PRObing the Structure of Plasma Energisation RegiOns (PROSPERO) in Near-Earth Space and future smallsat constellations

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** 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*

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Motivation

- Energy conversion and particle energization key open issue of space plasma physics and plasma astrophysics.

- Near-Earth space best laboratory. Results can be exported to distant astrophysical objects.

- Recent constellation missions (e.g. Cluster, MMS) demonstrate the need of > 4 points of measurements

- A magnetospheric constellation of satellites is a top priority of the international heliophysics community. It is one of the four priorities identified in ESA Cosmic Vision Question 2.1 « *From the Sun to the edge of the Solar System* ». Magnetospheric constellations/ swarms also currently considered by other agencies (e.g. NASA, China)

- Earlier attempts e.g. Cross-Scale (ESA M-class constellation with 7 satellites) not successfull since considered too expensive by ESA

- **Need of a magnetospheric constellation of identical satellites with high-quality scientific paylaod but at reasonable cost -> smallsat approach**

- Such constellation will be the first necessary step for future constellation in deep space

PROSPERO: science theme & questions

Science theme

- **Energy conversion and particle acceleration** key open issue of space plasma physics and plasma astrophysics.
- Such processes occur at different kinds of **energy conversion sites** embedded in large-scale plasma boundaries such as shocks and shear boundary (magnetic, flow).
- It is crucial to determine the **spatial structure and temporal evolution** of energy conversion sites to understand how energetic particles are produced in space and astrophysical plasmas. Examples: reconnection is solar flares, Kelvin-Helmoltz turbulence in CMEs, particle acceleration at SN remnant shocks and galaxy clusters.

Science question and goals

SQ. ***How do energy conversion sites at large-scale plasma boundaries evolve in space and time?***

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

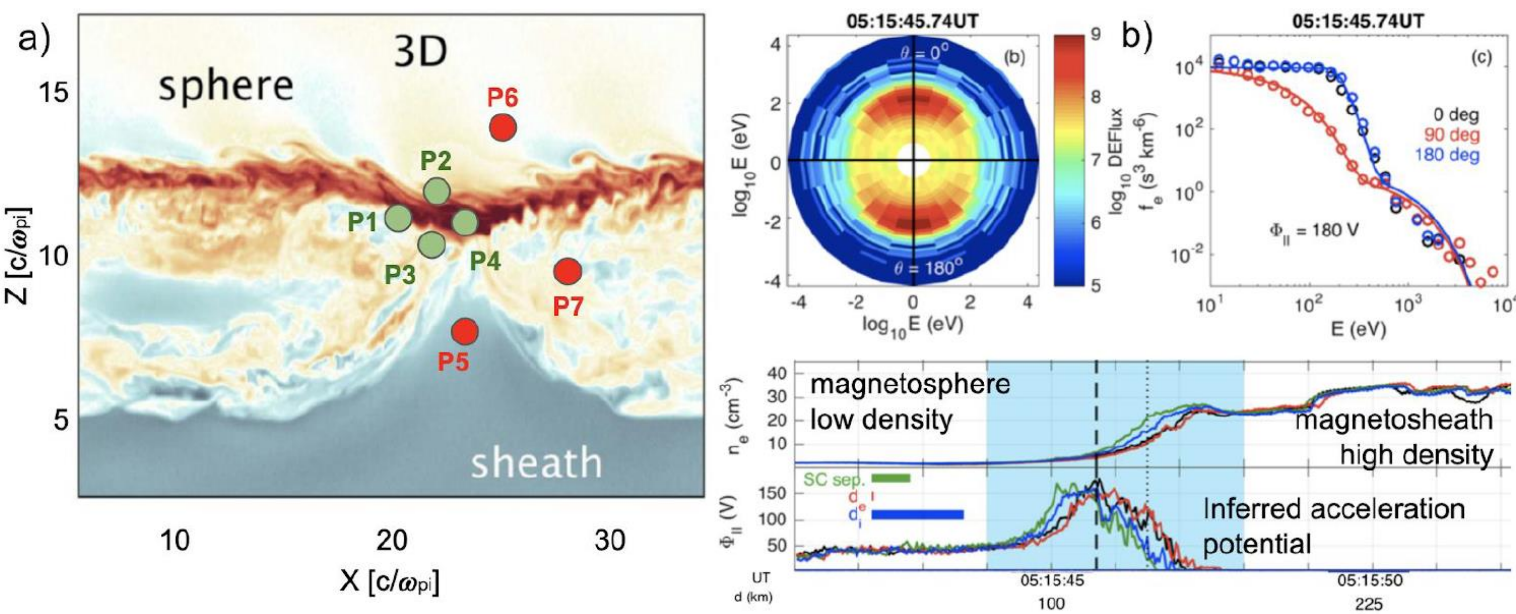
SG2. *To characterise the spatial and temporal evolution of shear boundaries by probing the Earth's magnetopause*

Multipoint measurements.

- Results from 4-spacecraft constellations (ESA / Cluster, NASA / MMS) are limited by many assumptions.
- In order to disentangle the complex 3D structure and temporal evolution of energy conversion sites as well as to study cross-scale coupling at least 8 spacecraft are required (7 + 1 redundant):
    - **At given scale:** 4 s/c to study linear gradients and planar structures moving at constant speed + one additional s/c in each dimension to explore evolution along this dimension
    - **At multiple scales (electron, ion, fluid):** 7 s/c required to study cross-scale coupling

PROSPERO: science (I)

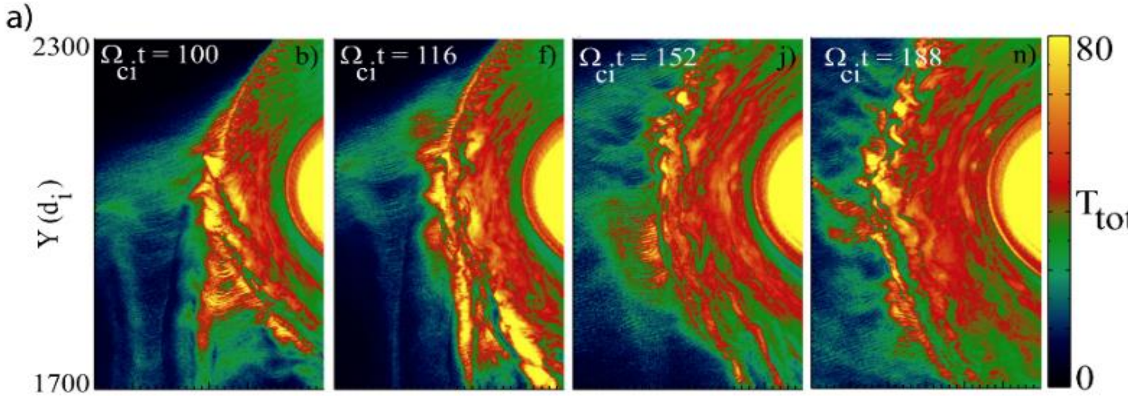
Supercomputer simulations and MMS obsevations of magnetopause reconnection



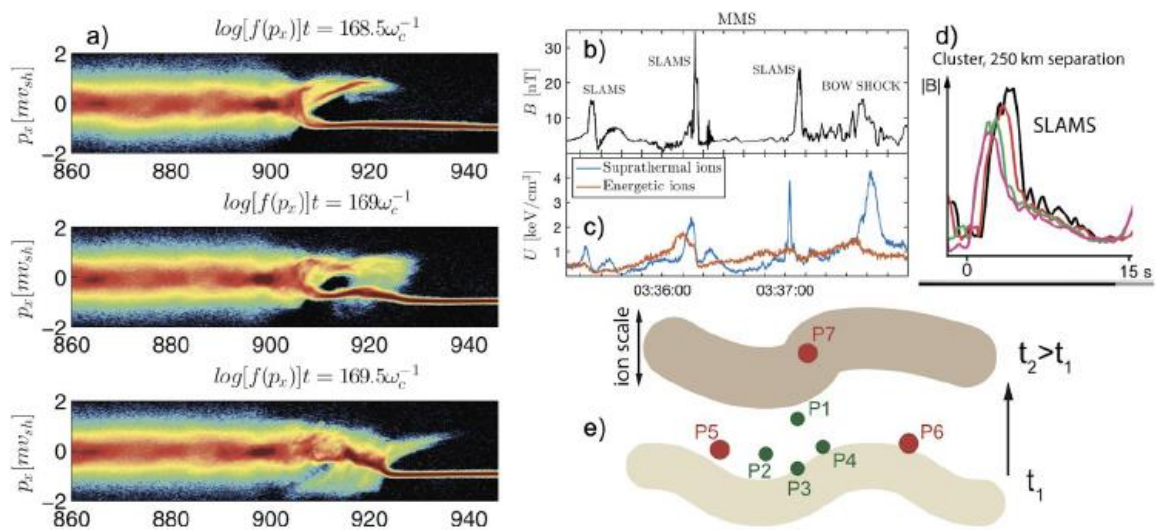
Electron heating parallel to ambient magnetic field in asymmetric reconnection. a) Numerical simulations show efficient parallel heating in 3D simulations (Le+, PoP, 2018). b) MMS small-scale observations show similar heating (top panels) at low density side and it is consistent with being due to parallel electric field potential (bottom panels) (Graham+, GRL, 2016). Schematic 7 spacecraft constellation, P1-P7, would allow to address the role of cross-scale coupling in the formation of acceleration sites.

PROSPERO: science (II)

Supercomputer simulation of terrestrial



Structure and evolution of one energy conversion site at terrestrial shock



Quasi-parallel shock. a) Kinetic simulations of the time evolution of ion injection at a quasi parallel shock with Mach number M=20 (Caprioli+, ApJL, 2015). b-c) MMS measurements of ion energization by SLAMS (Johlander+, 2019) d) SLAMS evolution in Cluster data (Lucek+, JGR, 2008), e) sketch illustrating the need of 7 spacecraft to resolve spatio-temporal variations at SLAMS.

F-PROSPERO: mission configuration

PROSPERO is a constellation 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: (1) carries the smallsats to the final orbit and deploy them, (2) serves as a communication relay (3) provides a time synchronisation beacon for the smallsats. Low speed deployment of smallsats is preferred so that configuration with short separation is reached more easily.

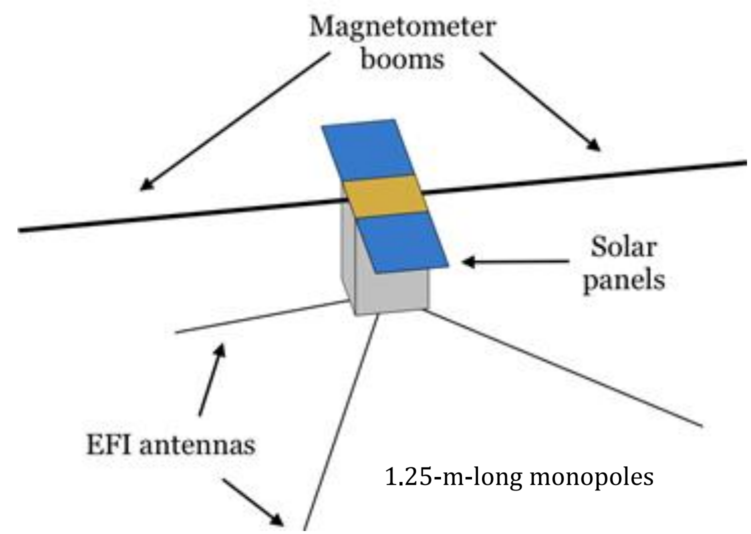
Smallsats: carry all of the scientific payload. The size of the smallsats is 12U (23 x 24 x 36 cm) with a mass of ~20 kg,.The smallsats will be spin stabilised with sun-pointing spin axis with a spin period < 30s (10s target).

Orbit : HEO equatorial 16 -18 RE x 7-8 RE. After reaching the final orbit, the mothercraft will deploy all 8 smallsats into a constellation 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 inter-s/c distances will be gradually increased over the course of the mission as the apogee moves from the dusk flank towards the dawn flank.

Payload : high TRL complete in-situ instrumentation

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

Design margin 20% included, 10% for high TRL instruments. Spin period of 30s assumed. Payload volume is approximately 5U.



M-PROSPERO: mission upgrade

- PROSPERO submitted in 2018 to ESA AO for F-class mission (Phase-1). Deemed too expensive and thus fitting better the M-class envelope
- PROSPERO concept submitted in 2018 (as « CrossScalePathfinder ») to CNES AO for Phase 0 studies (« PASO »). Proposal highly ranked (3rd over 31 proposals). Leader: A. Retino. **High priority for CNES**.
- The goal of CNES Phase 0 is to consolidate the PROSPERO concept and make it evolving towards an **M-class concept (M- PROSPERO)**. Identified improvements:
  - increase of the size of daughthers' smallsat size (e.g. from 12U to 27U) allowing higher resolution of measurements (namely particles)
  - include some high-resolution payload on the mother (e.g. the ion-mass spectrometer and the cold solar wind instrument) for mcrophysics studies
- Examples of planned actions during Phase 0:
  - **Platforms**: study of both mothercraft and smallsats including size and spin rate, AOCS, ranging, instrument accommodation, EMC aspects
  - **Orbit**: ΔV values, constellation dimension (inter-spacecraft separations) and constellation quality (deviations from tetrahedrical shape), smallsat orbit stability
  - **Communication**: InterSpacecraftLink (ISL) between smallsats and mothercraft (band, link budget etc.), communication between mothercraft and ground stations
  - **Mass and power budgets**
  - **Cost assessment**

M-PROSPERO “experiment” vs Cross-Scale “observatory” science

The M-class PROSPERO would allow the science questions of a larger Cross-Scale L-class mission to be partially answered, although it would be more a dedicated plasma experiment rather than a plasma observatory serving the broad space plasma community.

The availability of 8 points of measurements of electric and magnetic fields, which with current technology provide already high resolution, would establish the electromagnetic structure of particle energization regions beyond the linear and steady approximations, which will be an observational first. By using these measurements, important questions related to the coupling between scales would also be answered.

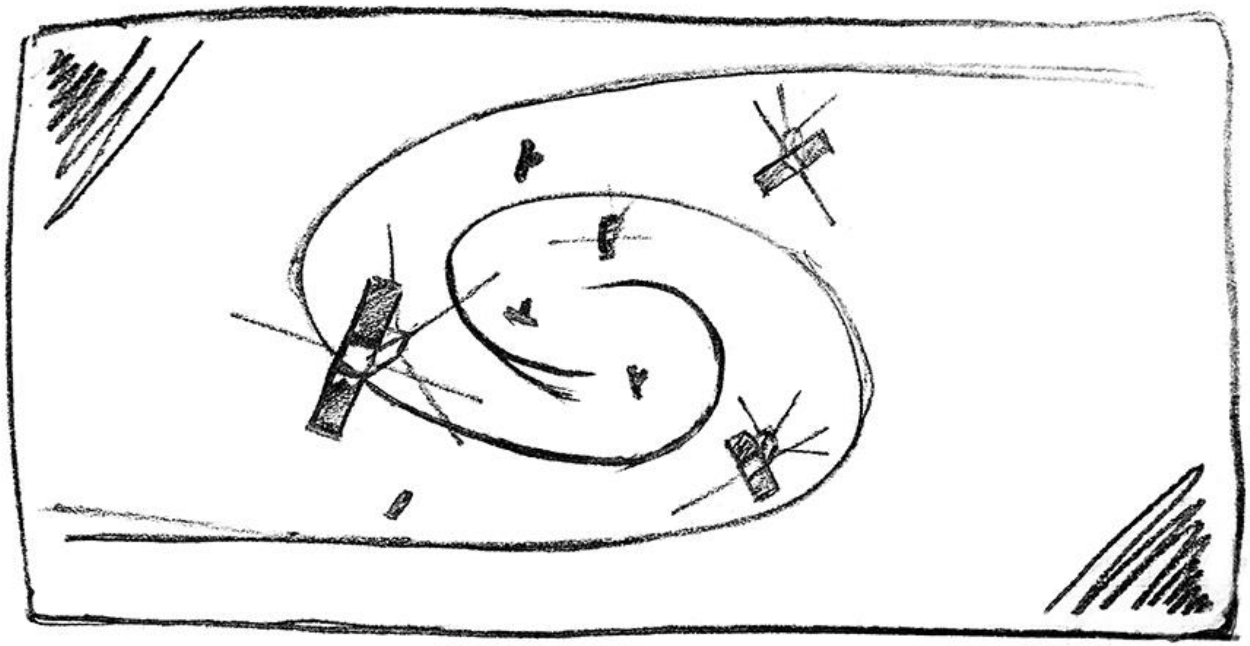
On the other hand, those questions requiring high resolution particle measurements, e.g. the identification of energization mechanisms and the quantification of energy partition among energy range and species, would be only partially answered due to the current limitations of particle detectors, which require high mass and power in order to address kinetic scales
(in particular electrons).

Yet, success in some of the technological developments in coming decade could reduce these limitations and could allow to answer a significant part of the L-class science even with M-PROSPERO.

PROSPERO/M-PROSPERO: importance

- **Energy converison and particle energization** key open issue of space plasma physics and plasma astrophysics. In situ measurements in near-Earth space with a constellation of >4 spacecraft needed.
- **Key mission aspects**: (1) equal platforms (2) equal payload (3) configuration flexibility
- Driver of many R&D activities on **smallsat platforms** (e.g. InterSpacecraftLink, ranging, EMC and AOCS, autonomous spacecraft operations, serial production and optimized AIT/AIV, …), **payload** (miniaturisation and/or new measurement techniques, serial production, AIT/AIV and calibrations of identical instruments, …) and **science operations** (autonomous science operations, automatic selective downlink, …) to overall reduce cost.
- **Outer magnetospheric constellation top priority** of main Agencies (ESA, NASA, China, CNES). Scientific community behind very large (Cluster, MMS, CrossScale) including supercomputer simulations. **Strong CNES support**.
- **PROPSPERO/ M-PROSPERO first constellation of smallsats providing high-quality in situ plasma measurements**. First necessary step for future constellations to explore deep space at reasonable cost.
- **PROSPERO/M-PROSPERO first mission with >4 spacecraft** allowing to significantly advance on the key issue of energy dissipation and particle energization and fundamental plasma physics in general.
- **Inter- agency collaborations crucial** between international agencies (ESA,NASA, JAXA, China,…) and national agencies (CNES) as well as other national agencies

Thank you for your attention



PROSPERO mission concept

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L-class plasma *observatory* concepts

Observatory to study the compelling science theme of fundamental plasma physics « **energy conversion and particle acceleration »**

CrossScale L

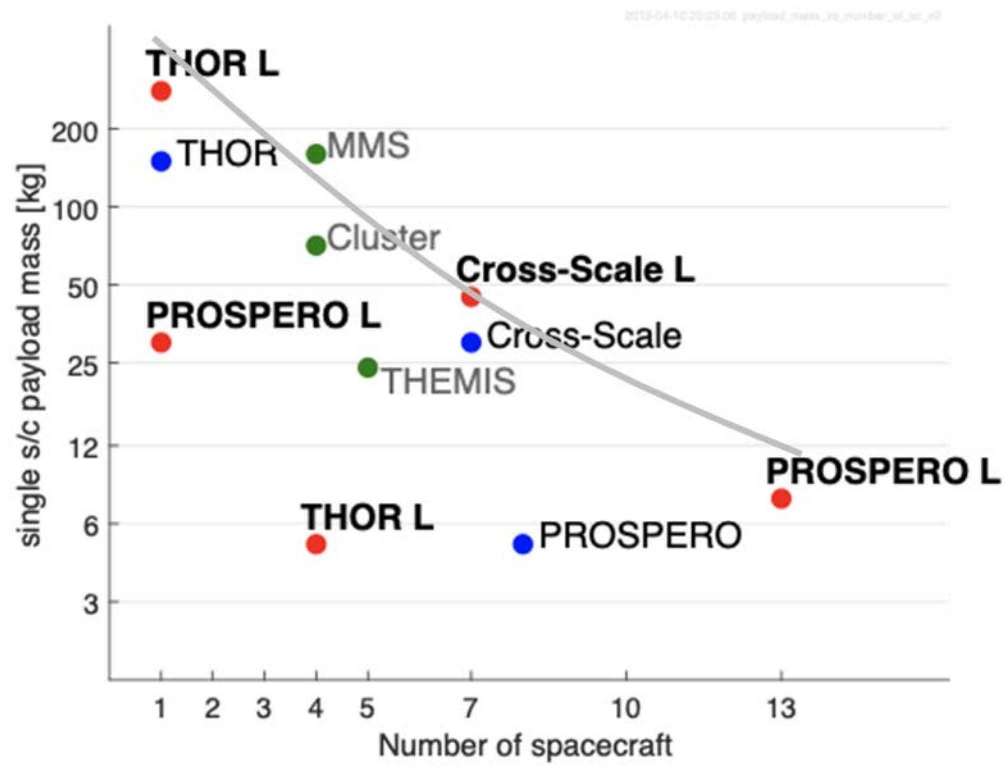
- Same number of identical spacecraft (7)
- 50% bigger payload (e.g. increased geometrical factors, 3D electric field etc.)

THOR L (« SCOPE-like »)

- 1MS + 6DSs
- Go from 6U to 12U DSs
- 50% bigger payload on DSs (e.g. add particle instruments)
- 25% bigger payload on MS (e.g. increased geometrical factors, full-sky energetic particle coverage, 3D DC electric field etc.)

PROSPERO L

- Go from 8 to 13 spacecraft (to get all three scales)
- Include payload on MS (e.g. DC electric field, ion composition, cold solar wind monitor etc.)



Solution will depend from technological developments and international collaborations