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Solar wind - magnetosphere coupling via magnetic reconnection and the effects of ionospheric plasma.

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Abstract

Magnetic reconnection is a key plasma process that couples the solar wind to the Earth's magnetosphere, permitting the exchange of energy and mass between these two plasmas, and converting large amounts of energy stored in the magnetic fields into kinetic energy of the particles. The magnetospheric side of the subsolar magnetopause is often populated by cold (10 eV) plasma of ionospheric origin, in addition to the hot (10 keV) magnetospheric plasma coming from the ring current. The presence of this cold plasma can mass-load the magnetospheric interface with the solar wind by 2-3 orders of magnitude, reducing the rate at which magnetic reconnection operates. In addition, the ion gyroradius of the cold plasma is much smaller than the hot ion gyroradius and introduces a new length-scale into reconnection and its associated processes. Finally, the cold plasma is heated inside the separatrix region of magnetic reconnection, although this mechanism is not always present.

1 Introduction

Our Sun is continuously expelling magnetized charged particles from its corona, the so-called solar wind. It expands along the Heliosphere, and interacts with the planets of the Solar system. Magnetic reconnection is a key plasma process which permits that magnetized planets like Earth, which are surrounded by a magnetosphere, exchange mass and energy with the solar wind. Magnetic reconnection enables breaking and merging antiparallel magnetic field lines locally, and therefore reconfigure the magnetic field topology at large scales, converting large amounts of energy stored in the magnetic field lines into kinetic energy of the charged particles during the process [1].

Magnetic reconnection initiates at electron scales of the plasma, in the so-called Electron Diffusion Region (EDR), a narrow region where electrons are not frozen-in to the magnetic field, and the magnetic field diffuses and reconnects. However, the mechanism that permits the magnetic field to diffuse in the required short time scale is a subject of debate, since in the collisionless regime of space plasmas the magnetic diffusion time is typically much larger than the required for reconnection to occur. The Magnetospheric MultiScale (MMS) mission [3] was launched in 2015 with the purpose of providing a better understanding of the processes that occur in the EDR and which mechanisms are responsible for the anomalous resistivity.

Magnetic reconnection occurs in many regions of the heliosphere, including the Solar corona, the turbulent solar wind, at the Earth's dayside magnetosphere, the Earth's magnetotail, or in Kelvin-Helholmtz vortices, to name a few. Here we focus in magnetic reconnection occurring at the dayside interface between the solar wind and the Earth's magnetosphere, the so-called magnetopause. This reconfiguration of the magnetic field lines occurs at large time- and space-scales, lasting tens of minutes to few hours, and producing X lines of several Earth Radii (R_E). It is responsible for magnetospheric convection and transport of magnetic flux towards the tail, where reconnection also occurs in order to keep the magnetic field divergence-free. This transport of magnetic field lines from the dayside to the tail and back to the dayside is known as the Dungey cycle.

The interface between the solar wind and the magnetosphere is largely asymmetric. The solar wind side is composed of solar wind plasma that has undergone through the bow shock, owing to the supersonic nature of the solar wind. The magnetospheric side is typically composed of hot plasma that comes from the ring current. Typical parameters of the solar wind near the magnetopause, i.e., at $\sim$12 R_E, are B = 15 nT, n = 20 cm^{-3}, T_i = 400 eV, while the typical parameters of magnetospheric plasma at $\sim$12 R_E are B = 40 nT, n = 0.1 cm^{-3}, T_i = 4 keV, where B stands for magnetic field magnitude, n stands for plasma density and T_i for ion temperature. But in the magnetospheric side, in addition to the (hot) ring current plasma component there is often a cold, and therefore difficult to measure, plasma component that originates in the Earth's ionosphere, see Figure 1. In this work we summarize some of the implications of this cold ionospheric plasma component for solar wind - magnetosphere coupling.

2 Cold ion length-scale and its implications for magnetic reconnection

In plasmas such as the Earth's magnetosphere, the density is so low (usually below 1 cm^{-3}) that Coulomb collisions between particles can often be neglected. Interaction between the particles occur indirectly via the electric and magnetic fields, such as wave - particle interactions. In this regime, the particle distribution function does not easily relax into a Maxwellian distribution, as classic statistical mechanics predict, and the phase-space density can remain far from equilibrium for very large time-scales. Under such situation, the definition of temperature itself is not well defined.

In the dayside magnetosphere, often a hot (several keV) ion population that originates in the ring current, and a cold (tens of eV) ion population that originates at the ionosphere can be observed together, although the cold plasma component is more difficult to detect and characterize with spacecraft detectors. The ion gyroradius of each of these populations

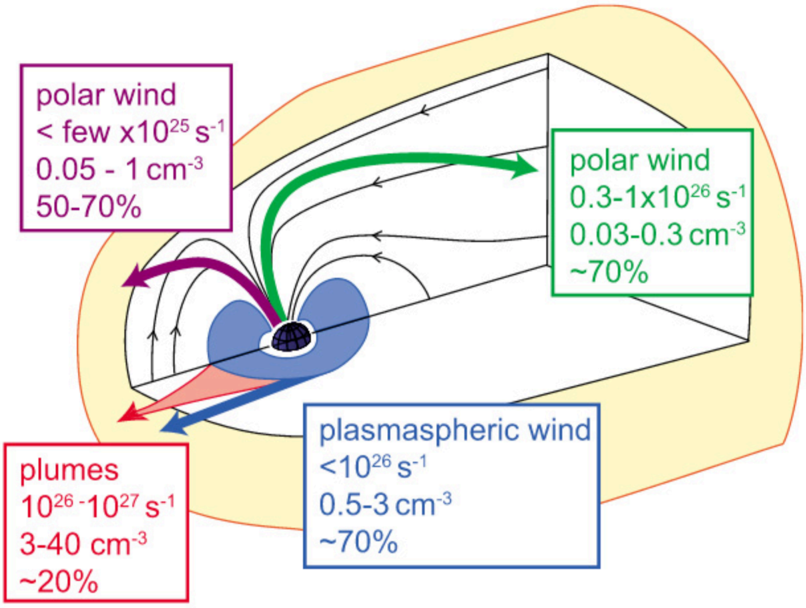

Figure 1: Extracted from [2]. Statistics of cold ionospheric ions at different regions of the Earth's magnetosphere using ten years of Cluster spacecraft mission observations. Cold ions dominate the magnetospheric mass density most of the time.

differs by roughly one order of magnitude, and therefore the cold ion population can remain frozen-in to the magnetic field lines inside small regions where the hot ions cannot, see Figure 2. Inside these small regions, the frozen-in term of the generalized Ohm's law must be split into two terms, one for the hot and one for the cold ion components. The generalized Ohm's law can be then written as follows, after neglecting the electron inertial term and assuming steady-state:

$$\mathbf{E} = \frac{1}{en}\mathbf{j} \times \mathbf{B} - \frac{1}{en}\nabla \cdot \mathbf{P_e} - \frac{n_{ih}}{n}\mathbf{v_{ih}} \times \mathbf{B} - \frac{n_{ic}}{n}\mathbf{v_{ic}} \times \mathbf{B}, \tag{1}$$

where $\mathbf{E}$ and $\mathbf{B}$ correspond to the electric and magnetic fields, $\mathbf{j}$ corresponds to the current density, $\mathbf{P_e}$ corresponds to the electron pressure tensor, n corresponds to the number density and subscripts ih and ic indicate hot and cold ions, respectively. The ability of the cold ionospheric ions to remain frozen-in at smaller length-scales has various implications for the microphysics of magnetic reconnection.

When magnetic reconnection between the Earth's magnetosphere and the solar wind occurs, a thin structure of enhanced normal electric field is created along the magnetospheric side of the separatrix region. The width of this narrow region is of the order of the hot ion gyroradius. Inside this region, hot ions are demagnetized and the Hall term (-$\mathbf{j}\times\mathbf{B}$/en) balances the electric field [5]. However, when cold ions are present, they $\mathbf{E}\times\mathbf{B}$ together with electrons, reduce the perpendicular currents and therefore the Hall term, see Figure 2. The ions are partially frozen-in, and the last term of equation 1 also contributes to the electric field. This has been shown using in-situ spacecraft observations [4, 6] and numerical

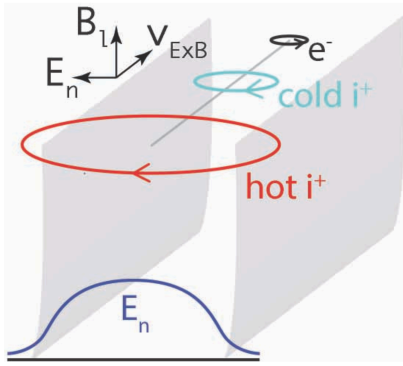

Figure 2: Extracted from [4]. Sketch of a narrow region, such as the Hall region in the magnetospheric separatrix region, where electron and cold ions can remain magnetized while hot ions do not. The cold ions **E**×**B** drift together with electrons and partially cancel the perpendicular current that electrons carry.

Particle-In-Cell (PIC) simulations [7, 8].

Figure 3 shows two examples of MMS in-situ observations of magnetic reconnection at the Earth's magnetopause. The left hand-side panels correspond to a magnetopause crossing without the cold ionospheric plasma component, while in the right hand-side panels the mass density of the magnetospheric side is dominated by cold ionospheric ions. In panels a1 and a3 the magnetic field gradient of the magnetopause can be observed. Panels b1 and b3 show the ion density. Panel b1 shows a density asymmetry between the solar wind (before 07:32:30 UT) and the magnetosphere (after 07:32:40 UT) of more than one order of magnitude. On the other hand, panel b3 shows roughly the same ion density in the solar wind (before 11:42:25 UT) and the magnetosphere (after 11:42:40 UT), owing to the cold ion density in the magnetosphere. Panels c1 and c3 show the ion velocity, where reconnection jets can be observed in the magnetopause. Panels d1 and d3 correspond to ion differential energy flux, and three ion populations can be distinguished: (hot) solar wind ions, (hot) magnetospheric ions, and (cold) magnetospheric ions of ionospheric origin (marked using a white box). Panels e1 and e3 correspond to measurements of the Ohm's law terms. In the crossing without cold ions, the electric field is roughly balanced by the Hall term, while in the crossing with cold ions the electric field is roughly balanced by the frozen-in cold ion term, with a small contribution of the Hall term.

Another consequence of cold ions in magnetic reconnection is that the Ion Diffusion Region (IDR) that surrounds the EDR is split into two subregions: a hot IDR (hIDR) and a cold IDR (cIDR). Again, this has been recently shown using in-situ MMS observations [9] and PIC simulations [10]. The cold ions remain frozen-in inside the hIDR, and are demagnetized only inside the much narrower cIDR region, where they are accelerated parallel to the electric field. Understanding the IDR is key for studying the EDR, the main goal of the MMS spacecraft mission.

The cold ions can in turn be accelerated and heated by magnetic reconnection, and their associated length-scale is therefore dynamically modified. The heating mechanisms are

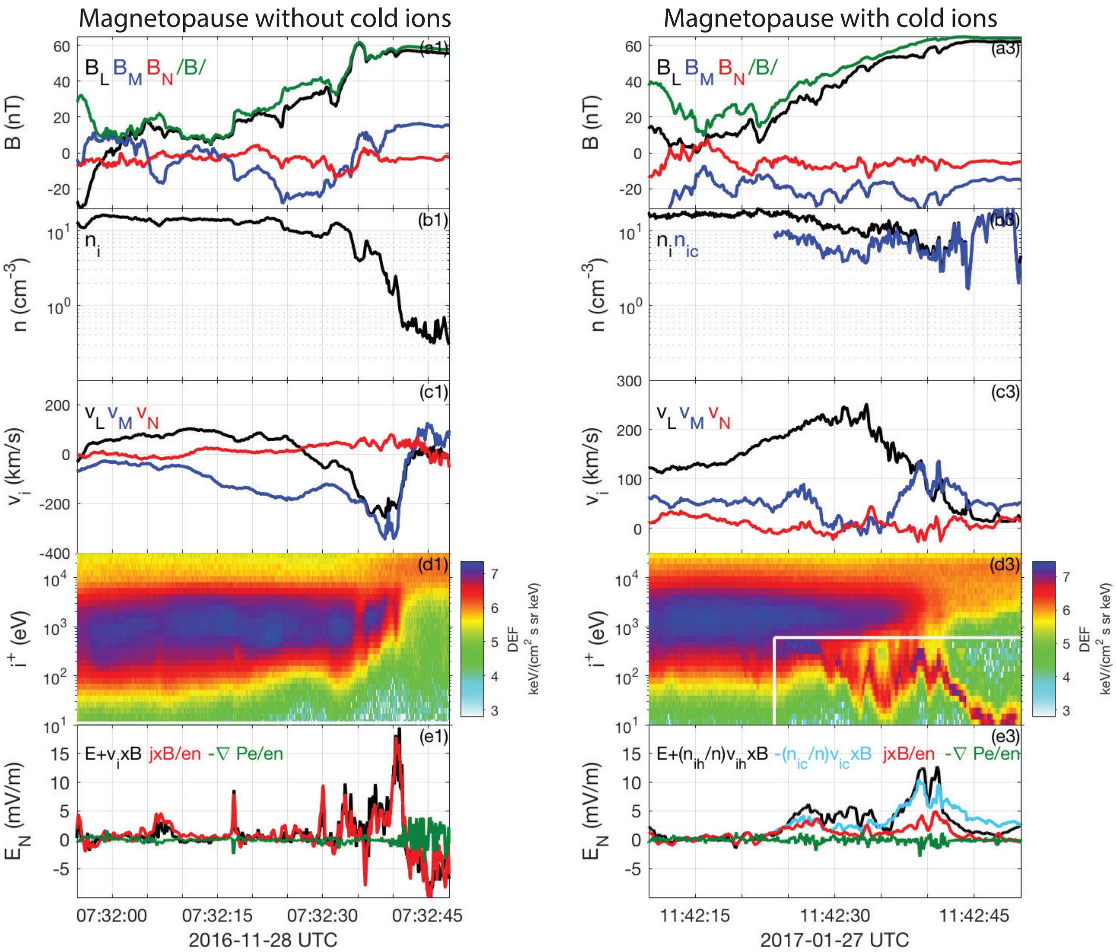

Figure 3: Extracted from [8]. MMS observations of magnetic reconnection at the Earth's magnetopause, without (left) and with (right) the presence of cold ions of ionospheric origin. (a) Magnetic field in LMN coordinates (magnetopause boundary coordinates). (b) Total (black) and cold (blue) ion densities. (c) Total ion velocity in LMN coordinates. (d) Ion differential energy flux. (e) Various terms of the Ohm's law, see equation 1.

associated to large electric field gradients and wave-particle interactions [11, 12]. Heating cold ions takes a non-negligible portion (25% of heating that goes into cold ions has been reported) of the energy budget of magnetic reconnection, and can have implications at large scales [13]. However, cold ion heating is not always observed in association with magnetic reconnection [14].

3 Conclusions

The main conclusions of this work can be summarized as follows:

- Cold ions of ionospheric origin dominate the mass density of the Earth's magnetosphere most of the time, introducing a smaller length-scale into magnetic reconnection owing to their smaller gyroradius.
- They reduce the perpendicular currents associated to the Hall term in the separatrix.
- They form a cIDR embedded in the wider hIDR that surrounds the EDR.
- Cold ions are heated by reconnection and take a significant part of the energy budget.

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References

[1] Biskamp, D. 2005, Magnetic reconnection in plasmas No. 3 (Cambridge University Press)

[2] André, M. & Cully, C. M. 2012, GRL, 39, L03101

[3] Burch, J. L., Moore, T. E., Torbert, R. B., & Giles, B. L. 2016, Spa. Sci. Rev., 199(5), 21

[4] Toledo-Redondo, S., Vaivads, A., André, M., & Khotyaintsev, Y. V. 2015, GRL, 42, 6146

[5] Khotyaintsev, Y. V., Vaivads, A., Retinò, A., A., et al. 2006, PRL, 97, 205003

[6] André, M., Li, W., Toledo-Redondo, S., et al. 2016, GRL, 43, 6705

[7] Dargent, J., Aunai, N., Lavraud, B., et al. 2017, JGR, 122, 5290

[8] Toledo-Redondo, S., Dargent, J., Aunai, N., et al. 2018, GRL, In press

[9] Toledo-Redondo, S., André, M., Khotyaintsev, Y. V., et al. 2016a, GRL, 43, 6759

[10] Divin, A., Khotyaintsev, Y. V., Vaivads, A., et al. 2016, JGR 121, 12001

[11] Toledo-Redondo, S., André, M., Vaivads, A., et al. 2016b, GRL, 43, 58

[12] Graham, D. B., Khotyaintsev, Y. V., Norgren, C., et al. 2017, JGR, 122, 517

[13] Toledo-Redondo, S., André, M., Khotyaintsev, Y. V., et al. 2017, JGR, 122, 9396

[14] Li, W. Y., André, M., Khotyaintsev, Y. V., et al. 2017, JGR, 122, 10194