Particle Energization in Space Plasmas: Towards a Multi-Point, Multi-Scale Plasma Observatory

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How are charged particles energized in space plasmas?

A grand challenge and unsolved problem of fundamental importance for plasma astrophysics, that can only be answered in the laboratory of near-Earth space with multi-point in situ measurements.

**Fundamental plasma physics in near-Earth space**

- Energy dissipation and particle heating in turbulence (in situ) [Wan+, PoP, 2016]

**Sun-Earth interaction (space weather)**

- Energetic particle injection into radiation belts (in situ) [Birn+, 1998; Birn+, 2011]

**Other planets**

- Electron acceleration at Saturn’s shock (in situ) [Masters+, Nature Physics, 2013]

**Solar corona and wind**

- Flares (remote) and SEPs (in situ) [Chen+, Science, 2015]

**Distant astrophysical objects**

- Radio image of galaxy jet and lobes (remote) [Image credit: NRAO/AUI]
Big open questions

Major particle energization is associated with fundamental processes:

- shocks,
- magnetic reconnection,
- turbulence and waves,
- plasma jets,
- Interplay between such processes.

How does energization take place during these fundamental processes?

What is the quantitative contribution of each of these processes?

Solving open questions requires assessing:

1. non-linearity and non-stationarity at given scale (electron, ion, fluid),
2. cross-scale coupling.

Exploratory science: discover unknown energization mechanisms and new plasma physics.
Limitations of current multi-point measurements

4 point measurements: Cluster and MMS:

- designed for studying one scale at a time (Cluster: fluid or ion, MMS ion or electron)
- measurement capability at each of these scales allowed important discoveries

However Cluster and MMS:

- cannot resolve **non-linearity and non-stationarity** of energization structures
- cannot resolve **cross-scale coupling**

These critical limitations hinder significant advances in particle energization and discovering new plasma physics.
Need for new multi-point, multi-scale measurements

- Particles and fields measurements from at least 7 points (4+3) are required to resolve:
  - non-linearity and non-stationarity
  - cross-scale coupling

- Need for an L-Class Plasma Observatory (PO) with at least 7 spacecraft and improved instrumentation

- PO next logical step following Cluster, THEMIS and MMS

- ESA has expertise

Ion energization at quasi-parallel shocks

Non-linear and non-stationary ion-scale turbulent fluctuations (Short Large-Amplitude Magnetic Structures) embedded in fluid-scale shock dynamics

[Image: Diagram showing ion energization at quasi-parallel shocks and related data]
**Impact**

- Paradigm shift in our comprehension of particle energization in space plasmas
- Interpret observations not accessible with high-quality multi-point in situ measurements
- Additional major impact on understanding:
  - magnetosphere-ionosphere coupling
  - space weather science
- European leadership in space plasma physics for both science and hardware
- Very large and active European and international community

**Relativistic electron acceleration at quasi-parallel shocks**

- Supernova remnant shock
- Saturn’s bow shock
- Earth’s bow shock

(Wilson et al., PRL, 2016)

Masters et al., Nature Physics, 2013

Reynoso et al., AJ, 2013
Mission profiles and technological developments

- Equatorial orbits through Key Science Regions:
  - pristine and shocked solar wind, bow shock, magnetopause and magnetotail

- Two L-class constellation options:
  - 7 identical spacecraft (Cross-Scale like)
  - 1 Mother + 6 smaller identical daughter spacecraft (Scope-like)

- Technological developments:
  - use of smallsats
  - constellation management (ISL, ranging, ...)
  - payload miniaturization, new instruments (e.g. particles) and industrial production and testing
  - more autonomous spacecraft and science operations
Worldwide context

- The need for a multi-point, multi-scale constellations to study space plasmas is recognized as important by ESA, NASA, JAXA, CSA, CAS-NSSC, Roscosmos, CNES

- Contributions by other agencies would enhance the science return of the Plasma Observatory

- Synergies with coordinated measurements from other near-Earth missions and ground observatories -- coverage of near-Earth space from kinetic to global scales.

- Plasma Observatory has strong support form international science community

...it is now vital to move on from Cluster, which has four satellites operating in company at relatively large distances, to simultaneous observations at a much larger number of points... (page 31)
Summary

- Science theme: “How are charged particles energized in space plasmas?” Unsolved problem of fundamental/astro plasma physics
- Open questions related to shocks, reconnection, waves and turbulence, jets and the interplay between these. Require resolving cross-scale coupling, nonlinearity and nonstationarity, which is not possible with existing observations.
- Science closure requires a new multi-point, multi-scale L-class Plasma Observatory with at least 7 spacecraft.
- Will enable a paradigm shift in particle energization with very important impact on solar and astrophysical plasmas.
- Next logical step after Cluster, THEMIS and MMS. ESA has expertise.
- European scientific and technical leadership in the space plasma research field.