Unveiling plasma energization and energy transport in the Magnetospheric System through multi-scale observations: the Plasma Observatory mission

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Understanding particle energization and energy transport is a grand challenge of plasma physics. These processes occur across a wide range of cosmic environments, including planetary and exoplanetary magnetospheres, stellar coronae, supernova remnant shocks, accretion disks, and astrophysical jets, and drive terrestrial space weather, which has harmful impacts on technology and human health. Despite plasma being ubiquitous in the universe and these processes playing a key role in shaping cosmic environments, the underlying physical mechanisms remain elusive. Natural plasmas have extreme scale-separations between the largest and smallest dynamically relevant scales, so direct measurements are needed to study the mechanisms at the basis of energization and transport. The Earth's Magnetospheric System — the complex dynamic region formed by the interaction of the solar wind with Earth's magnetic field — is a key example, where cold solar wind plasma gets energized by up to six orders of magnitude, driving vast energy transport throughout the magnetosphere. This makes Earth's magnetosphere the best natural laboratory for studying these processes through in situ measurements.

Theory, simulations and previous multi-point observations show that the physical processes governing plasma energization and energy transport operate across multiple scales ranging from the large fluid to the smaller particle kinetic scales, which begin around the ion thermal gyroradius. In addition, they are associated to three-dimensional plasma structures, e.g., magnetic islands, flux ropes, vortices and current sheets, which are neither planar nor stationary. Moreover, the scales where a significant amount of energy is converted into energized particles are the fluid and ion scales. To comprehend energization and energy transport processes it is required to understand specifically how plasma energy couples between fluid and ion scales by studying the plasma structures evolution simultaneously at ion and fluid scale in 3D. Previous multi-point observations in the Magnetosphere provided by the ESA/Cluster and NASA/MMS four-point constellations, as well as by the large-scale multi-point mission NASA/THEMIS, have greatly advanced our baseline understanding of collisionless plasma processes. However, all these missions shared a common limitation: the ability to observe only a single spatial scale at a time.

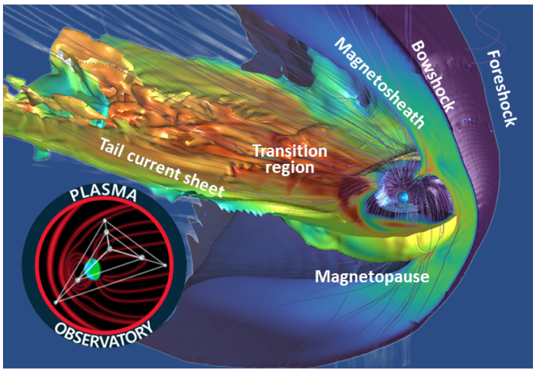

Figure 1: The Earth's Magnetospheric System: a natural laboratory to study the cross-scale energization in plasmas. Image: Vlasiator [3].

Plasma Observatory (PO) is the first multi-point mission tailored to unveil plasma energization and energy transport in the near-Earth plasma environment through multi-scale observations. The two grand science questions of the PO mission are:

SQ1: *How are particles energized in space plasmas?*

SQ2: *Which processes dominate energy transport and drive coupling between the different regions of the Earth's Magnetospheric System?*

These questions relate tightly to the need of progressing in our knowledge of the "Plasma Universe" and of "How our planet works" and target directly two ESA-led Medium Mission themes outlined in the final recommendations from the ESA Voyage 2050 Senior Committee: "Plasma Cross-scale Coupling" [1] and "Magnetospheric Systems" [2]. Answering the PO prime questions requires a thorough understanding of specific processes and their interrelations, as defined by the PO Science Objectives (SO). To unveil particle energization (SQ1), PO will focus on determining how particles are energized by the most important plasma processes: (SO1) at shocks, (SO2) during magnetic reconnection, (SO3) in plasma jets, (SO4) by waves and turbulent fluctuations, and (SO5) upon combination of these processes. To answer SQ2, the second set of SOs addressed by PO will determine: (SO6) how plasma jets interact with the Earth's dipole field in the transition region; (SO7) how field-aligned currents connect different regions of the Magnetospheric System; (SO8) which are the key plasma instabilities involved in energy transport; and (SO9) how energy flux is partitioned among different energy transport processes?

To address its Science Objectives, PO employs an optimal minimum configuration of seven spacecraft arranged in a two-tetrahedra formation with a shared common vertex, enabling simultaneous coverage of two distinct spatial scales in 3D. Such configuration will enable the simultaneous characterization of plasma waves and fluctuations at multiple length scales and their cross-scale energy exchange as well as the comprehension of the link of localized small-scale dynamics to larger-scale plasma structure. The PO baseline mission employs seven identical smallsat Sister SpaceCraft (SSC) in a highly elliptical orbit (HEO 7.2 × 17 RE), enabling observations in all key regions of the Magnetospheric System: the foreshock, the bow shock, the magnetosheath, the magnetopause, the magnetotail current sheet, and the transition region. The nominal mission duration is 3.5 years, with three Nominal Science Phases during which the scale of the inner/outer tetrahedra are progressively increased: 30–60/150–300 km, 100–200/500–1000 km, and 3500–6500 km. PO's orbit and the tetrahedrons scale separation strategy are designed to cover all typical ion and fluid scales of interest across the key magnetospheric regions, thereby ensuring a statistically significant set of observations. The PO's payload consists in a comprehensive set of advanced fields and particles instruments designed to satisfy science requirements and providing a complete characterization of electromagnetic fields and particles at ion and fluid scales across all key science regions. The high-precision Fluxgate Magnetometer provides magnetic field DC measurements up to 128 Hz, complemented by a Search Coil Magnetometer covering AC magnetic fluctuations from 1 Hz to 8 kHz. Electric fields and spacecraft potential are measured by the Electric Field Instrument's Spherical Double-Probe sensor (DC to 100 kHz) and the EFI Axial Dipole Antenna (10 Hz to 100 kHz). Waveform and spectral products from electric and magnetic sensors are processed by the BOX-W wave electronics unit. The ion and Electron Plasma Camera provides 3D distribution functions of thermal ions and electrons at 250 ms cadence. The Ion Mass Composition Analyser resolves H^+, He^{++}, and O^+ distributions at 2 s cadence. The Energetic Particle Experiment measures energetic elec-

trons and ions from 20 to 600 keV. Particle data are processed by the BOX-P electronics unit.
PO will deliver a wealth of valuable data. These will be fully exploited by the large PO science team, while data usage will be further maximized through an open data policy and by broadening the supporting scientific community. All data will be made publicly available through the ESA Heliophysics Archive after a short proprietary period. PO's extensive datasets will be supported by multi-spacecraft/multi-scale data analysis methods, as well as numerical modeling. Broad community involvement will be fostered including interdisciplinary scientists and establishing guest investigator programs. Within PO, Working Groups dedicated to relevant topics have already been set up (Numerical Simulation, Advanced Analysis Methods, Plasma Astrophysics, Synergy Science, Ground-based Coordination, Education and Outreach, and Early Career Researchers) and will continue to expand, broadening the support for data interpretation.
PO will be the first mission to resolve scale coupling in space plasmas, enabling major breakthroughs in our understanding of particle energization and energy transport. Beyond the near-Earth environment, the insights gained will make an important contribution to understanding these fundamental processes across astrophysical systems — shedding new light on the universal plasma phenomena that shape our cosmos.
PO has been recently recommended by ESA as the Medium-class mission M7 of the ESA scientific program. The ESA Science Program Committee will make the formal decision at its next meeting in November 2026. The launch of PO is expected in 2039. A state-of-the-art description of the PO mission can be found in the PO Assessment Study Report [4].

We acknowledge the fundamental support of the PO Science Consortium members (for a complete list see https://plasma-observatory.inaf.it/). Moreover, we acknowledge support by National Agencies/Offices contributing to the study phase: Austrian PRODEX, ASI, BELSPO, Business Finland/PRODEX, CNES, DLR, JAXA, NASA, Czech PRODEX/MEYS, Polish PRODEX, Hungarian PRODEX, SNSA, UKSA.

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