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Analysis of energy exchanges and turbulence in reconnection outflows

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Summary. — Magnetic reconnection converts magnetic energy into kinetic energy. We report here our recent studies on how reconnection causes highly dynamical outflows where intense energy conversion and even turbulence develops. We report the methods we developed and summarize the results of their application to the study of reconnection events for conditions relevant to the MMS mission.

1. – Introduction

In Nature as well as in laboratory, electromagnetic fields and particles engage in very complex exchanges of energy. Magnetic fields are extremely efficient in storing energy: they can be considered as springs that are winded stronger and stronger keeping energy stored in relatively localized regions. In the sun those are the sunspots and the active regions. Around black holes the magnetic energy is stored in accretion disks. But at a point this enormous energy is released in sudden eruptions. In the sun, these take the form of flares and coronal mass ejections, in accretion disks the form of jets that can extend for truly astronomical distances, expanding out of whole galaxies in the case of super massive black holes in the center if certain galaxies. The process sparking this release is magnetic reconnection. Magnetic reconnection takes its name from the fact that it breakers the winding of the magnetic fields, it breaks the spring so to say. Just like cutting loose a compressed spring produces an impulse of motion, magnetic reconnection produces powerful flows that tap into the magnetic energy and produce kinetic energy. The same processes on smaller scales take place also near the Earth in the magnetosphere. The magnetic field formed by the currents in the Earth interior, the same magnetic field that points the compass to the North Pole, shields the Earth from the solar wind and its storms arriving from the Sun. The shielding is effective and the fact that is present on the Earth but absent on Mercury is one of the reasons life developed on Earth and not on Mars: it prevents the atmosphere from being eroded by the solar wind. However, during solar storms the magnetic envelope around the Earth can open into portals where the energy if the storms can penetrate closer to the Earth, causing beautiful Auroras but also posing serious dangers to space activity and ground infrastructures. Our activity in the past years has tried to understand how this energy exchange takes place.

2. – Approach

Studying the processes of energy conversion during the types of events described above faces two challenges. First, we need to obtain observational data of the events and make simulations that represent the physics in those events. But, second and surprisingly equally complex, we need to make sense of the data by designing diagnostics and analysis tools designed to capture the essence of the events. To go beyond impressive pictures and make impressive progress it is not enough to capture and reproduce a solar flare or a coronal mass ejection, we need to analyze the processes happening within the event.

The great innovation of the last few years has been the successful launch of the Mangetospheric Multiscale (MMS) mission that has motivated and stimulated the research in this field [1]. MMS is a four spacecraft mission that costed close to 1 billion dollars and can analyze the processes of reconnection with unprecedented resolution, allowing us to analyze in great details the processes happening during reconnection.

To make full use of this new wealth of data, simulation methods with similar resolution have been developed. Modeling reconnection is especially challenging because the processes is intrinsically multi-scale [2]. In fact, one of the greatest discovery of the recent research has been the realization that during reconnection, the electrons and the ions behave completely differently. The electrons operate on much smaller spatial and temporal scales, while ions respond to larger scales. Modeling this multiplicity of scales has been the key inspiration of our research.

In our opinion, a very promising approach to handle multiple scales is the implicit particle in cell method (PIC) [2]. Implicit PIC has two key advantages.

First, it has superior properties of energy conservation compared with other methods. Following energy exchanges is our goal and it is obviously desirable that nothing compromises our ability to account every last erg of energy. But even more importantly, physical energy conservation bringing in mathematical numerical stability. Stability in a computer simulation means that small perturbations in the simulation data, for example caused by the finite precision of calculations done by the processors, do not alter dramatically the evolution of the system. We want to see real energy releases not energy releases caused by the simulation becoming inaccurate. Other methods do not have this conservation and stability property.

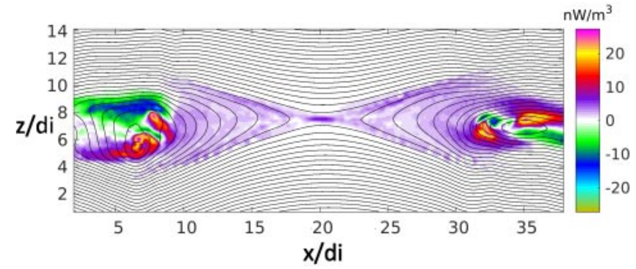

Fig. 1. – Energy exchanges between fields and particles, $\mathbf{J}_s \cdot \mathbf{E}$. False color representation on the mid plane $y = Ly/2$ at the end of the simulation.

Second, implicit methods allow us to set the resolution to the scales of interest without any waste. Competing methods have strict stability constraint that require the resolution of all scales, with any scale is not resolved accurately, the simulation becomes unusable and energy is not resolved. With this limitation, the resolution needed would be prohibitive. Implicit methods, instead, focus only on the range of scales of interest, averaging over the unresolved scales. We estimated that the simulations reported below done with the implicit PIC method required about 48 hours on 30,000 processors. The same simulations done with explicit PIC methods that resolve all scales would have required about 550,000 years on the same supercomputer. This extreme scaling comes from the simple observation that the ratio between the scales resolved by the implicit method, the electron skin depth and that of the explicit method, the electron Debye length is of the order 100. Similarly for time explicit methods need to resolve the plasma frequency and implicit methods need just to obtain accurate trajectories a task where cyclotron scales suffices, saving another factor 100-1000. Compounding this saving for each of the three dimensions and for time results in the extreme reduction in computational costs mentioned above [2].

In recent years, we have improved our implicit PIC method [3] with the development of the ECSim approach [4]. ECsim uses a mathematical tool called mass matrix to express the response of the particles to changes in the electric fields. The current written in terms of the changing fields using the mass matrix conserves energy exactly and leads to a very numerically stable method.

3. – Ion Heating in reconnection outflows

Ion energization has been studied using massively parallel 3D PiC simulations, reported in Ref. [5]. The region of reconnection outflow is characterised by an instability

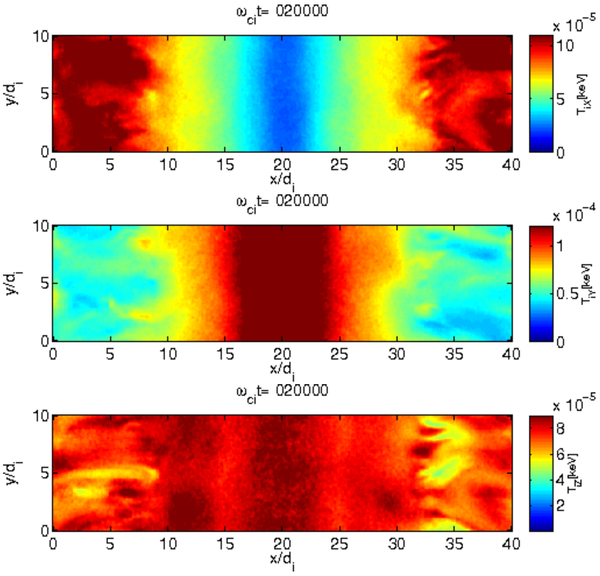

Fig. 2. – Ion temperature in the outflow: from top to bottom: T_x (a), T_y (b) and T_z (c). False color representation on the mid plane $z = Lz/2$ at the end of the simulation.

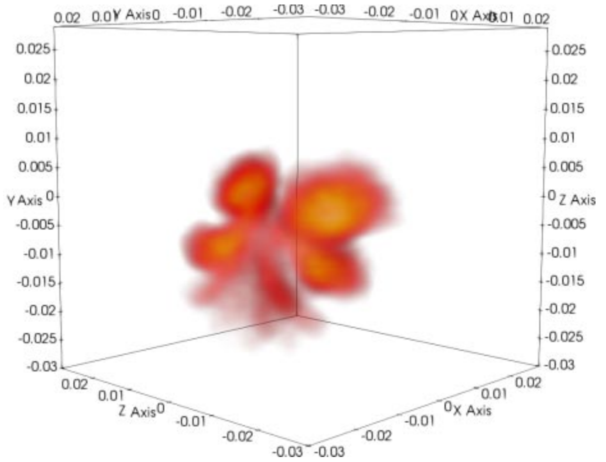

Fig. 3. – Volume rendering of the ion velocity probability distribution $f_i(vx, vy, vz)$ at the position $x/d_i = 15$, $y/d_i = 7.5$, $z/di = 5$, obtained averaging over particles contained within a box centred at that location and with side $0.5d_i$.

of the lower hybrid type [6, 7] leading to in intense energy exchange ($\mathbf{J}_s \cdot \mathbf{E}$). In the last year, we analysed in detail the energy budget [8]: a large fraction of the energy is deposited as particle energization, while a significant fraction is also transported by the Poynting flux.

Figure 2 reports the ion temperature at the end of the run. Ions are generally not magnetized in the reconnection region and projecting the pressure tensor in the parallel and perpendicular direction relative to the magnetic field is not productive. Ion energization in reconnection outflows and in reconnection fronts has been analysed in theory and in simulation. Complex processes are at play, requiring a full analysis of the phase space and of single particle trajectories to detect with accuracy the specific mechanisms accelerating the particles [9].

Figure 2 reports the three different kinetic temperatures defined as second order moments of the distribution from the pressure tensor. The primary region of reconnection tends to heat the ions primarily in the Y direction. This effect is due to the mixing of the two populations of ions coming from above and below from the inflow towards the reconnection region. In the outflow, instead, the plasma outflowing along the X-direction mixes with the plasma in the medium causing apparent heating in the x-direction. Heating in the Z direction is present both in the region of primary reconnection, where it is due to the acceleration of non-magnetised ions in the reconnection region due to the reconnection electric field, and in the region of the outflows, where it is a consequence of the instabilities in the outflows. These effects however should not be interpreted as heating in the meaning of increasing thermodynamic temperature. The plasma is far from Maxwellian and what appears as heating in the kinetic temperature (i.e. the second order moment of the distribution) is in reality the presence of multiple interpenetrating populations.

Figure 3 shows a volume rendering of the full 3D velocity probability distribution for the ions. The distribution is anisotropic and contains multiple populations. When the second order moment is taken to measure a kinetic temperature, the result can be misleading because multiple beams, each with its own temperature, appear as a single

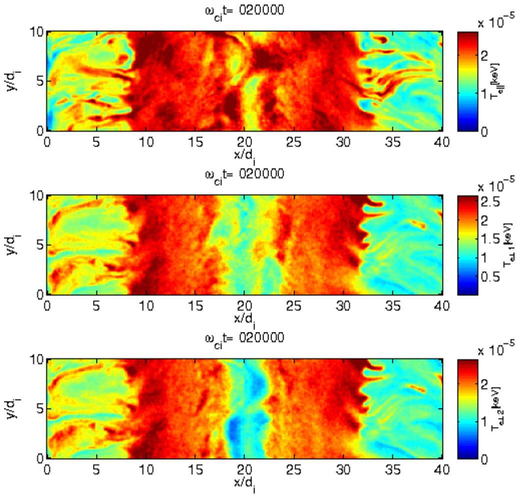

Fig. 4. – Electron temperature in the outflow: from top to bottom: $T_{||}$ (a), $T_{\perp 1}$ (b) and $T_{\perp 2}$ (c). False color representation on the mid plane $z = Lz/2$ at the end of the simulation.

plasm with a combined temperature much higher than that of the beams. However this is not a process of heating but one of bulk acceleration of ion populations. In a recent study, each ion component has been tracked back in time to its origin [10]. Each component originates from different regions and their trajectories brought them to the same location but with different speeds.

4. – Electron Heating in reconnection outflows

A similar study has also been conducted for the electrons in reconnection outflows using the same 3D simulations reported above.

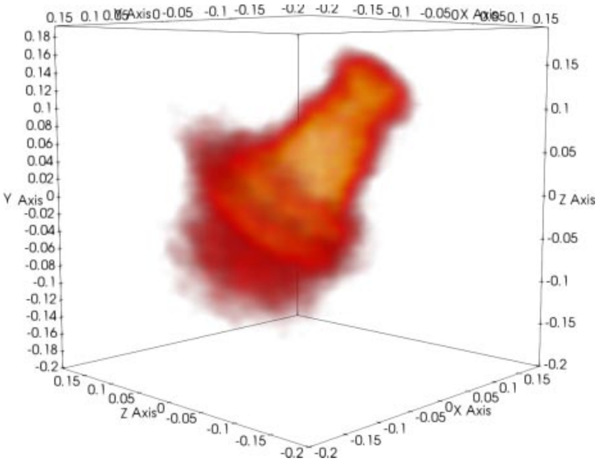

Fig. 5. – Volume rendering of the electron velocity probability distribution $f_e(vx, vy, vz)$ at the position $x/d_i = 15$, $y/d_i = 7.5$, $z/di = 5$, obtained averaging over particles contained within a box centred at that location and with side $0.5d_i$.

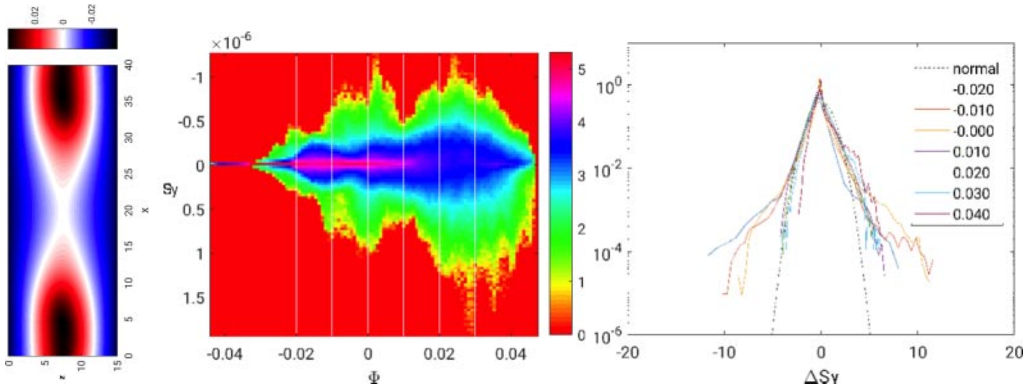

Fig. 6. – Topographical analysis of magnetic fluctuations. a) the flux function $\Psi(x, z)$, b) the spectrum of fluctuations in regions of different Ψ binned in 100 intervals), c) fluctuations at the 7 specific values of Ψ indicated by the vertical white lines in panel b.

Figure 4 shows the parallel and perpendicular electron temperature. The electrons are mostly magnetised and it is more convenient to report the electron temperatures in magnetic coordinates rather than along geometrical axes. The region of primary reconnection causes parallel heating. The cause is the reconnection electric field that accelerates the electrons along the Z direction: in this reason the guide field is the only field present and the acceleration is parallel. The region of secondary instabilities in the outflow shows strong parallel and perpendicular energisation caused by the conversion of electromagnetic energy.

The electron distribution is typically smoother than the ion distribution due to the higher thermal speed. However, in the region of the secondary front instability even the electron distribution becomes complex.

Figure 5 shows a volume rendering of the full 3D velocity probability distribution for the electrons computed as described above for the ions. In any stretch of imagination this has nothing to do with a Maxwellian. It is very asymmetric, it presents multiple features. Tracking the exact origin of all features is a daunting task, but not insurmountable. Particle tracking can reconstruct the origin and evolution of the particles in the different regions of the distribution [10].

5. – Turbulence cascade in reconnection outflows

In recent papers [11,12], it was shown that 3D full PIC numerical simulations are able to reproduce the observations [9,13] of electric and magnetic spectra at sub-ion scales produced by a reconnection event.

In a typical simulation of reconnection, turbulence appears to be neither isotropic nor homogeneous within and outside the outflows. Therefore, It is worth asking how turbulence evolves spatially moving away from the main reconnection site. We have developed a new type of turbulence diagnostics linked with the different regions: *topographical fluctuation spectrum*.

The idea is to subdivide the domain in different regions, in the same way a city is divided in different urban subdivisions (e.g the arrondissements in Paris). In the case of reconnection this is determined by the flux function computed in each plane y. The flux function is normalized to be 0 in the central point, corresponding to the intersection of the separatrices. The inflow then has negative values of $\Psi(x,z)$, more negative as one moves upstream, and the outflow is positive, more positive moving downstream.

We compute next the fluctuation spectrum in each interval of values of Ψ (we use 100 bins from minimum to maximum). The fluctuations are then plotted in false color. Figure 6 shows one example of this analysis. The fluctuations in this case are present both in inflow and outflow demonstrating that instabilities generate a cascade of fluctuations with a long power-law tail quite different from a gaussian spectrum (see panel c). This feature is an indication of intermittency in the fluctuations.

The highly fluctuating nature of the reconnection outflows has an important consequence: the possibility of secondary reconnection sites in the outflow. We reviewed several measures of reconnection identifying a number of secondary reconnection sites in the turbulent outflow [6].

The inflow turbulence, instead could affect the reconnection rate and cause unsteady reconnection with the possibility of spikes in the reconnection rate [14].

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