Coupling of fundamental plasmas processes: what would bring multiscale aspects for particle energization physics

Alessandro Retinò[(1)], Y. V. Khotyaintsev[(2)], O. Le Contel [(1)], M. F. Marcucci [(3)], F. Plaschke [(4)], A Vaivads [(5)] & core Team of the ESA Voyage 2050 White Paper *"Particle Energization of Space Plasmas: towards a multi-scale, multi-point Plasma Observatory."*

[(1)]*LPP-CNRS, Paris, France,* [(2)] IRFU*, Uppsala, Sweden,* [(3)]*IAPS-INAF, Rome, Italy,* [(4)] *IWF-OEAW, Graz, Austria,* [(5)] *KTH, Stockholm, Sweden*

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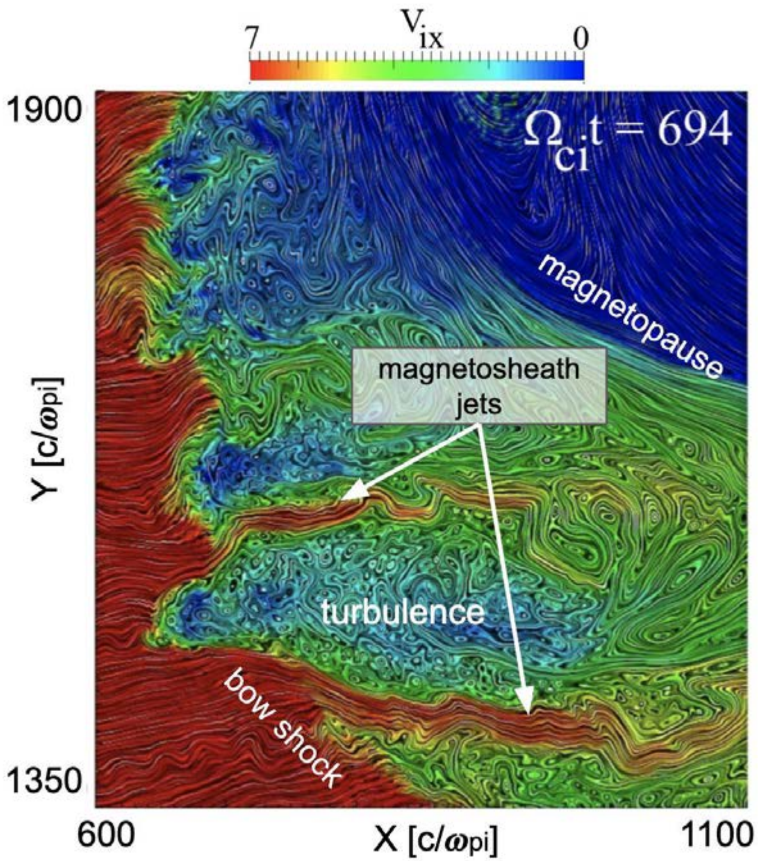
alessandro.retino@lpp.polytechnique.fr

Motivation

One of the major insights coming from Cluster, THEMIS and MMS missions, as well as from recent 3D supercomputer simulations, is that in real systems different particle energization processes are often combined in a complex way:



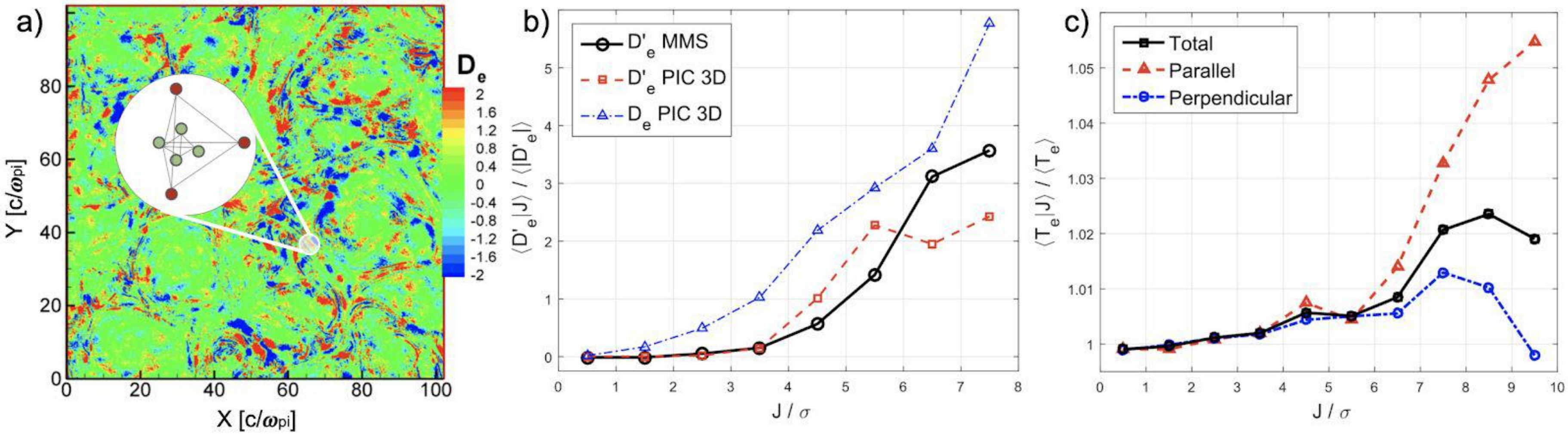
- small-scale reconnection in turbulence (Retino+,NatPhys, 2007; Phan+, Nature, 2018)
- turbulence in large-scale reconnection (Fu+, GRL, 2017),
- turbulence at shocks (Schwartz+, GRL, 1991)
- reconnection at shocks (Wang+,
- GRL, 2019; Gingell+., GRL, 2019).

Large-scale kinetic simulations even show the combination of shocks, reconnection, turbulence and jets in the same region (Karimabadi+, PoP, 2014; Matsumoto+ Science, 2015).

Addressing these questions requires designing missions that can go beyond the approach of existing missions focusing on a single process at a time.

Example 1
How are particles energized by turbulent fluctuations

One very important science case demonstrating the need for new multi-scale measurements is particle energization due to the energy dissipation in coherent structures generated by turbulence, which are localized both in space and time (Matthaeus+, PTRSA, 2015). These include thin current sheets, magnetic islands, isolated flux tubes, and small-scale vortices.



Energy dissipation and particle energization in turbulence due to coherent structures. a) spatial distribution of energy dissipation as seen in PIC simulations, showing that dissipation is concentrated at kinetic-scale coherent structures (Wan+, PoP, 2016). b) simulations and MMS observations (Chasapis+, ApJ,2018) showing that the strongest dissipation occurs in regions of highest current. c) MMS measurements of electron heating showing that strong parallel electron heating is associated to dissipation and high currents.

Example 1
How are particles energized by turbulent fluctuations

State of art.
Cluster measurements at ion scales have shown energy dissipation and particle energization at thin current sheets observed in the turbulent solar wind which can be associated to small-scale reconnection (Retino+, NatPhys, 2007). However, Cluster measurements could not resolve the electron scales. **MMS** measurements have resolved electron-scale coherent structures e.g. electron-scale reconnection events (Phan+, Nature, 2018; Stawarz+, ApJ, 2019) and other electron-scale coherent structures, such as magnetic holes and vortexes (Huang+, JGR, 2017). No simultaneous observations at ion and fluid scales that are driving the turbulent energy input and coherent structure formation and therefore does not allow the coupling between scales to be addressed.

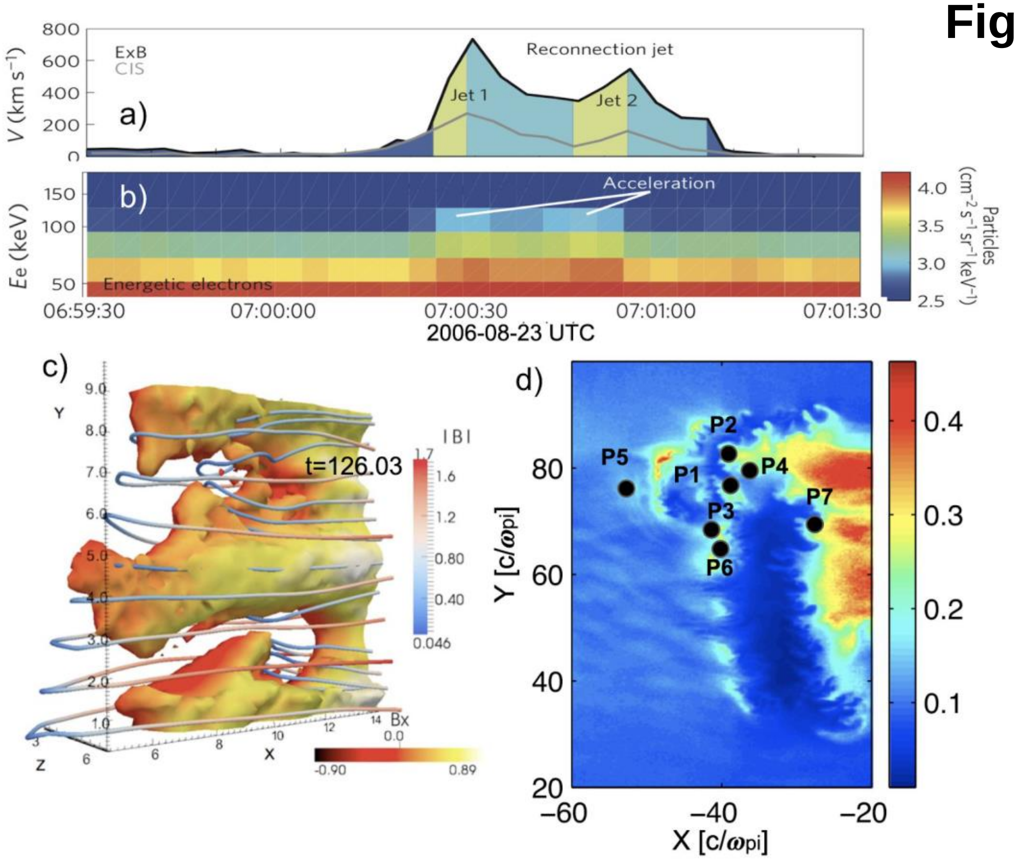
Future multi-scale, multi-point measurements.

At least 7 measurement points distributed in space to cover multiple scales are needed to resolve scale coupling in turbulent coherent structures and assess how it controls particle energization mechanisms. This would allow the correct identification and full description of coherent structures at different scales, as well as the turbulence conditions on larger scales. It would remove the severe approximations arising in the 4-spacecraft techniques, which are mostly based on linearity and stationarity assumptions for obtaining 3D propagation and shape. In addition, measurements of particle distributions should have higher time resolution electron measurements and higher phase-space resolution to resolve the fine details of the particle distributions that can reveal the nature of the dissipative processes (Schekochihin+, JPP, 2016; Servidio+, PRL, 2017). High time resolution mass-resolved ions should also be measured to evaluate the differential energization of protons and α particles (Perrone+, ApJ, 2013).

Example 2
How are particles energized in plasma jets

Another science case demonstrating the need of new multi-scale measurements is electron energization at plasma jet fronts in the magnetotail. Simulations and spacecraft observations indicate that fluid, ion and electron are strongly coupled as well as jet fronts are often very structured due to the développement of different instabilities.

Figure 1



In situ observations of reconnection jets (a) associated to large-scale energization (b) (Fu+, NatPhys,2013). Numerical simulations showing nonlinear structures at jet fronts: c) 3D isosurfaces of density with superimposed field lines from MHD simulations (Lapenta+,GRL, 2011). d) parallel electron temperature from PIC simulations (Pritchett, JGR, 2016). Schematic 7 spacecraft constellation, P1-P7, would allow to characterise the spatial and temporal evolution of electron energization at jet fronts as well as scale coupling.

Example 2
How are particles energized by turbulent fluctuations

State of art.

At large temporal and spatial scales, electron acceleration at jet fronts results from adiabatic betatron and Fermi mechanisms within large-scale magnetic flux tubes (Ashour-Abdalla+, NatPhys, 2011) and this prediction has been confirmed by observations (Fu+, GRL, 2011; Fu+, NatPhys, 2013), see Figure 1. On the other hand, Cluster and THEMIS observations indicate that important conversion of electromagnetic energy occurs at kinetic scales (Angelopoulos+, Science, 2013; Khotyaintsev+, GRL, 2017) and this was recently confirmed by MMS observations (Liu+, GRL, 2018). The scale coupling between fluid and kinetic scales is however not understood.

Future multi-scale, multi-point measurements.

At least 7 measurement points are needed in order to resolve the coupling between fluid and kinetic scales.

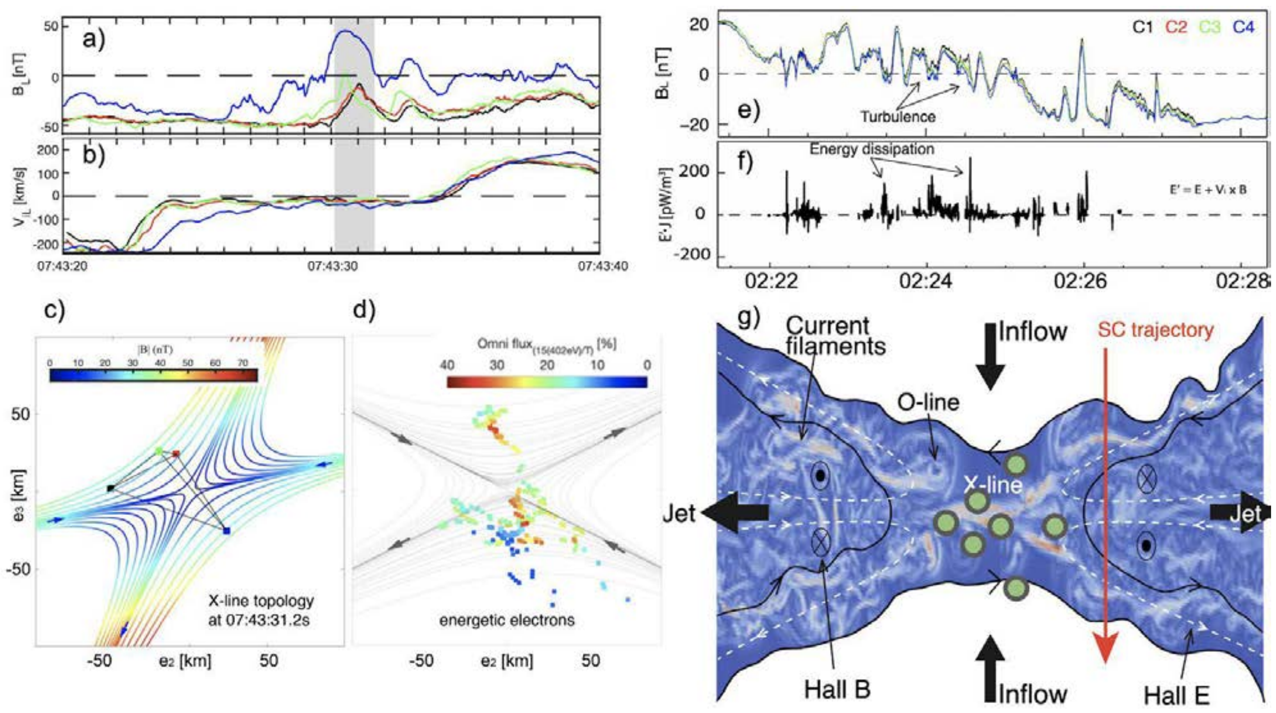
In addition, many 3D nonlinear structures at jet fronts fluid exist are important sites of electron energization (also for ions). All these structures are nonlinear and nonstationary structures whose spatial and temporal evolution cannot be resolved with 4-point measurements even at a given scale. At least 7 measurement points are needed to characterize the spatial and temporal evolution of jet fronts and associated electron energization sites.

Example 3

How are particles energized in turbulent reconnection

Another science case demonstrating the need of new multi-scale measurements is particle energization during turbulent reconnection, where reconnection and turbulence strongly couple (Lazarian+, ApJ, 1999; Daughton+, NatPhys, 2011).

Figure 2



Laminar EDR (Fu+, 2019) : MMS measurements of a) magnetic field and b) reconnection jet reversal. Results form FOTE method: c) magnetic field topology d) map of electron energization. Turbulent IDR (Fu+, GRL, 2017): Cluster measurements of e) magnetic field showing current filaments and f) energy dissipation and g) cartoon showing a schematic 7 spacecraft constellation that would allow to resolve the spatial and temporal evolution of the turbulent diffusion region and particle electron energization therein.

Example 3
How are particles energized in turbulent reconnection

State of art.
MMS measurements have shown examples of EDRs that are laminar. Panels a-d in Figure 2 shows one such laminar EDR at the magnetopause. For such laminar EDRs, 4-point measurements can reveal the electron and ion dynamics in a satisfactory manner.

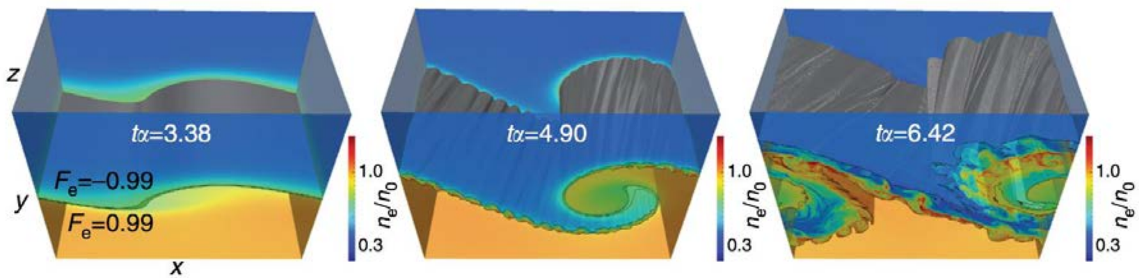
However, other cases (Daugthon+, NatPhys, 2011; Lapenta+, NatPhys, 2015; Fu+, GRL, 2017; Cozzani+, PRE, 2019) indicate that the reconnection diffusion regions can be rather turbulent, with the formation of many intermittent structures such as thin current sheets, magnetic islands, vortexes and magnetic holes which are very efficient to energize particles. See Panels e-g in Figure 2. Other spacecraft observations support this, e.g. observations of coalescing flux ropes (Wang+, NatPhys, 2016) and magnetic holes (Zhong+, GRL, 2019). For such nonlinear structures, available four-point measurements are not enough to reveal their topologies and the associated particle energization mechanisms.

Future multi-scale, multi-point measurements.

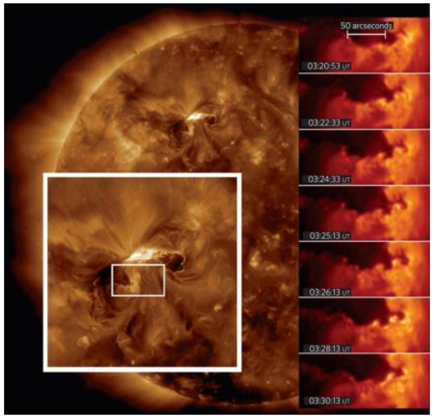
At least 7 measurement points are needed to fully characterize both the fluid-ion-electron scale coupling and the non-linear and non-stationarity structure of turbulent reconnection and associated particle energization sites

Other examples

1. Particle energization by Kelvin-Helmholtz waves
2. Particle energization in magnetosheath jets
3. Reconnection in shocks



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



CME eruption seen by the SDO spacecraft (Ofman+, ApJ, 2011). The large white box is a magnified view of the erupting structure. Right: temporal evolution of Kelvin–Helmholtz vortices at the boundary between the dark region, corresponding to evacuated material, and the surrounding ambient material (seen in the small white box). Strong heating may occur within Kelvin-Helmoltz vortices through wave-particle interaction. Adopted from Retino, Nat.Phys., 2016.

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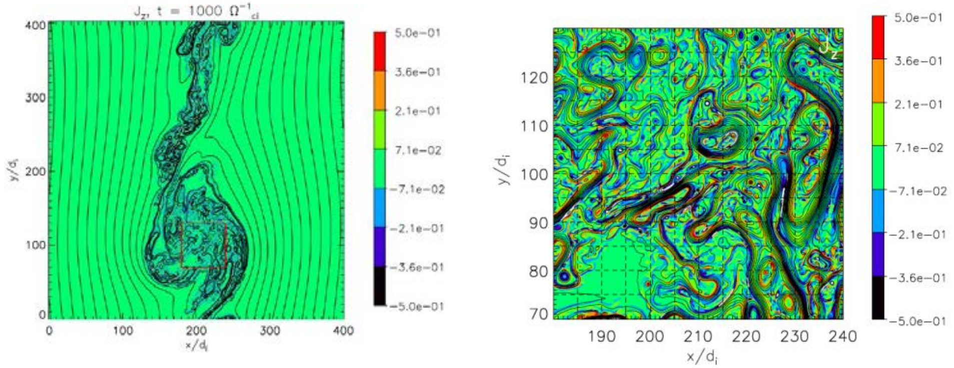

Formation of coherent structures and reconnecting current sheets in two-fluid KH simlulations (Rossi+, PoP., 2015)

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Conclusions

1. Supercomputer simulations and current multi-spaceraft data (Cluster, THEMIS, MMS) clearly indicate that the picture with separated processes (shocks, reconnnection, turbulence, jets) needs to be abandoned

2. Reconnection occurs in a variety of situations other than large-scale, laminar current sheets such as those in solar wind, magnetopause and magnetotail

3. Particle energization likely to be much enhanced thorugh coupling with other processes such as turbulence and waves, shock and jets.

4. **Current 4-point measurements cannot resolve such physics. At least 7 spacecraft are needed to resolve both scale coupling and non-linearity/non-stationarity at a given scale.**

5. An L-classs « Plasma Observatory » consisting of at least 7 spacecraft covering fluid, ion and electron scales is strongly needed to enable a paradigm shift in our comprehension of particle energization and space plasma physics in general. It will be the next logical step following Cluster, THEMIS and MMS for the very large and active international space plasmas community.

Thank you for your attention

Material adopted from the White Paper *“Particle Energization of Space Plasmas: towards a multi-scale, multi-point Plasma Observatory ”* submitted to the Voyage 2050 long term plan in the ESA’s Science Programme

Contact scientist: Alessandro Retinò

alessandro.retino@lpp.polytechnique.fr