Cross-Scale

Science Priority Document

Summary

A small number of phenomena dominate the behaviour and effects of plasmas throughout the Universe: shocks, reconnection and turbulence. All of these phenomena are controlled by dynamics on at least 3 scales simultaneously: electron kinetic, ion kinetic, and fluid. It is the nonlinear interaction of 3D, time-varying structures on these 3 scales which produces the complex behaviour and effects of these processes. To understand these processes, therefore, the particles and fields must be measured within and around them, simultaneously, at a sufficiently large number of locations to discover the time-varying 3D structure on electron, ion and fluid scales and how these interact with each other. This can only be achieved by flying a large number (up to 12) spacecraft in formation through these regions, equipped with state of the art instrumentation. Near-Earth space, which is relatively accessible and contains examples of all the phenomena of interest, is the obvious target for such a mission, which we call Cross-Scale.

This document details the key outstanding questions concerning these phenomena and their relative priorities. As a result, it is possible to prioritise the set of measurements required to answer these questions – such a list is also provided. These lists are intended to aid in the refinement of such a mission, to fly within ESA's Cosmic Vision 2015-2025 framework.

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1. Introduction

Space plasmas exhibit complexity and structure on a wide range of spatial and temporal scales. Despite the apparently bewildering array of plasma environments within the Solar System (the solar corona; the solar wind; planetary magnetospheres; cometary comas) and throughout the Universe (accretion disks; supernovae; galactic discs; planetary nebulae; and many more), there are just a small number of processes, one of which is dynamically and energetically dominant in most regions of interest:

- Shocks
- Reconnection
- Waves, turbulence and instabilities

These processes are significant because they transport, release or convert energy from one form to another. The conversion is typically from magnetic energy and bulk motion into kinetic and thermal energy. It can also result in highly energetic particles such as cosmic rays. Knowledge of the physics which governs these processes, therefore, is essential in understanding the most important regions and most energetic particles in the Universe today.

Near-Earth space contains examples of all of these key processes and is therefore an ideal natural laboratory in which to study them. It is relatively accessible to spacecraft, which can measure fields and particle distributions in great detail within and around regions of interest. In situ measurements by spacecraft over the last three decades in near-Earth space have greatly enhanced our knowledge of all of these processes.

The complex, three dimensional nature of plasma structures has long been recognised. Previous, existing and upcoming missions have been designed to measure this 3D structure, using multiple spacecraft. A minimum of four spacecraft are necessary to determine 3D structure: ESA’s Cluster and NASA’s upcoming MMS missions both use four spacecraft for this task. A fundamental restriction of multi-spacecraft measurements, however, is that they are sensitive to scales of the order of the spacecraft separation. By varying this separation, multiple scales can be probed, but only one scale can be measured at any time.

Plasmas are not just three dimensional: they also contain time-varying structure on many scales, simultaneously. Different scales are affected by different physical processes and it is the interplay of these processes which results in the complexity, and consequently the large scale effects, of plasma processes such as shocks and reconnection. For example, within collisionless shocks, small scale electron dynamics results in a highly structured, fluctuating electric field within the shock ramp. At scales around an order of magnitude larger, ions gyrate through the ramp, with trajectories determined by the fluctuating electric field. Reflected and gyrating ions then generate the even larger scale reformation and rippling of the shock front, which in turn affects the small scale dynamics of the electrons - as well as being pivotal in the acceleration of inflowing particles to high energies.

To understand the complex interplay of forces and dynamics within such regions and hence predict their effects, it is essential to measure the behaviour in 3D on all three scales – electron, ion and fluid – simultaneously. This can only be achieved with spacecraft positioned such that some have separations comparable to each of these three physical scales, simultaneously. This, combined with the requirement to measure the plasma in 3D at each scale, requires up to 4 spacecraft at each of the three physical scales. Instrumentation on the spacecraft at each scale must be tailored to the physical processes at that scale.

While simulations of collisionless plasmas have revealed a great deal about their dynamics and complexity, it is not possible to simulate the key phenomena of interest in sufficiently large simulation boxes to resolve the three physical scales in 3D. Indeed, this goal will not be achieved within the time scale of ESA’s Cosmic Vision 2015-2025 programme, assuming that computer power increases at its historical rate. The only way to study these phenomena in sufficient detail, therefore, is to measure them directly in space.

1.1.Cross-Scale – a summary

The Cross-Scale mission concept is of a fleet of spacecraft, flying in formation in Earth orbit, sampling the key plasma phenomena of reconnection, shocks and turbulence by passing through the magnetotail, bowshock and magnetosheath. The fleet would comprise around 12 spacecraft, with three nested groups of 4. The separation scale of each group would be tuned to one of the three important physical scales: electron kinetic (typically around 10km), ion kinetic (a few hundred km) and fluid (a few thousand km). Instrumentation on spacecraft in each group would be tailored to the phenomena that vary on that scale: for example, high speed electron detectors and electric field measurements at the smallest scale, ion detectors and field measurements at the medium scale; and contextual plasma and field measurements at the largest scale..

Cross-Scale measurements of plasma dynamics on three scales simultaneously will make it possible for the first time to study the multi-scale nonlinear dynamics of collisionless plasmas and observe how processes at these disparate scales interact to produce the complex behaviour that is observed, and which results in some of the most energetic and spectacular events in the Universe.

1.2.Relation to other missions

If plasmas did not vary in time, a single spaceraft would be sufficient to measure all spatial variations with multiple passes through the regions of interest. However, it was clear from the earliest spacecraft measurements that plasmas are, in fact, highly variable on many temporal scales. Several missions have been flown specifically to address this problem, such as ISEE and AMPTE which both included two closely separated spacecraft to disentangle spatial and temporal variability. The Cluster mission, with four spacecraft, can for the first time measure plasmas in 3D. However, multi-spacecraft measurements are sensitive to variations comparable to the spacecraft separations – to measure 3D structure on a particular scale, therefore, four spacecraft with comparable separations are required. The Cluster spacecraft have been manoeuvred to cover scales from around 100km (comparable to the proton gyroscale) to 10000km (a “macro” scale). The upcoming MMS mission will fly four spacecraft at separations as small as 10km to study electron dynamics. In this way, each physically important scale can be sampled. However, the links between variations on different scales are inaccessible to a four-spacecraft mission. Cross-Scale will provide 3D measurements of the three physically important scale at the same time. Lessons learned from Cluster and MMS will be helpful in aiding mission planning, but Cross-Scale will provide new measurements of an unexplored – and dynamically crucial – aspect of plasma physics.

1.3.Relation to the ESA science programme

The requirements of the Cross-Scale mission, although relatively modest compared with many current mission concepts, are beyond the resources of most nation states. The European Space Agency (ESA) is ideally placed to implement such a mission, building on Europe’s unique industrial and scientific experience of designing, building, operating and exploiting the multi-spacecraft Cluster mission.

Cross-Scale fits extremely well within the framework of ESA’s Cosmic Vision 2015-2025 programme. One of the key questions of the programme is “How does the Solar System work?” Cross-Scale can answer many of the questions surrounding the most compelling phenomena in our Solar System – and in the Universe at large.

A wide community of European scientists, including many of the authors of this document, intend to propose the Cross-Scale concept in response to a future Call for Proposals from ESA, with a prospective launch date soon after 2015.

1.4.International collaboration

The science addressed by Cross-Scale is of interest to researchers around the world. Inter-agency co-operation has been very successful in a number of past missions, increasing the science return while reducing the cost to each partner. Such a collaboration would obviously be welcome within the Cross-Scale mission.

Recently, a mission concept termed SCOPE has been developed by a group of Japanese scientists and engineers. With 5 spacecraft formation flying in Earth orbit, SCOPE would address some of the topics targeted by Cross-Scale – in particular, electron-ion coupling in plasma reconnection and shocks. The similarities between the science of SCOPE and Cross-Scale, combined with a similar timescale leading up to a launch in 2015 or soon after, make a collaboration between ESA and JAXA highly desirable.

We are actively exploring the potential for ESA/JAXA collaboration with the SCOPE team. However, this does not of course preclude collaboration with any other agency and we welcome any opportunity for discussions with other groups with similar science goals.

1.5.Format of this document

This document lists the outstanding scientific questions, with their relative priorities, for the three key plasma phenomena of reconnection, shocks and turbulence. These are detailed in sections 2.1, 2.2 and 2.3. As a result of this prioritisation, it is possible in turn to determine the relative priorities of various measurements that can be made – these are listed in sections 2.1.4, 2.2.3 and 2.3.6.

It is inevitable that compromises will have to be made when Cross-Scale is implemented, due to limited resources. The list of prioritised measurements is intended to inform the detailed design of the Cross-Scale mission and in particular to aid in deciding quite where these compromises should be made to maximise the science return.

Section 3 briefly describes some of the practical aspects of the Cross-Scale mission, such as orbits and possible instrumentation. While these are not finalised, some useful conclusions can already be made about what is, and is not, possible or desirable.

Finally, we stress that this document is the work of an informal collaboration between the co-authors. It has no official standing, but is intended to aid in the process of defining the final Cross-Scale mission.

2. Scientific priorities

While Cross-Scale can be used to investigate many plasma phenomena and regions of near-Earth space, there are three fundamental plasma processes that are the highest priority for study. These – reconnection, shocks and turbulence – are the most important phenomena in determining the dynamics of collisionless plasmas throughout the Universe. All require the multi-scale measurements of the entire Cross-Scale spacecraft fleet to allow us to make progress in their study.

2.1.Reconnection

Magnetic reconnection is a fundamental plasma process in the Universe. It plays a key role in the interaction of the Earth’s magnetospheric environment with the solar wind, in the onset of solar and stellar flares and CME formation, in the interaction of our solar system with its interstellar neighbourhood and in astrophysical contexts such as pulsar magnetospheres and active galactic nuclei. Indeed, we might expect the process to occur in any system in which magnetic fields and plasmas of different origin may interact.

Although the sizes of such systems are widely disparate, theoretically we expect that reconnection is initiated in each case on relatively small scales, where the kinetic effects of the typical particle populations in each system become important, rather than the large, flow (MHD) scales. Specifically, these processes occur on the distance and time scales of the relevant electron and ion gyromotions. When gradients in the magnetic field become sharp, the ions in a plasma become demagnetized (i.e. they no longer obey the frozen-in field (MHD) approximation) and may diffuse across the field. However, the electrons remain magnetized until the gradient becomes significant on the electron gyroscale, and an electron diffusion region forms. A complex system of electron currents is then thought to arise within and around these regions. These currents control the change of topology of the magnetic field which is seen through observations of the larger scales, and which propagates the effects to global scales.

Regular in situ measurements of the magnetic reconnection process and its effects are only available from spacecraft which have explored the terrestrial magnetosphere. There are several observations of reconnection processes available from missions to the other magnetized planets, and there have been a handful of reports of reconnection occurring at discontinuities embedded in the solar wind flow. However, for the other solar, stellar and astrophysical contexts, the occurrence of the reconnection process can only be inferred from remote observation. In addition, laboratory studies of reconnection are still far from being able to measure detailed plasma properties near reconnection sites. Consequently, the terrestrial magnetosphere remains the only place in which we can reasonably expect to make detailed measurements of microphysical processes involved in reconnection and also to examine in detail both the external conditions controlling its occurrence and the large scale consequences it has on the system.

Previous missions have provided evidence that reconnection occurs regularly on the magnetopause boundary between the shocked solar wind and the magnetosphere, with the location of reconnection site depending on the direction of interplanetary magnetic field (IMF). For more southward IMF direction the reconnection sites tend to be on the dayside magnetopause while for more northward IMF they tend to be tailward of the magnetic cusps. Reconnection at the magnetopause is responsible for dynamically coupling the magnetosphere to the solar wind flow and thereby in large part driving the global scale magnetospheric convection cycle. At least at times reconnection on the magnetopause occurs in a sporadic fashion, probably in both space and time, and is responsible for erosion of the magnetosphere through multiple flux transfer events (FTEs), which act to transfer magnetic flux from dayside to nightside. In addition, particle acceleration associated with this process results in the injection of solar wind plasma down into the polar ionosphere, forming spatially- and temporally-dispersed ion signatures seen within the magnetospheric cusps.

Magnetic reconnection also occurs within the nightside magnetosphere, where its consequences are particularly dynamic due the large amount of energy that is available in the magnetic field of the tail lobes. Its occurrence in the near-Earth magnetotail close to the onset of magnetospheric substorms is crucial for the global reorganization of the tail and the associated energy release both into the inner magnetosphere, the polar ionosphere and back into the solar wind. This energy release manifests itself as auroral activity, auroral electrojet currents, energetic particle injection at geosynchronous orbit, particle acceleration within the tail plasma sheet and in the formation of plasmoid or flux rope type structures and their subsequent ejection back into the downstream solar wind. As with the reconnection at the dayside, magnetotail reconnection in the tail is often a localized and transient process. Reconnection may be initiated at multiple regions simultaneously, resulting in the bursty particle and field disturbances observed in the plasma sheet and its surroundings.

We know that reconnection occurs when magnetic fields are sheared across relatively thin current layers. However, we have little understanding of exactly where and when a reconnection site will form, for example during a substorm, because we have a poor understanding of the microphysics of the reconnection process. To date we have been unable to make the coordinated measurements, at high enough time resolution, to be able to reach an understanding of the processes which occur on the electron scales, and their relation to the larger scale boundary conditions, such as the degree of shear, whether the process is operating in a steady state or transitory fashion, etc. Cross-Scale will be the first opportunity to make the required coordinated measurements across all the relevant scales for reconnection, covering the electron dynamics at high time and spatial resolution, the ion scale to examine the field and plasma structures surrounding the diffusion regions and the MHD scale to examine both the external drivers and the large scale consequences, such as the level of particle acceleration, the formation of flux ropes or the properties of the plasma outflows.

2.1.1.How is reconnection initiated?

What triggers reconnection within a current sheet?

The most important issue in magnetic reconnection is to understand how magnetic reconnection is triggered or initiated. The onset mechanism for reconnection occurs on scales which are currently below our best measurement threshold, but may arise either through an of internal plasma instability, and/or by the occurrence of an external trigger. In the former case, we know that the development of thin current sheets is important, and that certain plasma waves and current sheet instabilities probably have a role to play in initiating this process. However, we do not know the critical thickness, relative to the prevalent ion and electron scales, for a current sheet to undergo reconnection, nor indeed how thin a current sheet can become before it breaks up through reconnection. We need to be able to make measurements at small enough spatial resolution to determine these basic properties of pre-reconnection current sheets. These measurements must include the determination of the current-carrying electron and ion velocity distribution functions at various positions with high time resolution. At the onset of reconnection, we would expect that the dynamics of the main current carriers, and indeed the current structure itself, would change, and dynamics leading to these changes would be reflected in the velocity-space distribution functions. Such changes are beginning to emerge from simulation results but current measurement capabilities are insufficient to confirm these results. The most important observation would be of a site that develops into the electron diffusion region, for which electron observations fast enough to resolve the electron-scale (with a time resolution of ~10 ms) are needed. In the ion diffusion region that surrounds the electron diffusion region, the current structure must also change, in order to accommodate the changes in the electron diffusion region, and thus the effects of reconnection begin to propagate across scales. Consequently, multipoint observations which resolve the relevant ion-scale also need to be carried out, and fine resolution measurements at each point are needed. On both these scales, a full three-dimensional measurement of the electric and magnetic field is also crucial to understanding the dynamics of the electrons and ions within the onset region and to be able to identify the dominant wave modes and instabilities which most likely control the reconnection microphysics within the ion and electron diffusion regions.. Furthermore, these measurements need to be done with an understanding of the large scale context, such as whether the global current sheet is tilted, whether the thin current sheet is embedded in a broader current carrying region, whether these two sheets have a common orientation, etc., since these properties are relevant to the overall inflow and outflow geometries.

The MHD scale is also crucial if we are to determine the possible role of external triggers, or variations, in the onset of reconnection. This scale represents the outer boundary conditions for magnetic reconnection, so it is especially important to have knowledge of changes in the parameters of the inflow plasmas in order to be able to assess their impact on the smaller scale microphysics. For example, the magnetic reconnection rate may well be determined by the properties of the inflow plasmas in the ion-electron decoupling region. It is also important to know how these flows evolve with changes in the electromagnetic structure which result from reconnection, in order to identify any feedback processes within the system.

The related problem of how and why magnetic reconnection ceases is rarely explored. It is clear, for example at the end of the substorm expansion phase, that significant amounts of unreconnected magnetic flux remains within the upstream region at the point that magnetic reconnection ceases. Hence reconnection does not simply stop when all the available flux, or magnetic stress, has been removed. The boundary conditions at MHD-scale do not seem to change significantly. It is therefore possible that the plasma and field structure at the ion-scale is changed, or that the current structure at the neutral sheet is destroyed by internal processes that then act as a governor for the process. Again, this problem could be addressed with simultaneous multi-point measurements over the electron-scale, the ion-scale, and the MHD-scale.

How are thin current sheets formed?

A central plank towards understanding the onset of reconnection is the determination of how current sheets thin prior to the onset of reconnection. In order to do this we need to resolve the current sheet structure over multiple scales. We need to simultaneously have knowledge of the global scale current and the development of any sub-structure, such as the thin embedded layers discussed above or bifurcated current layers within the overall structure. In order to properly quantify the physics of these layers we need to determine a number of properties of the plasma in addition to the current density distribution. For example, we need to determine simultaneously the wave properties (such as the role of the lower hybrid drift instability (LHDI)), electron temperature anisotropy, the occurrence of any electron holes, etc. The temporal development of the current sheet leading to the onset of reconnection (possibly over timescale as short as a few gyroperiods) may be observed by looking at variations of current sheet properties between crossings of a magnetopause or magnetotail current sheet by each of the spacecraft within the CrossScale flotilla. Indeed, Cluster has shown that there are applications for unusual spacecraft orientations, such as the string of pearls configuration, for the monitoring of such temporal development.

What is the role of external driving in reconnection onset?

Earlier spacecraft measurements have suggested that the reconnection processes at the magnetopause respond to the changes in the solar wind. Recent studies of tail reconnection similarly indicate that many cases of reconnection onset in the near tail region are associated with sudden changes of the driving electric field in the solar wind. This clearly suggests that external driving can play an important role in controlling the reconnection process even though the mechanism for this is not clear. A number of recent numerical simulations, employing different numerical schemes, all show that, in case of driven reconnection, the system responds in a consistent manner. This supports the idea that it is very important to make detailed multi-scale observations that would allow to reach an understanding of the response of the system to external driving conditions. This requires spacecraft located at very different scales. Spacecraft separated at scales larger than characteristic ion scales would be able to monitor external drivers while spacecraft separated at ion and electron scales would be able to monitor the response of the current sheet and the reconnection site to these drivers.

2.1.2. What parameters control the structure of the reconnection site?

What is the scale size of the reconnection neutral line?

Observations consistent with the expectations of the Hall reconnection model have been reported based on analysis of Cluster data from several crossings of the magnetotail current sheet. In this model, the ion diffusion region contains Hall currents which are closed by a larger-scale system of field-aligned currents extending away from the diffusion region along the separatrix between the inflow and outflow plasmas. However, the scale size of this Hall current system, in both the radial and cross-tail directions, cannot be determined without monitoring the diffusion region and its surroundings on the electron, ion and fluid scales simultaneously. We need to be able to directly compare observations from regions in which reconnection is observed to be occurring, with nearby regions in which it is clearly absent in order to reveal the factors which control, e.g. the length of the neutral lines.

In addition, magnetic reconnection is usually thought to start within a small region and develop into a large-scale structure, as evidenced, for example by the expansion of observable substorm effects following an isolated localized onset. This development suggests a coupling from the electron-scale (the origin), through the ion-scale (as the ions demagnetize within the developing field gradients), to the MHD-scale (on which the energy release, for example through the driving of high speed flows, is most obvious). Furthermore, three-dimensional development of the magnetic reconnection process has not been resolved, even within the most up-to-date and powerful of simulations. Thus the problem of how magnetic reconnection develops and thereby initiates significant large-scale topological changes and energy conversion among the surrounding fields and particle populations is another important issue that can only be addressed through appropriate in situ measurements across the 3 key scales.

How significant are the effects of a guide field, velocity shears and density gradients?

Simple models often invoke the idealized case of reconnection between exactly antiparallel fields embedded within two similar plasmas. However, in reality the reconnecting fields are often sheared such that a guide field, or non-reversing component, may occur in the direction parallel to the neutral line. This is particularly likely on the dayside magnetopause, where reconnection effects have been observed for inferred shear between the magnetosheath and magnetospheric fields as low as 70 degrees. Cluster has also observed a hemispheric asymmetry in tail current sheet structures which might arise as an effect of the guide field, but could also be temporal effect. Multi-point current density measurement (in contrast to the one point current density measurement obtainable from the curlometer technique applied to Cluster data) is needed to resolve such questions. In addition, reconnection at the dayside magnetopause is likely to occur in current sheets across which there is significant velocity shear and a strong gradient in other plasma properties. Gradients in density are also possible in the tail due to non-uniform filling of open field lines by solar wind and ionospheric plasmas. In order to quantify the effects of such asymmetries on the reconnection process, we need to be able to simultaneously resolve the development of the thin current sheets and the large scale inputs to the system.

What are the effects of different particle populations on the reconnection process?

Cluster observations in the magnetotail suggest that the presence of oxygen ions may have a significant effect on the reconnection process. During these events, the oxygen ions provided the predominant density and pressure contributions and appear to have resulted in multiple-scale current sheet structures. Thus additional ion populations are expected to add an additional scale to the process. In fact, several theoretical studies have predicted how multi-component ion populations may modify both the structure of the current sheets in the reconnection region and also the reconnection rate. Furthermore, it has been suggested that heavier ions could be more effective in propagating the effects of the high speed flows to the global scale. Multi-component plasma effects are also expected to be important at the magnetopause, as a significant oxygen component can be present on the field lines on the magnetospheric side of the boundary. In addition, mixtures of plasma populations with different temperatures may also occur on these field lines, such as cold plasma of ionospheric origin mixed with warm plasma from the plasma sheet. The effects on the reconnection process of such mixtures of plasmas have not yet been fully explored.

In order to understand these multi-component ion effects, spacecraft with different scales covering from electron to fluid scales are again needed, and it is desirable to make 3d measurements of the plasma composition on at least the largest of these scales. Combined with the minimum requirement for a fleet of spacecraft with separations covering the three different scales, this will allow the determination of the additional effects of the multi-component ion populations on current sheet structure and on the internal dynamics of the reconnection process.

2.1.3.What are the consequences of reconnection?

A major consequence of the reconnection process is that localized changes in the magnetic field topology (magnetic fields are “reconnected”) leads to release of magnetic field energy across large regions of space. Understanding how the small scale controlling influences of reconnection relate to the results of reconnection and its control of the global environment is particular important if we have ambition to extrapolate our results to other planetary, solar or astrophysical systems in which the parameter regimes may be widely different.

How does magnetic topology change during reconnection?

Magnetic topology changes following reconnection provide a mechanism to bring together two different plasmas on the same flux tube, and we need to develop a better understanding of the manner in which these different plasmas interact. From theoretical point of view topology changes are either due to parallel electric fields or due to magnetic flux transport through magnetic null points (lines). Thus the measurement of high quality 3D electric and magnetic field vectors is crucial to understanding of topology changes. However, not all parallel electric field leads to topology change. Hence, it is important to determine the distribution of parallel electric field with distance from a reconnection site to assess whether, or by how much, this field contributes to the topology changes. Similarly it is important to know the variation of the electric field along the magnetic neutral line. Both these sets of measurements can only be achieved through simultaneous multi-point observations across the systems of interest. On one level, we need small spacecraft separation as the typical scale of the strongest parallel electric fields is down to electron scales. On the other hand, we know that parallel electric fields can extend far from reconnection site along e.g. separatrix regions and thus measurements from spacecraft with large separations would also be required. In addition, fast electron measurements, at a similar cadence to the field measurements, are needed if we are to identify the topology changes, for example by defining open/closed field line boundaries through the changes in the electron distributions. Spacecraft at close separation (much below ions scales) with high temporal resolution of these electron distributions would also enable an estimation of the local speed of the open/closed boundary, and thus the reconnection rate, while spacecraft at larger separation (ions scales) would be required to observe the dynamical evolution of this boundary, e.g. indicating the formation of multiple X-lines or new X-line formations within the system.

How are ions and electrons energized as a consequence of reconnection?

Magnetic reconnection is also an efficient mechanism for ion and electron accelerations. Indeed, most of the energy released during the reconnection process goes into the energization of ions and electrons. A puzzle is how thermal electrons are accelerated very effectively to suprathermal energies, but only in a small scale region surrounding the X-line. The physical processes behind the heating of particles, formation of high-energy tails in particle distributions, formation of reconnection jets and field-aligned beams are not well understood. For this the relative importance of electric field (E_{perp} and E_{para}) at the boundaries, in the electron diffusion region, and at the trapping boundaries needs to be resolved. Cluster observations near reconnection sites show strong electric fields (E_{perp}) on scales smaller than ion scales, such that ions are demagnetized while electrons are magnetized. These fields are associated with strong potential jumps and can cause a large part of the ion, but not the electron, energization. For electron energization, electric fields must form on scales that are smaller than electron scales. At the same time energization along the magnetic field, such as formation of field aligned beams, can be either due to Speiser-type orbits (scales comparable to particle scale), very localized double layers (scales comparable to or below electron scales) or due to very extended regions (tens of ion length scales) of parallel electric field. The dominant processes are not clear. The formation mechanism for energetic tails in the particle distributions is also not clear, yet this is particularly important from point of view of astrophysical applications. The suggestions from existing numerical simulations show that these tails can form due to very extended X-lines (hundreds of ion length scales), due to interaction with multiple

X-lines, or through trapping by local mirroring of the particle near the current sheet. High quality observations are crucial for understanding these important processes.

From the above it is clear that to understand the energization processes of particles we need be able to resolve the ion distribution functions on scales much below the ion scales and the electron distribution on scales below the electron scales. This requires spacecraft separations on both the electron and ion scales. We need to know the spatial variation of the energy spectra and this requires coverage of the 1-100 keV energy range at multiple points separated across the ion-scale. Moreover, to identify the acceleration mechanism, sophisticated measurements enabling the identification of any wave-particle interactions are needed. To achieve this, three-dimensional electric field measurements are critical. Simultaneous measurements at fluid scales would also be required to understand the context of the reconnection process and to analyze the formation of energetic tails in the downstream particle distribution functions.

Formation of multiple vs single reconnection sites and how X or O lines move?

There is a considerable body of evidence that reconnection may initiate simultaneously at multiple sites or that reconnection may be sporadic and temporal in nature. This evidence includes the observations of multiple flux transfer events on the dayside magnetopause and multiple flux ropes and/or plasmoids in the magnetotail. There remains an ambiguity between whether reconnection initiates at multiple sites, creating a series of X- and O-lines at the same time, or whether switching on and off of the reconnection process creates a similar set of structures, but serially in time. This ambiguity can be only resolved with observations at several points along the magnetopause or magnetotail current sheets. Moreover, we need to determine the subsequent evolution of such X- and O-lines. Present models for the occurrence of multiple flux ropes in the tail suggest that a dominant X-line reconnects faster than others in a set, reaches open lobe field lines first and thereafter dominates the motion of the other X-lines and flux ropes in the sets, driving them either Earthward or tailward depending on their relative position to the dominant X-line. However, we do not understand the conditions that control the reconnection rate at a given site, and therefore cannot predict how the overall current sheet structure will evolve. Again, multiple observations along the current sheets are needed to resolve this question. Finally, we need to establish how the relatively small scale flux ropes observed, e.g. by Cluster in the near-Earth tail, evolve both as they propagate into the more distant tail, where we tend to observe much larger structures on average, or as they propagate Earthwards where they must be dissipated, perhaps by re-reconnection with the stronger, dipole-like magnetic fields close to the Earth. Similarly on the dayside, flux transfer events have a rather distinct size distribution and repetition rate, so we might again ask how reconnection is initiated on the small scale and how this couples to the observations of global transfer of magnetic flux from dayside to nightside.

How are Alfvén waves and other plasma waves generated near the reconnection site and how these waves interact with ambient plasma?

Observations at some distance from active reconnection sites indicate that reconnected magnetic field lines (such as those within the plasma sheet and cusp boundary layers) are regions of very strong wave activity. In these regions, waves contribute to particle energization, energy transport and energy redistribution. Waves can also be used as indicators of local plasma processes, as well as a remote diagnostics tool. As an example, we note that waves of Alfvénic character, with a large electromagnetic energy flux, are observed to propagate away from the reconnection site. The associated wave-particle interactions contribute significantly to such processes as local particle energization, remote ionospheric ion outflow and the formation of the aurora. However, the generation mechanism of these waves is not clear. Perpendicular to the magnetic field, these waves can be localized within a sheet with a thickness of the order ion scale or smaller, while along magnetic field they can extend for hundreds of ion scales. To make significant progress in understanding the origin and nature of these waves and their relation to reconnection processes again requires spacecraft that are separated at several scales: spacecraft at separation smaller than ion scales to study the wave properties across the magnetic field; spacecraft at separation larger than ion scale to study the environment of reconnection site and wave properties along the magnetic field and finally, if possible, spacecraft at hundreds of ion lengths along the magnetic field to see the development in the wave propagation along the magnetic field direction. Such range of different separations is also important when analyzing other plasma waves, e.g. drift lower hybrid waves, whistlers, and electron cyclotron waves, each of which would require separations simultaneously covering scales from tens of ions scales down to the electron scales.

How does the reconnection jet interact with Earth’s dipole field?

Previous observations show that the reconnection outflow jets are transient and localized. This is related to processes occurring within the reconnection region itself, but these processes are not yet fully explained. In the magnetotail, plasma jets emerging from the Earthward and from the tailward sides of an active reconnection region have significantly different characteristics. Earthward flows must eventually brake and/or divert due to the Earth dipole magnetic field, which acts as a magnetized obstacle. This is quite different from the tailward flow which can freely escape downtail until it rejoins the solar wind. The situation at the Earthward flow side, is therefore one in which transient flux tubes must interact with the ambient magnetic field. This problem of coupling of macroscopic motion and microdiffusion is also applicable to certain problems in other planets. Theories predict, for example, that the interface between the reconnection jet and the pre-existing plasma sheet plasma may become unstable to an interchange instability which may create a magnetic shear consistent with the currents flowing into and out from the ionosphere. To understand this entire process, in which plasma jets from the reconnection region evolve into localized plasma flow channels and interact with ambient field, we need observations which support a simultaneous monitoring of the entire plasma jet structure, together with the fast moving front structure. In addition to the multi-scale measurements, of particular importance in this study will be observations with high temporal-resolution to resolve the fast moving, thin front structures.

2.1.4. Matrix of Instrument Requirements based on Science Questions

Question priorities

Priority 5 questions:

- What triggers reconnection within a current sheet?
- What is the scale size of the reconnection neutral line?
- How does magnetic topology change during reconnection?
- How are ions and electrons energized as a consequence of reconnection?

Priority 4 questions:

- How are thin current sheets formed?
- How significant are the effects of a guide field, velocity shears and density gradients?
- Formation of multiple vs single reconnection sites and how X or O lines move?

Priority 3 questions:

- What is the role of external driving in reconnection onset?
- What are the effects of different particle populations on the reconnection process?
- How are Alfvén waves and other plasma waves generated near the reconnection site and how do these waves interact with ambient plasma?
- How does the reconnection jet interact with Earth dipole field?

Location

Magnetopause and tail current sheet (dayside: 10-15 R_E and nightside: 15 – 50 R_E respectively). Ideally would like long durations in the tail plasma sheet (suggests equatorial orbit) and skimming of magnetopause (GEOTAIL type orbit?). Measurements poleward of the cusps would be a bonus, but at low priority (2).

Physical scales

Note that for magnetopause and magnetotail current sheets there are disparate scales of variation in the direction normal to the sheet (N in following table) compared to those transverse (L and M) to it (10-100s km vs R_E) In addition, for the tail X>Y>Z, particularly for large scale phenomena. It will be very important to take these physical scales into account when designing spacecraft constellations.

What	**Lengthscale (can be different in different directions)**	**Timescale T**
Flow reversals, bursty bulk flows, flux-ropes, plasmoids, FTEs, current sheet oscillations, magnetopause curvature	Magnetopause: L: 0.5-2.5 (or greater) R_E, M: 0.5-2 R_E?, N: 0.2-1 R_E Magnetotail: X: 1-2.5 R_E, Y: 1 R_E, Z: 0.5-1 R_E	Magnetopause: 30s-2min Magnetotail: 1-15 min
Thin current sheets, current filaments	Magnetopause: L,M: < 500km, N: ~100km Magnetotail: X: 500 km – 1500 km, Y, Z < 500 km	Magnetopause: ~1s Magnetotail: several s
Electron dynamics (shock ramp, electric field spikes, ...)	Magnetopause: ~ 3 km Magnetotail: ~10 km	Magnetopause:50Hz-20kHz (0.1 f_{ce} – 2 f_{pe}) Magnetotail: 10Hz-5 kHz (0.1 f_{ce}-2f_{pe})

Required measurements

The matrix below sets out the measurement requirements for the reconnection component of this mission, including time resolutions, constellation requirements and priorities. The priority P and number of spacecraft N needed at that scale are also detailed. Assume an overall configuration of 12 spacecraft, 4 at each scale.

Instrument	**Electron scale (e)**	**P**	**N**	**Proton scale (p)**	**P**	**N**	**Fluid scale (f)**	**P**	**N**
B field 3D	1000 Hz	5	1	1000 Hz	5	3+1e	100 Hz	5	3+1p
	100 Hz	5	4						
	1000 Hz	4	4	1000 Hz	4	4	100 Hz	4	4
	100kHz+3x1000 Hz	3	4						
E-field	3D 100kHz	5	1	2D 100kHz	5	3+1e	2D 100Hz	4	1
	3D 100kHz	4	2	2D 100kHz	4	4	2D 100Hz	3	3+1p
	2D 100kHz	4	4	2x2D+2x3D 100kHz	4	4	2D 100Hz	3	4
	3D 100kHz	3	4	3D 100kHz	3	4	3D 100Hz	3	4
Ion (<30 keV), unresolved composition 3D f (v), 30*12*32.	10 Hz	5	1	1.0 Hz	5	3+1e	0.1 Hz	5	3+1p
				0.5 Hz	4	4	0.5 Hz	4	4
				2x0.5Hz +2x10 Hz	4	4			
				10 Hz	4	4			
Ion (30 - 100 keV), unresolved composition, 3D f(v), 30*12*32.	0.5Hz	5	1	0.5 Hz	5	1+1e	0.1 Hz	5	1+1p
				0.5 Hz	3	4	0.5 Hz	3	4
Ions (< 30 keV), Mass- resolved (O+ etc), 3D f(v), 30*12*32	0.5 Hz	5	1	0.5 Hz	4	1+1e	0.1 Hz	4	1+1p
	10 Hz	3	1	0.5 Hz	3	4	0.1 Hz	3	4
				10 Hz	3	4			
Ions (30 - 100 keV),Mass-resolved (O+ etc), 3D f(v), 30*12*32	0.5Hz	3	1	0.5 Hz	3	1+1e	0.1 Hz	3	1+1p
	10 Hz	3	1	0.5 Hz	3	4	0.1 Hz	3	4
Electrons (< 30 keV) 3D f(v), 30*12*32.	100 Hz	5	1	1.0 Hz	5	3+1e	0.1 Hz	5	1+1p
	10 Hz	5	2						
	100 Hz	4	4	0.5 Hz	4	4	0.5 Hz	4	3+1p
	500 Hz	3	1	2x0.5Hz+2x100 Hz	4	4	0.5 Hz	3	4
				100 Hz	3	4	2x100Hz+2x0.5Hz	3	4

Instrument	**Electron scale (e)**	**P**	**N**	**Proton scale (p)**	**P**	**N**	**Fluid scale (f)**	**P**	**N**
Ions > 100keV 3D f(v)	0.1 Hz	5	1	0.1 Hz	4	1+1e	0.1 Hz	4	1+1p
							0.1 Hz	3	3+1p
							0.1 Hz	3	4
Electrons > 30keV, 3D	0.5 Hz	5	1	0.5 Hz	4	1+1e	0.1 Hz	4	1+1p
	10 Hz	4	1	0.5 Hz	4	4	0.5 Hz	3	1+1p
	10 Hz	4	2	10 Hz	3	4	0.5 Hz	3	4
							2x10 Hz+2x0.5Hz	3	4

2.2.Shocks

Collisionless plasma shocks are some of the most spectacular, visually striking and energetic events in the Universe. Generated by supernovae, stellar winds, or the rapid motion of objects such as neutron stars, they can have a number of important effects. Supernova shock waves can trigger the collapse of galactic nebulae and hence the formation of planetary systems. They are also responsible for heating and deflecting the surrounding plasma, and can blow bubbles out of galactic disks, changing the large scale magnetic configuration of entire galaxies. Collisionless shocks can also accelerate particles to extraordinarily high energies.

The interaction of the fast-moving solar wind with the Earth's magnetosphere results in a bowshock. Its curvature means that regions of quasi-parallel (magnetic field parallel to the shock normal) and quasi-perpendicular shock front co-exist, and that the Mach number varies across the shock surface. Alfvén Mach numbers can reach 20, comparable to those in many astrophysical scenarios. The terrestrial bowshock is therefore a useful model for astrophysical shocks. The ability to measure particle distributions around and within the shock front makes it possible to study shock dynamics in great detail.

The in situ measurement of collisionless shocks within the solar system by spacecraft has revealed many of the fundamental properties of these phenomena –not least that they exist.

Above a critical Mach number, which is a weak function of various shock parameters but is typically near 3, collisionless shocks cannot slow the incoming plasma through conventional resistive dissipation. Some ions are reflected from the shock front and most gyrate around the upstream magnetic field before being carried back into the shock itself, although a small fraction can, in some geometries, escape upstream. These co-called "supercritical" shocks are of interest because of their ability to inject supra-thermal particles into the upstream medium and accelerate them to high energies.

Supercritical shocks are fundamentally variable in time and space. They exhibit reformation, a quasi-periodic variation in the shock profile on scales comparable to the proton gyroradius. This results in a non-planar, and varying, shock profile, with important consequences for how particles are deflected, heated and accelerated. In particular, it is clear that the average effects of a shock are not the effects of a shock with the average shock profile – that is, the spatial and temporal variations are an intrinsic and fundamental part of the action and consequences of a collisionless shock. It is essential to study these variations simultaneously on electron, ion and fluid scales to measure the interactions between physical processes which occur within shocks, and how these produce their large scale effects.

2.2.1.How is incident energy partitioned by the shock?

In the frame of the shock, the upstream, incoming plasma carries kinetic, thermal and electromagnetic energy into the shock front. This energy is then partitioned into a number of forms. Most is distributed between the downstream kinetic and thermal energies of the ions and electrons. Knowledge of the fraction distributed into each of these forms is essential for predicting the large scale effects of shocks, wherever they occur – such as electron heating and hence X-ray emission from astrophysical shocks. It is possible to measure this partitioning directly at the terrestrial bowshock. However, this does not mean that the physical processes by which the distribution of energy occurs are well known. Indeed, this partitioning varies considerably with shock parameters and is also highly variable in space and time, so the application of these measurements to astrophysical shocks is not straightforward without a detailed knowledge of the physical processes which govern the energy distribution. In the following sections, unanswered questions concerning shock dynamics and effects are described, along with details of how Cross-Scale can help to elucidate their behaviour.

How are ions reflected and decelerated by the structured shock electric field?

The potential difference across the shock front is responsible for decelerating the incoming ions, some of which are reflected at supercritical shocks. However, this potential is the integral of the electric field across the shock – and this electric field is known to be highly structured, and variable, on all measured scales, down to the electron scales. The trajectory of an individual ion through the shock ramp is controlled by the instantaneous electric field that it encounters – but since this field is structured and variable, it varies greatly between ions. This in turn leads to many complex trajectories within the shock, some of which result in ions being ejected into the upstream plasma. A knowledge of the complex interplay between very fine scale electric field structures and ion dynamics, and the resulting variability in the shock profile and structure, is essential for predicting the reflection and acceleration of ions around the shock, and in turn the bulk effect of shocks on the ambient medium.

How are electron dynamics affected by shock reformation and ion dynamics?

Just as ion trajectories within the shock are affected by small scale electric field structures, so electron trajectories and small scale electric field structures are altered by the large scale shock profile, which is constantly varying as a result of reformation and ion dynamics. Very little is known about the effect of large scale shock variability on the formation, size and lifetime of small scale electric field structures, but without this knowledge, the 3D electric field structure, and final electron distribution functions, cannot be understood.

Of key importance is the nature of the electron motion: magnetised or unmagnetised, dominated by steady fields or high frequency fluctuations or turbulence, and the feedback from the ion scales. Electrons with different energies or gyrophases may behave differently, requiring good coverage over the full range of velocity space.

How do ions thermalise?

The initial dispersal of ions is achieved at quasi-perpendicular shocks by the reflection and gyration of incident ions, which subsequently pass into the downstream region. This very coherent process results in a multi-component ion distribution which must then thermalise to complete the irreversible aspect of shock heating. Most likely, this thermalisation is a combination of gyrophase mixing (itself still a coherent process) and wave excitation and scattering. This process couples the ion gyroscale with the macroscopic fluid scale. At quasi-parallel shocks, some reflection also occurs but there is strong competition from and interference with the diffusive processes involved in the acceleration of ions (see below). It is very likely that different ion species behave in very different ways.

How do shocks respond to changes in the upstream plasma?

Several circumstances conspire to complicate the physics at real shocks. Some, described above, are intrinsic variability. Others are due to external variations which can have profound effects on the shock dynamics. For example:

- **Hot flow anomalies** are formed when a tangential discontinuity with suitable orientation and parameters impinges on a shock front. Despite the overall pressure balance through such a discontinuity, and its thin structure, the particle dynamics at the interaction region can give rise to dramatic explosive events which create a hot cavity upstream of and/or attached to the shock. At the bow shock, these are observed to have some of the hottest, most thermalised particle distributions seen in situ anywhere in the heliosphere. It is not at all clear how particles are accelerated within the cavity and small scale magnetic field structures within a hot flow anomaly, nor the role played by electron dynamics. As sources of energetic particles and possible triggers of further events, these structures require further study. Measurements of the large, fluid-scale cavity shape and evolution must be made simultaneously with ion distributions within and around the cavity, as well as fine scale electric field and electron variations in order to understand the dynamics and effects of these phenomena.

- **Shock response to dynamic pressure** changes include an overall acceleration of the shock front. Such accelerations displace planetary bow shocks and transmit the upstream dynamics deeper into the planetary system in a highly nonlinear manner. Fluid conditions up and downstream of the shock must be combined with ion distributions within and around the shock.
- **Shock-shock interactions** occur often in real systems, such as travelling interplanetary shocks colliding with planetary bow shocks, or forward shocks catching up with slower or reverse travelling shocks. Theoretically, such interactions provide conditions for extreme heating and particle acceleration.

2.2.2.How do shocks accelerate particles?

Particles are accelerated to extremely high energies within and around collisionless shocks. Such particles are reflected from the shock. Their propagation into the upstream plasma is unstable to the generation of waves, which in turn scatter them – a highly nonlinear process. Repeated reflection and scattering (the so-called “first order Fermi” process) can accelerate particles to very high energies. However, many aspects of this process are poorly understood, and involve spatially variable structures, both within the shock and in the upstream plasma.

How do ions generate and scatter from waves in the foreshock?

Fundamental to the first order Fermi process is the scattering length of the energised particles. Quantitative progress requires simultaneous measurements of the resonant plasma waves and particles over ion and fluid scales.

How does rippling and reformation affect reflection and acceleration?

The surface of shocks is believed to be rippled by local ion and current instabilities. It will be important to quantify the rippling process in terms of amplitude and particle parameters. Additionally, the ripples themselves provide time-varying fields which can trap some particles, enabling them to “surf” the shock front and systematically pick up energy from the large-scale motional electric field. Such surfing is potentially important for both ion and electron acceleration, and may “inject” suprathermal particles into the first order Fermi process, the efficiency of which is dramatically improved if fed a pre-accelerated population. Measurements are required of fluid scales ripples on the shock surface; ion distribution variations around and within the ripples, with variations on the scale of an ion gyroradius; and electron-scale heating and acceleration.

Electron foreshock processes

Beams of accelerated electrons penetrate the most sunward regions of the foreshock region. This is a classical laboratory for beam-plasma interactions, and numerous previous observations have highlighted the ubiquitous nature of Langmuir oscillations. Such observations contradict basic plasma theory, which suggests that the beams should be strongly unstable to the wave growth which, in turn, should scatter the beam particles relatively close to the bow shock, thereby destroying the beam before it can reach distances further upstream. This process is also critical for radio waves observed in connection with solar flares. Theoretical ideas, such as stochastic growth in an intrinsically inhomogenous environment, have received only circumstantial, indirect support. What is required is high quality combined electron and wave observations on both the electron microscale and electron foreshock (fluid) scales.

Development of structures in the parallel shock from energetic particle gradients

Quasi-parallel shocks are associated with Short Large Amplitude Magnetic Structures (SLAMS) which grow in the generally turbulent foreshock/shock region accompanied by energetic particles. Their polarisation suggests they grow due to a hot ion instability, essentially feeding off the particle pressure gradients, whereas other foreshock turbulence is beam-driven. Thus the relationship between SLAMS and the general turbulence is not clear. Again, the origin and evolution of the cycle of turbulence and particles needs to be explored by measurements at the disparate scales. SLAMS exhibit internal structure down to electron scales, and their overall size and shape is correspondingly difficult to determine without multi-scale observations. Yet their “filling factor” is critical to our picture of quasi-parallel shocks. Large scale measurements of the orientation of SLAMS, energetic particle gradients and ULF waves must be combined with ion-scale structures within SLAMS and electron-scale fine structure, with 3D electric field measurements.

2.2.3. Matrix of Instrument Requirements based on Science Questions

Question priorities

- How is incident energy partitioned by the shock? Overall Priority Level (1=lowest to 5=highest): 5
- How do shocks accelerate particles? Overall Priority Level: 5

Locations

At the bow shock, i.e., 15-20R_E generally on the dayside. Ideally, would like orbit to skim the bow shock, hence apogee not much more than 20R_E. Also at interplanetary shocks (15-50R_E) dayside at priority 2 (interplanetary shocks travel past the spacecraft much faster, and cannot be main driver for this question). For convenience, we have rolled these two questions together as they have similar environments and requirements.

Physical scales

The relevant physical length and time scales are summarised in the following table.

What	**Lengthscale L**	**Timescale T**
Foreshock (also curvature scale, macroscale, ...)	~ few Re	L/V_{sw} ~ 30-60 s
Ion dynamics (including shock foot, SLAMS, ...)	V_{sw}/Ω_{ci} ~ 1000 km v_{th}/Ω_{ci} ~ 100 km	$2\pi/\Omega_{ci}$ ~10-15 s
Electron dynamics (shock ramp, electric field spikes, ...)	c/ω_{pi} ~ 100km c/ω_{pe} ~ 2km	V_{sw}/L ~ 0.5 -250ms

Required measurements

The matrix below details the basic measurements needed, the resolutions, constellation requirements, and priorities. We provide below the requirements for *both* the thermalisation/partition question and also for the acceleration question. Essentially, these have similar requirements except for the provision of energetic particle detectors. We also assign a Priority P (1-5) to each measurement and constellation/number N of s/c. We assume an overall configuration of 12 spacecraft, 4 at each scale.

Quantity/ instrument	**Electron scale**	**P**	**N**	**Ion scale**	**P**	**N**	**Fluid scale**	**P**	**N**
Magnetic field (AC & DC)	dc -> 50 Hz	5	2	dc -> 50 Hz	5	3+1e	dc -> 10 Hz	5	4
	50-> 500 Hz	5	2	50 -> 500 Hz	3	2+1e	50 -> 500 Hz	1	2
	>500Hz	4	2	dc ->50 Hz	3	4			
	>500Hz	3	3						
Ions < 30keV E/Q	3D f(v) 1 Hz (30Ex12x32)	5	1	3D f(v) 1 Hz	5	3+1e	3D f(v) 0.2 Hz	5	4
	3D f(v) 1 Hz	3	2	3D f(v) 1 Hz	3	4			
Ions < 30keV M	3D f(v) 0.1 Hz	5	1	3D f(v) 0.1 Hz	4	2+1e	3D f(v) 0.1 Hz	3	1

Quantity/ instrument	**Electron scale**	**P**	**N**	**Ion scale**	**P**	**N**	**Fluid scale**	**P**	**N**
	3D f(v) 1 Hz	4	1	3D f(v) 0.1 Hz	3	4			
	3D f(v) 1 Hz	2	2						
Electrons < 30keV	3D f(v) 10 Hz (30Ex12x32)	5	1	3D f(v) 1 Hz	5	1	3D f(v) 0.1 Hz	4	2
	3D f(v) 100 Hz	4	2	3D f(v) 0.1 Hz	4	3+1e	3D f(v) 0.1 Hz	3	4
	3D f(v) 1 Hz	5	2	3D f(v) 1 Hz	3	4			
	3D f(v) 1 Hz	3	3						
Ions > 30keV	3D E/Q f(v) 0.1Hz	5	1	3D E/Q f(v) 0.1 Hz	4	2+1e	3D E/Q f(v) 0.1 Hz	4	2
	3D E/Q f(v) 0.5Hz	4	1	3D E/Q f(v) 0.1 Hz	3	3+1e	3D E/Q f(v) 0.1 Hz	3	4
	3D M f(v) 0.1Hz	3	1	3D E/Q f(v) 0.1 Hz	2	4			
Electrons > 30keV	3D f(v) 0.1Hz	5	1	3D f(v) 0.1 Hz	4	1	3D f(v) 0.1Hz	4	1
	3D f(v) 0.5 Hz	4	1	3D f(v) 0.1 Hz	3	3+1e	3D f(v) 0.1Hz	3	4
	3D f(v) 0.1Hz	3	2						
Electric field (3D)	dc->1 kHz	5	1	dc->1 kHz	3	2+1e	dc->1 kHz	3	2
	dc->1 kHz	4	2		2	3+1e		2	4
	->10 kHz	5	1						
Electric field (2D)	dc -> 10 kHz	5	2	dc->10 kHz @ 100 msecs	5	1+1e	dc->10 kHz	4	2
				dc->10 kHz @ spin	4	3+1e	dc->10 kHz @ spin	2	4
				dc->10 kHz @ spin	2	4			
Electric field (1D)	dc->10 kHz @ 10 msecs	5	1	dc->10 kHz @ 100 msecs	3	4	dc->10 kHz @ spin	4	2
	dc->10 kHz @ 10 msecs	4	2				dc->10 kHz @ spin	2	4

2.3.Turbulence

Turbulence is pervasive in many astrophysical and solar system plasmas, over a vast range of scales from the inter-galactic medium to sub-electron gyroscales. Plasma turbulence is present, and dynamically important, in many interesting plasma environments, is responsible for accelerating particles and also greatly affects their propagation: without an understanding of turbulence, we cannot predict many of the most important effects of plasmas within the Solar System, far beyond, and within technologically important devices such as tokamaks. Nevertheless, the time-varying, structured, bursty and highly nonlinear nature of turbulence make analysis very complex and many aspects are poorly understood. Indeed, some aspects which appear universal in both neutral fluid and plasma turbulence, such as intermittency, remain enigmatic after decades of study. A fundamental limitation is the availability of multi-point measurements of turbulent fluids, to allow detailed analysis of the interactions between scales which is the key property of turbulence. Cross-Scale offers the prospect of the most comprehensive plasma turbulence measurements to date and will shed light on both plasma turbulence, its consequences in Solar System, astrophysical and engineering plasmas, as well as on turbulence as a universal process.

The main outcome of turbulence theories is to obtain the stationary, i.e. spatial, spectra of the turbulent fluctuations of fields and particles. These spectra are important because they contain most of the physics of the system. From these spectra we can deduce the scales of the processes by which the energy, or other invariants, like for instance the magnetic helicity, are injected, transferred, and dissipated in the system. In classical fluids as well as in dissipative magnetofluids the existence of a non-linear cascade is well documented; in particular the last part of the diagram - the dissipation – is relatively clear. In the case of dissipative MHD, it is described by the viscosity term in the dynamical equation and the diffusivity term in the induction equation ($\nu\ \Delta\mathbf{v}$ and $\eta\ \Delta\mathbf{B}$). The dissipation then appears to be a simple function of the constraints exerted on the fluid; it is assimilated to ‘friction’ and ‘resistivity’, and results into heating. The main reason for this simplicity is the efficiency of the interaction between the particles, in a regime where the mean free path between collisions is very small.

The physics of the dissipation in hot and dilute plasmas met in the universe, and now in fusion machines, is radically different. These plasmas are essentially free of collisions; the mean free path between two binary collisions is comparable to, or larger than, the scale of the gradients. Collisionless plasmas have very specific properties; unlike fluids they are not scale invariant; different physical processes take place at different scales. In particular collisionless dissipation processes, which are due to phase mixing (for instance Landau and cyclotron damping, or bounce resonances), depend strongly on the scale, and even on the microscopic properties of the medium (for instance via gradients in velocity space). The dissipation scale can be small (Debye length, electron Larmor radius), or large (Ion Larmor radius, bounce length).

It is difficult to study collisionless plasma turbulence in astrophysical objects. Indeed remote sensing methods are based on the observation of thermal radiation, for instance synchrotron and bremmstrahlung, coming from the regions of the object where collisions dominate. The hot and dilute collision-free regions, where explosive release of magnetic energy is likely to take place, cannot be directly probed, at least not via thermal radiation. On the other hand, the investigation of plasma turbulence, in laboratory devices, is severely limited by wall effects. Furthermore non destructive measurements are difficult to carry out in laboratory plasma devices, in particular when the experiments are conducted in a regime where the temperature is such that the plasma becomes collision-free. The Earth magnetosphere offers the best opportunity to carry out in situ measurements, at the various relevant scales, to investigate plasma turbulence in the collisionless regime.

As said above, the k-spectrum contains the basic properties of the turbulence, namely it yields information about the relation between the different scales, as well as about injection and dissipation scales. In incompressible fluids no eigen mode exists; the system evolves directly in the strong non linear regime, for which Kolmogorov has predicted, under the hypothesis of isotropy and homogeneity, the related stationary spectrum ($k^{-5/3}$). On the contrary, when eigen modes exist, as it is the case in plasmas, a weak turbulence approach maybe relevant at least on some time scale. Indeed the eigen modes often evolve almost linearly, and are coupled by weak non linear effects. In weak turbulence the linear characteristics of the modes (i.e. their dispersion relations and polarisations) are more or less preserved, then they can either reach the dissipation scale in this weak turbulence regime or evolve to the strong turbulence state where their linear properties are completely lost, i.e. no deterministic ($\omega,\mathbf{k}$) relation is to be expected. In both cases, **k**-spectra of the energy cascade can, in principle, be obtained. However, due to the complexity of the calculation/simulations, only a few theoretical predictions exist for the plasmas, most of them are obtained in the incompressible limit, i.e. for shear Alfvén or whistler turbulence. A proper characterization of turbulence is a major goal, for space plasma physics, as well as for other collisionless plasmas met in fusion and in astrophysics, where in situ and non destructive measurements are difficult or impossible to implement.

Theoretical approaches to plasma turbulence

The advantage of the fluid and magneto-hydrodynamic (MHD) description of turbulence is that it provides a general framework for the description of the energy cascade, whatever the details of the particle distribution functions; hence its relative simplicity. MHD turbulence has been studied in the context of the solar wind, on the basis of numerical simulations and of the analysis of data from single spacecraft. For instance experimental evidence has been given for the equipartition, between fields and particles, of the energy contained in the fluctuations. However, the interpretation of observations carried out in the solar wind, with a single spacecraft, is based on the Taylor hypothesis. In the collision-free, super-Alfvénic solar wind the turbulence is assumed to be frozen in the plasma. Then the observed frequency spectrum can be transformed into a **k**-spectrum, but only along the flow direction. This approach has drastic limitations, namely

- it only applies to plasmas moving at $V>>V_A$, the Alfvén velocity (and larger than all other characteristic velocities for the propagation, such as the sound speed)
- it has been developed for homogeneous turbulence, and therefore does not necessarily apply to magnetospheric boundaries, and
- MHD approximation is not necessarily valid. In particular the dissipation, which occurs mostly at small scales, cannot be described by MHD; more refined theories need to be used.

In order to study turbulence in a regime where the plasma is not super-Alfvénic and not necessarily homogeneous, a multi-scale approach is needed; this is exactly what the Cross-Scale mission aims at. Scales at which MHD is not valid require the use of a more refince approach, such as the collapse of Langmuir waves, the dynamical evolution of drift wave turbulence, or the collapse of lower hybrid turbulence. In addition, the physics of hot collisionless plasmas is not scale-invariant. Several scales intervene; for instance the ion and the electron Larmor radius, or the ion/electron inertial scale. Each of these scales can correspond to a dissipative process. The physics at these different scales is usually described by different equations. The large (non dissipative) scale is usually described by ideal MHD, while smaller scales deserve more refined descriptions: Hall-MHD, bi-fluid, guiding center or even fully kinetic theory.

In natural plasmas, not constrained by wall effects, a full turbulent cascade, involving different kinds of interacting wave modes, and therefore different dissipation processes, is likely to develop and to determine the dynamical evolution of the system. The Cross-Scale mission will provide the appropriate tools to characterize this interaction.

Effect of Doppler shift

In space plasmas the level of fluctuations, for instance $\delta B/B$, is often very large, in particular within magnetospheric boundaries (1-10%), in the magnetosheath and in the solar wind (up to 100%). This suggests that “Plasma Turbulence” develops at, or is transported to, spacecraft location. The distinction between strong turbulence and weak turbulence (involving “almost” linear modes), on the basis of data, is not an easy task. Furthermore, even the spectrum of waves developing, in an almost linear regime, under the effect of an instability, can be washed up by a large Doppler shift associated with the fast motion of the plasma with respect to the spacecraft, which makes it difficult to identify the typical characteristics (cutoff, polarization…) of linearly developing modes. Thus a broad spectrum can either be due to a non linear turbulent cascade or merely to a large Doppler shift applied to almost linearly developing modes. In other words, the effect of the Doppler shift is embedded in the measured “frequency” spectrum, and it is generally impossible, with a single spacecraft to obtain the frequency spectrum in the plasma frame, and even more difficult to deduce the **k**-spectrum needed to analyze the properties of the turbulence. To resolve this fundamental difficulty a proper spatial coverage is needed, together with the use of appropriate methods. In the next sub-section we show that frequency and wave number spectra can be obtained, and we briefly describe the method that will be used, and the corresponding constraints in terms of spatial coverage by the spacecraft.

Interferometric techniques

The spatio-temporal ambiguity that characterizes single spacecraft measurements generally makes it impossible to determine wave vector spectra. Only in the case of the solar wind, wave number spectra can be deduced (only in one direction) from frequency spectra measured in the spacecraft frame. For most of the space plasmas; in the magnetosheath, in the magnetosphere, as well as in magnetic boundary regions, such a relationship cannot be determined, and the only solution is to use interferometric methods, based on multipoint measurements. The k-filtering (also called wave telescope) is one possibility. With the four Cluster spacecraft we are currently able to infer **k**-spectra over a range of scales and frequencies determined by the distance between the spacecraft and by the flow velocity. In order to investigate the small scales, where most of the energy dissipation and/or magnetic reconnection is expected to develop, a small distance between spacecraft and a very good time resolution are needed. The Cluster tetrahedron, however, can only be used to determine a limited range of scales at a time. Thus the dissipation and the injection range cannot be determined simultaneously. In subsection 3 we delineate the constraints, in terms of spatial coverage, number of spacecraft, and distance between them, to be able to obtain a full turbulent cascade from the **k**-filtering. We will also describe the needs for temporal resolution of fields and particles measurements.

Previous space missions, Cluster in particular, have led to address specific questions as to the role that could be played by collisionless turbulence, in the dynamics of the magnetosphere and its coupling to the solar wind and ionosphere. We will briefly describe below some of these questions and explain why the Cross-Scale mission is required to solve them.

2.3.1.Dissipation and cascades in turbulent collisionless plasmas

In the collisionless regime binary collisions cannot provide the dissipation needed to ensure the friction between electrons and ions (the resistivity) or the diffusion needed to move the plasma across boundaries. Plasma turbulence can, in principle, take over the role normally ensured by collisions. Yet, as discussed above, collisionless dissipation processes are complex. In general they cannot simply be described by “anomalous” friction and transport coefficients, because they critically depend on the spatial scale and on the microscopic properties of the medium. Then the first step is the determination, for a given region, of the nature and the scale of the dissipation process, and to identify the external or internal driver for the energy cascade. A few situations, where a turbulent cascade is expected to occur, are discussed below.

What is the nature (and direction) of the energy cascade in homogeneous turbulent collision free plasmas?

The magnetoheath is a broad region where plasma turbulence can be considered as homogeneous. The amplitude of the fluctuations being very large we can expect that a turbulent state is reached in the magnetoheath turbulent flow. The flow being sub-alfvenic, the Taylor hypothesis cannot be made. Recent Cluster estimates of the wavevector spectrum suggest that a non-linear interaction between mirror modes, ion-cyclotron and whistler mode waves, takes place. This is a strong indication that a turbulent cascade does occur, and that the energy present in the mirror modes is dissipated via ion-cyclotron and whistler mode waves. Yet Cluster can only cover a limited range of scales; a better spatial coverage is required to make sure that we cover properly the injection as well as the dissipation scale.

What is the relation between large and small scales in the case of inhomogeneous plasmas; is there an energy cascade in magnetospheric boundaries?

In the classical scheme, the energy (or the magnetic helicity) is injected at the large scale, and the non-linearity transports the energy towards the small scale where it is dissipated. There are, however, situations where an inverse cascade develops. For instance there is evidence, from numerical simulations of the Kelvin Helmoltz instability at the magnetopause, of an evolution towards larger scales, by pairing of adjacent structures. These simulations, however, were based upon MHD and cannot therefore properly describe the collisionless dissipation that eventually occurs at a (small) scale, where MHD is not valid. By measuring plasma parameters at the scale of the structures as well as at the dissipation scale, the Cross-Scale mission will offer a unique opportunity to assess the direction of the turbulent cascade.

Depending on specific conditions, a turbulent cascade could also lead to the generation of large scale structures, like helicoïdal force-free structures. The force-free structures observed in the solar corona, as well as tail flux ropes and day side Flux Transfer Events (FTE's), which are observed near/at the magnetopause, might be due to an inverse cascade. In both cases the determination of the direction of energy cascading is very important.

Does intermittency exist? What role does it play?

One of the fundamental questions in experimental studies of turbulence concerns intermittency: are intermittent structures present? at which scale(s)? what role do they play in the different physical processes? Intermittency was first discovered in fluid turbulence, after it had been ignored in the earlier works by Kolmogorov. It is usually evidenced in data as the appearance of non Gaussian wings in the Probability Distribution Function (PDFs) of the turbulent fields. When intermittent structures appear in the inertial range, the self-similarity hypothesis, i.e., the scale invariance (fundamental in the K41 theory) is broken, yielding thus a modification of the classical scaling laws ($k^{-5/3}$). Intermittent structures are nevertheless believed to be more important at the smaller scales (~ the dissipations ones), hence their potential role in the enhancement of the dissipation mechanisms. Intermittency is indeed expected to play a key role in the heating of the solar corona. This increase of the energy dissipation is likely to be much more important in collisionless plasmas, for instance in the terrestrial magnetosphere.

What is the role of turbulence at triggering explosive phenomena, such as magnetic reconnection?

Due to the lack of collisions to thermalize the system and to enable the transport across magnetic boundaries, collisionless plasmas often evolve towards situations where the magnetic energy accumulates in thin current sheets, such as the tail current sheet and the magnetopause. At some stage explosive release of magnetic energy is observed to take place, over time scales much shorter than the time to build the thin current sheets. Substorms and solar flares are examples of these explosive releases. They are associated with reconfigurations of the magnetic field, as discussed in the reconnection section. In the absence of collisions, (ideal) MHD cannot be used to describe magnetic reconnection; some form of collisionless dissipation is needed. Various types of fluctuations have been invoked, including ion cyclotron, and whistler turbulence, as well as lower hybrid drift and current driven instabilities. Each of these corresponds to a different scenario for magnetic reconnection. Then the identification of the type of waves/fluctuations that produces the collisionless dissipation is a critical issue to understand how the magnetic energy is explosively released, in collisionfree systems. This is a delicate issue because the frequency spectra are affected by large Doppler shifts, as discussed above. Yet, in order to go beyond a static description of magnetic reconnection, in terms of a geometric model, we need to obtain **k-**spectra and to determine the interaction between the various scales. For instance it is possible that externally applied large scale fluctuations produce, via a direct cascade the small scale fluctuations needed to produce the dissipation where magnetic reconnection occurs. On Cluster low frequency (LF) fluctuations (~1mn) together with broad band higher frequency (HF) fluctuations (~1sec), are regularly observed in the tail current sheet, at explosive breakup. Do these LF fluctuations trigger reconnection by cancelling the magnetic field locally? Are they produced by reconnection? Is there a cascade between the LF and HF fluctuations? What is the role of HF fluctuations; are they responsible for the collisionless dissipation? Answering these questions requires a proper characterization of the different scales associated with these two types of fluctuations and of the interaction between them, which can only be done via multi-scale measurements.

2.3.2.How does turbulence transport plasmas?

Magnetospheric plasmas are characterized by high Reynolds numbers and can develop turbulent flows. In particular, the velocity shear layer present between the streaming solar wind and stagnant magnetospheric plasmas can get Kelvin-Helmholtz (K-H) unstable and lead to highly turbulent vortical flows, as revealed by recent Cluster observations. A parent K-H vortex itself is an MHD-scale structure in which plasma mixing cannot be achieved, but structures with a scale comparable to or smaller than ion gyroradius can be created through the vortical flows, cascading, or secondary instabilities excited in the vortex. Consequently, plasmas are mixed diffusively or through magnetic reconnection triggered in the vortex. Large-scale vortex flows in turn carry the mixed plasmas over large distances, hence this whole system becomes an agent for an efficient plasma transport. However, identification of the exact transport process embedded in vortices is beyond the capability of the present measurements. To clarify the ultimate transport mechanism, it is indispensable to perform simultaneous measurements over multiple scales that can reveal the temporal evolution of current sheet structures/phenomena embedded in the vortices, along with the detection of large-scale vortices. Another key element is particle measurements that can resolve ion compositions, because ions other than protons occasionally become the dominant population in terms of the mass density and may significantly change the dynamics of the boundary layer. Heavy ions can also be used as tracers of the origin of plasmas constituting the mixed region. Particle instruments need to cover a wide dynamic range of particle fluxes, since the fluxes change several (more than four) orders of magnitude across the boundaries.

The magnetosheath is also a highly turbulent region and compressional MHD waves present in this region may undergo mode conversion into kinetic Alfven waves (KAWs), when interacting with the magnetopause boundary layer where substantial spatial gradients in the density and magnetic field exist. KAWs can scatter and transport particles across the boundary, since their wavelength is comparable to ion gyroradius. Furthermore, there is a suggestion that KAWs may be excited in association with the growth of K-H waves in the tail flank. To understand coupling among several wave modes and its eventual effects on particle transport, the above-suggested multi-scale observations are required.

2.3.3.What is the role of turbulence in accelerating particles?

The highest energy particles created in the Earth's magnetosphere are trapped in the near-Earth space and form the radiation belts at geocentric distances less than ~7 Re. Observations show that the Earth's magnetosphere acts as an efficient particle accelerator during large geomagnetic disturbances and creates relativistic-energy electrons. A variety of mechanisms has been proposed to account for the acceleration in the inner magnetosphere. In some of the proposed mechanisms, the interaction between particles and field turbulence (or waves) plays a critical role. However, what mode and scale of field fluctuation is the main contributor to the relativistic electron creation is still under debates, and awaits observational clarification. As shown below, the potentially important phenomena include different scales from electron-scale resonance to MHD-scale fluctuations. Multi-scale measurements to obtain k-spectrum of VLF/ELF waves as well as a global distribution of ULF waves are important to clarify the issue.

What is the efficiency of acceleration through particle interaction with stochastic waves?

Increase of relativistic electron flux observed in the region of strong ELF/VLF chorus waves indicates the importance of the resonant interaction of electrons above 100 keV with waves in the frequency range around 1-20kHz is a promising candidate for the acceleration mechanism. However, the lack of information about waveforms and k-spectrum of the chorus waves prevent us to understand their generation mechanism and to determine the nature of the acceleration mechanism. Theoretical studies with broadband (such as Kolmogorov type spectra) or waves having narrow suggest that characteristics of acceleration change with assumption in the k-spectrum. The former correspond to stochastic acceleration and results in a power law spectra, while non-linear effects are important in the latter case.

Electrons and ions with energies around a few tens of keV are expected to play an important role in the excitation of chorus waves and EMIC waves, respectively. Plasmaspheric cold plasma has large influence of the characteristics of waves. Statistical distributions of the electromagnetic fluctuations suggest that the acceleration has the highest efficiency outside the plasmapause and occur mainly in the regions of 4<L<6 Re. Therefore, the k-spectrum identification in the wavelength range above several km as well as capturing 3-D structure of the electromagnetic waves together with 3-D particle measurements in a broad energy range up to several MeV in the region will be essential to understand how waves can accelerate the relativistic particles. Direct observations of the phase diagram for waves of several kHz and corresponding resonant particles with a wave-particle correlator may also be used. Most of theoretical studies predict that the acceleration takes place near the equatorial plane and an orbit of low inclination is essential.

What is the role of ULF turbulence to accelerate relativistic electrons?

The radial transport and energization by ULF fluctuations are also an important candidate of acceleration mechanisms that can create relativistic particles. The basic concept of the mechanism is resonant acceleration between MHD-scale ULF field fluctuations and the periodic drift motion of particles, and particles satisfy favorable condition of the resonance can be transported inward and get accelerated. Recent theoretical studies suggest the importance of non-linear interaction rather than classical stochastic diffusion. Identification of wave modes, spectrum, and spatial distributions of ULF fluctuations in the equatorial acceleration region with multiple spacecraft will provide important information to understand the role of ULF fluctuations in the particle acceleration. Combination with multi-point ground-based field experiments that provide global distribution of ULF turbulence in different local times and L values will further enhance the MHD scale information.

2.3.4.Mode coupling, wave-particle coupling

The conventional view of a turbulent cascade invokes interactions between fluctuations that are local in wavevector space. Non-local interactions may also play an important role in several space plasma processes, however, particularly those involving wave-particle interactions. The multiple measurement points at several scales provided by the Cross Scale constellation will make it possible to use advanced data analysis techniques such as wavelet bi-coherence to study the non-local interactions between wave modes, as well as between field fluctuations and particle distributions.

It has become increasingly apparent that nonlinear plasma processes such as turbulence are not stationary in time or space. This intermittency is a fundamental property of both hydrodynamic and plasma turbulence and it pivotal to the acceleration, scattering and propagation of particles within turbulent media. However, traditional spectral techniques cannot be used to study such burstiness. More advanced methods, based on distribution functions and higher order statistics, have been used with single spacecraft data but these cannot provide information on the 3D nature of intermittent structures in plasma turbulence - and it is precisely this structure which controls the propagation of particles within the plasma. Data from the multi-scale Cross Scale formation will make it possible to study such structures in detail and determine how particles interact with them.

2.3.5.Constraints and requirements

As illustrated above, appropriate interferometric methods, for instance the **k**-filtering technique, can be used to characterize plasma turbulence. Let us now briefly describe the constraints associated with the use of these methods, and their consequences on mission design.

Constraints on distances between spacecraft

The application of the **k**-filtering method, drives two types of constraints regarding the distances between spacecraft. In order to avoid aliasing effects, the distance D between the spacecraft should be less than L, the scale/wave length to be measured (typically $D \leq 20$km for a scale L~40km). On the other hand the scale/wave length to be measured should not be too large as compared to the distance between the spacecraft, otherwise the uncertainty on the determination of the corresponding scale increases. For instance with D~20km, the uncertainty in the determination of a scale L~400km is ~30%. The uncertainty would be ~100% for L~1200km. Then a single, Cluster-like, tetrahedron can only cover a limited range of spatial scales, typically one decade. The investigation of a turbulent cascade requires a broader coverage of **k**-space, from the injection to the dissipation scale.

Waves and small scale structures are expected to determine the dispersion scale and the (collisionless) dissipation scale. Investigation of the dispersive/dissipative scale makes it necessary to cover an appropriate frequency domain with appropriate distances between the spacecraft For instance in the case of whistlers modes waves/structures (often invoked to accelerate electrons at reconnection), the frequency range to be covered is typically a few 100Hz (in the tail current sheet, or at the magnetopause), and the .typical scale is c/Fpe~50km, for an electron density of $0.1/\text{cm}^3$. Electrons should be measured simultaneously at the same scale, at least on 2 spacecraft. A high time resolution for electrons is desired (better than 10Hz). With 4 spacecraft measuring **E** and **B**, and 2 spacecraft measuring electrons, the small scale dissipation: can be characterized via the evaluation of the current density (**J**), the electromagnetic field (**E**, **B**), and the dissipation rate (**J**.**E**). High resolution electron measurements at 4 spacecraft are useful but not mandatory.

The same type of wave measurements is needed at the ion scale. This can be achieved via three additional satellites measuring **E** and **B** components, together with ions. This will provide an estimate of how much energy is transferred from electromagnetic fluctuations to ions. Indeed ion acceleration/heating is also a possible mean of dissipating the energy injected at larger scale.

At the fluid scale lower time resolution measurements (particles and magnetic field) are sufficient to give evidence for the injection scale.

In summary, measurements at 3 scales give access to the **k**-spectrum of the fluctuations over up to 3 decades. Let us now discuss the other constraints: the number of components and the accuracy of the timing.

Number of spacecraft and components

Two spacecraft at a scale give the k-spectrum, in one direction (defined by the two spacecraft), 4spacecraft are necessary to determine a 3D **k**-spectrum. Thus, with a minimum of 10 spacecraft evidence can be given for an anisotropic (3D) cascade over a large range of wave numbers/scales (up to 3 decades). Reducing the number of spacecraft at one or more scales will make it necessary to use assumptions, such as the isotropy of the cascade. This may hold in the solar wind, but not in strongly magnetized media, such as the magnetosheath.

In the **k**-filtering method the accuracy in the determination of the wave vector also depends on the number of components; the larger the number of components, the better is the estimate. On Cluster the time resolution of particle measurements was not good enough to be used to improve the determination of wave modes. High time resolution measurements of the density and of the flow velocity, at least for electrons improve the accuracy and the reliability of the method. For instance measurements of N and **V**, with 100msec time resolution, hopefully 10msec for electrons, would be extremely useful to study the partition of the energy, between fields and particles.

Inter-spacecraft timing accuracy

In order to correlate data from various spacecraft a good timing accuracy is required, at least at the small scale. Taking again the whistler mode range as an example, we can estimate that, the need for inter-spacecraft timing accuracy is ~0.25 msec, for a 100Hz bandwidth. If this constraint turns out to be a strong cost driver, it might be advantageous to implement an inter-spacecraft radio link, which would alleviate the request on the stability of the clocks. Since high time resolution is only requested at the small scale, the intersatellite link needs only to operate over short distances. Therefore a low power transmitter should suffice.

Summary of constraints

Recent measurements, made by Cluster, demonstrate that the **k**-spectrum of the turbulence can be deduced, for perturbation with a typical scale (for instance the wave length) between 2-20 times (one decade) the inter-spacecraft distance. In order to determine the scale of dissipation together with the scale of injection, a broader **k**-spectrum is generally needed. This implies a multi-scale approach with spacecraft covering 3 ranges of distances; then a spectrum over 3 decades can be obtained, at least part of the time (to limit maneuvers). The second constraint is the time resolution. If whistler turbulence is involved, the frequency range to be covered is at least ~100Hz, on $\delta\mathbf{E}$ and $\delta\mathbf{B}$. Then the accuracy in the knowledge of the timing between the spacecraft is ~0.25msec at the small scale. The time resolution is less critical at the fluid scale. The number of spacecraft at each scale is important. Two spacecraft at a scale give a **k**-spectrum, in one direction (defined by the two spacecraft), while 4 spacecraft at a scale give a full 3D **k**-spectrum, over a restricted range of **k**-vectors (a decade, see discussion above). With a minimum of 10 spacecraft evidence can be given for an anisotropic (3D) cascade over a large range of wave numbers/scales (up to 3 decades). Reducing the number of spacecraft will make it necessary to make assumptions, such as the isotropy of the cascade

2.3.6. Matrix of Instrument Requirements based on Science Questions

Science priorities and relevant locations

- P5: What is the nature (and direction) of the energy cascade in relatively homogeneous turbulent collision free plasmas (magnetosheath, and solar wind)
- P5: What is the relation between large and small scales in the case of inhomogeneous plasmas; is there an energy cascade in magnetospheric boundaries? (all targetted regions)
- P5: What is the role of turbulence in triggering explosive phenomena?, such as magnetic reconnection?(tail and magnetopause current sheets)
- P4: What is the role of turbulence at mixing plasmas without collision? (magnetopause)
- P3: What is the efficiency of acceleration through particle interaction with stochastic waves? (inner magnetosphere)

- P3: What is the role of ULF turbulence to accelerate relativistic electrons? (inner magnetosphere)

Location

The most important targets are the solar wind and the magnetosheath where a relatively homogeneous plasma is found (at least in the solar wind) and a turbulent cascade is likely to occur. The other primary targets of interest are magnetospheric boundaries such as the magnetopause boundary layer, the bowshock and tail current sheet. The inner magnetosphere (outer radiation belt region >4Re) is also of interest though with a lesser priority.

Physical scales

What	**Lengthscale (can be different in different directions)**	**Timescale T**
Large scale magnetosheath, solar wind, inner magnetosphere	~1-2Re along boundaries, ~3000km across boundaries	0.1sec – several minutes
Ion scale kinetic turbulence	~1000km	<proton gyroperiod, typically 0.1-0.5Hz
Electron scale kinetic turbulence	~5-100km	100Hz-100kHz

Required measurements

The matrix below sets out the measurement requirements for the turbulence component of the mission, including time resolutions, constellation requirements and priorities. The priority P and number of spacecraft N needed at each scale are also detailed. It assumes a minimum configuration of 10 spacecraft. Thanks to corner sharing, 10 spacecraft allow a proper 3D coverage of 3 scales, namely 4 measurement point at each scale. This is what is needed to achieve the P5 objectives of turbulence. It is assumed that there are two types of spacecraft: medium and small size. This combination of small and medium sized spacecraft is expected to reduce the total weight. For the electron scale a 2M+2S spacecraft is sufficient. For medium/ion scale 2M+1S, plus corner sharing is sufficient. For large/fluid scale 3S and corner sharing is adequate. More details in table below.

Instruments	Electron scale	P	N	Proton scale	P	N	Fluid scale	P	N
Magnetometers	dc-200Hz (wave form) for k-spectra.	5	4	dc-200Hz (wave form) for k-spectra	5	3	dc-50 Hz (wave form) for k-spectra	5	3
	200Hz-2kHz	5	4	200Hz-2kHz	5	3	50Hz-2kHz	3	3
Ion (<40 keV), unresolved composition 3D f(v)				1 Hz	5	2	Spin period	5	3
Ions (<40 keV), Mass-resolved (major species), 3D f(v)				Spin period	4	2	Spin period	4	3
Electrons (<40 keV) 3D f(v),	10Hz	5	2				Spin period	5	4
Electrons (20-100keV:3D f(v)	spin	5	2	spin	3	2	spin	3	3
density sounder	1Hz	5	4	1Hz	5	3	1Hz	3	3
E-field 2D Wave form& Spectral info	dc-200Hz (wave form)	5	4	dc-200Hz (wave form)	5	3	dc-50Hz (wave form)	5	3
	dc-few kHz			dc-few kHz	3	3	dc-few kHz	3	3
	200Hz-50 kHz	5	2	200Hz-50 kHz	5	3	50Hz-50 kHz	3	3
E-field 3D Wave form Spectral info	dc-200Hz (wave form)	5	2						
	dc-few kHz								
	1-50 kHz	5	2						

Note: The E-field 3D measurement, if present, will replace any E-field 2D requirement. E.g., at the electron scale, there is a requirement for 4 spacecraft 2D information; two of those spacecraft may actually have 3D instrumentation.

2.4.Other science targets

While reconnection, shocks and turbulence are the highest priority science goals of Cross-Scale, the multi-spacecraft fleet will also contribute to several other areas of plasma physics and the geophysics of the terrestrial plasma system, often in cooperation with worldwide space-based and ground-based assets.

- **Inner magnetosphere** If the Cross-Scale apogee is about 4 R_E the spacecraft will pass through the inner magnetosphere, allowing comprehensive 3D measurements of this interesting region, which is important for the study of particle trapping and transport in closed magnetic fields.

- **Energy transfer from the Sun to the Earth** Cross-Scale will be able to identify the location and extent of significant events such as magnetopause reconnection sites. In collaboration with auroral imagers and ground-based magnetometers and radars, the location, time scales and energy input into the Earth's ionosphere – and eventually the atmosphere – can be accurately traced back to the initial energy transfer from the solar wind for the first time.
- **Plasma instabilities** Cross-Scale will allow the first measurements of the development of plasma instabilities, such as mirror modes, while determining the changing distributions of ions within and around them which contribute to the instability growth.
- **Boundary acceleration and substructure** Many spacecraft flying in formation can be considered to form a large number of tetrahedra, covering many contiguous volumes within that of the largest. Combining data from the four spacecraft in each tetrahedron, during the passage through boundaries such as the magnetopause or solar wind discontinuities, it will be possible to measure their acceleration and their detailed substructure, such as surface waves.

3. Mission practicalities

The definition of any space mission involves deciding the optimal value of many variables such as propellant mass, orbits, telemetry and instrument capabilities. This is particularly the case for Cross-Scale, where even the number of spacecraft is a variable and the instrumentation is likely to vary considerably between spacecraft. However, there are nevertheless some clear restrictions on what is realistic for such a mission and this must inevitably limit its science capabilities. Therefore, while this document is primarily intended to list the science priorities for the Cross-Scale mission, the following sections provide some brief discussion about some of these practicalities which can affect the science return.

3.1.Orbit

A likely launch vehicle for Cross-Scale is a Soyuz-Fregat from Kourou. This makes a near-equatorial final orbit desirable. Such an orbit has several important advantages, such as passing through the dayside magnetopause stagnation point and spending long periods of time in the magnetotail – indeed, Geotail has spent considerable time in a near-equatorial ~8×30 R_E orbit which has proved very useful in studying reconnection. With suitable choice of apogee and perigee, “skimming” orbits of the magnetopause and critical regions of the magnetotail, with long intervals in the regions of interest, are possible.

A 500km (altitude) x 20-25 R_E orbit would pass through all the relevant regions and probably require the least fuel to achieve (thereby releasing mass resource). However, it passes more rapidly through the key boundary layers at intermediate distances, and also through the radiation belts.

A 4×20-25 R_E orbit would have apogee high enough to cover all the regions of interest in the magnetosphere, magnetosheath and solar wind. It would also allow access to additional interesting science targets in the inner magnetosphere. However, skimming opportunities would be very limited.

A 10×20-25 R_E orbit would provide ample skimming opportunities, but could result in a much reduced total on-orbit mass and therefore a more limited instrument package. A partial compensation is that it is far less perturbed than a 4x20 R_E orbit, and therefore require less station keeping or operational considerations.

Raising the mission apogee to 35 R_E would increase the speed through the dayside boundary layers (magnetopause and bow shock) which has some impact on the data resolution there. It would, however, have some positive benefits including measurements at interesting and relatively unexplored regions of the geomagnetic tail. On the dayside, it would result in longer intervals in the solar wind, with more time spent in regions not contaminated by bow shock produced particles. This would be particularly interesting for studies of turbulence. It would also facilitate intercalibration of the instruments on different spacecraft since the coherence lengths in the solar wind are typically larger than the spacecraft separations.

3.2.Mass

On-orbit mass obviously depends strongly on the orbit chosen. An approximate figure for total dry spacecraft mass into a 10×25 R_E orbit is 1050kg, and around 900-1100kg for a 4×20 R_E orbit. Assuming 12 spacecraft, this results in average masses, excluding propellant, of the order of 85kg. For comparison, the launch mass of each Cluster spacecraft was around 1200kg, of which 650kg was propellant and 71kg payload. The baseline MMS mass is 330kg per spacecraft, of which 110kg is propellant and 65kg payload. Both Cluster and MMS involve significant changes in orbital parameters and hence large fuel budgets. Without large manoeuvres, Cross-Scale would require much less fuel. Nevertheless, it is clear that the payload mass budget is much lower than for Cluster or MMS.

3.3.Instrumentation

A consequence of a low payload mass is that not all desirable instruments can be accommodated on every spacecraft, in contrast to the philosophy of the Cluster and MMS missions, which emphasised the similarity of the spacecraft. Indeed, it may even prove desirable to have different instrumentation on spacecraft within the same “scale.” Such variations might lead to more than one spacecraft design, although a solution with potentially lower cost and complexity could involve a common spacecraft bus, but a universal instrument interface to allow modular, “plug and play” instrument development and accommodation.

An additional problem is the large number of instruments required. A production-line approach to construction may be required. Calibration, both on the ground and in flight, is likely to be limited by personnel resources: a robust strategy for in-flight inter-spacecraft calibration must be determined before launch. Differences between spacecraft are also likely to lead to more complexities in the inter-calibration of instruments.

3.4.Communication

Many of the instruments listed in this document would require prodigious data downlink rates. The table given below provides indicative data volumes for the various instruments, a subset of which would be flown on any spacecraft. It is clear that continuous downlink at this rate would not be practical. Therefore, a strategy of selective download, or selective measurement (a so-called "burst mode") would be necessary. The former requires very large onboard storage; the latter requires sufficiently reliable onboard triggering algorithms that the correct events are identified, which may not be possible to achieve in practice.

Inter-spacecraft communication may prove useful to transfer data before transmission to the ground if some spacecraft support higher data rates than others. This would also facilitate inter-spacecraft ranging measurements, which may be the only way to determine separations to the required precision of a few hundred m (for the closest spacecraft pairs). Such communication may also help in triggering fleet-wide "burst mode" measurements of interesting events.

Data Volumes for Various Possible Instruments

						Electron Scale		Ion Scale		Fluid Scale	
	Dim 1 E, comp	Dim 2 th, freq	Dim 3 phi	Dim 4 species	Time	Sampling Rate (Hz)	Data Volume per sec)(science words	Sampling Rate (Hz)	Data Volume per sec) (science words	Sampling Rate (Hz)	Data Volume per sec) (science words
Field instruments											
DC B	3	1	1	1	1	500	2000	50	200	10	40
AC B	3	32	1	1	1	100	9700	10	970	0.5	48.5
2D E dc	2	1	1	1	1	500	1500	50	150	10	30
2D E ac	2	32	1	1	1	100	6500	10	650	0.5	32.5
3D E dc	3	1	1	1	1	500	2000	50	200	10	40
3DE ac	3	32	1	1	1	100	9700	10	970	0.5	48.5
Density sounder	1	1	1	1	1	500	1000	50	100	10	20
Particle instruments											
Thermal ion	30	12	32	1	1	10	115210	10	115210	0.5	5760.5
Thermal electron	30	12	32	1	1	100	1152100	10	115210	0.5	5760.5
Combined ion/electron	30	12	32	1	1	100	1152100	10	115210	0.5	5760.5
Ion composition	30	12	32	12	1	0.5	69120.5	0.5	69120.5	0.5	69120.5
Energetic ion composition	30	12	32	12	1	0.5	69120.5	0.5	69120.5	0.5	69120.5
High energy particles	30	12	32	1	1	0.5	5760.5	0.5	5760.5	0.5	5760.5

Notes:

1. Not all instruments will be on all spacecraft (!)

2. Science word is, e.g., a floating point number. To convert to telemetry requirement, multiply by bits/word and by suitable compression factor. Typically expect bits/word = 16. Highly optimised compression algorithms may yield a factor 5-10, especially for the particle measurements.
3. Particle resolution of 30x12x32 is maximum; minimum capability is 16x4x8. For moments, total science words is roughly 14 words per sampling time. For the highest sampling rates this will require some combination of multiple sensors and internal deflection systems.
4. Combined ion/electron sensor is typically devoted to one species at the resolution stated, with the other species returning a smaller science product (degraded distribution, moments, etc.). Thus only 1 species is shown. The other species is either negligible, or could be accounted for by altering the effective sampling rate. A similar comment applies to the high energy particle measurements.

3.5.Science Modes and Operations

With such a considerable number of spacecraft, operational streamlining will be a prime consideration in Cross-Scale. There are several areas where careful planning will be required.

3.5.1.Calibrations

Ground and inflight calibration of a large number of instruments cannot be accomplished by the manual methods employed on previous missions. Ground calibrations may be reduced to restricted ranges and spot-samples of instrument capabilities. In-flight calibration will require automation, with particular attention paid to cross-calibration issues over absolute, single spacecraft techniques. This may be facilitated by orbit strategies that include extended intervals in the solar wind, where correlation lenghts are typically larger than the interspacecraft distances planned.

3.5.2.Station Keeping and other Manoeuvres

Ground station contact and mission operations will be restricted and must be put to most effective use. Cross-Scale does not require perfect, co-centric tetrahedra and thus station keeping needs to be done only infrequently, assuming the initial insertion places the spacecraft at the appropriate relative scales. Further operational studies will be required to assess the impact of perturbations and other factors which may cause the spacecraft to drift.

The mission requirements also do not impose the need for any large-scale orbit changes. It would be prudent, though, to include enough fuel margin for at least one such gross manoeuvre should this become necessary or desirable in light of scientific advances between now and launch, or once the initial results are analysed.

3.5.3.Instrument Modes

Limited uplink to all spacecraft will force the mission to adopt a streamlined approach to instrument commanding. Long and/or frequent mode changes will not be practical in terms of ground resource and contact periods. Strategies to ensure that, despite this, the instruments will be in appropriate science modes must be developed. Solutions include a very minimal set of instrument modes (perhaps only slightly more sophisticated in most cases than simple “On” and “Off”), time-tagged predictive mode changes, and perhaps cautious use of onboard triggering (which has had mixed historical success).

3.5.4.Data Downlink

It is clear that the Cross-Scale instruments will be able to take data at volumes far in excess of available downlink capacity (see Section 3.4). Thus the highest data rates (which will be needed to address the science objectives) will only be available for a small fraction of the orbit. Ideally, this should not be less than 10%. Selecting that 10% could be accomplished in several ways:

1. Simple time-tagged burst-mode data dumps. These have worked reasonably well for Cluster, but it depends greatly on the relative duty cycle of burst mode. As the fraction decreases, boundary motions and other transients make this method increasingly difficult to catch the regions of interest.
2. Onboard triggers. As noted above, these have had mixed success in the past. It would be unwise to operate only through such onboard data selection. Additionally, this gives a narrow window of science data, making surprise discoveries unlikely.
3. Ground selection from a continuously available coarser resolution “survey mode” dataset. This offers the greatest scientific performance, although it requires a clear set of science priorities, suitable science personnel available on a daily basis, and adequate onboard memory to store all the data long enough for such data selection to occur and for subsequent downlinks to transmit it.

For ground selection, instrument monitoring, and correlative studies, a survey dataset providing 100% coverage around the orbit is required.

3.5.5.Data Handling

The volumes of data generated by Cross-Scale will require modern data systems to cope with the data reduction and dissemination. The present trend toward open data access will continue, and Cross-Scale will need to live up to these evolving standards. New tools, such as those developed for Cluster, will need to be employed to manipulate, analyse, and visualise the data.

Coupled with the probable need for daily data selection, this suggests that a Science Centre (physical or virtual) will need to be established. This needs to be a prominent component of the Science Management Plan, e.g., at Principal Investigator level for the lead of such a Centre.

4. Contact details

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