changes in the magnetic field and, e.g., the plasma density are different in fast and slow shocks: Whereas the magnetic field increases in a fast shock, it decreases over a slow shock. Furthermore, the plasma density correlates with the magnetic field amplitude in fast shock, whereas it does not in slow shocks. The Earth’s bow shock is a fast-mode shock.

An additional quantity which characterises a shock is the Mach number. There are several Mach numbers of interest due to different shock modes etc. One can define the fast and slow Mach numbers $M_f$ and $M_s$, respectively, as the ratios of the normally incident flow speed to the fast and slow MHD wave speeds in the upstream medium. These wave speeds are complicated, since they contain the propagation direction, see Equation (2.6). Thus, an additional Mach number, the Alfvén Mach number $M_A$ is defined in order to characterise
a shock. Note that $M_A$ does not depend on the propagation direction

$$M_A = \frac{v_n}{v_A},$$

(2.8)

where $v_n$ is the normal component of the speed of the incoming flow and $v_A$ is the Alfvén speed. Additionally, a critical Mach number $M_c$ is defined, above which simple resistivity cannot provide the total dissipation over the shock, see Section 2.6. At the Earth’s bow shock, one usually finds $1 < M_c < 2$. Having a Mach number larger than $M_c$ characterises shocks as supercritical, like the Earth’s bow shock.

Furthermore, the upstream plasma $\beta$ can be introduced as a further quantity to characterise a shock

$$\beta_u = \frac{p}{B^2/2\mu_0},$$

(2.9)

where $p$ is the plasma pressure. In the MHD regime, the parameters $\beta_u$, $M_A$ and $\theta_{Bn}$ completely specify the shock problem.

### 2.4 Quasi-perpendicular and quasi-parallel shocks in satellite data

The angle $\theta_{Bn}$ highly influences the behaviour of particles at the shock and thus the way in which heating of the plasma and dissipation of energy over the shock occurs. Figure 1.1 shows the location of the quasi-perpendicular and quasi-parallel regimes of the Earth’s bow shock for average solar wind conditions, i.e., the angle between the interplanetary magnetic field and radially outflowing solar wind is $\sim 45^\circ$ at the Earth. Figure 2.2 displays two typical crossings of the Earth’s bow shock under quasi-perpendicular and quasi-parallel conditions, respectively. For quasi-perpendicular crossings, see the upper panel of Figure 2.2, the transition tends to be abrupt in time and spatially well-defined. Quasi-parallel crossings, see the lower panel of Figure 2.2, extend over large distances where unshocked and shocked solar wind plasmas form complex and transient structures. It is obvious that the scales of shock transition and dissipation regions are significantly different for these two different regimes.

Note that Figure 1.1 resembles a gross oversimplification of the conditions that are actually observed upstream of the Earth’s bow shock. The direction and magnitude of the interplanetary magnetic field are highly variable on spatial scales comparable to the dimensions of the bow shock. Thus, quasi-perpendicular and quasi-parallel conditions may occur at any point on the surface of the Earth’s bow shock.
Figure 2.2: Cluster measurements of the magnetic field strength during crossings of the Earth’s quasi-perpendicular (upper panel, March 31, 2001) and quasi-parallel (lower panel, February 2, 2001) bow shock. Note the different time periods for each subplot: 1.45 minutes for the upper panel and 26 minutes for the lower panel.

2.5 Characteristic ion populations upstream and at the Earth’s bow shock

The incident solar wind distribution has an energy of $\sim 1$ keV. In addition, both quasi-perpendicular and quasi-parallel regions are characterised by a few distinct ion distributions. Upstream of the quasi-perpendicular shock, a very collimated ion beam propagating upstream along the magnetic field is found. This population exhibits a sharply peaked energy spectrum with energies of up to a few tens of keV. Within one gyroradius of the shock front, reflected gyrating ions are observed. In contrast, the upstream region of the quasi-parallel shock is characterised by diffusive (almost isotropic) ion distributions with a relatively flat energy spectrum extending up to a few hundred keV. Regions with moderate shock normal angles ($\theta_{Bn} \sim 45^\circ$) often exhibit so-called intermediate distributions with properties intermediate to the field-aligned beam and diffusive distributions. Figure 2.3 displays typical examples of the three upstream distributions. See also [38] for further information on these distributions.

In the past the reflected gyrating distribution has been distinguished from the field-aligned beam distribution. Recent Cluster results, however, show that
Figure 2.3: Examples of the three characteristic ion populations upstream of the Earth’s bow shock. On the left, two-dimensional plots of the counting rate in velocity space are plotted (integrated over ±55° of elevation about the ecliptic plane). The peak represents the solar wind distribution. On the right, two-dimensional contour plots of constant phase space density for the same events are shown. Adapted from [38].

the beam distribution is closely related to the gyrating distribution, which is formed by specularly reflected ions [36]. It was shown that the beam distribution that escapes from the shock along the magnetic field lines emerges from the low-pitch-angle wing of the specularly reflected ion distribution in the shock ramp.

Specular reflection means that the normal component of the ions’ velocity is reversed at the shock and is often explained as reflection by the shock potential [20].
2.6 Dissipation in collisionless shocks

![Figure 2.4: Examples of trajectories for reflected particles under quasi-perpendicular and quasi-parallel conditions. For quasi-parallel regimes, the guiding centre motions point upstream, for quasi-perpendicular shocks they point downstream. Adapted from [8].](image)

In all shock formations there is, by definition, irreversible dissipation that transforms the ram energy of the plasma flow into thermal energy. The understanding and modelling of this dissipation can be considered a major problem in shock physics. For an ordinary hydromagnetic shock, the viscosity $\mu$ is responsible for dissipation. Hence, the characteristic thickness scale is associated with the viscous, i.e., collisional, scale length. For obvious reasons, the Earth’s bow shock is a collisionless shock, since the mean free path of a particle in the solar wind is about $10^8$ km. Thus, if the Earth’s bow shock would be collisional, it would almost fill the region between the Earth and the Sun. In other words, Coulomb collisions are completely negligible which implies that the collisional viscosity is effectively zero.

For subcritical, quasi-perpendicular shocks, dissipation can occur because of effective, or anomalous, resistivity and viscosity due to waves (as opposed to collisions). The waves grow due to some instability, which is driven by departure from equilibrium of the particle distribution function.

As $M_f$ for the solar wind exceeds 5.6 about 95% of the time, the bow shock on the sunward side is mostly supercritical [17]. In supercritical, quasi-perpendicular shocks anomalous resistivity cannot provide the required dissipation. Specularly reflected ions have guiding centre motions pointing downstream [20], see also Figure 2.4. These ions are eventually transmitted downstream after being reflected. The fact that these reflected ions only propagate upstream of the shock up to distances of one gyroradius explains the spatially
well-defined transition for quasi-perpendicular shocks. It has long been recognised that the coarse dispersion in velocity space resulting from ion reflection at a supercritical shock represents a substantial amount of effective dispersion, e.g., [46]. The basic mechanism for collisionless shocks can thus be described as follows. The shock creates free energy (reflected ions) which excite instabilities. These instabilities can in their turn thermalise the ion distribution.

Under quasi-parallel geometries, specularly reflected particles have guiding centre motions pointing upstream and are free to escape into the upstream region [20], see also Figure 2.4. These particles can thus not directly contribute to downstream thermalisation. The necessary dissipation must thus be achieved by different means, i.e., different mechanisms must contribute to the dissipation and/or the upstream propagating, shock-reflected particles must be returned to the shock where they can be thermalised. The coupling between reflected, upstream propagating particles and the incident population is achieved via scattering in a self-consistently excited wave field. This large amplitude turbulence is ultimately convected back to the shock, which responds in a time-dependent, cyclic reformation process. Thus, the quasi-parallel shock is an intrinsically more complicated and spatially more extended transition.

2.7 Shock currents and the electrostatic cross-shock potential

The bow shock can be described as a current layer as indicated by the jump in the tangential magnetic field, i.e., \( |B_t| \neq 0 \). The current density \( j_{sh} \) then accounts for the change in the magnetic field and is given by

\[
\dot{j}_{sh} = \frac{|B_t|}{\mu_0 d_{sh}},
\]

where \( d_{sh} \) is the shock width. Since ions and electrons incident on a perpendicular shock have different gyroradii, ions penetrate deeper into the field than the electrons. This generates a charge separation electric field in the shock normal direction which reflects (a number of) ions and attracts electrons. It is given by

\[
\varepsilon_0 E_{sh} = e (n_{i,sh} - n_{e,sh}) d_{cs},
\]

where \( d_{cs} \) is the width of the charge separation layer and the densities are the values inside the shock. Using \( n_i = n_e - n_{ir} \) with \( n_{ir} \) the density of the reflected ions, the charge separation field can be rewritten such as

\[
E_{sh} = \frac{en_{e,sh}d_{cs}}{\varepsilon_0} \left( 1 - \frac{n_{ir}}{n_{e,sh}} \right).
\]
Low-energy ions are repelled by the cross-shock potential. In a perpendicular shock, these ions will be accelerated in the convection electric field of the solar wind to about twice the solar wind velocity and then transmitted downstream. See Figure 2.5 for a sketch of ion reflection and acceleration at a perpendicular shock.

2.8 The characteristics of different shock frames

As already mentioned in Section 2.2, several vectors play a role in the analysis of a shock transition, such as the bulk flow velocity $v$, the magnetic field $B$, the electric field $E$ and the shock normal $n$. In order to transform a velocity measured in an arbitrary frame, $v_{\text{arb}}$, e.g., the spacecraft frame of reference, to a shock rest frame, one needs to subtract the shock velocity in the arbitrary frame. Using the normal component of the shock velocity, $v_{\text{sh}}$, this gives

$$v_{\text{shockrest}} = v_{\text{arb}} - v_{\text{sh}} n.$$  \hspace{1cm} (2.13)

There is a wealth of shock rest frames with different velocities in the shock plane. Two useful frames in shock physics are the Normal Incidence Frame (NIF) and the deHoffmann-Teller Frame (HT) [37, Ch. 10.3.1]. In the Normal Incidence Frame, the upstream flow is aligned with the shock normal. Only this component of the flow enters into the shock Mach number. In the deHoffmann-Teller Frame (HT), see also [13], the upstream flow is directed along the upstream magnetic field. Thus, the $v_u \times B_u$ electric field vanishes.
Figure 2.6: The various field, flow and normal vectors in the Normal Incidence Frame (NIF) (left) and deHoffmann-Teller Frame (HT) (right). Adapted from [37].

Note that the flow and field are also aligned in the downstream region, since the tangential electric field is constant over any plane layer, see Section 2.2. Figure 2.6 gives an overview of the field, flow and normal vectors in these frames.

In order to transform a quantity from any shock frame into the NIF, the NIF velocity needs to be determined

\[ v_{\text{NIF}} = \hat{n} \times (v_u \times \hat{n}) . \]  

(2.14)

Here, \( v_u \) is already assumed to be in the shock rest frame. The upstream bulk velocity in the NIF then reads

\[ v_u^{\text{NIF}} = v_u - v_{\text{NIF}} . \]  

(2.15)

The NIF is used to determine the electrostatic potential over SLAMS (Short Large-Amplitude Magnetic Structures) which are thought to play an important role at the Earth’s quasi-parallel bow shock, see papers III and IV.

For transformations into the HT frame, the HT velocity must be calculated according to

\[ v_{\text{HT}} = \frac{\hat{n} \times (v_u \times B_u)}{B_u \cdot \hat{n}} \]  

(2.16)

so that the upstream bulk velocity in the HT frame is given by

\[ v_u^{\text{HT}} = v_u - v_{\text{HT}} . \]  

(2.17)

Note the shaded plane, the Coplanarity Plane, in Figure 2.6. It is defined by
the magnetic field and normal vectors and contains the flow, magnetic field and normal vectors on both sides. The so-called *Coplanarity Theorem* is a consequence of the jump conditions at the shock. It can be expressed as

\[ \mathbf{n} \cdot (\mathbf{B}_d \times \mathbf{B}_u) = 0. \] (2.18)

Considering only the transverse component, the equation of momentum conservation (Equation (2.2)) for an isotropic pressure \( p \) can be rewritten as

\[ \rho v_n v_t - \frac{B_n}{2\mu_0} \mathbf{B}_t = 0. \] (2.19)

Equation (2.5) can be rewritten as

\[ [v_n \mathbf{B}_t - B_n v_t] = 0. \] (2.20)

Thus, using Equation (2.4) one finds that \([\mathbf{B}_t]\) and \([v_n \mathbf{B}_t]\) are parallel to \( [v_t] \) and therefore also parallel to each other. This gives

\[ [\mathbf{B}_t] \times [v_n \mathbf{B}_t] = 0 \] (2.21)

which can be resolved and we obtain

\[ (v_{n,u} - v_{n,d})(\mathbf{B}_{t,u} \times \mathbf{B}_{t,d}) = 0. \] (2.22)

The upstream and downstream tangential magnetic components must be parallel to each other, since \([v_n]\) does not vanish. Hence, the upstream and downstream magnetic field vectors are coplanar with the shock normal vector and the magnetic field across the shock has a two-dimensional geometry. Note that the bulk velocity is coplanar with the shock, too.

### 2.9 Particle acceleration at shocks

This chapter gives an overview of the most common classes of shock acceleration. Detailed reviews can be found in, e.g., [47, 53].

Amongst others, the following mechanisms play a major role for the particle acceleration at collisionless shocks:

- **shock drift acceleration** (SDA) in the electric induction field in the shock front,
- **diffusive shock acceleration** (DSA) due to repeated reflections in the plasma converging at the shock front (1st order Fermi acceleration),
- **stochastic acceleration** in the turbulence behind the shock front (2nd order Fermi acceleration).

The effectiveness of these mechanisms depends on the properties of the
shock. Shock drift acceleration is significant at perpendicular shocks, since the electric induction field is maximal, but vanishes for parallel shocks. Diffusive shock acceleration is only efficient in the case of sufficient scattering both upstream and downstream of the shock and is thus effective at quasi-parallel shocks. Stochastic acceleration requires a strong enhancement in downstream turbulence. These processes may act together at a given point of the bow shock, and thus given shock parameters, but with different degrees of efficiency.

In the case of shock drift acceleration (SDA), particles are accelerated in the electric induction field in the shock front. Simply speaking, a charged particle drifts in the electric induction field, which in the shock rest frame is

\[ E = -v_u \times B_u = -v_d \times B_d. \]  

(2.23)

This field is along the shock front and perpendicular to both magnetic field and bulk flow. It maximises at perpendicular shocks and vanishes at parallel shocks. Additionally, the shock is a magnetic field discontinuity and thus a particle can drift along the shock front. The drift direction depends on the charge of the particle and is always such that the particle gains energy (for fast-mode shocks). It can be noted that the energy gain of the particle depends on how long the particle can interact with the shock front, which in its turn depends on the particle’s speed perpendicular to the shock. If it is small, the particle sticks to the shock. If it is large, the particle escapes before it has gained a large amount of energy. Shock drift acceleration at the Earth’s bow shock up to some tens of keV can be observed.

Diffusive shock acceleration (DSA) is dominant at quasi-parallel shocks, where shock drift acceleration is negligible due to the vanishing electric induction field. In DSA, the particle scattering both upstream and downstream of the shock is essential. For this type of acceleration, two mirrors continually approach each other head on, and so the particles bounce off these mirrors many times and gain energy at each reflection.

For stochastic acceleration, the energy gain of the particles is achieved by reflections off mirrors moving in random directions. This type of acceleration is less efficient than diffusive acceleration.

Concerning the Earth’s quasi-parallel bow shock, one has to consider a mixture of different acceleration mechanisms. This is due to the high variability of the magnetic field, especially for Short Large-Amplitude Magnetic Structures, which are thought to built up the quasi-parallel bow shock [29], see Section 2.10. Locally, the magnetic field is changed into a quasi-perpendicular regime, giving rise to different conditions for the acceleration mechanisms described above.
2.10 The Earth’s quasi-parallel bow shock

As already mentioned in Section 2.6, particles that are reflected at the Earth’s quasi-parallel bow shock may escape far upstream from the shock, since the guiding centre of reflected ions is directed upstream [21]. Interactions of the backstreaming ions with the incoming solar wind ions generate a variety of waves situated in the foreshock region [24, 25]. In contrast to quasi-perpendicular shocks, the transition at quasi-parallel shocks is more extended and unsteady [22, 50]. Observations, e.g., [26, 44, 50], combined with simulations, e.g., [7, 42, 49], led to the model of a shock, which is cyclically reforming and built up of a patchwork of magnetic field enhancements, so-called Short Large-Amplitude Magnetic Structures (SLAMS) [43], which are sketched in Figure 2.7.

SLAMS are characterised by their magnetic field enhancement of at least a factor 2 over the undisturbed field. They have durations of a few seconds or so in the spacecraft frame. SLAMS are thought to grow out of the ULF wave field in the foreshock [44]. They attempt to propagate sunwards, but are convected back by the supersonic solar wind. Statistical studies show a rotation of the magnetic field from a quasi-parallel to a quasi-perpendicular regime [29].
SLAMS-like features are also suggested to exist in the solar corona where they could be responsible for electron acceleration which could lead to commonly observed solar type II radio bursts [28].

Simulations revealed further interesting features of SLAMS-like structures. It was found that SLAMS-like features were growing out of the ULF wave field [15, 18]. Simulations have also shown that SLAMS evolve very rapidly, i.e., on subsecond or second scale, and that these structures might not be planar on the Cluster separation scale (100-10000 km) [19]. The ULF waves have observational scale sizes of $\sim 1 \, R_E$ [23].

![Figure 2.8: Different scale lengths at the quasi-parallel bow shock. Adapted from [27].](image)

The Earth’s quasi-parallel bow shock could thus be described as an extended transition region characterised by the growth, deceleration and merging of SLAMS rather than a single shock surface. The structures within the quasi-parallel shock transition are expected to be complex, e.g. [43, 45], with different sets of scale lengths in different directions, see Figure 2.7 and 2.8.

### 2.11 Solitary structures

Many regions in space exhibit narrow boundaries with large gradients in particle properties and/or fields. Such regions often contain currents as well as other sources of free energy such as ion and/or electron beams. Wave growth often results in very large amplitudes and nonlinear electric structures are often observed at these boundaries, e.g., [2, 10, 11]. Solitary waves, which represent one special type of nonlinear waves, have been studied extensively.
Figure 2.9: Ion distribution in velocity-configuration space and evolved ion holes. Adapted from [52].

Such structures were first observed in the auroral zone and interpreted as ion phase space holes [5, 48], i.e., they form vortices or holes in the ion phase space. Thus, they represent negatively charged potential structures.

In order to understand the physics of these solitary structures, one needs to determine their speed. One possible method is described in [14] and is sketched in Figure 2.10. During events for which the background magnetic field lies approximately in the spin plane and is almost aligned with one probe pair, one can determine the velocity of the solitary structure as follows. A centre voltage $V_C$ is determined by taking the average of the two probes mostly perpendicular to $B$. The use of the difference between probe potentials rather than the probe-to-spacecraft potential excludes problems due to different responses to plasma changes. Then the potential differences, $V_+$ and $V_-$ between the probe in the $+B$ direction and $V_C$ and between $V_C$ and the probe in the $-B$ direction can be defined, respectively. The time lag between $V_+$ and $V_-$ yields the propagation speed of the structure $v_{IH}$. The parallel electric field can then be obtained from $E_\parallel = -V_\pm L_B$, where $L_B$ is the effective boom length and assuming that $E_\parallel$ is constant on the scale of the probe-to-probe separation. The parallel electric field can be integrated in order to obtain the potential over the structure

$$\Phi_\parallel = -v_{IH} \sum_{t'=0}^t E_\parallel \Delta t',$$  

where $v_{IH}$ is the velocity of the ion hole and $\Delta t'$ is the time between samples.
Figure 2.10: Probe configuration for determining the speed of solitary structures. Adapted from [14].
3. Instrumentation: The Cluster satellites

Figure 3.1: Artist’s view of the Cluster spacecraft. Adapted from [32].

The data for this thesis were obtained by the Cluster spacecraft [16], see also Figure 3.1. The Cluster project is a unique ESA cornerstone mission performing the first ever truly three-dimensional study of processes in the magnetosphere. This mission includes four identical spacecraft in nearby, non-coplanar orbits. The satellites were launched in two pairs during the summer of year 2000. These spacecraft are now in polar orbits with perigees and apogees of
about 19,000 and 119,000 km, respectively, see Figure 3.2. Typical distances between the satellites vary from a hundred to several thousand km. This exciting mission is for the first time providing measurements of local magnetospheric structures in three dimensions and is improving the possibilities to separate temporal and spatial variations of the plasma and field parameters. Each identical cylindrical satellite has a diameter of 2.9 m and a height of 1.3 m and carries an identical set of 11 instruments. The spacecraft are spin-stabilised at 15 rpm with the spin axis pointing towards the south ecliptic pole.

After a commissioning period, the scientific part of the Cluster mission officially started February 1, 2001. The mission was initially planned to last two years, with coverage of 50% of the orbit. Data are now obtained during 100% of each orbit (starting June 2002), and the mission has been extended until the end of 2009.

The importance of the Cluster mission for, in this case, shock physics can be explained as follows. Single and dual spacecraft missions have clarified many properties of the Earth’s bow shock under most conditions and described many details of its phenomenology. Many of the shock parameters are however vector quantities. Analysing single or dual spacecraft mission data thus involves certain assumptions to derive these quantities. Cluster’s four-spacecraft measurements can reexamine and clarify these assumptions by making unambiguous determinations of the quantities in question.

Cluster observations at the Earth’s bow shock in particular are reviewed in [1] for the quasi-perpendicular regime and in [9] for the quasi-parallel domain.
3.1 The Electric Field and Wave (EFW) instrument

The Swedish Institute of Space Physics, Uppsala division (IRF-U), bears the PI responsibility for one of the eleven scientific instruments on board each of the four spacecraft: the Electric Field and Wave experiment (EFW) designed to measure the electric field and density fluctuations with high temporal resolution. The EFW instrument on each satellite includes two pairs of probes on wire booms in the spin plane, each with a probe-to-probe separation of 88 m. EFW is designed and manufactured by a consortium of laboratories managed by IRF-U. The EFW instrument has several important capabilities. These include:

- Measurements of quasi-static electric fields of amplitudes up to 700 mV/m with high amplitude and time resolution,
- Measurements over short periods of time at sampling frequencies up to 36 000 samples per second, for example sampling four probe signals at 9 000 samples per second,
- Measurements of plasma density at high time resolution using the probe-to-spacecraft potential.

Typically EFW is measuring electric fields at 25 or 450 samples per second, but sampling rates up to 36 000 samples per second can be used during short time periods (about 10 seconds). The 25 samples per second mode is used in Cluster normal mode, while the 450 samples per second option is used in
Cluster burst mode, targeting magnetospheric boundaries and other interesting regions for a few hours every week. Higher sampling rates can be stored in an internal EFW memory (internal burst mode). In addition, the probe-to-spacecraft potential (an estimate of the plasma density) is routinely obtained at 5 samples per second, and is used, e.g., to identify density gradients. It can also be sampled at a higher rate during internal burst mode. Figure 3.4 shows how the probe-to-spacecraft potential translates into density. This figure has been obtained by comparing EFW observations with the density estimated from the plasma frequency as observed with the active WHISPER instrument on Cluster [39].

Data from the EFW instruments were used in four of five publications included in this thesis. Paper I used the probe-to-spacecraft-potential as an estimate for the plasma density in order to establish the fast-mode character of SLAMS, i.e., the plasma density correlates with the magnetic field magnitude. In addition, timing analysis was performed using probe-to-spacecraft-potential data between the four spacecraft in order to obtain propagation speeds and directions for SLAMS. Furthermore, electric field data in normal mode (25 samples per second) revealed the behaviour of
the large-scale electric field over SLAMS as well as small-scale electric field spikes in the leading edge of SLAMS. Paper II utilised internal burst mode resolution of 9,000 samples per second for the study of solitary structures within SLAMS. Timing analysis between the four probes of a single spacecraft returned the propagation speed and direction of these structures. This was used to calculate the potential over the solitary structures. Papers III and IV again used the probe-to-spacecraft potential as an estimate for the plasma density and for timing analysis to obtain the speed and normal vector of SLAMS. The electric field in normal mode resolution was transformed into the Normal Incidence Frame (NIF) and the electric cross-SLAMS potential was calculated.

### 3.2 The Cluster Magnetic Field Investigation (FGM)

![Figure 3.5: The Cluster FM6 Spacecraft being prepared for testing at the IABG Space Environment Test Facility in Ottobrun, near Munich. The two FGM sensors can be seen on the boom (shown stowed) at the front. The Outboard sensor is mounted at the end of this boom (left side), with the Inboard sensor also visible. Adapted from [34].](image)

The primary objective of the Cluster Magnetic Field Investigations (FGM) is to provide accurate measurements of the magnetic field vector at the location of the four Cluster spacecraft [3]. The FGM instrument on each spacecraft consists of two tri-axial fluxgate magnetic field sensors on one of the two radial booms of the spacecraft and an electronics unit on the main equipment.
platform, see also Figure 3.5. In order to minimise the magnetic background of the spacecraft, one of the magnetometer sensors (the outboard, or OB sensor) is located at the end of one of the two 5.1 m radial booms of the spacecraft, the other (the inboard, or IB sensor) at 1.5 m inboard from the end of the boom. In flight, either sensor can be designated as the Primary Sensor, for acquiring the main data stream of magnetic-field vectors. The magnetometers can measure the three components of the magnetic field in different ranges with a sampling rate of up to 67 Hz.

Data from the FGM instruments were used in all publications included in this thesis. Generally, magnetic field data enabled and/or confirmed the identification of SLAMS and confirmed propagation speeds and directions for SLAMS, obtained by the EFW instrument, by timing of the magnetic field signature or Minimum Variance Analysis [37, Ch. 8]. In Paper I, the magnetic field was used for calculating the motional electric field within the SLAMS \( \mathbf{E} = -\mathbf{v}_{\text{SLAMS}} \times \mathbf{B} \). In Paper II, the propagation speeds of the solitary structures were estimated and the parallel electric field was calculated by using the magnetic field. In Papers III and IV, magnetic field data were again used for obtaining SLAMS propagation velocities and vectors and for the calculation of the electric cross-SLAMS potential. In addition, FGM data were included in the analysis of data from the ion spectrometry (CIS) instrument. See Section 3.3 for a description of this instrument.

3.3 The Cluster Ion Spectrometry (CIS) instrument

The CIS (Cluster Ion Spectrometry) experiment is a comprehensive ion plasma spectrometry package onboard the four Cluster spacecraft, capable of obtaining full three-dimensional ion distributions with good time resolution (one spacecraft spin) and with mass-per-charge composition determination [40]. The CIS package consists of two different instruments, a Hot Ion Analyser (HIA) and a time-of-flight ion Composition Distribution Function (CODIF), see Figure 3.6. A sophisticated dual-processor based instrument control and data processing system (DPS) permits extensive onboard data-processing.

The major magnetospheric ions (\( \text{H}^+, \text{He}^+, \text{He}^{++}, \text{and O}^+ \)) are observed from thermal energies up to 40 keV/e. The CODIF instrument returns the mass per charge composition with medium (22.5°) resolution. The HIA instrument has a better angular resolution (5.6°) but without mass resolution. Each analyser has two different sensitivities in order to increase the dynamic range.

CIS data were used for Papers IV and V. The bulk flow speed of the solar wind obtained from CIS measurements showed a decrease over SLAMS.
This decrease was compared with the magnetic field magnitude and calculated cross-SLAMS potential. In addition, three-dimensional measurements of ion velocity space distributions were used to evaluate ion dynamics at SLAMS.
4. Summary of publications

Paper I

**Multi-point electric field measurements of Short Large-Amplitude Magnetic Structures (SLAMS) at the Earth’s quasi-parallel bow shock.**

R. Behlke, M. André, S. C. Buchert, A. Vaivads, A. I. Eriksson, E. A. Lucek, and A. Balogh,


This paper presents the first electric field observations of SLAMS and the first high-resolution plasma density measurements of SLAMS. The good correlation between magnetic field and plasma density confirms the fast-mode structure of SLAMS. A sharp rotation of the electric field is observed in association with a sharp rotation of the magnetic field changing the magnetic field configuration from quasi-parallel to quasi-perpendicular. Utilising the four spacecraft, the propagation speed and direction of these structures is obtained and it is found that the structures move against the solar wind but are swept towards the shock by the faster solar wind flow. At the leading edge of some SLAMS a small-scale electric field on the scale of the electron gyroradius is found, which confirms simulation studies. The observations reveal astonishingly high variability on the scale of the spacecraft separation (600 km). Earlier observations suggested scale lengths of the order of $\sim 1 \, R_E$. Downstream of several SLAMS, a wake-like decrease in the plasma density is observed suggesting a clear three-dimensional structure of the SLAMS.

Paper II

**Solitary structures associated with Short Large-Amplitude Magnetic Structures (SLAMS) upstream of the Earth’s quasi-parallel bow shock.**

R. Behlke, M. André, S. D. Bale, J. S. Pickett, C. A. Cattell, E. A. Lucek, and A. Balogh,


Using the high-resolution capability of the EFW instrument with a resolution of 9 000 samples per second, solitary structures are observed within SLAMS. These solitary waves are characterised by their bipolar
electric field signature. Utilising the four probes on a single spacecraft, the propagation speed and direction of these structures could be determined and it was found that they propagate along the magnetic field lines with velocities of 400-1200 km/s. This yields parallel scale sizes of these solitary waves of the order of $L_\parallel \sim 10 \lambda_D$. In addition, these structures do not exhibit any net potential drop, but have negative potentials of $|\Phi_\parallel| = 0.4 - 2.2$ V, i.e., $e\Phi_\parallel/kT_e \sim 0.1$.

Interestingly, these structures are not in agreement with common theories. Firstly, their negative potentials would imply their interpretation as ion phase space holes. However, they move at speeds above the ion thermal speed or the solar wind speed. In addition, ion solitary structures in weakly magnetised plasmas ($f_{ce}/f_{pe} \ll 1$) have not been reported on in observations or simulations and represent a challenge for new theoretical considerations.

Paper III

The electric potential at the Earth’s quasi-parallel bow shock: Initial Cluster results,
R. Behlke, H. Kucharek, S. D. Bale, M. André, and E. A. Lucek,

This paper summarises an invited talk given at the 4th IGPP Annual International Astrophysics Conference on "The Physics of Collisionless shocks" held in Palm Springs, USA, February 26 - March 3, 2005. Observations with the Cluster spacecraft show that SLAMS are associated with a significant electric potential across them. These initial findings are elaborated in Paper IV.

Paper IV

Cluster observations of the electric potential at the Earth’s quasi-parallel bow shock,
R. Behlke, H. Kucharek, S. D. Bale, M. André, and E. A. Lucek,

The four Cluster spacecraft are used to obtain propagation speeds and directions for SLAMS. Then, the electric field measured in the spacecraft frame is transformed to a frame which is at rest relative to the SLAMS. In the Normal Incidence Frame (NIF) in which the incoming solar wind flow is aligned with the SLAMS’ normal vector, the normal electric field is integrated and thus yields the cross-SLAMS potential in this frame. It is found that SLAMS are associated with an electric potential of a few hundred to up to 2000 V. The potential across SLAMS increases as these structures approach the shock.
and increase in magnetic field magnitude. However, large deviations for the calculated potential for a single SLAMS between different spacecraft occur for a few events. Other structures reveal very similar potentials for a single SLAMS between different satellites. This indicates large spatial and temporal variations of the observed SLAMS. The solar wind bulk flow is decelerated over SLAMS. Larger potentials seem to be associated with a large decrease of the bulk flow, but further investigations are needed to establish this finding. In addition, it is found that the solar wind is broadened and heated over SLAMS, which indicates pre-dissipation of the solar wind flow upstream of the shock.

Paper V

**Dissipation properties of SLAMS upstream of the Earth’s quasi-parallel bow shock.**

R. Behlke, H. Kucharek, M. André, and E. A. Lucek,

In this paper, the ability of the CIS instrument to deliver three-dimensional ion distributions is used. The aim of this paper is to study the differential flux of ions reflected off SLAMS. This ion reflection would present 1) a way of pre-dissipation of the solar wind energy in the upstream region of the shock and 2) might return shock-reflected, upstream propagating particles back to shock where they in their turn can contribute to dissipation at the shock. We find that SLAMS are associated with a clear peak in the differential flux for gyrating ions in different energy channels. Well upstream and downstream of the SLAMS, the counting rate of these ions is close to the noise level of the instrument. However, close to the SLAMS the differential flux of the gyrating ions increases significantly by an order of magnitude and peaks within the SLAMS. Comparing this with the differential flux of the solar wind distribution, we find reflection rates of the order of a few percent. This indicates that SLAMS indeed pre-dissipate solar wind energy already in the upstream region of the quasi-parallel bow shock.
5. Summary and Outlook

One very important question concerning collisionless shock physics is how dissipation is achieved at the shock. At the Earth’s quasi-perpendicular bow shock, ions reflected off the shock and then transmitted downstream represent an effective way of dissipation. However, ions reflected off the quasi-parallel shock have guiding centre motions pointing upstream and may propagate far upstream. These ions can thus not contribute directly to downstream thermalisation.

This thesis studies how Short Large-Amplitude Magnetic Structures (SLAMS) upstream and at the Earth’s quasi-parallel bow shock can contribute to dissipation over the shock. Firstly, SLAMS could return shock-reflected particles propagating upstream back to the shock where they can be transmitted downstream and contribute to downstream thermalisation. Secondly, SLAMS may locally predissipate solar wind energy upstream of the actual shock.

Observations with the Cluster spacecraft revealed new insights into the physics of SLAMS. High-resolution measurements of the magnetic field and probe-to-spacecraft potential as an estimate for the plasma density confirmed the fast-mode character of SLAMS. The electric field within SLAMS exhibits characteristic features at different scale lengths. Firstly, the magnetic field rotation over the SLAMS is associated with an electric field rotation on the scale of an ion gyroradius. This often leads to a change from quasi-parallel to quasi-perpendicular conditions within the SLAMS. Secondly, spiky electric field structures are found at the leading edge of some SLAMS on the scale of an electron gyroradius. Thirdly, solitary wave structures with bipolar electric field signatures along the magnetic field are found on the scale of a few Debye lengths. These contain however no net potential across them and are interpreted as ion phase space holes.

A wake-like decrease in the plasma density behind a large number of SLAMS indicates that SLAMS indeed are three-dimensional structures as suggested by simulations. Earlier observations indicated that the scale of SLAMS is on the order of 1 \( R_E \). Cluster observations show however variations even on scales down to 100 km. SLAMS are thus highly structured upstream features.

Utilising the ion spectrometer instrument on the Cluster spacecraft, it is
found that SLAMS are associated with gyrating ions. These ions seem to be reflected off the SLAMS and thus SLAMS might be responsible for returning shock-reflected ions back to the shock where they again can contribute to downstream thermalisation.

Calculations of the electric potential across SLAMS established a significant potential in the Normal Incidence Frame. The growth of SLAMS is associated with an increasing potential. Cluster observations indicate that the electric cross-SLAMS potential is at least partly responsible for decelerating the solar wind over these structures. In addition, the incident solar wind is broadened and slightly heated. This suggests that SLAMS play an important role for local pre-dissipation in the upstream region of the Earth’s quasi-parallel bow shock.

Future studies need of course to establish the three-dimensional structure of SLAMS which is important for ion dynamics at these structures. The studies of reflection rates at SLAMS should be extended to a larger data set covering a wider range of $M_A$, $\theta_B$, and $\beta$. In combination with sorting out the relative importance of the electric potential and magnetic field for the reflection at SLAMS, the actual reflection mechanism(s) should be studied. In addition, it is not well-understood what the selection process for the growth of some ULF waves into SLAMS is. Also here, statistical studies can provide further progress. It should be mentioned that comparisons with simulation studies are essential in order to clarify these questions. The results obtained at the Earth’s quasi-parallel bow shock should then be used in order to study shock phenomena in, e.g., the solar corona. It has been suggested that electrons can be accelerated to high energies by quasi-parallel shock waves in the solar corona leading to solar radio burst radio emissions.

Of course, scientists are never happy with the things they already have to their disposal. Future spacecraft missions should provide particle instruments with much higher temporal resolution in order to resolve particle dynamics at SLAMS. In addition, a large number of satellites at different separations could study the different temporal and spatial scale lengths present concerning the regions upstream and at the Earth’s quasi-parallel bow shock.
6. Summary in German


Der Sonnenwind strömt mit Überschallgeschwindigkeit relativ zur Erde. Es entsteht eine Bugstoßwelle, genauso wie vor einem mit Überschallgeschwindigkeit fliegenden Projektil oder Flugzeug. An der Bugstoßwelle wird ein Teil der Strömungsenergie des Sonnenwindes in thermische Energie umgewandelt, d.h., hinter der Bugstoßwelle strömt der Sonnenwind verdichtet und aufgeheizt mit Unterschallgeschwindigkeit um die Magnetopause (in einem vereinfachten Bild eine Grenzschicht zwischen dem Sonnenwind und im Erdmagnetfeld gefangenen Teilchen).

Bild 6.1 zeigt schematisch die Form der Erdbgstoßwelle in der Ebene der Ekliptik. Das interplanetare Magnetfeld hat einen Winkel von 45° relativ zur Richtung des anströmenden Sonnenwindes, was einer durchschnitt-
**Figure 6.1:** **Deutsch:** Schematische Übersicht über die Erdbugstoßwelle in der Ekliptik zusammen mit interplanetaren Magnetfeldlinien. Der Sonnenwind kommt von links und bewegt sich auf die Bugstoßwelle vor der Erde, die sich auf der rechten Seite befindet, zu. Außerdem sind die Regionen gezeigt, in denen unterschiedliche Ionenpopulationen stromaufwärts von der Bugstoßwelle beobachtet werden. Übernommen aus [41].

**Svenska:** Skiss över chockvågen framför jorden, i ekliptikalplanet. Solvinden (Sonnenwind) kommer från vänster och övergår i bogchockvågen (Bugstoßwelle) framför jorden som befinner sig till höger. I överdelen av bilden är chockvägen kvasiparallell, medan den i underdelen är kvasivinkelrät. Olika ionfamiljer som observeras upströms för bogchocken visas också (översättning från tyska): Vorschockgrenze = förchockgräns, diffusive Ionen = diffusa ioner, intermediäre Ionen = mellanliggande ioner, Magnetfeldparallelle Strahlen = magnetfältparallela strålar. Tagit från [41].

lichen Situation entspricht. Dieses Magnetfeld wird mit dem Sonnenwind gegen die Bugstoßwelle konvektiert. Eine Magnetfeldlinie berührt dadurch die
Figure 6.2: **Deutsch**: Beobachtungen der Magnetfeldstärke bei Durchgängen der Cluster-Satelliten durch eine quasi-senkrechte (oberes Panel, 31. März 2001) und eine quasi-parallele Stoßwelle (unteres Panel, 2. Februar 2002). Der Leser sei auf die unterschiedlichen Zeitintervalle der Messungen hingewiesen: ca. 1 Minute und 45 Sekunden für das obere Panel und ca. 26 Minuten für das untere Panel. Das stromaufwärtige Gebiet ist durch eine niedrige Magnetfeldstärke und das stromabwärtige Gebiet durch eine hohe Magnetfeldstärke gekennzeichnet.


Einfach ausgedrückt, betrachtet man also die quasi-senkrechte Stoßwelle als eine (einzige), mehr oder minder stationäre Grenzschicht. Für die

Diese stark angewachsenen Wellen werden im Englischen als SLAMS (Short Large-Magnitude Magnetic Structures) bezeichnet, was in etwa Kurze, Große Magnetische Strukturen bedeutet. Diese Doktorarbeit befaßt sich genau mit diesen Strukturen und ihrem Einfluß auf den Sonnenwind. Es wird gezeigt, daß SLAMS sowohl reflektierte Ionen zurück zur Stoßwelle befördern können, als auch für eine lokale Vorheizung des Sonnenwinds sorgen, d.h., schon weit stromaufwärts wird ein kleiner Teil der Strömungsgenergie in thermische Energie umgewandelt. SLAMS scheinen also eine bedeutende Rolle im stromaufwärtigen Gebiet der quasi-parallelen Stoßwelle und auch für die quasi-parallele Stoßwelle selbst zu spielen.
7. Summary in Swedish


Chockvågen framför jorden kan indelas i två områden som karakteriseras av vinkeln mellan normalvektorn till chocken och riktningen av magnetfältet i solvinden, \( \theta_{Bn} \). Figur 6.1 på sidan 34 visar en skiss av chockvågen framför jorden. Om vinkeln \( \theta_{Bn} \) är större än 45°, normalvektorn är alltså nära att vara vinkelrät mot normalen, kallas chocken kvasivinkelrät. Choker med \( \theta_{Bn} \) mindre än 45° kallas på motsvarande sätt kvasiparallella. Den övre delen av
figur 6.2 på sidan 35 visar mätningar gjorda av en Clustersatellit som kor-
sar en kvasivinkelrät chock framför jorden. Man ser tydligt att övergången är
väldefinierad, skarp och varar några sekunder. Den undre delen av figur 6.2
visar mätningar från en kvasiparallell chock. Övergången tar cirka tjugo mi-
nuter och är inte alls skarp. Andra övergångar kan ta flera timmar. Att kva-
sivinkelrätta och kvasiparallella chocker ger så olika övergångar beror främst
på hur jonerna rör sig i de två fallen. I båda fallen åker de flesta av solvin-
dens joners igenom chockvägen, medan en liten del reflekteras. De reflekterade
jonerna orsaker skillnaderna mellan de två typerna av chocker.

Vid kvasivinkelrätta chocker rör sig reflekterade joners bara en kort sträcka
uppröms innan de relativt snabbt förs tillbaka till chockvägen av solvinden.
Detta ger den jämma, laminära, övergången mellan områdena uppströms och
nedströms. Jonerna som först reflekteras och sedan förs tillbaka till chocken
svarar för största delen av dissipationen, alltså omvandlingen av ordnad energi
i den strömmande solvinden till oordnad termisk partikelrörelse.

Vid kvasiparallella chocker kan joners röra sig långt tillbaka uppströms efter
att ha blivit reflekterade. Därmed skiljer sig en kvasiparallell chock från en
kvasivinkelrät på två sätt. För det första, de joners som spelar huvudrollen för
dissipationen vid kvasivinkelrätta chocker försvinna uppströms, och kan alltså
inte omedelbart bidra till att överföra ordnad rörelse till oordnad. Detta be-
tyder att en annan mekanism måste överta de reflekterade jonernas roll vad
gäller dissipation och/eller att de reflekterade jonerna förs tillbaka till chock-
vägen och på det viset kan bidra till energiomvandling. För det andra, de re-
lekterade joners som rör sig uppströms möter de inkommande jonerna i solvin-
den och växelverkar med dessa. Det leder till att olika plasmavågor gener-
ras. Vågorna växelverkar naturligtvis också med de reflekterade jonerna och
jonerna i den inkommande solvinden. Dessa processer orsakar en utbred och
turbulent kvasiparallell chockväg. Som tidigare nämnts visar figur 6.2 exem-
pe på en kvasivinkelrät och en kvasiparallell chockväg.

I en förenklad bild kan man betrakta den kvasivinkelrätta chockvägen som
ett andra tämligen stationärt gränsskikt. Detta är inte fallet för en kvasiparal-
lell chockväg. De senaste modellerna beskriver en mer komplicerad process.
Några av vågorna som skapas genom växelverkan mellan reflekterade och
inkommande joner växer till hög amplitud. Strukturerna kan då börja verka
som små chockvägor. När de kommer fram till den stora, egentliga, chockvä-
gen övertar de denna roll. Den kvasiparallella chockvägen är alltså en mycket
dynamisk struktur. Beskrivningen av chockvägen som ett andra gränsskikt är
helt enkelt inte bra.

De vågor som växer till hög amplitud i solvinden kallas SLAMS (Short
Large-Amplitude Magnetic Structures) på engelska. Det betyder Kortvariga,
Stora Magnetiska Strukturer. Denna doktorsavhandling handlar om satellitob-
servationer av sådana strukturer och dess påverkan på solvinden. Vi visar att
SLAMS kan föra reflekterade joner tillbaka till chockvägen och att de kan orsaka lokal upphettning av solvinden. Redan uppströms av chockvägen omvandlas alltså en liten del av solvindens ordnade energi till oordnad termisk energi. Allt tyder på att SLAMS spelar en viktig roll i området uppströms av jordens chockväg, och för chockvägen direkt.
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