PROSPERO

PRObing the Structure of Plasma Energisation RegiOns

Science theme: Exploring the space-time plasma Universe

Phase-1 proposal

In response to the “Call for a Fast mission opportunity in ESA's Science Programme for a launch in the 2026-2028 timeframe (F1)”

Lead Proposer

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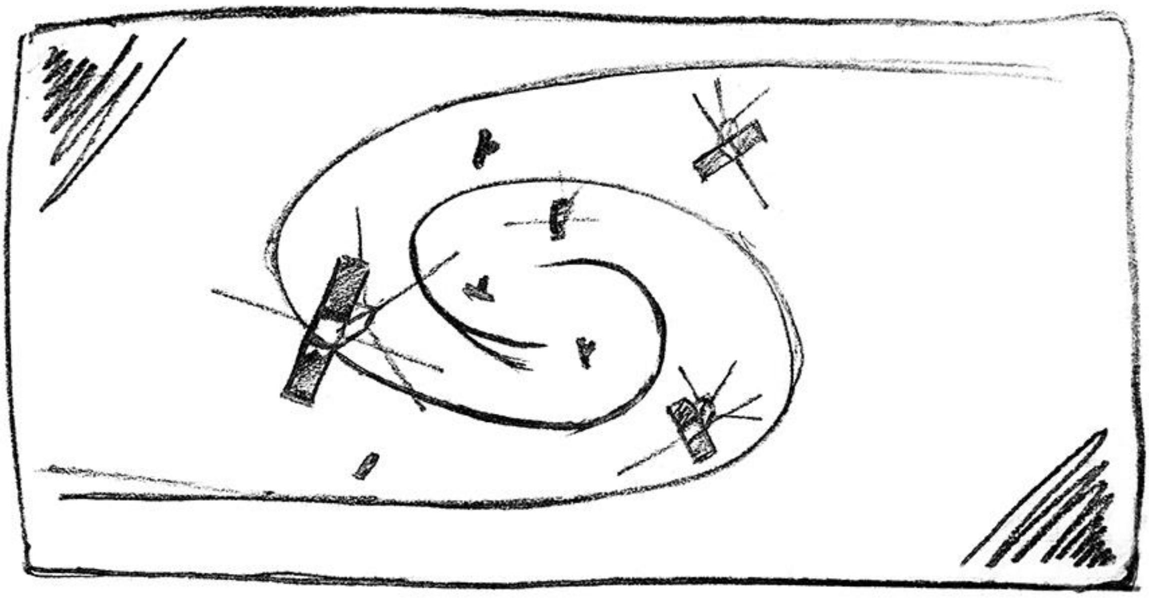

Prospero is a magician in Shakespeare's play “The tempest”, to whom the spirit Ariel is bound to serve.

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The full Science Team is currently composed by about 150 scientists from Austria, Belgium, Canada, Chile, China, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Israel, Italy, Japan, Latvia, Netherlands Norway, Poland, Romania, Russia, Spain, Sweden, Ukraine, United Kingdom, USA

PROSPERO will answer the science question *"How do energy conversion sites at large-scale plasma boundaries evolve in space and time?"*, by probing the Earth's bow shock and magnetopause, our closest accessible astrophysical plasma boundaries. Energy conversion sites are important sources of accelerated particles and radiation. Going beyond the limitations of previous 4-spacecraft missions, PROSPERO will assess for the first time the spatial and temporal evolutions of complex 3D and nonstationary energy conversion sites, by making measurements of fields and particles through a fleet of 8 identical daughter spacecraft controlled by one mother spacecraft.

1. Science case

Science theme. Baryonic matter in the Universe is almost exclusively in a plasma state, where the motion of ions and electrons is governed by their interaction with electromagnetic fields. The complex interaction between fields and particles enables the conversion among electromagnetic, kinetic, thermal and non-thermal energies. This conversion occurs in a variety of sites, typically at the boundaries of plasma regimes, resulting in the rich dynamics that is common to all plasma systems. Understanding energy conversion at local astrophysical boundaries will enable us to understand how these universal physical processes produce energetic particles and radiation, which are the major way to study distant astrophysical objects. As such, the physics of energy conversion is a key target of scientific endeavours.

Scientific goals. Energy conversion in astrophysical plasmas typically occurs at large-scale boundaries between different plasma regimes, e.g., planetary, interplanetary, termination and astrophysical shocks, planetary magnetopauses, flux tube boundaries in the solar corona, interaction regions between streams in solar and stellar winds, the heliopause and accretion disks. Existing observations along with supercomputer simulations suggest that energy conversion sites within these boundaries have complex 3D structure, which evolves in time and over a broad range of plasma scales (electron, ion and fluid). Understanding energy conversion therein requires the knowledge of the spatio-temporal evolution of these boundaries. A fundamental yet unanswered question is: ***"How do energy conversion sites at large-scale plasma boundaries evolve in space and time?"***

Two major types of energy conversion boundaries exist: shocks and shear boundaries. PROSPERO will probe the bow shock and the magnetopause - key science regions for the mission - as universal examples of collisionless shocks and shear boundaries. The key scientific goals of the PROSPERO mission are:

Scientific Goal SG1: ***To characterise the spatial and temporal evolution of collisionless shocks by probing the Earth's bow-shock.***

Scientific Goal SG2: ***To characterise the spatial and temporal evolution of shear boundaries by probing the Earth's magnetopause.***

Understanding the physics of shocks and shear boundaries is an essential contribution to ESA Cosmic Vision, by addressing the question "How does the Solar System work?"

Near-Earth space. To explore the space-time evolution of energy conversion sites, in-situ observations at multiple points in space over prolonged times are required. Although plasma boundaries are ubiquitous in the Universe, not all are equally accessible. As laboratory plasmas are severely restricted in terms of scales, the closest accessible system to perform the required measurements is near-Earth space.

Multi-point measurements. Formation-flying four-spacecraft (4 s/c) missions (ESA's Cluster and NASA's MMS missions) improved our understanding of the size, orientation and local motion of a variety of different space plasma structures at different scales. However, results from these missions are limited by the assumptions that measurements vary linearly between the s/c, and that any observed structures are locally planar and moving with constant velocity. The observations themselves show that these assumptions are not fulfilled most of the time. In order to disentangle the complex structure and temporal evolution of plasma structures at key astrophysical plasma boundaries, significantly more observation points are required: linear gradients and planar structures moving at constant speed can be characterised by 4 s/c; one additional s/c in each dimension adds the capability to explore evolution along this dimension; one more s/c adds full redundancy, yielding 8 s/c carrying instrumentation- that's PROSPERO.

Scientific Goal SG1: To characterise the spatial and temporal evolution of collisionless shocks by probing the Earth's bow-shock.

The Earth's bow shock is the most accessible example of an astrophysical shock. State-of-the-art simulations and in situ observations indicate that the bow shock is very complex and non-stationary. The interplanetary magnetic field (IMF) controls this non-stationarity, in particular the fraction of particles being reflected (Caprioli+, ApJL, 2015), driving waves upstream. When the IMF is aligned with the shock normal (quasi-parallel shock), this non-stationarity is enhanced, resulting in a patchwork of foreshock structures, downstream jets, and interwoven current sheets where major energy conversion and particle energisation occurs, seeding the Diffusive Shock Acceleration (DSA, Caprioli & Spitkovsky, ApJ, 2014).

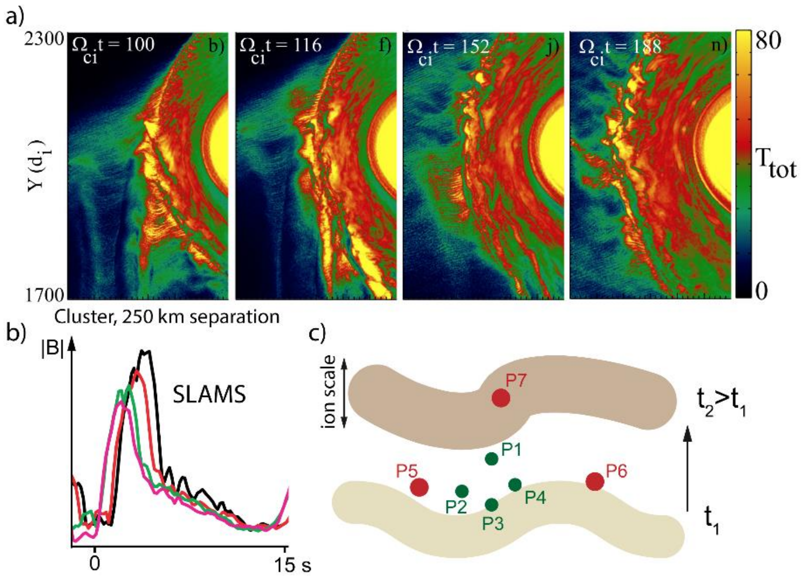


Figure 1. a) Supercomputer simulations of the interaction of SLAMS with the quasi-parallel shock in near-Earth space. (Karimabadi+, Phys. Plasmas, 2014), b) SLAMS seen in Cluster data (Lucek+ JGR, 2008), c) sketch illustrating the need of 7 s/c to resolve spatio-temporal variations.

As one example, previous observations provided evidence that Short Large Amplitude Magnetic Structures (SLAMS) are common features of quasi-parallel shocks (Schwartz & Burgess, GRL, 1991; Lucek+, 2002) and are important sites of ion acceleration (Johlander+, ApJLett., 2016). Figure 1a illustrates the complex spatial structure and temporal evolution of the quasi-parallel shock upon interaction with SLAMS, which are neither planar nor stationary. Cluster 4-point measurements, Fig1b, show that SLAMS evolve. However, to disentangle spatial from temporal variations, at least 7 measurement points are needed. This is required to fully characterise the morphology and separate the growth of SLAMS from their motion. One point in addition to 4 s/c will allow to resolve the growth in time of the SLAMS' amplitude along the propagation direction (P7 in Fig1b). Having two additional s/c in different directions perpendicular to the propagation direction (P5 and P6) will allow to resolve the 3D morphology of SLAMS (e.g., non-planarity). To achieve this, the magnetic field shall be measured on sub-ion scales (<0.1s cadence) and cuts of the 3D ion distribution in thermal, suprathermal and energetic energy ranges shall be measured on ion scales (<1s). Background parameters density, flow velocity and temperature (e.g., to measure Mach number) shall be measured at fluid scales (<30s). All this would allow to assess the efficiency of SLAMS as ion acceleration sites, as a function of space and time.

Another example of energy conversion sites are reconnecting current sheets in the shock boundary, which are predicted by simulations (Gingell+, JGR, 2017) and recently observed by MMS (Wang+, GRL, 2018; Gingell+, PRL, 2018). The electron-scale MMS measurements are valuable for describing electron physics. However, as for the case of SLAMS, at least 7 measurement points are necessary to capture the time evolution and 3D structure of current sheets. To achieve this, the magnetic field shall be measured on sub-ion scales and cuts of electron and ion distributions on ion scales. Magnetic fluctuations up to the electron cyclotron frequency and electric fluctuations up to plasma frequency shall be measured, to identify whistler and plasma waves which are proxies of energy conversion at time resolution higher than particles. All this would allow to quantitatively assess the link between reconnection sites and the shock.

Resolving the spatio-temporal evolution of energy conversion sites at the bow shock is a necessary step to understand particle acceleration mechanisms at astrophysical shocks. Multi-point in-situ observations can provide valuable information to interpret remote measurements and to develop more realistic models of astrophysical shocks, e.g., of particle injection, as well as testing competing acceleration mechanisms such as DSA and turbulent reconnection (Matsumoto+, Science, 2015; Zank+, ApJ, 2015).

PROSPERO will boost our understanding of energy conversion at astrophysical shocks by probing, for the first time, the spatio-temporal evolution of the terrestrial bow shock.

Scientific Goal SG2: To characterise the temporal and spatial evolution of shear boundaries by probing the Earth's magnetopause.

The magnetopause is a local example of an astrophysical boundary with both flow and magnetic shears. Two fundamental energy conversion processes occur there: the Kelvin-Helmholtz Instability (KHI), which converts velocity shear into electromagnetic energy, and Magnetic Reconnection (MR), which converts magnetic shear into particle kinetic and thermal energies (Yamada+, Rev. Mod. Phys., 2010).

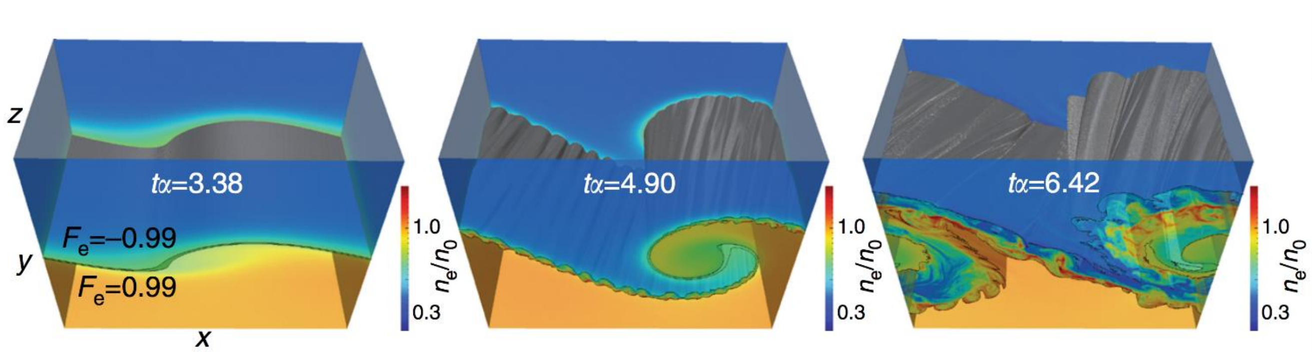


Figure 2: simulations of the turbulent evolution of KH vortices at the magnetopause (Nakamura+, Nature Comm., 2017).

Kelvin-Helmholtz Instability. Theory and recent supercomputer numerical modelling predict that linear KH waves excited at the dayside magnetopause evolve into non-linear vortices towards the terminator (Fig. 2). Further evolution of vortices leads to a complex 3D configuration with the formation of many energy conversion sites such as reconnecting current sheets over scales from electron to fluid (Nakamura+, Nature comm., 2017). At fluid scales, Cluster could only infer the existence of vortices (Hasegawa+, Nature, 2004; Foullon+, JGR, 2008) under 2D and steady-state assumptions. At smaller scales, MMS was able to study current sheets within vortices (Eriksson+, PRL, 2016), assuming planarity and steady-state, but lacking context information on the vortex (Retinò+, Nature Phys. 2016; Moore+, Nat. Phys., 2016). At least 7 measurement points are necessary to address the complex 3D structure and evolution of vortices. To achieve this, similarly to the shock case, magnetic field (sub-ion scales), 2D cuts of particle distribution functions (ion scales) and electromagnetic waves, as well as background parameters (fluid scales), shall be measured. All this would allow the link between energy conversion sites and vortices to be assessed. This is a necessary step for understanding energisation mechanisms in astrophysical flow shear boundaries. In situ measurements at multiple points provide information that could help the interpretation of remote observations, e.g., CMEs in the corona (Foullon+, ApJ, 2011), solar (Li+, Nature, 2018) and astrophysical jets (Lobanov+, Science, 2001) and molecular clouds (Berné+, Nature, 2010).

Magnetic reconnection. Cluster and MMS provided valuable observations of magnetopause reconnection. In particular, MMS was designed to study the microphysics of MR at electron scales. State-of-the-art simulations (e.g., Daughton+, Phys. Plasmas, 2014) and observations (e.g., Phan+, GRL, 2016; Kacem+, JGR, 2018) indicate that the magnetopause is very complex and includes 3D non-planar and unsteady structures such as flux ropes and vortices over scales from electron to fluid. Such structures are sites of strong energy conversion that can be fully resolved with at least 7 measurement points.

PROSPERO will boost our understanding of energy conversion at astrophysical shear boundaries by probing, for the first time, the spatio-temporal evolution of the terrestrial magnetopause.

Additional supported science targets

PROSPERO will advance our understanding of energy conversion sites in other regions surrounding the shock and magnetopause boundaries (pristine solar wind, foreshock, magnetosheath and outer magnetosphere), revealing the energetics of the couplings between all these regions. At least 7 measurement points are required to elucidate the formation, dynamics, and interactions as well as to test generation hypotheses with respect to these sites.

Particle acceleration sites in the outer magnetosphere. Radiation belts are powered by wave-particle interactions that redistribute particle kinetic energy. Different wave modes are supported: from global-scale oscillations to highly-localised whistler-mode chorus wave packets (Santolik & Gurnett, GRL, 2003; Nishimura+, JGR, 2011; Aryan+, JGR, 2016). The efficiency of these interactions critically depends upon wave properties, wave packet morphology, localisation and dynamics.

Magnetosheath jets. The downstream side of the quasi-parallel shock is permeated by magnetosheath jets - localised fluid-scale flow streams featuring dynamic pressure enhancements (Plaschke+, SSR, 2018). Simulations indicate that jets are ubiquitous at quasi-parallel shocks, yet their morphology, formation and dissipation processes are unclear (e.g., Hietala+, PRL, 2009; Karlsson+, JGR, 2015).

Pristine solar wind and foreshock transients. Solar wind transients, e.g., reconnecting current sheets (Lavraud+, Solar Physics, 2009), interplanetary shocks and sheath regions associated with CMEs (Chian+, ApJLett., 2011) and corotating interaction regions (Horbury+, SSR, 1999), and foreshock structures, e.g. hot flow anomalies (e.g., Schwartz+, Nature, 1985) and foreshock cavitons (Blanco-Cano+, JGR, 2009), are complex and non-stationary energy conversion sites, often associated with strong turbulence and energetic particles (Desai+, L. Rev. Sol. Phys., 2016, Turner+, Nature, 2018). Evaluating the turbulent heating and energy cascade rates is possible by two-point correlation techniques (e.g., Osman+, PRL, 2011), which enormously benefit from many available measurements points (Matthaeus+, PRL, 2016).

Impact

PROSPERO will achieve major breakthroughs in our understanding of energy conversion in near-Earth, heliospheric, and astrophysical plasmas. This will improve the synergy between the space and astrophysical communities, and will also impact on laboratory and numerical simulation fields. PROSPERO would be a crucial step forward after Cluster and MMS, and would serve as a pathfinder for future cost efficient multi-s/c plasma missions. It would also serve as technology pathfinder towards the exploration of distant solar system bodies with a mother-daughters configuration and miniaturised high-quality payload. Space physics is a very active field within and outside Europe and PROSPERO allows the strong European leadership in space physics to continue,

Mission and payload requirements

The requirement to reach full science closure on the scientific goals SG1 and SG2 traces down to the following mission and payload requirements.

Key science regions (KSR). KSRs are the bow shock and the dayside magnetopause, particularly shock regions close to the subsolar point and magnetopause regions close to the equatorial plane.

Number of spacecraft. At least 7 points (4 s/c + 3 additional s/c in different directions in three dimensions) are needed to disentangle the spatio-temporal evolution of energy conversion regions at a given scale. The 3 additional s/c will allow to assess deviations from linear gradient and time stationarity assumptions, used in 4 s/c analysis. An additional s/c is needed for redundancy, as required by the F1 call, giving a total of 8 s/c carrying scientific payload.

Spacecraft separation. To assess scales from sub-ion to fluid, the s/c shall have separations from ~10 km up to ~1000 km. Tetrahedron formation flying (as on Cluster and MMS) is not required. In KSRs, s/c shall be spread in all three dimensions, e.g., not all being in the same plane or aligned.

Orbit The s/c orbit shall be optimised for the spacecraft to spend most of their time in the KSRs and to maximise data return. The orbit apogee shall be higher than the expected distances of the subsolar shock (12-15 Earth radii, R_E) and the perigee lower than the distance of the subsolar magnetopause (10-12 R_E).

Payload requirements

Overall plasma parameters. Density, ion velocity, electron and ion temperatures and background magnetic field shall be measured at least with 30s cadence (fluid scales) to characterise plasma parameters such as beta, Mach number, temperature ratios, velocity and magnetic shear.

Morphology of energy conversion sites: electric and magnetic fields shall be measured with sufficient sampling rate to resolve at least Doppler shifted sub-ion scales.

Energy conversion observations in plasma. Energy conversion sites shall be identified in thermal (~100 eV to 1 keV), suprathermal (~10s keV) and energetic (~100 keV) ranges. 3D distributions of ions and electrons in thermal/suprathermal range and 2D cuts in energetic range shall be measured with at least 30s cadence (fluid scales). In addition: (a) 2D cuts of ion and electron distributions in thermal/suprathermal range with cadence of at least 0.1 s (sub-ion scales), and (b) 1D cuts of electron/ion distributions in energetic range with cadence of at least 1s (ion scale).

Energy conversion observations in waves. Energy conversion sites shall be identified in the following frequency ranges: (1) magnetic fluctuations up to at least the electron cyclotron frequency ~1 kHz, and (2) electric fluctuations up to at least the electron plasma frequency ~100 kHz.

2. Mission configuration

PROSPERO is a fleet of 1 mothercraft and 8 identical smallsats (daughtercraft) orbiting the Earth in an elliptical orbit. No scientific payload will be on the mothercraft, with all instrument onboard the 8 smallsats.

Mothercraft

The mothercraft will: (1) carry the smallsats to the final orbit and deploy them, (2) serve as a communication relay, distributing telecommands to the smallsats, receiving smallsat telemetry, buffering the data and transmitting them to ground, and (3) provide a time synchronisation beacon for the smallsats. Low speed deployment of smallsats is preferred such that a configuration with short separation is reached more easily. Cost efficient deployment solutions exist and will be investigated in the technical study for Phase-2 proposal. There are no scientific requirements on mothercraft design or electromagnetic cleanliness (EMC), which offers flexibility for a cost driven design.

Smallsats (daughtercraft) and payload

The 8 smallsats will carry all of the scientific payload. The smallsats will be based on a cubesat form factor, taking advantage of the growing selection of readily available cubesat components and subsystems. The estimated size of the smallsats is 12U (23 x 24 x 36 cm) with a mass of ~20 kg, of which ~5 kg will be allocated for scientific payload. The smallsats will be spin stabilised with sun-pointing spin axis. The spin is important for particle instruments with a fixed lateral field of view to cover all look directions. The spin period satisfying scientific requirements shall be at most 30s.

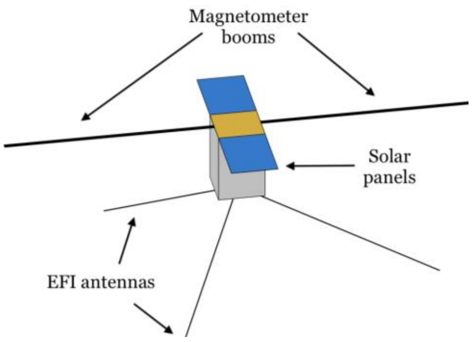


Figure 3: smallsat sketch showing accommodation of field instruments. Particle instruments will be accommodated on the sides or edges of the smallsats to have an unobstructed lateral view.

The smallsats will have their own propulsion (electric or chemical) for attitude corrections, fine orbit adjustments and constellation control. Only 7 functional smallsats are required to answer the science questions. Using 8 smallsats provides redundancy and allows to use non-redundant design for the smallsats. Economies of scale associated with building 8 identical smallsats should result in significantly lower cost per kilogram and enable cost efficient use of upscreened COTS components.

The smallsats carry a suite of scientific instruments for measurements of fields and plasma. The instruments will be miniaturised versions of their counterparts from previous plasma-targeting s/c missions and will fit the constraints of small satellites while maintaining the performance required to fulfill the scientific goals. Ground data processing techniques will be used to combine the measurements from several smallsats to obtain full solid angle coverage at a higher time resolution.

An adequate level of EMC of the smallsat platform and payload will need to be assured to avoid perturbation of measurements by spacecraft generated fields. The small platform, the absence of high power transmitters and the expected limited impact of reaction wheels will render the EMC program simple and manageable. In comparison to EMC-demanding missions such as Cluster or THOR, the smallsat fields measurements are much less sensitive and impose less strict EMC requirements. In addition, magnetic field sensors are mounted on rigid booms to ensure unperturbed measurements.

Fluxgate magnetometer (FGM) FGM will provide measurements of magnetic field vectors at a sampling rate up to 128 sps. The proposed low-resource magnetometer design, suitable for small s/c missions, consists of two miniaturised sensors (mass <40g) mounted on a deployable boom with dedicated front-end electronics. The fluxgate sensor was qualified by IWF in the frame of the SOSMAG activity.

Search coil magnetometer (SCM) SCM will provide measurements of the three components of magnetic fluctuations from 1 Hz to 6 kHz in the form of analogue signals, digitised and processed by the wave analyser unit (WAU). SCM consists of a tri-axial magnetic sensor with a preamplifier and is mounted on a rigid boom, opposite to the FGM boom. The SCM sensor is based on the heritage from MMS spacecraft.

Electric field instrument (EFI) EFI will provide measurements of the three components of the electric field fluctuations from 1 kHz to 1 MHz based on the design heritage from the mission ChangE'4. EFI consists of three orthogonal 1.25-m-long monopole antennas attached to a preamplifier/deployer box. The tubular boom strip is stored on a reel in stowed configuration and when deployed forms a rigid cylindrical tube with 10 mm diameter and weight of only 20 g/m.

Electrostatic electron analyser (ELA) ELA will measure the electron distribution function in the range ∼1 eV - ∼30 keV at 15° angular resolution. ELA is a top-hat type electrostatic analyser based upon MSSL's heritage (Cluster PEACE, Cassini CAPS-ELS) and technological advancements made for Solar Orbiter EAS. With each energy sweep, the instrument measures the electron flux in 12 directions and 32 energy channels, providing a cut of the particle distribution; 32 sweeps are performed in a single spacecraft spin, providing a 3D distribution.

Ion instrument (IOI) IOI is a top-hat type electrostatic analyser, measuring the ion distribution function in the energy range 5eV/q - 20 keV/q. Incoming ions are binned according to their energy per charge (32 energy bins) and velocity direction with an angular resolution of 11.25°. Similar to ELA, the IOI instrument provides a cut of the distribution function with every sweep (32 sweeps per spin) and relies on s/c spin to cover the 3D distribution. IOI is based upon heritage from the BepiColombo MMO/MPPE-MEA and MIA instruments.

Energetic particle instrument (EPI) EPI will detect electrons in the energy range 50 keV to 500 keV and protons from about 100 keV to over 6 MeV. The instrument is based on a solid-state telescope structure with three adjacent Si detector layers with different thicknesses, allowing for particle species identification and energy measurement. A similar instrument is being developed for a CubeSat mission in the Finnish Centre of Excellence in Sustainable Space.

Wave analyser unit (WAU) The WAU instrument is an electronics unit responsible for digitisation of electromagnetic field measurements from the SCM sensor and EFI antennas. It will be implemented as one circuit board integrated in the same electronics stack with the MPU. In addition to providing time series of electric and magnetic fields, it will perform on-board spectral analysis and selection of waveform snapshots. WAU is based upon the heritage of the Institute of Atmospheric Physics (IAP) in Prague in providing similar instruments for Solar Orbiter, JUICE, TARANIS and ExoMars 2020.

Miniaturised data processing unit (MPU) The MPU provides a single data interface between FGM, ELA, IOI, EPI and WAU instruments and the smallsat platform. The main functions of MPU are the collection of telemetry from the instruments, its compression and forwarding to the mothercraft as well as handling of telecommands and time synchronisation. The MPU will store instrument configurations and allow the entire smallsat payload to be commanded with a single telecommand. The design of the MPU is based upon consolidated heritage of the Institute for Space Astrophysics and Planetology(IAPS), e.g. from Solar Orbiter, and recent developments of nano-satellite electronics.

Instru-ment	Measurement	Nominal cadence	TM rate [kbps]	Mass [g]	Power [W]
FGM	Magnetic field (< 64 Hz).	32 Hz	4	470	1.8
SCM	Magnetic field (1 Hz to 6 kHz) sampled by WAU	512 Hz	15	520	0.2
EFI	Electric field (1 kHz to 1 MHz) sampled by WAU	under WAU		450	1
ELA	Electron velocity distributions (1 eV - 30 keV)	1 cut/sec	3	1150	2
IOI	Ion velocity distributions (5 eV/q - 20 keV/q)	1 cut/sec	6	1000	2
EPI	Energetic particles (e: 50-500 keV, p: 0.1-6 MeV)	1 cut/4 sec	1	750	2
WAU	Spectral matrices (SM) and waveform snapshots (WS) from SCM and EFI	SM: 2 sec, WS: 1 min	68	150	2
MPU	Common data processing unit			300	3
Totals			**97**	**4 790**	**13**

Note: Design margin 20% included, 10% for high TRL instruments. Spin period of 30s assumed. Payload volume is approximately 5U, to be confirmed by accomodation study in Phase-2 proposal.

Orbit and mission profile

The mothercraft, with smallsats stored in deployers, will be launched to the Sun-Earth L2 Lagrange point as a piggyback to the primary payload. It will use its own propulsion to reach the final Earth-bound orbit. The baseline orbit is equatorial with an apogee at 16 to 18 RE and perigee between 7 and 8 RE having a good coverage of KSRs. The orbit is similar to the "HEO" orbit suggested in Table 2 of the F Mission Call - Technical Annex. For the Phase 2 proposal, the orbit will be further refined to maximise the science return. The orbit, well beyond geostationary orbit, is stable and acceptable as a graveyard orbit from a space debris mitigation point of view. After reaching the final orbit, the mothercraft will deploy all 8 smallsats into a formation with inter-s/c separations of several kms. The smallsats will then use their own propulsion to adjust the orbit to the required configuration. The nominal mission is planned for 10 months: 2 months of commissioning followed by 8 months of science operations. The inter-s/c distances will be gradually increased over the course of the mission as the apogee moves from the dusk flank, through the subsolar region towards the dawn flank. The following timeline is foreseen:

- Initial short separations starting at several kms, suitable for studies of plasma waves and sub-ion scale energy conversion sites, will be used at the dusk magnetopause, magnetosheath and outer magnetosphere
- During the subsolar phase, the inter-s/c separations will increase from tens to hundreds of km allowing to study energy conversion sites at scales from sub-ion to several ion within both the KSRs and in solar wind/foreshock, magnetosheath and outer magnetosphere
- Finally, separations will be increased to several thousand kilometers (fluid scales) near the dawn flank. These separations are particularly suitable for large-scale studies of the evolution of KH vortices and of reconnection flux ropes at the magnetopause, as well as for studies of magnetosheath jets.

Communication and operations

The smallsats will communicate with the ground via the mothercraft, transmitting all scientific and housekeeping telemetry via the Inter-Spacecraft Link (ISL). A summary of scientific measurements is given in the above table, showing that the average data rate over the ISL from each smallsat toward the mothercraft is approximately 97 kbps per smallsat, assuming some compression is already performed by the MPUs on the smallsats. This bandwidth is within the estimate provided on the ESA F1 call webpage (under Q7 in the Q & A section), assuming the smallsats communicate with the mother one at a time. As the bandwidth of ISL strongly depends on distance, the data rate will be larger at small separations and decrease as the s/c separations increase beyond a few hundred km. The relatively low total data rate, combined with the low perigee, should allow nearly all of the collected data from KSRs to be transmitted to the ground, assuming that a perigee pass of 8h can be used for data downlink every orbit using 35m ESTRACK antennas (X-band). The operations of the smallsats will be kept very simple. In normal operation, a single telecommand from the mother to the smallsats will switch the smallsats to one of several predefined configurations. Afterwards, the scientific data acquisition should be handled autonomously by the smallsats. The number of instrument modes will be strictly limited to reduce operations and testing cost.

In order to resolve waves up to the electron plasma frequency, the relative timing of data from different s/c needs to be reconstructed with 1 microsecond accuracy. To this end, the mothercraft will transmit a periodic synchronisation beacon signal used by all smallsats as a clock reference.

Payload and mission optimisation options

Options to optimise payload and spacecraft will be considered during the technical study for the Phase-2 proposal. Particularly: 1) Inclusion of two miniaturised Langmuir probes in the EFI instrument. Heritage is available. This will increase science return by providing measurements of s/c potential with small impact on mass and power budget. 2) Several options for reducing mass, power and volume as well as for simplifying instrument accommodation, with an acceptable impact on science, are considered. One example is the combination of IOI and ELA into one miniaturised dual electron-ion-spectrometer. Heritage is available. 3)s Once the relative telemetry budgets of ISL and ground link are confirmed by the technical study, the need for selective downlink of science data will be evaluated. In this scenario, high resolution data is buffered in the mass memory of the mothercraft and/or smallsats and only selected sections of the data are downloaded. Based on MMS experience, automatic selection of relevant intervals is sufficient. Implementing this method would lead to substantial saving of SOC resources.

Innovation

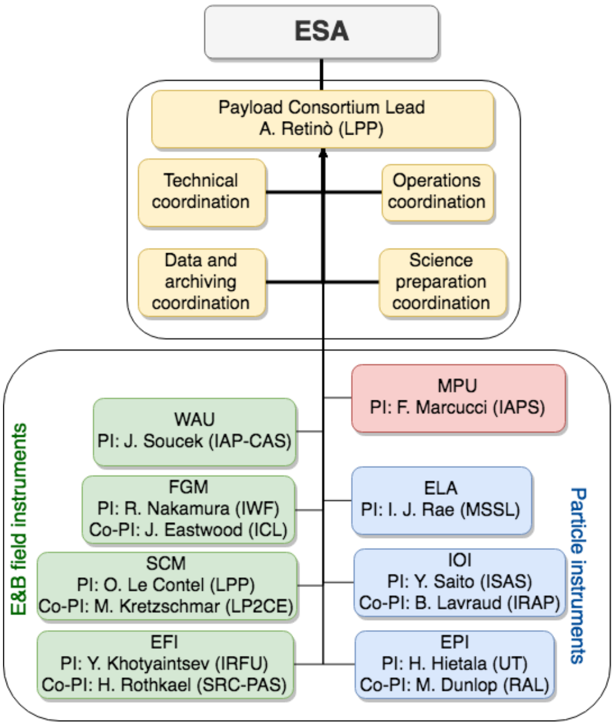
Additional innovation options are considered for inclusion in the Phase-2 proposal. For example, passive plasma tomography using dispersion of natural radio waves, e.g., auroral kilometric radiation, to reconstruct the shape of plasma density structures. A study of automatic selective downlink based on machine learning algorithms could be performed in Phase A, e.g., in the context of the EU project AIDA (https://aida-space.blogspot.com) which several PROSPERO Core Team members are part of.

3. Management structure

Procurement scheme. ESA is responsible for the spacecraft manufacturing, providing subsystems (e.g., booms), launch and operations, as well as the data archiving and distribution. ESA will take care of the Phase-A scientific payload activities. National Agencies shall fund all the scientific payload through phases B1-F of the mission, including instrument operations, data calibration and data processing,.

Payload Consortium Lead (CL), the coordinator of the entire payload consortium and single interface to ESA (currently the Lead Proposer). Main responsibilities are to coordinate: 1) science preparation, 2) payload development, 3) payload operations, 4) data and archiving. The CL has the right of final decision concerning trade-off issues at the consortium level.

Principal Investigator (PI), head of an instrument. Instrument can have internally co-PI, Lead-CoI and CoIs. Main responsibilities are instrument provision, instrument operation, data calibration and archiving, and to provide to CL. PI activities are funded by National Agencies.



Interdisciplinary Scientist (IDS), an expert in specific overarching science themes connected to the mission objectives, who takes advantage of synergistic use of the PROSPERO data. Responsibility: to participate in the Science Working Team (SWT) and support CL.

Science Working Team (SWT), consisting of an ESA Project Scientist, CL, PIs and IDSs. Other participants will be invited to participate in SWT meetings as appropriate. Responsibility: to monitor and advise CL and ESA on all aspects of the mission which affect its scientific performance, to plan science operations. CL has a veto right in the SWT decisions.

Science Team (ST), all scientists actively supporting the mission.

Payload consortium management The payload consortium consists of 8 instruments and is led by the CL. This management will allow tightly coordinated design, building, testing, operations, data processing and archiving, similar to coordinated efforts by the Rosetta Plasma Consortium (RPC). The PROSPERO payload consortium shares common science objectives and will be operated as a single instrument. Moreover, it has a single electrical/data interface to the s/c. Such coordinations allows to optimise time and resources in several ways, e.g., shared documentation (such as common EID-B, Operations Manual, etc), common payload consortium reviews preceding unit/instrument reviews (similar to JUICE RPWI), coordination of CPPA requests and of schedule, EMC testing, etc. Additional optimisation can be achieved by more stringent tailoring of requirements, with focus on technical aspects, better handling of long-lead items etc.

National agencies with PI, co-PI and Lead CoI responsibilities

Austria (PRODEX), Czech Republic (PRODEX), Finland, France (CNES), Italy (ASI), Poland (PRODEX), Sweden (SNSA), UK (UKSA)

National agencies with undergoing discussions

Belgium, Estonia, Greece, Hungary, Norway, Romania

International agencies contributing payload

The Japanese space plasma community is an important part of the PROSPERO Core Team. The PI of the IOI instrument is a member of that community. A contribution in terms of one smallsat in addition to the PROSPERO baseline is being discussed.

International agencies with collaboration discussions and optional contributions

The US, Chinese and Russian space plasma communities are strongly interested in missions having more than 4 s/c to study science similar to PROSPERO's, and they strongly support the PROSPERO concept. Similar mission concept studies are ongoing within the US and China. Contributions in terms of payload and/or smallsats in addition to the PROSPERO baseline mission could be possible.