From L1 to the Ground

Global Magnetospheric Dynamics Caused by Solar Wind/IMF Structures

Contents

1 Introduction

1.1 Magnetospheric dynamics: Dungey cycle

The interaction of the solar wind, a stream of charged particles (mainly protons and helium nuclii or alpha particles) with an embedded magnetic field, with the Earth's magnetic field results in the creation of a bow shock, where the super-magnetosonic wind is decelerated. The magnetoplasma then flows in the region between the bow shock and the magnetopause, which is called the magnetosheath. This region is highly dynamic and filled with various plasma wave modes and turbulence. The magnetic field is transported towards the Earth and piles-up until a equilibrium situation is reached where the pressure of the piled-up magnetic field equals the pressure of the Earth's compressed internal magnetic field. This gives the location of the magnetopause, mentioned above. The magnetic field is draped around the Earth's field and compresses and stretches it into a tail shape, the magnetotail.

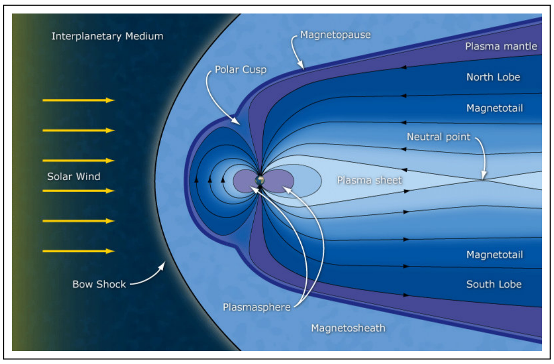

Figure 1: The Earth's magnetosphere showing the different regions created by the solar wind interaction.

The stable picture of the Earth's magnetosphere shown in Fig. 1 holds when the z-component (B_z) of the magnetic field in the solar wind, the so-called Interplanetery Magnetic Field (IMF) is positive. Then the field direction of the IMF and of the Earth's magnetic field are the same. However as soon as B_z turns negative the situation changes, as then oppositely directed magnetic field lines are pressed together at the magnetopause and reconnection can occur.

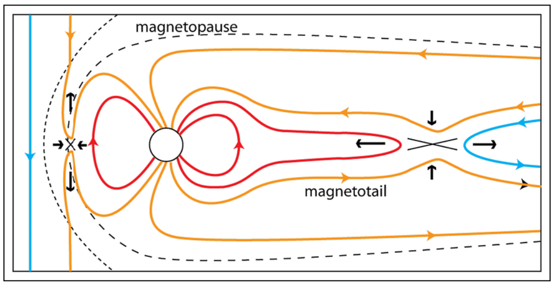

Figure 2: A schematic view of reconnection taking place when $B_z < 0$.

As shown in Fig. 2, when $B_z < 0$ magnetic field lines of the IMF and of the Earth's internal field can reconnect. The field lines are then pulled along with the shocked solar wind plasma through the magnetosheath and added at the night-side of the Earth to the magnetotail. Here the magnetic field in the tail from field lines connected to the Earth increases and the tail gets compressed even further until an unstable situation is created and reconnection is also started in the tail. Hereby the newly closed field lines (red) relax from a stretched configuration to a more dipolar like one, and "the other ends" of the field lines (blue) are accelerated down the tail and eventually expelled. This process stops when the IMF turns northward again.

As during the reconnection at the magnetopause magnetic field is eroded a the dayside, it needs to be replenished in order to avoid a magnetic catastrophy. This is done through the motion of the newly formed closed field lines, which move from the night side to the dayside, a process called the Dungey cycle [Dungey, 1961], which takes about 1 hour. This also means that the whole magnetosphere is set into motion through this process.

The main driver of the dynamics of Earth's magnetosphere is the solar wind, through e.g. reconnection at the magnetopause during southward Interplanetary Magnetic Field (IMF) B_z eroding the magnetic field at the dayside or compression of the magnetosphere during high ram pressure with northward IMF B_z. Nishida [1983] already described how the IMF influences the Earth's magnetosphere. The interaction of specific structures in the solar wind and how they transport energy from the solar wind to the magnetosphere is discussed e.g. by Lundin [1988]. The compression of the magnetosphere by a period of high ram pressure solar wind, ~ 4.5 nPa (similar to the ram pressure for the event discussed later in this proposal) was observed during a passage of WIND through the magnetosheath and magnetopause [Phan et al., 1996]. The reaction of the Earth's magnetosphere to interplanetary coronal mass ejections (ICMEs), observed by ACE and Wind, was studied in a set of papers by e.g. Farrugia et al. [1993, 2002] and for low Mach number CMEs by e.g. Lavraud and Borovsky [2008].

Single spacecraft measurements of the solar wind interaction with the bow shock and the magnetopause include studies of Flux Transfer Events (FTEs) by Geotail [see e.g. Sibeck and Siscoe, 1984; Korotova et al., 2009]. The motion of the magnetopause and its statistical location was studied using Geotail [Ivchenko et al., 2000]. And the erosion of the magnetopause during southward IMF was studied by e.g. Pudovkin et al. [1997]; Shue et al. [2001].

In this age of multi-spacecraft missions, as Cluster and THEMIS, it has become easier to investigate the motion of solar wind structures and their properties in various locations. For instance FTEs have been studied with THEMIS by Wild et al. [2005]; Fear et al. [2008] and with Cluster by Lockwood et al. [2001]; Wang et al. [2007]. The motion of interplanetary shocks through the magnetosheath have been studied using Cluster [Keika et al., 2008, 2009; Pallocchia et al., 2010] and THEMIS [Zhang et al., 2009].

The connection between something happening in the solar wind, such as an IMF rotation, and what happens deeper in the magnetosphere has been studied by Sandholt et al. [2004, and references therein]. They discuss the dayside aurora and its relation to the IMF magnetic field orientation. They show that for "intermediate" clock angle (B_y dominant and $90° < \theta < 135°$) the aurora moves to higher latitudes. For strongly southward field ($135° < \theta < 180°$) they find a strong erosion of the magnetopause. Sandholt and Farrugia [2002] found that observations of the dynamics of the aurora could well be used to monitor global changes in the magnetospheric magnetic topology.

Also, it should be noted that, as described in above in the Dungey cycle, the rotations of the IMF lead to the generation of substorms, through reconnection in the Earth's magnetotail. Dai et al. [2023] studied the interactions of IMF Alfvén waves and their geo-effectiveness. They showed that this kind of interaction drives substorms and are closely associated with CIRs. Using multi-point observations the magnetospheric dynamics and the magnetosphere-ionosphere coupling was studied. Their conclusion is that "*Magnetopause reconnection induced by large-amplitude interplanetary Alfvén waves is likely an intermittent driver of geomagnetic activity. Through directly driven substorms, magnetopause reconnection produces prompt increases of AE/AU.*"

Here the AE index (= Auroral Electrojet index) is designed to provide a global, quantitative measure of auroral zone magnetic activity produced by enhanced Ionospheric currents flowing below and within the auroral oval. Ideally, It is the total range of deviation at an instant of time from quiet day values of the horizontal magnetic field (h) around the auroral oval [Davis and Sugiura, 1966]. This index is provided by SuperMAG.

1.2 Following an example structure from L1 to the ground

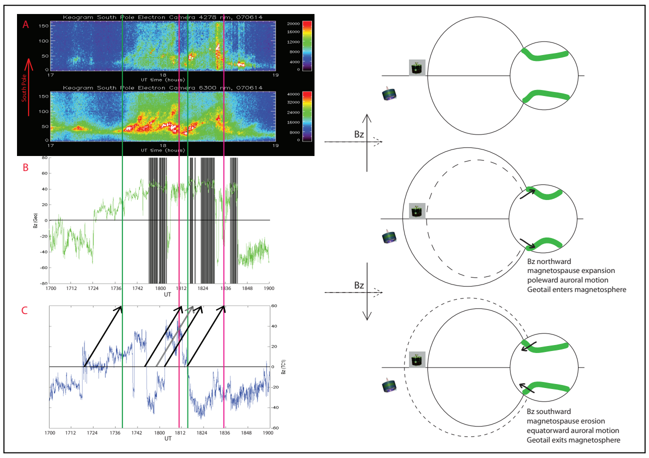

Figure 3: (left) (A) The south-polar keograms for 4278Åand 6300Å. (B) Geotail Bz (C) TC1 Bz, with arrows pointing from $B_z = 0$ crossing to change in aurora behaviour. (right) Schematic showing the behaviour of the magnetopause (solid curved line) and aurora (green slinky) after northward and southward turning of the IMF. [Volwerk et al., 2011]

Volwerk et al. [2011] studied the rotation of the IMF observed by WIND and ACE and the disturbance it caused in the Earth's magnetosphere, using all the available datasets of IMF, magnetospheric and ground based observatories, Fig. 3 (left) BC, including also auroral images Fig. 3 (left) A, and radar backscatter data. This showed that the rotation of the IMF and pressure pulses in the solar wind had a strong effect on the location of the aurora and the magnetopause.

The SuperDARN measurements show how the ionospheric flows change as the magnetic field in the solar wind changes. For the interval shown in Fig. 3 one can see the changes in the flows in Fig. 4.

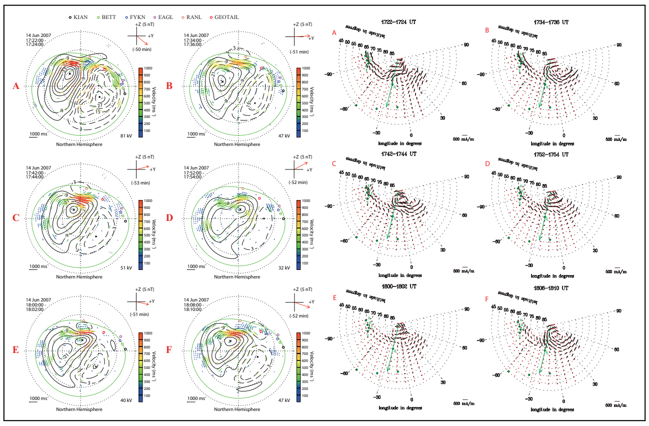

Figure 4: (left) SuperDARN backscatter radar observations during the rotation of the IMF as in Fig. 3. (right) The averaged equivalent currents calculated from the SuperDARN observations. [Volwerk et al., 2011]

The data show that when the field changes quickly, e.g. around 1724 UT there are strong flows (Fig. 4 left Panel A), and when the field is rather stable then the flows are reduced, e.g. around 1736 UT (Fig. 4 left Panel B).

From the flows ($\mathbf{v}$) the equivalent currents in the ionosphere can be calculated, Fig. 4 (right), as well as the field aligned currents ($J_{\|}$) currents are approximately given by [Chisham et al., 2007]: $J_{\|}/\Sigma_{\mathrm{P}} \approx \mathbf{B}\cdot(\nabla\times\mathbf{v})$, where $\Sigma_{\mathbf{P}}$ is the Pederson conductivity. These field aligned currents can be compared to measurements by Cluster and MMS using the curlometry technique [Dunlop et al., 2002].

1.3 Numerical simulations

Not only in-situ and remote sensing data are used to investigate the solar wind-magnetosphere interaction, but numerical simulations also play an important role.

Various global simulations of near-Earth space are being run, such as *OpenGGCM* (Open Geospace General Circulation Model, `https://ccmc.gsfc.nasa.gov/models/OpenGGCM~5.0/`) where simulation runs are performed on request in an open-for-all website approach. An example is shown in Fig. 5 of a pressure pulse arriving at and the subsequent reaction of the Earth's magnetosphere [e.g., Connor et al., 2014]. This simulation tool is based on an resistive MHD approach and includes ionospheric boundary conditions, field aligned currents and a thermosphere-ionosphere model.

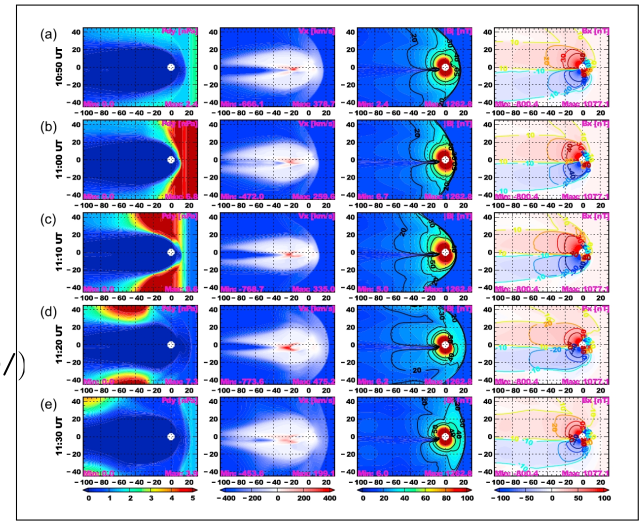

Figure 5: Simulation of the arrival of a pressure enhancement in the solar wind. Each column represents from left to right the dynamic pressure (Pdy), Xgse component of plasma velocity (Vx), total magnetic field ($|B|$), and Xgse component of magnetic field (Bx) on the noon-midnight meridian plane. [Connor et al., 2014].

Another approach is taken by *Vlasiator* (`http://vlasiator.fmi.fi`), which is a self-consistent hybrid-Vlasov simulation code, where the distribution functions of the ions are self-consistently coupled to the electromagnetic fields, whereas the electrons are modeled as a neutralizing fluid [see e.g., von Alfthan et al., 2014].

Numerical simulations, using input from in-situ observations, can be a great help in understanding the dynamics of the magnetosphere and in interpreting other measurements taken in the magnetosphere. At every grid point of the simulation the various quantities, like magnetic field, ion density and velocity, etc. will be available at every time step. Also, numerical simulations can be used as a predictive tool. Naturally, the processes that can be investigated depend on the modeling method: for an MHD approach one can only look at processes that are larger than the largest ion gyro radius and on time scales that are longer than the longest gyration period. For a Vlasov approach, where the ion distribution functions are calculated, one can get to smaller scales and model how the (macro)particles are behaving.

It is not forseen in this proposal that the PhD candidate will develop their own numerical modeling of the magnetospheric dynamics. However, this will be done through collaboration with co-workers at IWF who are developing their own codes. Also, modeling certain events with the OpenGCCM tool can be performed by a student assistent in the context of a Master's thesis.

1.4 Upcoming mission SMILE

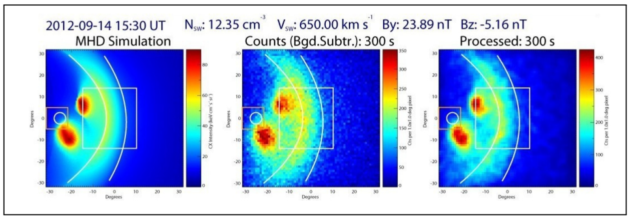

Figure 6: Simulation of the charge-exchange X-ray emission in the Earth's magnetosphere (left), the predicted measured counts (middle) and the final processed image from SMILE [Raab et al., 2016].

With the upcoming Chinese-European mission SMILE [Solar wind Magnetosphere Ionosphere Link Explorer, Raab et al., 2016], planned for launch in 2025, a new window on the dynamics of the magnetosphere will be opened with an X-ray camera that can monitor the motion of the magnetopause and an ultra-violet camera to monitor the aurora from space (unfortunately the "old" UV camera on the IMAGE satellite was lost in 2018). The mission will also perform in-situ measurements of the solar wind and IMF.

The interaction of the solar wind and IMF does not only create the effects described above, but solar wind ions will interact with exospheric neutrals near the magnetopause [Snowden et al., 2009]. For example, the highly-ionized oxygen in the solar wnd, O^{7+}, can undergo a charge-exchange collision with an exopheric neutral N:

$$O^{7+} + N \rightarrow O^{6+^*} + N^+$$

whereby a strongly excited O VII ion (another name for O^{6+}) is created and positive ion N^+. The relaxation of the excited O VII leads to the emission of an X-ray photon [Cravens, 2002]. The process will mainly occur in the Earth's magnetosheath, near the magnetopause, and in the cusp, as shown by the simulation in Fig. 6.

1.5 Recap

The aim of this project is to study the global dynamics of the Earth's magnetosphere, both with case-studies and statistically, driven by changes in the solar wind conditions. The project will be concentrated on three different structures in the solar wind/IMF (rotation of the IMF, strong dynamic pressure increase, and a coronal mass ejection). The end result of the project will be knowledge of the specific individual characteristics of the global magnetospheric dynamics linked to these three structures and their statistical behaviour, as well as insight in the magnetosphere-ionosphere coupling and the energy flows in near-Earth space.

The obtained knowledge will, eventually, be directly applicable to the interpretation of the data of the upcoming SMILE mission, which will be launced during the period over which this project will run. At the end of this, the PhD candidate will be an experienced space physicist and a good addition for the future Global Magnetospheric Dynamics and the future SMILE community.

1.6 Anticipated level of originality and innovation

This project is, amongst others, necessary in order to be able to analyse and understand the data that will be obtained by the upcoming SMILE mission. The innovative part is that, for the first time, there will be a detailed analysis of the actual differences in the interaction of different solar wind/IMF structures with the Earth's magnetosphere. This project will look at the interaction of "clean" structures to find the set of main characteristic magnetospheric responses, which can be used to understand the observations of remote-sensing instruments observing the Earth's magnetosphere. This will lead to a "catalog" of responses for space weather application. At the same time, the energy flows from the magnetosphere to the ionosphere and further down to the ground will be studied, which will be different for different structures. This collected information will also be important, on a larger scale, for the protection of important infrastructure such as electrical systems, telecommunications and low Earth orbit spacecraft. The results from this project will fit well in the proposed support science that was recently published: "*Ground based and additional science support for SMILE*" [Carter et al., 2024].

1.7 Spacecraft and ground-based stations

This project will make use of very many spacecraft missions and ground-based observatories, in order to get a global view of the Earth's magnetosphere. Data availability and access is given in Sect. 5.

- Cluster – This four-spacecraft ESA mission was launched in 2000 and is still measuring in near-Earth space, with another two-year extension approved in 2022. Its special constellation, the four spacecraft are in a tetrahedral configuration, makes it possible to separate spatial from temporal variation in the measured fields and particles. The inter-spacecraft separations are between 500 and 10000 km.

- THEMIS/ARTEMIS – The five-spacecraft NASA mission THEMIS was launched in 2007 to study the substorm phenomenon in the Earth's magnetotail. The spacecraft were spatially separated with apogees at $\sim$ 10, 20 and 30 Earth radii (R_{E}). In 2010 it was decided that the two outermost spacecraft would be sent to orbits around the Moon, thereby creating the ARTEMIS mission. This mission also included ground-based auroral imagers and magnetometers.

- MMS – This four-spacecraft NASA mission was launched in 2015 and is doing similar investigations in near-Earth space as Cluster, however, in this case the inter-spacecraft separations are 10s to 100s km.

- Wind & ACE – These two NASA solar wind monitors are parked at the Sun-Earth first Lagrange point, L1. They measure the solar wind velocity and composition as well as the IMF vector.

- SuperDARN – The Super Dual Auroral Radar Network (SuperDARN) was started in 1993 and is a very successful tool for studying dynamical processes in the Earth's magnetosphere, ionosphere, and neutral atmosphere. It consists of ground-based coherent-scatter radars that operate in the HF frequency band. Its fields of view combine to cover extensive regions of both the northern and southern polar ionospheres. SuperDARN plays an important role in understanding the magnetosphere-ionosphere coupling.

- SuperMAG – This international colaboration joins all of the ground magnetometer across the globe (at the moment nearly 600 stations). It provides the magnetic field vector on the ground for easy access as well as magnetospheric indices.

- SMILE – This upcoming mission, with launch planned in 2025, will study the coupling of the solar wind and the Earth's magnetosphere through observations by an ultraviolet and a soft X-ray imager, whilst at the same time there will be in-situ mearuments of the solar wind magnetic field and plasma.

2 The Project

This project foresees the research being done by a PhD student over a time period of four years, supported by national and international collaboration teams. At IWF Graz the PhD student will be supported by members of the permanent staff and a postdoctoral researcher, who will be described further below.

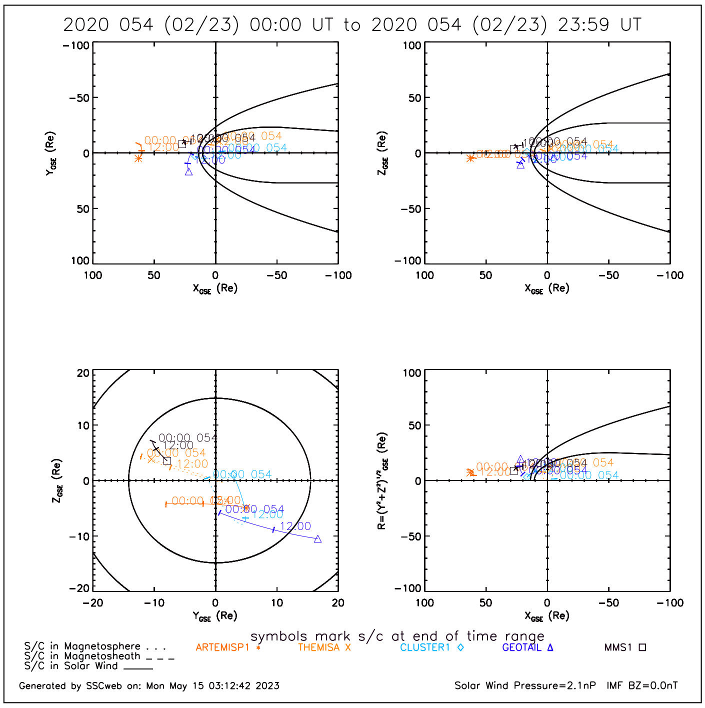

Figure 7: An overview of the locations of the various spacecraft in near-Earth space. (source: `https://sscweb.gsfc.nasa.gov/`)

The goal of this project is to use a fleet of spacecraft to investigate the global effects of changes in the solar wind and IMF on the Earth's magnetosphere. An example of this fleet is given in Fig. 7 for 23 February 2020. The solar wind monitors ACE and Wind at the first Lagrange point (L1) at $\sim 235\,R_\mathrm{E}$ are not draw, in order to keep the visibility of the other spacecraft in the plot.

In near-Earth space, solar wind and IMF changes are observed by ACE/Wind, are propagated (while they evolve) to the Artemis spacecraft around the Moon, and then are propagated towards the Earth's bow shock, magnetosheath, mangetosphere and magnetotail. This sets the dynamics of the magnetosphere in motion, which can be observed by the ground-based observatories mentioned in the list above in Sect. 1.7.

In Fig. 8 the magnetic field data for four spacecraft are shown and illustrates how disturbances in the solar wind propagate. Two "boundaries," marked with vertical dashed lines, which can be found in the data of all four missions. Only the first is not visible in the Cluster data, as the spacecraft were still in the Earth magnetosheath, close to the bow shock, and the signal is obscured. Knowing the time differences between the observations and the distance between the spacecraft it is possible to determine the velocity, which leads to a roughly estimated value ∼ 477 km/s, which agrees well with the measured solar wind velocity by ACE of ∼ 425 km/s. However, the solar wind velocity can vary over time. But it is clear that structures can be well identified at different locations, however, they can also change their looks.

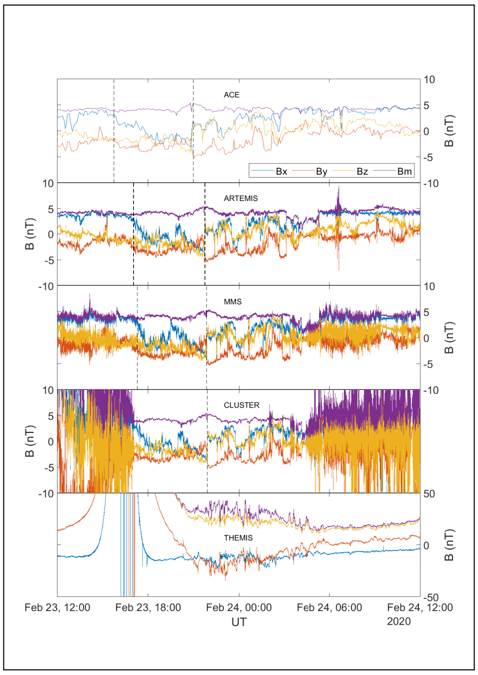

Figure 8: The magnetic field data from four missions: ACE, ARTEMIS, MMS, Cluster and THEMIS. Two boundaries are marked with vertical dashed lines with which one can determine the propagation velocity of an IMF structure.

These IMF disturbances will interact with the Earth's magnetopause, and where the IMF $B_z < 0$ (yellow in Fig. 8) reconnction will commence, otherwise, the variations of the field will set the magnetospere oscillating. This can be seen in the bottom panel where the THEMIS-A data are shown, a spacecraft which remains well inside the Earth's magnetosphere.

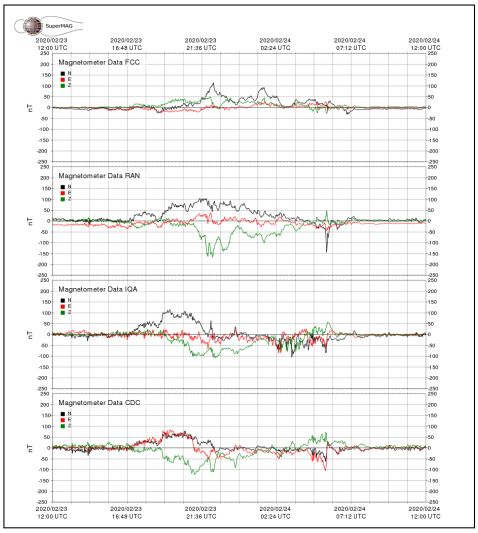

Figure 9: The ground magnetometer data.

The IMF disturbance is transported into the magnetosphere, where it can be measured by the ground magnetometers (Fig. 9), which are now all joined into the SuperMAG consortium [Gjerloev, 2012]. The data from the stations in east coast Canada, near the Hudson Bay, show that there are strong disturbances in the magnetic field starting at ∼ 1700 UT. This activity is related to the IMF signatures observed in space (Fig. 8) and the start is around the time that Cluster crosses the bow shock.

Notice that the disturbances can be in opposite directions, e.g., B_z (green) at FCC (Fort Churchill) and RAN (Rankine Inlet), which means that the stations are at opposite sides (i.e. north and south) of the east-west ionospheric current, driven by the structures in the IMF and the subsequent reaction of the magnetosphere. However, as one can see, the sign of B_z can also change in time, indicating that the ionospheric current moves north- or southwards.

One of the particular qualities of the Cluster and MMS missions is that, because of the tetrahedral configuration of the spacecraft, gradients in the magnetic field can be measured. This can be used in the so-called "curlometry" [Dunlop et al., 2002] to calculate the currents flowing within the tetrahedron. For example, when flying over auroral regions the field aligned currents can be calculated driving the northern lights. The plasma instruments on MMS, however, are also well equipped to calculate currents directly from the moments of the particle distribution functions.

With all these data, we get a good view of the dynamics of the Earth's magnetosphere. This was an example of mainly a rotation of the magnetic field which onsets and stops the reconection at the nose of the magnetosphere. The solar wind velocity is constant at a rather "normal" level (~ 350 km/s) and the proton density only shows very small variations around ~ 8 cm^{-3}.

2.1 Project 1: Identifying main differences in interaction

In this first project the response of the magnetosphere is looked at for different structures in the solar wind, which may (or may not) have a different influence on the Earth's magnetosphere.

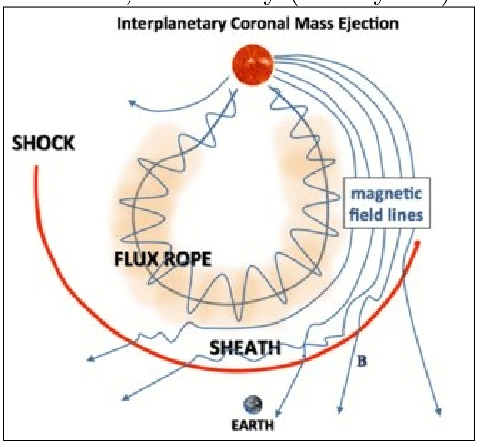

Figure 10: A model of a Coronal Mass Ejection [Kilpua et al., 2017]

- **Strong rotation of the IMF**: An example has been discussed above, where the nominal solar wind shows rotations of the IMF, and reconnection starts and stops at the dayside magnetopause.
- **Strong dynamic pressure increase**: When the solar wind speed and/or density increases strongly, then so does the ram pressure pushing on the magnetosphere. This will lead to a compression of the magnetosphere.
- **A Coronal Mass Ejection**: A CME is a magnetoplasma structure in the solar wind created by an explosion in the corona of the Sun. It takes the form of a fast-moving flux rope [e.g., Gopalswamy, 2016], which can lead to a strong interaction with the Earth's magnetosphere, depending in the polarization of the magnetic field. This can also be accomplished, for example, by a **Corotational Interaction Region (CIR)**, where there is a "collision" between fast solar wind with slow solar wind, creating a shock.

The importance of L1 in this study lies in the fact that the spacecraft "parked" there, Wind and ACE, are measureing the solar wind upstream of the Earth as a far-enough distance that it will be a pristine solar wind. This is the right place to look for the clean events that are needed for this study. The spacecraft will measure both the IMF and the plasma, which is then continuing its way towards the Earth. As a service to the space physics community, there also exists the OMNI database (`https://omniweb.gsfc.nasa.gov/`), where the data taken at L1 are transported to the nose of the Earth's magnetosphere. This reduces the work for researchers to calculate the travel time of the structures after they pass L1 and arrive at Earth [King and Papitashvili, 2005].

In order to find these structures a *search engine* needs to be created, which is based on the magnetic field and plasma data from the L1 probes. The OMNI dataset delivers all necessary parameters of the solar wind, the magnetic field and the plasma parameters (velocity, density) as well as derived quantities such as ram-pressure, plasma beta, and Alfvén Mach number. The search engine will have to scan the data for the three sturctures, based on various parameters, which will have to be chosen and adjusted by the PhD candidate and the team around them. In Table 1 possible criteria are listed for the categories "Rotation" and "Pressure". In the case of "CME" the project will refer to the already existing (and expanding) list from *ICMECAT* (`https://helioforecast.space/icmecat`, Möstl et al. [2017]).

Table 1: Search Engine Parameters: Possible examples for the criteria on the magnetic field and plasma data. $\Phi = \tan^{-1}(B_z/B_y)$ and $\Theta = \tan^{-1}\left(\sqrt{B_y^2 + B_z^2}/B_x\right)$ are the IMF clock and cone angles, respectively. P_{ram} is the solar wind ram (dynamic) pressure. MRx = magnetic reconnection.

Rotation	$\Delta\Phi > 90° - \Delta P_{ram} < 20\%$	
	North-South rotation	no sign-change B_z no MRx
	North-South rotation	sign-change B_z MRx
	East-West rotation	$B_z > 0$
Pressure	$\Delta\Phi < 20° - B_z > 0 - \Delta P_{ram} > 50\%$	
	$45° \leq \Theta \leq 135°$	$B_z > 0$ no MRx
	$\Theta \leq 20°$ or $\Theta \geq 160°$	$B_z > 0$ no MRx radial field

Some of the questions that need to be answered are e.g.: *What is the motion of the magnetopause? What is the magnetic signature measured by ground magnetometers caused by the motion of the current systems in the ionosphere?* These are important to understand the dynamics of the magnetosphere Other questions that can be answered are: *What is the reaction of the aurora? What do the SuperDARN radar data show as activity in the ionosphere?*

By studying clear examples of these three solar wind/IMF disturbances mentioned above, a first impression of the dynamics of the Earth's magnetosphere shall be obtained. The individual unique specifics in the global magnetospheric dynamics caused by these three different strucutures will be identified, as well as the MI-coupling.

2.2 Project 2: Statistical Processing

After looking at the different responses, it has to be deteremined what the real major differences are in clean examples of the three different solar wind/IMF structures. This part of the study will split into two part: one directly related to the preparation for SMILE and one more general about the global magnetospheric dynamics and MI-coupling and energy flows in near-Earth space.

Some of this is of course already known [see e.g., Eastwood et al., 2015], but now we should already relate this to the possible consequences this has for observations by SMILE. In principle this would also include looking at the charge-exchange processes in the magnetosphere, which may be altered because of the dynamic magnetosphere, which will be addressed in **Project 3** below. This may be beyond the scope of this proposal, but can be discussed in papers with collaborators in this project.

2.2.1 Project 2A: Global magnetospheric response

From clear examples the major differences between the various interactions can be determined. To obtain a general overview of how these differences behave themselves, a statistical study has to be performed. Does the increased ram pressure by a southward-pointing CME lead to greater motion of the magnetopause boundary? Does the aurora move further southward than for a "regular" southward turning of the IMF? And if the answer is "yes" to these two questions, then the question remainse "in what measure?" The example in Fig. 3 shows how the aurora moves to higher latitudes when $B_z > 0$ nT, in the case of a high-speed solar wind ~ 550 km/s with south- and northward turnings of the IMF and some slight increases of the ram pressure [Volwerk et al., 2011].

The obtained statistical results on the dynamics of the magnetosphere, i.e. the motions of the magnetic field and the aurora, can directly be used in the determination of what "should" be observed by the SMILE mission.

A statistical result on the specific individual magnetospheric responses to the three specified solar wind/IMF structures shall be obtained. How statistically different are the three interactions on the global magnetospheric dynamics, such as compression, motion of the field lines, etc.?

2.2.2 Project 2B: Coupling to the ground

The obtained statistical results with respect to the ionospheric flows from SuperDARN, field aligned currents and auroral activity give further information about the global dynamics of the magnetosphere and the Magnetosphere-Ionosphere (MI) coupling [see e.g., Lakhina, 1994]. This is not only important to study the energy flow in the magnetosphere-ionosphere, but "*has also important implications for other planets and astrophysical systems, how they behave and evolve throughout the* *universe, specifically those involving partially ionized gases connected by magnetic fields*" as stated by Mauk et al. [2002].

The question to ask now is if these flows and currents are significantly different for the three cases of solar wind/IMF structures. All three structures lead to the creation of aurora, and thus currents and ionospheric flows. *Are these the same in location? What is the difference in power the currents inject into the aurora?* Indeed, surface waves on the magnetopause, for example, lead to signatures in the aurora, ionosphere and in ground based observatories [Archer et al., 2023].

Field aligned currents have been observed to be generated by rotations of the IMF using AMPERE (Active Magnetosphere and Planetary Electrodynamics Response Experiment). This experiment uses the magnetometers onboard the 66 IRIDIUM (`https://www.iridium.com/`) satellites in order to map the large-scale Birkeland currents [Anderson et al., 2014], and to study their development in time and space [Anderson et al., 2018].

The SuperDARN radars deliver information about the ionospheric flows [Chisham et al., 2007]. The clock angle of the IMF also has a control over these flows. In a statistical study Abel et al. [2009] show that intermittency measured in moments of the velocity structure functions may be inherited from intermittency in the solar wind. Maybe not quite the topic of this project, but one can also combine the SuperDARN data with those of AMPERE to obtain the ionospheric energy input caused by changes in the solar wind/IMF [Billett et al., 2022].

A statistical study of the possible differences in electric currents and ionospheric flows for the three specified solar wind/IMF structures will deliver increased insight in the energy flows connected to MI-coupling and global magnetospheric dynamics.

2.3 Numerical Modeling by Master's Student

In order to put some of the data from the chosen event into a global context, numerical simulations can clearly be of benifit. As already stated above, this task will not be part of the work of the PhD candidate, as the whole project is already challenging.

However, using the *openGGCM* to model some of the interactions would be a good task for Master's projects. After the determination of acceptable events in the different categories, the modeling can start and a comparison between data and model can be performed. Will the global view of these selected events, based on the spacecraft flotilla and ground based observatories agree, on large scales (as the code is MHD) with the modeling results.

3 Project 3: SMILE please

3.1 Project 3A: Application of study to SMILE data

The SMILE [Solar wind Magnetosphere Ionosphere Link Explorer, SMILE Study Team, 2018] is planned for launch in 2025, which would be right inside the period planned for the PhD project.

By knowing how e.g. the magnetopause statistically moves, a reverse study can be performed compared to Jorgensen et al. [2022] and Wang and Sun [2022]. These authors will use the X-ray observations of SMILE soft X-ray imager [SXI Sembay et al., 2024] as a kind of tomography to determine e.g. the location of the magnetopause, whereas in this project, the location of the magnetopause will be used to esitmate where the X-ray emission will occur. Indeed, Kim et al. [2024] (local team member at IWF) showed how to estimate the magnetopause position from X-ray images, using low-pass images created from numerical simulations with the OpenGGCM.

SMILE will also have a ultraviolet imager (UVI), which will observe Earth's northern auroral regions. It will study the connection between the processes taking place in the magnetospheric boundaries - as seen by the SXI - and those acting on the charged particles precipitating into our ionosphere.

Depending on the successful launch of the spacecraft and the commissioning time, some of the first results of the mission will be compared to the results obtained in the study of the solar wind/IMF structures interacting with the Earth's magnetosphere.

3.2 Project 3B: What happens if you don't smile?

In the unlikely event that the SMILE mission is not started successfully, and there are no data to analyse, there is a back-up plan. In this case the study of the dynamics of the Earth's magnetosphere will be expanded to the magnetotail region.

As described in Sect. 1.1, after magnetic reconnection takes place at the nose of the magnetosphere, the newly connected field lines are transported to the magnetotail region by the solar wind flow. There they are gathered, increasing the magnetic field in the tail and pressing the (oppositely directed) magnetic field lines together. This eventually leads to magnetic reconnection in the tail, where the stored magnetic energy is explosively released, and is used to energize the ions and electrons in the magnetotail, in so-called substorms.

Similarly, compression of the magnetosphere and magnetotail can be produced by an increase in ram pressure of the solar wind, or by the draping of the magnetic field of a "wrongly-directed" CME (i.e. with northward point magnetic field on the leading side), which will not lead to magnetic reconnection at the nose, but will be able to strongly compress the magnetosphere.

During different seasons (summer/winter), the near-Earth spacecraft have their apogee at different locations around the the Earth. This is caused by the fact that the spacecraft orbits are fixed in space and therefore rotate around the Earth as the Earth orbits the Sun. This makes that Cluster and MMS will have there apogee in the Earth's magnetotail during summer and in the solar wind in winter. For THEMIS this is reversed.

The dynamics of the Earth's magnetotail will also be different for different structures interacting with the magnetosphere. Therefore, as a back-up project, the dynamics of the tail will be studied for the three different structures listed as targets in the previous projects above.

Questions to be answered in this project are: Does the magnetotail react differently for the different structures interacting with the magnetosphere?; What is the difference in energy flow from the tail to the Earth's ionosphere?; How does the magnetotail-ionosphere coupling work?

4 Dissemination of the project and milestones

This, rather challenging, project will be spread over a 4-year PhD study with the following breakdown:

Y1
- Finding clean examples of the three IMF structures
- Obtaining the space and ground based data
- Analysis of the three events, determining similarities and differences
- **Paper 1 - On the different response of the magnetosphere**

Y2
- *Continuation of previous work*
- Search engine for obtaining multiple events of the three structures
- Statistical analysis of the major differences in global dynamics
- **Paper 2: A statistical study of global magnetospheric responses**
- Numerical modeling of selected events by Master's student

Y3
- *Continuation of previous work*
- Statistical analysis of the magnetospher-ionosphere coupling
- **Paper 3: A statistical study of MI-coupling for different IMF structures**
- Continuations of numerical modeling of selected events by Master's student

Y4
- *Continuation of previous work*
- Depending on successful launch and commissioning of the SMILE mission
  - Successful start of SMILE
    * Collaboration in SMILE data analysis, using the results obtained in the previous years

    * **Paper 4: Global dynamics observed by SMILE**
  - Unsuccessful start of SMILE
    * Magnetotail dynamics study related to the three solar wind structures
    * **Paper 4: Magnetotail dynamics and ionospheric coupling**
- Continuations of numerical modeling of selected events by Master's student

The results of this project will be presented at a selection of various conferences: the yearly EGU General Assembly in Vienna, the AGU Fall Meetings, Cluster/MMS workshops and/or other not yet specified meetings.

The project will finish with the successful PhD defense by the candidate at the Karl-Franzens-Universität in Graz.

5 Data availability

All the data that are needed in this project are publicly available:

- ACE: `https://izw1.caltech.edu/ACE/ASC/index.html`
- Cluster: `https://cosmos.esa.int/web/csa`
- SuperDARN: `https://www.bas.ac.uk/project/superdarn/`
- MMS: `https://lasp.colorado.edu/mms/sdc/public/`
- SUPERMAG: `https://supermag.jhuapl.edu/`
- THEMIS: `https://artemis.igpp.ucla.edu/overview_data.shtml`

6 Collaborations

National and international collaboration is important for a young PhD student. This will give them a view on how things work in institutes other than where they are working. It will give them the opportunity to come into contact with other PhD students, as well as postdocs and staff members. The collaborating institutes will have to be chosen in such a way that they are complimentary to the home institute and beneficial both in scientific and career view of the PhD student.

6.1 International Collaborators

- Dr. Steve Milan, School of Physics and Astronomy, University of Leicester, UK, is professor of heliospheric physics, is an expert on solar wind-magnetosphere-ionosphere-atmosphere coupling, using observational tools such as the SuperDARN radar network, space-based auroral imagery, and AMPERE.

- Dr. Gareth Chisham is PI of the British Antarctic Survey (BAS) SuperDARN radar and is a Space Weather researcher in the Space Weather and Atmosphere Team, with exerience in The calibration, analysis and interpretation of SuperDARN HF radar observations, and solar wind - magnetosphere - ionosphere coupling.

6.2 National Collaborators

- Dr. Manuela Temmer, Heliospheric Physics Research Group (HPRG) Institute of Physics, University of Graz, Austria, is an expert on solar and heliospheric physics, with application to the impact of solar activity on Earth as well as human and robotic explorers across the solar system (Space Weather).

7 Large scale impact of the study

The interaction of the solar wind magnetoplasma with the Earth's magnetosphere is an important area of study in space physics, and usually referred to as "space weather." Understanding the processes that take place in near-Earth space is necessary as they can have a strong influence on the health of spacecraft orbiting the Earth and on satellite telecommunication and even on electrical power networks on the ground.

Through understanding the global dynamics of the Earth's magnetosphere and the energy flows associated with it, the safeguarding of important infrastructure can be improved. This project investigates the specific characteristics of the interaction of often-occurring solar wind/IMF structures with the Earth's magnetosphere. It will give insight in what the different effects are when a rotation of the IMF, an increased ram-pressure and a CME or CIR interact with Earth's magnetic field.

At the same time, knowing the global magnetospheric dynamics caused by these structures will help with interpreting data from remote sensing observations, for example by the upcoming SMILE mission. This mission will observe the Earth's magnetosphere in soft X-ray and ultra-violet wavelengths, whilst at the same time measuring the local solar wind and IMF parameters. Indeed, the built-up of this project fits well in the recently published paper on "*Ground based and additional science support for SMILE*" [Carter et al., 2024].

Furthermore, the study of the dynamics of the Earth's magnetosphere is important also for the study of extra-terrestrial magnetospheres. The effect that are observed at Earth can also be found at other magnetized planets such as Mercury. With the upcoming BepiColombo mission at Mercury, with orbit insertion in 2025, there will be, for the first time, a dedicated two-spacecraft mission at another planet. One spacecraft will be able to measure the solar wind/IMF, whereas the other will measure the response of the magnetosphere. The results obtained at Earth can directly be applied/checked at Mercury, and teach us about the similarities and differences in the behaviour of a very small and weaker magnetosphere.

8 Ethical and gender aspects

There are no ethical aspects to consider in this research. Gender & Diversity is a central issue for the ÖAW - and thus also for the IWF. The Academy and its institutes work continuously to create and maintain a working environment free of discrimination and are committed to equality for all employees. All members of the ÖAW should be able to develop their individual potential and performance in a climate characterised by openness and integration. They should be supported in their various phases of life and careers.

9 Abbreviations

AGU - American Geophysical Union; **AMPERE** - Active Magnetosphere and Planetary Electrodynamics Response Experiment; **BAS** - British Antarctic Survey; **CIR** - Corotational Interaction Region; **CME** - Coronal Mass Ejection; **CSA** - Cluster Science Archive; **ESA** - European Space Agency; **EGU** - European Geosciences Union; **IMF** - Interplanetary Magnetic Field; **FGM** - Flux Gate Magnetometer; **MI-coupling** - Magnetosphere-Ionosphere-coupling; **FWF** - Fonds zur Förderung der Wissenschaftlichen Forschung, Austrian Science Fund; **IWF** - Institut für Weltraum Forschung; **MMS** - Magnetospheric MultiScale mission; **MRx** - Magnetic Reconnectino; **ÖAW** - Österreichische Akademie der Wissenschaften; **PI** - Principal Investigator; **SMILE** - Solar wind Magnetosphere Ionosphere Link Explorer; **SXI** - Soft X-ray Imager; **TC1** - Tan Ce 1, Double Star 1; **THEMIS** - Time History of Events and Macroscale Interactions during Substorms; **UVI** - UltraViolet Imager

ANNEX 1

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ANNEX 2

10 Local Infrastructure

The Institut für Weltraumforschung (IWF) of the Österreichische Akademie der Wissenschaften (ÖAW) in Graz is the main space research institute in Austria, with approximately 100 scientists and engineers. The institute is involved in many Earth magnetospheric missions such as Cluster, DoubleStar, THEMIS, MMS and SMILE, as well as planetary magnetospheric missions such as Venus Express, Cassini-Huygens, Rosetta, Bepi-Colombo and JUICE.

The PhD student will work in a team of magnetospheric and plasma physics experts:

- Rumi Nakamura (space plasma physics group leader), is an expert in magnetospheric physics, specializing in magnetotail reconnection and other processes, based on data analysis from satellites and ground-based measurements.
- Martin Volwerk (project leader) is an expert in space plasma physics at various solar system objects: Earth, Venus, Mercury, Comets and solar wind.
- Daniel Schmid is an expert in planetary magnetospheric physics concentrating on the Earth (Cluster, MMS) and Mercury (BepiColombo).
- Hyangpyo Kim is an expert in magnetospheric physics, concentrating on magnetic field oscillations and the inner magnetosphere and will drive the SMILE investigations at IWF after the mission has successfully started.
- Evgeny Panov is an expert in magnetospheric physics, concentrating on reconnection in the magnetotail and the creation of various structures in the aurora.
- Seiji Zenitani is an expert in numerical simulations of plasma processes in the Earth's magnetosphere and space plasmas.

Apart from the project leader, these persons will not have an official role in this project. However, it cannot and shall not be excluded that collaborations will develop.

11 Finances

11.1 Personel costs

This research project seeks for the financing of a PhD, for four years at the rates mentioned in Table 2 per year. Included in the financial request are trips to the international collaborators by the PhD student, as support for the research and to build a professional network (see Sect. 6.1).

There is also a request for three student assistants to support the project at the rates mentioned in Table 2 per year. The topics for the Master's theses will be to numerically model relevant events found in the study by the PhD student, using the OpenGCCM tool and compare the results with the observations.

The PhD student will work full-time on the project, i.e. 30 hours per week for four years. The project leader will spend 10% of his working time on the project, i.e. 4 hours per week, not paid from the project. The possible master students will work full-time on the project, i.e. 20 hours per week for six months.

11.2 Travel costs

As explained above in Sect. 6.1, international collaborations and visits to external instutes are very important for the development of a young scientist. Therefore, the following visits are included in the project, whereby the first two visits will be by both the PhD student and the project leader, in order to consolidate the collaboration between IWF, University of Leicester and the Britisch Antarctic Survey.

Y1 In the first year the PhD student and the project leader will pay a one-week visit to the university of Leicester. This visit will introduce the PhD student to the group of Prof. Milan, where there is strong expertise on MI-coupling, which will be of great help in interpreting data sets from ground based stations. The project leader will use the visit to strengthen and expand the collaboration between the University of Leicester and IWF.
Costs: Flight Graz-Birmingham €1100, Taxi €100, Train €200, Hotel €1662, Per Diem €338 – Grand Total €3400

Y2 In the second year the Phd student and the project leader will pay a one-week visit to BAS, Cambridge. The PhD student will be introduced to the specifics of the SuperDARN radar technique and how to use and interpret the data. The project leader will use this visit to build a new collaboration between the BAS SuperDARN team of Dr. Chisham and IWF, which has existed only sparingly until now.
Costs: Flight Graz-Stansted €1000, Taxi €100, Bus €70, Hotel €1662, Per Diem €338 – Grand Total €3170

Y3 A one-week visit to the university of Leicester. The PhD student will discuss with the team of Prof. Milan about the results obtained in the project and what further investigations that can be done in collaboration with that team that will be benificial for both sides.
Costs: Flight Graz-Birmingham €550, Taxi €100, Train €100, Hotel €831, Per Diem €169 – Grand Total €1750

Y4 A one-week visit to BAS, Cambridge. The PhD student will discuss with the team of Dr. Chisham about the results obtained in the project and further investigations that can be done