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ORIGINAL ARTICLE

What are the fundamental modes of energy transfer and partitioning in the coupled Magnetosphere-Ionosphere system?

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Abstract

The fundamental processes responsible for energy exchange between large-scale electromagnetic fields and plasma are well understood theoretically, but in practice these theories have not been tested. These processes are ubiquitous in all plasmas, especially at the interface between high and low beta plasmas in planetary magnetospheres and other magnetic environments. Although such boundaries pervade the plasma Universe, the processes responsible for the release of the stored magnetic and thermal plasma energy have not been fully identified and the importance of the relative impact of each process is unknown. Despite advances in understanding energy release through the conversion of magnetic to kinetic energy in magnetic reconnection, how the extreme pressures in the regions between stretched and more relaxed field lines in the transition region are balanced and released through adiabatic convection of plasma and fields is still a mystery. Recent theoretical advances and the predictions of large-scale instabilities must be tested. In essence, the processes responsible remain poorly understood and the problem unresolved. The aim of the White Paper submitted to ESA's Voyage 2050 call, and the contents of this paper, is to highlight three outstanding open science questions that are of clear international interest: (i) the interplay of local and global plasma physics processes: (ii) the partitioning during energy conversion between electromagnetic and plasma energy: and (iii) what processes drive the coupling between low and high beta plasmas. We present a discussion of the new measurements and technological advances required from current state-of-the-art, and several candidate mission profiles with which these international high-priority science goals could be significantly advanced.

Keywords Earth · Magnetosphere-Ionosphere coupling · Voyage 2050 · Space missions

1 Introduction

Energy exchange between electromagnetic fields and plasma is the fundamental physics that drives all Solar System plasmas and beyond. Theoretically, these processes are well understood in benign, uniform situations. However, in planetary magnetospheres and other magnetic environments, those conditions rarely exist. In particular, energy exchange processes between plasma-dominated environments and magnetic field dominated environments is a big unknown.

The Earth's magnetosphere is the nearest example of a physical region where such energy conversion, exchange, and transport occurs. Significant progress has been achieved in understanding the basic nature of the energy input into the system, but not its release. Detailed understanding of dayside and nightside reconnection, and its global consequences have been achieved on fluid and ion scales with missions such as Cluster [26], Geotail,[1] and THEMIS (Time History of Events and Macroscale interactions during Substorms, [2], and most recently now on electron scales following the launch of the Magnetospheric Multiscale (MMS)[2] mission in 2015. Energy transfer into energetic particles in the ring current and radiation belts has also been significantly advanced by the Van Allen Probes and Arase mission, but have focussed on the nature of wave-particle interactions *in-situ* in the inner magnetosphere. However, how the energy released from reconnection is processed in the transition region and inner magnetosphere following the large-scale topological changes associated with magnetic reconnection is not understood. Indeed, the lack of knowledge about the physical processes which control the energy exchange in this transition region between stretched magnetotails and more dipolar inner magnetosphere represent a fundamental challenge to understanding the overall energy transfer in highly coupled magnetised plasma systems under forcing from solar, stellar, and astrophysical plasma winds.

1.1 Recent advances and current state-of-the-art

Historically, solar wind-magnetosphere-ionosphere science concentrated on the system-level coupling of the magnetosphere to the external driving of the solar wind. However, it has been shown on multiple occasions that the system-level dynamics respond to external driving to, at best, a 50% level [77]. This means that barely half of system-level dynamics can be characterised on magnetohydrodynamic (MHD) fluid scales as a simple driven system, dependent upon input solar wind and magnetic indices, while the remainder of the variability in the system cannot be explained. As a result of this, studies have sought to concentrate on smaller and smaller scales, starting from ion scales with the Cluster mission [26], and towards electron scale microphysics with the current state-of-the-art of the NASA MMS mission studying magnetic reconnection processes [13].

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[1] https://www.isas.jaxa.jp/en/missions/spacecraft/current/geotail.html

[2] https://mms.gsfc.nasa.gov/

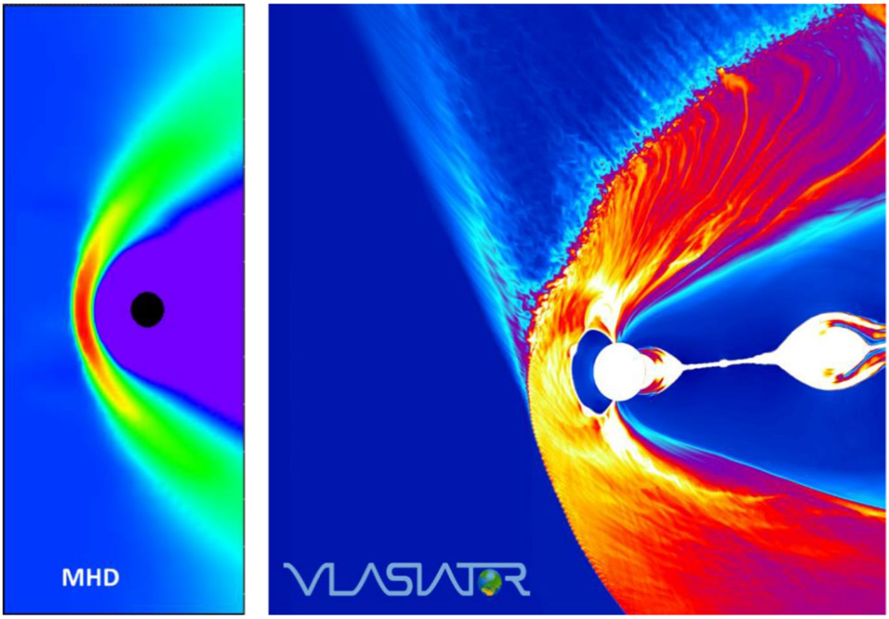

Fig. 1 Global magnetospheric simulations on (left) MHD fluid scales, and (right) hybrid kinetic-ion scales highlighting the complexity of solar wind-magnetosphere interaction across kinetic scales (M. Palmroth and Vlasiator team; [64])

In tandem, and around the time when the Cluster mission was launched in 2000, the modelling community recognised the need to push current capabilities beyond fluid scales, in order to place the new ion scale measurements in context. Together with advances in computing capabilities, this push led to new developments and approaches such as coupling Global MHD codes to inner magnetospheric convection models and ionosphere-thermosphere models [84] or developing an entirely new methodology described as a “hybrid approach”, whereby ion kinetic scales are modelled accurately but electrons are still treated as a fluid. These new approaches gave us the first glimpses of the impact of small, kinetic-scale physical processes on the global magnetosphere-ionosphere plasma system (e.g., [64]), see Fig. 1.

In kinetic simulations, dayside magnetospheric processes in the form of flux transfer events (FTEs) have been shown to have an impact in both the magnetosphere in the form of electromagnetic wave propagation but also on the shocked plasma of the magnetosheath [66]. Electron kinetic scale simulations can describe both the electron acceleration that plays a key role during dynamic aurora [89], and how global changes in field-aligned currents may be supported through the propagation of short perpendicular scale (dispersive) Alfvén waves [88]. There are, however, regions of the magnetosphere-ionosphere system that are very difficult to model due to the large gradients between different plasma parameter regimes (e.g., close to the ionosphere) or due to the large differences between the length and time scales of the kinetic processes and the size of the system (e.g., the inner magnetosphere). However, it is clear that models are now leading the search for new kinetic physics and their impact on near-Earth space, primarily due to the lack of multiple scale state-of-the-art observations. Observations at the ion- and electron-scales by missions such as Cluster and MMS, respectively, are currently used in conjunction with multi-scale kinetic modelling to examine components of the multi-scale physical processes. However, it is only by providing simultaneous observations across multiple scales that we will achieve science closure on the fundamental physical coupling of these processes within our own, dynamic plasma environment and, by extension, other environments.

Historically, our field has tried to advance our knowledge in one of a number of ways. Firstly, the effects of kinetic plasma physics at the system-level have been simply parameterised as a function of a given plasma regime, without knowing the controlling factors or non-linear coupling behaviour between temporal or spatial scales. Specific examples of this might include the effects of anomalous resistivity on magnetic reconnection [15], and current disruption in the magnetotail (e.g., [48] and references therein) or electron decay timescales for radiation belt losses in place of wave-particle interaction inside the plasmasphere (e.g., [78]). Secondly, the search for electron-scale microphysics has been performed with MMS with very little direct information on the global, fluid-scale context. Finally, we have sought increasingly complicated and complex empirical coupling functions between plasma regimes with which to attempt to better correlate external and internal measures of plasma physics operating in near-Earth space (e.g., [6, 57, 10]). Understanding the coupling between small-scale and large-scale physical processes is essential to understand the time-varying coupling of the magnetosphere-ionosphere system.

1.2 Recent state-of-the-art observations

Previous multi-point measurement of space plasmas has focussed on individual scales, which imposes particular constraints on the spacecraft constellation. No previous mission has been able to simultaneously measure more than one 3D scale at any given time; the "Cross-scale" concept. The notable context for a multi-scale mission has been provided by the close configurations achieved during the Cluster and MMS missions. Cluster has covered a range of spatial coverage (from 200 km to thousands of km) with a relatively close array of four spacecraft, which freely evolved around the polar eccentric orbit (initially 4×19.6 R_E) and was normally adjusted during a series of orbital manoeuvres at 6 monthly to 1-year intervals. In the later part of the Cluster mission, some spacecraft were allowed to drift relative to the others to achieve some coverage of more than one spatial scale by one or two spacecraft (see Fig. 2). This attempt was limited by the orbit, and multiple scales were only achieved at the expense of fully resolving 3-D gradient information (an example of which is shown in Fig. 3). MMS followed Cluster in achieving a tight configuration, targeted at the outer magnetospheric boundaries, on scales of a few 10 s km. Other missions, such as THEMIS, have used a distributed constellation, with two or more spacecraft flying closely together only in certain mission phases.

Swarm [29] on the other hand is a set of now four spacecraft in Low Earth Orbit, including the Canadian Space Agency's CASSIOPE/e-POP [92] at altitudes ranging

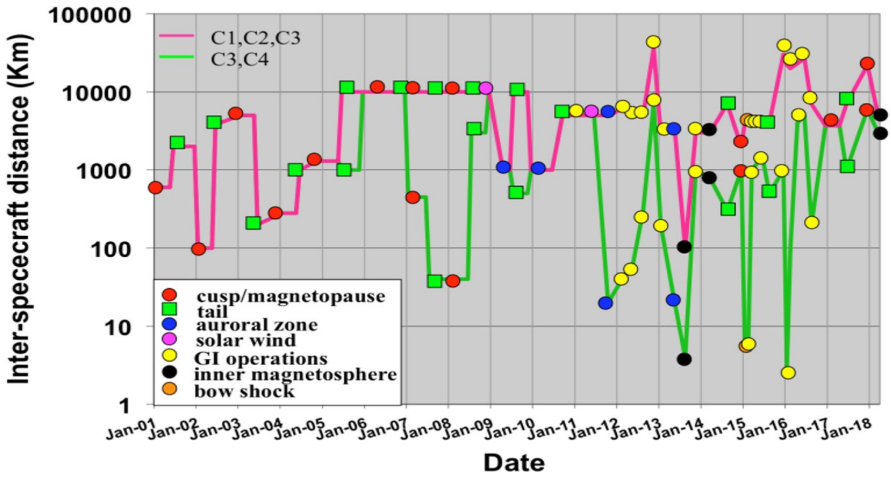

Fig. 2 Cluster separation strategy during the first 16 years of its operations. (Credit: ESA)

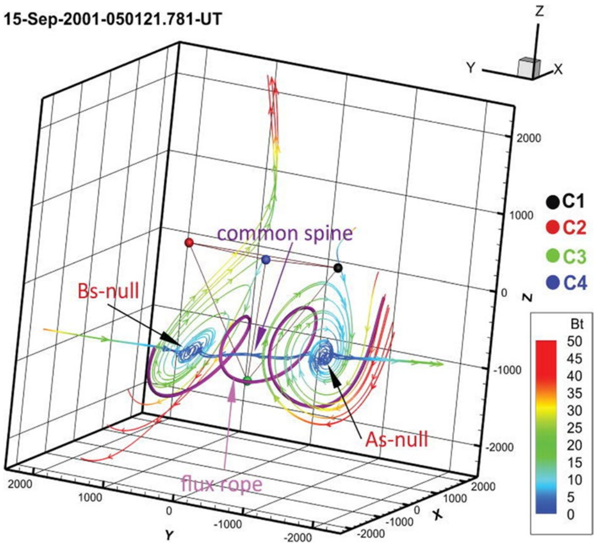

Fig. 3 Magnetic field reconstruction results for a flux rope event showing a separator connecting a pair of A-B null points (after, [33]) and the limitation of a small spacecraft array for multiple structure

from 300–1500 km, where two satellites Swarm A and C are side-by-side to distinguish spatial and temporal scale changes in magnetosphere-ionosphere coupling through field-aligned currents and Alfvén waves at of order 50 km separation (e.g., [21, 28, 58, 65]).

1.3 Upcoming advances and/or missions

Within magnetospheric physics, upcoming and potential missions from ESA include SMILE [12] and Daedalus.[3] SMILE will image the global magnetospheric topology for the first time and is due for launch in 2024. Daedalus, under the ESA Earth Observation Programme, completed a Phase 0 study in 2021 as a constellation mission to study the link between the ionosphere and the thermosphere. Although it was recommended as a potential Phase-A candidate it was not proposed for selection by ESA at that time due to cost constraints.[4] Upcoming missions from NASA include: Geospace Dynamics Constellation (GDC)[5] and the Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites (TRACERS).[6] GDC is a similar constellation mission to Daedalus, and TRACERS is a Low Earth Orbit twin spacecraft mission to study the interaction of the solar wind with the magnetosphere in Earth's magnetospheric cusps.

There are a number of Cubesat missions targeting elements of the specific science targets covered by this article, but no other magnetospheric or ionospheric mission is planned to the authors' knowledge. Ground-based facilities exist to monitor the electrodynamics and coupling of the magnetosphere and ionosphere, such as EISCAT 3D, SuperDARN, and TREX; all of which would be highly complementary for the science goals of this White Paper, assuming their continued existence up to and including the Voyage 2035–2050 window.

2 Breakthrough space plasma science and key plasma physics concepts

The study of the coupled terrestrial magnetosphere-ionosphere system is key to understanding a huge range of plasma physics environments. The exchange of energy between electromagnetic fields and plasma is governed by system-level coupling, large-scale transport processes, and highly localised and typically non-linear plasma instabilities. All of these elementary physical processes occur on varying temporal and spatial scales that are controlled by both changing internal conditions or changes in external solar wind driving. Thus, in order to understand the coupled system, a wide range of plasma regimes and driving conditions must be understood. One way to describe this cross-temporal and –spatial coupling is to characterise the plasma system in terms of fundamental plasma physical parameters, such as plasma frequency (f_{pe}), electron gyrofrequency (f_{ce}), and plasma beta (β). Combined with ion and electron Larmor radii, and Debye length, these parameters define which *fundamental* plasma

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[3] https://daedalus.earth/

[4] https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Preparing_for_tomorrow/ESA_moves_forward_with_Harmony

[5] https://science.nasa.gov/heliophysics/resources/stdts/geospace-dynamics-constellation

[6] https://www.nasa.gov/press-release/nasa-selects-missions-to-study-our-sun-its-effects-on-space-weather

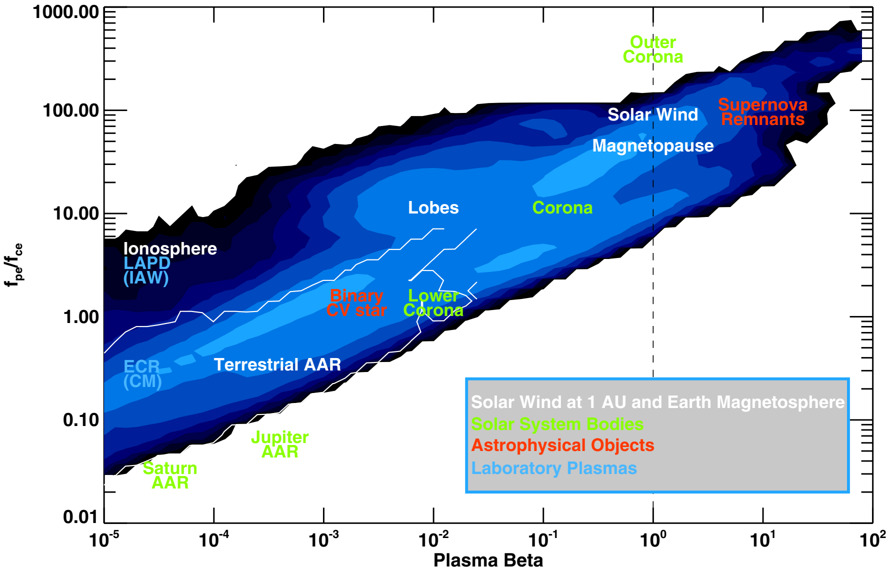

Fig. 4 Properties of various Solar System, astrophysical objects, and lab plasma regimes as a function of plasma frequency (f_{pe}), electron gyrofrequency (f_{ce}), and plasma beta (β). In colour are real measurements from the Cluster spacecraft over the mission lifetime, superimposed on this are regimes of each Solar System, lab plasma, or astrophysical object

physical processes can operate to exchange energy between electromagnetic fields and plasma in any given system. Earth's coupled magnetosphere-ionosphere system provides a small astrophysical volume in which these parameters vary by eight orders of magnitude, ranging from the plasma-dominated plasmasheet, to the magnetic field dominated ionosphere, where collisions become important, in particular with atmospheric neutrals. Given that the Earth's coupled magnetosphere-ionosphere system uniquely spans all of these plasma regimes (Figs. 1 and 4) we can effectively and efficiently study the underlying plasma processes characteristic of environments throughout the Universe without leaving Earth's orbit. Moreover, this cross-regime coupling exists in all regions in the magnetosphere, where the characteristic velocities in the plasma approach the speed of light. This means that new observations are needed to drive new modelling results. In short, we cannot study the Earth's magnetosphere by using modelling alone, as there are a continuum of rapid changes in fundamental plasma properties moving from region to region inside of near-Earth geospace.

Our key plasma physics questions can be separated into three groups, interlinked on specific temporal and spatial scales, that are required to answer the overarching scientific question of "what are the key processes that couple the magnetosphere and ionosphere?". We present the questions in logical order: how local (small-scale) processes manifest as global dynamics and how the state of the magnetosphere is then fed back into these local processes; how and where energy is partitioned between plasmas and fields in the magnetosphere, and finally defining the aspects needed to answer what are the key processes that couple the magnetosphere to the ionosphere.

3 How do local plasma processes have global consequences?

What are the roles of electron-scale physics in driving global magnetospheric dynamics?
How does the large-scale magnetospheric system feed-back and control electron dynamics?

Global magnetospheric dynamics are driven by the variability of the solar wind and the internal processing of the magnetosphere, and can be relatively well described by the macroscale parameters of the solar wind and magnetospheric topology. However, at each stage of this coupling, the energy transfer is critically dependent upon electron-scale physics. Solar wind plasma is a highly structured and turbulent medium [85] that evolves in time and space and supports a variety of wave modes and the intrinsic large-scale topological discontinuities and solar wind plasmas that are frozen-in to the interplanetary magnetic field (IMF) within the solar corona. As the solar wind and IMF rapidly expand out into the heliosphere its interaction with planetary magnetic fields results in a bow shock, whereby the solar wind and IMF are processed before interacting with the planetary magnetosphere.

Since its postulation by Dungey [18–20], it has been widely accepted that magnetic reconnection is the dominant coupling process between magnetically disconnected plasma and field regimes. At Earth, magnetic reconnection between the IMF and terrestrial field is the primary mechanism that drives the global energy flow in the outer magnetospheric system. Essentially, when the IMF is anti-parallel to, or has a component anti-parallel to, that of the terrestrial field, then the field lines can become interconnected and plasma from the solar wind can be accelerated and gain access to the near-Earth environment. Magnetic reconnection releases stored magnetic energy that is quickly converted to plasma kinetic energy, resulting in dramatic changes both in the large-scale magnetic topology of the Earth’s magnetic field, and in the flux of energetic particles in near-Earth space. At the heart of the reconnection region, extremely small “diffusion regions” on the scale of an electron gyroradius dictate the evolution of 30 $R_E{}^3$ regions of geospace.

Transient dayside magnetic reconnection allows solar wind energy, mass, and momentum to be extracted through particle energisation, the support and evolution of field-aligned currents across the dayside magnetosphere, and the transport of flux into the nightside magnetotail [23, 86]. These dayside processes therefore directly couple to the cusp and high latitude auroral zone, playing a role in driving Region 1 and cusp field-aligned currents. The dayside magnetosphere can also be perturbed by kinetic plasma phenomena known as Hot Flow Anomalies (HFAs),localised kinetic plasma phenomena first postulated by kinetic plasma simulations [9] and recently discovered to be a major component of energy transfer from the solar wind into the magnetosphere [3]. The Kelvin–Helmholtz instability at the dayside and flank magnetopause is a prime example of a process that spans spatial and temporal scales, whereby a system-level process develops into non-linear vortices that operate across the small spatial scale of the magnetopause boundary. In turn, the vortices produce anti-parallel magnetic fields as a consequence of their evolution, and so it is also highly likely that small-scale magnetic reconnection may additionally contribute to energy exchange within the spatially localised magnetopause interface [62]. This energy can be accumulated in localised regions of resonant magnetic field lines, where field line resonances [72, 81] can shape the energy transfer via Joule heating [69], drift-resonance [24], and localised electron losses [70].

Since Earth's magnetosphere and ionosphere form a tightly coupled system, this information is communicated over great distances by changes in electric currents flowing along the magnetic field [7]. Indeed, Birkeland pioneered the transfer of energy from one medium to another via currents flowing along the magnetic field, which we now know is the fundamental mode of energy transfer from the solar wind into the magnetosphere.

In the magnetotail, the explosive release of stored energy within a terrestrial substorm marks the beginning of the most dynamic and vibrant auroral display in the solar-terrestrial environment [4, 5]. Stored magnetic and thermal plasma energy is quickly converted to plasma kinetic energy, resulting in dramatic changes in both the large-scale magnetic topology of the Earth's nightside magnetic field, and the increased flux of accelerated energetic particles in near-Earth space. More generally, explosive energy transfer between fields and plasma is a ubiquitous process throughout the Solar System and electron-scale physics will be key to understanding this energy release. Processes such as solar flares proceed rapidly and unpredictably, but with many common characteristics to substorms [8]. However, we now know that MHD does not describe the full physics of plasma interactions in planetary environments that dramatically change in response to the solar wind in both time and in space. Hence, MHD processes can only capture around 50% of the total variance of a system,electron- and ion-scale physics must provide the other 50%.

Electron-scale physics feeds into the global dynamics both through magnetic reconnection processes and plasma instabilities. Detailed understanding of the local operation and initiation of both dayside and nightside reconnection; and a limited understanding of its global consequences, has been achieved on fluid and ion scales with missions such as Cluster, Geotail, and THEMIS, and most recently now on electron scales following the MMS launch in 2015. Equally, for over 60 years, the extensive theory of fluid and kinetic plasma instabilities has driven the sparse observations on a single plasma scale. Despite these advances, however, the nature of how electron-scale physics feed into global dynamics of the magnetotail remains unknown, since consistent, simultaneous measurements across the different regions has been lacking.

In the Van Allen Radiation Belts, electron-scale physics shape the overall topology through the processes of wave-particle interaction at Very Low Frequencies (VLF). These gyroresonant interactions break the adiabatic invariants, leading to acceleration of the trapped particle population, pitch angle scattering and potential loss of electrons to the atmosphere and energy diffusion. Radiation Belt electrons will encounter several different types of VLF electromagnetic wave as they drift around the Earth, such as chorus waves and plasmaspheric hiss waves [52, 55]. Outside the plasmasphere, electrons encounter nonlinear wave packets of chorus which have been subject of intense research using the data of ESA's Cluster, NASA's THEMIS and Van Allen Probes, and newly also JAXA's Arase missions [35, 39, 45, 46, 75, 82, 83] but many gaps in our knowledge of their generation mechanisms and effects still remain. These waves interact strongly with electrons with energies from a few electron volts up to several MeV across a range of L shells from the plasmapause out to beyond large radial distances (8 Earth Radii, [56]). Inside the plasmasphere and plasmaspheric plumes, electrons encounter broadband plasmaspheric hiss activity which fills the entire plasmasphere. The plasmaspheric hiss is largely responsible for the formation of the slot region between the inner and outer radiation belts and energetic electron losses through cyclotron resonant pitch angle diffusion throughout the outer radiation belt [53].

Auroral electron acceleration remains a key challenge in the magnetosphere-ionosphere system. Traditionally, the system-level auroral oval is described in terms of a series of upward- and downward field-aligned currents. However, this simple picture does not describe the key physics operating at electron scales. Two key electron-scale physical mechanisms are the generation and sustenance of quasi-static electric potential drops [1, 59] that form in the auroral region due to charged particle motion, and dispersive shear Alfvén waves [49, 73, 90, 89] that communicate the stresses on the coupled time-varying system which carry field-aligned currents. What roles each acceleration mechanism play in the gamut of auroral forms from the generation of quiescent, stable arcs to hemispheric auroral measurements to rapidly varying “flickering aurora” remain to be determined.

While the electron-scale physical processes are ubiquitous within the magnetosphere, they are not omnipresent, and wax and wane with energy content, energy partitioning and large-scale topological conditions within the plasma and electromagnetic field environment; conditions which are, in turn, dictated by other ongoing processes and the coupling of the system to the solar wind. This feedback between electron and fluid, and indeed ion, scales is critical to understanding the physical processes themselves. Instabilities involve a redistribution of energy between plasma particles and electromagnetic waves; by monitoring the different types of energy density in the plasma, it is possible to diagnose how electromagnetic (EM) waves gain energy at the expense of the plasma, such as the temperature, density, and plasma anisotropy of the plasmasheet that dictates the growth and evolution of instabilities discussed above. Cold plasma plays a vital role in magnetic reconnection, the presence of which acts to quench reconnection through the modification of the local Alfvén speed, $v_A = B/\sqrt{\mu_0 \rho}$. Cold plasma also dictates where energy can penetrate from local processes such as whistler-mode waves through reflection and refraction of their ray paths and field line resonance through the Alfvén continuum of field line eigenfrequencies. In this way, plasma regimes of vastly different magnetic field topologies, plasma betas, and energies are inextricably linked and feed back to each other.

3.1 What are the roles of electron-scale physics in driving global magnetospheric dynamics?

A myriad of electron-scale physical phenomena contribute hugely to the global morphology of the magnetosphere-ionosphere system. These electron-scale processes occur in highly limited time or space regions, which makes the measurement of their initiation and the global consequence essentially impossible with measurements that either focus only on the small- or electron-scale structure (MMS) or are limited in distribution across the different regions (e.g., Cluster and THEMIS). Small-scale measurements tell us detail about the phenomena operation on those scales but not how they affect the global response. Key examples of their operation are given below:

a electron-scale physics initiate magnetic reconnection at the dayside magnetopause and in the near- and distant-Earth magnetotail;
b electron-scale waves and instabilities that are key to the initiation of the magnetospheric substorm;
c small (electron)-scale magnetosphere-ionosphere coupling and auroral acceleration through highly-localised small-scale dispersive Alfvén waves;
d electron-scale wave-particle interaction shape the acceleration and loss of relativistic electrons in the Van Allen Radiation Belts;
e energy exchange through Kelvin–Helmholtz Instability across an electron-scale magnetopause boundary;
f kinetic (electron)-scale magnetosheath Hot Flow Anomalies impacting localised regions of the magnetopause;
g locally generated currents and energised plasma impacting the large-scale boundaries, Region 1 and 2, ring current, and cusp current systems.

3.2 How does the large-scale magnetospheric system feed back into and control electron dynamics?

As discussed above, the large-scale plasma and electromagnetic field topology dictate the presence and ultimate contributions of plasma instability to the coupled magnetosphere-ionosphere system. Key examples of the operation of these processes are given below:

a How does the plasmasheet control the initiation and growth of different plasma instabilities and wave-particle interactions?
b How does the cold plasma content of the magnetosphere impact the energisation and propagation of electron-scale wave-particle interaction?
c How does the large-scale magnetospheric topology impact on wave-particle interaction?
d How does the solar wind and the magnetospheric substorm set the large-scale field-aligned current structure?
e What process(es) create the thin, stable electron auroral arc?
f Are there any mechanisms in the Earth's magnetosphere that are scale-free?

4 How is energy converted and partitioned across plasmas and fields in different regions of the magnetosphere, particularly between more stretched and dipolar-like magnetic fields?

In general, the Earth's magnetosphere would seem to be a rather quiescent body which is in general dominated by relatively slow dynamical processes and small magnetic fields on an astrophysical scale. However, the magnetospheric substorm and the energisation of relativistic electrons in the inner magnetosphere are highly dynamic and often explosive examples of energy exchange. For example, the magnetospheric substorms release 10^{15} J of energy in a matter of minutes, which is transferred into the energisation of particles in the inner magnetosphere to relativistic energies [82, 38, 28], and into the ionosphere and ultimately the atmosphere through Joule heating and charged particle precipitation across a wide energy range [80, 17].

The Van Allen radiation belts house a torus-shaped region of relativistic plasma around Earth, the origins of which are unclear. The physics of the inner magnetosphere are dictated both by forces external to the magnetosphere from the solar wind, and processes internal to the magnetosphere such as the development of field-aligned currents and the explosive energy release corresponding to the substorm. Both processes are key to the energisation of near-Earth space. The overwhelming majority of electromagnetic wave modes that mediate wave-particle interaction are highly localised in space or in time. However, each of these proposed wave modes can have a global consequence on the energisation of the radiation belts and ring current, as energetic particles (i.e., relativistic electrons and hot ring current ions) drift through these localised, intermittent, bursty wave fields. Previous studies of wave-particle interactions have depended upon a localised process occurring at the right place and at the right time to be able to start to distinguish their effects on the inner magnetosphere, near-Earth instability, or transition region energy exchange.

The magnetospheric substorm is a repeatable earthquake-like disturbance to near-Earth Space. It is a major mode of variability in near-Earth space which, apparently unpredictably, dissipates a considerable and variable amount of energy into inner magnetosphere and upper atmosphere. Plasma instabilities and reconnection act to rapidly reconfigure the geometry and topology of the magnetotail magnetic field over ~ 20–30 min, releasing some or all of the stored magnetic energy into various forms of energy which are transported and dissipated into the upper atmosphere, the ring current, and into plasmoids that are released into interplanetary space.

What has become clear is that the region between stretched and dipolar magnetic field lines is the key region for energy exchange in the Earth's magnetosphere. Energy transfer into energetic particles in the ring current and radiation belts has been significantly advanced by the Van Allen Probes and Arase mission. However, how the energy released from reconnection and plasma instabilities is processed in the transition region and inner magnetosphere following the large-scale topological changes associated with magnetic reconnection is not understood. Moreover, if we do not understand the energy exchange region between stretched and dipolar magnetic field lines in the nightside magnetosphere, the energy partitioning and conversion between stationary fields, transient fields, and particle energisation will not be understood.

Indeed, the lack of knowledge about the physical processes which control the energy exchange in this transition region between stretched magnetotails and more dipolar inner magnetosphere represent a fundamental challenge to understanding the overall energy transfer in highly coupled magnetised plasma systems under forcing from solar, stellar, and astrophysical plasma winds. The results from this science topic will provide extensive observations with quantitative constraints on where energy is converted, processed, and deposited in plasma and magnetic fields to quickly drive future theoretical and simulation advances.

4.1 What fraction of energy is associated with particle acceleration, particle transport, and plasma wave generation in the coupled magnetospheric system?

Energy is stored in open magnetic flux and in plasma distributions in key regions such as the plasmasheet and ring current and radiation belts. The substorm rapidly converts stored magnetic and particle energies into particle acceleration both along and across magnetic fields, the generation of highly localised plasma wave activities and radiation belt energisation, and in the deposition of energy into the ionosphere through Joule heating and particle precipitation.

a How does energy partitioning between electromagnetic fields and plasma affect the plasma instability that likely causes substorm onset?
b Does energy partitioning between magnetic field and plasma **before** the substorm affect how the energy is partitioned in the inner magnetosphere **after** the substorm?
c How does energy partitioning between different electron and ion populations determine the wave activity in the inner magnetosphere?
d How much energy from the substorm can be transferred into the ring current or radiation belt?
e What is the fraction of energy loss in the radiation belts due to wave-particle interactions?

4.2 How does plasma beta impact the exchange of energy between plasmas and fields between stretched and more dipolar field regions?

Plasma beta is a key quantity that enables plasma instabilities to grow and participate in energy exchange in the near-Earth magnetotail. Key questions include, but are not limited to:

a What is the influence of plasma beta on the growth phase of the substorm?
b Does plasma beta control the substorm instability?

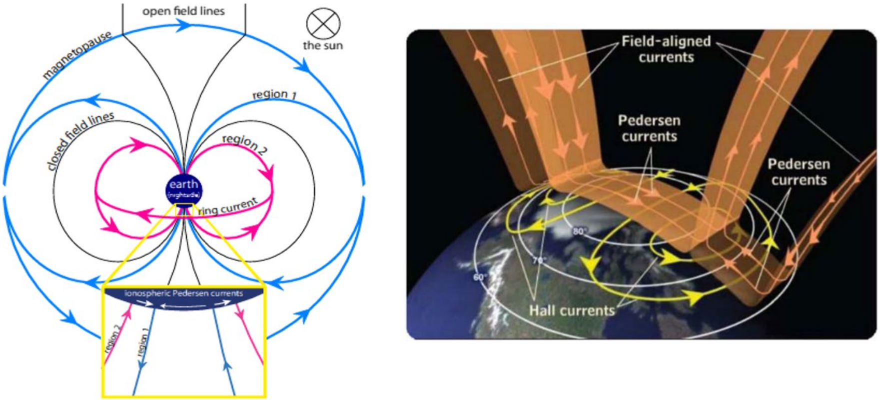

Fig. 5 Magnetospheric current systems, linked via field-aligned currents (left) Coxon et al. [16] and (right) COMET program, UCAR (https://www.comet.ucar.edu/)

c Is plasma beta a key factor in the control of wave activity in the magnetosphere as predicted by theory?
d How does plasma beta in the plasma sheet control the formation of field-aligned currents and shear Alfvén waves in the auroral region?

5 What are the spatial and temporal scales of magnetosphere-ionosphere coupling and what are the respective roles of field-aligned-currents (FACs), momentum transfer, waves, and energetic particles in this coupling?

How are the auroral ionosphere and magnetosphere connected through its time-varying magnetic field?
How do processes in the coupled magnetosphere-ionosphere system produce conditions necessary for aurora and ionospheric outflow to occur?
What is the nature of plasma and electromagnetic coupling between the near-Earth transition region magnetotail, the inner magnetosphere, and ionosphere?

Typically, the coupled magnetosphere-ionosphere is thought of as having preferred spatial and temporal scales which dictate the coupling mechanism mentioned above. For example, the large-scale Birkeland region 1 and 2 currents that couple the solar wind-magnetosphere-ionosphere are thought to be system-scale currents (Fig. 5). The scale-size of these Birkeland currents is limited by the size of the magnetosphere, but what the smallest scales are related to is unknown. Presumably electron scale physics plays some role in this, but with recent advances, it is clear that the large-scale current systems are not static, homogenous current systems (e.g., [31]). Instead, these currents systems are, in fact, made up of smaller-scale filamentary currents that in total can be described as the large-scale coupled system described by Fig. 5. What processes can be described by large-scale, static current systems and what can be described as processes occurring on ever smaller or shorter scales is currently unknown.

The steady-state interaction of the solar wind with the magnetosphere sets up a series of currents that are in principle, relatively stable. These Birkeland currents are the way in which stress is communicated between the magnetopause (the interface between the solar wind and Earth's magnetic field) and the ionosphere. Magnetosphere-ionosphere (MI) coupling refers to the physical processes that couple the magnetic and electric fields and plasma in the magnetosphere to the fields and plasma in the ionosphere. This coupling allows energy to transfer between two very different plasma regimes – the collisionless, energetic plasma of the magnetosphere with the much denser and cooler plasma of the ionosphere. The plasma of the ionosphere is rigidly connected to the rotation of the Earth and treated as a thin shell, whereas much of the magnetospheric plasma is controlled by convection due to large-scale electric fields. The physical processes that couple these regions are responsible for the generation of aurora throughout the Solar System. It is this key concept of frozen-in plasmas and fields that mean that it is typically assumed that the ionosphere can be used as a 2-D "TV screen" for 3-D magnetospheric processes. In fact, the ionosphere is an active participant in the dynamics of M-I coupling through a combination of ionospheric conductivity (and hence collisions), vertical structuring, and heavy ion outflow, which all feed back to the magnetospheric processes at play. Hence, it is clear that there are a huge range of non-ideal MHD wave processes that are at play in M-I coupling, all of which contribute to energy exchange and partitioning in the system. The physical processes act from the electron scale through ion scales and upwards to fluid scales as described above.

The coupling between the ionosphere and magnetosphere is controlled both by the stored energy in the magnetosphere, and by variations in the ionosphere, leading to a complicated two-way coupling. This coupling is far more complicated than the simplified Birkeland picture described above, and can include some or all of these physical processes:

- pitch-angle scattering and its contribution to energetic particle losses, auroral particle precipitation, and field-aligned current sustenance;
- dispersive Alfvén waves and their role in auroral acceleration and the transfer of field-aligned current;
- quasi-static potential drops and their role in auroral acceleration;
- radial diffusion from large-scale electromagnetic waves and their role in the transport and acceleration of the radiation belts and ring current;
- an active ionosphere and its role in Joule heating and ionospheric outflow.

Hence, magnetospheres and ionospheres are linked by magnetic fields, but most importantly by the action of temporally- and spatially-varying FACs. These FACs are responsible for the acceleration of electrons and protons, and subsequently the generation of the aurora. Multi-point observations of the plasma and the electric and magnetic fields are essential to diagnose the formation and evolution of FACs, and these must be obtained in three key regions: (i) the ionosphere, (ii) the low-altitude magnetosphere, and (iii) the high-altitude magnetosphere, which all cover

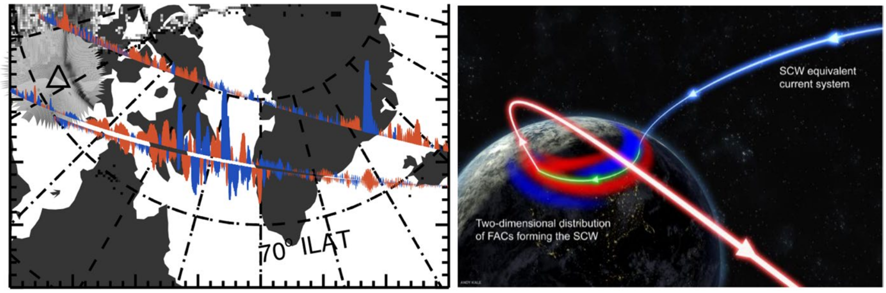

Fig. 6 (left) Cluster observations of the spatial scales of FACs in the nightside magnetosphere-ionosphere; blue denoting FACs directed towards the ionosphere and red denoting FACs directed away from the ionosphere, together with (right) a schematic representation of the FAC structure on fluid scales. Left: adapted from Forsyth et al. [27], right: Murphy et al. [60]

vast regions of plasma parameter space as shown in Fig. 1. In our Solar System such multipoint observations are only available at Earth.

At Earth there are broadly two types of aurora; quiescent slowly varying aurora such as auroral arcs and the large-scale auroral oval, and highly dynamic rapidly evolving aurora such as auroral beads and pulsating aurora. The slowly varying aurora are always present across the auroral oval, while the dynamic aurora occurs less frequently, typically during enhanced magnetospheric activity and extreme solar wind-magnetosphere-ionosphere driving such as during substorms and storms. This large-scale, general understanding breaks down at ion and electron scales, which in turn requires new data and new simulations to drive the science forward on understanding magnetosphere-ionosphere coupling specifically and low–high plasma beta coupling in general. Figure 6 shows a structured large-scale current in the nighttime ionosphere from the Cluster spacecraft. In a region defined as net upward and downward currents, it is clear that there are many pairs of field-aligned currents that exist within one nominal large-scale current system, and with larger peak-to-peak values than the net average current. The question then becomes what spatial scales can be considered to be stationary in response to solar wind forcing and which are transient wave-driven processes? A key component of this question is whether there are in fact no preferred spatial and temporal scales for field-aligned currents and wave-driven perturbations, and what impact this has on the energetics of the coupled system [51].

Moreover, even if we assume that the ionosphere and magnetosphere map perfectly to one another, accurately mapping field lines into the huge 3D volume of space is non-trivial. It is typically assumed that the near-Earth magnetosphere inside radial distances of ~ 5 R_E is relatively dipolar. However, solar wind driving distorts even the near-dipolar regions into a compressed dipole, such that field lines that are thought to thread the auroral ionosphere at a given location can be significantly distorted. This distortion from dipolar fields only increases as the strength of the dipole decreases into the outer magnetosphere, and is compounded by the existence of electrical currents flowing in the magnetosphere, or coupling the magnetosphere to the ionosphere, the result of which is that neighbouring field lines can map to vastly different radial and indeed azimuthal locations [32]. We can estimate where field lines map to through the implementation of empirical, steady-state magnetospheric magnetic field models that parameterise average field line locations as a function of external driving and/or internal magnetospheric conditions (e.g., the Tsyganenko magnetic field model suite). However, the magnetosphere exists in anything but an equilibrium state for the vast majority of time. It is clear that, in this way, large uncertainties can be introduced into physics-based models of magnetosphere-ionosphere coupling processes, or indeed magnetospheric processes such as radiation belt particle acceleration. An example of this making a huge difference in understanding and modelling physics of the terrestrial environment is in radiation belt research. Electrons trapped in the Earth's radiation belts encounter a variety of electromagnetic waves as they drift around the Earth. Each type of wave has a different magnetic local time (MLT) dependence and can interact with the electrons, causing loss, acceleration, or transport, or a combination of these. The role of each wave can only be properly assessed by using a global radiation belt model (GRBM) that includes all the waves, as combinations of the waves can have a greater effect on the dynamics than would be expected by considering the waves individually [54, 79].

One way to determine this on a case study basis is to understand the physics of wave-particle interaction. Pitch-angle scattered whistler-mode chorus has been shown to be able to be observed in the diffuse aurora (e.g., [61]). This leads to a significant open question, which is that the physics of wave-particle interaction itself can be used to determine field line topology. Hence the physics of wave-particle interaction identifies the connectivity between the magnetosphere and ionosphere.

There have been huge leaps in observational measurements using the FAST satellite, demonstrating that both quasi-static and Alfvénic auroral signatures are seen, but there is no self-consistent theory of auroral arcs or indeed the generator that must power them. Indeed, there are clear demonstrations of how complex the interplay between electric and magnetic fields and precipitating particles that depend on the structuring of the ionosphere, the cavity referred to as the Ionospheric Alfvén Resonator, and the driving characteristics along the entire geomagnetic field that cannot be distinguished between to determine the generator without new leaps forward in observations (e.g., [41, 14]).

Global morphology in the form of magnetic reconnection processes and field line eigenfrequencies are influenced by the magnetic field strength and, critically, by plasma mass density along the field. Ion outflow during geomagnetic storms (e.g., [91]) would certainly influence the plasma mass density. However, there is also a secondary effect, which is that there is also enhanced helium and oxygen ring current ions in the inner magnetosphere as a result of substorm injection (e.g., [74]). The enhanced ring current (and its significant contribution to mass densities) will increase the heavy ion content in the inner magnetosphere, whilst also reducing the local magnetic field strength at ring current radial distances leading to stronger geomagnetic storms [40, 42]. Indeed, simulations have shown that the addition of ionospheric ions can weaken a geomagnetic storm (e.g., [30, 37]). What processes drive ionospheric outflow is only partially known and understanding ion outflow and its contribution to local and global processes is certainly an outstanding remaining question in space plasma physics (Fig. 7).

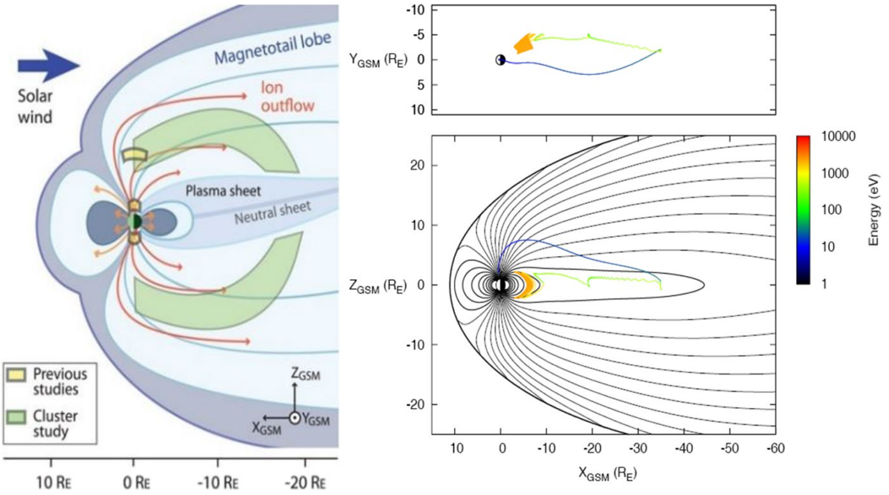

Fig. 7 Left: Schematic of "cold hidden" H^+ ion outflow in the magnetosphere, regions of existing satellite observations (adapted from [25]), right: Typical trajectory of an $O.^+$ ion originating from the cleft ionosphere as it transits the magnetosphere (after [36])

In terms of the near-dipolar inner magnetosphere, even small changes in magnetospheric location have a huge effect on understanding the governing physical processes whereby electrons drifting through electromagnetic waves during their orbits are described in terms of global parameters from equilibrium magnetic field models. Their motion is described using diffusion coefficients, whose exponents are between $L*^4$ and $L*^{10}$, where L* is an estimate of radial distance from the Earth in R_E in a realistic magnetic field model, meaning that even a small uncertainty in where these waves reside produces significant differences in their physical descriptions. Hence, knowing where field lines map to with accuracy becomes as critical as understanding the electromagnetic wave powers that will interact with the radiation belt electrons themselves.

5.1 How are the auroral ionosphere and magnetosphere connected through its time-varying magnetic field?

Models of magnetosphere-ionosphere coupling are numerous and invoke a wide range of physics across the widely varying plasma and field conditions between the magnetosphere and ionosphere. These processes include large-scale field-aligned currents, and quasi-static and field-aligned electric potential drops, and the role of dispersive Alfvén waves, kinetic-scale field line resonances and active ionospheric feedback. Alfvén waves have been shown to dig out density cavities on electron scales at the low-altitude portion of the field line [47], the ionospheric Alfvén resonator may play a role in any coupling (e.g., [50]), and typically field lines are modelled as perpendicularly intersecting a thin sheet ionosphere. Advanced modelling [76] has shown that this is not the case and that reflection and refraction through a realistic, vertically structured ionosphere must be taken into account. Critically, in many regions of the magnetosphere-ionosphere system, small changes in location have huge implications for any physical processes operating even in the near-dipolar region of radiation belts (e.g., [71 63]). An important question regarding ion outflows is the fate of thermal ion outflows (i.e. the polar wind and auroral bulk up-flow) originating from the topside ionosphere as they traverse to higher altitudes.

a Where do magnetospheric field lines map to?
b What is the role of the ionosphere in magnetosphere-ionosphere coupling?
c What physical processes drive ionospheric outflow?

5.2 How do processes in the coupled magnetosphere-ionosphere system produce conditions necessary for aurora and ionospheric outflow to occur?

Despite decades of advanced modelling, theoretical and observational advances, the most simple question of what physics drives an auroral arc is still an outstanding open science question.

a What are the M-I coupling processes that produce a quiescent auroral arc and their structuring?
b What are the M-I coupling processes that produce dynamic auroral arcs and their structuring?

5.3 What is the nature of plasma and electromagnetic coupling between the near-Earth transition region magnetotail, the inner magnetosphere, and ionosphere?

Of fundamental importance is not only to follow the energy pathways between the magnetotail and ionosphere but also between the near-Earth transition region and the inner magnetosphere, where pressure gradients, wave-particle interaction and the injection of energetic particles drive the coupling and secondary energy transfer from the magnetotail into the ionosphere.

6 Technology requirements

Clearly in order to understand the physics of magnetosphere-ionosphere coupling, measurements of the distribution functions, waves, and fields are a necessity, as they have been required throughout the space-based in-situ plasma era. Thus, below, we concentrate on either how these measurements need to be combined, or instead where new measurements are required to make that scientific advance, in order to address the high-level science goals discussed in detail above.

6.1 Measurement requirements

Although limited in the multi-scale capability, MMS and Cluster, in particular, have placed practical limits on the measurement performance for multi-point analysis. It is now clear from the wealth of analysis that has been done (primarily on: timing analysis of plasma and current boundaries and other structures, and the magnetic field and plasma spatial gradients, but also on other related techniques) that multi-point methodology requires two competing factors to be addressed:

1. The absolute error requirements on the onboard instruments; the pointing and position accuracy, and the inter-spacecraft timing knowledge. MMS has demonstrated that the last two of these was vital to address the smaller scales suitable to probe the electron physics.
2. The spatial structure to be resolved by the multi-point coverage; its principle structural form (e.g., 1D, 2D, or 3D) and degree of non-linearity, and its temporal behaviour. Both MMS and Cluster have shown that disentangling temporal behaviour from spatial structure cannot be done in general with only 4-point measurements on similar spatial scales unless assumptions of either the temporal evolution (stationarity) or spatial structure (linear form) are made.

Below, we summarize the scientific objectives, scientific goals, and general measurement requirements which would flow down to suggested mission profiles in Sect. 10. All mission concepts require full measurement of the ion, electron, and electromagnetic field, and here we discuss measurement requirements in terms of either scale, region, or whether there are new measurements required (Table 1).

It is therefore vital that an array of spacecraft that can access more than one spatial scale at the same time is deployed in any cross-scale constellation. With more than four spacecraft, there is the combined effect of allowing non-linear analysis (determination of non-linear gradients), and identifying temporal evolution between measurement points. To fully resolve multiple scales requires a minimum of seven points. Nevertheless, the absolute error requirements above needs addressing at the same time, so that measurement accuracy (and cadence) needs to be sufficient to apply non-linear analysis techniques, which are generally more demanding on the spatial differences in measurement between spacecraft.

6.2 Technological advances

As discussed above, there are not many technological advances that are required for these science topics, but there are several advances in technological development that would provide smaller, faster, and more radiation hard instrumentation. One new technological development that is expected within the next decade is to pursue active experiments in space. This technology, in the form of a relativistic electron instrument, would revolutionise the biggest problems in space plasma physics; namely, where do magnetic field lines map to and how do waves and particles

Table 1 Measurement requirements in addition to electromagnetic, ion, and electron measurements, with electron scale (es), fluid scale (fs), magnetopause (MP), magnetotail (Mt), transition region (TR), inner magnetosphere (IM), Low Earth Orbit (LEO), Ionosphere (Io), and finally new measurements (NM) that are discussed in Sect. 9

	Measurement Requirements								
	es	fs	MP	Mt	TR	IM	LEO	Io	NM
How do local plasma processes have global consequences?									
What are the roles of electron-scale physics in driving global magnetospheric dynamics?	x	x		x	x	x	x	x	
How does the large-scale magnetospheric system feed back and control electron dynamics?	x	x	x	x	x	x	x	x	
How is energy converted and partitioned across plasmas and fields in different regions of the magnetosphere, particularly between more stretched and dipolar-like magnetic fields?									
What fraction of energy is associated with particle acceleration, particle transport, and plasma wave generation in the coupled magnetospheric system?	x	x		x	x	x			
How does plasma beta impact the exchange of energy between plasmas and fields between stretched and more dipolar field regions?	x	x		x	x	x			
What are the spatial and temporal scales of magnetosphere-ionosphere coupling and what are the respective roles of FACs, waves, and energetic particles in this coupling?									
How are the auroral ionosphere and magnetosphere connected through its time-varying magnetic field?	x	x		x	x		x	x	x
How do processes in the coupled magnetosphere-ionosphere system produce conditions necessary for aurora and ionospheric outflow to occur?	x	x		x	x		x	x	x
What is the nature of plasma and electromagnetic coupling between the near-Earth transition region magnetotail, the inner magnetosphere, and ionosphere?	x	x			x	x	x	x	x

interact? The ability to map between magnetic field regimes is fundamental to magnetosphere-ionosphere coupling. Moreover, the same technology can be used to drive specific electromagnetic wave modes and, with a constellation mission in close connection, the precise effects of these waves on the plasma can be determined.

Ground-based active experiments use microwave technology to heat and locally modify the ionosphere, and Low Earth Orbit spacecraft such as FAST (e.g., [67]) are able to receive signatures of this modulation through the physics of Alfvén wave propagation. It has long been proposed that similar active experiments based upon pulsed electron beams in space would also be possible (e.g., [34]). A prototype of this active experiment is currently being developed in the US at the Los Alamos National Laboratory, and it is expected to be space ready within a decade. This active experiment would allow magnetic field lines to be "painted" to provide precise mapping between the spacecraft location and the ground. Moreover, this active experiment acts as a large radio-frequency (RF) transmitter in space, which can be used to modify the local plasma and generate specific electromagnetic wave modes and plasma conditions to directly test wave-particle interaction theories. We refer the reader to both the BEAM-PIE experiment (Los Alamos National Laboratory (LANL), [44] and DSX mission (US Air Force, [11] for details on current active space-based experiments. In order to directly test wave-particle interaction, a multi-spacecraft constellation would be required to determine the 3D plasma structuring in phase space. Previous missions have attempted to use active experiments in space, such as the AMPTE spacecraft barium release to empirically measure plasma convection. A recent launch of a radiation belt mitigation technology from the US DSX spacecraft could also be classified as an active mission, using the physics of wave-particle interaction to try to perform pitch-angle diffusion-mediated electron losses.

Recent advances in plasma and wave measurement technology mean that the in-situ properties of the plasma environment can be accurately determined on very high time-scales (e.g. MMS). However, whilst these high fidelity measurements of the plasma environment can be made, there are severe limitations on the amount of data that can be transmitted back to the ground. Advances in communications technology (e.g. optical data links), data compression, and onboard data processing techniques using machine learning (e.g. work by the ESA Advanced Concepts Team) will mean that future space plasma missions would be able to process and download significantly more and more high quality data. Removal of this constraint will enable high quality science instruments to be able to be run over far longer duty cycles which, combined with higher cadence measurements, may lead to potentially future developments to push these measurements further than is currently required. Specific examples would be to push electron-scale measurements to higher temporal and phase space across both auroral and relativistic energies in order to distinguish between the different drivers of electron acceleration described above.

Expanding multi-spacecraft observations beyond the current state-of-the-art relies upon cost-effective platforms, rather than bespoke single-use platforms currently modified for scientific use. Ongoing developments in industry have been providing an initial gateway for more generic spacecraft with more capability that may, in future, provide ideal platforms for multi-spacecraft magnetospheric facilities. Ion drives, used currently by several commercial spacecraft providers (e.g.,

Table 2 High level overview of the proposed science goals, concepts, and mission scenarios

Goal	What are the fundamental modes of energy transfer and partitioning in the coupled Magnetosphere-Ionosphere system?
Concepts	How do local plasma processes have global consequences? How is energy converted and partitioned across plasmas and fields in different regions of the magnetosphere, particularly between more stretched and dipolar-like magnetic fields? What are the spatial and temporal scales of magnetosphere-ionosphere coupling and what are the respective roles of FACs, waves, and energetic particles in this coupling?
Mission Scenarios	A true multi-scale, magnetospheric constellation to understand the link between electron-scale physics and its impact and dependence on both outer and inner regions of the global system A multi-spacecraft mission to determine the energy exchange between particles and fields in the stretched to dipolar region of near-Earth space An active experiment in the magnetosphere to unambiguously reveal the connection between the magnetosphere and the ionosphere (tracers) A Low Earth Orbit, multi-spacecraft mission to study the active link between magnetospheric processes and the ionosphere

SES Systems) provide a lower-cost lower-mass mechanism to insert spacecraft into their final orbits. Of note here is that one additional benefit of ion drives is a slow traversal through crucial regions of the magnetosphere for the science objectives above. Hence, this technology is highly suited to missions of the types described.

7 Mission goal and scenario

Of particular note is that the potential mission concepts below are not mutually exclusive to each other; here, we simply highlight four mission concepts required to fully address the science presented within this manuscript. These mission concepts could be linked through a magnetospheric programme that would constitute an L-class mission concept, or a multi-agency series of M- and S-class missions (Table 2).

One key component for suggested mission profiles may be the addition of ground-based instrumentation that could be supported as a key element of these mission concepts. One recent excellent example of this is the NASA THEMIS mission, whose ground-based programme was a fundamental aspect of their space-based mission and allowed a far simpler and cheaper space-based mission as a consequence. In brief, the THEMIS ground-based campaign proved that a network of ground-based auroral observatories fulfil the need for a comprehensive and cost-effective magnetospheric mission. It was the cutting-edge ground-based network that allowed the most significant progress to be made on determining the plasma physics responsible for onset. Although technically crude white-light auroral imagers, the Time History of Events and Macroscale Interactions during Substorms (THEMIS) All-Sky Imagers (ASIs) provided a low-cost, high-impact science product with which to time, locate, and characterise many

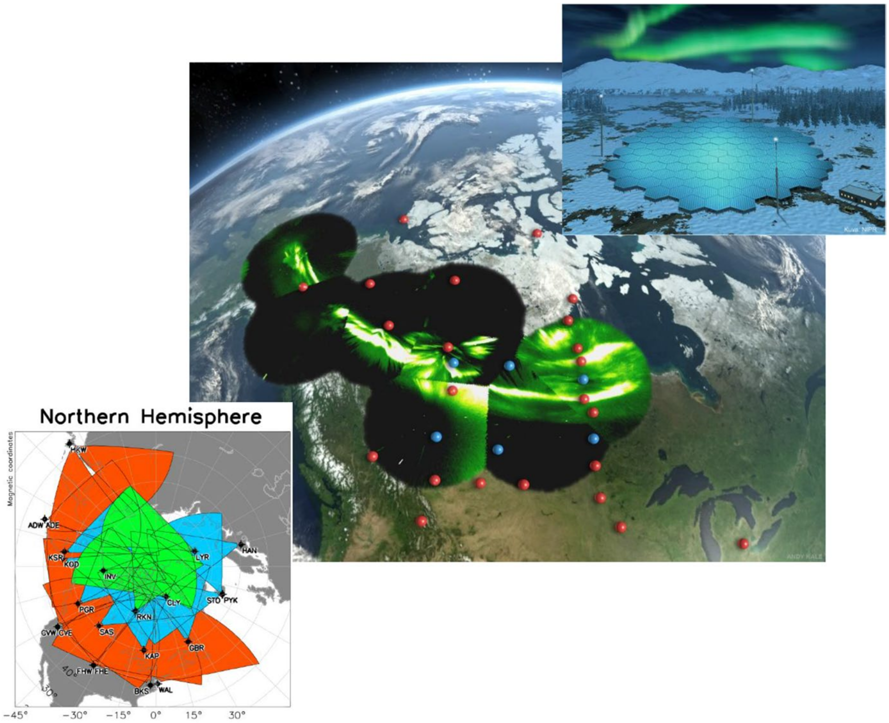

Fig. 8 Schematics of a potential ground-based auroral addition to a magnetosphere-ionosphere coupling mission proposed here with (top right) EISCAT 3D and (bottom left) SuperDARN radar systems (adapted from http://vt.superdarn.org/)

aspects of substorm physics over the large-scale sizes of the magnetosphere. In this scenario, it would be envisaged that multi-wavelength or hyper-spectral auroral cameras could play key roles in both an ionospheric large-scale context, as well as the target for active magnetosphere-ionosphere coupling experiments or facilities described above. However, the in-situ mission spacecraft could also be supplemented by a platform specifically dedicated to imaging tasks. Global imaging of the proton and electron aurora will provide a direct measurement of the effects of the precipitating flux, as well as the dynamic, global auroral morphology that results from the evolution of the magnetosphere. If 24/7 full coverage is sought, duplicating the imaging platform will become necessary. Over smaller scales, auroral images obtained at high cadence and high resolution over a limited portion of the aurora can provide a very detailed description of the effect of the acceleration of auroral particles, not only in the distant magnetosphere, but also in the acceleration region located between 2000 km and 10,000 km of altitude, the microphysics of this region of space being of paramount importance to evaluate the detailed response of the ionosphere at small scales, such as the development of auroral arcs, for example. For the study of the global response of the magnetosphere, EUV imaging of the Earth space environment can reveal the time evolution of the trapped population and how it transits between corotation and sub-corotation (forming plasmaspheric plumes, for example).

Indeed, context can be provided by large scale networks of radars (e.g. SuperDARN), magnetometers (e.g. SuperMAG), and auroral cameras which monitor key parameters, such as electric fields and currents, in a large portion of the ionosphere, while context from incoherent scatter radars such as EISCAT 3D provide context for active experiments whereby heating of the ionosphere could be achieved both on the ground and in-situ to finally understand magnetosphere-ionosphere coupling processes that underpin planetary magnetospheres (Fig. 8).

8 Potential mission profiles

This manuscript describes the concept of what could be described overall as a future ESA L-class mission concept. A mission consisting of active experiments in space surrounded by a number of smaller spacecraft must be considered to be M-class by itself. The combined measurements from LEO of the ionospheric end of the field line and resultant energy transfer would also be considered to be M-class in cost and complexity. However, one advantage is that a full magnetosphere-ionosphere coupling mission could be considered to be modular M-class, with a combination of agencies working together to create an overall magnetospheric programme. There is clear precedence of this in the form of the International Solar Terrestrial Programme (ISTP), which formed in the late 1990s, which was a collaboration by NASA, ESA, and JAXA. ISTP comprised Geotail, Polar, Wind, SOHO, Cluster, and was augmented by ground-based coherent and incoherent ionospheric radar and magnetometer measurements, with the aim of providing a coherent, international cooperation for scientific advancement of the Sun-Earth space environment. We suggest that it is time to revisit this opportunity, given the scale of investment and interest in space-based mission programmes across the international communities (Table 3).

One interesting concept for this combined L-class mission described above would be that of an active experimental facility in the same vein as astrophysics missions such as Chandra, XMM-Newton, or HST. Guest investigators could propose to use this total mission concept as a facility, whereby investigators could make specific requests for these space facilities to be run in specific modes to study specific plasma physics phenomena. Examples of this could include using a relativistic electron gun to study magnetosphere-ionosphere coupling, to launch whistler-mode waves and study their propagation or effects on electron distribution functions. By using ground-based facilities in conjunction with space missions, low-altitude spacecraft may not require a spin-stabilised platform for auroral imaging.

9 Voyage 2050 synergy across solar and space plasma disciplines

It is clear that particle energisation and energy transfer between plasmas and fields is an outstanding open question in space plasma physics that spans the fields of solar, solar wind, magnetospheric, and planetary physics. Voyage 2050 White Papers on the physics

Table 3 Exemplar mission requirements for the proposed mission concepts, together with the new capabilities desired to address the stated science goals beyond current state-of-the-art

Science Question	Min # spacecraft	Measurements Required	New Capabilities Desired
3.1	7	10-100 km electron scales 100 s km + ion-fluid scales	Multi-constellation formation flying Increased/smart data return
3.2	7	10-100 km electron scales 100 s km + global scales	Multi-constellation formation flying Increased/smart data return
4.1	8	10–100 km electron scale tetrahedron Active magnetospheric experiment/facility 100 s km + ion-fluid scale global context	Multi-constellation formation flying Active space-based wave experiments
4.2	8	10–100 km electron scale tetrahedron 3 spacecraft 100 s km + ion-fluid scale global context for azimuthal and radial pressure gradients Ground-based or LEO spacecraft	Multi-constellation formation flying
5.1	2	Along field equatorial spacecraft and LEO spacecraft with ground facilities	Space-based relativistic electron beam experiment/facility
5.2	2	Along field equatorial spacecraft and LEO spacecraft with ground facilities	Increased/smart data return
5.3	6	1 equatorial spacecraft with four spacecraft at ion-fluid scale separation and one LEO spacecraft with ground facilities	Space-based relativistic electron beam experiment/facility

of particle acceleration and energy exchange between plasma and electromagnetic fields within the solar context include science themes addressing the processes that drive high energy particle acceleration in the solar atmosphere, energy exchange in the solar wind, particle acceleration from shocks and discontinuities that are all linked via the physics of particle energisation. Large-scale topological science goals are highlighted in continuous multi-point imaging of near-Earth space, and plasma-neutral energisation is highlighted as a further mechanism for energy transfer and particle acceleration. These proposals are: Solar Particle Acceleration, Radiation and Kinetics (SPARK; Reid et al., this issue), Solar Cubesats for Linked Imaging Spectropolarimetry (SULIS; Scullion et al., this issue), understanding energy exchange via turbulence at electron scales in the solar wind ("A case for Electron Astrophysics"; Verscharen et al. [87]) and particle energisation via interaction with shocks and discontinuities ("Particle energisation in space plasmas"; Retinò et al., this issue). Together with White Papers on continuous monitoring of the solar-terrestrial interaction ("Exploring Solar-Terrestrial Interactions via Multiple Observers"; Branduardi-Raymont et al., this issue), this presents a clear push to understand energy exchange within the Solar System. Moreover, particle acceleration processes in the form of Radiation Belt particle acceleration is the focus of outer planetary White Papers such as "The In-situ exploration of Jupiter's Radiation Belts" (Roussos et al., this issue). Energy exchange is key across all Solar System bodies.

One option that could be considered in the context of Voyage 2050 would be the instigation of an L-class opportunity that combines one or more missions from the fields of solar, heliospheric, magnetospheric, and ionospheric physics to provide a Grand European Heliospheric Observatory that not only addresses major challenges in the Solar-Terrestrial physics discipline but provides rapid scientific advances in a holistic approach to sciences that underpins our European space weather requirements for decades to come.

We also wish to highlight that the topic of this White Paper is strongly linked with a number of other Voyage 2050 submissions across Solar System and Astrophysical plasmas. Therefore, the lead author of this White Paper is a co-signatory of the joint statement "The Plasma Universe: A Coherent Science Theme for Voyage 2050", submitted by D. Verscharen et al. on behalf of all co-signatories and subsequently published (Verscharen et al. [87]).

In the summary that follows, we outline additional information that was presented to the ESA Topical Teams, based upon questions asked and discussions at the Voyage 2050 workshop in Madrid.

10 Summary of mission concept

We refer the reader to our presentation for more details on the history behind the field of coupled plasma systems and the breakthrough space plasma science that has culminated in this White Paper.[7]

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[7] This presentation included material that was not part of the original White Paper on: historical context, scientific breakthroughs, lessons learned from previous missions and, critically, measurement requirements, constitute the sum of this mission concept:

https://www.cosmos.esa.int/documents/3273648/3495481/2_02_JRae_ESA_V2050_v7.pdf/3edba0ae-1636-8753-a991-075326b6486f?t=1573466575417

Any coupled electromagnetic plasma system requires study of all sources of energy transfer and the magnetosphere-ionosphere system is no different. We currently assume that the magnetosphere can be largely characterised by ideal MHD processes or ideal MHD processes with some small corrections applied to current theory. We also assume that the ionosphere is passive in this coupling, despite observational and theoretical evidence to the contrary. Nevertheless, this basic description of the coupled system allows us to understand the large-scale topology of the magnetosphere-ionosphere system to a reasonable extent in limited circumstances, and so has been an excellent starting point in previous missions.

However, new capabilities have demonstrated just how our current picture of the 3D solar wind-magnetosphere-ionosphere interaction can be misleading, as evidenced by kinetic simulations such as those from the Vlasiator [64]. Indeed, even sophisticated simulations cannot capture all temporal and spatial coupling processes along one geomagnetic field line which means we cannot answer straightforward questions like “why are auroral arcs long and thin?”. The rapid changes in fundamental plasma properties such as the plasma frequency, electron and ion gyrofrequencies along field lines linking ionosphere and magnetosphere mean that modelling alone cannot provide the answer to “How does a coupled electromagnetic plasma system work?”. In order to do this, we require three key strategies:

- **To be able to measure kinetic physics in space on multiple scales with nested tetrahedra.** Formation flying in tetrahedral formations required at 10-100 s km separation
- **To measure the consequences and coupling in the ionosphere.** Low Earth orbit spacecraft required to sample the in-situ connection between the magnetosphere and ionosphere. Ground-based instrumentation such as EISCAT 3D to understand the vertical coupling of the magnetosphere into the ionosphere with the potential for active experiments within the ionosphere to understand this coupling.
- **To physically connect the magnetosphere and ionosphere through active space plasma experiments.** We must understand the space-ionosphere connectivity in a highly dynamic plasma system. This can be done fortuitously through wave-particle interactions (e.g., [61]), or via active experiments from space. ESA have previously supported a wide number of active experiments from space from, for example, AMPTE to more current day Cluster Active Spacecraft Potential control experiments. Electron accelerator technology has advanced to a point where accelerators can be launched on rocket-based platforms to “paint” ionospheric and magnetospheric field lines close to LEO, and experiments designed to interact with relativistic plasma are already employed in space. We refer the reader to both the BEAM-PIE experiment (Los Alamos National Laboratory (LANL), [44] and DSX mission (US Air Force, [11]) for details on current active space-based experiments.

In order to achieve our science goals, we have identified a potential mission and orbit scenario as follows:

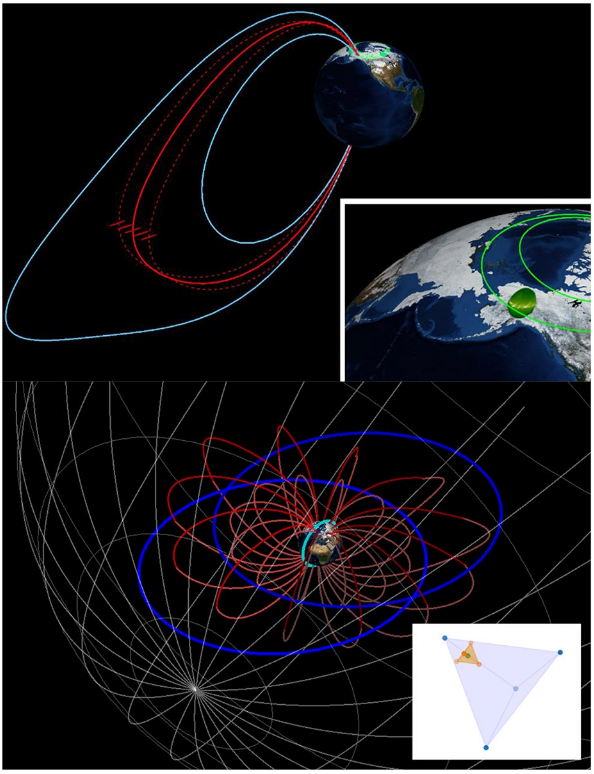

Fig. 9 (top) Studying kinetic plasma physics in the region of explosive energy release during a terrestrial substorm (inset). The nested tetrahedra are shown with an active experiment in green in the smallest tetrahedron to study the physics of MI coupling. (bottom) An example mission scenario with a magnetospheric constellation mission in a 9 × 4.3 R_E orbit for "geostationary" capability (dark blue orbit), and a low Earth orbiting Sun-synchronous pair of spacecraft at 600 km altitudes to study the consequences of magnetosphere-ionosphere coupling. Example field lines at 4 R_E and 6.6 R_E are shown in red and a magnetopause shown in white. The inset describes the potential nested tetrahedra

- A nested magnetospheric tetrahedra constellation of 8–9 spacecraft in 9 × 4.3 R_E "geostationary" orbit (Fig. 9)
- A Sun-synchronous spacecraft pair at 600 km altitude for repeat coverage in energy release locations
- Auroral imaging, SuperDARN radar, ground-based magnetometry, and EISCAT 3D for conjugacy between the magnetosphere, LEO, and ground stations

10.1 What we learn from multi-scale plasma physics simulations for our mission goals?

We have highlighted the new understanding of kinetic physics that arises from new modelling capabilities such as Vlasiator [64]. As system-wide modelling becomes more and more advanced to include six full dimensions in physical and velocity space, and includes a more realistic ionosphere, and inner magnetosphere, more new physics is being discovered. As an example, simulations have demonstrated that the pressure due to inner magnetospheric warm plasma changes the global dynamics of the system,the feedback between the ionosphere and magnetosphere changes the scale of physical processes such as field-aligned current systems. These new modelling capabilities open new science questions that we simply cannot answer with current/future planned missions.

10.2 What is the current state of the art in active experiments in space?

ESA have a long history in supporting active experiments in space, dating back to the AMPTE mission. Lithium and Barium releases created an artificial comet that were measured by sister spacecraft. Active spacecraft potential control is another example of a compelling active experiment, in this instance reducing the spacecraft potential by ion emission for Cluster and Double Star.

Fast forward thirty years, and there is a clear, renewed interest in active experiments, both from actively heating the ionosphere and measuring the consequences in space with the NASA FAST spacecraft in LEO (e.g., [67]), and in painting a geomagnetic field line all the way from the magnetosphere to the ionosphere through physical processes such as wave-particle interaction (e.g., [61]). We do not know where field lines map to and active experiments with relativistic particle beams in space has led to the development of solid-state radio-frequency (RF) linear accelerators that can deliver MeV electron beams but operate with low-voltage DC power supplies, such as the Beam-PIE experiment discussed above.

10.3 What has previously been achieved with multi-satellite constellations?

In the recent past there has been significant coordination between multi spacecraft missions not just in the magnetosphere (such as MMS, Cluster, and THEMIS) at Medium Earth Orbit (MEO) and highly elliptical orbit (HEO), but also with spacecraft near the ionosphere/magnetosphere transition (such as Swarm and AMPERE/Iridium, etc.). Opportunities for coordinated coverage have been limited (mainly serendipitous, not planned) but have highlighted, for example, significant improvements in the estimate of crucial field-aligned currents [22], and rare insight into the solar wind driving of ULF wave processes that couple ionosphere and magnetosphere [68 43]. The development of mission scenarios where sampling is maintained between MEO (and outer) and LEO locations, and the end points of the relevant field lines guiding the coupling are suitably tagged, is vital to explore the open questions posed in this proposal. The macroscopic behaviour between different regions is as critical as the small, multiscale processes driving that behaviour.

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Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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