2021 SWARM+SCIENCE WORKSHOP ON MAGNETOSPHERE-IONOSPHERE-LOWER ATMOSPHERE INTERACTIONS

Summary and Recommendations

TABLE OF CONTENTS

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INTRODUCTION

The **2021 Swarm+ Science Workshop**, held virtually on last 28-29 June with the participation of ESA and Swarm science experts, focussed on the more relevant science results gained from Swarm-based ESA projects with the purpose to identify the upcoming science challenges, in the context of physics of the Earth's ionosphere, and its interactions with the magnetosphere and lower atmosphere. (Figure 1 illustrates the interaction of the solar wind Earth's magnetosphere).

The workshop was organised in six different sessions, focussing on;

1. Geomagnetic activity, ionospheric currents and boundaries monitored from s/c data;
2. Extreme events, driven from solar wind and/or perturbations from lower atmosphere;
3. The ionospheric fluctuations/irregularities/tur bulence Alfvén waves and their impact on GPS signals;
4. Swarm contribution to Ionospheric models, and possible new developments;
5. Synergies with other existing or planned missions in the Sun-Earth connections domain.
   An open discussion about achievement and next scientific challenges for upcoming ESA Swarm projects was held at the end of each session, and then summarized in the last sixth session.

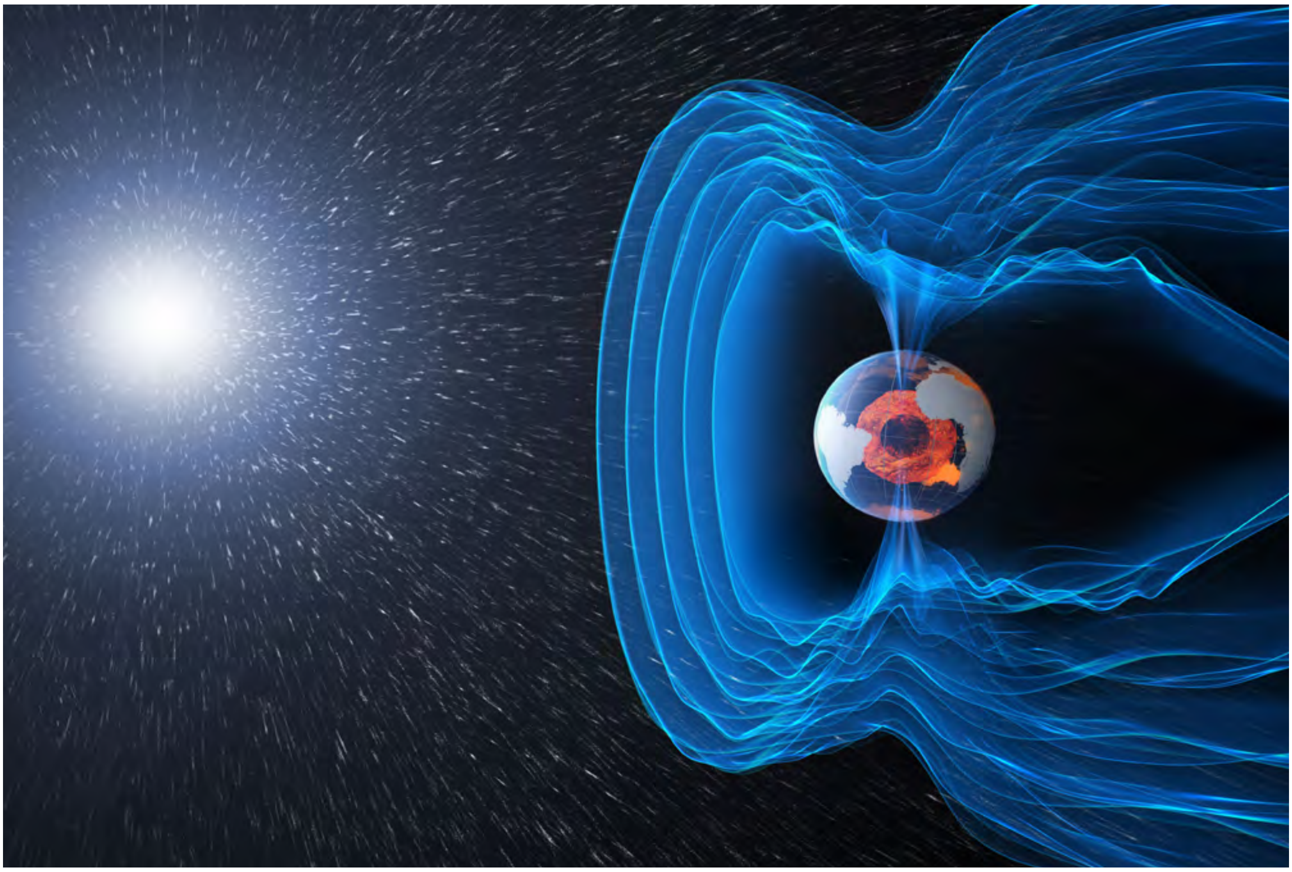

Figure 1: an illustration of the Earth's magnetosphere, and geomagnetic field lines, interacting with solar wind plasma.

The variability of the ionosphere: how to monitor geomagnetic activity, ionospheric currents, ionospheric boundaries from s/c data

This session included four dedicated presentations, illustrating the results of three different ESA projects: Swarm Data Quality Investigation of Field-Aligned Current products, Ionosphere and Thermosphere systems (SIFACIT), characterization of IoNospheric TurbulENce level by Swarm Constellation (INTENS), and New Space Weather Information Exploited from the Swarm Observations (EPHEMERIS).

Two presentations focussed on the results of SIFACIT project, about the innovative methods to compute the Field Aligned Currents (FAC) [objective 1], and about the investigation of Joule Heating due to the Pedersen currents in the high latitude ionosphere with Swarm data and simulations [objective 2].

The INTENS Team presented in this session the new Swarm based indexes to monitor the geomagnetic activity [objective 1], and EPHEMERIS team illustrated the recent results about identifying the Mid-latitude Ionospheric Through (MIT) with Swarm data [objective 1].

The discussion, at the end of this session, identified three possible scientific challenges that can be tackled with Swarm data in future studies.

The first challenge regards a better characterization of the geomagnetic quiet ionosphere, when disturbances induced by solar wind are minimum.

How the ionosphere behaves during quiet conditions is still poorly understood, since the majority of the studies on external field focus on disturbed geomagnetic conditions, which are only rarely verified (only 5% of data have Kp>4). In this respect, Swarm represent now the optimal mission to perform this investigation, having collected a very large amount of data with the 3-s/c and 16 orbits per day by 8 years (so far).

This investigation can be achieved both with statistical studies, from example based on the new Swarm-based indexes developed by INTENS (see Fig.2), the distribution of FAC using the new techniques and online tools developed under SIFACIT, Plasma Pause (PP) position from EPHEMERIS, but also with a number of event studies over a broad range of phenomena observed in Swarm data.

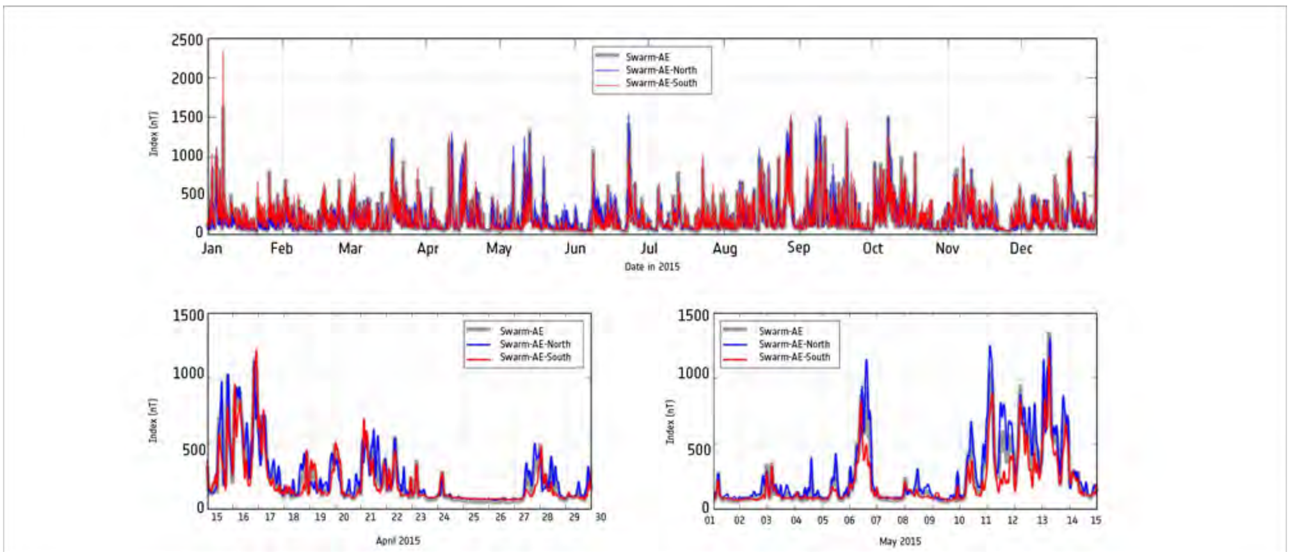

Figure 2: The Swarm-AE North/south Index. Swarm Auroral-Electrojet indexes, able to cover separately the two hemispheres.

Another possible future investigation with Swarm data concerns the study of asymmetries between the two hemispheres.
Some of the asymmetries are expected according to the asymmetries in external drivers, like interplanetary magnetic field, energetic particles precipitation, and geometry of magnetic reconnection at the magnetopause, or internal asymmetries such as magnetic dipole effect [Pakhotin et al 2021 Nature communication communications, see Figure 3, seasonal variation], seasonal variation, ionospheric anomalies. Other asymmetries, instead, remain unexplained, and shall be studied in this project. Understanding the inter-hemispheric asymmetries would allow to better understand the ionospheric response to internal and external drivers. Swarm is the ideal mission to study the inter-hemispheric asymmetries.
Indeed, Swarm satellites cover 'democratically' both hemispheres, and the large amount of data collected so far can complement ground information (e.g., made available under SuperMag initiative), and add important insight to the standard geomagnetic indices. Indeed, standard geomagnetic indices are based on sparse networks of ground stations (e.g., 4 ground stations adopted for DST index of which 3 in the Northern hemisphere, and 12 stations for AE index, all in the Northern hemisphere).

This investigation can be performed by analysing the distribution of FAC, AE index computed from Swarm data (see Fig.2) possibly complemented by platform magnetometers on other spacecraft, the Midlatitude Ionospheric Through + Small Scale FAC, Joule Heating.

The third possible activity addresses the investigation of Plasmaspheric Plumes through the local time asymmetries of the Midlatitude Ionospheric Through. Plasmaspheric plumes are structures of cold and dense equatorial ionospheric plasma that form during disturbed geomagnetic conditions extending up to the magnetopause, corotating with the Earth and causing an asymmetry in the plasmapause.
Several statistical studies of plasmaspheric plumes relied on ground-based observations, such as total electron content (TEC) maps, as well as on space-based observations of magnetospheric missions such as Cluster and Themis.
Swarm observations are also quite relevant to perform statistical studies to understand the plasmaspheric plumes formation, through the analysis of MIT, which is the ionospheric signature of the plasmapause.
Low altitude observations by Swarm can help characterizing a phenomenon believed to influence the magnetic reconnection process at the magnetopause (by changing the local plasma parameters) and thus the overall magnetospheric dynamics.

Figure 3: an illustration of auroral particle in the northern auroral oval

Extreme events, driven from solar wind and/or perturbations from lower atmosphere

This session included five dedicated presentations, illustrating the results of five different ESA projects: VERtical coupling in Earth's Atmosphere at mid and high latitudes (VERA), investigation of energetic ion up/outflow High-Low Atmospheric Interactions (HLAI), Contribution Of Swarm data to the prompt detection of Tsunamis and Other natural hazards (COSTO), Swarm for Anomalies (Swarm4Anom), and Investigating Lightning-Generated ELF Whistlers to improve ionospheric models (ILGEW). This session focussed, in particular, on vertical coupling among the different layers of the ionosphere, and signals due to perturbations in lower layers below Swarm altitude, such as sudden stratospheric warming events, energetic ion outflows, disturbances due to earthquakes / tsunamis (see Fig.4) and magnetic disturbances caused by electric currents induced by lightning.

The discussion at the end of the session focussed on how the study of the extreme events described in this session can improve our understanding of the ionsopsphere under normal conditions, and ionospheric models. It was pointed out that such extreme events are very rarely observed, and are therefore only at the tail of the statistics.

Can future global ionsospheric models include also the response to these extreme events?
If yes, what are the most important effects to be included?

An interesting possible future investigation as an outcome of these projects concerns the **different response of the two hemispheres (Arctic and Antarctic) to these extreme events.**
This analysis would help understand the physical processes responsible for the asymmetries between the two hemispheres, separating the ones related to internal drivers (such as, for example, neutral environment), from the external drivers, considering also the seasonal dependence and the configuration of geomagnetic field.

Another interesting activity as an outcome of these projects regards **the study of propagation /delay of the signals during these extreme events with the aim to improve coupled ionospheric models.**
Indeed, it is often possible to identify the sources of these extreme events in the lower atmosphere/ground with other instruments ground-based, knowing the exact time of the event and its location in space. The delay/propagation path of signals measured by Swarm with respect to source of the disturbances can be used to impose constraints on the acoustic and electromagnetic propagation trough the neutral atmosphere/ionosphere.
Vertical coupling in the atmosphere-ionosphere-magnetosphere system can have global and long-term impacts.
Comparing these observations with the models prediction would then provide corrections or validation for the current ionospheric models.

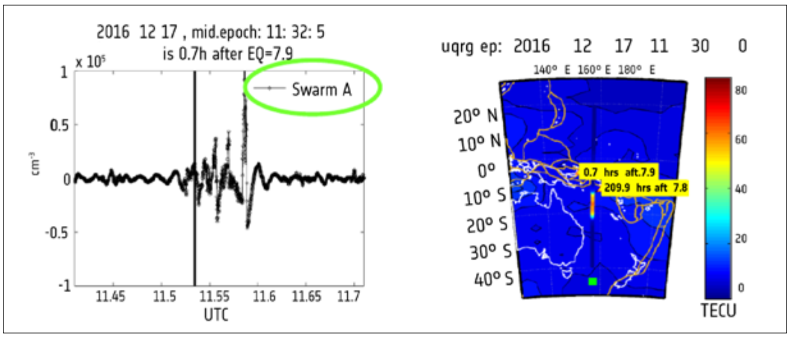

Figure 4: Swarm electron density gradient signals mea sured by Swarm A soon after the 2016 Tsunamiin Papua New Guinea.

Understanding the origin and processes of ionospheric fluctuations / irregularities / turbulence / Alfvén waves and their impact on GPS signals

Session 3 included five presentations illustrating the results of five Swarm ESA projects: INTENS [objective 2], Swarm Polar Cap Patches, EPHEMERIS [objective 2], Swarm SuperDARN ICEBEAR Collaboration – Turbulent E-region Aurora Measurements (SSIC-TEAM), and Swarm Investigation of the Energetics of Magnetosphere-Ionosphere Coupling (SIEMIC).

The results presented in this session showed how the presence of the small-scale irregularities analysed in these projects constitute a fundamental component of the ionosphere.

Their detailed characterization, made possible with the high-resolution Swarm in-situ measurements, allow better understanding of several phenomena in the ionosphere, and also to better quantify their interference on radio signals such as GNSS signals (see Fig.5).

The discussion at the end of this session identified a couple of scientific challenges, which can be tackled in the future.

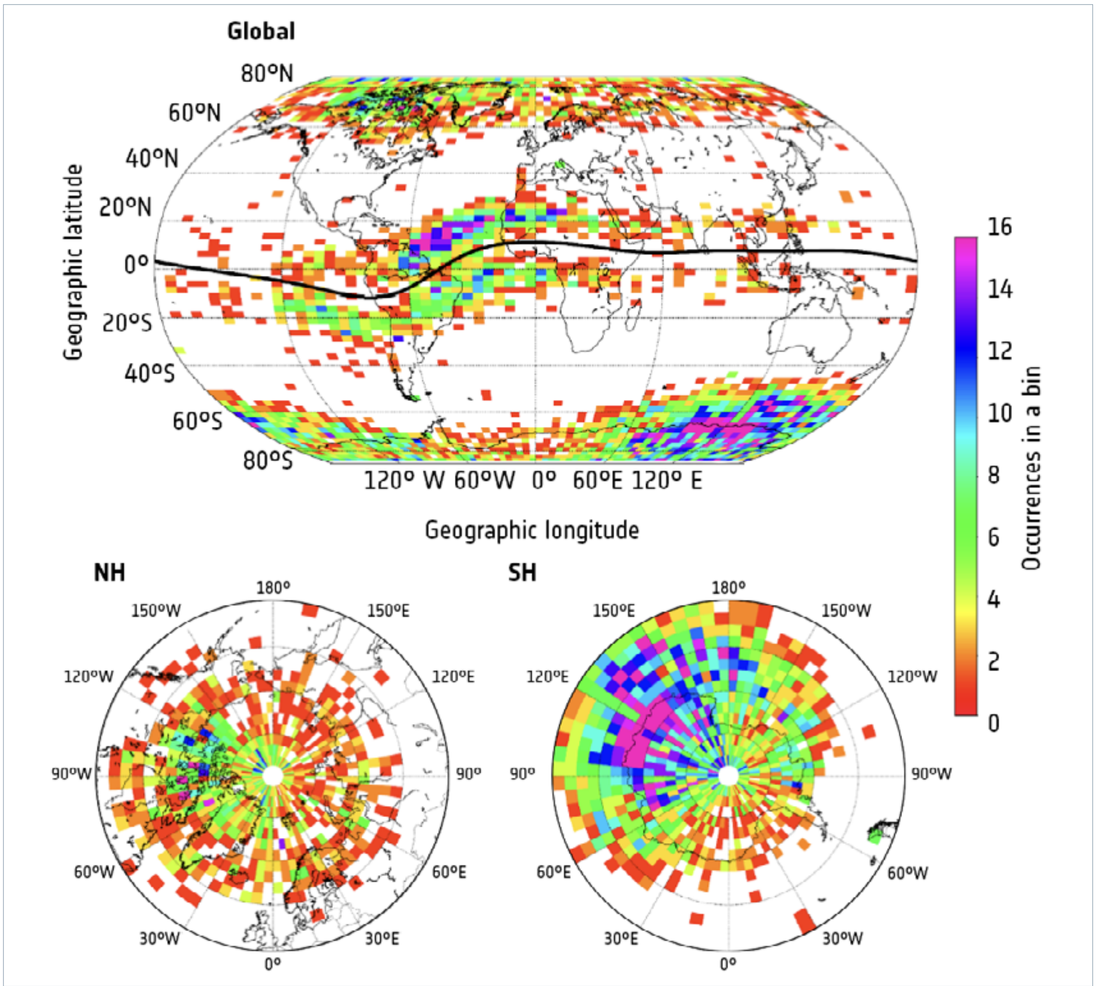

Figure 5: **GPS LOSS OF LOCK.** Swarm A GPS Loss Of Lock between April 2014 and March 2018.

The first one regards the possibility to **incorporate, in a future model** for ionospheric state and dynamics, **the more relevant information obtained about small-scale fluctuations / irregularities / turbulence / Alfvén waves** achieved in these studies.

This would allow making a step forward in Space Weather modelling and forecast, providing an in-situ based estimate of the energy input and plasma dynamics in the ionosphere, considering also the role of Alfvén waves and small-scale turbulent fluctuations, which are relevant with this respect, and assessing the different behaviour of the two hemispheres.

The second one regards the possibility to develop a Swarm-based irregularities statistical occurrence model to assess the relevance of turbulence, plasma instabilities and magnetic field intermittent structures in generating **the Loss-of-Lock (LOL) of GNSS** signals (see Fig.5).

This objective can be tackled constructing an empirical model of LOL, and investigating in detail the dependence of LOL on various parameters from the aforementioned Swarm-based irregularities model.
In particular, this investigation should compare the appearance of LOL as a function of the statistical features of electron density fluctuations / irregularities, also considering the possible influence of the various boundaries in the ionosphere that are identified by Swarm, such as auroral oval, polar cap, mid-latitude ionospheric through, etc, their seasonal behaviour, the solar activity, etc.

Swarm contribution to ionospheric models and possible new develoments

This session included five presentations, describing some of the main existing ionsospheric models capable of representing the topside ionosphere (covering the altitude at which Swarm s/c are flying), and potential future activities based on Swarm data to improve them. The main features of the Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIE-GCM), and the NeQuick Ionospheric Model were examined in three dedicated presentations, also illustrating the more recent efforts, based on Swarm data, aimed at improving these models.

As an outcome of this session, a number of improvements for these models have been discussed. In particular, for the TIE-GCM model the neutral dynamic is a critical part, which needs to be improved: some of the waves from the lower atmosphere such as mesoscale waves and gravity waves are not resolved. In addition, the temporal variability of atmospheric tides on a few days is not well captured by observation and models.
Swarm can indirectly contribute to the evaluation of thermospheric dynamics by using the neutral density derived from the ACC observations.
Combining it with neutral density data from GRACE as well as with electron density measured by Swarm, would provide further insights to the thermospheric dynamics.
Another area where the TIE-GCM model can be improved concerns the Magnetosphere Ionosphere coupling, and in particular, the accurate estimation of the energy input, which is usually underestimated by the models that do not represent the small-scale structures.
The Swarm high-resolution data can be useful to monitor the electric field variability and the presence of small scale Alfvén waves / turbulence / irregularities, addressing the variability due to seasons, solar wind conditions, inter-hemispheric asymmetries, etc.

Swarm in-situ electron density data (Ne) are giving an important contribution to the improvement of the NeQuick model topside profile formulation.
Indeed, NeQuick is an empirical climatological model, which allows calculating the electron concentration at any given location in the ionosphere.
NeQuick provides also the total electron content (TEC) along any ground-to-satellite ray-path, making it very important for telecommunication purposes, as testified by a relevant ITU (International Telecommunication Union) recommendation.
For an accurate description of TEC, a reliable modelling of the topside profile is of paramount importance, because this is the ionospheric region most contributing to TEC. Recent studies highlighted the need of improving the ionospheric topside description made by empirical models, which is particularly difficult under disturbed geomagnetic conditions and at low and high latitudes.
To this end, a number of research studies have focused on the improvement of the NeQuick model topside by using Swarm-measured Ne data and F2-layer peak characteristics, in particular through a specific modelling of the effective ionospheric topside plasma scale height (H0) as a function of foF2 and hmF2.
The original results limited to European sector, have been recently extended to the entire globe (adopting IRTAM instead of IRI UP to compute foF2 and hmF2).
A possible future development regards the introduction of some physics in the model, in order to better understand the observed behaviors.

Another presentation illustrated the status and objectives of the ESA project Swarm Space Weather Variability of Ionospheric Plasma (Swarm-VIP), which aims at developing a new dynamic, semi-empirical ionospheric model, by applying multiple data analysis techniques to the Swarm L1 and L2 datasets, and combine with supporting external relevant datasets.
In particular, this project is applying innovative scale analysis to Swarm data in order to investigate the spatio-temporal variability of the Earth ionosphere in relation to external drivers, both during quiescent and extreme conditions.

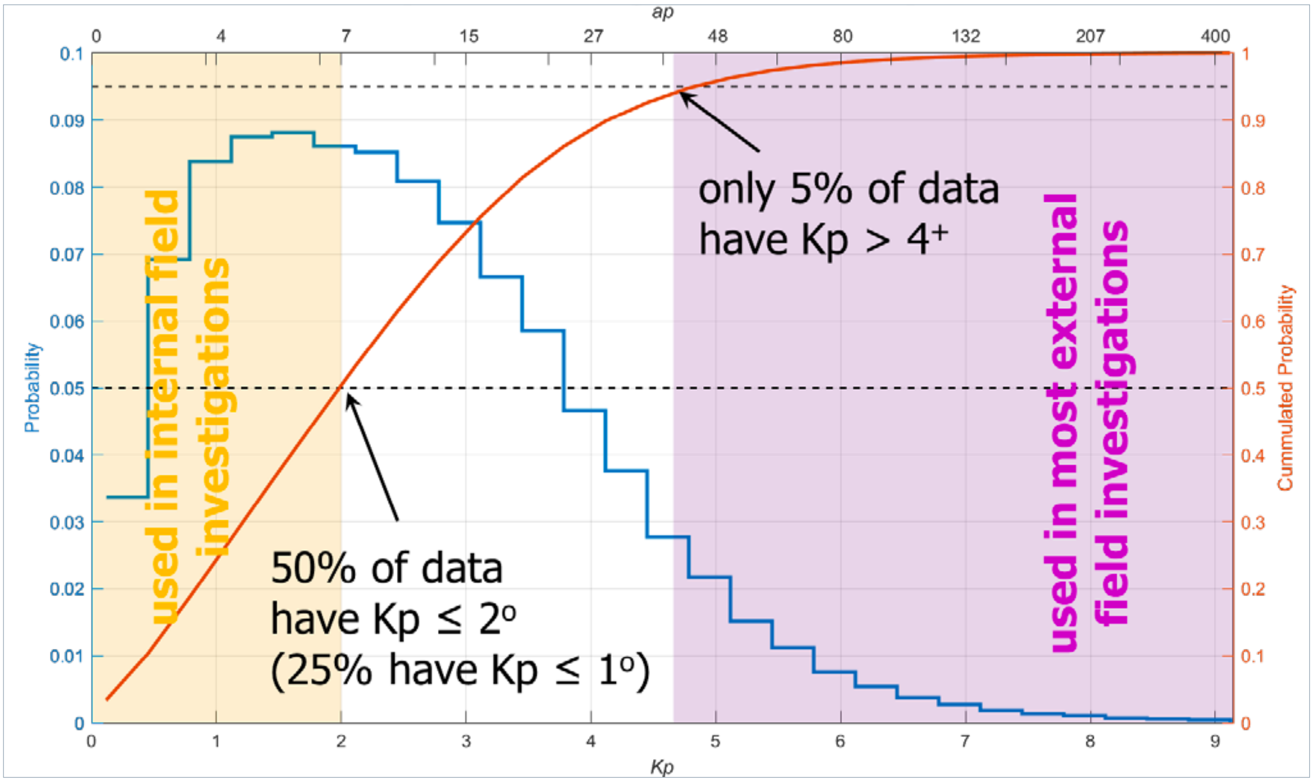

Figure 6: Distribution of Kp index, from 1932 to 2015.

The aim is to understand the processes that dominate in the various regions, and to integrate all available data into a statistical model and produce datasets with predicted plasma variability.

The last talk focused on the ionosphere during geomagnetic quite conditions, and demonstrated the importance of advancing our understanding of the quiescent time behaviour.
The quiet condition (Kp<2) is statistically the most common status of the ionosphere (see Fig.6), but is still characterized by an unexplained coherent magnetic signals with an intensity of up to 5 nT.
Therefore, a better description of the quiescent time ionosphere, highlighting the long-term variability and their main drivers is needed to better understand the background ionosphere, which is important for internal magnetic field studies.

Synergies with other existing or planned missions in the Sun-Earth connections domain

This session included five dedicated presentations focussing on potential synergies of Swarm with other existing or planned missions like Daedalus, INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory), Cluster, SMILE (Solar wind Magnetospheric Ionosphere Link Explorer), SMOS (Soil Moisture and Ocean Salinity) and NanoMagSat with the purpose to discuss the role of Swarm data in a 'bigger' context, highlighting broader interactions with other scientific communities.

In particular, it has been shown that continued operations would allow a continuous synergetic ESA multi-mission, multi-directorate dataset covering the Earth's magnetosphere/ionosphere system from Swarm and Cluster.
This would continue the ongoing collaborations between these two missions and provide a unique data set covering the peak of Solar cycle 24 through to solar maximum of solar cycle 25.
This would also be highly synergetic with the SMILE mission, due to launch in 2025.
The combined dataset from these missions would allow to better understand the magnetosphere-ionosphere coupling under all solar driving conditions, investigating in detail the auroral acceleration mechanism, and other key science topics like plasmapause, polar cap patches, ion outflow, FAC, ring currents, north-south asymmetries (see Fig.7), with simultaneous measurements at different altitudes covering the various spatial scales.

Another unique opportunity will occur at the time of Cluster re-entry in the lower atmosphere, allowing simultaneous measurements from Swarm and Cluster in the lower magnetosphere.
The first re-entry is foreseen with Cluster 2, in fall 2024, when all the instruments will continue collecting data up to 4-5000 km altitudes. Dedicated acquisition campaign, in synergy with Swarm, may be envisaged before the re-entry of the Cluster spacecraft.

The INTEGRAL mission usually focuses on high-energy astrophysics far outside the solar system, but it has been shown to also have potential in examining energetic emissions in the auroral regions of Earth.
As such, it is propsed that INTEGRAL will carry out remote sensing observations to complement in-situ measurements but Swarm and Cluster to examine auroral activity mechanisms.
Indeed, a small part of the signals measured by INTEGRAL during Earth occultation campaigns aimed at measuring the intensity of the cosmic X-ray background (considered as noise for this purpose), was actually coming from energetic particles accelerated in the Earth's auroral oval [Figure 8].

The INTEGRAL measurements due to Earth's auroral particles showed energy fluxes exceeding 100 keV, more intense during periods of intense magnetic storms (AE index > 1000 nT).
Therefore, dedicated INTEGRAL acquisition campaigns focussing on Earth's aurorae would be quite unique, coordinated with Swarm flying in the auroral oval and Cluster measurements in the geomagnetic tail, demonstrating again a multi- mission, multi-directorate 'one-ESA' approach to science.
SMOS (Soil Moisture Ocean Salinity) mission can also be complementary to Swarm for space weather studies. Indeed, the instrument on board SMOS, which is the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS), while aimed Earth's surface observations, can also provide precise estimates of Polarimetric L-band solar Flux in near real time, and Ionospheric Total Electron Content with a global coverage of Earth surface.
These new SMOS prototype products that are under development, in synergy with Swarm data, can be used to study the ionospheric response to impulsive events like CMEs (Coronal Mass Ejections), or to improve the TEC coverage.

Another new mission, which would be very useful in synergy with Swarm, is the NanoMagSat.
This mission would consist of three identical Cubesats, with miniaturized high precision / high frequency magnetometers, Langmuir probes, and GNSS receivers.

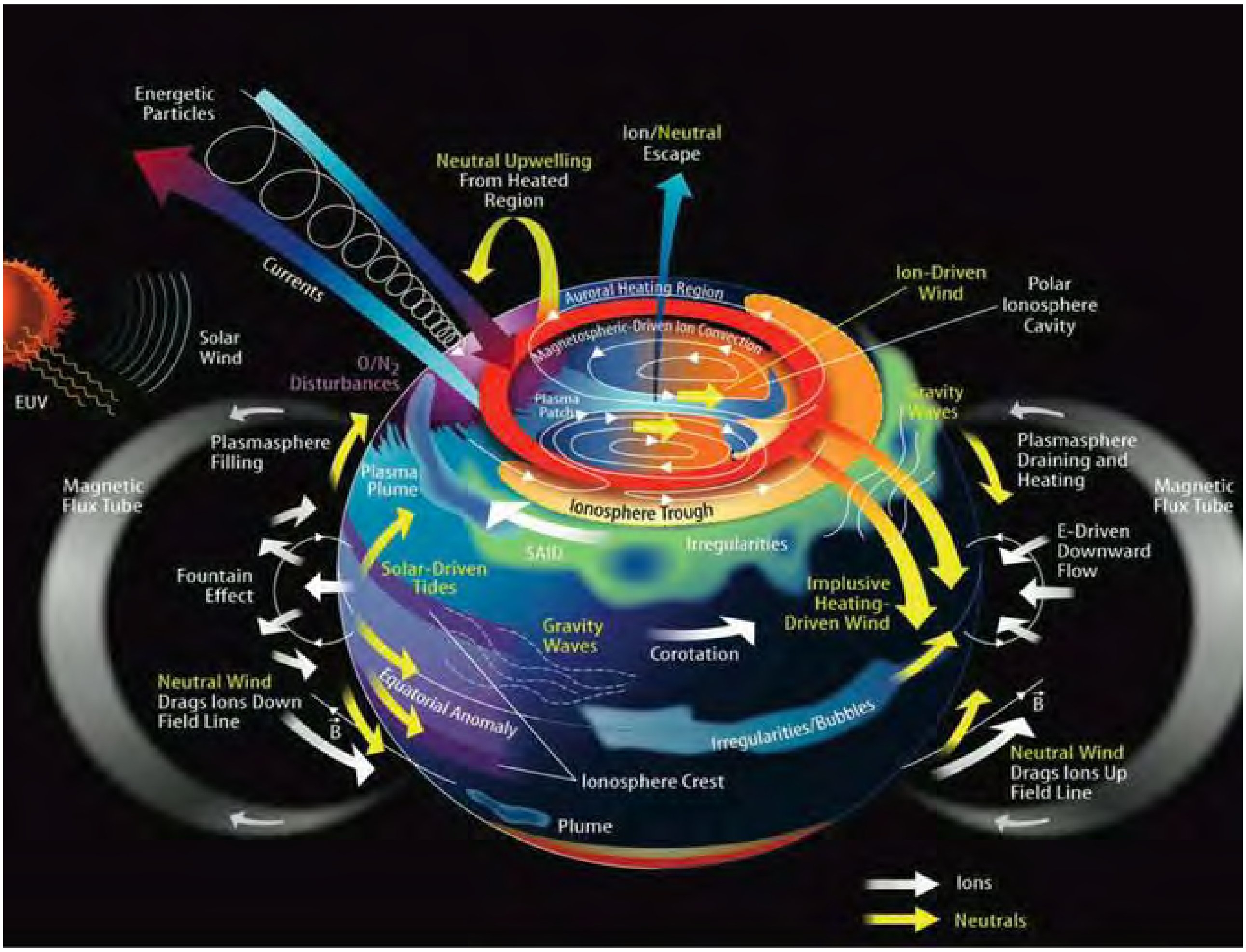

Figure 7: The complexity of the ionosphere-thermosphere-mesosphere system of planet Earth and the range of physical processes operating. Credit: NASA/J. Grobowsky.

The different orbits of these NanoMagSat spacecraft (two with a 60° inclination, with different local times, one in near-polar orbit) would allow to measure the Earth's magnetic field with high precision, covering all the Local Time in a much shorter time with respect to Swarm.

This would allow to focus on the fast planetary changes in core, ionospheric and magnetospheric fields, also improving recovery of crustal and oceanic signals, the rapid changes in solar-terrestrial interactions, and possible signatures of climate change.

Although not presented, the synergies with the EE10 candidate mission Daedalus were discussed.

Daedalus did not continue through to Phase A, but there are ongoing discussions with NASA Heliophysics and ESA EOP on a potential joint mission looking at the Lower Thermosphere-ionospheric connections.

Swarm is already carrying out campaigns with ground-based facilities, which are addressing broader LTI connectivity questions using incoherent scatter radars to examine altitude profiles of plasma temperature and density. As such, Swarm can play a key role in supporting this collaboration.

SUMMARY OF MAJOR SCIENTIFIC CHALLENGES FOR THE FUTURE COMING FROM THIS WORKSHOP

A better characterization of the geomagnetic quiet ionosphere

The quiet ionosphere, identified through the low values of the Kp index that quantifies the disturbances in the horizontal component of earth's magnetic induced by solar wind, is statistically the most common status of the ionosphere: 50% of data have Kp $\leq 2^0$, 25% have Kp $\leq 1^0$ and only 5% of data represents the active conditions, i.e. have Kp > 4^+. During these quiet conditions, the ionosphere is not undisturbed as expected, but coherent magnetic signals with intensity up to 5 nT are observed, which remain currently unexplained.
In addition, also the electron density and the low latitude electric field show a not negligible variability during these quiet conditions.
A better description of the quiescent time ionosphere, highlighting the long-term variability and their main drivers is needed to better understand the background ionosphere, and this would be beneficial also for internal magnetic field studies.
In this respect, Swarm represents now the optimal mission to perform this investigation, having collected a very large amount of data with the 3-s/c and 16 orbits per day by 8 years (so far).
This investigation can involve both statistical studies, based on the new Swarm-based geomagnetic indexes developed by INTENS, the distribution of FAC using the new techniques and online tools developed under SIFACIT, Plasma Pause (PP) position from EPHEMERIS, but also a number of event studies over a broad range of phenomena observed in Swarm data.

Asymmetries between the two hemispheres

Another scientific challenge concerns the understanding of asymmetries between the two hemispheres (Arctic and Antarctic), which results in differences in ionospheric plasma convection, auroral intensity, thermospheric wind, total electron content, and magnetic field perturbations and associated currents. Some of the asymmetries are expected according to the asymmetries in external drivers, like interplanetary magnetic field, energetic particles precipitation, geometry of magnetic reconnection at the magnetopause [Trenchi et al., 2008], or internal asymmetries such as magnetic dipole effect [Pakhotin et al., 2021], geometry of geomagnetic field [Laundal et al., 2016], seasonal variation, ionospheric anomalies. Analysing in detail the inter-hemispheric asymmetries would therefore allow a better understanding of the ionospheric response to internal and external drivers, and to unravel the other observed asymmetries, which remain unexplained. Swarm is the ideal mission to study the inter-hemispheric asymmetries. Indeed, Swarm satellites cover 'democratically' both hemispheres, and the large amount of data collected so far can complement ground information (made available under SuperMag initiative), and add important insight to the standard geomagnetic indices, which are based on limited number of sparse ground stations (4 stations for DST index, and 12 stations for AE index, all in the Northern hemisphere). This investigation can involve the new Swarm-based AE indexes developed by INTENS that cover separately the two hemispheres, the distribution of FAC measured by Swarm (using the new techniques developed under SIFACIT), the Midlatitude Ionospheric Through (EPHEMERIS), and can also examine the different response of the two hemispheres to the extreme events under the projects: VERA, HLAI, COSTO, Swarm4Anom, and ILGEW.

Investigation of Plasmaspheric Plumes with Swarm data

Another scientific challenge concerns the investigation of Plasmaspheric Plumes. Plasmaspheric plumes are structures of cold and dense equatorial ionospheric plasma that form during disturbed geomagnetic conditions extending up to the magnetopause, corotating with the Earth and causing an asymmetry in the plasmapause. Several statistical studies of plasmaspheric plumes relied on ground-based observations, such as total electron content (TEC) maps, as well as on space-based observations of magnetospheric missions such as Cluster and Themis. Swarm observations are also quite relevant to perform statistical studies to understand the plasmaspheric plumes formation, through the analysis of Midlatitude Ionospheric Through developed under EPHEMERIS, which is the ionospheric signature of the plasmapause. Low altitude observations by Swarm can help characterizing a phenomenon believed to influence the magnetic reconnection process at the magnetopause (by changing the local plasma parameters) and thus the overall magnetospheric dynamics.

Combined observation from Swarm and Cluster, with the complement of SMILE data when available, would be highly beneficial for this investigation.

A new model about small-scale fluctuations / irregularities / turbulence / Alfvén waves

The analysis performed in the five projects [INTENS, Swarm Polar Cap Patches, EPHEMERIS, SSIC-TEAM, SIEMIC] demonstrated that the small-scale irregularities / structures / turbulence constitute a fundamental component of the ionosphere. Their detailed characterization, made possible with the high-resolution Swarm in-situ measurements, allow better understanding of several phenomena in the ionosphere, and better quantifying their interference on radio signals such as GNSS signals. A future model for ionospheric state and dynamics could incorporate all the more relevant information obtained about small-scale fluctuations / irregularities / turbulence / Alfvén waves achieved in these studies. This would allow making a step forward in Space Weather modelling and forecast, providing an in-situ based estimate of the energy input and plasma dynamics in the ionosphere, considering also the role of Alfvén waves and small-scale turbulent fluctuations, which are relevant with this respect, and assessing the different behaviour of the two hemispheres.

Figure 8: Picture of an aurora borealis in United States.

A new model for Loss-of-Lock (LOL) of GNSS signals

The presence of the small-scale irregularities in the ionosphere is responsible for degradation of GNSS signals, which can result, in the more severe events, in the Loss-of-Lock (LOL) of GNSS signals.
The large amount of data collected by Swarm would allow studying in detail the occurrence of LOL assessing the role of turbulence, plasma instabilities and magnetic field intermittent structures in generating them. This objective can be tackled constructing an empirical model of LOL, and investigating in detail the dependence of LOL on various parameters from the aforementioned Swarm-based irregularities model.
In particular, this investigation should compare the appearance of LOL as a function of the statistical features of electron density fluctuations / irregularities, also considering the possible influence of the various boundaries in the ionosphere that are identified by Swarm, such as auroral oval, polar cap, mid-latitude ionospheric through, etc, their seasonal behaviour, the solar activity, etc.

Improving the existing ionospheric models with Swarm data

The large amount of high-resolution Swarm data collected so far provides a unique opportunity to improve the existing ionospheric models.
In particular, for the TIE-GCM model the neutral dynamic is a critical part, which needs to be improved. Swarm can indirectly contribute to this purpose by using the neutral density derived from the ACC observations, combined with neutral density data from GRACE. Another area where the TIE-GCM model can be improved concerns the Magnetosphere Ionosphere coupling, and in particular, the accurate estimation of the energy input, which is usually underestimated by the models that do not include the small-scale structures. The Swarm high-resolution data can be useful to monitor the electric field variability and the presence of small scale Alfvén waves / turbulence / irregularities, addressing the variability due to seasons, solar wind conditions, inter-hemispheric asymmetries, etc.

For the Swarm NeQuick model, in-situ electron density data (Ne) measured by Swarm can give an important contribution for the improvement of the model in the topside profile formulation. Recent studies highlighted the need of improving the ionospheric topside description made by empirical models, in particular under disturbed geomagnetic conditions. To this end, Swarm-measured Ne data can improve the effective ionospheric topside plasma scale height (H0) as a function of foF2 and hmF2, allowing to introduce some physics in the model, in order to better understand the observed behaviors.

Another interesting contribution from Swarm data for improving the existing models concerns the study of propagation / delay of the signals during the extreme events examined in the projects VERA, HLAI, COSTO, Swarm4Anom, and ILGEW.
It is often possible to identify the sources of these extreme events in the lower atmosphere / ground with other instruments ground-based, knowing the exact time of the event and its location in space.
The delay / propagation path of signals measured by Swarm with respect to source of the disturbances can impose constraints on the acoustic and electromagnetic propagation trough the neutral atmosphere / ionosphere, providing corrections or validation for the current ionospheric models.

A new multi-mission, multi-directorate and a multi-agency collaboration

The connection between the Sun, the solar activity (solar wind, radio bursts, solar flares, CMEs) and the Earth's magnetosphere, ionosphere and atmosphere can be viewed as a collection of interconnected systems, each with distinct processes and varied coupling [see Fig.9]. Enhancing our understanding and the characterisation of this system of systems and its impacts on our environment and human activities requires a major multi-observatory, interdisciplinary research effort, dedicated missions and tools, where open science, sharing of knowledge and collaborative research should be a critical factor for success.

This is also particularly critical if we consider how conditions in space (Space Weather) affect technology and activities therein, especially with current European growth in space activities.

EO missions, such as Swarm, can address part of this challenge by continuing to provide its unique data across as long time as possible, providing access to long-term trends driven by changing solar activity. However an holistic view of the Earth-sun system can only be provided by a multi-mission interdisciplinary approach to science where EO satellites, data and scientific results are combined with ground based facilities and also other ESA missions both ongoing (e.g. Cluster, SOHO and Solar Orbiter) and in the near future (e.g SMILE, L5, D3S and LEOP-Gateway).

Looking further in time and from a cross agency perspective, there are missions coming with specific focus on magnetospheric – ionospheric and atmospheric coupling (e.g. NASA's Geospace Dynamics Explorer and DYNAMIC mission, JAXAs FACTORS mission).

In this context, an ambitious multi-mission, multi-directorate and a multi-agency collaboration, is needed, aimed at providing a step change in the way we observe and understand the Earth-Solar system where the final output in bigger than the sum of the individual parts.

This is also highly relevant to ESA's role in Europe related to Space Weather related activities. In addition, with the inter-directorate approach, Swarm is a key part of the ESA Agenda 2025 and in turn plays a key part in ESA's inter-agency interactions in this area (both space and ground based).

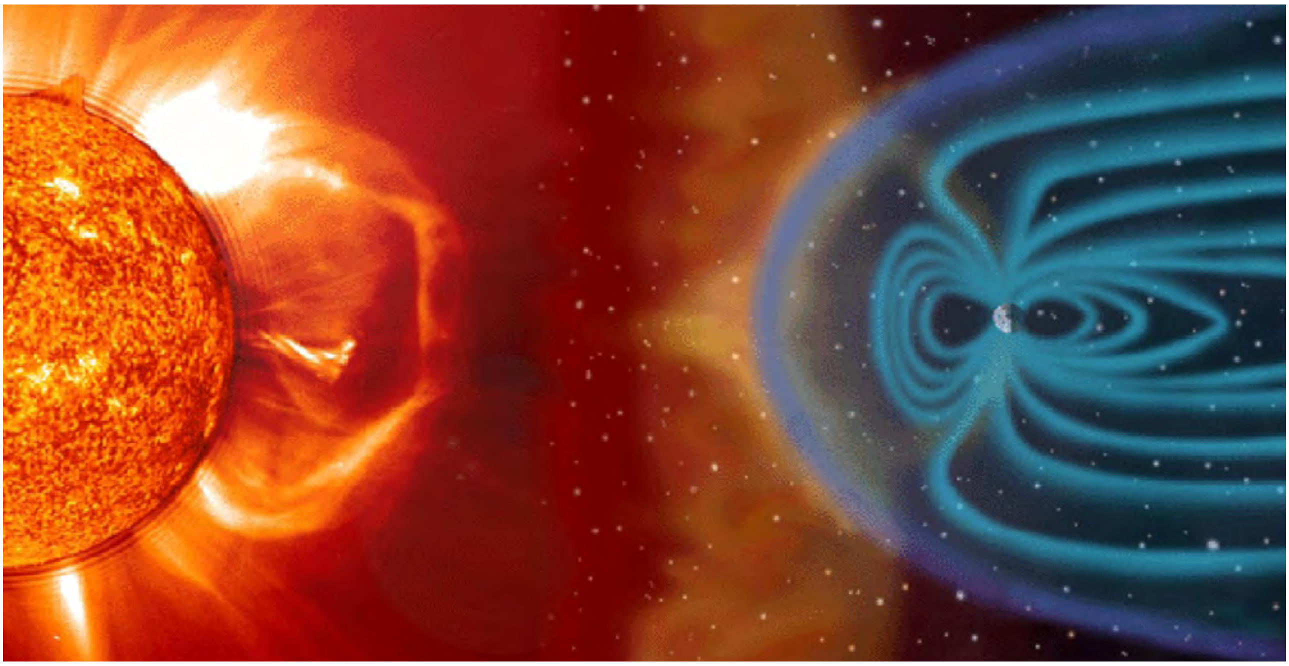

Figure 9: This composite image shows a SOHO image of the Sun and an artist's impression of Earth's magnetosphere.

REFERENCES

- Laundal et al., 2016, North–South Asymmetries in Earth's Magnetic Field, Space Sci Rev DOI 10.1007/ s11214-016-0273-0

- Pakhotin et al., 2021, Northern preference for terrestrial electromagnetic energy input from space weather, Nature communication, https://doi.org/10.1038/s41467-020-20450-3

- Trenchi et al., 2008, Occurrence of reconnection jets at the dayside magnetopause: Double Star observations, J. Geophys. Res., 113, A07S10, doi:10.1029/2007JA012774