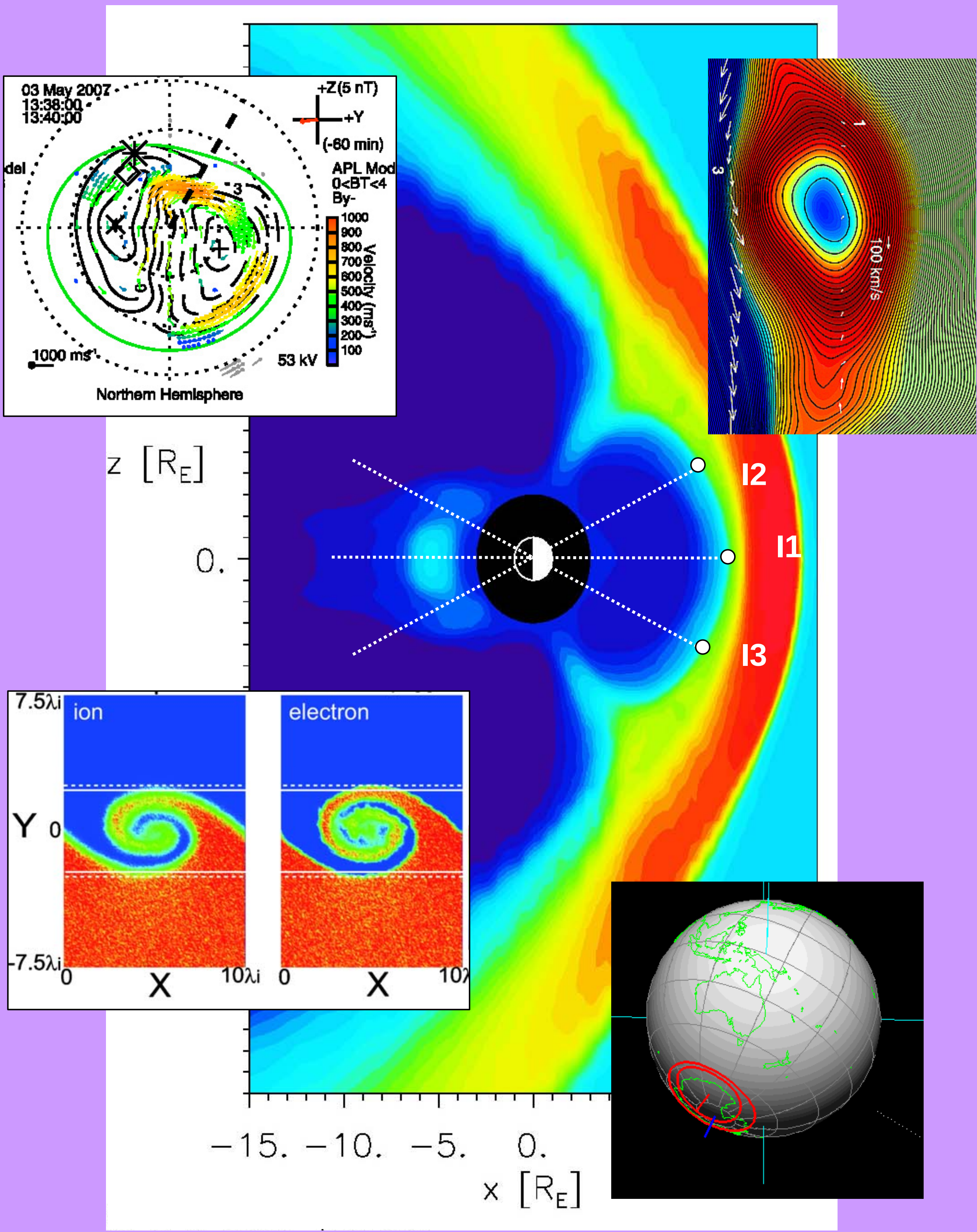
IMPALAS: Investigation of MagnetoPause Activity using Longitudinally-Aligned Satellites

A Mission Concept for the ESA M3 2020/2022 Launch.



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Proposal: IMPALAS: Investigation of MagnetoPause Activity using Longitudinally-Aligned Satellites – a Mission Concept for the ESA M3 2020/2022 Launch.

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Front cover Images: (Main): Simulation of dayside magnetospheric density distribution (Courtesy GSFC/CCMC); (Top Left): SuperDARN radar polar ionospheric flow vectors and potential maps (Fear et al., 2009); (Top Right): Reconstruction of a flux Transfer Event (Sonnerup et al., 2004); (Bottom Right): Simulation of IMPALAS view of the southern auroral oval (Courtesy S. Milan); (Bottom Left): Simulation of Kelvin-Helmholtz boundary waves on the magnetopause (Nakamura et al., 2010)

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Executive Summary

The dayside magnetopause is the primary site of energy transfer from the solar wind into the magnetosphere, and processes on this boundary modulate much of the activity observed within the magnetosphere itself (including 'space weather'), and that propagating down to the ionosphere. Plasma processes known to operate on this boundary include magnetic reconnection, boundary wave generation, propagation of pressure-pulse-induced deformations of the boundary, formation of boundary layers and generation of Alfvèn waves and field-aligned current systems that connect the boundary to the inner magnetosphere and ionosphere. However, many details of these processes, how they operate on the magnetopause and how they evolve are not fully understood. For example, magnetic reconnection is known to occur sporadically to produce flux transfer events, but how and where these arise, and their importance to the global dynamics of the magnetosphere are still unresolved.

ESA's Cluster mission has addressed, and NASA's MMS mission will address aspects of magnetopause dynamics, but on scales that are small relative to the size of this boundary. However, magnetopause phenomena often involve propagation of waves and other structures across this surface. In many cases, this motion is strongly influenced by the northward pointing direction of the terrestrial magnetic field. Understanding of these phenomena would be enhanced by measurements made at more widely-spaced ($\Delta s \sim 5\ R_E$) points along the direction of dayside terrestrial magnetic field at the magnetopause. We propose a mission deploying of a state-of-the-art fields and plasmas payload on 3 identical spacecraft. IMPALA 1 (I1) would be in a circular equatorial orbit of radius ~10.65 R_E, which has a period of exactly 2 days. This orbit radius is very close to the average location of the dayside magnetopause, such that the spacecraft would be expected to 'skim' along (and thus sample) this boundary over many hours during its dayside passage. IMPALA 2 and IMPALA 3 (I2 and I3) would be placed in orbits of +30 degrees and -30 degrees inclination, with slight eccentricity to increase their apogee to ~11 R_E, the typical position of the noon magnetopause at these inclinations, while maintaining the 2 day period and phase with respect to I1. These spacecraft would thus skim the magnetopause at distances up to ~5 R_E north and south of I1, while all 3 spacecraft maintain common longitude and thus can sample along the same terrestrial magnetic field line when located just inside the magnetopause. The orbits should also be phased such that when the spacecraft are at maximum separation at local midday, northern European ground-based facilities are also very near local midday, and will thus sample near the foot of the conjugate field line when the spacecraft are in their prime science locations.

Throughout this proposal, we tune the mission parameters to target science goals concerning the dayside magnetopause and its surrounding regions, which will also be sampled due to the natural variability in the position of the boundary. However, we recognise that orbital dynamics require the mission to visit other regions of the magnetosphere. There are thus many opportunities for the mission data set to support secondary science goals, such as the dynamics of the magnetotail near the region of substorm onset.

The payload proposed for the IMPALAS mission is a modest set of high-heritage instruments. The core payload for each of the 3 spacecraft, necessary to achieve the science goals, consists of a magnetometer, a pair of dual head ion and electron electrostatic analysers, and an energetic particle spectrometer. Although these may be deployed in a novel format, each of these payload elements has previously been flown on many European spacecraft, for example, Cluster. An addition to the core payload on the 2 spacecraft (I2 and I3)

in high inclination orbits consists of an auroral UV imager, which provides further information on activity around the foot-point of the terrestrial field line sampled by the 3 spacecraft. Although this instrument has lower overall TRL (~4-5), elevating this to an acceptable level is a matter of developing only one or two subsystems in the instrument. The entire instrument suite is supported by a common payload processor, handling all command, control and data handling functions for the instruments. The resource requirements for the core payload are estimated to be (i) Mass: 19.5/14.5 kg (I2 & I3/I1); (ii) Power: 35.3/20.3 W; (iii) Telemetry: 54.5/53 kbps.

We also detail 2 'highly desirable' instruments: electric field double probes, and an Ion mass spectrometer. These would add significantly to the scientific return and should be included during the study phase if resources allow. Indeed, much benefit would arise if even a single ion mass spectrometer unit was deployed in the vacant auroral imager slot on I1. Inclusion of these instruments would add 7.5 kg / 2.5 W / 1 kbps and 3.5 kg/ 6 W / 6 kbps to the resource envelopes of each spacecraft for the electric field and ion mass experiments respectively.

The spacecraft system design should be derived from the studies performed by ESA recently for the Cross-Scale mission concept, and we have sized the spacecraft resource budgets accordingly. The Cross-Scale mission would have flown some similar sensors, although in far greater number and complexity than is required for the present application. The 3 spacecraft should be identical to minimise development costs. One major difference to Cross Scale is that we propose that each spacecraft proceed, from either GTO or GSO injection by the launcher, to its operational orbit under its own propulsion.

We estimate that the dry mass of each spacecraft (not including main engine, fuel and fuel tanks) to be 200.4 kg. Each spacecraft requires an estimated power budget (including payload) of 349.6 W. We have included resources for a main engine and fuel tanks on each of the 3 spacecraft to perform our calculations for launcher resources. The total launch mass (3 spacecraft + engine + fuel) is 2400 kg if the spacecraft are initially inserted into GTO by the Soyuz-Fregat launcher and 1770 kg for initial insertion into GSO. We believe both these results to be well within the capability of the launcher system.

The IMPALAS mission generates scientific data at a rate of 12.5 Gbits per day. The 3 spacecraft will be in the view of the Kourou ground station for continuous periods of ~19 hours per 2 day orbit. Assuming download rates of ~6 Mbps, using X-band and a 15m dish, transmission of IMPALAS scientific data requires ~1.2 hours per day.

The procurement of the payload should be that typical of ESA space plasma missions, i.e. through PI investigations with instrument development supported by national agencies. There is sufficient heritage within Europe for provision of the entire payload. Contributions from other agencies could be considered but are not necessary. We estimate ROM total costs to European national agencies to be 23.4 (31.4) MEuro for the core (core + desirable) payload elements for the 3 spacecraft.

We do not have the expertise to provide detailed analysis of the overall mission costs. Hence we confine ourselves to direct comparison with the outcome of the Cross-Scale Assessment Study in December 2009 for which the ESA-estimated cost for 7 spacecraft carrying 107 separate instruments was ~600 MEuro. In contrast, the IMPALAS mission consists of 3 spacecraft carrying 17 rather simpler sensors. Although we recognise that there are one-off costs (e.g. launch) applicable to every mission, we contend on this basis that the IMPALAS mission will easily fit in the 475 MEuro cost cap for the M3 opportunity.

1 Introduction

In July 2010 the European Space Agency issued a call for proposals from the broad scientific community for the competitive selection of mission concepts to be candidates for the implementation of one medium-size (M-class) mission for launch in 2022. The ceiling to the cost to ESA for an M-class mission is 470 MEuro, although a mix of smaller missions approximately equivalent, in terms of overall financial envelope and profile, to one M-class mission could also result from the call.

The call also comes against a recent background in which the European space plasmas community responded, with some degree of unity, to the M1/M2 opportunity with the proposal, followed by a full study phase, for the Cross-Scale mission. This mission, which was not ultimately selected for the launch opportunity, had broad science goals addressing fundamental processes relevant to space and astrophysical plasma systems. Lessons from that Assessment Study include, perhaps, the understanding that the ESA M-Class budget is sufficient for only 2 or 3 ESA-sponsored spacecraft capable of making science-quality *in situ* fields and plasma measurements, although clearly this is a function of orbit, payload mass, etc. A further lesson from the Cross-Scale experience is that attempts to address very broad science goals are susceptible to mission resource creep, and difficulty in maintaining community support when descopes become necessary to keep the mission concept within resource envelopes.

In contrast, the NASA/THEMIS mission shows that significant progress on major unanswered questions in magnetospheric physics can be made by tailoring a multi-spacecraft mission to make *specific* measurements in *specific* locations in the magnetosphere, and that this progress will be augmented if ground-based capability is included as an extra measurement point.

The issues noted above suggest that a mission proposal with a set of focussed science goals and an equivalently focussed payload may be a sound approach under the M-Class opportunity. Providing options for augmentations to a baseline may be more palatable to ESA and the scientific user community than enforcing descopes later in the program. Under this philosophy, therefore, we broadly describe a mission aimed at Investigation of MagnetoPause Activity using Longitudinally-Aligned Satellites (IMPALAS). We demonstrate that there are compelling science goals to be met, and attempt to demonstrate the feasibility of a three spacecraft mission, with moderate payload, to address these goals within the M-Class budget and resources. However, we emphasise at the outset that we present a feasible, but by no means optimal, set of solutions for the mission, and the latter will need to be derived from a full ESA-sponsored assessment study.

2 Scientific Objectives and Requirements

2.1 Science Rationale: Why target Earth's magnetopause?

The magnetopause is the boundary between the solar and terrestrial plasma regimes. It is a critical interface in the field of solar-terrestrial relations, in that the coupling processes that ultimately control all magnetospheric dynamics occur there. These include some fundamental plasma processes, such as magnetic reconnection, particle acceleration and boundary wave generation. In the regions surrounding this interface other important processes, such as plasma turbulence, can also be found. The magnetopause is also the key interface for defining the influence of 'space weather' on the Earth system, with the effects of, for example, Solar Particle Events (SPEs) and Coronal Mass Ejections (CMEs) mitigated by, or transmitted, through this boundary before they affect near-Earth space. The magnetopause is also the most readily accessible analogue to other space and astrophysical plasma boundaries. There is much interest in the magnetopause, or the equivalent outer boundary of the spheres of influence, at the other planets. Generally speaking, telemetry constraints on missions to the other planets mean this boundary is always more poorly resolved and sampled than at the Earth, such that knowledge of the Earth system is crucial to put the more distant observations in context. Other plasma boundaries, for example the heliopause (the boundary between solar and interstellar plasma regimes), or those between other stellar and galactic spheres of influence, cannot be directly sampled. Thus understanding the interactions that occur at the terrestrial magnetopause can provide important ground truth for understanding these more remote interaction regions.

Over the last few decades we have assembled a significant database of spacecraft encounters with the magnetopause. Early observations from a number of missions consist of many brief single spacecraft traversals of the magnetopause, which generally occur when the boundary sweeps past the spacecraft as it rapidly moves in and out in response to changes in the solar wind ram pressure. These observations have certainly provided indications of the dynamic nature of this boundary, for example revealing the occurrence of reconnection-associated flux transfer events (FTE's) and regions containing accelerated particle populations. Although not originally a target for the mission, ESA/Cluster has recently made multi-point measurements over relatively small scales (compared to its extent) at the magnetopause. This provides insights into the underlying physics of the interactions, for example revealing the detailed fields and currents in the vicinity of active reconnection regions. Further progress in understanding this plasma microphysics can be expected from the NASA Magnetospheric Multi-Scale Mission (MMS). This 4 spacecraft mission is to be launched in 2014 and will make measurements of the magnetosphere, including the magnetopause, but at much smaller separations than Cluster. Conversely, we have only a few rare and fortuitous spacecraft conjunctions over larger scales. Most recently, for example, the Cluster and Double Star missions provided a handful of events in which 2 spacecraft sample the magnetopause nearly simultaneously, but at large separations. Nevertheless, these sporadic observations are extremely useful in providing indications of the more global dynamics of the magnetopause, for example in tracking the motion of FTE's.

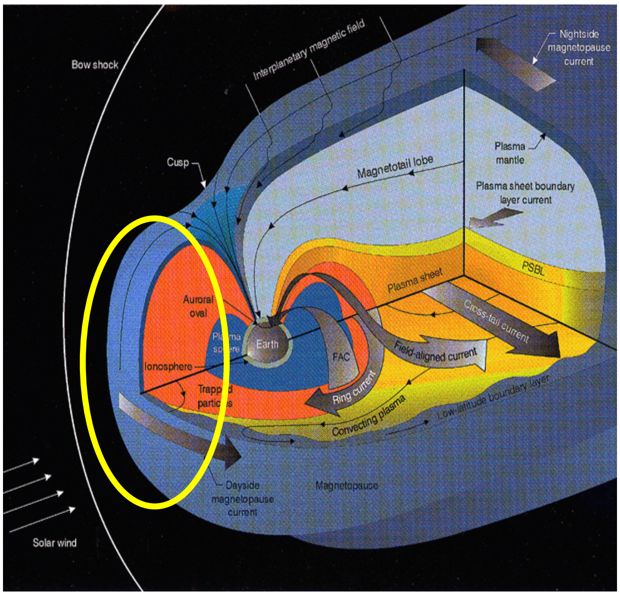

Figure 2.1: Schematic of the terrestrial magnetosphere, showing key regions. The dayside magnetopause, the prime target of the IMPALAS mission is highlighted towards the left of the figure.

Significant progress could thus be made in the latter area, the global dynamics of the magnetopause, if we could generate a statistically significant number of 'controlled' conjunctions with multiple spacecraft taking simultaneous *in situ* measurements at the magnetopause and spread relatively *widely* compared to the Cluster mission (Δs ~ 5 R_E) and particularly if that separation were along, say, a reconnecting magnetic field line. These *in situ* measurements could also be considerably enhanced if they were made in association with concurrent measurements of the ionosphere at or near

Question:	How solved:
What is the location of the MP reconnection site for given conditions?	Large number of measurements of particle dispersions/cut-offs at different locations along the same reconnected field line.
What is the importance of FTE's in global dynamics of the magnetosphere?	Determine if FTE's appear in only one or in both hemispheres simultaneously (adding open flux or not?).
How do boundary waves evolve as they propagate across the magnetopause?	Regular multi-point observations of boundary deformations at different distances from their origin.
Which mechanisms form boundary layers at the MP and how do they vary or evolve with position?	Regular and simultaneous multi-point observations of boundary layers across the dayside MP.
How do disturbances, discontinuities and waves propagate within the magnetosheath and how and where can they impact the MP?	Widely spaced measurements within the magnetosheath at times when the magnetosphere is compressed and MP is located below average position.
How do MP disturbances of all types propagate along field lines and into the ionosphere?	Multi-point measurements of Alfvènic disturbances and field aligned currents along the same field line, combined with regular observations of those field line foot-points by ground-based facilities.

Table 2.1: Examples of top level science objectives to be addressed with the IMPALAS mission concept.

the foot-points of the terrestrial magnetic field lines that lie just inside the dayside magnetopause. Such complementary measurements could be made by remote sensing from the spacecraft of the auroral emissions around these foot-points and/or by designing a mission which has magnetic conjunctions between the spacecraft located along these field lines and European (or other) ground-based facilities making observations in the vicinity these foot-point regions. Some examples of top level science goals that could be addressed by such measurements are summarised in Table 2.1 and described in the remainder of this section.

2.2 Steady State Reconnection at the Dayside Magnetopause

Magnetic Reconnection is a fundamental and ubiquitous process within plasma systems throughout the universe. It breaks down the barriers between neighbouring plasmas, releasing energy from their magnetic fields, transferring material and momentum between those plasmas, and accelerating a part of the plasma population to high energies. Astrophysical plasma systems in which reconnection is expected to occur and to play a significant role in the dynamic evolution including the Sun and other stars (exotic and otherwise) and planetary systems at all stages of their life cycles. Reconnection also governs the interactions of those systems with their surrounding interstellar media. It also occurs in laboratory plasmas, although in these cases the dynamics are controlled by collisional microphysics, in contrast to the largely collisionless process which occurs in the space environment.

The global dynamics of the Earth's magnetosphere are dominated primarily by the action of magnetic reconnection at the dayside magnetopause, as first recognised by Dungey (1961). When a strong magnetic shear exists across this dayside boundary, primarily during periods when the highly-variable IMF direction is significantly different to that of the terrestrial field, magnetic reconnection may occur, either locally or on a semi-global scale. In essence, the process consists of a 'breaking' of the previously independent solar wind and terrestrial field lines and a 'rejoining' to create 2 field lines which have one end on the Earth and the other extending into interplanetary space. This coupling results in a 'peeling' away of magnetic flux tubes from the dayside magnetopause surface, an acceleration of particles along field lines in a direction away from the reconnection site, a transportation of magnetic flux and particles over the poles, and an eventual storage of that flux in the nightside magnetospheric tail. The ongoing flux storage eventually destabilises the nightside tail region of the terrestrial magnetosphere, leading to a 'magnetic substorm', which results in a major reconfiguration of the magnetosphere and disruptions extending down into the polar ionospheric regions. Long periods of enhanced coupling between the solar wind and the magnetosphere result in magnetic storms, which in turn can result in extremely high fluxes of energetic particles in the radiation belts, significant electrical currents driven in the ionosphere, increased ionospheric drag on LEO satellites, together with other effects which can have serious consequences for our ground- and space-based technological assets. Thus magnetic reconnection at the dayside magnetopause can be seen as the key controlling influence on so-called 'space weather' effects within the terrestrial environment.

Despite having developed a workable understanding of the consequences of magnetic reconnection on the dayside magnetopause, there remain open a large number of significant scientific questions about the process itself. This is primarily due to a lack, to date, of relevant coordinated multi-point observations at this boundary. Most previous space missions encountering the magnetopause have made brief crossings of this boundary, usually with a near-perpendicular relative trajectories, at the point their orbits intersected this surface. The multi-point ESA Cluster mission has made significant progress on understanding the consequences of magnetic reconnection on the medium scale (a few hundred to a few thousand kilometres). The NASA MMS mission will specifically target the magnetic reconnection process at the microphysical/ kinetic scales (at a few tens of kilometres). However, there remains much to learn about the reconnection process from targeting the magnetopause on a more global scale. Key questions that can be addressed using data returned from the mission proposed here include:

- What is the location of the magnetopause reconnection site for given solar wind and interplanetary magnetic field conditions?
- What is the relative occurrence of anti-parallel versus component reconnection at the dayside magnetopause?
- What governs the transition between the anti-parallel and component reconnection scenarios?
- Is magnetic reconnection a continuous or intermittent process at the dayside magnetopause?

Our understanding of the reconnection process would be significantly enhanced if we could generate a statistically significant number of accurate determinations of the location of the reconnection site(s) and its mode of operation as a function of the prevailing conditions upstream of the magnetopause. For example, there is a long-standing and unresolved debate (e.g. Trattner et al., 2007 and references therein) as to the preferred location of this process on the magnetopause for given IMF conditions. In particular, we do not know whether this process occurs when magnetic fields on either side are near-exactly parallel, which implies the reconnection site will migrate around the magnetopause surface as the IMF clock angle rotates, or whether it can occur with a more reduced shear. In the latter case, anti-parallel components of the magnetic field vector may reconnect, and the site of reconnection may remain, say, near the subsolar point for a large range of IMF clock angles. In both the above cases, we also do not know the extent of the active reconnection site – whether it occurs at an extended neutral line stretching a significant distance across the magnetopause, in small singular or multiple patches, or whether indeed it occurs in a quasi-steady manner at all.

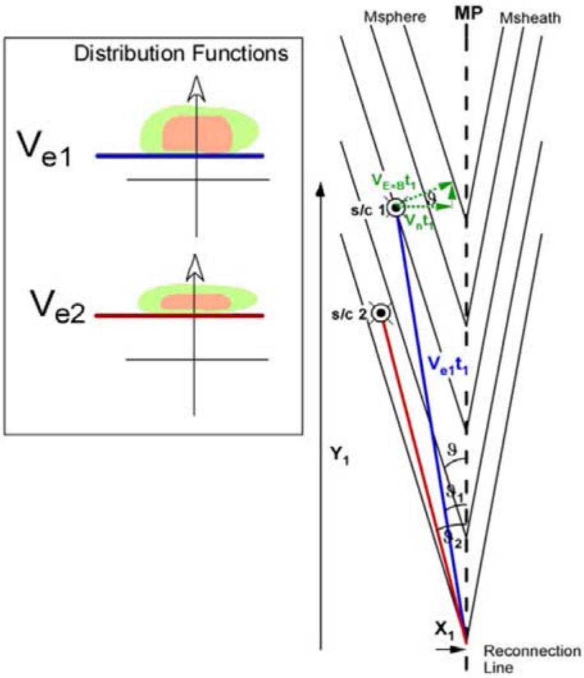

Figure 2.2: Two-dimensional geometry used to compute the inflow velocity and the distance to the reconnection line given two spacecraft observations in the reconnection layer. For the spacecraft locations in the layer, the velocity distributions in the spacecraft reference frame will resemble those in the inset. In particular, the cut-off velocity (V_{e1}) for spacecraft 1 will be lower than that for spacecraft 2 (V_{e2}) because spacecraft 2 is closer to the edge of the reconnection layer (defined as the magnetic field line directly connected to the reconnection line). The blue and red lines emanating from the reconnection site show the trajectories of these ions moving at the cut-off velocity (from Fuselier et al., 2005).

One of the prime goals of the IMPALAS mission is to determine the location of the MP reconnection site for given IMF conditions. The configuration of the mission should allow the return of a large number of simultaneous measurements of particle dispersions/ cut-offs at multiple positions in the magnetopause boundary layer broadly occupied by the same reconnected field lines. Very few such cases exist in current databases, since the required conjunctions between spacecraft have to date occurred only fortuitously and very rarely. The IMPALAS concept should be defined so as to make these a routine occurrence, by placing multiple spacecraft in permanent conjunction in their orbits. Once the data have been generated, the methodology applied to a few case studies by Fuselier et al. (2005) could be used on every conjunction event. This method relies on determining low-energy cut-offs in particle distributions in the reconnection-associated boundary layer just inside the magnetopause, as illustrated in Figure 2.2. If these cut-offs can be observed at 2 or more different points along the field line, a straightforward calculation can be made of the relative position of the reconnection site from the spacecraft. Once this basic parameter is established for a large number of events, the answers to the questions posed above follow in a natural way. We will determine how that location changes with changes in the IMF by comparison with observations of the prevailing solar wind conditions. We will establish whether the configuration of the magnetic field on either side is anti-parallel or not, and whether this depends on the external conditions. In addition, since the mission profile leaves the spacecraft in permanent conjunction along the magnetic field lines, we will be able to establish, for the first time, the temporal evolution of the reconnection site over timescales of minutes to hours. Finally, if the mission profile is such that we obtain conjugate ionospheric measurements at the foot-points of the field lines being sampled by the space-segment, then we will be able to infer, for example, the longitudinal extent of the processes observed in space. This can be achieved by imaging the auroral forms at this point, or by obtaining ground-based radar data of the form of the ionospheric flows associated with these field lines, or ideally both.

We thus contend that a mission profile of the type described here will make critical advances in our understanding of the magnetic reconnection process.

2.3 Transient Reconnection at the Dayside Magnetopause

It has long been recognised that magnetic reconnection may operate in a transient and/or sporadic and patchy manner on the dayside magnetopause. Russell and Elphic (1978, 1979) introduced the concept of the “Flux Transfer Event (FTE)” to interpret characteristic magnetic field perturbations observed by ISEE-1 and -2 in the vicinity of the low-latitude magnetopause. These perturbations are now regularly interpreted as signatures of spatially and temporally localized reconnection events which produce isolated open flux tubes. FTE’s are usually identified by a bipolar variation in the magnetic field component normal to the magnetopause surface, although there are differences in signature from event to event depending on which side of, and how far from, the magnetopause they are observed (e.g. Elphic,1995) The plasma observed within FTE’s often consists of a mixture of magnetospheric and magnetosheath plasma (e.g. Thomsen et al., 1987) usually associated with fast plasma flows (Paschmann et al., 1982) and ion D-shaped distributions (Smith and Owen, 1992). Moreover, most FTE’s are observed during southward IMF conditions e.g. Rijnbeek et al., 1984). These observations are strong indications that these structures are most likely associated with transient and localised magnetic reconnection occurring on the nearby magnetopause.

Again, despite this general understanding of the origin and nature of these events, there remain many unanswered scientific questions concerning their formation, structure and evolution. A dedicated mission tuned to the study of the magnetopause, such as that proposed here, has great potential to make very significant advances to closing many such questions. These questions include:

- What are the preferred locations for FTE formation under different solar wind and IMF conditions?
- What is the spatial extent of FTE’s?
- How do FTE’s move and evolve across the dayside magnetopause?
- Do FTE’s contribute significantly to the global open flux cycle?
- Do FTE’s form only in the winter hemisphere, as recent simulations (Raeder et al. 2006) suggest?
- Is the apparent quasi-periodicity in FTE occurrence (Rijnbeek et al., 1984) inherent to the magnetopause formation process or related to solar wind variations (or other transient events) which trigger FTE’s?
- What is the ultimate fate of FTE’s - How

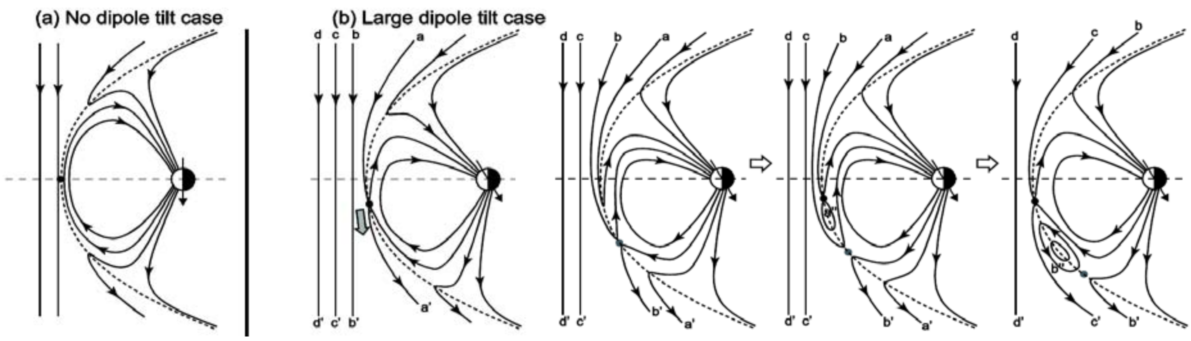

Figure 2.3: The IMPALAS mission will confirm, or otherwise, the importance of FTE’s in global dynamics of the magnetosphere. The observations will help determine whether FTE’s play a significant role in the addition of flux to the magnetotail (formed by reconnection between IMF and closed terrestrial field lines, similar to case (a)), or whether they are simply a restructuring of already reconnected field lines caused by dipole tilt effects (as in case (b)), as suggested by e.g. Raeder (2006). IMPALAS will resolve this issue by discovering if matched FTE’s appear in both hemispheres simultaneously or as single structures appearing in one hemisphere only (and thus if they add net open flux to the magnetosphere or not).

far do they travel from the point of origin?
- How do FTE's at the magnetopause affect the polar cusps and polar ionosphere?

As in the case of steady-state reconnection, our understanding of the formation and evolution of FTE's on the magnetopause would be considerably enhanced if we were able to obtain a statistically significant number of observations of each FTE at relatively widely-spaced separations (compared to most previous and currently planned multi-spacecraft missions). This would allow us to validate models of their motion across the dayside magnetopause (e.g. Cooling et al., 2001), and thereby determine, on a regular basis, the location of their formation as a function of the prevailing conditions upstream of the magnetopause. In addition, obtaining observations of matched pairs of FTE's in both the southern and northern hemispheres will not only help this process through the ability to triangulate back to a common point of origin, but will help answer some fundamental questions as to the role of FTE's in the global magnetic flux cycle. For example, recent simulations by Raeder (2006) have suggested that FTE's do not occur in pairs, as the original interpretations of their formation require, but form only in the winter hemisphere through re-reconnection of already opened field lines, as illustrated in Figure 2.3. In this scenario, FTE's have no impact on magnetic flux transport in the magnetosphere, and are merely an interesting by-product of more steady processes. Simultaneous measurements on the magnetopause in both north and south hemisphere, as would be available from the mission proposed here, will provide a definitive answer to this open question. Moreover, Milan et al. (2004), noted the apparent discrepancy in the typical size of an FTE, in terms of its magnetic flux content, determined from spacecraft observations and the global rate of flux transport derived from ionospheric radar measurements. This implies FTE's occur on the magnetopause at a significantly higher rate than has been observed. This may be a result of the mostly relatively short 'dwell' times of previous missions in positions close enough to the relevant parts of the magnetopause, which means that most FTE's may be missed. The IMPALAS mission should be designed to maximise this 'dwell' time and thereby obtain the observations necessary to make a final quantitative assessment of the rate that open flux is added to the magnetosphere by FTE's.

The specific science questions detailed above relate to the location of FTE formation for given solar wind/IMF conditions, solar wind triggering of FTE formation, the typical size of FTE's, how they recoil and evolve across the dayside magnetopause and ultimately merge into the background magnetosphere. Many of these questions have been asked since the discovery of FTE's in the late 1970s, but have not been answered due to the sporadic, isolated and patchy nature of the available observations. By targeting the dayside magnetopause specifically, the IMPALAS mission described in this proposal will enable a comprehensive examination of the formation and evolution of FTE's on the dayside magnetopause and will bring closure to such questions.

2.4 Magnetopause Boundary Waves and Deformations

As well as the reconnection phenomena that are intrinsic to the magnetopause current sheet, this boundary is also susceptible to local deformations which create waves travelling across the surface. Some of these are externally driven, for example by changes in pressure in the upstream solar wind. We know that the magnetopause moves significant distances inwards or outwards to maintain the balance of pressures from one side to the other, but we have little idea of how such pressure fronts propagate across the surface or how they may be dissipated. Furthermore, a second genre of waves, those generated by instabilities intrinsic to the magnetopause, may also cause a local magnetopause deformation. Due to the flow shear that generally exists across the magnetopause boundary between the dense, fast-flowing magnetosheath and the more tenuous, but more static plasma of the magnetosphere proper, the Kelvin-Helmholtz (KH) instability is often invoked as a source of magnetopause boundary motion. Indeed a recent popular model (e.g. Hasegawa et al., 2009, see Figure 2.4) for the diffusion of magnetosheath plasma onto closed magnetospheric field lines involves the steepening of KH waves to form flow vortices at the magnetopause, in which localised reconnection processes allow the plasma to effectively leak across the

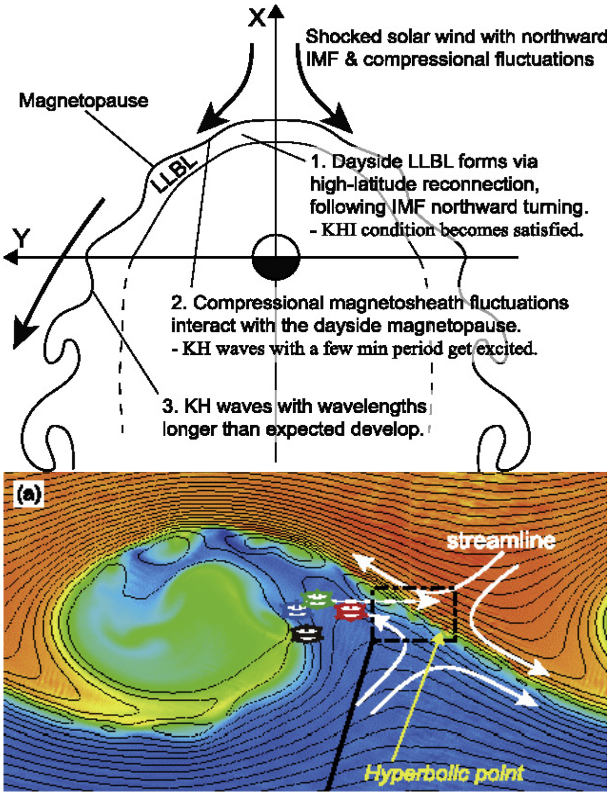

Figure 2.4: (top) Schematic of the equatorial magnetosphere showing how KH waves with wavelengths longer than predicted by the linear theory can be excited under northward IMF; (bottom) Two-dimensional two-fluid simulation of the KH instability [Nakamura et al., 2008], showing plasma density (red, dense; blue, tenuous) in a nonlinear stage, with in-plane magnetic field lines overlaid. The hyperbolic point is a stagnation point in the KH-wave rest frame around which flow lines form hyperbolae and reconnection occurs (after Hasegawa (2009)).

otherwise closed boundary. Other processes intrinsic to the magnetopause also generate boundary waves. For example, Owen et al. (2008) recently interpreted Cluster observations in the wake of an FTE as the passage of a 'travelling magnetopause erosion event', in which the indentation left by the removal of magnetic flux from the dayside magneto-sphere by an FTE was driven across the magnetopause surface by the action of the magnetosheath flow. This interpretation has since been confirmed by simulation (Kuznetsova et al., 2009). However, the specific configuration during this observation was rather unusual, and there have yet to be further observational reports of this phenomenon. Specific questions that will be addressed with observations from the mission proposed here include:

- How do solar wind pressure pulses deform the magnetopause, and how does that deformation move and evolve across the magnetopause surface?
- Where do KH and other boundary waves develop on the magnetopause, and how is this affected by the upstream solar wind conditions?
- What is the role of the KH instability in the transport processes operating at the terrestrial magnetopause, particularly under northward IMF conditions?
- How do the indentations resulting from magnetic flux erosion dissipate across the magnetopause?
- Can solar wind pressure pulses generate FTE-like signatures? If so, how do the magnetosheath signatures differ from the magnetospheric signatures?

2.5 Magnetopause Boundary Layers

Previous missions carrying *in situ* plasma packages have revealed that a variable set of boundary layers can generally be found on either side of the magnetopause current layer, with their occurrence and location being controlled by the upstream solar wind and IMF conditions.

It is known that under certain conditions a region forms upstream of the magnetopause in which the magnetic field piles up ahead of the boundary, and the plasma is 'squeezed out' away from the region along the field direction. However, observations of this plasma depletion layer (PDL) are sporadic, indicating that its formation, thickness, extent and degree of plasma depletion are highly variable, and most likely depend heavily on the prevailing solar wind and magnetopause conditions. For example, during periods of northward IMF, or low shear in the magnetic field at the magnetopause, this boundary may be expected to be relatively impervious to the solar wind flow, while at high shear the occurrence of magnetic reconnection allows some degree of flow through the boundary. Hence the degree of 'pile-up', and thus depletion, may generally be weaker in the latter case, depending on the extent of the reconnection on the magnetopause. In addition, the inherent flow pattern in the solar wind and magnetosheath (e.g. laminar or turbulent flows in the latter) may affect the nature, size and location of the PDL regions. One particularly relevant point is the degree to which this boundary may extend to regions of high-latitude and particularly to cover regions of the magnetopause poleward of the cusp. During periods when the PDL is absent, these regions are expected to be adjacent to magnetosheath flows which are super-Alfvènic, a condition which is expected to limit the occurrence of magnetic reconnection in this region (Cowley and Owen, 1989). However, if a PDL extends to high latitude, this may reduce the flows in this region, and/or increase the local Alfvèn speed, such that the flow is sub-Alfvènic and susceptible to quasi-steady reconnection processes. This in turn has important consequences for the structure and dynamics of the magnetosphere under northward IMF conditions.

Immediately downstream from the magnetopause boundary, a further set of boundary layers is known to exist (and there most probably exists a comparable set in the upstream region also). The plasma in these layers generally consists of a mixture of magnetosheath and magnetospheric plasma, indicating that some degree of mixing of these populations has occurred across the magnetopause. At high-latitudes, a natural explanation for such a boundary layer (the high-latitude boundary layer, HLBL) is the mixing and acceleration of plasmas as a consequence of the magnetic reconnection process. The plasmas in such layers have been observed to have the characteristics, expected from modelling, imposed by reconnection, such as low-velocity cut-offs in the distribution (e.g. Smith and Rodgers, 1991) and velocity-dispersed layers (e.g. Gosling et al., 1990). A second class of boundary layer has also been identified and given the term low-latitude boundary layer (LLBL), although it may encompass layers formed by a number of different processes which have yet to be unambiguously identified.

Again although we know of their existence, we have yet to fully determine the global nature of these boundary layers (extent along the magnetopause, thickness as a function of solar wind parameters, etc.) and their formation processes as a function of location and upstream conditions. This is due to the lack, to date, of global coverage of their structure.

Specific science questions which will be addressed include:

- Where do the boundary layers (LLBL and HLBL) form under different solar wind conditions?
- What is the thickness and magnetic topology of the LLBL as a function of distance along the field direction from the subsolar point?
- What are the relative roles of reconnection and diffusive entry (e.g. breaking of KH vortices) in the generation of the LLBL?
- What plasma waves are generated in the magnetopause? How does the intensity

of such waves affect diffusive plasma transfer across the magnetopause to form the boundary layers?

- What are the timescales for the generation/dissipation of the HLBL and LLBL following a change in solar wind conditions?
- How do these boundary layers map to the ionosphere?
- Under what solar wind conditions does a plasma depletion layer arise at different locations on the magnetopause?
- What is the PDL location, thickness, depth of depletion, etc. as a function of distance from the subsolar point?
- How far does the PDL extend poleward across the MP – does it support steady-state reconnection occurring poleward of the cusps?

By targeting the dayside magnetopause specifically with multi-point measurements spread widely along the terrestrial magnetic field direction, and allowing for significant dwell times in the vicinity of these boundary layers, the IMPALAS mission described in this proposal will enable a comprehensive examination of the formation, structure and evolution of the various boundary layers on and around the dayside magnetopause and bring closure to the questions posed above.

2.6 The Impact of Solar Wind Transients on the Magnetosheath and Magnetopause

The magnetosheath is the global boundary layer occupying the region between the bow shock upstream and the magnetopause downstream. It contains solar wind plasma which has been shocked, heated and deflected in order to pass around the magnetospheric cavity. Observations of this region have shown that the flow pattern can at times appear very turbulent and at others more laminar in nature. Other observations are consistent with the occurrence of mirror mode waves standing in the magnetosheath flow (e.g. Horbury and Lucek, 2009). At present the evolution of these types of flow, both with distance across and along the magnetosheath, and their direct effects on the magnetopause boundary are poorly understood. Understanding of the nature of the flow, particularly immediately upstream of the magnetopause (for example, whether the flow pattern forms a singular stagnation point or a stagnation line (Phan et al. 1994), or whether there are asymmetries in the flow patterns from north to south (similar to those reported for dawn-dusk by Paularena et al., 2001)) is a critical input to our models of magnetospheric dynamics.

Moreover, the effects of disturbances and discontinuities inherent to the upstream solar wind flow on the magnetosheath and magnetopause system are also not well known at present. For example, Sibeck et al. (1999) demonstrated that under certain circumstances when the IMF is quasi-radial, a hot flow anomaly (HFA) can develop upstream of the bow shock which can have a significant effect on the pressure profile being transmitted through the magnetosheath and ultimately to the magnetopause. Sibeck et al., (2004) argued that pressure reductions associated with HFA can cause a very significant outward deformation of a relatively localised region of the magnetopause surface, although we do not currently have measurements which can definitively confirm this interpretation, nor determine the extent of such a region, how it moves across the dayside magnetopause or how it evolves as it does so. The propagation of a number of other transients in the solar wind, such as interplanetary shocks and current sheets, through the magnetosheath and along the magnetopause surface are similarly poorly understood, predominantly as a result of the lack of appropriately-spaced monitoring points within these regions. For example, Sibeck (1990) has argued that transient solar wind pressure pulses produce ripples on the magnetopause surface which mimic many of the signatures of FTE's. Full understanding of the effects of the FTE process on the magnetosphere clearly requires that we learn how to separate their signatures from those of pressure-driven local variations in the magnetopause. Moreover, other solar wind effects can have more subtle consequences for the dynamics of the magnetopause. For example, Denton and Borovsky (2008) argued that the occurrence of magnetic storms may drive plasmaspheric plumes from the inner magnetosphere which can redistribute cold plasma populations as far out as the magnetopause, and thereby have a significant effect on the coupling of that boundary with the solar wind. No systematic study of the effect of cold plasma as a function of position on the magnetopause has yet taken place.

Hence some of the key questions that need to be addressed concerning the structure of the magnetosheath and the effects of transients include:

- How does the global structure of the magnetosheath vary as a function of IMF and solar wind parameters?
- Does the global structure of the magnetosheath exhibit north-south asymmetries?
- Does the overall magnetosheath flow structure vary significantly for different conditions (does the magnetosheath exhibit turbulent or laminar flows, are there stagnation lines or points in the flow structure)?
- How do disturbances, discontinuities and waves propagate within the magnetosheath and how and where can they impact the magnetopause?
- How can we reliably separate signatures of transient pressure pulses from those of FTE's at the magnetopause?
- How do transient injections of cold plasma from the inner magnetosphere affect magnetopause dynamics and how do these evolve?

Understanding of the global structure of the magnetosheath and the propagation of the transient phenomena occurring within it clearly requires more widely-spaced, simultaneous measurements within the magnetosheath than have been hitherto available. The mission proposed here will provide such measurements during periods when the magnetopause is compressed to a position below its average location and hence we contend will help make considerable advances in our under-standing of the magnetosheath and its dynamics.

2.7 Propagation of Magnetopause Phenomena to the Polar Ionosphere

Many of the phenomena described above are directly coupled along terrestrial magnetic field lines into the auroral ionosphere. The IMPALAS mission proposed here therefore offers a unique opportunity to further our understanding of the dynamics of the coupled magnetosphere-ionosphere system driven by momentum and energy transfer from the solar wind at the dayside magnetopause. For example, the production of open magnetic flux, either as a result of quasi-steady reconnection or as part of the FTE process, and its transport into the tail, will drive ionospheric flows poleward and into the polar cap from the dayside auroral region. The global configuration of these auroral zone and polar cap flows can be determined using the multi-point measurements available from the SuperDARN network of ionospheric radars, while the currents driven in the ionosphere as a result of this coupling can be determined using measurements form appropriately located networks of ground magnetometer stations. From these data, it is possible to determine, for example, the position of the ionospheric boundary between open and closed field lines, which maps to the edge of the HLBL that we expect to be regularly sampled at multiple points by IMPALAS in space. Moreover, the global nature of these ionospheric measurements provides a context for the space-based observations which are more locally confined around a given magnetic field line. For example, these measurements can be used to determine the longitudinal extent of the active reconnection site, and the overall production rate of open magnetic flux (Chisham et al., 2004), which cannot be determined from space-based measurements alone. It is also possible to examine the ground signatures of FTE's generated on the dayside magnetopause, for example by determining the localised currents driven in the ionosphere. With magnetically conjugate measurements from multiple points along FTE field lines, we will be able to determine the electromotive force delivered towards the ionosphere, and the outgoing reflected part (Amm et al., 2010). This enables us to determine the contribution of the reflection and polarization processes to the energy deposition in the ionosphere, and to determine the parts of the horizontal ionospheric current systems related to these processes. In combination with auroral images of the same region we can solve the longstanding question of the importance of the polarization process for the ionospheric feedback, especially at the edges of auroral forms where strong conductivity gradients exist. This approach will also allow us to resolve the conundrum of the apparent imbalance between open flux transported in individual FTE's observed at the magnetopause, and that determined from ground-based measurements (Milan et al., 2003). We will be able to determine the causes of non-conjugacy in the flows and auroral forms between hemispheres. Finally, a combined IMPALAS-ground based study of the mapping of boundary waves and deformations from the magnetopause to the ionosphere will help reveal the origin and coupling of ULF wave power into the inner magnetosphere and ionosphere. In summary, some specific questions that will be addressed include:

- How do processes (reconnection, FTE's, boundary waves) occurring on the day-side magnetopause map down the field lines and affect the auroral ionosphere?
- How does the ionosphere provide feed-back to processes occurring on the day-side magnetopause – can this saturate the reconnection rate, for example?
- How does the connection to the ionosphere affect KH stability of the boundary and the development of the KH and other boundary waves?
- What is the width of the merging gap (the footprint of reconnection) in the iono-sphere as a function of magnetopause and IMF conditions?
- How much open magnetic flux is added to the magnetosphere by FTE's?
- What causes inter-hemispherical asymmetries in the auroral forms and polar ionospheric flow patterns?

We thus contend that the matching of the IMPALAS mission proposed here with existing ground-based capabilities to make measurements of the auroral and polar cap ionosphere would provide a very powerful extension to the overall scientific output from the proposed mission. In particular, the mission will reveal coupling processes driving plasma dynamics generated by the transport of open flux from the dayside magnetopause into the geomagnetic tail, and the generation of ULF waves. This will be achieved through multi-point measurements of, e.g., Alfvènic disturbances and field-aligned currents along the same field line, combined with regular observations of those field line foot-points by ground-based facilities. The mission profile described below thus makes high priority of obtaining magnetopause measurements in magnetic conjunction with ground-based facilities.

2.8 Other Magnetospheric Science Topics that may be Serendipitously Addressed

The IMPALAS orbit design proposed here will be tuned to answer the magnetopause-related science questions posed above. However, orbital dynamics necessarily means the 3 spacecraft must visit other parts of the magnetosphere at varying separations over the course of a year. For example, the spacecraft will also pass through the transition region between dipolar and stretched tail-like magnetic field configurations in the nightside magnetosphere. This would be the first time that multiple spacecraft in such a configuration will have visited this region, despite this being a key region of the magnetotail and near the onset region for magnetospheric substorm dynamics. Using the mission configuration proposed here, the spacecraft will be able to probe the latitudinal structure and extent of the plasma and observe the evolution with latitude of depleted flux tubes or plasma bubbles which have been a focus of much recent substorm research (e.g. Xing et al., 2010). The IMPALAS configuration will support a survey of the cross-tail current density (integrated north-south) and its variation during flow bursts, thus providing new insight into cross-tail current disruption, and identifying possible current density thresholds. During periods when the spacecraft are located in the lobes we will be able to determine the total energy density in the tail which can be used as a proxy for geomagnetic activity. The IMPALAS orbit will also be ideally suited to study the field-aligned variations in magnetic structure and plasma parameters during field line resonances (FLR), which are known to be an important means of transferring energy from the magnetosphere to the ionosphere (Rae et al., 2007). The role of FLRs in trapping and accelerating electrons could also be investigated using the longitudinally-aligned IMPALAS spacecraft, and in the proposed orbits the spacecraft would also sample the acceleration region of the broadband aurora suggested by Watt and Rankin (2009). Furthermore, while in the prime science configuration, the auroral imagers on the IMPALAS spacecraft will also be able to observe any conjugacies (or lack of thereof) in the substorm aurora in opposite hemispheres, and link these to the particle and field characteristics observed *in situ* by each spacecraft. This potentially provides a key link between processes occurring in the onset region in the magnetotail and those occurring in the conjugate auroral ionosphere, and thereby could provide important tests of models of substorm onset.

We note that the separation of the 3 IMPALAS spacecraft changes over a single orbit, so there are opportunities to investigate the magnetosphere and the physical processes operating within it at a variety of latitudinal spacecraft separations. At the opposite extreme to the separation used for the prime science discussed above, the spacecraft will all be relatively close as they cross the ecliptic plane. At this point in the orbit proposed below, for example, the spacecraft are likely to be almost radially aligned with a separation of the order of $2R_E$. This configuration has the potential to return highly valuable observations pertaining to the radial extent of features such as Bursty Bulk Flows in the magnetotail plasma sheet and the detailed pressure profiles of the transition region between dipolar and tail-like field lines, both of which are considered important aspects of substorm dynamics. The radial profile, formation and evolution of energetic particle injection fronts, dipolarisation fronts and the region of flow braking and current disruption (e.g. Nakamura et al., 2009, Spanswick et al., 2010) could also be determined by spacecraft in this configuration. When the spacecraft have this radial alignment on the flanks, the radial structure of the low latitude boundary layer could be also be systematically probed in more detail than has been possible in the past.

2.9 IMPALAS Measurement Requirements

The IMPALAS mission primarily targets the dynamics of the dayside magnetopause over relatively large scales compared to previous missions. The primary requirement is to make *in situ* magnetic field and plasma measurements over long durations at 3 points spaced at several R_E along the terrestrial magnetic field line direction just inside the average magnetopause position.

Required Measurement	Required Instruments	Required for:
3D magnetic field vector @ ~1 sec resolution	Magnetometer	Identification of MP crossings, plasma waves and FTE's, Walen tests for identification of reconnection outflows
3D velocity distribution functions of electrons and ions, few eV to ~30 keV @ ~3 sec (half spin) resolution.	Ion & Electron Spectrometers	Calculations of plasma moments (density, velocity, temperature, pressure), identification of MP crossings, particle cut-offs to locate reconnection site, Walen tests for identification of reconnection outflows.
3D velocity distribution function of energetic ion and electrons, > 30 keV @ ~6 sec (spin) resolution.	Energetic Particle Detectors	Determine boundary motions and identify particle acceleration signatures.
Imaging of auroral dynamics at footpoint of magnetic field line threading spacecraft locations @ 30 sec cadence. *High inclination orbits only.*	Auroral Zone Imager	Provides context and additional link between *in situ* and ground-based measurements.
	Desirable Instruments	
2D electric field vector @ ~1 sec resolution (3rd component derived from E.B=0).	Electric field booms	Identification of plasma waves, measurement of convection electric fields within boundary layers, measurement of s/c potential, total plasma density
Measurement of composition of ambient thermal plasma @ ~6 sec (spin) resolution.	Ion Mass Spectrometer	Plasma composition for correct analyses, tracers of particle origins within boundary layers;

Table 2.2: Strawman payload for the IMPALAS mission concept.

The regions targeted in the science objectives above will then be sampled regularly due to the natural variability in the actual position of the magnetopause. Given the typical time and spatial scales of the phenomena being targeted, the *in situ* instruments should return measurements in the 1 – 10 second range. Given the low telemetry demands of the fields instruments, we baseline these at 1 second cadence. Given the necessity of the particle instruments to use spacecraft spin to sample the full sky, these are baselined in the 3-6 second cadence for full 3D measurements. In addition, measurements of the dynamics of the auroral foot-point of that field line will significantly add to the science return from the mission. The IMPALAS bus should therefore be capable of imaging the dayside auroral zone, ideally in both hemispheres. The measurements required to meet the science goals described above, the instruments that therefore need to be included in the payload, and a brief description of their role in meeting the science goals are listed in Table 2.2 below:

2.10 Other Measurement Requirements

The orbits should be phased so that the spacecraft remain in longitudinal alignment and also such that they are conjugate with relevant ground-based facilities during the prime science windows, when the spacecraft are at large separation near local noon. Given the European leadership and funding of the proposed mission, it would be highly preferable to enable, through mission design, the use of European facilities in the Scandinavian sector, although similar facilities also exist in the Canadian sector. The IMPALAS mission should make longitudinally conjugate measurements, which in principle provide multiple measurements along the same field line when the spacecraft are

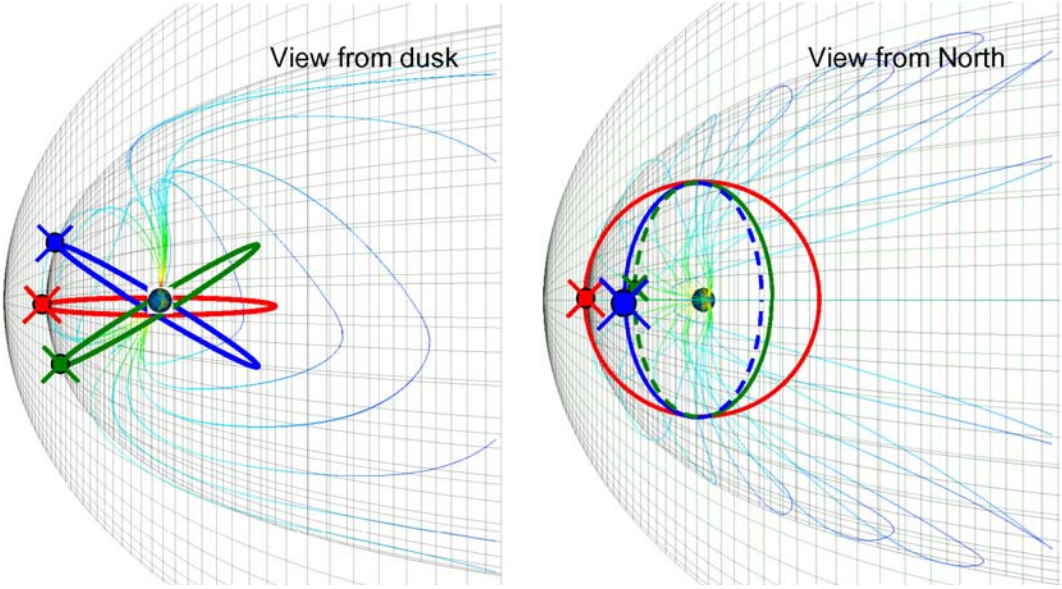

Figure 3.1: Schematic illustrations of the orbits of the 3 IMPALAS spacecraft. The left hand panel shows the view from dusk, with the 3 spacecraft located at the magnetopause boundary. The right hand panel shows the view from the north, and illustrates how the 3 spacecraft skim along the dayside magnetopause boundary for many hours during their 2-day orbit.

located at and just inside the dayside magnetopause. The imaging capability should be deployed on the 2 spacecraft in high-inclination orbits to provide information about the dynamics of the foot-point of that field line in the auroral ionosphere. However, a number of other key measurements can be made when the spacecraft are also in magnetic conjunction with ground-based magnetometer arrays, such as the IMAGE array. This consists of 31 magnetometer stations in Scandinavia which enable the study of auroral electrojets and moving two-dimensional current systems above this region with ~50 km resolution. These observations are complemented by, for example, high time-resolution measurements (~2 mins) of the ionospheric flow vectors in the same sector by the CUTLASS radar system and measurements by the international EISCAT radar facility and the EISCAT Svalbard radar. The CUTLASS radars are part of the wider SuperDARN radar network, combined measurements from which can provide the ionospheric flow pattern over the entire auroral and polar cap region, thereby providing a global context for the IMPALAS *in situ* measurements. These ground-based measurements are highly beneficial for the overall science return of the IMPALAS mission, and can be made relevant by phasing the IMPALAS orbits such they are located with maximum separation at the centre of the dayside magnetopause at local noon in Scandinavia.

Finally we note that some IMPALAS science goals require upstream solar wind and IMF measurements. Over the last few decades such measurements have been provided by spacecraft at L1 or in orbits that transit upstream of the bow shock. We assume that similar observations will be available in the IMPALAS era.

3 Mission Profile Proposed to Achieve the Objectives

3.1 Overview

We propose that the mission assembled to completely address the science goals described above needs to provide simultaneous observations of the terrestrial dayside magnetopause and/or its environs at a minimum of 3 points with latitudinal separation (i.e. along the direction of a terrestrial magnetic field line) of order 5 R_E. Variations of this distance are likely to be scientifically valuable to the outcome of the mission and are therefore highly desirable. We thus propose that the mission should consist of a baseline of 3 spacecraft, which for the purposes of the discussion here we designate I1, I2 and I3.

3.2 Orbit requirements

The overall requirement for the selected orbits is to provide extended periods of conjunction of the 3 spacecraft widely separated in latitude along the magnetic field (longitudinal) direction at the known average location of the dayside magnetopause. The latitudinal separation requires that the 3 spacecraft have individual orbits in 3 separate planes. The requirement for longitudinal conjunction suggests that the 3 orbits should have exactly the same period, or have enough fuel to correct for significant medium term drifts. The requirement for conjunctions at the dayside magnetopause implies that each of the orbits be chosen to minimise the average net distance from the known average location of the dayside magnetopause in the 9 to 15 hours magnetic local time sector. Furthermore, it is highly desirable that the orbits are phased so that the main science periods, when the spacecraft are widely separated at local noon, coincide with relevant European ground-based facilities also being located at local noon.

A possible example of the kind of orbit envisioned for the IMPALAS mission is shown in Figure 2. I1 could be placed in a circular orbit with a 10.65 R_E radius (1 R_E = 1 Earth Radius = 6371 km) at 0º inclination. I2 should be placed in a slightly eccentric orbit with apogee ~11 R_E and +30º inclination. Finally I3 should be placed in a similarly eccentric orbit as I2 but with -30º inclination. The point of these orbits is that each spacecraft should then have an exactly 2 day period which 'skims' dawn-to-dusk very close to the average position of the dayside magnetopause, as defined, for example, in the Fairfield (1971) model. Each of the 3 orbits can thus be phased so that each spacecraft remains in longitudinal (magnetic) alignment with other 2, but separated by up to ~5 R_E. Furthermore, the 2 day period means that the spacecraft orbit can be further phased so that the foot-point of the field line connecting the spacecraft is over European ground-based facilities when the spacecraft are at local noon on every orbit.

Thus the 3-spacecraft fleet sweeps across the dayside magnetopause, remaining in longitudinal alignment, once per orbit. We contend this provides a scientifically highly valuable set of platforms from which to make *in situ* measurements of the fields and plasma environment. The separation at local noon will vary from ~5 R_E to near-zero due to orbit precession through the year, providing scientifically highly desirable variations in inter-spacecraft distances. In addition, for more than 50% of each orbit, the spacecraft will be inside the magnetosphere as they pass through the flanks and the tail. Although not the focus of the science addressed here, this will also provide highly valuable science data for community members interested in internal magnetospheric processes such as field line resonances, substorm current disruptions and onsets, etc.

3.3 Launcher requirements

IMPALAS is expected to be launched from Kourou using the Soyuz Fregat 2B. We have performed a preliminary analysis of the launch scenario to the representative orbits described above, via either GTO or GSO, assuming 3 spacecraft with dry mass of 200 kg (see Section 5), not including main engine and its subsystems. Here we propose that the 3 IMPALAS spacecraft are injected into the GTO or GSO by the launcher system, and then proceed under their own propulsion to their individual operational orbits. We have calculated the total launch mass of the IMPALAS mission by considering the delta-V required on each spacecraft to move from the initial orbit

Spacecraft Details	**GTO**	**GSO**
Engine Specific Impulse	270	270
Dry Mass (kg) – See Section 5.	200	200
Fuel for operations (kg)	20	20
Mass to orbit (kg)	220	220
Initial orbit (provided by launcher)		
Apogee altitude (km)	35768	35768
Perigee Altitude (km)	250	35768
Inclination (deg)	7	0
Total velocity change for raising 3 s/c to elliptic operational orbit, individually changing inclination, then circularising the I1 orbit		
Total Delta V, I2 (km/s)	3.46	2.70
Total Delta V, I3 (km/s)	2.17	0.90
Total Delta V, I1 (km/s)	3.06	2.57
Fuel and propulsion system masses required		
Fuel Required, I2 (kg)	591.9	388.8
Fuel Required, I3 (kg)	279.1	89.6
Fueld Required, I1 (kg)	478.2	361.1
Engine Mass (per spacecraft)	10.0	10.0
Fuel Tank Mass (per spacecraft, 20% max fuel mass, kg)	118.4	77.8
Total Launch Mass (3 s/c + fuel, kg)	**2394.4**	**1762.7**

Table 3.1: Launch Mass Estimates for the IMPALAS mission, assuming initial injection by the launcher system into GTO or GSO.

provided by the launcher to the operational orbit. This includes first raising all 3 spacecraft to the apogee height of the final elliptical orbit used for I2 and I3, then making the relevant inclination change and finally circularising the I1 orbit to the required height. Table 3.2 shows the total delta-V required for these manoeuvres on each spacecraft, and thus the fuel mass required, assuming hydrazine dual propellant. We allow 10 kg for the main engine mass, and 20% of the maximum fuel mass requirement to size the fuel tanks. Combining the calculations for each of the 3 spacecraft, we estimate that the mission launch mass is ~2400 kg for injection into GTO and 1770 kg for injection into GSO. We note that both these estimates are well within the lift capability of the Soyuz-Fregat launch system.

3.4 Ground segment requirements

The ground segment includes the Mission Operations Centre (MOC), ground receiving stations and communications network, and a dedicated IMPALAS Data Archiving System (IDAS) for data distribution to the scientific community.

The mission requires ground stations to communicate with the 3 spacecraft via X-band communications systems in order to support all telemetry, telecommand and tracking functions. From launch until all 3 spacecraft have reached their operating orbits and have gone through the commissioning phase, we anticipate that several ESA ground stations will be required to maximise the ground contact during these crucial activities. When the IMPALAS mission is in nominal operations phase we anticipate that it can largely be supported by one ESA receiving station.

The IMPALAS Science Team consist of instrument PI's and other key investigators. They will define the science requirements for each part of the mission and feed these to the MOC via the IMPALAS Science Operations Centre (ISOC). The MOC will provide the mission control functions for both the spacecraft and payload, and will deliver the scientific requirements within the overall system resources. The mission operations will remain the responsibility of ESA throughout the mission.

The IMPALAS raw data will be initially processed at the ISOC from which all Principal Investigators will be able to retrieve their data for calibration and production of higher level data products. The IDAS will store raw data and high-level IMPALAS science products to ensure that they are permanently available to the science community.

4 Proposed Model Payload

4.1 Overview of all proposed payload elements

The IMPALAS science goals can all be accomplished using a modest payload comprising, with one exception, instruments with a high TRL that have previously been flown with great success on missions such as Cluster and THEMIS. The core payload concept, which should be identical on each of the 3 spacecraft, consists of a DC magnetometer, plasma ion and electron spectrometers and an energetic particle detector. These are supplemented by a nadir-pointing auroral imager which would fly only on the 2 spacecraft in inclined orbits. This payload would be controlled by a common payload processor, saving mass and allowing for efficient payload operations. Should the resource budget allow, 2 further instruments, measuring electric fields and ion composition, are rated as highly desirable. The accommodation of these instruments and their potential impact on the resource envelopes should be assessed in the study phase for the mission.

Payload procurement is identical for all payload elements and will be accomplished in the same way as for prior space plasma physics missions: National funding agencies funding payload development and operations by universities and other research institutes. All payload components have heritage in ESA member states.

The model payload described in this proposal is largely based on instruments that are currently available or are already at a high TRL. However, it is likely that within the timeframe of the M3 development and build phases alternate concepts providing higher capability and/or reduced resource requirements will become available. Thus an alternative payload concept could be considered in which the mission provides flight opportunities for the next generation miniaturised instrumentation, if appropriate technology development plans exist. For example, UCL/Mullard Space Science Laboratory is developing a MEMS-based plasma analyser, while Imperial College London is working on low-mass magnetometer designs. Both initiatives are currently at TRL < 5, but have potential flight opportunities on various Cubesat programs within the next few years and are thus expected to be at TRL 9 by 2014.

The core payload and the optional elements, which could be included if resources allow, are described in the rest of this section.

4.2 Summary of Core Instruments Key Resources and Characteristics

4.2.1 Magnetometer

4.2.1.1 Description of the measurement technique, Instrument conceptual design and key characteristics

The magnetic field measurements must be made on all 3 spacecraft by a dual sensor fluxgate magnetometer, of the type flown on many previous missions. Each sensor being comprised of the sensor itself and a near-sensor electronics module. The 2 sensors will both be located on a rigid boom at differing distances from the spacecraft body. These magnetometers will be deployed on all three spacecraft, typically returning field vectors sampled at 10-20 Hz.

4.2.1.2 Performance assessment with respect to science objectives

Magnetic field vectors are required to fulfil all of the science goals of IMPALAS. They are needed to determine the position of the spacecraft with respect to the magnetopause current layer, identify and characterise flux transfer events, waves, discontinuities, etc. This instrument also supports operation of other payload units, for example by enabling measurement of particle pitch angle distributions.

4.2.1.3 Resources: mass, volume, power, and telemetry

To return the magnitude and direction of the magnetic field at a rate of 10 Hz, a telemetry rate of 960bps per sensor will be required, without onboard compression. Required mass and power are 1.5 kg and 0.5 W respectively. Each sensor requires a volume of 11 x 5 x 5 cm^3.

4.2.1.4 Pointing and alignment requirements

The orientation of the flux-gate assembly with respect to the spacecraft must be known with a precision of 0.1–0.2 degrees.

4.2.1.5 Calibration and other specific requirements

Prior to launch, a ground calibration campaign will be necessary, as will regular in flight calibration. Magnetically clean spacecraft will be required to avoid contamination of the magnetic field measurements.

4.2.1.6 Current heritage, TRL and Critical Issues

Sensors of a similar design have recently been flown successfully on Cassini, Cluster, Double Star and THEMIS thus the DC magnetometer has a TRL of 9. The only critical issue for this instrument concerns boom deployment. The boom should be a spacecraft provided element.

4.2.2 Dual Sensor Ion and Electron Spectrometer

4.2.2.1 Description of the measurement technique, Instrument conceptual design and key characteristics

Measurements of the ion and electron velocity distribution functions (VDF) must be made on all three IMPALAS spacecraft. These measurements can be provided by traditional top-hat electrostatic analysers, as commonly flown on space plasma physics missions, in which E/q selection of incoming particles is accomplished through varying an electrostatic potential between two hemispheres, altering the path of incoming particles such that only particles in a narrow energy band can pass through the sensor to impact on MCP detectors. Each sensor will have a field-of view of a few degrees by 180 degrees. Thus a spin-stabilised spacecraft is required to scan the whole sky and hence measure the full 3D VDF of ions and electrons, from which basic plasma parameters such as density and bulk velocity can be derived.

We propose that these instruments can be deployed on each spacecraft packaged as two dual-head sensor units mounted on opposite sides of each spacecraft. Each unit would have one head configured for measuring electrons and one head configured for measuring ions. Both the ion and electron sensors will be optimised for the more tenuous magnetospheric plasma sampled by the IMPALAS spacecraft, but will include variable geometric factor systems in order to measure denser magnetosheath plasma without saturating the MCP’s. Each sensor should have an energy range of a few eV to ~30KeV and an energy resolution of approximately 10-15%. An angular resolution of 10°x10° or 20°x20° will be sufficient to fulfil the IMPALAS science goals. Overlap in energy with the high energy particle experiment (below) is desirable but not essential. As the instrument design consists of two sensor heads for both ions and electrons a full 3D velocity distribution will be collected every half spin. Thus in order to provide plasma parameters at the required temporal resolution of ~3s, a spacecraft spin rate of ~10rpm would be required.

4.2.2.2 Performance assessment with respect to science objectives

These sensor heads provide measurements leading to the characterisation of the thermal ion and electron populations in and around the magnetopause current layer which are required to fulfil all of the science goals of IMPALAS. They are needed to determine the position of the spacecraft with respect to the magnetopause current layer, identify and characterise FTE's, waves and boundary layers. Plasma distributions (or as a minimum moment parameters) should be returned from each spacecraft with a time resolution of ~3s.

4.2.2.3 Resources: mass, volume, power and telemetry

Current conceptual designs for the dual head system (Figure 4.1) suggest each dual head sensor unit would have a mass of 3kg and a power requirement of 3W. This is based on studies undertaken for the NASA MMS mission and for the Cross-Scale ASR, which in turn were based on a long heritage for such top-hat analysers in their single head format. For sensors with an approximate 11°x11° angular resolution and 64 energy levels (implying ~15% energy resolution to cover the full energy range without gaps), a full 3D velocity distribution requires ~256 kb. Thus a data rate of ~86 kbps each is needed for ½-spin resolution 3D ion and electron distributions to be telemetered to the ground. Data compression and selection strategies, such as onboard creation of 2D pitch angle distributions and the onboard calculation of moments, can be implemented to reduce this if necessary. We baseline a telemetry rate of 24 kbps for each species, assuming a conservative compression ratio of 4 and allowing for housekeeping data.

4.2.2.4 Pointing and alignment requirements

The entrance apertures for each top-hat sensor must be mounted pointing away from the spacecraft body with centre of the fields-of-view perpendicular to the spacecraft spin axis, in order to achieve full 4π steradian coverage of the sky every one half spacecraft spin period.

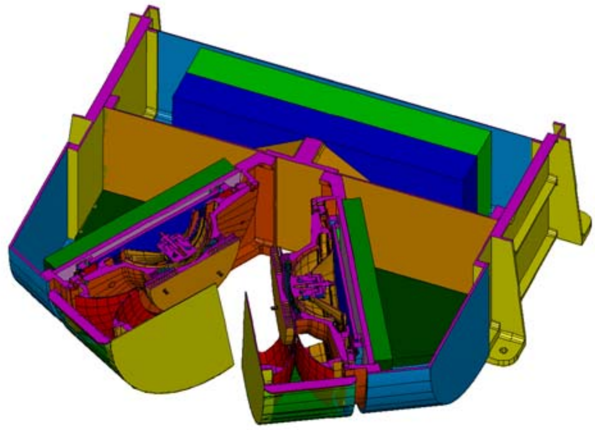

Figure 4.1: A cutaway of the design for dual head ion/electron spectrometer

4.2.2.5 Calibration and other specific requirements

The each of the dual sensor head units should be mounted on the spacecraft such that the fields-of-view do not include any significant obstructions. The spacecraft should be designed to minimise surface charging effects, especially near sensor apertures. Both preflight and inflight calibration will be required. In order to sample the full 3D distribution function a spin-stabilised spacecraft will be necessary.

4.2.2.6 Current heritage, TRL and Critical Issues

Basic electrostatic analysers have a long heritage and have been flown successfully on numerous plasma physics missions (e.g. Cassini, Cluster, Double Star) and thus have a TRL of 9. Combined ion and electron sensors have also been flown recently on the THEMIS spacecraft. Other new elements include the active variable geometric factor system, and these are already in development for Solar Orbiter and Bepi Columbo. Thus the overall TRL for the Dual Head Plasma Spectrometer is estimated to be 5-6. The critical issue for this instrument concerns the minimisation of the spacecraft charging and the emission of spacecraft photo-electrons, particularly near the instrument apertures.

4.2.3 Energetic Particle Package

4.2.3.1 Description of the measurement technique, Instrument conceptual design and key characteristics

These measurements should be provided on all three spacecraft by an ion implanted silicon based solid state detector of a simple pin hole design, similar to the Imaging Electron Spectrometers employed on Cluster and Polar. Incident energetic particles generate electron-hole pairs that produce a signal pulse proportional to the energy of the incident particle. A pulse height distribution is then collected corresponding to the energy spectrum of the energetic particles. Each sensor consists of three detector modules providing an azimuthal slice (20° x 180° field of view), similar to the plasma spectrometers. Thus a 3D distribution will be built up over the course of a spacecraft spin. The detector will have an energy resolution of 30-40%. Angular resolution depends on the instrument electronics however typical resolutions are of order 10 x 10 degrees.

4.2.3.2 Performance assessment with respect to science objectives

The supra-thermal component of particle distributions is a ubiquitous feature of non-equilibrium, collisionless plasmas including those observed in the near-Earth environment. These populations are most readily described in terms of a kappa function representing a combination of a thermal Maxwellian distribution and a power-law tail. The non-thermal population and rapid field-aligned transport provide the unique capability to remotely sample the acceleration processes and mechanisms taking place within boundaries, and particlularly regions of magnetic reconnection. Within the near-Earth plasma environment the non-thermal tail of the distribution is most commonly observed from a few tens of keV and above. The Energetic Particle Package on IMPALAS should thus measure the full 3D ion and electron particle distributions in the energy range from ~20 to 1000 keV, with a temporal cadence of once per spin (i.e. ~6 sec).

4.2.3.3 Resources: mass, volume, power and telemetry

Based on the similar instrument described in the Cross-Scale ASR (2009), we base-line a mass and power envelope of 2 kg and 2 W respectively for this instrument. A full 3D distribution consisting of 16 azimuthal angles, 9 polar angles, and 10 energies for both ions and electrons, and returned as 16 bit words at a cadence of once per spin (~6 s) implies an uncompressed telemetry rate for this instrument of ~7.5 kbps. Assuming a conservative compression rate of 4, and allowing for house-keeping, we baseline a telemetry rate of 2 kbps for this instrument.

4.2.3.4 Pointing and alignment requirements

The instrument will need to be mounted on the spacecraft such that the detector fan is perpendicular to the spacecraft body, with the centre of the fan perpendicular to the spacecraft spin axis. The FoV should be clear of any spacecraft appendages.

4.2.3.5 Calibration and other specific requirements

A spin-stabilised spacecraft will be required to collect a 3D distribution. Both ground and inflight calibration will be necessary.

4.2.3.6 Current heritage, TRL and Critical issues

Detectors of a similar design have been flown on Polar, Cluster, THEMIS and Demeter, thus the Energetic particle instrument has a TRL of 9.

4.2.4 Auroral Imager

4.2.4.1 Description of the measurement technique, Instrument conceptual design and key characteristics

Auroral images will be provided by a FUV camera operating in the wavelength range 140-180nm (i.e. the molecular N2 Lyman-

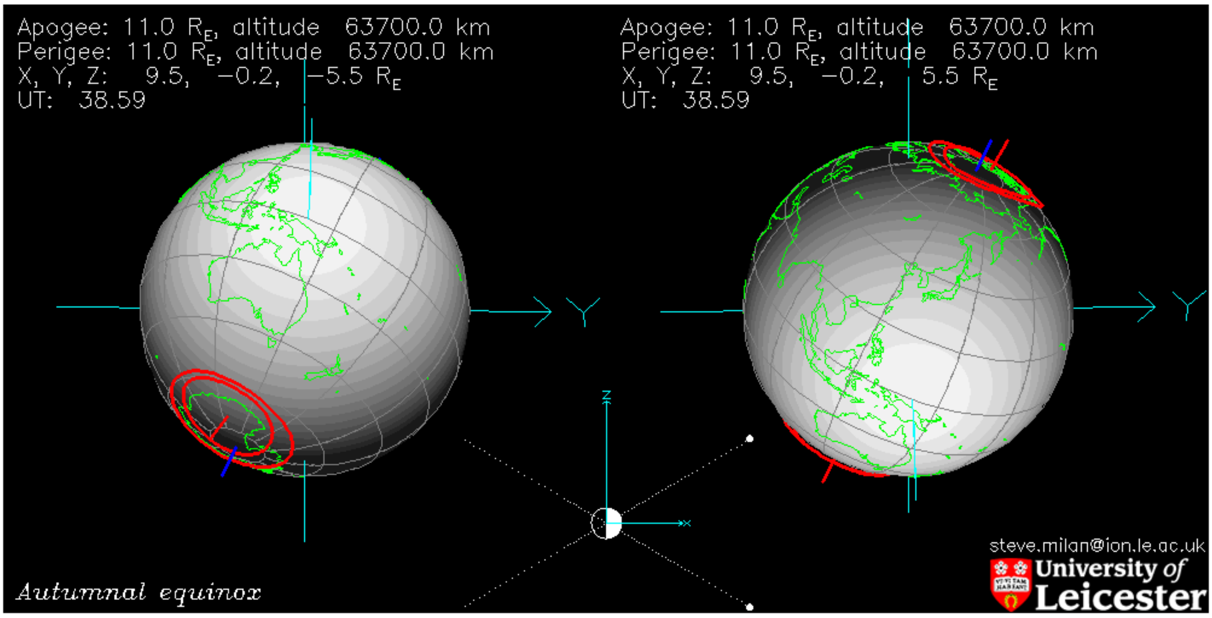

Figure 4.1. A snapshot from a simulation of the view of the dayside auroral oval (contained nominally within the red rings) obtained from the IMPALAS 2 and 3 spacecraft in inclined orbits. The simulation shows that the foot point of the field lines threading the 3 spacecraft would be visible in both northern and southern hemisphere.

Birge-Hopfield emissions). The camera will not have any spectral capabilities within this wavelength range. UV is necessary in order to capture images of the dayside auroral oval. A concept instrument has been previously studied for use in lower orbits for the Kua Fu flight opportunity and a similar concept is base-lined here. The instrument would consist of a radially-slumped square-pore MCP focussing optical system, giving a field of view of 22.5°x 90°, and a slumped MCP detector. Image acquisition is accomplished using a photon counting system, whereby the detector records the arrival time of each photon. Thus with knowledge of the spacecraft attitude as a function of time an image in an appropriate geophysical coordinate system can be constructed. The camera will be installed on the two non-equatorial IMPALAS spacecraft, I2 and I3 only, providing images of the northern and southern dayside auroral zones concurrently.

4.2.4.2 Performance assessment with respect to science objectives

Auroral imagery is necessary to provide context for the *in situ* measurements from the rest of the payload. The images will essentially provide a further measurement at the footpoints of the magnetic field lines sampled by the spacecraft. The angular resolution of the baselined instrument is 6 arcminutes (FWHM), providing a spatial resolution of 110 km for I2 and I3 at their perigee. The imager assembles the image by integrating photon counts over time, and it is anticipated that an effective integration time of 30 seconds will be compatible with the IMPALAS science requirements. However, time resolution as short as the spacecraft spin period is in principle possible if data storage and telemetry allow. A snapshot from a simulation of the view of the auroral ovals from the I2 and I3 spacecraft is shown in Figure 4.1 (courtesy S. Milan, University of Leicester).

4.2.4.3 Resources: mass, volume, power and telemetry

The camera and associated electronics weigh 5kg and consume 15W in the configuration defined for Kua Fu. An optimisation study to identify the optical arrangement which produces the most useful image characteristics should be a high priority for work during the assessment phase. However, for the present application, in which the field of view of the instrument can be considerably reduced (potentially to use a single detector MCP, rather than the

4 base-lined for Kua Fu), it is likely that there is scope to reduce these numbers by as much as 50%. Given the current resolution of the base-lined instrument, the Earth could be viewed in its entirety with an image size of 128x128 pixels. Using an 8 bit pixel depth implies each image size is 128 kbits. At a cadence for image production of 30 seconds, assuming a conservative image compression ratio of 4 and allowing for the telemetry of image metadata and housekeeping, we estimate that the telemetry requirement for this instrument is of order 1.5 kbits/second.

4.2.4.4 Pointing and alignment requirements

The instrument should be mounted on the spacecraft body with the centre of the field of view pointing perpendicular to the spacecraft spin axis (assuming the latter points approximately perpendicular to the ecliptic plane). This ensures that the Earth (and thus the auroral zones) passes through the ±45º field of view every spacecraft spin at all phases of the orbit.

4.2.4.5 Calibration and other specific requirements

In order to perform aspect reconstruction of photon event data to create an image of the auroral emission, millisecond-resolution time tagging of photon events will be required. In addition, the relationship between the pointing directions of the instrument and attitude sensor (e.g. star tracker) must be established before launch to an accuracy of ~1 arcminute for these purposes.

4.2.4.6 Current heritage, TRL and Critical issues

Uniquely among the instruments proposed here for the IMPALAS mission, several elements of the Auroral Imager technology has not previously been flown in space. A study of a similar concept mission has been carried out at the University of Leicester as part of the work for the Kua Fu mission opportunity. Hence the overall TRL for this instrument is ~4. However, elevating the TRL is a matter of developing only one or two subsystems within the instrument. In addition, the Kua Fu study was predicated on imaging the auroral oval from a perigee at 1.8 R_E and used 4 optical elements in a 2x2 arrangement. For the purposes of this proposal, we have base-lined an imager in the 1 x 4 configuration, which is expected to have the same mass, volume and power envelops as the Kua Fu arrangement, but will image the Earth from an inclined orbit of 30 degrees at apogee of 11 R_E. Nevertheless, a detailed trade study of this instrument for the IMPALAS mission configuration would need to be undertaken in the assessment phase in order to confirm its suitability.

4.2.5 Common Payload Processor (CPP)

4.2.5.1 Description conceptual design and key characteristics

A common processor will be employed to handle data processing for the entire payload, reducing overall required resources. It will be required to provide instrument functionality control and have the necessary memory and computational resources to receive and decode commands from the spacecraft; provide a buffer for onboard data handling; format, perform lossless compression and transmit instrument science and housekeeping data at a rate depending on spacecraft telemetry mode. It is anticipated that the common payload processor will be based on a Field Programmable Gate Array (FPGA) based processor, such as the Leon 3 Fault Tolerant derived processor, and will be able to provide instrument operations, control and perform loss-less data compression. Connectivity to the instruments will be provided by a SpaceWire system.

4.2.5.2 Performance assessment with respect to science objectives

The CPP provides DPU services to all instruments. It will provide all commanding and data buffering and handling functions for all the instruments, including data compression and/or other data reduction activities (for example the generation of 2D pitch angle distributions from the particle instruments if required). It will provide power distribution to the instruments and monitor their health and status to protect them from damage.

4.2.5.3 Resources: mass, volume, power and telemetry

Based on the Cross-Scale ASR, we allocate a mass budget of 5 kg and a power budget of 12 W for the CPP. This payload element generates no scientific data, but we baseline 1 kbps of telemetry for housekeeping purposes.

4.2.5.4 Current heritage, TR) and Critical issues

There is significant heritage in DPU design for space missions within Europe. Designs for processor services for multiple instruments are being developed for Bepi-Colombo and Solar Orbiter. Nevertheless, a bespoke design will probably be required for the IMPALAS application. A hot/cold redundant design will be needed since the CPP represents a single point of failure for the whole payload. Thus TRL for this payload element is assessed to be ≥ 5.

4.3 Summary of Highly Desirable Instruments Key Resources and Characteristics

Although all the science objectives of IMPALAS can be accomplished with the core payload described above, the following instruments will enhance the mission's capabilities and provide added value and further science return.

4.3.1 2D Electric Field Instrument

4.3.1.1 Description of the measurement technique, Instrument conceptual design and key characteristics

By measuring the potential difference between two spherical probes at the end of two wire booms, extending radially from the spacecraft in opposite directions, one can measure a single vector component of the electric field local to the spacecraft. Additional probe pairs mounted orthogonally to the first can be employed to measure additional vector components. The science drivers for the IMPALAS electric field instrument only require a 2D electric field instrument, measuring the electric field components in the spin plane of the spacecraft, which avoids the need for costly and technically challenging spin axis booms. Using the same technique, measuring the potential difference between one or more of the end of boom probes and the spacecraft body provides an estimate of the spacecraft potential, which is a highly advantageous parameter in accurately reconstructing the true velocity distribution of charged particles (particularly electrons) which may have been modified by the acceleration of particles as they pass through the potential gradient between the spacecraft and the ambient plasma. Both AC and DC electric fields can be measured, DC fields up to a cadence of a few tens of Hz at a resolution of 0.1mV/m.

4.3.1.2 Performance assessment with respect to science objectives

The double probe instrument will provide local electric field measurements and act as a monitor the spacecraft potential. This is a useful proxy for the background plasma density, but also provides information by which to correct particle distributions that have been affected by spacecraft charging effects. The instrument is capable of sampling the DC electric field at 100 samples per second, but this can be reduced or averaged to provide electric field vectors at the lower cadences required for the IMPALAS application.

4.3.1.3 Resources: mass, volume, powe, and telemetry

The instrument will consist of 4 wire boom units each of which have an undeployed volume of 20x15x30 cm and mass of 7.5 kg. Total power requirements for the instrument are ~2.5 W. Electric field telemetry requirements for the mission would be comparable to those for the magnetometer.

4.3.1.4 Calibration and other specific requirements

The length of each wire boom pair should be as long as possible to minimise the effect of the spacecraft potential on the electric field measurements. We propose a pair of wire booms which each have a length of 100m for consideration in the augmented payload, should resources allow. In order to obtain as close to a uniform spacecraft potential as possible the spacecraft surface should be conductive.

4.3.1.5 Current heritage, TRL and Critical issues

Similar instruments have flown on THEMIS, Cluster, Polar, Fast and numerous other spacecraft and as such the 2D electric field instrument has a TRL of 9. Deployment of the booms during the commissioning phase is a critical issue.

4.3.2 Ion Composition Analyser

4.3.2.1 Description of the measurement technique, Instrument conceptual design and key characteristics

Should resources allow, an ion mass spectrometer instrument would be a significant augmentation to the payload. Indeed, at the minimum level, we suggest that it could be designed to use a common interface slot to the auroral imager, and then readily deployed in that slot on I1. This spacecraft does not need to carry the imager as it is not in an appropriate orbit for viewing the auroral zones. This single spacecraft augmentation would therefore not impact heavily on the desirable common design for each payload bus.

A popular method of mass discrimination is with an electrostatic analyser combined with a time of flight system. After the incoming ions have been energy/charge selected by the electrostatic analyser, they pass through a thin carbon foil which generates a start signal when the resultant electron is detected by a dedicated MCP. The detection of the ion itself by a different MCP provides the stop signal, giving the E/q of the ion. The velocity of the ion through the time of flight system (as determined from the known geometry and the difference between the start and stop times) allows the ion m/q to be calculated. In this manner H^+, He^+, He^{++} and O^+ can be distinguished.

4.3.2.2 Performance assessment with respect to science objectives

Mass discrimination capability, even on one spacecraft in the fleet, would provide significantly better context for the interpretation of all the other measurements. This is because the various physical processes which are the target for the IMPALAS mission on the magnetopause (e.g. magnetic reconnection, boundary wave formation) are known to be mediated by the presence of heavier ions in the system. These may arise, for example, from heavy ion outflow from the dayside auroral zone, and may then populate the regions of space immediately around the magnetopause.

4.3.2.3 Resources: mass, volume, power and telemetry

The ion composition analyser would require a volume of 20x30x20 cm, have a mass of 3.5 kg per sensor and an average power consumption of 3.5 W. A single spin 3D distribution for each of the four ion species measured over 32 energies with angular resolution of 22.5 deg x 22.5 deg, occupies 128 kb of memory. Telemetering this data product after compressing by a factor 4 produces a data rate for the instrument of ~6kbps, allowing for housekeeping.

4.3.2.4 Pointing and alignment requirements

As for the other particle instruments, the composition analyser requires a spin-stabilised spacecraft to sample the full 4π steradians field of view. It should be mounted such that the viewing fan points perpendicular to the spin axis.

Required Instruments		Mass	Power	Telemetry rate	Volume	Source / Reference
Magnetometer		1.5 kg	0.5 W	1 kbps	11x5x5 cm^3	Cluster, Cassini
Ion & Electron Spectrometers (x2)		6 kg	6 W	24 kbps (ions) 24 kbps (electrons)	26x15x26 cm^3	NASA MMS / Cross Scale ASR/ Solar Orbiter SWA/EAS
Energetic Particle Detector		2 kg	2 W	2 kbps (ions and electrons)	20x10x20 cm^3	Cross Scale ASR
Auroral Zone Imager [1]		5 kg	15 W	1.5 kbps	10x20x15 cm^3	Kua Fu Study
Common Payload Processor		5 kg	12 W	1 kbps (HK)	20x12x10 cm^3	Themis CPP (supporting 5 instruments)
TOTAL	I2, I3	19.5 kg	35.3 W	54.5 kbps		
	I1	14.5 kg	20.3 W	53 kbps		
Desirable Instruments						
Electric field booms		7.5 kg	2.5 W	1 kbps	20x15x30 cm^3	Cross Scale ASR
Ion Mass Spectrometer [2]		3.5 kg	6 W	6 kbps	20x30x20 cm^3	Cross Scale ASR

Table 4.1: IMPALAS Strawman payload resource envelopes.
[1] Auroral Imager to be flown on I2 and I3 only;
[2] Ion Mass Spectrometer could be flown in Auroral Imager slot on I1 only?

4.3.2.5 Calibration and other specific requirements

Similarly to the plasma spectrometer, the ion composition analyser would require an unobstructed field of view on a spin-stabilised spacecraft. Both ground and in-flight calibration would be required.

4.3.2.6 Current heritage, TRL and Critical issues

Similar instruments have flown on Cluster and STEREO, so the ion composition analyser could be considered to have a TRL of 9.

4.4 Payload Summary

The IMPALAS science payload largely uses proven technology. With the exception of the Auroral Imager, the TRL of the individual instruments is already high, with most critical subsystems already flown in space. A summary of the payload resources is provided in Table 4.1.

5 System Requirements and Spacecraft Key Issues

The 3 IMPALAS spacecraft should be identical in design. As a minimum, they should house the core payload packages described in the previous section, although I1, the spacecraft bound for the in-ecliptic orbit need not carry the Auroral Imager due to the poor viewing angle from this orbit. Consideration could be given to instead housing the highly-desirable ion composition analyser on this spacecraft, assuming a common interface slot can be designed for the 2 instruments to avoid non-identical bus design costs. If resources allow the other highly desirable instruments should also be included in the payload.

The IMPALAS spacecraft should be spin-stabilized, similar to the Cluster satellites. We envision the architecture of the spacecraft will resemble a miniaturised Cluster bus, being cylindrical in design. (We note that the core IMPALAS payload is considerably smaller in both number and size of sensors than that of the Cluster mission). Solar panels will be mounted around the curved surfaces of the body to provide power, and the external dimensions of the cylinder will be driven, at least in part, by the need to provide sufficient power to the payload and spacecraft systems. The payload will be mounted on an observation deck at one end of the cylinder in a manner that satisfies the FoV's of the particle sensors. The magnetometer will be mounted on a boom which will be deployed from the observation deck.

The IMPALAS satellite bus should provide command and data handling, telecommunications, attitude control, power systems, thermal control and propulsion. Star-trackers and other attitude control sensors can also be mounted to the observation deck. Other spacecraft systems will be accommodated within the body of the cylinder, as should the fuel tanks and propulsion modules. The heat dissipated in the spacecraft systems and accumulated through the radiation from the Sun can be removed from the spacecraft by a heat pump and radiator system. Critical components of both the payload and spacecraft subsystems may need to be covered by thermal protection material.

We anticipate that all the required system and service components of the spacecraft bus have heritage from previous successful space missions and can be used with only minor modifications. Hence we believe that the TRL of the component comprising the IMPALAS spacecraft bus would range from 7 to 9. However, a proper accommodation study will be required to determine how the 3 spacecraft should be packed to fit within the fairing of the Soyuz Fregat 2B launcher.

The total dry mass of each spacecraft, including the scientific payload, but excluding the propulsion system necessary to achieve orbit insertion is estimated to be 200.4 kg, including a 30% ESA margin. The estimated mass distribution is shown in Table 5.1. This estimate is based mainly on information contained within the Cross Scale Assessment Study Report, which considered a number of similar instruments, but more numerous in number than the present application. However, we consider

System	Subsystem	Mass (kg)	Power (W)	Source
Spacecraft Bus	Structure	41.8	116.8	Cross Scale ASR, Solution 2
	Thermal Control	4.6	0.0	
	Mechanism	6.6	22.2	
	Communication	11.7		
	Data Handling	6.6		
	AOCS	3.6	4.3	
	Propulsion	11.5	5.5	
	Power	38.3	16.8	
	Harness	6.0	0.0	
	RF system	4.0	68	
Science Payload	Instruments	19.5	35.3	Section 4, Table 4.1
Subtotal		154.20	268.90	
ESA Margin	30%	46.2	80.7	
TOTAL		200.4 kg	349.6 W	

Table 5.1: Mass and Power requirements for the IMPALAS spacecraft bus, without fuel and engine subsystems

that the Cross-Scale bus subsystems will be more than sufficient for the IMPALAS mission and thus provide a conservative estimate of required resources for the latter.

5.1 Attitude and orbit control

Monitoring the spin axis orientation and spin phase of the spacecraft requires deployment of a star tracker and sun sensor on each spacecraft. These are required to time attitude control thruster firings and for the operation of instruments. The spin axis must be maintained at the correct attitude for science operations. The pointing know-ledge and the accuracy of the spin rate are of 0.1 deg and 1%, respectively. The spacecraft attitude control is achieved using cold gas thrusters. Radial 1-N thrusters can be located at the edge of top and bottom surfaces of the cylindrical spacecraft to optimise their capability. In addition, thrusters directed along the spin-axis are required to provide Δv for out-of-plane manoeuvres.

5.2 On-board data handling and telemetry

The two major tasks of the IMPALAS Data Handling System (IDHS) are to control the spacecraft subsystems and to provide storage of science data.

The IMPALAS scientific model payload consists of 5 core sensors with options to include 2 highly desirable instruments. We propose that onboard data handling occurs within the CPP system. In addition to the main data processing and compression functions, the CPP schedules the scientific operations and controls the flow of science data to the spacecraft IDHS. We propose that all data exchange and instrument commanding be done via spacewire links from the IDHS to the CPP. This approach will afford a decrease in the overall payload mass and readily allow communication between different instruments.

The IDHS should contain sufficient mass memory to store 2 entire orbits (4 days) of data. Given the data production rate of the combined core payload (152 kbps) and allowing 2 kbps per spacecraft in housekeeping, this amounts to ~ 50 Gbits.

5.3 Mission operations concept

The 3 IMPALAS spacecraft operate in orbits that are phased such that the spacecraft at the same local time at all times. From the ground, they may be separated by up to 60 degrees on the sky. However, twice per orbit (i.e. once per day) the spacecraft will appear, from the ground, to be very close together, when their phased orbits cross the ecliptic plane (the plane of the I1 orbit). Thus a single ground link could be used for all 3 satellites at the same time and hence all 3 satellites could share that communications link. In order to establish feasibility, we assessed the visibility of the 3 spacecraft from the Kourou ground station (5.3°N, 52.8°W) for ±5 days either side of spring equinox, assuming that the constellation reaches maximum separation at 12 MLT over Scandinavia on that day. The 3 panels of Figure 5.1 show (black/red trace) the angle from the zenith and (blue/light blue trace) the distance to each of the 3 spacecraft from the ground station. Periods in which the spacecraft are above 15 degrees from the horizon are designated with the red and light blue line sections. This shows the communications link to Kourou for the IMPALAS satellites could be available for ~40% of the orbit, or in continuous periods of ~ 19 hours per 2 day orbit. During these periods, the 3 spacecraft range from 9.0 – 10.5 R_E from the ground station.

The downlink requirement for the mission (3 satellites) is ~12.5 Gbits of data per day. Communications will be direct to ground stations using an X-band system such as that base-lined for GAIA. This provides variable data-rates up to ~6.5 Mbps. Hence transmission of scientific data from the mission takes a combined ~1.2 hrs per day.

These simple calculations demonstrate that it is entirely feasible to return the full IMPALAS dataset to a single ground station

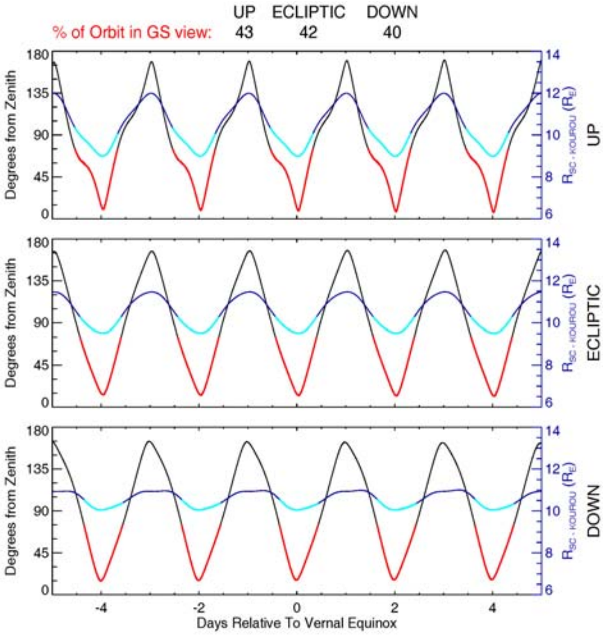

Figure 5.1: Coverage of the IMPALAS orbit with the Kourou ground station for a period of 10 days around spring equinox. Analysis shows there are ~19 hours per 48 hour orbit available for download (corresponding to red sections of plot when spacecraft are > 15 deg above the horizon) when the spacecraft range from 9.0 – 10.5 R_E from the ground station.

at this rate, using less than 10% of the available communications window for each spacecraft. However, the final choice of ESA ground stations to be used should be made during the assessment phase.

5.4 Estimated overall resources

The overall mass (see Table 3.1) is estimated as 2400 kg (for launch into an initial GTO orbit) or 1770 kg (for launch into an initial GSO orbit) and includes the 3 satellites, as well as the fuel for injection into the required orbit and changing the inclinations. This also includes 30% margins for the bus and payload (see Table 5.1). The dimensions of the IMPALAS spacecraft will need to be chosen to comply with the fairing of the Soyuz Fregat 2B when the 3 spacecraft are stacked on top of each other inside the fairing. The power requirement for each spacecraft is of order 350 W, including 30% margin, for the bus and payload subsystems (Table 5.1). The entire IMPALAS constellation downlinks daily about 1.7 Gbits of scientific data (Table 4.1 + 20% margin), which is realistic using the X-band antennas at ESA ground stations.

5.5 Specific environmental constraints

The spacecraft must be magnetically clean. This means that intrinsically magnetic as well as magnetically soft materials should not be used in its construction or within the payload components. A program to document the magnetic activity on the spacecraft should be carried out prior to launch and steps taken to reduce residual magnetic fields of spacecraft origin at the position of the magnetometer on the boom. The outer surface of the spacecraft must also be electrically conducting to avoid differential surface charging and to provide electrically clean environment for low-energy electron and ion measurements (and electric field measurements if flown). Instruments containing MCP's (ion and electron spectrometers, auroral imager) require a vacuum in which to operate. These instruments must be maintained under constant dry nitrogen purge until launch. Before power-up of the instruments on-orbit, a period of time will be required to allow evacuation of gas from the instrument volume (via specific out-gassing apertures in the structure in the case of the auroral imager). No instrument should be placed in the path of gas venting from another.

5.6 Current heritage and TRL

With the exception of the auroral imager, all instruments baselined in this proposal have significant heritage within Europe and high (> 5) TRLs. Most instruments have flown in a relevant configuration on previous ESA missions. The auroral imager proposed here has not previously flown, and would need to be the subject of a specific feasibility and trade study before being confirmed as part of the payload for I2 and I3. There are no novel requirements on the spacecraft bus beyond those which have become standard for a space plasmas mission. Significant heritage exists within European industry (e.g. through Cluster, MEX/VEX, Bepi-Colombo, Solar Orbiter) to suggest that this area is also at a high level of technical readiness.

5.7 Proposed Procurement Approach

It is anticipated that the payload be procured by standard ESA procedures for national agency funded instruments. The bus will be procured by standard ESA invitations to tender to European industry.

5.8 Critical issues

There are no specific critical issues, although the use of a mechanism for the deployment of the magnetometer boom deployment is recognised as carrying a certain risk. From the technological point of view, the IMPALAS mission is a relatively straightforward space plasmas mission, an area in which ESA and European industry has significant experience. As usual for such missions, there will need to be programs to ensure the spacecraft and payload have sufficient electromagnetic and electrostatic cleanliness.

6 Science Operations and Archiving

6.1 Science Operations Architecture

The European Space Operations Centre (ESOC) will be the Mission Operations Centre (MOC) for the IMPALAS mission and will prepare a ground segment including all facilities, hardware, software, documentation, the respective validation, and trained staff, which are required to conduct the mission operations. The MOC will use operational concepts proven with Solar and Planetary Science missions (Cluster, Rosetta, VEX, MEX, Bepi Colombo) and will adapt them to the IMPALAS mission. All operations will be conducted by ESOC according to procedures in the long- term plan, contained in the Flight Operations Plan.

As with the MOC, the implementation of a Science Operations Centre (SOC) should be based on experience and heritage of the operation of recent space plasma missions, particularly the ESA Cluster mission. The SOC will implement constraints or rules, provided by the instrument PIs and the Science Working Team (SWT), regarding the operation of the spacecraft and instruments, with the aim to make commanding as autonomous as possible. The SOC will have the sole responsibility to provide, via predicted orbit data, time-tagged information for input into the planning files that are the basis for the PI-SOC commanding cycle. This information will include event times of any eclipses, orbit corrections etc. The SWT will provide advice as to scientific priorities and/or policies to be used in the planning files.

6.2 Archive approach and Proprietary data policy

The mission should adopt a modern approach to data access, with the full dataset for each of the IMPALAS instruments being made available to the IMPALAS community, and open to the entire scientific community after a suitable delay (≤ 6 months) to ensure adequate calibration and quality control. We propose that the model developed for the Cluster mission, in which distributed data centres and an Active Archive form the basis of serving mission data products to the community. Planning for these facilities should be included in the mission concept from the outset. We suggest that an opportunity to propose for the mission science data handling network, with the successful proposer offered a lead role, equivalent to that of an instrument PI. This would provide the appropriate resource and schedule for coordination amongst the instrument teams and for the construction of the necessary software, standards, and data facilities.

7 Technology Development Requirements

7.1 Payload readiness, technology challenges and development strategy

Since most of the required payload listed above currently exists in a form that would meet the measurement requirements likely to be imposed by the flow-down from the science goals, there are no significant technical issues likely to arise from the payload. However, the mission could be seen as providing a flight opportunity for next generation instruments, such that some technology development should be accommodated in this area (c.f. Figure 7.1). The Auroral Imager proposed for the mission is a notable exception to the overall level of payload readiness. Although MCPs and filters have TRL = 9, some elements of the MCP readout and optics are currently TRL 4-5. However, elevating the TRL of the instrument to an acceptable level depends on developing only one or two of its subsystems.

7.2 Mission and Spacecraft technology challenges

No novel technologies are necessary for the development of the spacecraft bus or the mission operation. The spacecraft and their required subsystems have high heritage within European industry. The spacecraft will need to undergo a magnetic and electrostatic cleanliness program. In addition, a means of stacking the set of 3 spacecraft within the launcher fairing, together with a mechanism for their dispensing after reaching GTO/GSO orbit, will need to be developed by industry. A proper optimisation of the orbit parameters is required, together with a study of the options for launch and delivery of the spacecraft to their 3 distinct operational orbits from a single launch. Otherwise we believe this mission concept will require standard development for a small satellite measuring fields and plasmas in near-Earth space.

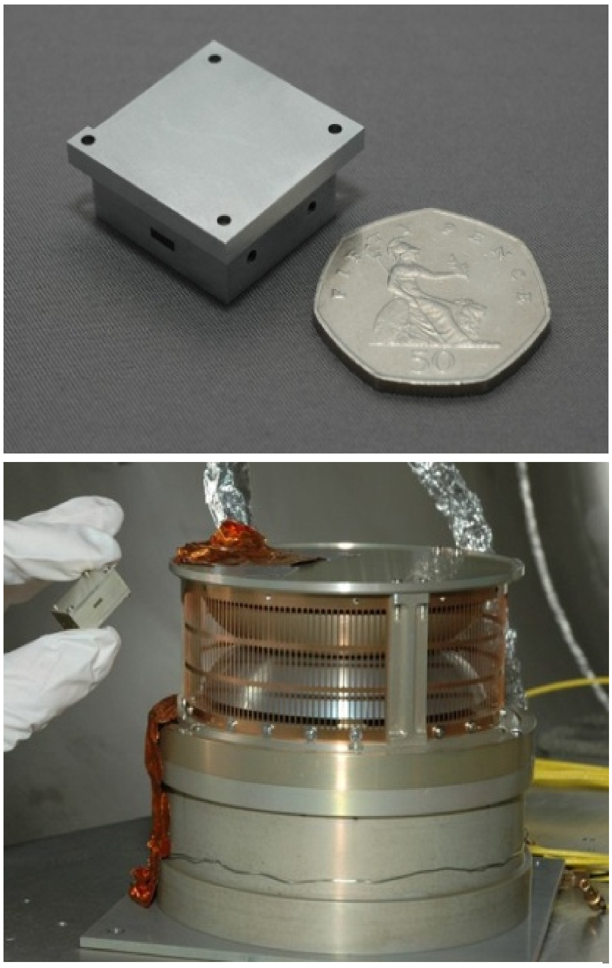

Figure 7.1. Example of the sensor technology advancements that could be employed on the IMPALAS mission to reduce required resources. The photographs show a prototype miniaturised plasma analyser, roughly the size of a coin, in comparison to current state-of-the-art analysers that will be flown, for example, on Solar Orbiter

8 Preliminary Programmatics and Costs

8.1 Overall proposed mission management structure

The IMPALAS mission is a relatively straightforward solar system fields and plasmas mission, of a type that ESA has much experience. The scientific goals centre on targeting the dayside magnetosphere with 3 spacecraft, separated by distances of a few R_E, and carrying a relatively modest payload (c.f.

Cluster and the Cross-Scale ASR, for examples). The usual modus operandi is for these payload elements (instruments and associated processing, data handling and control components) to be provided by member states, using their own funding, as PI-led investigations. We anticipate that IMPALAS will follow this philosophy, although we note that the magnetometer boom should be provided as part of the spacecraft architecture. The straight-forward nature of the mission readily suggests that it could be achieved within ESA/Europe, without recourse to external partnerships. However, there is expertise in the target science area around the world, and particularly in the United States and Japan, so there is opportunity for one or both of NASA or JAXA to become a junior partner on the mission, perhaps providing or contributing to instrumentation hardware through their 'mission of opportunity' programs. However, this is not necessary for mission closure, which, from a heritage point of view, can be achieved with contributions of instruments from European institutes only, and subject only to sufficient funding being made available by national agencies. Moreover, the design of the spacecraft bus and its subsystems is also well within the capabilities of European industry. It is envisioned that the bus can be a slimmed-down version of the spacecraft concept developed for the Cross-Scale mission, which was studied as a candidate for the M1/M2 launch slot, since we wish to deploy only a fraction of that instrumentation for this application. Two competing industrial studies were performed during the Cross-Scale Assessment phase, indicating the abilities and readiness of European industry to deliver the required spacecraft bus.

8.2 Payload/Instrument Cost

8.2.1 Assumed share of payload costs to ESA

It is assumed that the full scientific payload will be provided under the usual model for solar system fields and plasmas investigation, in which the instruments are built in universities and other scientific institutions using funded provided, after peer review, by the ESA member states. It is possible that non-European institutes may also seek to contribute to the provision of the payload, either through contributions to European-led instruments, or through their own PI led contributions. However, it is anticipated that ESA need make no contribution to the payload costs in order to achieve the mission goals. Thus ESA should have overall responsibility for the industrial contracts that provide the overall spacecraft design and build, integration of the payload into the spacecraft and system level testing. Through Arianespace, ESOC and ESAC, ESA should also provide the launch services, the mission operations and the acquisition and distribution of the data to the PI institutes and the Science Data Centre and Archive.

8.2.2 Estimated non-ESA payload costs

The payload costs should all be borne by the national agencies. All instruments, with the exception of the auroral imager, are of high heritage and have flown in similar configurations to those required for the IMPALAS mission. A preliminary estimate of the payload costs, by instrument, is provided in Table 8.1, although it should be noted that this is very much a function of the funding model in the country that ultimately will lead the development of a given sensor.

8.3 Overall mission cost analysis

We do not have access to the detailed tools available to industry and ESA for calculating the overall mission costs. Hence, in order to demonstrate the feasibility of the IMPALAS mission within the ESA M-class cost envelope, we confine ourselves only to make direct comparison to the Cross-Scale assessment study. The Cross-Scale mission report considered a fleet of 7 spacecraft, carrying a total of 107 instruments. In contrast, the IMPALAS mission proposed here consists of 3 spacecraft carrying a total of 17 sensor units. Comparison to Cluster, which flew 72 sensor units on 4 spacecraft, could also be made. Although we recognize that there are one-off costs (launch, initial spacecraft design, ESA study costs) applicable to both missions, we contend that the relative sizes of the proposed IMPALAS mission to the ESA-assessed Cross-Scale mission imply the former will require less than half the recurrent industrial build costs and a small fraction of the operating costs. Since ESA estimated the cost of Cross-Scale to be ~600 M€ in December 2009, we conclude that the IMPALAS mission will easily fit within the 475 M€ cost cap for the M3 opportunity. Beyond this simple analysis, we leave it to ESA to estimate, using its own methodology, the ROM cost of this proposed mission.

8.4 Mission Schedule Drivers, Risks and Alternate Strategies

IMPALAS is a modest and relatively low-risk multi-spacecraft mission based largely on flight-proven spacecraft technology and instrumentation. There are no significant developments required that could significantly impact the schedule once the mission has kicked-off and the instrument design and build phases funded. Nevertheless, for both financial reasons and in consideration of in flight spacecraft failure, it is important to assess the extent to which the science objectives could be addressed with fewer spacecraft. Firstly we note that a single spacecraft mission most likely cannot add significantly to what has been achieved by previous missions. Indeed, given the success of the Cluster mission (4 spacecraft flying in relatively close formation compared to the proposed IMPALAS separations), it is unlikely that a single spacecraft mission will add anything *at all* to current understanding. Failure of a single spacecraft, or a descope to provide a dual spacecraft mission, will provide very useful conjunctions for which a subset of the science goals would be achievable. Primary loss (depending on which spacecraft is lost) will be the ability to make simultaneous dual hemispheric measurements at the magnetopause with the consequent failure to meet the related science goals. Finally, in the unexpected event that ESA wishes to support this mission with greater resource than has been proposed here, providing a 4th spacecraft, identical to I1 and in the same equatorial orbit, but a few hours ahead or behind that spacecraft, will allow the scientific studies described herein to be extended to the second dimension along the magnetopause surface, and thus *increase* the overall scientific return.

Sensor	Develop-ment costs	Per Unit build cost	Number Req'd	Total Cost
Magneto-meter	1.0 M€	0.3 M€	3	1.9 M€
Ion/Electron Dual Sensor		0.5 M€	6	7.0 M€
Energetic Particle Detector	2.5 M€	0.5 M€	3	4.0 M€
Auroral Zone Imager [1]	5.0 M€	1.0 M€	2	7.0 M€
Common Payload Processor	2.0 M€	0.5 M€	3	3.5 M€
Total (Core P/L only)	14.5 M€	8.9 M€ (17 Sensors)		23.4 M€
2D Electric Fields	1.5 M€	0.5 M€	3	3 M€
Ion Mass Analyser	4.5 M€	0.5 M€	1	5 M€
Total (Core + Desirable P/L)	20.5 M€	10.9 M€		31.4 M€

Table 8.1: ROM costs (MEuros) to National Agencies for the development and build of the IMPALAS mission payload

9 Communication and Outreach

9.1 Scientific dissemination

Analysis of IMPALAS data will provide major scientific discoveries in the field of space physics. These results will be presented at major international conferences and published in leading scientific journals, including Nature and Science as well as other dedicated and more topical journals in the field of space physics. The IMPALAS data should be made publicly available through a dedicated IMPALAS science data archive immediately after the raw data has been calibrated. This will both facilitate an enhanced output from the mission itself, and also promote the use of the data with that from the missions of other agencies that may be operational in the same timeframe (e.g. NASA's MMS mission which will be looking at the microphysical plasma processes operating in the Earth magnetosphere, including the magnetopause, and the JAXA SCOPE mission, which, if approved will be examining at some level the coupling of plasma processes across the natural scales of the system). A particular effort will be made to distribute the knowledge gained from IMPALAS to a wider scientific base, for example by including members of the planetary and astronomy communities in specially convened workshop activities.

9.2 Digital dissemination

We will actively develop the mission website (available in rudimentary form at http://www.mssl.ucl.ac.uk/www_plasma/missions/IMPALAS), following selection for the assessment phase, to include both scientific content and popular pages. A scientific data archive site will be established to provide data, publications, and presentations to other scientists. The popular pages will present and distribute material, based on IMPALAS results, in a form suitable for a general audience.

9.3 Education of students

The IMPALAS mission will offer potential opportunities to both undergraduate and graduate students to be involved, from the early definition stages through to the analysis of the data once the mission is operational. The mission goals can provide a focus and a context for their formal education in topics such as electromagnetism and plasma physics. More advanced students can use the mission as a basis for understanding instrument capabilities, mission planning and execution. For example, the M.Sc. Space Science and Technology students at University College London each year undertake a project to work on a definition study for a prospective space mission such as IMPALAS. Finally the science questions which can be addressed with this mission are sufficiently numerous that it can be confidently expected that the mission will support many tens of PhD's during its lifetime – from technical studies of the instruments, their calibration exercises, development of data handling and analysis techniques through to the scientific analysis and interpretation of the data.

9.4 Outreach to the General Public

The nature of the Sun-Earth connection, its relationship to 'space weather' and the potential effects on everyday life are topics that can easily catch public attention. Members of the space plasma community associated with IMPALAS regularly engage with school children of all ages and engage with more general audiences through open days, public lectures, seminars, web pages and articles in the popular press. We anticipate that this will continue and be enhanced through the use of IMPALAS data which we will present in an easily understandable format through the use of animations and interactive presentations. We will work with teachers and trainee teachers to develop IMPALAS-related teaching materials suitable for a number of age groups. This material will be available through the mission website.

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11 List of Acronyms

AOCS	Attitude and Orbit Control System
ASR	Assessment Study Report
bps	bits per second
CME	Coronal Mass Ejection
CPP	Common Payload Processor
CUTLASS	Co-operative UK Twin Auroral Sounding System
DPU	Digital Processing Unit
EISCAT	European Incoherent SCATter
ESA	Electrostatic Analyser
ESA	European Space Agency
ESAC	European Space Astronomy Centre
ESOC	European Space Operations Centre
FPGA	Field Programmable Gate Array
FTE	Flux Transfer Event
FLR	Field Line Resonance
FoV	Field of View
FUV	Far UltraViolet
FWHM	Full Width Half Maximum
GSO	Geostationary Satellite Orbit
GTO	Geostationary Transfer Orbit
HFA	Hot Flow Anomaly
HK	House Keeping
HLBL	High Latitude Boundary Layer
IMAGE	International Monitor for Auroral Geomagnetic Effects
IMF	Interplanetary Magnetic Field
IMPALAS	Investigation of MagnetoPause Activity using Longitudinally Aligned Satellites
ISEE-1,-2	International Sun-Earth Explorer -1 and -2
ISOC	IMPALAS Science Operations Centre
JAXA	Japan Aerospace Exploration Agency
KH	Kelvin Helmholtz
LEO	Low Earth Orbit
LLBL	Low Latitude Boundary Layer
MCP	Micro-Channel Plate
MEMS	Micro-Electro-Mechanical Systems
MEX	Mars Express
MP	Magnetopause
MMS	Magnetospheric Multi-Scale
MOC	Mission Operations Centre
MSSL	Mullard Space Science Laboratory
NASA	National Aeronautics and Space Administration
PDL	Plasma Depletion Layer
PI	Principal Investigator
ROM	Rough Order of Magnitude
SCOPE	cross Scale COupling in Plasma universE
SOC	Science Operations Centre
SPE	Solar Particle Event
SuperDARN	Super Dual Auroral Radar Network
SWA/EAS	Solar Wind Analyser / Electron Analyser System
SWT	Science Working Team
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TRL	Technology Readiness Level
VEX	Venus Express