SF2A 2016
C. Reylé, J. Richard, L. Cambrésy, M. Deleuil, E. Pécontal, L. Tresse and I. Vauglin (eds)

KINETIC SIMULATIONS OF COLLISIONLESS MAGNETIC RECONNECTION

N. Aunai[1], J. Dargent[1, 2], B. Lavraud[2,], A. Ciardi[3], M. Drouin[3,] and R. Smets[1]

Abstract. This paper focuses on magnetic reconnection and its role in magnetospheric physics, where collisions are inexistant. In this context, the presence of a very cold ion population of ionospheric origin is known to have an important contribution to the particle density at the magnetopause. However, besides this mass loading effect, consequences of their extremely low temperature, and therefore of their must smaller gyroscale, have not yet been addressed from a modeling viewpoint. This study presents two fully kinetic simulations with and without cold ions in the magnetosphere and highlights how their small Larmor radius can change signatures expected to be proxy of the X line in spacecraft measurements. In a second part, this paper addresses shortly the problem of the X line orientation in an asymmetric system. Using this time hybrid kinetic simulations, we show the X line aligned with the bisector of upstream magnetic field vectors results in faster reconnection rate. This have consequences regarding where reconnection at the magnetopause, although models here do not include large scale dynamics. We conclude with perspectives regarding future developments to address multi-scale magnetic reconnection dynamics at the magnetopause.

Keywords: magnetic reconnection, Particle-In-Cell, magnetopause

1 Introduction

Magnetic reconnection is undoubtedly one of the most important process in astrophysical plasma physics. First, by suddenly releasing magnetic energy stored in large scale systems for long times it often is an interesting candidate for acceleration and heating events observed in the universe. Second, by enabling large scale magnetic connectivity to be changed, it can drastically impact plasma transport. The Earth magnetosphere and nearby solar wind constitute the best environments to study the phenomenon, since theories and models can directly be compared to in situ spacecraft measurements. Numerical models have and continue to be a major asset in understanding basics mechanisms at the root of the complex nonlinear reconnection dynamics, and an important source of data to interpret in situ measurements. The goal of this paper is to highlight in a small review the main conclusion of recent studies we did on the magnetic reconnection process occurring at the magnetopause. We first discuss recent numerical results regarding how an often observed very cold ionospheric ion population impacts expected signatures of the X-line region and may enable us to assert its identification in spacecraft in situ data(Dargent et al. 2016). We will then focus on hybrid kinetic modeling, which, by neglecting the kinetic nature of electrons, enable us to model larger domain for longer times to understand how is the reconnection X-line oriented in the general case of asymmetric magnetopause reconnection. The full details of this study have been published recently (Aunai et al. 2016). We will then conclude our paper with perspectives regarding large scale modeling of magnetopause magnetic reconnection.

2 Fully kinetic simulations: role of cold ions in magnetopause reconnection

In collisionless systems, particle dynamics is the result of collective effects, and populations are free to mix without any bulk energetization (heating). Whenever reconnection occurs in current sheets separating different

[1] Laboratoire de Physique des Plasmas, Ecole Polytechnique, CNRS, UPMC, Université Paris Sud, route de Saclay, 91128 Palaiseau Cedex
[2] Institut de Recherche en Astrophysique et Planétologie, CNRS, Toulouse, France
[3] LERMA, Universite Pierre et Marie Curie, Observatoire de Paris, Meudon, France c Ecole Normale Superieure, Paris, France. UMR 8112 CNRS

plasma sources, it unavoidably mix particle populations otherwise separated. Interpreting the overall dynamics with a fluid (macroscopic) formalism, becomes questionable. The Earth magnetopause is one such environment, as it separates the solar wind plasma, from the comparatively hot and tenuous magnetospheric one. The so-called *asymmetric reconnection* process taking place here is far richer and more complex than *symmetric reconnection* where reconnected plasmas have identical field and particle properties. The numerical modeling of Solar wind/ magnetosphere reconnection has been the topic of intense research over the last decade, including comparisons to in situ spacecraft measurements(Mozer & Pritchett 2011; Mozer et al. 2008). One ingredient has however been neglected so far in models though it may play an important role at the magnetopause: the omnipresence of very cold ions of ionospheric origin on the magnetosphere side of the boundary(Sauvaud et al. 2001; André & Cully 2012; Walsh et al. 2014; Toledo-Redondo et al. 2015; Fuselier et al. 2016). Although here most of the time, and in important proportions (if not dominant), these particles are almost always forgotten because their low energy make them almost invisible to particle detectors. What is the consequence of accounting for this population in addition to the hot magnetospheric population in reconnection models? An immediate answer is that they bring more material than otherwise and should therefore lower the reconnection rate(Borovsky & Denton 2006; Borovsky et al. 2008; Wang et al. 2015). This so-called *mass loading* effect has been noticed several times already. However the fact that this additional population has an extremely low temperature, and therefore brings lots of particles with a tiny gyroradius has yet been unexplored and should lead to sensible changes in the microphysics of reconnection. In this study, we therefore performed two fully kinetic Particle-In-Cell (PIC) simulations in a two-dimensional geometry, differing only by the velocity distribution function of magnetospheric ions. Keeping both identical total density, current and temperature profiles through the initial current sheet, and so ruling out the previously observed mass-loading effect, we represent, in run **A**, the magnetosphere protons as a single locally maxwellian population, while run **B** represents them as two distinct populations, one being 500 times colder than the other. In both simulations, the ratio between the plasma density in the magnetosphere and in the magnetosheath is 0.25, and the magnetic field is twice stronger in the magnetosphere side than in the magnetosheath side. Simulations are ran until reaching a quasi-steady state, i.e. a time at which upstream magnetic flux is reconnected at constant rate. Both simulations reach that point after ≈ 120 inverse cyclotron frequencies and reveal very similar reconnection rate and overall evolution. This great similarity is expected since, although enabled by small scale microphysics processes, reconnection overall mostly depends on macroscopic quantities and two-fluid effects, which are here identical in both runs. However, when looking carefully at small scale signatures, the two simulations differ noticeably in an interesting way.

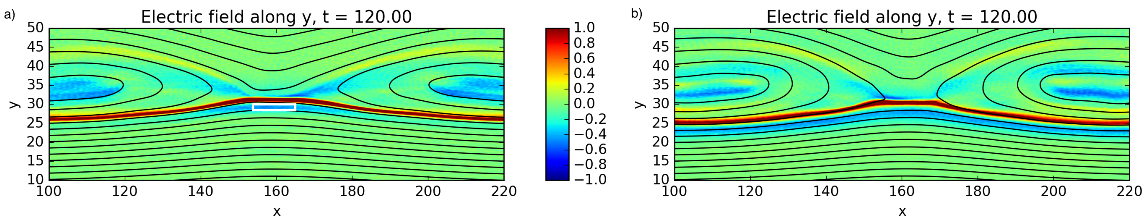

Fig. 1. E_y component of the electric field represented in color, with superimposed in-plane magnetic field lines as solid black lines. **Left:** snapshot from run A **Right:** Snapshot from run B.

Figure 1 shows the vertical component (E_y) of the electric field of both simulations. As very well known now, the magnetospheric separatrix is the locus of an intense electric field pointing towards the magnetosheath. This field, already noticed in spacecraft measurements, easily allows observers to discriminate the magnetosheath separatrix from the magnetospheric one. However, it exists all along the separatrix and is useless to identify the X-line region. More recently, another electric field structure has been pointed out as an interesting proxy of the X-line. The so-called Larmor electric field, is a small area, confined to the X-line region, on the magnetospheric side, where the vertical component of the electric field reverses and points towards the magnetosphere(Malakit et al. 2010). Although its amplitude (much weaker than the strong magnetospheric peak) and width can vary from one case to the other, PIC simulations of asymmetric reconnection consistently show this structure, which is therefore actively searched in spacecraft data when trying to identify X-line crossings. Interestingly however, when cold ions are present in the simulation (panel b), this negative electric field is not confined to the X line region anymore and extends all along the separatrix too, therefore becoming useless as an X-line proxy. Careful analysis of the simulations revealed the negative electric field arises from the initial phase of the simulation when reconnection had not started yet. It is associated with the bouncing of magnetosheath ions at the field reversal, which happen to mostly all make their U-turn at the same distance from the mid-plane. This statistically results in an apparent out-of-plane bulk velocity which, associated with the positive horizontal magnetic field here results in a vertical negative electric field. Once reconnection starts, it broadens the current sheet and this ion bounce mechanism becomes impossible everywhere but around the X line, where the current sheet stays thin, and the electric field disappears everywhere but there. However when cold ions are present, their Larmor radius is so small that the width of the initial electric field structure is actually larger. They therefore just $\mathbf{E} \times \mathbf{B}$ drift there thus maintaining the electric field. The full analysis would be too long to describe in this short review and can be found in (Dargent et al. 2016). An important conclusion to this study is that the presence of cold ions at the magnetopause should carefully be checked as their density is non negligible and their extremely low temperature will make them evolve quite differently from other ions, therefore modifying expected signatures.

3 Hybrid kinetic simulations: X-line orientation in asymmetric magnetic reconnection

Magnetopause reconnection involves vastly different plasmas, but also occurs on a surface where the magnetic shear strongly and continuously varies. The latter property leads to the very basic yet unsolved question of what is the local orientation of the reconnection X line, i.e. how is the line joining reconnection sites on the magnetopause surface oriented locally? Is this orientation set-up by the large scale interaction of the solar wind magnetic field and plasma with the magnetosphere ? Locally fixed by the reconnection process itself as a function of local relevant parameters such as the magnetic shear, amplitude jump and plasma asymmetry? Or is it the result of both large and small scale dynamics? Both ends of the problem have been addressed over the past, from global magnetohydrodynamic simulations to two-dimensional PIC models. Hybrid models, assuming an adequate dissipation mechanism is chosen(Aunai et al. 2013a), seem to result in reconnection rates and overall dynamics similar to those observed in full PIC models (Aunai et al. 2013b). In this work we take advantage of this to do a parametric study investigating what the orientation of the X line is as a function of the magnetic shear angle. Due to computing limitations, we restrict ourselves to 2D simulations, looking for the reconnection plane, given a magnetic and plasma configuration, maximizing the reconnection rate, and assuming that nature chooses the plane having the larger reconnection rate as the local orientation.

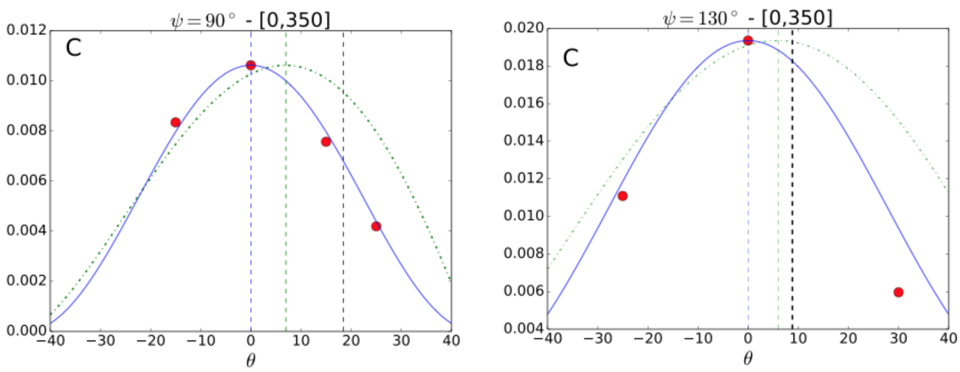

Fig. 2. Red points represent the reconnection rate, averaged over the entire simulation time, as a function of θ, the angle by which the simulation plane is rotated with respect to the magnetic configuration. The solid blue curve shows $B_1^2(\theta)B_2^2(\theta)$, the dashed-dotted green curves shows the Cassak-Shay scaling law for asymmetric reconnection rates based on upstream in-plane magnetic field amplitudes(Cassak & Shay 2007). The blue and green vertical lines represent the maximum of the blue and green curve, respectively. The black vertical line denotes the plane orientation for which the out-of-plane magnetic component is symmetric. This last orientation is the one routinely used in observations as the one of the reconnection plane, but is not, by far in the present results, the plane maximizing the reconnection rate.

Figure 2 shows, for two different magnetic shears, the average reconnection rate of an otherwise identical system, rotated around the direction normal to the current sheet. As we can see by looking at the red points on the plots, in either case the reconnection rate presents a strong variation as the simulation plane is rotated, and this variation presents a maximum. This trend, obtained from simulation data, is compared to different models, all predicting the most probable reconnection plane. Among the different models, the best fit is the blue curve, which is the product of the in-plane magnetic energy on each side of the current sheet $B_1^2(\theta)B_2^2(\theta)$, which incidentally is maximized for the plane defined by the bisector of upstream magnetic field vectors(Hesse et al. 2013). Other models either fit less the data or are completely off. An immediate conclusion of this study is that if reconnection evolves in 2D or quasi-2D fashion, that is that large scale inhomogeneities pre-existing reconnection and those developed by reconnection are dominantly contained in a plane, the reconnection rate will drastically change depending on what that plane is. Other studies seems to indicate this trend survives in full-PIC, in 2D as in 3D simulations. Whether the global path X-lines draw on the magnetopause surface strongly or marginally depend on this trend imposed locally, is an important question to solve. This will likely require multi-scale simulations, including a maximum of relevant microphysical effects as well as global solar wind / magnetosphere interaction.

4 Towards multi-scale kinetic modeling

The coupling of the solar wind and the earth magnetosphere is largely controlled by magnetopause reconnection. Although it has been clear for several decades now, that southward IMF leads to dayside reconnection and larger geo-effectiveness of solar wind structures than northward IMF, knowing of where, when and how reconnection occurs on the magnetopause surface clearly remains poorly understood. It is very likely that both microphysics and large scale dynamics play key roles in this interaction. Hybrid models represent an interesting compromise between the too computationally demanding description of the full Vlasov-Maxwell system and the rough solutions obtained from single or two fluid approaches. Moreover hybrid PIC models offer the advantage (over Vlasov hybrid approaches) to very easily account for multiple relevant ion populations as we have seen can co-exist. However, state of the art hybrid codes suffer from having to resolve propagation of dispersive waves coming with Hall physics which drastically limit simulation domains and times if one wants to have good separation between the ion gyroscale processes and well resolved dissipation scales. Therefore so far, most hybrid simulations either focus on detailed process modeling requiring high resolution and therefore can't include large scale dynamics, or on large scale physics but then usually badly resolve key processes enabled and largely controlled at small scales. An interesting fact about hybrid codes, that comes from calculating the electric field from an Ohm's law rather than using Maxwell's equations, is that they actually don't need to resolve Hall and smaller spatial scales to be stable. One only needs to resolve these terms where they are needed. This is a great advantage, compared to fully kinetic codes that usually have to resolve intrinsic plasma scales such as the Debye length. Based on these observations, we are currently working on designing a massively parallel hybrid code with block adaptive mesh refinement. Such a code should be able to focus space time resolution dynamically on regions that need it, and therefore confine intense computational load in small regions of space, while keeping a lighter resolution elsewhere. In the case of magnetopause reconnection for instance, such code would enable to account for both a good separation of ion and dissipation scales around X-lines and at the same time include large scale geometry and dynamics at a coarser level. Using the Multi-Level-Multi-Domain method, different levels of refinements are evolving in a rather independent way. This lets us imagine that within this decade, the hierarchy of levels could not only involve mesh refinement but also physics refinement, i.e. coarse levels could also be treated with a lighter formalism. For instance, regions involving only weak gradients in comparison to the local ion Larmor radius will not only see their mesh size increased but at some point should fall in a regime where the fluid approximation is more acceptable. Such multi-scale multi-physics developments are imperiously needed for more realistic simulations of systems having even larger scale separations such as the solar corona environment.

The authors acknowledge the ANR for funding the project MON-ANR (ANR-13-PDOC-0027) and the LabEx Plas@Par (project PHARE) supporting this research. The authors also thank the SMILEI development team. This work was granted access to the HPC resources of IDRIS and CINES under the allocation i2015047231.

References

André, M. & Cully, C. M. 2012, Geophysical Research Letters, 39, n/a

Aunai, N., Hesse, M., Black, C., Evans, R., & Kuznetsova, M. 2013a, Phys. Plasmas, 20, 042901

Aunai, N., Hesse, M., Lavraud, B., Dargent, J., & Smets, R. 2016, Journal of Plasma Physics, 82, 535820401

Aunai, N., Hesse, M., Zenitani, S., et al. 2013b, Phys. Plasmas, 20, 2902

Borovsky, J. E. & Denton, M. H. 2006, Geophysical Research Letters, 33, n/a, l20101

Borovsky, J. E., Hesse, M., Birn, J., & Kuznetsova, M. M. 2008, Journal of Geophysical Research: Space Physics, 113, n/a, a07210

Cassak, P. A. & Shay, M. A. 2007, Physics of Plasmas, 14, 102114

Dargent, J., Aunai, N., Lavraud, B., & Toledo-Redondo, S. 2016, submitted to J. Geophys. Res.

Fuselier, S. A., Burch, J. L., Cassak, P. A., et al. 2016, Geophysical Research Letters, 43, 1435, 2015GL067358

Hesse, M., Aunai, N., Zenitani, S., Kuznetsova, M., & Birn, J. 2013, Physics of Plasmas, 20

Malakit, K., Shay, M. A., Cassak, P. A., & Bard, C. 2010, Journal of Geophysical Research (Space Physics), 115, 10223

Mozer, F., Pritchett, P., Bonnell, J., Sundkvist, D., & Chang, M. 2008, J. Geophys. Res., 113

Mozer, F. S. & Pritchett, P. L. 2011, Space Science Reviews, 158, 119

Sauvaud, J.-A., Lundin, R., Rème, H., et al. 2001, Annales Geophysicae, 19, 1523

Toledo-Redondo, S., Vaivads, A., André, M., & Khotyaintsev, Y. V. 2015, Geophys. Res. Lett., 42, 6146

Walsh, B. M., Phan, T. D., Sibeck, D. G., & Souza, V. M. 2014, Geophysical Research Letters, 41, 223

Wang, S., Kistler, L. M., Mouikis, C. G., & Petrinec, S. M. 2015, Journal of Geophysical Research: Space Physics, 120, 6386, 2015JA021524