CROSS-SCALE: A MULTI-SPACECRAFT MISSION TO STUDY CROSS-SCALE COUPLING IN SPACE PLASMAS

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ABSTRACT

Collisionless astrophysical plasmas exhibit complexity on many scales: if we are to understand their properties and effects, we must measure this complexity. We can identify a small number of processes and phenomena, one of which is dominant in almost every space plasma region of interest: shocks, reconnection and turbulence. These processes act to transfer energy between locations, scales and modes. However, this transfer is characterised by variability and 3D structure on at least three scales: electron kinetic, ion kinetic and fluid. It is the nonlinear interaction between physical processes at these scales that is the key to understanding these phenomena and predicting their effects. However, current and planned multi-spacecraft missions such as Cluster and MMS only study variations on one scale in 3D at any given time - we must measure the three scales simultaneously fully to understand the energy transfer processes. We propose a mission, called Cross-Scale, to study these processes. Cross-Scale would comprise three nested groups, each consisting of up to four spacecraft. Each group would have a different spacecraft separation, at approximately the electron and ion gyroradii, and a larger MHD scale. We would therefore be able to measure variations on all three important physical scales, simultaneously, for the first time. The spacecraft would fly in formation through key regions of near-Earth space: the solar wind, bowshock, magnetosheath, magnetopause and magnetotail.

1. INTRODUCTION

Plasmas pervade the Universe and control many of the most dynamically important astrophysical phenomena that we observe. Over the last four decades, considerable theoretical and experimental progress has been made in the understanding of collisionless plasma behaviour. Experimentally, both remote observations of astrophysical environments and direct measurements in the solar system have been used to study plasma behaviour. In particular, the inherently structured, three dimensional, time-varying nature of plasmas – and the importance of this to many of their large scale effects such as particle acceleration and the transport of energy – has increasingly come to be appreciated. Three dimensional plasma behaviour has recently been explored using the four spacecraft Cluster mission, which orbit in formation around the Earth, passing through shocks, reconnection sites and highly turbulent regions. Cluster data have revealed many aspects of fundamental plasma behaviour such as the dominant wave modes in large amplitude turbulence; the scale size of the collisionless shock transition; and particle behaviour within reconnection regions.

Despite these recent advances, however, many fundamental questions remain: how is reconnection triggered? How are particles accelerated within and around shocks? How is energy transferred between scales in plasma turbulence? In particular, plasmas exhibit structure on many scales simultaneously. The nonlinear interactions between dynamical behaviour on multiple scales – for example, between ion-scale reformation processes at collisionless shocks and electron-scale electric field structures within the shock transition – are responsible for the large scale behaviour that we observe. However, it has not been possible to date to measure such cross-scale coupling. Ignoring these cross-scale interactions is to miss a pivotal aspect of plasma dynamics. In the case of collisionless shocks, electrons would pass straight through an "average" collisionless shock transition. The fact that significant numbers of electrons are, in contrast, reflected and accelerated at collisionless shocks is the direct result of the multi-scale, dynamic and structured nature of the shock transition. This multi-scale behaviour is also fundamental to processes such as reconnection and turbulence. We must, therefore, study plasmas on several scales simultaneously if we are to understand their behaviour, and ultimately their large scale effects such as particle acceleration and energy transport.

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In this paper, we present a concept for a mission which is closely targeted at the study of multi-scale coupling in collisionless plasmas. Cross-Scale would comprise up to 12 spacecraft in Earth orbit, flying through key plasma regions such as the Earth's bowshock, reconnection regions around and within the magnetosphere, and turbulent plasmas around the Earth and in the solar wind. We discuss how Cross-Scale would provide fundamental advances over existing or planned missions, the challenges of such a project and how the mission could be achieved in practice. First, though, we discuss the important phenomena and scales that Cross-Scale must measure if it is to be successful.

2. IMPORTANT PLASMA PHENOMENA

Many of the most dynamic phenomena in the Universe – jets from around black holes, shocks around supernovae – occur in plasmas. The most energetic particles in the universe – cosmic rays – are accelerated by electric and magnetic fields which are the result of plasma dynamics. Plasmas are also responsible for some of the most visually striking objects in the Universe such as planetary nebulae. Within the Solar System, solar flares and coronal mass ejections release large quantities of energy and mass. The flow of the solar wind past the magnetic fields, atmospheres, surfaces and moons of planets produces a bewildering variety of interactions, such as aurorae.

All of these phenomena are structured, three dimensional and dynamic on several scales. Their remarkable diversity illustrates just how complex are the possible consequences of a small number of physical interactions: those of electromagnetic fields with charged particles. The complexity of plasmas is due to the nonlinearity of these interactions and the fact that they occur on more than one scale simultaneously. To be able to measure, understand and predict such complex phenomena throughout the Universe, therefore, we need to measure plasmas on multiple scales, in three dimensions, simultaneously. These measurements must capture important plasma properties such as particle distributions and electric and magnetic fields. For most of the Universe this is simply impossible, even with the most advanced remote sensing tools. How, then, can one hope to make progress in understanding the plasma universe?

While plasmas throughout the Universe are strikingly diverse there are a small number of key processes, one of which dominates the behaviour of most plasmas of interest:

- Reconnection
- Shocks
- Turbulence

These processes are important because they transform energy from one form to another (for example, magnetic to kinetic in the case of reconnection; bulk kinetic to thermal in the case of shocks) or transport it from one location to another (for example, shocks and turbulence). By understanding these universal phenomena we can predict the most important aspects of plasma behaviour in many diverse environments.

The problem of understanding plasma dynamics can therefore be considered to be largely the problem of the measurement and prediction of the three phenomena of reconnection, shocks and turbulence.

The universality of these phenomena also helps in their measurement, for they all occur in the only directly accessible space plasma environment: the solar system. Indeed, they all occur in near-Earth space. The solar wind plasma from the Sun interacts with the Earth's magnetic field and forms a shock upstream of the Earth, with an Alfvénic Mach number between 5 and 15 – and sometimes higher. The shocked solar wind plasma is highly turbulent and exhibits many plasma instabilities and wave modes. Reconnection occurs both at the boundary layer between the solar wind and terrestrial plasma – the magnetopause – and in the Earth's magnetotail, where it energises particles which flow Earthwards and ultimately cause the aurora. By flying spacecraft into these regions with appropriate instrumentation, one can therefore measure the electromagnetic fields and particle distributions within and around shocks, reconnection sites and plasma turbulence with exquisite precision.

Spacecraft measurements of plasma around the Earth, notably the recent European Cluster mission, have revealed the remarkable complexity of space plasmas. While these have provided many insights into plasma dynamics, they have all been limited in their ability to measure variations on more than one scale at the same time. As we will see, such multi-scale processes are central to the overall effects of plasmas and must be studied if we are to be able to predict these effects.

3. THE THREE PLASMA SCALES

All the phenomena of interest discussed here show 3D structure on many scales simultaneously. It is impossible to launch enough spacecraft to measure variations on many scales at the same time. A four spacecraft tetrahedron is only sensitive to variations on scales similar to the inter-spacecraft separations. To cover ten scales, therefore, one would require 40 spacecraft, all carefully positioned in formation – a technological impossibility at this time. However, simultaneous measurements are not required on so many scales. Indeed, there are only three fundamental scales in a plasma: measurements of these three scales are sufficient to determine the multi-scale interactions in regions of interest. These three scales are determined by electron kinetics, ion kinetics and the bulk, fluid motion of the plasma.

3.1 Fluid scale

At sufficiently large scales, we may consider plasmas to be fluids, using magnetohydrodynamics (MHD). Since many of the most interesting and important plasma phenomena involve kinetic effects, one can consider the fluid scale – typically several thousand km in near-Earth space – to be a large scale "context" in which other phenomena occur: for example, the bulk plasma parameters around a reconnection region. Relative to this scale, we could consider reconnection to occur on a very thin sheet. However, the orientation of the sheet and the properties of the plasma around it are essential contextual information for understanding the kinetic effects within the reconnection volume. Similarly, one can consider the fluid scale as that scale on which energy is input into a turbulent cascade which ultimately produces effects such as plasma heating and magnetic field line braiding; the latter results in anomalous particle transport (e.g. Pommois *et al.,* 2005).

In addition to contextual information, however, the fluid scale is important in other ways. For example, reconnection is known to be spatially variable: this variability can occur on many scales including those much larger than the proton gyroradius.

3.2 Ion kinetic scale

The thermal ion gyroradius (typically a few hundred km near the Earth), and to a lesser extent the ion inertial length is a key physical scale. It is on this scale that energy is transferred between protons (and other ions) and electric and magnetic fields. Cluster has revealed dramatic spatial variability on this scale in many regions, as well as temporal variability on timescales comparable to a proton gyroperiod. Field-particle interactions are highly nonlinear and are responsible for instabilities, particle acceleration and transport on this scale.

Full particle distributions must be recorded on several spacecraft separated by approximately the proton gyroradius to measure these vital wave-particle interactions.

3.3 Electron kinetic scale

Just as ions interact with electromagnetic fields on scales near their gyroradii, so electrons interact on a correspondingly smaller scale, which is typically around 10km in near-Earth space. Cluster data have shown that large amplitude electric field spikes occur on electron kinetic scales within reconnection regions and shocks – these could be responsible for ion energisation. These spikes are likely to be generated by electron interactions with electromagnetic fields, but can greatly affect ion dynamics and therefore the bulk behaviour of plasmas.

The dynamics of electrons themselves are of course affected by fields on these scales, including waves, instabilities and turbulent variations.

3.4 Other scales

Needless to say, the three scales discussed above are not the only ones present in plasmas. For example, we have considered just one "fluid" scale when in practice plasmas are variable on scales many orders of magnitude larger than the proton gyroradius. However, the cross-scale interactions within the fluid regime are governed by the same physics and can therefore in principle be analysed by only considering one fluid scale.

Smaller than the electron kinetic scale is the Debye length, typically a few tens of metres in Solar System space plasmas. In practice, electric field variations on this scale are accessible to spacecraft using wire boom antennas which extend to tens of metres in length. Therefore, while we do not discuss this scale any further here, one can consider it to be another scale of interest which would be accessible to a multi-scale mission.

4. EXISTING AND PLANNED MISSIONS

We have seen the importance of cross-scale coupling in plasmas and how near-Earth space is an ideal environment in which to study it. However, a number of spacecraft have measured plasmas in near-Earth space, are currently doing so, or will be launched in the next decade. Why can these missions not address cross-scale coupling?

4.1 Cluster

ESA's four-spacecraft Cluster mission is revolutionising our understanding of plasma phenomena. By comparing measurements at the four spacecraft, we can directly investigate collisionless space plasmas in 3D for the first time. There is no space here to list Cluster's achievements: see *Space Science Reviews* (vol. 118, 2005) and other papers in these proceedings for recent reviews of Cluster results.

Since launch, the Cluster orbits have been adjusted so that the four spacecraft form a near-regular tetrahedron while passing through regions of interest, such as the magnetotail and the cusp. However, a tetrahedron of spacecraft can only measure the 3D properties of plasmas on scales comparable to the spacecraft separation. The scale of the tetrahedron has therefore been varied, from ~100km to ~10000km, allowing variations in key regions, such as reconnection sites and shocks, to be measured on many scales.

The limitation of Cluster measurements to just one scale at a time means that we cannot measure cross-scale coupling. For example, we have knowledge of how reconnection sites are structured on ion scales, but we cannot link that to the larger scale variations in conditions around them that drive the reconnection.

The Cluster project has recognised the importance of multi-scale phenomena and during the so-called "Multi-Scale Extension" of the mission to 2010, the tetrahedron will be altered to produce a pair of spacecraft at around 100km separations, at one corner of a triangle with sides of around 10000km. This will provide a first measure of variations on two scales simultaneously – but not in 3D.

The two Chinese/European Double Star spacecraft are providing complementary information to Cluster. In some sense, one can consider Cluster-Double Star comparisons to be the probing of another, larger (several Earth radii) scale in near-Earth space. However, with only two points on this very large scale, such comparisons are typically more useful for determining variations in plasma properties through the terrestrial system, rather than those around one particular phenomenon.

4.2 MMS

The NASA-funded MMS (Magnetospheric Multi-Scale) mission is planned to launch in 2013. Similar in many ways to Cluster, MMS will comprise four spacecraft in Earth orbit. In a near-equatorial orbit, MMS will pass through many of the same regions as Cluster, including the magnetopause, bowshock and near-Earth magnetotail.

The most significant advance of MMS over Cluster will be a shrinking of the formation down to just 10km, allowing measurements at the electron kinetic scale. In addition, 3D electric field measurements (Cluster can only measure 2 components of the electric field) and very high time resolution electron data will allow MMS to investigate the small scale, rapidly varying electric field/electron interactions within key regions, in particular within the reconnection volume.

MMS will, in some sense, complete the "survey by scale" of key 3D plasma phenomena that Cluster has begun. Like Cluster, however, MMS will not be able to measure two scales in 3D simultaneously. Although it will undoubtedly provide important data on electron dynamics in key plasma regions, MMS will not provide the measurements we need to understand cross-scale plasma coupling.

4.3 Geospace constellations

A number of missions have been planned or proposed which distribute a large number of spacecraft throughout the Earth's magnetosphere. NASA's Themis mission, and further in the future a possible magnetospheric constellation, will distribute several spacecraft throughout the magnetosphere. Such missions will reveal the global dynamics of the Earth's magnetospheric system, but will not study the detailed physics of individual processes such as reconnection and shocks.

4.4 Deep space constellations

Shocks, reconnection and turbulence occur not just around the Earth, but throughout the Solar System. In particular, they occur in the solar wind plasma flowing from the Sun. A number of spacecraft are distributed in the solar wind, such as ACE and Wind near the Earth and others further away such as Cassini, Ulysses and Messenger. In the future, ESA's Solar Orbiter and NASA's Sentinels will add to this fleet. However, these spacecraft will be separated by such large distances that only the very largest structures, such as interplanetary counterparts of coronal mass ejections and fast or slow speed solar wind streams, can be probed by multi-spacecraft comparisons. They will not be able to address cross-scale coupling – rather, they will study the influence of the Sun on solar system plasmas.

5. CROSS-SCALE COUPLING

In the previous sections, we have discussed the three scales which are most important in plasma dynamics. These scales are currently being explored by the Cluster mission, or will be investigated by the upcoming MMS mission. However, as we have seen, these missions are essentially measuring one scale at a time. Why is it so important to measure several scales simultaneously? To illustrate the importance of multi-scale processes, we discuss collisionless shocks in the next section (see Figure 1).

5.1 Shocks: an example of cross-scale coupling

On MHD scales, collisionless plasma shocks can often be considered to be a sharp transition. In this view, there are certain parameters which determine the effects of the shock, such as the Mach number, the shock orientation and motion and the angle between the upstream magnetic field and the shock normal, known as θ_{BN}. This final parameter is particularly important: when θ_{BN}~90º, the quasi-perpendicular case, the shock is a relatively sharp transition; when θ_{BN}~0º, the quasi-parallel case, reflected particles can travel far upstream of the shock resulting in an extended transition.

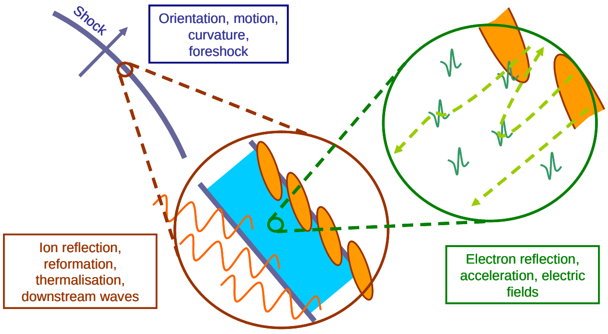

Figure 1. Schematic illustrating the three scales of variability in a collisionless shock: a fluid scale on which the shock can be regarded as a sharp transition; an ion scale where effects such as reflection and reformation are apparent; and an electron scale, where small electric field spikes can greatly affect electron dynamics and alter the cross-shock potential.

Even the quasi-perpendicular shock is not a perfectly sharp transition, however. Bale *et al.* (2003) recently used Cluster data to demonstrate that the shock transition scales with the downstream convected ion gyroradius. As well as having a finite width, at moderate to high Mach numbers the quasi-perpendicular shock is unsteady, with ion reflection leading to a quasi-periodic reformation process on scales comparable to a gyroradius and times comparable to a gyroperiod. Such variability is difficult to measure with Cluster: when the spacecraft are close enough together to measure variations due to reformation, they cannot measure the larger scale "average" orientation and motion of the shock front, which are required to understand these variations. Observations of the large scale shock structure and parameters are required simultaneously with ion-scale variations to determine how reformation is affected by the bulk parameters of the shock – and how the shock's large scale effects, such as the fraction of ions that are reflected upstream, are affected by reformation.

Fundamentally, ion motion is controlled by magnetic and electric fields. Cluster has revealed large amplitude electric field structures in the shock ramp (Walker *et al.*, 2004) on electron scales. These interact with electron distributions within the shock itself and may be responsible for anomalously heating and reflecting some electrons and ions. Their small scale and very bursty nature means that the cross-shock potential – the integral of the electric field across the shock, which acts to slow the inflowing plasma – will vary greatly between individual particles. What generates these electric field spikes? How are they related to ion reflection processes? How are both of these determined by the large scale shock parameters? Current and planned missions such as Cluster and MMS cannot answer these questions, because they cannot measure variations on ion and electron scales, let alone fluid scales, at the same time.

The quasi-parallel shock is even more structured than the quasi-perpendicular case: isolated nonlinear structures (known as SLAMS: see e.g. Schwartz *et al.*, 1992; Burgess *et al.*, 2005) are generated upstream and convected back into the very wide shock transition, producing a patchwork-like structure on many scales. Many aspects of the variability of quasi-parallel shocks are very poorly understood, precisely because they are controlled by multi-scale 3D coupling.

Transient shock phenomena triggered by changes in upstream conditions, such as hot flow anomalies (e.g. Schwartz *et al.*, 2000) and foreshock cavities (e.g. Sibeck *et al.*, 2002) also have large effects on shock dynamics and may be important in astrophysical scenarios. Again, these are fundamentally kinetic phenomena and are variable on several scales simultaneously: single scale measurements cannot completely describe their behaviour.

Fundamentally, therefore, collisionless plasma shocks are spatially and temporally variable. This, combined with the nonlinear coupling between fields and particles, means that the average shock profile, either in space or in time, cannot be used to calculate the effects of the shock: one must also consider the variations and how they couple between scales. It is therefore essential to measure such variability, on the three physical scales, simultaneously if we are to make progress in understanding shocks and their effects on plasmas throughout the Universe.

5.2 Cross-scale coupling in reconnection

Reconnection is a fundamentally kinetic process that has many important consequences: it is the only way to alter magnetic topology and connectivity in highly conducting plasmas; and it accelerates particles to high energies by converting magnetic energy into kinetic energy. Reconnection occurs when magnetic fields are sheared, such as in the Earth's magnetotail, where particles are accelerated Earthwards and eventually precipitate into the Earth's upper atmosphere to form the aurora.

Several fundamental questions remain about plasma reconnection. For example, how is reconnection triggered? Cluster has flown through reconnection sites, but small scale measurements of the details of the reconnection process cannot reveal the large scale context which is responsible for triggering the event. Large scale measurements, simultaneous with measurements of the small scale electron and ion kinetics within reconnection regions, are essential if we are to probe the causal links between the bulk plasma and its bursty energy release. A related issue is the presence of multiple, transient reconnection sites: it is not clear how patchy the reconnection process is, and how it turns off as well as on. Again, multi-scale measurements are essential to answer this fundamental question.

The energisation process within reconnection sites is also poorly understood, such as the acceleration of electrons in a very small region while de-magnetised ions are accelerated over a larger volume. Ion and electron distributions must be measured at several locations within and around reconnection sites, while the large scale orientation of the region is simultaneously determined, if we are to make progress on this issue, which is pivotal in predicting the consequences of reconnection.

A more detailed case for a multi-scale investigation of reconnection has recently been made by Owen *et al.* (2005) and we refer the reader to that paper for more information.

5.3 Cross-scale coupling in turbulence

Turbulence, the nonlinear transfer of energy between scales, involves cross-scale coupling by its very definition. It has important effects in transporting and accelerating particles. Many aspects are poorly understood, however, such as intermittency (burstiness) and 3D structure – both vital in predicting its effects on particle transport, but difficult to study in space. Multi-scale measurements would allow a far better determination of the 3D structure of the magnetic fields within a turbulent plasma than has previously been possible.

Turbulence occurs on both fluid and kinetic scales but is perhaps most interesting at scales in the transition between the two: it is here that fluid kinetic energy is transferred into plasma heating. Many aspects of this process are poorly understood at present.

Related issues of wave-particle interactions and instabilities are also fundamentally multi-scale and time-varying. For example, the study of the mirror mode instability requires measurements of the full ion distribution function within and around the structures which have scales comparable to the ion gyroradius, combined with simultaneous measurements of their large scale structure and evolution.

6. THE CROSS-SCALE MISSION

The previous sections have made the case for the study of cross-scale coupling in plasmas. How can we achieve this in practice?

The most obvious solution is to fly 12 spacecraft, with three nested tetrahedral, each of four spacecraft. The typical scale of the tetrahedra would be ~10km (electron kinetic scale), a few hundred km (proton kinetic scale) and a few thousand km (fluid scale). This is shown schematically in Figure 2.

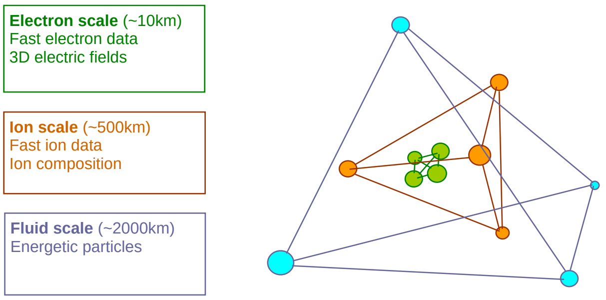

Figure 2. Schematic of a possible Cross-Scale mission, composed of three tetrahedra, each of four spacecraft. Spacecraft on different scales have different instruments targeted at the most important phenomena. Some of the highest priorities at each scale are listed on the left.

As we have seen, the physical behaviour and timescales of variability that are of interest are different on different physical scales. One needs to measure 3D electron distributions at sub-second resolution for the electron kinetic scale, but this is much less important on the fluid scale where moments every few seconds may be sufficient. Spacecraft within different tetrahedra would therefore have different instrumentation, targeted at the most important measurements on each scale. In this simplest scenario, all four spacecraft on each scale would have the same instruments.

An important consideration is the final orbit of the spacecraft. Various orbits are possible, but at this stage the most likely is near-equatorial with an apogee near 20 R_E, allowing sampling of key regions such as the bowshock, magnetosheath, magnetopause and magnetotail. The solar wind would also be encountered. Perigee could be around 10 R_E, which would allow skimming orbits of the magnetopause and magnetotail. Spacecraft mass (and hence payload) could be increased by reducing perigee to around 4 R_E, with the additional benefit of sampling the inner magnetosphere – but the increased radiation dose, combined with a less stable orbit due to its higher eccentricity, may preclude this option.

One obvious variable in this mission is the number of spacecraft. Twelve is an ideal – but it may be possible to achieve the key science goals with fewer, which would greatly reduce cost and mass. For example, one could arrange the spacecraft so that four electron-scale spacecraft sat at the location where one of the ion scale spacecraft would be, making the latter unnecessary. However, there are drawbacks to this approach, most obviously in terms of the increased instrumentation that these spacecraft would have to carry to replicate those on the ion-scale spacecraft and the reduction in redundancy. More subtly, this would make the formation shape asymmetric and remove the capability of the ion scale formation to completely enclose the electron scale, reducing Cross-Scale's ability simultaneously to measure multi-scale variations.

6.1 Practical considerations

The case for the investigation of multi-scale coupling in space plasmas is clear. However, compromises will have to be made with such a mission. The ideal case of 12 Cluster-class, fully instrumented spacecraft in tightly controlled Earth orbits is impractical: each Cluster spacecraft weighed 1200kg with a 71kg payload. It is not practical to launch 12 such spacecraft. Each MMS spacecraft will have a mass of around 330kg – it is still impractical, given launcher and budgetary constraints, to construct launch and operate 12 such spacecraft. It is imperative, therefore, to identify the key requirements that must be met for such a mission and a practical mission design which will meet those requirements.

An obvious restriction is cost but there are several other challenges that must be met. Many of these require technology development by the aerospace industry, and are likely to have important future applications in the commercial satellite sector.

The construction of ~12 spacecraft and all their instruments within only a few years will challenge the European aerospace industry and national scientific institutes alike. Such a rapid construction effort will probably require a "production line"-style process. In such an effort, standardisation of components and interfaces will be highly beneficial, but may compromise instrument and spacecraft capabilities. Such a multi-spacecraft scientific mission has never been flown and indeed the only existing multi-spacecraft constellations, such as the GPS and Iridium series, were built and launched in series over many years.

With several particle detectors per spacecraft, over several spacecraft, there may be no single institute which is capable of their construction alone. Collaboration will be essential, again with standardisation challenges.

With many instruments comes the challenge of calibrating them. If a single instrument takes 3 months to calibrate, 12 will take 3 years – which is impractical. It may be necessary to calibrate a subset on the ground, and cross-calibrate the remainder in flight – but in this case, absolute precision may be reduced. Such issues must be addressed long before launch, if they are to be successfully overcome.

The resources required to operate 12 independent spacecraft in the traditional manner are huge. The Cross-Scale spacecraft must therefore be either highly autonomous, or the ground segment must be highly automated. As with calibration, this issue must be considered early in the mission design.

The requirements of high time resolution, particularly on electron scales, necessitate high data rates. However, telemetry will be limited, by both mass and power. Mother-daughter scenarios, with inter-spacecraft communication, may be essential. In any case, variable data rates (burst modes) will be required. The spatially localised and variable plasma phenomena of interest make it extremely difficult to predict where they will occur with sufficient precision to target burst modes if they fill only a small fraction of an orbit. Onboard triggering of burst modes may therefore be required. Alternatively, large onboard data storage, and after-the-fact data selection for download, may be possible – in effect, a post-measurement burst mode.

Budgetary constraints inevitably result in mass restrictions. A baseline of a Soyuz-Fregat launch from Kourou would result in around 1200kg of useable mass in a relevant orbit (M. van den Berg, *personal communication*). 100kg-class spacecraft are practical for this mission, but a corollary is that not all spacecraft can carry all possible instruments: only those absolutely necessary to the science at each scale will be accommodated.

7. CROSS-SCALE: THE FUTURE

Cross-Scale would provide a new view of plasma dynamics and help us to explain the most important phenomena that occur in plasmas throughout the Universe. How, though, can we realise such a mission in practice?

The European Space Agency's recent *Cosmic Vision 2015-2025* exercise has identified the science targeted by Cross-Scale as vital to the investigation of space plasmas. We expect ESA to announce a call for mission proposals during 2006, in response to which the authors of this paper intend to be part of a community-wide submission of such a mission.

We note that ESA's Advanced Concepts and Payloads Office is beginning a study of a mission concept similar to Cross-Scale, with the aim of determining a practical, realistic mission scenario. The results of this study, which should be available during 2006, should help ESA and the space plasmas community to focus on the definition of the Cross-Scale mission, identify the tradeoffs that are required, and remove some of the larger uncertainties in the current strawman mission design discussed above.

ESA's Cosmic Vision 2015-2025 programme would allow the first launches soon after 2015. Cross-Scale is a reasonably simple mission concept whose challenges do not require large technological developments. Those advances that are required, such as in inter-spacecraft communication and ranging, and perhaps in autonomous station-keeping, are likely to be of interest to the aerospace industry for future applications.

7.1 Inter-agency collaborations

The compelling science of Cross-Scale is, unsurprisingly, of interest to scientists outside Europe. Indeed a group of Japanese scientists, led by Masaki Fujimoto, has proposed a five spacecraft mission to study cross-scale coupling, termed SCOPE, with an emphasis on electron and ion scale.

The science goals of SCOPE and Cross-Scale are very similar and the two missions fit very naturally together. We are actively pursuing the possibility of a Japanese-European collaboration for this mission. For example, some spacecraft or instruments could be built in Japan.

NASA's longstanding interest in space plasma physics means that there is a clear potential for collaboration on this mission. It is also conceivable that US colleagues could provide additional resources in kind, such as auroral imagers to provide links with the terrestrial response to the phenomena that Cross-Scale will measure. Other missions within the upcoming NASA programme such as a magnetospheric constellation or auroral imagers could help to provide a larger, global scale to complement the Cross-Scale data just as the twin Double Star spacecraft currently do for Cluster, greatly increasing the science return. An upstream solar wind monitor at L1, a role currently filled by the ACE spacecraft, would also be highly beneficial to Cross-Scale science.

Other nations, such as China and India, could also provide either space hardware or other important contributions, for example ground stations to enhance the data return from the Cross-Scale spacecraft.

Inter-agency collaborations require cooperation at the highest levels. We hope that leaders within all of the world's space agencies will actively pursue the potential for collaboration offered by the Cross-Scale mission, resulting in a reduced burden for every agency, and an enhanced science return for the global scientific community.

8. SUMMARY

Nonlinear, spatially and temporally variable multi-scale coupling dominates key plasma phenomena, but is poorly understood. Cross-Scale offers a practical opportunity to study multi-scale plasma dynamics, in the natural laboratory of near-Earth space, that no other mission or Earth-based experiment can match. ESA has an opportunity to continue its unique heritage of world-leading missions by being the first to fly this bold, challenging but scientifically revolutionary mission.

We hope that the international scientific community will support our efforts. We welcome all comments and suggestions.

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