Title of the Project :

Magnetic reconnection at the magnetopause : effects of cold ions and guide field

Supervisors :
Olivier Le Contel, directeur de recherche CNRS, HDR
Alessandro Retino, CRCN CNRS

Laboratory : Laboratoire de Physique des Plasmas (UMR7648)

1. Context and Research Problem

The NASA Magnetospheric Multiscale (MMS) mission was successfully launched on 12th of March 2015. As the European (ESA) Cluster mission, it consists of four identical satellites evolving in a tetrahedral configuration with separations near the electron Larmor radius in the Earth magnetosphere. Such a configuration allows to estimate the local current density from the calculation of the curl of the magnetic field measured on four points (neglecting the displacement current for perturbations with velocity smaller than the speed of light). Furthermore, the unprecedented high temporal resolution of the particle detectors, which provide the distribution functions at 30ms for electrons and at 150ms for ions, allows to measure the current density independently of the magnetic field measurements.

The satellites also measure the three-dimensional electromagnetic fields from quasi-static to few kHz and evolve around the Earth along an equatorial orbit with apogees between 12 and 30 Earth radii. Along this orbit, the satellites cross the Earth's magnetopause many times, the boundary between the solar wind and the magnetosphere. When the interplanetary magnetic field (IMF) transported by the solar wind is oriented southward, magnetic reconnection with the Earth's magnetic is favored in the subsolar region. During this process, which has been studied for a long time thanks to various space missions (Geotail, Polar, Cluster, THEMIS, MMS, ...), the magnetic energy is transferred to plasma which is heated and accelerated. Such conditions are also relevant during impact to the Earth's magnetosphere of large scale solar wind disturbances coming from the Sun. This PhD research project is part of the studies needed to improve our knowledge of Sun-Earth relations and our capability in terms of space weather forecasting. A better understanding of energy and mass transfers from the solar wind to the magnetosphere will help us better anticipate the effects of large-scale solar disturbances. These large-

scale disturbances are important to study, as they can cause major disruption to human activities on the ground (power plants, communications, positioning, etc.) as well as in near-Earth space.

2. Science Objective

The PhD thesis aims at studying the dependence of the collisionless magnetic reconnection process at the Earth's magnetopause on the presence of magnetospheric cold ions, which can be detected by MMS, as well as on the existence of a magnetic field component perpendicular to the reconnection plane, named guide field. Indeed, these two elements are often present in relation to impacts of large-scale perturbations generated by the Sun and transported by the solar wind (coronal mass ejection, corotating interaction regions, high speed solar wind from coronal holes, …). They are important as they can modify the energy and mass transfers from the solar wind to the magnetosphere. Indeed, it was shown that the presence of cold ions reduces the reconnection rate and the current density perpendicular to the background magnetic field, enhances the parallel currents and increases the electron pressure gradient normal to the magnetopause, causing an enhancement of the electron decoupling from the magnetic field (Toledo-Redondo et al. 2017, Baraka et al., 2025a,b). On the other hand, the presence of an out-of-plane magnetic field component during the reconnection process can move the reconnection region along the magnetopause by the effect of a new Lorentz force and could even inhibit the reconnection process (Swisdak et al. 2003, Pritchett and Mozer, 2009, Eastwood et al. 2013, Aunai et al. 2013, Baraka et al., 2025b).

References

Aunai, N., M. Hesse, S. Zenitani, M. Kuznetsova, C. Black, R. Evans, and R. Smets, Comparison between hybrid and fully kinetic models of asymmetric magnetic reconnection: Coplanar and guide field configurations, Physics of Plasmas, 20(2), 022,902, doi:10.1063/1.4792250, 2013.

Baraka, M., O. Le Contel, P. Canu, S. W. Alqeeq, J. Dargent, and et al, MMS analysis of a dayside compressed magnetospheric separatrix in the presence of cold ions and a moderate guide field, JGR – Space Physics, under review, 2025a.

M. Baraka, PhD thesis (ED AAIF-127), Study of Dayside Magnetic Reconnection in the Presence of Cold Ions and Guide Field : A Focus on Magnetospheric Separatrix, Sorbonne Université, Paris (10th of February 2025), 2025b.

Eastwood, J. P., T. D. Phan, M. Øieroset, M. A. Shay, K. Malakit, M. Swisdak, J. F. Drake, and A. Masters, Influence of asymmetries and guide fields on the magnetic reconnection diffusion region in collisionless space plasmas, Plasma Physics and Controlled Fusion, 55(12), 124,001, doi:10.1088/0741-3335/55/12/124001, publisher: IOP Publishing, 2013.

Pritchett, P. L., and F. S. Mozer, Asymmetric magnetic reconnection in the presence of a guide field, Journal of Geophysical Research: Space Physics, 114(A11),doi:10.1029/2009JA014343,_eprint:https://onlinelibrary.wiley.com/doi/pdf/10.1029/2009JA014343, 2009.

Swisdak, M., B. N. Rogers, J. F. Drake, and M. A. Shay, Diamagnetic suppression of component magnetic reconnection at the magnetopause, Journal of Geophysical Research: Space Physics, 108(A5), doi:10.1029/2002JA009726, _eprint:https://onlinelibrary.wiley.com/doi/pdf/10.1029/2002JA009726, 2003.

Toledo-Redondo, S., et al., Energy budget and mechanisms of cold ion heating in asymmetric magnetic reconnection, Journal of Geophysical Research: Space Physics, 122(9), 9396–9413, publisher: Wiley Online Library, 2017.

3. Justification of the Scientific Approach

This PhD project will be carried out by analyzing and comparing in situ measurements from MMS and numerical results from 2D Particle-In-Cell (PIC) simulations, performed with similar plasma conditions using the collaborative SMILEI code. In situ space data, results from numerical simulations as well as tools of data analysis developed in python are available. New kinetic simulations using national high-performance computers (CINES/Adastra) will be run with initial conditions as close as possible of in situ conditions based on results from a statistical study. For the preparation of the new projects of multi-satellite missions HelioSwarm/NASA (1 plateform + 8 small satellites, selected in 2022) and Plasma Observatory/ESA (1 plateform + 6 small satellites, in a competitive Phase A until June 2026) in which LPP is strongly involved, the study of virtual spacecraft trajectories across the simulated reconnection region as well as the development of new multipoint analysis tools are also planned. The PhD student will also collaborate with postdocs M. Baraka, J. Dargent from the LPP space plasma team, with Arnaud Beck form laboratoire Leprince-Ringuet (LLR), and with the international teams from the mentioned space missions in particular J. Burch (MMS PI/SWRI Texas), R. Torbert (MMS coPI, UNH New Hampshire), B. Ergun&N. Ahmadi (LASP, colorado), D. Gershman&K. Bromund (GSFC, Maryland), H. Wei (UCLA, California), Y. Khotyaintsev&D. Graham&C. Norgren (IRF, Uppsala), R. Nakamura (IWF, Graz).

4. Work Plan

1st year: November 2025 –November 2026 (in collaboration with M. Baraka postdoc at LPP)

Statistical study of magnetopause reconnection events detected by MMS with cold ions and guide field. Analysis of the current density structure of the magnetopause and generalized Ohm's law. Analysis of energy conversion and partitioning (ions and electrons).

2nd year: November 2026 –November 2027 (in collaboration with J. Dargent postdoc at LPP, A. Beck (IR at LLR)

Run 2D PIC simulations (SMILEI code) using initial conditions based on the results of the statistical study. Analysis of the current density structure of the magnetopause and generalized Ohm's law. Analysis of energy conversion and partitioning (ions and electrons). Comparison with results of the statistical study.

3rd year November 2027 –November 2028

Using most representative 2D PIC simulations, trajectories of virtual satellites will be used to prepare the analysis of the future multi-satellite missions HelioSwarm (9 satellites, in NASA phase B) and Plasma Observatory (7 satellites, in an ESA competitive phase A). New tools for data analysis of more than 4-point measurements will be studied.

5. Alignment with the Plas@par Program

Magnetic reconnection is an universal and ubiquitous physical process in plasma physics (astrophysical plasmas, fusion plasmas, plasmas for thruster, plasma generated by laser, ..), this PhD project is therefore at the heart of the plas@par federation's research.

6. Supervision and Expertise

O. Le Contel is Lead CoI of the SCM instrument onboard the MMS mission and is author and co-author of many publications, which focused on the collisionlesss magnetic reconnection process at the Earth's magnetopause. He co-supervised three PhD students working on MMS data and in particular M. Baraka until his

PhD defense on Feb. 10, 2005. This PhD research project is a follow-up of his PhD work.

A. Retino is an international expert on magnetic reconnection. He co-supervised two PhD students and in particular G. Cozzani who investigated the electron diffusion dynamics using MMS data.

7. Publications and Collaborations

O. Le Contel, et al., The Search-Coil Magnetometer for MMS, Space Science Reviews, Springer Verlag, 2016, 199 (1-4), pp.257-282. ⟨10.1007/s11214-014-0096-9⟩.

O. Le Contel, **A. Retino,** et al., Whistler mode waves and Hall fields detected by MMS during a dayside magnetopause crossing, Geophysical Research Letters, American Geophysical Union, 2016, 43 (12), pp.5943 - 5952. ⟨10.1002/2016GL068968⟩.

G. Cozzani, **A. Retinò**, F. Califano, A. Alexandrova, **O. Le Contel**, et al., In situ spacecraft observations of a structured electron diffusion region during magnetopause reconnection, *Physical Review E*, 2019, 99 (4), pp.043204 (2019). ⟨10.1103/PhysRevE.99.043204⟩

M. Akhavan-tafti, D. Fontaine, J. Slavin, **O. Le Contel**, D. Turner, Cross-Scale Quantification of Storm-Time Dayside Magnetospheric Magnetic Flux Content, Journal of Geophysical Research Space Physics, American Geophysical Union/Wiley, 2020, 125 (10), ⟨10.1029/2020JA028027⟩.

M. Baraka, **O. Le Contel**, et al., MMS analysis of a dayside compressed magnetospheric separatrix in the presence of cold ions and a moderate guide field, Journal of Geophysical Research Space Physics, under review, 2025a.

M. Baraka, PhD thesis (ED AAIF-127), Study of Dayside Magnetic Reconnection in the Presence of Cold Ions and Guide Field： A Focus on Magnetospheric Separatrix, Sorbonne Université, Paris (10th of February 2025), 2025b.

CVs of superviser and co-superviser (O. Le Contel and A. Retino)

Olivier Le Contel			
Institution:	Laboratoire de Physique des Plasmas (UMR7648)		
Current Position:	Director of research at CNRS, CoLead of the Space Plasma Team		
Education:	Ph.D.	University of Paris 7, Paris	19/12/1997
	M.S.	University of Paris 7, Paris	06/1992
	B.S.	University of Paris 6, Paris	06/1990
Relevant Background and Demonstrated Experience			
2024	ESA M7 (phase A) Plasma Observatory SCM PI, LPP		
2023-2024	ESA Cluster STAFF PI, LPP		
2022-now	NASA HelioSwarm SCM CoI, LPP • Responsible (Lead instrument) for the 9 HS SCM Supervision of Design, fabrication, assembly, testing and calibration. Ground segment, L2 data validation, French (CNES) archiving.		
2002-now	NASA MMS SCM Lead-CoI, LPP • Co-Responsible with Alain Roux (LPP) for the MMS SCM until 2008, Responsible from 2008 until now. Supervision of Design, fabrication, assembly, testing and calibration. Ground segment, L2 data validation, French (CNES) archiving, and Science data analysis.		
2002-now	NASA THEMIS SCM CoI, LPP • Co-Responsible with Alain Roux (LPP) for the THEMIS SCM until 2008, Responsible from 2008 until now. Supervision of Design, fabrication, assembly, testing and calibration. Ground segment, L2 data validation, French (CNES) archiving, and Science data analysis.		
2002-now	ESA Solar Orbiter SCM&LFR CoI and BepiColombo MMO DB-SC CoI, LPP • Support Design, Calibration tasks, ground segment and Science data analysis.		
Relevant Awards and Honors			
• MMS "RHG Exceptional Achievement for Engineering Award" (NASA) 04/2016 • MMS "Group Achievement Award" (NASA) 09/2016 • THEMIS "Group Achievement Award"(NASA) 03/2007 • THEMIS "Project Recognition" , Space Science Laboratory 03/2007			
Selected Publications related to wave/particle interaction, plasma confinement&transport			
D. Graham, Yu. Khotyaintsev, M. André, A. Vaivads, A. Divin, J. Drake, C. Norgren, **O. Le Contel**, P.-A. Lindqvist, A. Rager, D. Gershman, C. Russell, J. Burch, K.-J. Hwang, K. Dokgo, **Direct observations of anomalous resistivity and diffusion in collisionless plasma**, *Nature Com*, 2022, (10.1038/s41467-022-30561-8)			
J. Stawarz, J. Eastwood, T. Phan, I. Gingell, P. Pyakurel, M. Shay, S. Robertson, C. Russell, **O. Le Contel**, **Turbulence-driven magnetic reconnection and the magnetic correlation length: Observations from Magnetospheric Multiscale in Earth's magnetosheath**, *PoP,doi:* (10.1063/5.0071106), 2022			
Le Contel, O., et al. **Lower Hybrid Drift Waves and Electromagnetic Electron Space-Phase Holes Associated With Dipolarization Fronts and Field-Aligned Currents Observed by the Magnetospheric Multiscale Mission During a Substorm**, JGR, doi: 10.1002/2017JA024550, 2017			
Le Contel, O., et al., **The search-coil magnetometer for MMS**, Space Sci. Rev., doi: 0.1007/s11214-014-0096-9, 2016.			
Le Contel O., A. Roux, et al., **First results of the THEMIS Search Coil Magnetometers**, Space Science Review, doi:10.1007/s11214-008-9371-y, 2008.			
Professional Societies, Committees, and Boards			
EGU and SF2A member More details: https://www.lpp.polytechnique.fr/-Olivier-Le-Contel-?lang=en			

Curriculum vitæ et studiorum - Alessandro Retinò

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Education
5/2007: Ph.D. in Space and Plasma Physics, Uppsala University, Uppsala, Sweden
11/2002: M.Sc. *cum laude* in Astro and Space Physics, University "La Sapienza", Rome, Italy

Research positions
From 01/2024: Co-leader of the Space Plasmas Group of LPP
01/2018 – 12/2021: Co-leader of the Space Plasmas Group of LPP
01/2012 – 3/2012 : visiting professor, ISAS – JAXA, Japan
From 10/2010: permanent CNRS associate researcher, LPP, France
10/2007 – 09/2010: junior scientist, Space Research Institute, Graz, Austria
06/2007 – 09/2007: postdoc, Swedish Institute of Space Physics Uppsala, Sweden
05/2006 – 08/2006: visiting scientist, Space Sciences Lab., University of California, Berkeley, USA
12/2002 – 05/2007: graduate student, Swedish Institute of Space Physics, Uppsala, Sweden

Research activity
- Analysis and interpretation of in situ spacecraft observations in solar system plasmas (solar wind, planetary magnetospheres)
- Development of data analysis routines, including machine-learning techniques
- Development of in situ spacecraft instrumentation (search coil magnetometers, ion mass spectrometers)
- ElectroMagnetic Compatibility (EMC) studies and spacecraft simulations (SPIS)
- Definition of concepts for future spacecraft mission
- Management of payload and spacecraft projects (phases: 0/A, development, commissioning, cruise, science)

Selected spacecraft projects responsibilities
- From 2022: co-Lead Scientist of the ESA Plasma Observatory mission (Phase 0/A as M7 candidate) and Lead CoI of the Ion Mass Spectrometer (IMS-M)
- From 2020: Calibration Lead of the Search Coil Magnetometer (SCM) of the NASA HelioSwarm mission
- From 2015: Lead CoI of the Search Coil Magnetometer (SCM) of the Radio and Plasma Waves Instrument (RPWI) onboard the ESA JUICE mission
- 2015-2017: Science Coordinator of the ESA THOR mission (Phase 0/A as M4 candidate) and PI of Ion Mass Spectrometer (IMS)

Publications
Dr. Retinò is author of 110 peer-reviewed articles in international journals (H-index 43), 196 (proceedings, conference presentations, posters, white papers etc.), 15+ technical reports (payload/mission proposals, Assessment Study Report, project data packs etc.) and 45+ Invited presentations in international conferences & workshops (first author only). He has supervised a total of 10 PhD students and postdocs.

Schematic illustrating the PhD research project