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KINETIC AND MHD SIMULATIONS OF PROCESSES IN A COLLISIONLESS HELIOSPHERIC PLASMA

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Introduction

The Earth, planets and other bodies of the solar system are surrounded by the collisionless hot plasma of the solar wind and are constantly exposed to it. The nature of the interaction depends on whether the celestial body has an internal magnetic field or the presence of an atmosphere. If the solar wind is deflected by the internal magnetic field at a great distance from the planet, then a cavity in the solar wind is formed, called the magnetosphere. Almost all planets of the solar system have similar large-scale magnetospheres, with the Earth's magnetosphere being the most studied object. Under the influence of the solar wind, the magnetosphere is compressed on the day side; on the night side, a magnetotail is formed, which contains strongly elongated magnetic field lines separated by the current sheet. A characteristic feature of magnetospheres of this type is extremely diverse internal dynamics, which manifests itself in the processes of slow accumulation of magnetic energy and its rapid release, which is accompanied by the generation of accelerated particles, plasma heating and disturbances in the entire magnetosphere-ionosphere-atmosphere configuration. A wide range of phenomena occurring in the near-Earth space under the influence of heliophysical factors is called "space weather". The study of the effects of space weather on technical systems and human health, as well as its forecast, is an urgent fundamental and practical task.

Large-scale plasma processes are accompanied by a change in the topology of the magnetic field under the influence of magnetic reconnection, which actually sets the rate of energy transformation and also controls the amount of magnetic flux entering from the solar wind into the magnetosphere. Understanding the magnetosphere as a whole requires a detailed analysis of the main parameters of magnetic reconnection, namely: its rate, the spatial scale of the diffusion region, the structure of the vicinity of magnetic reconnection in the presence of other species, as well as obtaining estimates of its energy efficiency, which in the case of a collisionless plasma is most fully revealed by means of numerical simulations.

The Moon and asteroids represent an interaction of a qualitatively different kind. The absence of an atmosphere and a global magnetic field causes the solar wind and high-energy particles to fall directly onto the surface of the Moon. However, the so-called lunar magnetic anomalies, where small-scale areas of residual magnetization of the crust are present, can provide protection from energetic particles. The relevance of research in this direction is due to the increased interest in the exploration of the Moon at present by Russia, China, the USA, the EU and India, as well as future prospects of establishing a manned lunar station there. This task requires predicting radiation risks on the lunar surface, therefore it is necessary to create an accurate picture of the lunar magnetic field, as well as to study the structure of plasma flows under the influence of local magnetic fields.

The structures formed during the interaction of the solar wind with comets are even more different from "ordinary" magnetospheres. The comet's nucleus is a lump of loose mixture of ices (both water ice and dry ice), rocks, and some more complex compounds. Away from the Sun, the comet's nucleus behaves like an asteroid, but as it approaches the Sun, the substance of the comet's nucleus evaporates in the process of degassing, forming a coma. The size of this atmosphere can be many orders of magnitude larger than the size of the comet's nucleus, while the comet's weak gravity is not able to prevent the escape of cometary matter into space. The main interaction occurs due to the gradual ionization of neutral gas and the introduction of heavy ions of cometary origin into the solar wind. Previous approaches to the numerical modeling of the cometary atmosphere were based on the fluid approach, but it has now become clear that this approach is not capable of adequately explaining the experimental satellite data, especially in the weak comet regime.

The existing term "space weather" refers mainly to the physics of solar-terrestrial relations. The manned exploration of the heliosphere requires the creation of high-precision models of the interaction of various bodies with the solar wind, the estimation of the intensity of energetic particle fluxes, and the prediction of plasma dynamics for various parameters of the solar wind. Taking into account the insufficiency of experimental data (which is especially typical for observations of the near Lunar space and comets), numerical simulation appears to be the main available research tool.

The experiment is the starting point in the study, its foundation, on which further theoretical and computational constructions are built. The permanent increase in the accuracy of measurements (spacecraft, optical, laboratory), as well as the quality of experimental data, requires the creation of more and more accurate models to interpret the nature of the occurring phenomena. Over the past decades, a number of satellite missions have been focused at studying the dynamics of energy conversion and related processes in near-Earth space, for example: Cluster (European satellites launched in 2000), MMS (satellites launched in 2015 specifically to study magnetic reconnection and its consequences). Satellite observations provide data only at one (or several) points, which, unfortunately, provides indirect information about physical processes throughout space in a dynamic, moving environment. It is theoretical and numerical models based on experimental data that are capable of constructing a quantitative self-consistent model of the process that complements and interprets observations.

The complexity of the problems posed is such that the only comprehensive research tool for studying multiscale processes in a wide range of parameters is numerical simulation. Computational complexity balances between the desired resolution and the size of the computational domain, on the one hand, and the available computational resources, on the other. For some numerical calculations, ordinary workstations are sufficient. However, for many computational problems at the forefront of science, this approach is not applicable due to, for example, the requirements for the amount of RAM. The use of supercomputers is typical in such cases.

Modern numerical computing code is a complex software product. The development of such a product is a long and difficult task. To use the available supercomputer resources, a parallel algorithm is needed that effectively splits the computational problem into threads that run on separate processors (cores). The computational code processes the result of the calculations, organizes the exchange of data between the threads and stores the result in disk. Creating, debugging, testing and adapting such a product for a specific physical problem takes years and requires the cooperation of a large group consisting of programmers, mathematicians, physicists and end users. Each created code is a unique computing tool with its own features and optimizations. In addition to the calculation module itself, post-processing and visualization methods play an important role, which is critical when interpreting the results of large three-dimensional calculations.

There are several approaches to describing plasma dynamics. Magnetohydrodynamics (MHD) equations are the equations of conservation of mass, momentum, and energy of a fluid medium. In this approximation, plasma is considered as a conducting gas interacting with a magnetic field. At each point, there is a local thermodynamic equilibrium, and the plasma state is described uniquely by such a set of parameters as density, temperature, velocity, and magnetic field. This approach is used to model objects that are large compared to the characteristic plasma scales (for example, the ion gyroradius). At present, there are a number of global dynamic MHD models of the Earth's magnetosphere and other heliospheric objects that are successfully used both to study fundamental phenomena and to predict space weather. A qualitatively different approach is required when describing processes in which distribution functions are formed in plasma that are far from local thermodynamic equilibrium. In such processes, the distribution function can take a rather complicated form, and to adequately reproduce the plasma dynamics, one must either use the macroparticle method or fully resolve the velocity space.

The dissertation aimed at numerical modeling of processes in the collisionless plasma of magnetosphere and heliosphere by the Particle-in-Cell (PIC) method. For calculations, the parallel open-source code iPIC3D [1] is used, in its basic version presented on `https://github.com/CmPA/iPic3D`. The semi-implicit moment method is implemented in the code. The Applicant took an active part in its support and development. Computations on the topic of the dissertation were carried out using both Russian computing resources (supercomputer “Lomonosov” of the Research and Development Center of Moscow State University) and European and American machines (supercomputers Curie, Beskow, Pleiades and others). The high efficiency of the code has been tested in calculations using up to 10,000 cores. The research is mainly theoretical; however, spacecraft observations were directly applied to some selected simulations. The dissertation results are reliable due to the correct formulation of numerical experiments, confirmed by direct comparison with spacecraft measurements and approbation in leading scientific journals.

Aims and Tasks of the Study

The purpose of this work is to study the effects of magnetic reconnection as the most important element of magnetospheric activity, as well as to create models for the interaction of the solar wind and evaluate the effects of space weather in the vicinity of the Moon and comets. The Applicant is developing **numerical simulation of kinetic processes in the plasma of the solar system using supercomputer research methods**. Numerical simulations of the plasma environment of the Moon and weak comets are innovative, since computing resources sufficient for three-dimensional plasma modeling in a fully kinetic approximation became available in the last decade only .

To achieve this goal, the following technical tasks were set and solved by the Applicant:

1. Create a set of two- and three-dimensional numerical models of collisionless magnetic reconnection to study the features of the process at different parameters of the inflowing plasma (density, temperature, composition) and to reveal new patterns of the process. A large set of models makes it possible to thoroughly study such subtle effects as the rate of magnetic reconnection, the structure of the diffusion region, and the balance of forces in the vicinity of the neutral line.

2. Study the influence of the effects of wave activity on the process of magnetic reconnection; carry out a self-consistent accounting of the energy of the wave-particle interaction in the vicinity of the fronts and separatrices. The main technical challenge here is in-depth post-processing and visualization of the results of three-dimensional calculations. Compare the obtained model to the satellite data.

3. Create a numerical model of lunar mini-magnetospheres, study the mini-magnetosphere structure, the pattern of particle precipitation and the dynamics of ion reflection. Adapt the computational method to solve this problem. Develop new versions of the iPIC3D code, in which the following external magnetic fields are implemented: a magnetic dipole, a magnetic quadrupole, an empirical magnetic field of the Moon [2]. Taking into account the small scale of magnetic anomalies, the approbation of calculations on the in-situ spacecraft data is more qualitative than quantitative. However, 3D modeling makes it possible to

obtain the distribution of particle precipitation on the surface, which is directly comparable to the optical observations.

4. Investigate the characteristic kinetic features of the plasma environment of a weak comet. Adapt the code to numerical simulation of the solar wind interaction with comet 67P/Churyumov-Gerasimenko. The choice of this particular comet is based on the availability of experimental observations by the Rosetta spacecraft in its vicinity. In addition, the comet was in a weak outgassing regime at a distance of 3-4 astronomical units from the Sun at the beginning of the Rosetta mission, which suggests the need for a kinetic approach to modeling.

5. Implement MHD solver in the iPIC3D code to study large-scale oscillations of the magnetic tail current sheet ("flapping" instability). Provide the possibility of specifying complex initial conditions for assessing the effect of tail bending on the breakup of a magnetospheric substorm. The use of such a code instead of side parallel MHD codes is justified by the fact that in order to study slow dynamics, it is necessary to accurately estimate the numerical effects of the scheme and the influence of boundary conditions.

A Brief Review of the Current State of Research and Description of the Results Obtained by the Applicant

1. Numerical simulations of magnetic reconnection and presentation of the EDR model structure

Magnetic reconnection is a universal plasma process that plays an important role in the interaction of the solar wind and the magnetosphere, initiation of coronal mass ejections, solar flares in astrophysical and laboratory plasma. The very first models of magnetic reconnection were depeloped in the middle of the 20th century [3], [4]. In the Sweet-Parker model, a theoretical study was made of the rate of transformation of the accumulated magnetic energy into the energy of accelerated plasma flows in a current sheet with uniform conductivity. A theoretical scaling was presented, which, however, gave characteristic reconnection rates several orders of magnitude lower than those observed. The characteristic times of solar flare development predicted by the Sweet-Parker model turned out to be about 10^7 s, instead of the observed 10-100 s. The Petschek model [5] postulates the existence of shock waves on which the inflowing plasma is accelerated. The microscopic Sweet-Parker current sheet in this model is present in the vicinity of the neutral line and is necessary to change the topology of the magnetic field lines. The main process of transformation of magnetic energy in this case occurs on shock waves. A big advantage of the Petschek model is the weak (logarithmic) dependence on the plasma resistance. The Sweet-Parker and Petschek models were the first quantitative models of magnetic reconnection. Their basic elements formed the basis of many further works, which take into account electronic and ionic kinetics. A detailed discussion of the limits of applicability of the MHD approximation in plasma is given, for example, in the book [6].

Classical resistivity due to binary collisions between plasma particles provides dissipation in the Sweet-Parker model and violates the condition of the magnetic field being frozen into the plasma in the diffusion region. Using the analysis of the generalized Ohm's law, in early works on magnetic reconnection in a collisionless plasma [7] it was shown that the role of the classical resistivity can be performed by the electron inertia, if the expression $\nabla \cdot \mathbf{P}_e$ introduces contribution to the force balance near the neutral line (there are off-diagonal components in the electron pressure tensor $\mathbf{P}_e$). Despite the fact that the first models of magnetic reconnection in the MHD approximation appeared as early as the middle of the 20th century, it was only in the 21st century that it was possible to extend the research for a collisionless kinetic plasma. *GEM reconnection challenge* [8] gave momentum to the study of various aspects of the process. Using various approaches to the description of plasma dynamics (both the fluid approximation and the fully kinetic approach), it was shown that the presence of the Hall effect is the main factor supporting the process of fast magnetic reconnection. With the development of simulation software, and also due to the better availability of computing resources, accurate quantitative descriptions of the diffusion regions of magnetic reconnection in the kinetic regime have appeared. The structures of the electron distribution functions inside the diffusion region were studied [9], [10], the characteristic scales of ion and electron diffusion regions [8] were determined. The spatial distribution of the electron pressure $\mathbf{P}_e$ is well structured in the vicinity of magnetic reconnection. In the inflow region there is a parallel electric field [11], [12] with a potential drop of up to 1 KeV. The electrons are pre-accelerated before entering the diffusion region, and the $\mathbf{P}_e$ pressure exhibits strong anisotropy parallel to the magnetic field.

Earlier papers [13], [14] proposed an algorithm for partitioning the distribution function in the vicinity of the diffusion region into separate populations. These populations are significantly different: the velocity of the incoming particles is directed mainly along the normal to the current sheet, while the accelerated particles move in the direction of the current. The study of the trajectories of individual particles made it possible to take a fresh look at the structure of an accelerated population of electrons. It was found that in the space of velocities a sequence of structures in the shape of the letter “C” (patterns C-shaped) is formed. Further numerical studies [15], [16], [17] and observations (e.g. [18]) showed that such structures are commonly found in regions with a localized perpendicular electric field. Structures of this type are usually called “crescents” and are currently considered the most important indicator of electron demagnetization near the diffusion region. Successful experimental studies of the Earth’s magnetosphere by satellites have revealed the need for an in-depth theoretical interpretation of the obtained observational results. To quickly classify different regions in a large amount of data, a number of features have been developed based on the anisotropy and non-gyrotropy of the electron pressure [19—21] and the structure of the ion distribution function [A35].

The Applicant proposed a simple model of the off-diagonal component of the electron pressure: $\mathrm{P}_{eyz} = nm_eV_{ey}V_{ez}$, which is true inside the electron diffusion region. A scaling of the electron diffusion region was obtained as a function of plasma properties in inflow regions [14]. The conductivity turns out to be of the order of Bohm diffusion, despite the collisionless plasma dynamics. The most important results were obtained by the Applicant [A19] when solving the problem of matching the known parallel anisotropy in the inflow region [11] with the approximation P_{eyz}. The rotation of the electron pressure tensor into a frame of reference related to the velocity of the electron component of the plasma was considered. The work made it possible for the first time to prove that the separation into external and internal parts is misleading and that the electron diffusion region along the entire length from the neutral line to the electron deceleration region is a single object in its structure. For this model, the dependence $\sim \beta^{1/8}$ of the reconnection rate on the plasma β in the inflow region was demonstrated in [A27]. A qualitatively similar dependence with external parameters appears in the calculation of the large-scale force balance [22] for a wider range of β parameters. Based on the research results, in a large collaboration, a numerical model of the vicinity of the diffusion region [A33], [A34] was created, based on the Grad-Shafranov equation. The model was validated by numerical simulation of magnetic reconnection [A33] and also tested on MMS satellite data [A34].

2. Dynamics of Reconnection (Dipolarization) Fronts and Separatrices

Fast plasma flows are regularly observed in the Earth's magnetotail, associated with wave activity enhancements and fluctuations of plasma parameters [23], [24], [25]. There are a large amount of works aimed at the study of specific events, as well long-term data statistics. Close attention to such phenomena is because it is through such non-stationary events that the transfer of most of the magnetic flux and plasma inside the magnetotail [26] occurs from a macroscopic point of view. The fast flow and the surrounding plasma are separated by a thin boundary, which in various sources is called the dipolarization front or the magnetic reconnection front. The thickness of the front is only a few hundred kilometers (of the order of the ion gyroradius), while the length of the entire fast flow is about 60,000 km ($\sim 10 R_E$, Earth's radii) [27]. The front is not a static boundary on the microscale, but acts as a powerful accelerator of ions and electrons [A9] and a source of waves in the magnetosphere. Calculations and observations show that the main release of the reconnection energy occurs not in the vicinity of the diffusion region, but in the outflow region and at the fronts [A5], [A6], [A10], [A21].

Magnetic reconnection explains the structure and parameters of plasma flows in the Earth's magnetosphere [25]. In particular, the velocity of the fast flow is of the order of the characteristic Alfvén velocity V_A; at the point of contact of the fast flow with the surrounding plasma, reconnection fronts are formed, which have the form of shock waves [28] in the MHD approximation; a local peak of the magnetic field and density appears at the magnetic reconnection front. Simultaneous observations of fast flows in the plasma sheet by several satellites are presented in [26] (located both in the near tail and at a distance of $\sim 55\ R_E$ from the Earth). Observations of plasma flows both in the direction from the Earth and towards the Earth at different distances correspond to the magnetic reconnection model.

Sharp gradients of plasma parameters at the fronts of magnetic reconnection contribute to the development of instabilities from micro- to macroscales. Rayleigh-Taylor type instability develops in MHD and hybrid approximations [29], [30], [31], [32]. In particle-in-cell simulations, a kinetic interchange instability and an ion-ion mode appear at the reconnection front [33], [34], [35], [36], as well as the lower hybrid drift instability (LHDI). A lower hybrid-type instability at the reconnection front were first described in 3D simulation by the iPIC3D code in a series of papers by the Applicant and co-authors [A2], [A5], [A8], [A12]. In [A8], [A21], [A38], kinetic simulations were carried out by replicating the results of a 2D simulation in the third dimension. The use of this technique made it possible to significantly reduce the computational resources required for the calculation.

Magnetic separatrices are virtual surfaces projected into a neutral line, which separate the inflow and outflow regions. Magnetic reconnection separatrices are highly dynamic [37], [38], while the crossing of separatrices by satellites is a much more frequent event (than an exact fly through the diffusion region). Numerical simulations of magnetic reconnection in two- and three-dimensional approximations show that electron beams lead to excitation of the Buneman instability and the electron Kelvin-Helmholtz mode. The results of these calculations are presented in the works [A3], [A13] and in earlier works of the Applicant [39], [40], [41], and are also confirmed in the data [A24], [A30] , [A38]

3. Magnetic Reconnection with Cold Ions

The theoretical problem of kinetic magnetic reconnection in a multicomponent and multitemperature plasma appeared while interpreting spacecraft observations of the Earth's magnetosphere. In the magnetosphere, there is a population of cold ions of ionospheric origin with energies of several eVs. The main difficulty in observing such a population is the presence of a positive potential in satellites illuminated by the Sun. The sensitivity of the ion spectrometer on the Cluster satellite to such cold ions (with energies from 7 eV) was improved by turning on the ASPOC [42] instrument, which compensates for the photoelectron current and reduces the floating potential of the satellite.

In [43], a rare crossing of the Earth's magnetosphere in the Earth's shadow by the Geotail spacecraft was presented. The absence of a photoelectron current leads to a short-term drop in the floating potential of the satellite to -300 V. In such events, the ions are accelerated to the potential of the satellite before entering the spectrometer, which makes it possible to observe even the lowest temperature component. Among 97 eclipsing events (during which the current sheet was crossed at distances of 9-19 R_E), the cold population was observed in 10% - 50% cases. In a number of events, the density of the cold component is comparable to the density of hot ions in the current sheet, which affects the magnetic reconnection. First, the presence of an additional background component increases the total plasma density and leads to a decrease in the magnetic reconnection velocity [44] due to a decrease in the characteristic plasma ejection velocity (Alfvén velocity), which is confirmed by numerical simulations [45], [46] . This effect is especially pronounced at the magnetopause, where heavy oxygen ions from the Earth's plasmasphere enter the region of asymmetric magnetic reconnection [47]. Second, the observations demonstrate significant differences in the motion of identical ion components but having different temperatures. It has been suggested that cold ions are completely magnetized when crossing the vicinity of the neutral line [48]. As a consequence, the cold ion current should partially reduce the electron Hall currents on the separatrices [49], [50], which is shown in [51] through both observations and numerical kinetic modeling.

In early observations of the low-temperature plasma component in the magnetosphere, it was assumed that such ions have a relatively short gyroradius and therefore remain magnetized when crossing separatrices. That is, it was assumed that cold ions can pass through the region of magnetic reconnection without significant acceleration [44].

Numerical simulations presented in this dissertation revealed a number of new effects, created by cold ions in the vicinity of the neutral line [A20]. First, cold ions are demagnetized and experience acceleration and heating when they enter the outflow region. A separate diffusion region is formed in which the cold ion component is demagnetized. The size of this region is much greater than the gyroradius of cold ions, but smaller than the characteristic dimensions of the demagnetization region of hot ions. Second, the rate of magnetic reconnection and the structure of the Hall fields practically do not change with a change in the temperature of the inflowing plasma and depend mainly on the magnitude of the magnetic field and the total plasma density. This confirms that in the presence of a poorly observed cold component, the rate of magnetic reconnection will be lower than expected. Thirdly, heating is equally effective for both hot and cold components.

The large-scale dynamics of magnetic reconnection with cold ions at the magnetopause was studied in experimental papers [A14], [A15]. The existence of a separate diffusion region of the plasma component, which is embedded in a more extended diffusion region of the hot component, is confirmed. Observations show that the inflowing cold ions are heated inside the diffusion region, but far from the neutral line they travel into the outflow region without thermalization and move with the drift velocity $\mathbf{E} \times \mathbf{B}$. In the computational work [A36], a simple explanation was given: cold ions can enter the outflow region through far separatrices, since acceleration requires the presence of both a Hall electric field and a reconnection electric field. The combination of acceleration by the reconnection electric field and the Hall (perpendicular) electric field forms distribution functions of the crescent type on the [52], [53], [A42] separatrices, which can be used as the main indication of the presence of cold ions in the inflowing plasma. In addition to this result, [A36] demonstrated the dependence of the magnetic reconnection efficiency on the plasma temperature due to the temperature dependence of the plasma ejection velocity [54].

Cold plasma outflowing from the ionosphere moves parallel to the magnetic field and have a significant speed. The influence of such a motion [55] consists in the displacement of the X-line with the average velocity of the stream, ultimately leading to the asymmetry of the outflow regions. It is noteworthy that, in the case of a uniform plasma flow, the reconnection rate does not change; however, in the presence of a velocity shift, it decreases. The limit value of this shift is about $2V_A$ [56]. When cold ions are accelerated by the reconnection electric field, the inertial term in the equation of motion plays an important role [57]. A similar result was obtained in [A36], which shows the collective acceleration of ions, but not heating (i. e., diffusion of beams in velocity space). The calculations show the formation of complex structures in the velocity space.

An unresolved issue in the process of magnetic reconnection is how the thermal distribution is formed (and is it formed at all?). It is assumed that the main role in this process is played by the wave-particle interaction, which leads to the transformation of individual accelerated cold beams into a Maxwellian type distribution. The MMS satellites confirm the presence of wave activity in observations of accelerated cold beams in the vicinity of magnetic reconnection [58], [59]. Waves in the lower hybrid range [60], [61], as well as ion-acoustic waves [60], [62] are excited, leading to a gradual heating of the cold ion population [63]. Nevertheless, the problem of thermalization mechanisms has not yet been unambiguously solved either in calculations or with the help of observational data.

4. Solar Wind Interaction with Lunar Magnetic Anomalies

A promising direction of modeling studies is the creation of a complete kinetic model of the entire magnetosphere. Since the end of the 20th century, a number of early works have been made, which present the fully kinetic approximation simulations [64], [65], [66], [67], [68]. First of all, the very possibility of applying the particle method to the problem of numerical modeling of the entire magnetosphere was demonstrated. The papers qualitatively reproduce the main magnetospheric structures: a cavity is formed in the solar wind and a standing shock wave is formed; there is a ring current in the near magnetosphere; there is a current sheet in the magnetotail and individual magnetic reconnection events occur. Typical for the particle method was the use of highly artificial parameters, such as the ratio of the masses of electrons to protons (1/16) and the magnitude of the solar wind speed to the speed of light ($\sim 1/2$).

The global numerical study of the entire Earth's magnetosphere by means of kinetic methods requires huge computing power. Even now, despite the rapid growth of available resources, kinetic global models of the magnetosphere [69] are very rare and, as a rule, use numerical parameters that simplify the calculation. Other ways to simplify calculations while maintaining scientific complexity are to use a two-dimensional model (for example, [70]), or to limit the calculation to a single region of the magnetosphere (shock wave, magnetosheath) [71], [72], or in the reduction of the magnetic moment of the dipole [73].

The magnetosphere belongs to the category of "large" magnetospheres if its characteristic size is on the order of or greater than 20 ion inertial lengths [74], [75]. Using particle-in-cell kinetic modeling, [76] found that smaller-scale magnetospheres demonstrate qualitative differences from "large" magnetospheres. The shock wave disappears, but the mini-magnetosphere becomes a source of a weak standing whistler wave (whistler). The magnetic field of the source penetrates into the solar wind [77], [78]. In such regimes, the ions are demagnetized on the scale of interaction between the plasma flow and the magnetic field, and as a result the Hall effect [78] [77] and ion kinetic effects [73], [76] dominate in the interaction dynamics.

In 1959, the Soviet mission Luna-2 travel in the vicinity of the Moon and did not detect the magnetic field. Further studies by the Explorer 35 missions in 1967 and Apollo 12 missions in 1969 were able to detect only separate areas of an increased magnetic field (magnetic anomalies) near the surface [79], [80]. Local fields are not dynamo-generated, but are due to the lunar crust remanent magnetization. A three-dimensional picture of the distribution of the magnetic field with high accuracy was created much later based on the results of observations made by the Lunar Prospector (NASA, 1998-1999) and Selena (JAXA, 2007-2009) satellites. The main measurements were carried out at altitudes of 10-70 km. It is shown that the fields are irregular and the characteristic sizes of magnetic anomalies do not exceed 200 km, which corresponds to the kinetic scales of ions in the solar wind. Based on the measurements, an empirical model of the Moon's magnetic anomalies [81], [2] was constructed. Thus, the disturbances in the solar wind created by the Moon's magnetic fields are mini-magnetospheres in terms of their scale.

Mini-magnetospheres are a more convenient target for particle-in-cell studies compared to classical "large" magnetospheres, since the desired spatial and temporal resolution is available even with limited computing resources. It is extremely important that mini-magnetospheres can be considered an intermediate object of study on the way to fully kinetic calculations of the entire Earth's magnetosphere, as well as the fact that fully three-dimensional calculations are available for mini-magnetospheres.

Studies where the Applicant is co-authored [A4], [A11], [A17], [A18], [A23], [A32], [A37], [A40] investigated various kinetic effects in plasma in the vicinity of mini-magnetospheres and lunar magnetic anomalies. The Applicant improved the iPIC3D code to the conditions of the problem, namely: the external field of the magnetic dipole was added, the boundary conditions were adjusted and the normalization scheme was proposed. In [A4], for the first time, a numerical simulation of the magnetic anomaly in the Reiner Gamma region was carried out by a fully kinetic method under the assumption that the magnetic dipole is oriented parallel to the surface. It is found that under typical conditions of the solar wind, a mini-magnetosphere with a height of $\sim$ 10 km is formed, into which the solar plasma does not penetrate. The mini-magnetosphere is surrounded by a region of strong electron current ("halo"), which, in turn, creates a normal electric field through the Hall effect. However, the electron current does not completely shield the solar wind from the magnetic field of the anomaly, as happens in “large” magnetospheres. As a result of the superposition of the magnetic field of the anomaly and the solar wind, magnetic nulls are formed without signs of active magnetic reconnection [A16].

The ion deflection is determined mainly by the dynamic pressure of the solar wind and weakly depends on the magnitude of the interplanetary magnetic field [A11], [A17]. At low dynamic pressure, the magnetic field of the anomaly protects the surface from the solar wind, which qualitatively corresponds to the observations of energetic neutral atoms (ENA) made by the Chandrayaan-1 satellite [82]. The reflection also depends on the orientation of the magnetic dipole relative to the surface and the direction of the solar wind [A17], [A18]. In the case when the magnetic moment is directed perpendicular to the surface, a magnetic cusp region is formed, which effectively reflects the solar wind electrons. In such a case, the electron distribution function contains individual beams moving parallel to the magnetic field, which was also observed by the Selena satellite [83].

Of great interest is the problem of the so-called "Lunar swirls". These formations are regions with an increased albedo, which have an irregular complex shape. Lunar swirls show a wide variety of shapes, from simple diffuse bands (Descartes region) to well-structured formations (Reiner Gamma region). A significant momentum to the development of these models was given when a connection was discovered between lunar magnetic anomalies and lunar swirls [84]. For a more realistic simulation of the dynamics of anomalies in the kinetic calculation [A23], an empirical magnetic field model [2] was added to the iPIC3D computational code. The morphology of the region with increased albedo was reproduced with high accuracy for the first time. The alternation of dark and bright lobes of the lunar vortex was explained by the complex structure of the magnetic fields that form the mini-magnetosphere. The effect is also preserved when the conditions in the solar wind are averaged over one lunar day [A32], taking into account the different direction of the solar wind velocity vector, as well as when heavier Helium ions are taken into account [A37].

5. Weak Cometary Atmosphere: a Kinetic Model

Early comet missions (for example, the Vega, Giotto, Sakigake spacecraft launched to Halley's comet in 1986) made a single high-velocity flyby through a coma, and therefore could not provide detailed information about dynamics of the cometary atmosphere. In 2014-2016 ESA satellite "Rosetta"studied the comet 67P/Churyumov-Gerasimenko, namely: the chemical composition of the cometary atmosphere, plasma environment, dust and gas flows from the surface. The satellite accompanied the comet for a long time at a close distance, which made it possible to obtain a large amount of new unique data on the structure and variations of the coma in various modes of cometary activity [85].

With the advent of modern high-performance supercomputers, large-scale 3D modeling has become possible to explain and predict the plasma environment of comets. Since the 1990s, a three-dimensional approach has been developed in the fluid approximation for the problem of the structure of cometary atmospheres [86], [87], [88]. The calculations were also performed using the hybrid description [89], [90], [91], which, however, could not explain the observed energy spectra of electrons with satisfactory accuracy [92], [93].

The Applicant developed a three-dimensional fully kinetic model of the interaction of the solar wind with the atmosphere of the weak comet 67P/Churyumov-Gerasimenko. One of the main parameters of cometary activity is the outgassing rate, which determines the rate of evaporation of cometary material and is expressed in the number of particles per second. At a heliocentric distance of 3 Astronomical Units (AU), the outgassing rate of 67P was approximately $\sim 10^{26}\ s^{-1}$ [85]. At a distance of 4.5 AU the outgassing was $\sim 10^{25}\ s^{-1}$, respectively, which is typical for the comet's weak regime. These parameters are used in the simulations. Noteworthy, at heliocentric distances less than 3 AU, the cometary atmosphere becomes too dense so it is necessary to take into account the effects of collisions between plasma components and neutral gas [94].

The Applicant adapted the code to this problem, performed calculations and constructed a mathematical model of the process. At each time step, the solar wind is loaded with water ions H_2O^+ and electrons [A22], [A26]. Water ions are demagnetized on the scale of the interaction, so they are accelerated directly by the electric field of the solar wind. At the same time, the electrons are magnetized and tied to the magnetic field lines. To satisfy the quasi-neutrality condition, an ambipolar potential is formed, which captures electrons of cometary origin and accelerates solar wind electrons parallel to the magnetic field [A29]. In good agreement with the experiment [95], [93], there is a separate very dynamic population of suprathermal electrons with energies of 20-100 eV [A31], [A39] moving parallel to the magnetic field.

6. Double-Gradient Instability (Flapping Instability)

Flapping is a large-scale perturbation of the magnetotail current sheet. Observations of such waves by Cluster satellites were first described in [96], [97], [98]. They are slow (an order of magnitude less than the typical Alfvén velocity V_A) waves propagating in the current sheet with a characteristic velocity of 20—60 km/s, an amplitude of 1—2 R_E and a quasi-period of 2—10 minutes .

Several theoretical approaches have been proposed to describe the magnetotail flapping oscillations in the kinetic approximation. The drift kink instability of the current sheet of the Harris type was discussed [99], [100]. Also the influence of the background steady plasma and the more complex structure of the current sheet is well understood [101], [102], [103], and the existence of a faster ion-ion drift instability is shown. Flapping oscillations are also interpreted as a Kelvin-Helmholtz instability caused by the current velocity gradient [104]. In these works, thin current sheets without a normal magnetic field component were considered, which imposed restrictions on the applicability of the results to the Earth's magnetosphere.

In the MHD approximation, models have been developed that describe the main properties of the flapping oscillation, taking into account the normal component of the magnetic field. In the presence of a finite curvature of magnetic field lines [105] ballooning instability is excited. In this case, the curvature radius must be larger than the wave length of the flapping oscillations. [106] developed the so-called double gradient model in the MHD approximation. A detailed identification of [107] magnetotail oscillations was carried out using data from several THEMIS satellites. It was shown that the nature of the observed rotation of the velocity vector is in good agreement with the theoretical parameters, however, the existence of several possible sources of waves or the presence of noise made it very difficult to identify the wave.

A three-dimensional numerical model of the double gradient instability in the MHD approach was developed [A1]. The current sheet with the normal component growing from the Earth was taken as the background. The theory predicts the existence of unstable solutions in such a configuration, which was also confirmed by calculations using a linearized model. In subsequent papers, the results were generalized to more realistic current sheets [A7], [A28]. Variants with a current sheet containing a guide magnetic field [A7] are considered and it is found that even a small value ($\sim$ 10% of the magnetic field in lobes) suppresses a part of the spectrum with wavelengths smaller than the typical thickness of the current sheet. In [A28], a bent current sheet was taken as the initial state and it was shown that instability develops in such a sheet even with the normal component B_z decreasing into a tail. The bent current sheet turns out to be more unstable with respect to the flapping instability, which can be important for the breakup of a magnetospheric substorm.

The Main Provisions That are Put for the Defense

New results are obtained for several problems relevant to space plasma physics, for which a comprehensive study of the process is possible only through numerical simulation and where the plasma dynamics is collisionless:

1. A model [13], [14] of the electron diffusion region was constructed, which takes into account the anisotropy of the electron pressure in the inflow region [A19]. It has been established that the rate of reconnection, the main explosive process in space plasma, in the kinetic regime is not a constant of the order of ~ 0.1, but has a weak (but clearly noticeable) dependence on external parameters [A24], [A27]. In a foreign cooperation, an analytical model of the electron diffusion region [A33, A34], [108], [109] was created, which was successfully tested on satellite data [A34].

2. Kinetic numerical simulations of magnetic reconnection in the presence of cold ions were carried out for the first time. A model of the diffusion region in a multitemperature plasma is developed, and the earlier assumption that cold ions slow down the process of magnetic reconnection is rejected [A20], [A42], [A36], [A41]. Cold ions are accelerated by the reconnection electric field [A20], they experience energization at the separatrices [A14], [A15], [A36], and are also heated by the waves [A15], [A41], [A42].

3. Dynamics of dipolarization (reconnection) fronts [110], [A2], [A3], [A5], [A12], [A16] and magnetic reconnection separatrices [A13], [A24], [A30] is investigated by means of PIC simulations and Cluster data. Electrons are heated [A8] and experience diffusion [A38] due to the lower hybrid drift wave activity. The mechanisms of energy conversion at the front [A5], [A9], [A13], [A21], [A25] were studied. In cooperation with foreign colleagues, the calculation of the effects of lower hybrid wave activity was tested on data from the MMS spacecraft [A38].

4. The interaction of the solar wind with the atmosphere of the weak comet 67P/Churyumov-Gerasimenko at a distance of 3-4 astronomical units from the Sun was studied. A numerical model of the plasma environment was developed [A22], [A26], [A39] for the first time. The mechanism of acceleration of suprathermal electrons by an ambipolar electric field was demonstrated [A29], which made it possible to explain the observed fluxes of energetic electrons found by the Rosetta satellite [A31], [A39], [93], [95].

5. The precipitation of solar wind particles in the lunar regions of local magnetic fields enhancements was studied by means of numerical simulation. The existence of mini-magnetopheres of several kilometers in size (areas where the solar wind does not penetrate) has been proven [A4], [A11], [A16], [A17], [A18]. The formation of mini-magnetospheres and the reflection of ions from them is confirmed in a laboratory experiment [A40]. For the first time, a numerical model of the lunar magnetic anomaly Reiner Gamma was constructed using the empirical magnetic field of the Moon [2] and the formation of a lunar swirl on the surface due to the influence of cosmic weathering was proved [A23], [A32], [A37]. Mini-magnetospheres provide protection from the constantly flowing solar wind throughout the entire lunar day, including the periods of time when the Moon passes through the Earth's magnetosphere [A32]. The numerical simulation results were tested with the Chandrayaan-1 spacecraft data [A23].

6. Three-dimensional MHD simulations were used to study the linear and nonlinear stages of the double gradient instability ("flapping" instability) of the Earth's magnetotail [A1], which shapes the dynamics of the current sheet of the Earth's magnetosphere and affects the breakup process of a magnetospheric substorm. The model is extended for the case of the presence of a guide field [A7] and a bent initial current sheet of the magnetotail [A28]. It is shown that the bending of the current sheet is a critical parameter of the magnetotail, which possibly leads to the substorm breakup.

A List of the Applicant's Publications

A1. Korovinskiy, D. B., **Divin, A.**, Erkaev, N. V., Ivanova, V. V., Ivanov, I. B., Semenov, V. S., Lapenta, G., Markidis, S., Biernat, H. K. & Zellinger, M. MHD modeling of the double-gradient (kink) magnetic instability. Journal of Geophysical Research (Space Physics) 118, 1146—1158. doi:10.1002/jgra.50206 (Mar. 2013).

A2. Vapirev, A. E., Lapenta, G., **Divin, A.**, Markidis, S., Henri, P., Goldman, M. & Newman, D. Formation of a transient front structure near reconnection point in 3-D PIC simulations. Journal of Geophysical Research (Space Physics) 118, 1435—1449. doi:10.1002/jgra.50136 (Apr. 2013).

A3. Markidis, S., Henri, P., Lapenta, G., **Divin, A.**, Goldman, M., Newman, D. & Laure, E. Kinetic simulations of plasmoid chain dynamics. Physics of Plasmas 20, 082105. doi:10.1063/1.4817286. arXiv: 1306.1050 [physics.plasm-ph] (Aug. 2013).

A4. Deca, J., **Divin, A.**, Lapenta, G., Lembège, B., Markidis, S. & Horányi, M. Electromagnetic Particle-in-Cell Simulations of the Solar Wind Interaction with Lunar Magnetic Anomalies. Physical Review Letters 112, 151102. doi:10.1103/PhysRevLett.112.151102 (Apr. 2014).

A5. Lapenta, G., Goldman, M., Newman, D., Markidis, S. & **Divin, A.** Electromagnetic energy conversion in downstream fronts from three dimensional kinetic reconnectiona). Physics of Plasmas 21, 055702. doi:10.1063/1.4872028. arXiv: 1402.0082 [physics.plasm-ph] (May 2014).

A6. Olshevsky, V., Lapenta, G., Markidis, S. & **Divin, A.** Role of Z-pinches in magnetic reconnection in space plasmas. Journal of Plasma Physics 81, 325810105. doi:10.1017/S0022377814000725. arXiv: 1509 . 07962 [physics.space-ph] (Jan. 2015).

A7. Korovinskiy, D. B., **Divin, A. V.**, Erkaev, N. V., Semenov, V. S., Artemyev, A. V., Ivanova, V. V., Ivanov, I. B., Lapenta, G., Markidis, S. & Biernat, H. K. The double-gradient magnetic instability: Stabilizing effect of the guide field. Physics of Plasmas 22, 012904. doi:10.1063/1.4905706 (Jan. 2015).

A8. **Divin, A.**, Khotyaintsev, Y. V., Vaivads, A., André, M., Markidis, S. & Lapenta, G. Evolution of the lower hybrid drift instability at reconnection jet front. Journal of Geophysical Research (Space Physics) 120, 2675—2690. doi:10.1002/2014JA020503 (Apr. 2015).

A9. Peng, I. B., Vencels, J., Lapenta, G., **Divin, A.**, Vaivads, A., Laure, E. & Markidis, S. Energetic particles in magnetotail reconnection. Journal of Plasma Physics 81, 325810202. doi:10.1017/S0022377814001123 (Apr. 2015).

A10. Olshevsky, V., **Divin, A.**, Eriksson, E., Markidis, S. & Lapenta, G. Energy Dissipation in Magnetic Null Points at Kinetic Scales. The Astrophysical Journal 807, 155. doi:10.1088/0004-637X/807/2/155. arXiv: 1509.07961 [astro-ph.EP] (Jul. 2015).

A11. Deca, J., **Divin, A.**, Lemb‘ege, B., Horányi, M., Markidis, S. & Lapenta, G. General mechanism and dynamics of the solar wind interaction with lunar magnetic anomalies from 3-D particle-in-cell simulations. Journal of Geophysical Research (Space Physics) 120, 6443—6463. doi:10.1002/2015JA021070 (Aug. 2015).

A12. **Divin, A.**, Khotyaintsev, Y. V., Vaivads, A. & André, M. Lower hybrid drift instability at a dipolarization front. Journal of Geophysical Research (Space Physics) 120, 1124—1132. doi:10.1002/2014JA020528 (Feb. 2015).

A13. Lapenta, G., Markidis, S., **Divin, A.**, Newman, D. & Goldman, M. Separatrices: The crux of reconnection. Journal of Plasma Physics 81, 325810109. doi:10.1017/S0022377814000944. arXiv: 1406.6141 [physics.plasm-ph] (Jan. 2015).

A14. Toledo-Redondo, S., André, M., Vaivads, A., Khotyaintsev, Y. V., Lavraud, B., Graham, D. B., **Divin, A.** & Aunai, N. Cold ion heating at the dayside magnetopause during magnetic reconnection. Geophysical Research Letters 43, 58—66. doi:10.1002/2015GL067187 (Jan. 2016).

A15. Toledo-Redondo, S., André, M., Khotyaintsev, Y. V., Vaivads, A., Walsh, A., Li, W., Graham, D. B., Lavraud, B., Masson, A., Aunai, N., **Divin, A.**, Dargent, J., Fuselier, S., Gershman, D. J., Dorelli, J., Giles, B., Avanov, L., Pollock, C., Saito, Y., Moore, T. E., Coffey, V., Chandler, M. O., Lindqvist, P.-A., Torbert, R. & Russell, C. T. Cold ion demagnetization near the X-line of magnetic reconnection. Geophysical Research Letters 43, 6759—6767. doi:10.1002/2016GL069877 (Jul. 2016).

A16. Olshevsky, V., Deca, J., **Divin, A.**, Peng, I. B., Markidis, S., Innocenti, M. E., Cazzola, E. & Lapenta, G. Magnetic Null Points in

Kinetic Simulations of Space Plasmas. The Astrophysical Journal 819, 52. doi:10.3847/0004-637X/819/1/52. arXiv: 1512.02018 [physics.space-ph] (Mar. 2016).

A17. Deca, J., **Divin, A.**, Wang, X., Lembège, B., Markidis, S., Horányi, M. & Lapenta, G. Three-dimensional full-kinetic simulation of the solar wind interaction with a vertical dipolar lunar magnetic anomaly. Geophysical Research Letters 43, 4136—4144. doi:10.1002/2016GL068535 (May 2016).

A18. Deca, J. & **Divin, A.** Reflected Charged Particle Populations around Dipolar Lunar Magnetic Anomalies. The Astrophysical Journal 829, 60. doi:10.3847/0004-637X/829/2/60 (Oct. 2016).

A19. **Divin, A.**, Semenov, V., Korovinskiy, D., Markidis, S., Deca, J., Olshevsky, V. & Lapenta, G. A new model for the electron pressure nongyrotropy in the outer electron diffusion region. Geophysical Research Letters 43, 10, 565—10, 573. doi:10.1002/2016GL070763 (Oct. 2016).

A20. **Divin, A.**, Khotyaintsev, Y. V., Vaivads, A., André, M., Toledo-Redondo, S., Markidis, S. & Lapenta, G. Three-scale structure of diffusion region in the presence of cold ions. Journal of Geophysical Research (Space Physics) 121, 12, 001—12, 013. doi:10.1002/2016JA023606 (Dec. 2016).

A21. Khotyaintsev, Y. V., **Divin, A.**, Vaivads, A., André, M. & Markidis, S. Energy conversion at dipolarization fronts. Geophysical Research Letters 44, 1234—1242. doi:10.1002/2016GL071909 (Feb. 2017).

A22. Deca, J., **Divin, A.**, Henri, P., Eriksson, A., Markidis, S., Olshevsky, V. & Horányi, M. Electron and Ion Dynamics of the Solar Wind Interaction with a Weakly Outgassing Comet. Physical Review Letters 118, 205101. doi:10.1103/PhysRevLett.118.205101 (May 2017).

A23. Deca, J., **Divin, A.**, Lue, C., Ahmadi, T. & Horányi, M. Reiner Gamma albedo features reproduced by modeling solar wind standoff. Communications Physics 1, 12. doi:10.1038/s42005-018-0012-9 (Apr. 2018).

A24. Eriksson, E., Vaivads, A., Graham, D. B., **Divin, A.**, Khotyaintsev, Y. V., Yordanova, E., André, M., Giles, B. L., Pollock, C. J., Russell, C. T., Contel, O. L., Torbert, R. B., Ergun, R. E., Lindqvist, P.-A. & Burch, J. L. Electron Energization at a Reconnecting Magnetosheath Current Sheet. Geophysical Research Letters 45, 8081—8090. doi:10.1029/2018GL078660 (Aug. 2018).

A25. Liu, C. M., Fu, H. S., Cao, D., Xu, Y. & **Divin, A.** Detection of Magnetic Nulls around Reconnection Fronts. The Astrophysical Journal 860, 128. doi:10.3847/1538-4357/aac496 (Jun. 2018).

A26. Deca, J., Henri, P., **Divin, A.**, Eriksson, A., Galand, M., Beth, A., Ostaszewski, K. & Horányi, M. Building a Weakly Outgassing Comet from a Generalized Ohm's Law. Physical Review Letters 123, 055101. doi:10.1103/PhysRevLett.123.055101 (Aug. 2019).

A27. **Divin, A.**, Semenov, V., Zaitsev, I., Korovinskiy, D., Deca, J., Lapenta, G., Olshevsky, V. & Markidis, S. Inner and outer electron diffusion region of antiparallel collisionless reconnection: Density dependence. Physics of Plasmas 26, 102305. doi:10.1063/1.5109368 (Oct. 2019).

A28. Korovinskiy, D. B., **Divin, A. V.**, Semenov, V. S., Erkaev, N. V., Ivanov, I. B., Kiehas, S. A. & Markidis, S. The transition from "double-gradient" to ballooning unstable mode in bent magnetotail-like current sheet. Physics of Plasmas 26, 102901. doi:10.1063/1.5119096 (Oct. 2019).

A29. Sishtla, C. P., **Divin, A.**, Deca, J., Olshevsky, V. & Markidis, S. Electron trapping in the coma of a weakly outgassing comet. Physics of Plasmas 26, 102904. doi:10.1063/1.5115456 (Oct. 2019).

A30. Khotyaintsev, Y. V., Graham, D. B., Steinvall, K., Alm, L., Vaivads, A., Johlander, A., Norgren, C., Li, W., **Divin, A.**, Fu, H. S., Hwang, K. .-J., Burch, J. L., Ahmadi, N., Le Contel, O., Gershman, D. J., Russell, C. T. & Torbert, R. B. Electron Heating by Debye-Scale Turbulence in Guide-Field Reconnection. Physical Review Letters 124, 045101. doi:10.1103/PhysRevLett.124.045101. arXiv: 1908.09724 [physics.space-ph] (Jan. 2020).

A31. **Divin, A.**, Deca, J., Eriksson, A., Henri, P., Lapenta, G., Olshevsky, V. & Markidis, S. A Fully Kinetic Perspective of Electron Acceleration around a Weakly Outgassing Comet. The Astrophysical Journal Letters 889:L33. doi:10.3847/2041-8213/ab6662 (Feb. 2020).

A32. Deca, J., Hemingway, D. J., **Divin, A.**, Lue, C., Poppe, A. R., Garrick-Bethell, I., Lembège, B. & Horányi, M. Simulating the Reiner Gamma Swirl: The Long Term Effect of Solar Wind Standoff. Journal of Geophysical Research (Planets) 125, e06219. doi:10.1029/2019JE006219 (May 2020).

A33. Korovinskiy, D. B., **Divin, A. V.**, Semenov, V. S., Erkaev, N. V., Kiehas, S. A. & Kubyshkin, I. V. Grad-Shafranov reconstruction of the magnetic configuration in the reconnection X-point vicinity in compressible plasma. Physics of Plasmas 27, 082905. doi:10.1063/5.0015240 (Aug. 2020).

A34. Korovinskiy, D. B., Kiehas, S. A., Panov, E. V., Semenov, V. S., Erkaev, N. V., **Divin, A. V.** & Kubyshkin, I. V. The Inertia Based Model for Reconstruction of the Electron Diffusion Region. Journal of Geophysical Research (Space Physics) 126, e29045. doi:10.1029/2020JA029045 (May 2021).

A35. Olshevsky, V., Khotyaintsev, Y. V., Lalti, A., **Divin, A.**, Delzanno, G. L., Anderzén, S., Herman, P., Chien, S. W. D., Avanov, L., Dimmock, A. P. & Markidis, S. Automated Classification of Plasma Regions Using 3D Particle Energy Distributions. Journal of Geophysical Research (Space Physics) 126, e29620. doi:10.1029/2021JA029620. arXiv: 1908.05715 [physics.space-ph] (Oct. 2021).

A36. Zaitsev, I., **Divin, A.**, Semenov, V., Kubyshkin, I., Korovinskiy, D., Deca, J., Khotyaintsev, Y. & Markidis, S. Cold ion energization at separatrices during magnetic reconnection. Physics of Plasmas 28, 032104. doi:10.1063/5.0008118 (Mar 2021).

A37. Deca, J., Poppe, A. R., **Divin, A.** & Lembège, B. The Plasma Environment Surrounding the Reiner Gamma Magnetic Anomaly. Journal of Geophysical Research (Space Physics) 126, e29180. doi:10.1029/2021JA029180 (Sept. 2021).

A38. Graham, D. B., Khotyaintsev, Y. V., André, M., Vaivads, A., **Divin, A.**, Drake, J. F., Norgren, C., Le Contel, O., Lindqvist, P. .-A., Rager, A. C., Gershman, D. J., Russell, C. T., Burch, J. L., Hwang, K. .-J. & Dokgo, K. Direct observations of anomalous resistivity and diffusion in collisionless plasma. Nature Communications 13, 2954. doi:10.1038/s41467-022 30561-8 (May 2022).

A39. Goetz, C., Behar, E., Beth, A., Bodewits, D., Bromley, S., Burch, J., Deca, J., **Divin, A.**, Eriksson, A. I., Feldman, P. D., Galand, M., Gunell, H., Henri, P., Heritier, K., Jones, G. H., Mandt, K. E., Nilsson, H., Noonan, J. W., Odelstad, E., Parker, J. W., Rubin, M., Simon Wedlund, C., Stephenson, P., Taylor, M. G. G. T., Vigren, E., Vines, S. K. & Volwerk, M. The Plasma Environment of Comet 67P/Churyumov-Gerasimenko. Space Science Reviews 218, 65. doi:10.1007/s11214-022-00931-1 (Dec. 2022).

A40. Rumenskikh, M. C., Chibranov, A. A., Efimov, M. A., Berezutsky, A. G., Posukh, V. G., Zakharov, Y. P., Boyarintsev, E. L., Miroshnichenko, I. B., Trushin, P. A., **Divin, A. V.** & Shaikhislamov, I. F. Laboratory Modelling of Solar Wind Interaction with Lunar Magnetic Anomalies. Astronomy Reports 67, 78—85. doi:10.1134/S1063772923010079. arXiv: 2208 . 10566 [physics.plasm-ph] (Jan. 2023).

A41. Dargent, J., Toledo-Redondo, S., **Divin, A.** & Innocenti, M. E. Energy Conversion by Magnetic Reconnection in Multiple Ion Temperature Plasmas. Geophysical Research Letters 50, e2023GL103324. doi:10.1029/2023GL103324 (Jun. 2023).

A42. **Divin, A.**, Zaitsev, I., Paramonik, I., Semenov, V., Korovinskiy, D., Mao, A., Dargent, J. P., Toledo-Redondo, S. & Deca, J. Cold ion crescent echoes in the exhaust of symmetric magnetic reconnection. Physics of Plasmas 30, 062901. doi:10.1063/5.0155958 (Jun 2023).

References

1. Markidis, S. & Lapenta, G. Multi-scale simulations of plasma with iPIC3D. *Mathematics and Computers in Simulation* **80,** 1509—1519 (2010).
2. Tsunakawa, H., Takahashi, F., Shimizu, H., Shibuya, H. & Matsushima, M. Surface vector mapping of magnetic anomalies over the Moon using Kaguya and Lunar Prospector observations. *Journal of Geophysical Research: Planets* **120,** 1160—1185 (2015).
3. Sweet, P. The production of high energy particles in solar flares. *Il Nuovo Cimento (1955-1965)* **8,** 188—196. doi:10.1007/BF02962520 (1958).
4. Parker, E. N. The Solar-Flare Phenomenon and the Theory of Reconnection and Annihiliation of Magnetic Fields. *Astrophysical Journal Supplement* **8,** 177. doi:10.1086/190087 (1963).
5. Petschek, H. E. Magnetic Field Annihilation. *NASA Special Publication* **50,** 425 (1964).
6. Priest, E. & Forbes, T. *Magnetic Reconnection* (2007).
7. Vasyliunas, V. M. Theoretical Models of Magnetic Field Line Merging, 1. *Reviews of Geophysics* **13,** 303—336. doi:10.1029/RG013i001p00303 (1975).
8. Birn, J., Drake, J., Shay, M., Rogers, B., Denton, R., Hesse, M., Kuznetsova, M., Ma, Z., Bhattacharjee, A. & Otto, A. Geospace Environmental Modeling (GEM) magnetic reconnection challenge. *Journal of Geophysical Research: Space Physics* **106,** 3715—3719 (2001).
9. Kuznetsova, M. M., Hesse, M. & Winske, D. Kinetic quasi-viscous and bulk flow inertia effects in collisionless magnetotail reconnection. *J. Geophys. Res.* **103,** 199—214. doi:10.1029/97JA02699 (1998).
10. Hesse, M. & Winske, D. Electron dissipation in collisionless magnetic reconnection. *J. Geophys. Res.* **103,** 26479—26486. doi:10.1029/98JA01570 (1998).
11. Egedal, J., Øieroset, M., Fox, W. & Lin, R. In situ discovery of an electrostatic potential, trapping electrons and mediating fast reconnection in the Earth's magnetotail. *Physical review letters* **94,** 025006 (2005).

12. Egedal, J., Fox, W., Katz, N., Porkolab, M., Øieroset, M., Lin, R., Daughton, W. & Drake, J. Evidence and theory for trapped electrons in guide field magnetotail reconnection. *Journal of Geophysical Research: Space Physics* **113** (2008).

13. Divin, A., Markidis, S., Lapenta, G., Semenov, V., Erkaev, N. & Biernat, H. Model of electron pressure anisotropy in the electron diffusion region of collisionless magnetic reconnection. *Physics of plasmas* **17,** 122102 (2010).

14. Divin, A., Lapenta, G., Markidis, S., Semenov, V., Erkaev, N., Korovinskiy, D. & Biernat, H. Scaling of the inner electron diffusion region in collisionless magnetic reconnection. *Journal of Geophysical Research: Space Physics* **117** (2012).

15. Hesse, M., Aunai, N., Sibeck, D. & Birn, J. On the electron diffusion region in planar, asymmetric, systems. *Geophysical Research Letters* **41,** 8673—8680 (2014).

16. Shay, M., Phan, T., Haggerty, C., Fujimoto, M., Drake, J., Malakit, K., Cassak, P. & Swisdak, M. Kinetic signatures of the region surrounding the X line in asymmetric (magnetopause) reconnection. *Geophysical Research Letters* **43,** 4145—4154 (2016).

17. Egedal, J., Le, A., Daughton, W., Wetherton, B., Cassak, P., Chen, L.-J., Lavraud, B., Torbert, R., Dorelli, J. & Gershman, D. Spacecraft observations and analytic theory of crescent-shaped electron distributions in asymmetric magnetic reconnection. *Physical review letters* **117,** 185101 (2016).

18. Norgren, C., Graham, D. B., Khotyaintsev, Y. V., André, M., Vaivads, A., Chen, L. .-J., Lindqvist, P. .-A., Marklund, G. T., Ergun, R. E., Magnes, W., Strangeway, R. J., Russell, C. T., Torbert, R. B., Paterson, W. R., Gershman, D. J., Dorelli, J. C., Avanov, L. A., Lavraud, B., Saito, Y., Giles, B. L., Pollock, C. J. & Burch, J. L. Finite gyroradius effects in the electron outflow of asymmetric magnetic reconnection. *Geophys. Res. Lett.* **43,** 6724—6733. doi:10.1002/2016GL069205 (2016).

19. Karimabadi, H., Daughton, W. & Scudder, J. Multi-scale structure of the electron diffusion region. *Geophys. Res. Lett.* **34,** L13104. doi:10.1029/2007GL030306 (2007).

20. Swisdak, M. Quantifying gyrotropy in magnetic reconnection. *Geophys. Res. Lett.* **43,** 43—49. doi:10.1002/2015GL066980. arXiv: 1509.00787 `[physics.space-ph]` (2016).
21. Aunai, N., Hesse, M. & Kuznetsova, M. Electron nongyrotropy in the context of collisionless magnetic reconnection. *Physics of Plasmas (1994-present)* **20,** 092903 (2013).
22. Li, X. & Liu, Y.-H. The Effect of Thermal Pressure on Collisionless Magnetic Reconnection Rate. *The Astrophysical Journal* **912,** 152 (2021).
23. Angelopoulos, V., Baumjohann, W., Kennel, C. F., Coronti, F. V., Kivelson, M. G., Pellat, R., Walker, R. J., Luehr, H. & Paschmann, G. Bursty bulk flows in the inner central plasma sheet. *J. Geophys. Res.* **97,** 4027—4039. doi:10.1029/91JA02701 (1992).
24. Angelopoulos, V. Statistical characteristics of bursty bulk flow events. *J. Geophys. Res.* **99,** 21257. doi:10.1029/94JA01263 (1994).
25. Ohtani, S.-i., Shay, M. A. & Mukai, T. Temporal structure of the fast convective flow in the plasma sheet: Comparison between observations and two-fluid simulations. *Journal of Geophysical Research (Space Physics)* **109,** 3210—+. doi:10.1029/2003JA010002 (2004).
26. Angelopoulos, V., Runov, A., Zhou, X.-Z., Turner, D., Kiehas, S., Li, S.-S. & Shinohara, I. Electromagnetic energy conversion at reconnection fronts. *science* **341,** 1478—1482 (2013).
27. Runov, A., Angelopoulos, V., Sitnov, M. I., Sergeev, V. A., Bonnell, J., McFadden, J. P., Larson, D., Glassmeier, K.-H. & Auster, U. THEMIS observations of an earthward-propagating dipolarization front. *Geophys. Res. Lett.* **36,** 14106. doi:10.1029/2009GL038980 (2009).
28. Heyn, M. F. & Semenov, V. S. Rapid reconnection in compressible plasma. *Physics of Plasmas* **3,** 2725—2741 (1996).
29. Nakamura, M. S., Matsumoto, H. & Fujimoto, M. Interchange instability at the leading part of reconnection jets. *Geophys. Res. Lett.* **29,** 1247. doi:10.1029/2001GL013780 (2002).

30. TanDokoro, R. & Fujimoto, M. Three-dimensional MHD simulation study of the structure at the leading part of a reconnection jet. *Geophys. Res. Lett.* **32,** 23102. doi:10.1029/2005GL024467 (2005).

31. Guzdar, P. N., Hassam, A. B., Swisdak, M. & Sitnov, M. I. A simple MHD model for the formation of multiple dipolarization fronts. *Geophys. Res. Lett.* **37,** 20102. doi:10.1029/2010GL045017 (2010).

32. Lapenta, G. & Bettarini, L. Self-consistent seeding of the interchange instability in dipolarization fronts. *Geophys. Res. Lett.* **38,** 11102. doi:10.1029/2011GL047742. arXiv: 1105.0485 `[astro-ph.EP]` (2011).

33. Pritchett, P. L. & Coroniti, F. V. A kinetic ballooning/interchange instability in the magnetotail. *Journal of Geophysical Research (Space Physics)* **115,** 6301. doi:10.1029/2009JA014752 (2010).

34. Pritchett, P. L. & Coroniti, F. V. Plasma sheet disruption by interchange-generated flow intrusions. *Geophys. Res. Lett.* **381,** 10102. doi:10.1029/2011GL047527 (2011).

35. Pritchett, P. L. Structure of exhaust jets produced by magnetic reconnection localized in the out-of-plane direction. *Journal of Geophysical Research (Space Physics)* **120,** 592—608. doi:10.1002/2014JA020795 (2015).

36. Nakamura, T., Nakamura, R. & Hasegawa, H. Three-dimensional development of front region of plasma jets generated by magnetic reconnection. *Geophys. Res. Lett.* **43,** 8356—8364. doi:10.1002/2016GL070215 (2016).

37. Nagai, T., Shinohara, I., Fujimoto, M., Machida, S., Nakamura, R., Saito, Y. & Mukai, T. Structure of the Hall current system in the vicinity of the magnetic reconnection site. *Journal of Geophysical Research (Space Physics)* **108,** 1357. doi:10.1029/2003JA009900 (2003).

38. Sergeev, V. A., Apatenkov, S. V., Nakamura, R., Plaschke, F., Baumjohann, W., Panov, E. V., Kubyshkin, I. V., Khotyaintsev, Y., Burch, J. L., Giles, B. L., Russell, C. T. & Torbert, R. B. MMS Observations of Reconnection Separatrix Region in the Magnetotail at Different Distances From the Active Neutral X-Line. *Journal of Geophysical Research (Space Physics)* **126,** e28694. doi:10.1029/2020JA028694 (2021).

39. Lapenta, G., Markidis, S., Divin, A., Goldman, M. & Newman, D. Scales of guide field reconnection at the hydrogen mass ratio. *Physics of Plasmas* **17,** 082106. doi:10.1063/1.3467503 (2010).

40. Lapenta, G., Markidis, S., Divin, A., Goldman, M. V. & Newman, D. L. Bipolar electric field signatures of reconnection separatrices for a hydrogen plasma at realistic guide fields. *Geophys. Res. Lett.* **38,** L17104. doi:10.1029/2011GL048572. arXiv: 1108.2492 `[physics.plasm-ph]` (2011).

41. Divin, A., Lapenta, G., Markidis, S., Newman, D. & Goldman, M. Numerical simulations of separatrix instabilities in collisionless magnetic reconnection. *Physics of Plasmas* **19,** 042110 (2012).

42. Torkar, K., Riedler, W., Escoubet, C. P., Fehringer, M., Schmidt, R., Grard, R. J. L., Arends, H., Rüdenauer, F., Steiger, W., Narheim, B. T., Svenes, K., Torbert, R., André, M., Fazakerley, A., Goldstein, R., Olsen, R. C., Pedersen, A., Whipple, E. & Zhao, H. Active spacecraft potential control for Cluster implementation and first results. *Annales Geophysicae* **19,** 1289—1302. doi:10.5194/angeo-19-1289-2001 (2001).

43. Seki, K., Hirahara, M., Hoshino, M., Terasawa, T., Elphic, R. C., Saito, Y., Mukai, T., Hayakawa, H., Kojima, H. & Matsumoto, H. Cold ions in the hot plasma sheet of Earth's magnetotail. *Nature* **422,** 589—592. doi:10.1038/nature01502 (2003).

44. André, M. & Cully, C. M. Low-energy ions: A previously hidden solar system particle population. *Geophysical Research Letters* **39** (2012).

45. Mao, A. & Wang, Z. Multiple ion temperature effects on collisionless magnetic reconnection. *AIP Advances* **11,** 025316 (2021).

46. Spinnangr, S. F., Hesse, M., Tenfjord, P., Norgren, C., Kolstø, H. M., Kwagala, N. K. & Jørgensen, T. M. The Micro-Macro Coupling of Mass-Loading in Symmetric Magnetic Reconnection With Cold Ions. *Geophysical Research Letters* **48,** e2020GL090690 (2021).

47. Darrouzet, F., Gallagher, D. L., André, N., Carpenter, D. L., Dandouras, I., Décréau, P. M. E., de Keyser, J., Denton, R. E., Foster, J. C., Goldstein, J., Moldwin, M. B., Reinisch, B. W., Sandel, B. R. & Tu, J. Plasmaspheric Density Structures and Dynamics: Properties Observed by the CLUSTER

and IMAGE Missions. *Space Sci. Rev.* **145,** 55—106. doi:10.1007/s11214-008-9438-9 (2009).

48. André, M., Vaivads, A., Khotyaintsev, Y. V., Laitinen, T., Nilsson, H., Stenberg, G., Fazakerley, A. & Trotignon, J. Magnetic reconnection and cold plasma at the magnetopause. *Geophysical Research Letters* **37** (2010).

49. Toledo-Redondo, S., Vaivads, A., André, M. & Khotyaintsev, Y. V. Modification of the Hall physics in magnetic reconnection due to cold ions at the Earth's magnetopause. *Geophysical Research Letters* **42,** 6146—6154 (2015).

50. Alm, L., Andre, M., Vaivads, A., Khotyaintsev, Y. V., Torbert, R. B., Burch, J. L., Ergun, R., Lindqvist, P.-A., Russell, C. T. & Giles, B. L. Magnetotail Hall physics in the presence of cold ions. *Geophysical Research Letters* **45,** 10—941 (2018).

51. Toledo-Redondo, S., Dargent, J., Aunai, N., Lavraud, B., André, M., Li, W., Giles, B., Lindqvist, P.-A., Ergun, R. E. & Russell, C. T. Perpendicular current reduction caused by cold ions of ionospheric origin in magnetic reconnection at the magnetopause: Particle-in-cell simulations and spacecraft observations. *Geophysical Research Letters* **45,** 10—033 (2018).

52. Dargent, J., Aunai, N., Lavraud, B., Toledo-Redondo, S., Shay, M., Cassak, P. & Malakit, K. Kinetic simulation of asymmetric magnetic reconnection with cold ions. *Journal of Geophysical Research: Space Physics* **122,** 5290—5306 (2017).

53. Dargent, J., Aunai, N., Lavraud, B., Toledo-Redondo, S. & Califano, F. Signatures of cold ions in a kinetic simulation of the reconnecting magnetopause. *Journal of Geophysical Research: Space Physics* **124,** 2497—2514 (2019).

54. Haggerty, C. C., Shay, M. A., Chasapis, A., Phan, T. D., Drake, J. F., Malakit, K., Cassak, P. A. & Kieokaew, R. The reduction of magnetic reconnection outflow jets to sub-Alfvénic speeds. *Physics of Plasmas* **25,** 102120 (2018).

55. Tenfjord, P., Hesse, M., Norgren, C., Spinnangr, S. F., Kolstø, H. & Kwagala, N. Interaction of Cold Streaming Protons with the Reconnection Process.

Journal of Geophysical Research (Space Physics) **125,** e27619. doi:10.1029/2019JA027619 (2020).

56. Doss, C. E., Cassak, P. A. & Swisdak, M. Particle-in-cell simulation study of the scaling of asymmetric magnetic reconnection with in-plane flow shear. *Physics of Plasmas* **23,** 082107. doi:10.1063/1.4960324. arXiv: 1607.05611 `[physics.plasm-ph]` (2016).
57. Spinnangr, S. F., Hesse, M., Tenfjord, P., Norgren, C., Kolstø, H. M., Kwagala, N. K. & Jørgensen, T. M. The Micro-Macro Coupling of Mass-Loading in Symmetric Magnetic Reconnection With Cold Ions. *Geophys. Res. Lett.* **48,** e90690. doi:10.1029/2020GL090690 (2021).
58. Li, Y.-X., Li, W.-Y., Tang, B.-B., Norgren, C., He, J.-S., Wang, C., Zong, Q.-G., Toledo-Redondo, S., André, M., Chappell, C., Dargent, J., Fuselier, S. A., Glocer, A., Graham, D. B., Haaland, S., Kistler, L., Lavraud, B., Moore, T. E., Tenfjord, P., Vines, S. K. & Burch, J. Quantification of cold-ion beams in a magnetic reconnection jet. *Frontiers in Astronomy and Space Sciences* **8,** 193. doi:10.3389/fspas.2021.745264 (2021).
59. Liu, C., Vaivads, A., Graham, D. B., Khotyaintsev, Y. V., Fu, H., Johlander, A., André, M. & Giles, B. Ion-beam-driven intense electrostatic solitary waves in reconnection jet. *Geophysical Research Letters* **46,** 12702—12710 (2019).
60. Toledo-Redondo, S., André, M., Khotyaintsev, Y. V., Lavraud, B., Vaivads, A., Graham, D. B., Li, W., Perrone, D., Fuselier, S. & Gershman, D. J. Energy budget and mechanisms of cold ion heating in asymmetric magnetic reconnection. *Journal of Geophysical Research: Space Physics* **122,** 9396—9413 (2017).
61. Graham, D. B., Khotyaintsev, Y. V., Norgren, C., Vaivads, A., André, M., Toledo-Redondo, S., Lindqvist, P.-A., Marklund, G., Ergun, R. & Paterson, W. Lower hybrid waves in the ion diffusion and magnetospheric inflow regions. *Journal of Geophysical Research: Space Physics* **122,** 517—533 (2017).
62. Norgren, C., Tenfjord, P., Hesse, M., Toledo-Redondo, S., Li, W.-Y., Xu, Y., Kwagala, N. K., Spinnangr, S., Kolstø, H. & Moretto, T. On the presence and thermalization of cold ions in the exhaust of antiparallel symmetric reconnection. *Frontiers in Astronomy and Space Sciences,* 149 (2021).

63. Toledo-Redondo, S., André, M., Vaivads, A., Khotyaintsev, Y. V., Lavraud, B., Graham, D. B., Divin, A. & Aunai, N. Cold ion heating at the dayside magnetopause during magnetic reconnection. *Geophysical Research Letters* **43,** 58—66 (2016).

64. Buneman, O., Neubert, T. & Nishikawa, K.-I. Solar wind-magnetosphere interaction as simulated by a 3-D EM particle code. *IEEE transactions on plasma science* **20,** 810—816 (1992).

65. Nishikawa, K.-I., Neubert, T. & Buneman, O. *solar wind-Magnetosphere Interaction as Simulated by a 3-D EM Particle Code* в *Plasma Astrophysics and Cosmology: The Second IEEE International Workshop, Princeton, New Jersey, May 10–12, 1993* (1995), 265—276.

66. Nishikawa, K.-I. Particle entry through reconnection grooves in the magnetopause with a dawnward IMF as simulated by a 3-D EM particle code. *Geophysical research letters* **25,** 1609—1612 (1998).

67. Baraka, S. & Ben-Jaffel, L. Sensitivity of the Earth's magnetosphere to solar wind activity: Three-dimensional macroparticle model. *Journal of Geophysical Research: Space Physics* **112** (2007).

68. Baraka, S. & Ben-Jaffel, L. *Impact of solar wind depression on the dayside magnetosphere under northward interplanetary magnetic field* в *Annales Geophysicae* **29** (2011), 31—46.

69. Palmroth, M., Pulkkinen, T. I., Ganse, U., Pfau-Kempf, Y., Koskela, T., Zaitsev, I., Alho, M., Cozzani, G., Turc, L. & Battarbee, M. Magnetotail plasma eruptions driven by magnetic reconnection and kinetic instabilities. *Nature Geoscience,* 1—7 (2023).

70. Peng, I. B., Markidis, S., Laure, E., Johlander, A., Vaivads, A., Khotyaintsev, Y., Henri, P. & Lapenta, G. Kinetic structures of quasi-perpendicular shocks in global particle-in-cell simulations. *Physics of Plasmas* **22** (2015).

71. Yang, Z., Huang, C., Liu, Y. D., Parks, G. K., Wang, R., Lu, Q. & Hu, H. Global explicit particle-in-cell simulations of the nonstationary bow shock and magnetosphere. *The Astrophysical Journal Supplement Series* **225,** 13 (2016).

72. Omidi, N., Berchem, J., Sibeck, D. & Zhang, H. Impacts of spontaneous hot flow anomalies on the magnetosheath and magnetopause. *Journal of Geophysical Research: Space Physics* **121,** 3155–3169 (2016).

73. Ashida, Y., Usui, H., Shinohara, I., Nakamura, M., Funaki, I., Miyake, Y. & Yamakawa, H. Full kinetic simulations of plasma flow interactions with meso-and microscale magnetic dipoles. *Physics of Plasmas* **21** (2014).

74. Omidi, N., Blanco-Cano, X., Russell, C., Karimabadi, H. & Acuna, M. Hybrid simulations of solar wind interaction with magnetized asteroids: General characteristics. *Journal of Geophysical Research: Space Physics* **107,** SSH–12 (2002).

75. Omidi, N., Blanco-Cano, X., Russell, C. & Karimabadi, H. Dipolar magnetospheres and their characterization as a function of magnetic moment. *Advances in Space Research* **33,** 1996–2003 (2004).

76. Moritaka, T., Kajimura, Y., Usui, H., Matsumoto, M., Matsui, T. & Shinohara, I. Momentum transfer of solar wind plasma in a kinetic scale magnetosphere. *Physics of Plasmas* **19,** 032111–032111. doi:10.1063/1.3683560 (2012).

77. Fujita, K. Particle simulation of moderately-sized magnetic sails. *The Journal of Space Technology and Science* **20,** 2_26–2_31 (2004).

78. Shaikhislamov, I., Antonov, V., Zakharov, Y. P., Boyarintsev, E., Melekhov, A., Posukh, V. & Ponomarenko, A. Mini-magnetosphere: Laboratory experiment, physical model and Hall MHD simulation. *Advances in Space Research* **52,** 422–436 (2013).

79. Dyal, P., Parkin, C. W. & Daily, W. D. Magnetism and the interior of the Moon. *Reviews of Geophysics* **12,** 568–591 (1974).

80. Sonett, C., Colburn, D. & Currie, R. The intrinsic magnetic field of the moon. *Journal of Geophysical Research* **72,** 5503–5507 (1967).

81. Purucker, M. E. & Nicholas, J. B. Global spherical harmonic models of the internal magnetic field of the Moon based on sequential and coestimation approaches. *Journal of Geophysical Research: Planets* **115** (2010).

82. Vorburger, A., Wurz, P., Barabash, S., Wieser, M., Futaana, Y., Holmström, M., Bhardwaj, A. & Asamura, K. Energetic neutral atom observations of magnetic anomalies on the lunar surface. *Journal of Geophysical Research (Space Physics)* **117,** A07208. doi:10.1029/2012JA017553 (2012).

83. Nishino, M. N., Saito, Y., Tsunakawa, H., Takahashi, F., Fujimoto, M., Harada, Y., Yokota, S., Matsushima, M., Shibuya, H. & Shimizu, H. Electrons on closed field lines of lunar crustal fields in the solar wind wake. *Icarus* **250,** 238—248. doi:10.1016/j.icarus.2014.12.007 (2015).

84. Blewett, D. T., Coman, E. I., Hawke, B. R., Gillis-Davis, J. J., Purucker, M. E. & Hughes, C. G. Lunar swirls: Examining crustal magnetic anomalies and space weathering trends. *Journal of Geophysical Research (Planets)* **116,** E02002. doi:10.1029/2010JE003656 (2011).

85. Hansen, K. C., Altwegg, K., Berthelier, J. .-J., Bieler, A., Biver, N., Bockelée-Morvan, D., Calmonte, U., Capaccioni, F., Combi, M. R., de Keyser, J., Fiethe, B., Fougere, N., Fuselier, S. A., Gasc, S., Gombosi, T. I., Huang, Z., Le Roy, L., Lee, S., Nilsson, H., Rubin, M., Shou, Y., Snodgrass, C., Tenishev, V., Toth, G., Tzou, C. .-Y., Simon Wedlund, C. & Rosina Team. Evolution of water production of 67P/Churyumov-Gerasimenko: An empirical model and a multi-instrument study. *MNRAS* **462,** S491—S506. doi:10.1093/mnras/stw2413 (2016).

86. Gombosi, T. I., De Zeeuw, D. L., Häberli, R. M. & Powell, K. G. Three-dimensional multiscale MHD model of cometary plasma environments. *J. Geophys. Res.* **101,** 15233—15252. doi:10.1029/96JA01075 (1996).

87. Jia, Y., Combi, M., Hansen, K., Gombosi, T., Crary, F. & Young, D. A 3-D global MHD model for the effect of neutral jets during the Deep Space 1 Comet 19P/Borrelly flyby. *Icarus* **196,** 249—257 (2008).

88. Rubin, M., Koenders, C., Altwegg, K., Combi, M. R., Glassmeier, K. .-H., Gombosi, T. I., Hansen, K. C., Motschmann, U., Richter, I., Tenishev, V. M. & Tóth, G. Plasma environment of a weak comet - Predictions for Comet 67P/Churyumov-Gerasimenko from multifluid-MHD and Hybrid models. *Icarus* **242,** 38—49. doi:10.1016/j.icarus.2014.07.021 (2014).

89. Gortsas, N., Motschmann, U., Kührt, E., Knollenberg, J., Simon, S. & Boesswetter, A. Mapping of coma anisotropies to plasma structures of weak comets: a 3-D hybrid simulation study. *Annales Geophysicae* **27,** 1555—1572. doi:10.5194/angeo-27-1555-2009 (2009).

90. Koenders, C., Glassmeier, K. .-H., Richter, I., Motschmann, U. & Rubin, M. Revisiting cometary bow shock positions. *Planetary and Space Science* **87,** 85—95. doi:10.1016/j.pss.2013.08.009 (2013).

91. Koenders, C., Glassmeier, K. .-H., Richter, I., Ranocha, H. & Motschmann, U. Dynamical features and spatial structures of the plasma interaction region of 67P/Churyumov-Gerasimenko and the solar wind. *Planetary and Space Science* **105,** 101—116. doi:10.1016/j.pss.2014.11.014 (2015).

92. Clark, G., Broiles, T. W., Burch, J. L., Collinson, G. A., Cravens, T., Frahm, R. A., Goldstein, J., Goldstein, R., Mandt, K., Mokashi, P., Samara, M. & Pollock, C. J. Suprathermal electron environment of comet 67P/Churyumov-Gerasimenko: Observations from the Rosetta Ion and Electron Sensor. *Astronomy & Astrophysics* **583,** A24. doi:10.1051/0004-6361/201526351 (2015).

93. Madanian, H., Cravens, T. E., Rahmati, A., Goldstein, R., Burch, J., Eriksson, A. I., Edberg, N. J. T., Henri, P., Mandt, K., Clark, G., Rubin, M., Broiles, T. & Reedy, N. L. Suprathermal electrons near the nucleus of comet 67P/Churyumov-Gerasimenko at 3 AU: Model comparisons with Rosetta data. *Journal of Geophysical Research (Space Physics)* **121,** 5815—5836. doi:10.1002/2016JA022610 (2016).

94. Engelhardt, I. A. D., Eriksson, A. I., Vigren, E., Valliéres, X., Rubin, M., Gilet, N. & Henri, P. Cold electrons at comet 67P/Churyumov-Gerasimenko. *Astronomy & Astrophysics* **616,** A51. doi:10.1051/0004-6361/201833251. arXiv: `1806.09833 [astro-ph.EP]` (2018).

95. Myllys, M., Henri, P., Galand, M., Heritier, K. L., Gilet, N., Goldstein, R., Eriksson, A. I., Johansson, F. & Deca, J. Plasma properties of suprathermal electrons near comet 67P/Churyumov-Gerasimenko with Rosetta. *Astronomy & Astrophysics* **630,** A42. doi:10.1051/0004-6361/201834964 (2019).

96. Sergeev, V., Runov, A., Baumjohann, W., Nakamura, R., Zhang, T., Volwerk, M., Balogh, A., Reme, H., Sauvaud, J. & André, M. Current sheet flapping motion and structure observed by Cluster. *Geophysical research letters* **30** (2003).

97. Runov, A., Nakamura, R., Baumjohann, W., Zhang, T., Volwerk, M., Eichelberger, H.-U. & Balogh, A. Cluster observation of a bifurcated current sheet. *Geophysical Research Letters* **30** (2003).

98. Sergeev, V., Runov, A., Baumjohann, W., Nakamura, R., Zhang, T., Balogh, A., Louarnd, P., Sauvaud, J.-A. & Reme, H. Orientation and propagation of current sheet oscillations. *Geophysical Research Letters* **31** (2004).

99. Daughton, W. Kinetic theory of the drift kink instability in a current sheet. *Journal of Geophysical Research: Space Physics* **103,** 29429—29443 (1998).

100. Daughton, W. Two-fluid theory of the drift kink instability. *Journal of Geophysical Research: Space Physics* **104,** 28701—28707 (1999).

101. Karimabadi, H., Daughton, W., Pritchett, P. & Krauss-Varban, D. Ion-ion kink instability in the magnetotail: 1. Linear theory. *Journal of Geophysical Research: Space Physics* **108** (2003).

102. Karimabadi, H., Pritchett, P., Daughton, W. & Krauss-Varban, D. Ion-ion kink instability in the magnetotail: 2. Three-dimensional full particle and hybrid simulations and comparison with observations. *Journal of Geophysical Research: Space Physics* **108** (2003).

103. Sitnov, M., Swisdak, M., Drake, J., Guzdar, P. & Rogers, B. A model of the bifurcated current sheet: 2. Flapping motions. *Geophysical research letters* **31** (2004).

104. Ricci, P., Lapenta, G. & Brackbill, J. Structure of the magnetotail current: Kinetic simulation and comparison with satellite observations. *Geophysical research letters* **31** (2004).

105. Golovchanskaya, I. & Maltsev, Y. P. On the identification of plasma sheet flapping waves observed by Cluster. *Geophysical research letters* **32** (2005).

106. Erkaev, N., Semenov, V. & Biernat, H. Magnetic double-gradient instability and flapping waves in a current sheet. *Physical review letters* **99,** 235003 (2007).

107. Kubyshkina, D., Sormakov, D., Sergeev, V., Semenov, V., Erkaev, N., Kubyshkin, I., Ganushkina, N. Y. & Dubyagin, S. How to distinguish between kink and sausage modes in flapping oscillations? *Journal of Geophysical Research: Space Physics* **119,** 3002—3015 (2014).
108. Korovinskiy, D., Semenov, V., Erkaev, N., Divin, A. & Biernat, H. The 2.5-D analytical model of steady-state Hall magnetic reconnection. *Journal of Geophysical Research: Space Physics* **113** (2008).
109. Korovinskiy, D., Semenov, V., Erkaev, N., Divin, A., Biernat, H. & Möstl, U. A 2.5-D electron Hall-MHD analytical model of steady state Hall magnetic reconnection in a compressible plasma. *Journal of Geophysical Research: Space Physics* **116** (2011).
110. Sitnov, M. I., Swisdak, M. & Divin, A. V. Dipolarization fronts as a signature of transient reconnection in the magnetotail. *Journal of Geophysical Research (Space Physics)* **114,** A04202. doi:10.1029/2008JA013980 (2009).