Convocatoria 2020 - «Proyectos de I+D+i»

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Energy transport and dissipation processes in the inner heliosphere: the role of magnetic reconnection and cyclotron waves in multi-ion plasmas (Multi-Ion)

Summary

The solar wind is observed to be turbulent. Turbulence in plasmas involves a complex cross-scale coupling of fields and distortions of particle velocity distribution functions, with the emergence of non-thermal features. How the energy contained in the large-scale fluctuations of electromagnetic and velocity fields cascades all the way down to the kinetic scales, and how such turbulence interacts with particles, remains one of the major unsolved problems in plasma physics, with strong implications for space, astrophysical, and laboratory plasmas. The heliosphere, characterized by nonlinear processes, such as the generation of shocks, waves, coherent structures, magnetic reconnection and particle acceleration, represents the best natural laboratory to study kinetic plasma physics. The interaction of the solar wind with the Earth's magnetosphere is responsible for geomagnetic activity, which displays the magnificent aurora borealis, but can also lead to dangerous space weather events.

Thanks to new spacecraft missions visiting the Sun, namely the NASA Parker Solar Probe (PSP), launched on 2018, and the ESA/NASA Solar Orbiter (SolO), launched on 2020, it is now finally possible to study, at unprecedented time scales, the radial evolution of the solar wind as it expands in the inner heliosphere, from the solar corona out to 1 AU. Moreover, the study of these plasma processes will be significantly enhanced by the knowledge acquired by near-Earth missions, such as the Magnetospheric Multiscale (MMS) mission, launched by NASA in 2015, which provides multi-spacecraft measurements of both the Earth's magnetosphere and the solar wind at 1 AU, down to electron scales. We will study in detail two processes that are expected to play major roles in the transport and dissipation of magnetic energy in the inner heliosphere and in space plasmas in general: magnetic reconnection and cyclotron waves. Both processes involve kinetic scales, and therefore depend on the ion plasma composition. The satellite missions involved in this project have unprecedented capabilities to resolve the multi-ion nature of the inner heliosphere at kinetic scales. These spacecraft observations, focused on investigating the microphysics of energy transport and conversion in the solar wind, will be supported by numerical simulations. We propose various numerical approaches to model the generation, transport and dissipation of plasma waves in space plasmas.

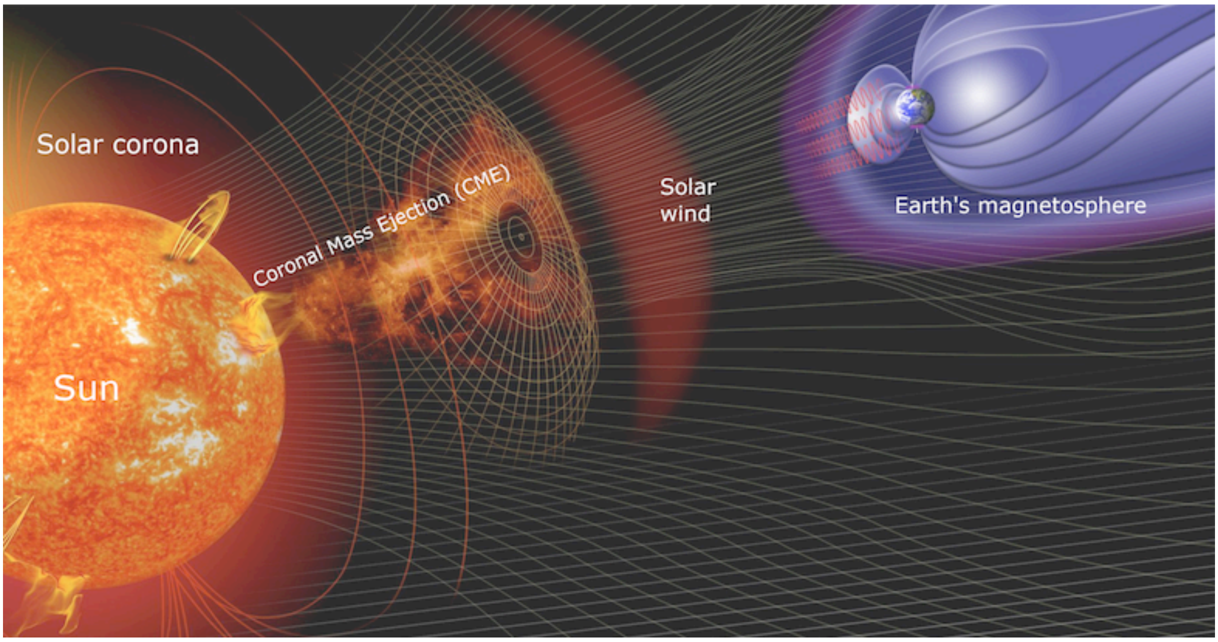


Figure 1. Artist rendition of solar-terrestrial interactions and the inner heliosphere. Credit: NASA

1. SCIENTIFIC PROPOSAL

1.1 Purpose and aims

Magnetic reconnection and wave-particle interactions are universal processes for converting magnetic energy into kinetic energy in plasmas. They are of particular interest in space plasmas, where the effect of particle collisions is often negligible. Our Sun's heliosphere constitutes an accessible natural laboratory to study in detail how these two processes operate. *The specific aim of this project is to understand how the magnetic field energy originated in the Sun is transported and dissipated through the heliosphere*. The initial hypothesis is that magnetic reconnection and ion cyclotron waves make significant contributions to energy transport and dissipation in the inner heliosphere. The energy is injected at large scales in the transition region and corona of the Sun, transported by the turbulent solar wind, and dissipated at kinetic scales. We will investigate how the multiple ion populations present in the solar wind dissipate the available electromagnetic energy at various heliocentric distances, as a function of solar wind type.

List of acronyms used in this research proposal

EDR: Electron Diffusion Region
FDTD: Finite Differences in Time Domain
HCS: Heliocentric Current Sheet
HPC: High-Performance Computations
IDR: Ion Diffusion Region
MMS: Magnetospheric Multiscale
PSP: Parker Solar Probe
SolO: Solar Orbiter
TLM: Transmission Line Matrix
WHAMP: Waves in Homogeneous Anisotropic Magnetized Plasma
WP: Work Package

1.2 Survey of the field

Context

Solar system plasmas: solar wind and magnetospheres

The most common state of matter in the known universe is in the form of plasma. Our Sun, is mainly composed of H^+, He^+ and electrons, plus a minority of other heavy ion species. Dynamo processes in its interior generate the Sun's magnetic field, which permeates the solar system and forms the heliosphere. In the outer layers of the Sun, convection processes dominate the energy transport, resulting in the emergence of magnetic flux tubes and charged particles. Many electrons are accelerated beyond the Sun's escape velocity, and generate ambipolar electric fields that allow the ions to escape as well. The Sun's magnetic field is dragged by the escaping particles and the solar wind is formed: a supersonic, highly-variable, stream of plasma that fills the heliosphere and interacts with the planets hosted by the Sun. Depending on the conditions of the Sun's atmosphere, where the particles are first accelerated and originate the solar wind, one can divide the solar wind into two main categories: fast wind (order of 700 km/s at 1 AU), originated at open field line regions in the corona, and slow wind (order or 400 km/s at 1 AU), originated at various coronal regions, including active regions. The fast wind is often associated to coronal holes in the Sun's atmosphere, while the slow wind is associated with the streamer belt, which lies predominantly near the Sun's equatorial plane. In addition to fast and slow winds, there is an additional subtype of solar wind: coronal mass ejections. These are large releases of mass and energy related to large reconfigurations in the Sun's corona via magnetic reconnection. When these coronal mass ejections encounter a planet on their journey through the heliosphere, they have strong impacts on their plasma environments, causing for instance geomagnetic storms.

The interaction between the solar wind and the planets strongly depends on whether the planet has an intrinsic magnetic field, that forms a magnetosphere surrounding the planet, as is the case of the Earth (see Figure 1). The plasmas of the solar wind and the Earth's magnetosphere couple via various mechanisms, most notably magnetic reconnection and Kelvin-Helmholtz waves occurring at the magnetopause boundary, at 12 – 15 R_E from the Earth. This coupling drives magnetospheric activity, and it is responsible of geomagnetic storms, auroras, and a set of space weather events. The magnetosphere is also coupled to the ionosphere, a partially ionized plasma above the atmosphere. The main mass escape mechanism of the Earth is in the form of ions, and is driven by these complex relations between the solar wind, the magnetosphere and the ionosphere. It has been estimated to be, on average ~10^{26} ions/s (André et al., 2012). For planets without an intrinsic magnetic field or magnetosphere, like Mars or Venus, the solar wind directly interacts with their exospheres and atmospheres, and it is believed to play a major role in their evolution at geological scales (Barabash et al., 2007).

Fluid and kinetic description of space plasmas

Space plasmas are often fully ionized and in a collisionless regime, i.e., the mean time between Coulomb collisions is much larger than other characteristic time scales such as the involved particle gyro periods. Under this regime, plasmas are often not in thermodynamic equilibrium. At large spatial and time scales, i.e., scales much larger than the particle characteristic scales, the plasmas can be treated as single fluids that contain currents and therefore respond to electromagnetic fields, in the so-called Magnetohydrodynamics (MHD) formalism. This formalism can be extended to multiple fluids, where each particle population is treated as a coupled fluid. However, this formalism is not valid for processes occurring at scales similar or below the ion scales, where the particles need a kinetic treatment that accounts for their velocity distribution functions (statistical mechanics) and their interactions with the electromagnetic fields. Both the solar wind and the solar-system planetary magnetospheres are essentially collisionless, so a kinetic description is needed to account for the microphysics of the processes that occur in them, including magnetic reconnection, while the meso-scales of these processes can be described using fluid approaches.

Magnetic reconnection

Magnetic reconnection is one of the most important transport and energy conversion process in collisionless plasmas. It causes the transport of mass, momentum and energy across topologically distinct plasma regions, initially separated by a thin current sheet (Figure 2). Reconnection regulates solar eruptions, plays a key role in determining the shape and dynamics of planetary magnetospheres, and is involved in major disruptions in astrophysical systems, such as magnetar flares. Even on the ground, in the laboratory, reconnection is an important, albeit undesirable, process in fusion machines, as it can destroy magnetic field confinement. At the Earth's dayside magnetopause, it facilitates the entry of solar wind particles and magnetic energy into the magnetosphere, leading to substorms, storms and auroras. It also powers the majority of the deleterious space environment effects collectively referred to as Space Weather.

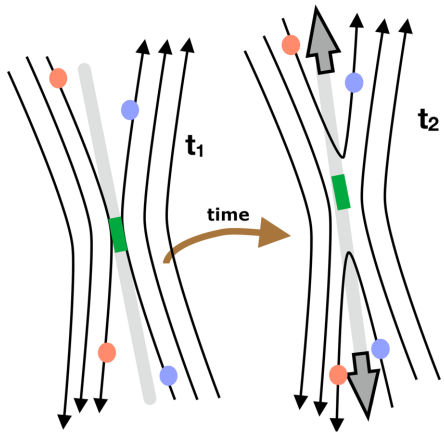


Figure 2 Schematics of magnetic reconnection. Black arrows represent magnetic field lines and the gray shadowed region illustrates a current sheet.. At t_1, blue and red plasma elements are not topologically connected, and become connected at t_2 due to the reconnection process. Plasma jets (gray arrows) are generated due to the magnetic field tension of the reconnected lines.

Owing to its importance, magnetic reconnection has been studied for quite some time, see for instance the review by Yamada (2010), and the review of observations of reconnection by Fuselier and Lewis (2011) and Cassak and Fuselier (2016). Magnetic reconnection is enabled through a local decoupling between the particles and the magnetic field, which occurs at the smallest spatial scales of the plasma, i.e., the electron inertial length and gyroradius, in the so-called Electron Diffusion Region (EDR) depicted in green in Figure 2. Owing to the different mass of ions and electrons, they decouple at different scales. Ions decouple in the Ion Diffusion Region (IDR), with a characteristic spatial scale corresponding the ion inertial length. The presence of additional particle populations, e.g. cold ions, leads to a multi-ion diffusion region and modifies the energy conversion mechanisms at work in magnetic reconnection (Toledo-Redondo et al. 2016, 2018). Therefore, the presence of heavy ions such as He^{2+} or O^{6+} in the solar wind, must have an impact on the different characteristic time and spatial scales associated with the diffusion regions, and must affect how the process converts magnetic energy into thermal and kinetic particle energy. If the plasma contains a heavier plasma population (e.g. He^{2+}, O^{6+}), the cyclotron frequency will be smaller (assuming a comparable thermal speed), which has a profound influence on the time evolution of the reconnection process.

EMIC waves

Electromagnetic Ion Cyclotron (EMIC) waves are a particular subset of the Alfvén normal dispersion surface branch, when the wave frequency approaches the characteristic ion cyclotron frequency. Figure 3 shows spacecraft observations of an EMIC wave in the Earth's magnetosphere. The fluctuations can be observed in the magnetic and electric fields (Figures 3a and 3b), as well as in the particle energy spectrogram (Figure 3c). The wave energy concentrates between the H^+ and He^+ cyclotron frequencies (Figure 3d). Figure 3e shows the dispersion relation surface and the expected wave growth (color coded) of the Alfvén branch, using a numerical dispersion solver, for the measured wave in Figures 3a-d. EMIC waves are efficient in converting electromagnetic energy into kinetic ion energy via gyro-resonant interaction, are commonly observed in the solar wind at various heliocentric distances (e.g., Jian et al. 2010), and are expected to develop as well in the inner solar corona (Cranmer et al., 1999). When multiple ion populations are present, multiple bands, near the gyrofrequency of each ion population, can be generated, and the properties of each band are interrelated (e.g., Lee et al., 2019). The main source of free energy for exciting EMIC waves in the solar wind is believed to be pickup ions (Gloecker et al. 1993), i.e., initially neutral atoms that lose one or more electrons, suddenly become frozen-in to the magnetic field, and are picked up by the supersonic solar wind stream. The pickup process is highly dependent on the orientation of the magnetic field with respect to the velocity of the solar wind, and the largest anisotropies are generated when the angle between **B** and **v** is small. In these situations, the ion velocity distribution functions are deformed and become unstable to EMIC waves. These waves are left-handed in the plasma frame during generation, and have frequencies comparable to the ion cyclotron frequency but always below it, since the cyclotron frequency corresponds to a cutoff frequency. These waves propagate mostly parallel to **B**, and can transport energy far away from the generation region, until their electromagnetic energy is dissipated via cyclotron resonant interactions with ions.

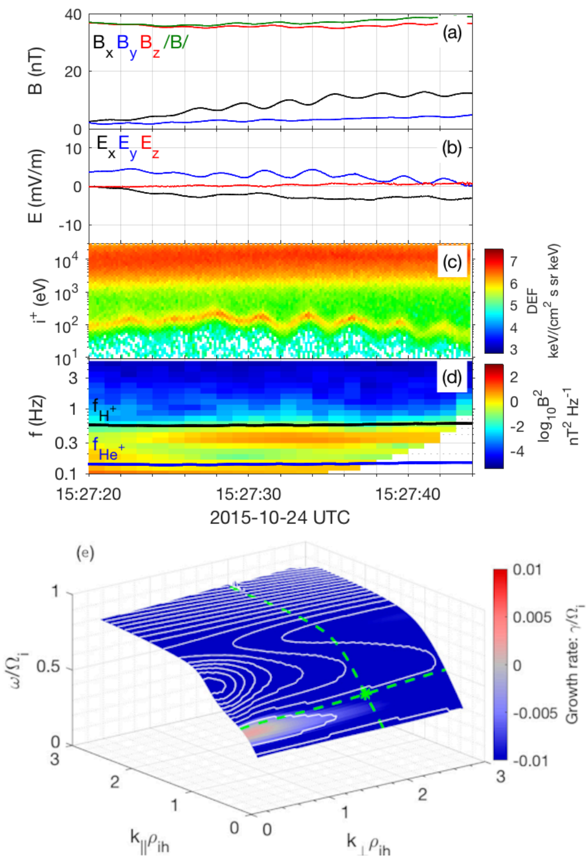


Figure 3. (a-d) Magnetospheric Multiscale (MMS) in-situ observations of an EMIC wave in the Earth's magnetosphere. (a) Magnetic field. (b) Electric field. (c) Ion energy spectrogram. (d) Magnetic field spectrogram. The wave energy lies between the H^+ and He^+ cyclotron frequency. (e) Wave growth numerical solution of the Alfvén branch dispersion relation for the observed wave parameters above. Adapted from Toledo-Redondo et al. (2017)

State of the art and recent results

It has been well assessed that the solar wind temperature decreases with the distance from the Sun more slowly than expected for an adiabatic expanding gas (e.g., Marsch et al., 1982, Hellinger et al., 2013), meaning that locally some heating mechanisms are at work. This project will advance the understanding of the physical mechanisms that produce magnetic field dissipation in collisionless plasmas, providing key insights into the general problem of solar wind heating.

The Sun's corona surrounds its atmosphere, extends up to ~10 R_S, and corresponds to the region where the solar wind is formed. While the chromosphere's temperature is at ~6000 K, the temperature in the corona is of the order of 10^6 K. It is still unclear how the corona is heated, although recent observations pointed that Alfvén waves may carry sufficient energy to account for the coronal heating (Cirtain et al., 2013). Another mechanism that has been suggested to play a major role is magnetic reconnection, possibly in association with small-scale turbulence (Drake and Swisdak, 2012). During the closest approaches to the corona by Parker Solar Probe, we expect to observe signatures of these processes, which take place in the inner layer of the corona.

Review of magnetic reconnection in the solar wind

Direct, unambiguous observations of magnetic reconnection in the solar wind have been reported in the last 10 – 20 years, see for instance Gosling (2005) and references therein. Magnetic reconnection can expand in the unbounded solar wind for long time and form structures as large as 390 R_E (Phan et al., 2006), but it is also associated to intermittent coherent structures (ion length-scales, i.e., tens to hundreds of km) observed in association with small-scale turbulence (Osman et al., 2014). It has been suggested that it plays a major role in energy dissipation of the turbulent cascade at ion scales at 1 AU (Vech et al., 2018). Recent observations, reported by team members, in the shocked solar wind near the Earth's magnetosphere have also revealed that magnetic reconnection can proceed at electron scales only (Phan et al. 2018). Therefore, there is compelling evidence that magnetic reconnection is at work at many plasma spatial scales in the solar wind near 1 AU, supporting our initial hypothesis.

Recent observations reported by team members of this project, using Parker Solar Probe observations, have shown that large-scale (tens of s) current sheets near the corona (40 - 100 R_S) do not exhibit local signatures of active reconnection, but correspond instead to Alfvenic fluctuations (Phan et al. 2020). Many of these current sheets observed near the corona are associated to switchbacks, i.e., highly bended magnetic field lines whose origin is still unclear (Kasper et al., 2019). Magnetic reconnection occurring deeper in the corona and being no longer active when the switchbacks encounter the spacecraft could explain the observed signatures. Magnetic reconnection at smaller scales, down to ion-scale current sheets, using the recent Parker Solar Probe have not been investigated, and constitutes one of the pillars of this project.

Another recent discovery by the team members is that magnetic reconnection seems ubiquitous in the large-scale Heliocentric Current Sheet (HCS), the layer that separates the Sun's outward magnetic flux from inward magnetic flux (Lavraud et al. 2020). This is, to a certain degree, surprising, since the HCS is quite thick, and therefore reconnection is thought to be difficult to initiate. We will explore which conditions favor the onset of reconnection in the HCS using in-situ observations of the process.

Review of EMIC waves in the solar wind

Kasper et al. (2013) derived an analytical theory of differential heating between H^+ and He^{2+} in the solar wind by parallel propagating EMIC waves, based on second-order Fermi acceleration, and confirmed it using spacecraft observations at 1 AU. The differential heating attained by each species strongly depends on the angle between **v** and **B**, and on the relative parallel velocity between the two species. Navarro et al. (2019) further confirmed the theory using a Vlasov solver and discussed the implications of other kinetic instabilities, such as the mirror and fire hose instabilities. Only very recently, using Parker Solar Probe data, Vech et al. (2020) have calculated the estimated wave damping on an EMIC wave observed at 0.23 AU, and concluded that the wave was originated in the solar wind, rather than in the corona due to the strong observed damping. This unambiguous observation of energy dissipation by EMIC waves at 0.23 AU gives strong credit to our initial hypothesis. The spacecraft missions used in this project will allow to further study the differential heating at varying heliocentric distances. Solar Orbiter will allow to obtain the full velocity distribution function of H^+, He^{2+} and minor heavy ions, opening the door for detailed, multi-ion studies of EMIC waves in the solar wind.

Finite Differences in Time Domain (FDTD) and Transmission Line Matrix (TLM) modelling

Computational physics relies on two pillars: the conceptualization of a physical problem that results in a complex mathematical relation (model), often not treatable analytically, plus a computational approach to the solution (simulation). In a collisionless and fully ionized plasma, the Vlasov equation for each particle species, self-consistently coupled to Maxwell equations, provides a complete description of the system dynamics, but it is not analytically treatable even for simple cases. PIC and

Vlasov codes typically use a basic FDTD implementation to model the Maxwell equations, and the complex collective behavior of the plasma particles is provided by the PIC and Vlasov solvers. Numerical solutions of the Vlasov equations and Particle-In-Cell simulations are capable of treating the kinetic interactions of plasmas and are widely used, but are computationally very expensive (e.g., Palmroth et al., 2018). In general, for treating large-scale plasma phenomena, including expansion of the solar wind or the dynamics of planetary magnetospheres, kinetic physics are not modelled and fluid codes (MHD) are used (e.g., Tóth et al., 2012). Each of the modelled fluids represents one particle population, which is assumed to be in thermodynamic equilibrium. These codes can also be hybrid, where some particle populations are treated as fluid (typically the electrons) and some are treated with a kinetic description (typically ions).

The method Finite Differences in Time Domain (FDTD) is a traditional method that solves differential equations by translating them into finite variations (Taflove & Hagness, 2005). On the other hand, the Transmission Line Matrix (TLM) method (Christopoulos, 1995) relies on a different philosophy: it constructs a TLM mesh, or super circuit, which behaves in analogy to the problem to be solved. The TLM mesh is formed by circuit elements, or nodes, which describe the microphysics of the original problem. The propagation of electromagnetic pulses through the mesh, can then be translated, by inverting the initial analogy, into the physics of the original problem.

In the context of space plasmas and waves, pure FDTD and TLM approaches make possible to self-consistently certain plasma waves. Using a fluid description and under the cold plasma approximation, the plasma can be modeled as a time varying, anisotropic dispersive media. Wave properties can be studied, including absorption, refraction, evolution of group and phase velocities, frequency variations, polarization or Faraday's rotation. Although there exist some FDTD and TLM works that deal with anisotropic and dispersive media (Paul et al., 1999ab, 2002), there is no extensive use of these works, to our knowledge, with the notable exception of the team led by J.J. Simpson (e.g. Yu et al., 2012, Samini et al., 2014, Samimi and Simpson, 2015, Pokhrel et al., 2018). The difficulty of these kind of problems, in combination with the difficulty of the methods, have led to very limited amount of practical uses, to date. The ample experience of the research team with these two methods, and particular their use in the context of planetary atmospheres and ionospheres, will be employed to advance their capabilities and use them in the context of wave transport in space plasmas.

1.3 Experience of the team

The PI has been recently appointed as permanent staff at the University of Murcia, after a long and successful international trajectory (2 years at the Swedish Institute of Space Physics, 3 years at the European Space Agency, 1 year at the *Institut de la Recherche en Astrophysique et planétologie*, and an average publication record of 7.4 papers/year during the last 5 years). During these years, the PI has acquired extensive experience in the field of Space Physics, in particular related to kinetic processes at ion scales. He has also demonstrated experience in managing research projects and teams (1 ESA Fellowship, 1 CNES Fellowship, 3 ISSI teams as leader or co-leader). This project aims to consolidate this research line and stablish a team in Spain. The research team (*equipo de investigación*) is composed by four members, including the PI, from 3 institutions: S. Toledo (PI, University of Murcia), A. Salinas and J. Portí (University of Granada), and E. A. Navarro (University of Valencia). The members have long-standing experience in modelling electromagnetic phenomena, are pioneers of the TLM method, have co-authored more than 80 papers together and carried out several research projects, national and international, on the topic of computational electromagnetism. This project is also supported by the work team (*equipo de trabajo*), composed of 3 key international researchers of high relevance in relation to the proposed scientific objectives. This project relies on two methodologies: spacecraft observations, whose expertise is provided by the PI and the international team members, plus numerical simulations, whose expertise is provided by the Spanish research team members, including the PI. Supporting in-situ spacecraft measurements with numerical simulations enables the study of the inner heliosphere as a whole, by using the satellite measurements, which are local by their nature, as input to global 2D and 3D computational models.

Experience in magnetic reconnection and multiple ion populations

The PI has co-authored more than 25 papers during the last five years on the topic of magnetic reconnection in space plasmas. He is part of the Science Working Team of the Magnetospheric Multiscale (MMS) spacecraft constellation since 2015, specifically designed to study magnetic reconnection in the Earth's magnetosphere. He has also been appointed as Early Career Scientist in the ESA Cluster mission, and a targeted campaign to study magnetic reconnection in conjunction between the Cluster and MMS mission is being carried out in 2020. Of particular interest for this project is his interest in the effect of multiple ion populations in magnetic reconnection. He has led two international teams of 12 scientists funded by International Space Science Institute (ISSI) in Bern, Switzerland: 2016 – 2018 (Magnetic reconnection), 2018 – 2020 (ionospheric ions in magnetic reconnection).

Previous research by the PI has concluded that multiple ion populations in reconnection proceed at different characteristic time and spatial scales, resulting in varying efficiencies for particle energization (Toledo-Redondo et al., 2015, 2016a, 2018). He has reported various energization mechanisms which operate at kinetic scales and depend on the particle gyrofrequency and atomic mass unit, including wave-particle interactions at ion frequencies and stochastic heating by ion-scale electric fields (Toledo-Redondo et al., 2016b, 2017a).

The previous knowledge on how reconnection proceeds under the presence of multiple ion populations in the magnetosphere will be now applied to study magnetic reconnection in the inner heliosphere, where He^{2+} and minor heavy ion species are present, in addition to H^{+} and electrons. The PI is currently co-leading another ISSI international team on the topic of magnetic reconnection and solar wind turbulence (2020 – 2022), whose activities are of direct interest to the proposed project.

Moreover, Dr. Phan and Dr. Lavraud, members of the work team, have extensive experience in both magnetic reconnection and kinetic ion and electron processes, and have authored and co-authored more than 200 works on the topic, including *Nature* and *Science* journals.

Experience in solar wind

The PI has also experience in studying the dynamics of the solar wind and has co-authored 5 papers on the topic during the last five years. He is member of the Science Working Team of the recently launched Solar Orbiter Mission, and of the Ion instrument onboard Parker Solar Probe. Dr. Zouganelis, member of the work team, is the Deputy project scientist of the Solar Orbiter Mission, i.e., one of the main liaisons between the European Space Agency and the scientific community. He is experienced in studying turbulence and kinetic processes in the solar wind. Dr. Phan and Dr. Lavraud, members of the team, also have long-standing experience and are well recognized for their contributions to solar wind dynamics.

Experience in plasma waves

The PI has been recently involved in studying the generation and propagation of ion-scale waves in the Earth's magnetosphere, and has co-authored 6 papers on the topic during the last five years. These studies include the effects of multiple ion populations in the production and characteristics of EMIC and lower-hybrid waves in the Earth's magnetosphere and magnetopause. This knowledge will be applied to study the generation and evolution of these waves in the solar wind.

Experience in TLM and FDTD modeling of wave transport in complex media

The members of the research team have extensive experience in modelling the transport of electromagnetic waves in complex media using the Transmission Line Matrix (TLM) method. They work in the topic since many years ago, with more than 80 papers published in the literature, some of them dating back to the early conception of the TLM method in the 1980s. The team contributions can be categorized into theoretical and applied studies of the method. Some examples of the first group are Portí et al., (1992, 2006), Toledo-Redondo et al. (2013) or Salinas et al. (2015), where various TLM nodes and their corresponding efficient implementation are treated. Examples of applications of the method by the research team members include planetary atmospheres (Morente et al. 2003ab, Toledo-Redondo et al. 2016c, 2017b), inhomogeneous systems (Blanchard et al., 2007), electromagnetic cloaking (Blanchard et al., 2008), and time varying media (Portí et al., 2006). All this previous experience in developing and applying the method to real problems will now be used to model plasma wave transport. Of particular interest for this project is the previous experience in modelling anisotropic media and two powerful methods proposed by the team members for the design of new and specific nodes TLM for the modeling of particular situations (specific wire nodes, metamaterials, time-varying media and initial results in anisotropic media, among others) which will be now applied to model the plasma as an anisotropic, dispersive media. The extensive previous experience with these methods will allow to implement and extend the few contributions that exist in the literature about using TLM for modelling anisotropic, dispersive media.

The team has also extensive experience with FDTD since the 1990s, and they have contributed to its development, including novel excitation sources, adaptive meshing in curvilinear coordinates, perfect matching layers in curvilinear coordinates (e.g., Navarro et al 1994, Wu et al. 1995, Navarro et al. 1996, Reig et al. 1997, Navarro et al. 2003), or GPU optimization (Calatayud et al., 2020). There is also extensive experience within the team using FDTD to solve complex problems, such as for instance quantum devices (Soriano et al., 2004), which was a Special Selected Awarded paper, ionization in the top layers of the ionosphere (Soriano et al., 2005, Navarro et al., 2008). All these works were carried out in the frame of more than 10 research projects, led by Prof. Portí, Prof. Salinas, Prof. Morente (1956 - 2012) and Dr. Fornieles at the University of Granada.

International work team

The project incorporates three key international scientific advisors to the work team, which have a long trajectory in studying the solar wind and magnetic reconnection, and are active collaborators of the PI. The PI of this project has been co-located with Dr. Lavraud during more than 1 year at IRAP-CNRS, Toulouse, and during 3 years with Dr. Zouganelis at the European Space Agency. The PI is currently leading an ISSI international team, awarded in 2020, which involves 15 scientists from 12 institutions and 6 different countries, including the 3 members of the work team.

	**Dr. T. Phan** (University of California, Berkeley) is an expert in magnetic reconnection, and is strongly involved in the Parker Solar Probe and Magnetospheric Multiscale missions. Recently, he has reported the existence of electron-only reconnection occurring in magnetosheath turbulence. He has published 259 papers, including 7 in *Nature* and 4 in *Science*, with more than 11,000 citations, and has an h-index of 54 (Scopus).
	**Dr. B. Lavraud** (CNRS, France) is also an expert in magnetic reconnection, and is strongly involved in the Solar Orbiter, Parker Solar Probe and Magnetospheric Multiscale missions. He is also an expert in the design and operation of ion-sensing instruments. He has published 276 papers in refereed journals, including 3 in *Nature* and 2 in *Science*, and have received more than 7,000 citations, scoring an h-index of 42 (Scopus).
	**Dr. Y. Zouganelis** (European Space Agency) is the deputy project scientist of the Solar Orbiter mission, and has a very strong scientific background on the Sun's atmosphere and the solar wind. He knows in detail all the scientific and operational aspects of the Solar Orbiter mission, a key infrastructure for the completion of this project. He has co-authored 39 papers, with more than 1,000 citations, and has an h-index of 14 (Scopus).

1.4 Project description

Description and motivation

The main objective of this project is to advance our current understanding of two key processes that facilitate energy exchange and transport across the heliosphere: magnetic reconnection and wave-particle interactions.

Magnetic reconnection is an active subject of investigation not only in solar system plasmas, but also in laboratories and other astrophysical plasmas. It has gained a lot of attention in the recent year due to the launch of the Magnetospheric Multiscale mission in 2015, specifically designed to resolve down to electron scales of reconnection in the Earth's magnetosphere. The PI and members of the work team have been strongly involved in the mission since the beginning, and this proposed work builds upon previous expertise. The knowledge previously acquired observing how magnetic reconnection proceeds in the magnetosphere will be now applied to in-situ observations in the inner heliosphere, down to the solar corona. Magnetic reconnection is known to be responsible of coronal mass ejections, a major phenomenon that has large consequences on the Earth's magnetosphere. Understanding how magnetic reconnection onsets and proceeds in the solar corona at large scales can be of benefit for future prediction models of space weather events. In addition, small-scale (electron and ion scales) magnetic reconnection can play a role both in the generation of the solar wind, accelerating electrons in the Sun's atmosphere and corona, and in energy dissipation through the heliosphere, in association with intermittent coherent structures observed in plasma turbulence.

Wave-particle interactions, and in particular EMIC waves, are common both in the Earth's magnetosphere and in the solar wind. The PI has been recently investigating the effect of multiple ion populations to these waves in the Earth's magnetosphere, which change the instability threshold for generation, as well as the transport and dissipation characteristics. This project will continue investigating preliminary results of the effect of cold and heavy ionospheric ions that are often found in the magnetosphere, which facilitate the generation and transport of EMIC waves. This knowledge will be then applied to the solar wind in the inner heliosphere, where multiple ion populations are also present. We anticipate that EMIC waves play a key role in the transport of electromagnetic energy by the solar wind, which is carried by the waves in the direction parallel to the magnetic field, and dissipated only when certain conditions are met, such as for instance increased occurrence of pickup ions or perpendicular ion heating mediated by other processes. EMIC waves could provide significant energy transport to explain the non-adiabatic expansion of the solar wind. The study of EMIC waves will be based not only on the most recent in-situ spacecraft observations, but also in numerical simulations. The team will improve their current FDTD and TLM models for application to wave propagation in space plasmas.

Novelty

Magnetic reconnection and EMIC waves are two processes that operate differently depending on the ion populations involved, and this has been a main subject of investigation by the PI in the last years. Directly observing the different dynamics of each ion population in space plasmas is challenging, because it is required to fully resolve the ion distribution function below the ion characteristic time-scales. This is possible in the Earth's magnetosphere with the Cluster and MMS missions, and our understanding of ion kinetic dynamics has been advanced in the recent years using them.

Even more challenging is to carry out these detailed ion measurements in the inner heliosphere, where mission and instrument design are totally different, and telemetry also poses a serious restriction. Two novel spacecraft missions, Parker Solar Probe (2018) and Solar Orbiter (2020), are capable of providing detailed measurements at high time cadence of the full distribution function of H^+ and He^{2+} at various heliocentric distances. For Parker Solar Probe, the ion electrostatic analyzer instrument can do that at close distances to the Sun, which were never measured before. For Solar Orbiter, the ion electrostatic analyzer is designed to sample the distribution function at all the distances of the orbit, from 1 AU down to ~60 R_S. In addition, Solar Orbiter carries mass-resolving ion spectrometer, an instrument that can resolve full distribution functions of minor heavy ions. This is the first time that these measurements are taken in the solar wind with such detail, and will be key for understanding how the heavy ions interact with magnetic reconnection and EMIC waves.

Scientific objectives

The project is divided into two general objectives: one for each energy conversion mechanism that will be studied, namely magnetic reconnection and EMIC waves. Each objective is decomposed into two subtopics. The first subtopic of each objective will explore, with unprecedented detailed enabled by new spacecraft observations, how these mechanisms evolve at various heliocentric distances, including the outer solar corona. The second subtopic will focus in the differentiated dynamics of the multiple ion populations present in the solar wind and the magnetosphere. For objective 2, spacecraft observations will be complemented with numerical simulations in the time domain. Table 1 summarizes the general objectives of this project and formulates the scientific questions that this project will address.

Objective 1: Magnetic reconnection in the inner heliosphere
<u>O1.1 The role of magnetic reconnection in the outer corona and the heliocentric current sheet</u> *- Is magnetic reconnection at work in the outer solar corona? At which scales proceeds? Is it important for the generation of the solar wind? Are switchbacks signatures of non-active magnetic reconnection?* *- How is reconnection initiated in the heliocentric current sheet? Is large-scale reconnection common in the heliocentric current sheet?*
<u>O1.2 Differential energization of multiple ion populations in the solar wind</u> *- Is magnetic reconnection steady at the characteristic time scales of heavy ions? In which regions?* *- How does magnetic reconnection modify temperature anisotropy as a function of mass and charge?*
Objective 2: Ion Cyclotron waves in the Earth's magnetosphere and inner heliosphere
<u>O2.1 EMIC waves: generation, transport and dissipation</u> *- Where do EMIC waves generate in the solar wind preferentially? Do they suffer strong or weak damping?* *- Under which conditions EMIC waves can be transported at large wave normal angles?* *- Which EMIC ion bands are prevalent as a function of solar wind region and heliocentric distance?*
<u>O2.2 Multiple ion populations effects on EMIC waves</u> *- What is the microphysics that facilitate wave growth and transport by cold ions?* *- How multiple ion populations shape the energy transport and dissipation by EMIC waves?*

Table 1. Summary of scientific objectives of the project.

1.5 Methodology

The project will be carried out using two methodologies: in-situ spacecraft observations of space plasmas and numerical simulations of plasma waves transport, combined with analytical modeling.

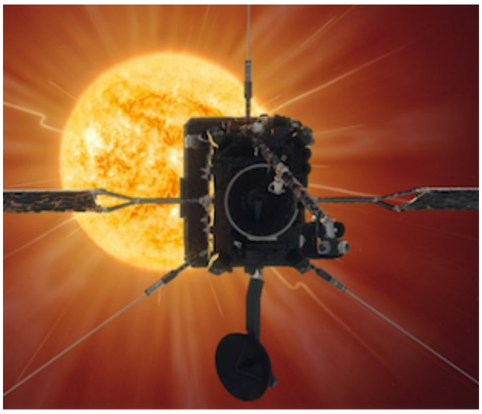
In-situ spacecraft observations

This is the main methodology that will be used to carry out this project. Direct measurements of space plasmas allow to obtain, among others, background and fluctuating electric and magnetic fields, plus full velocity distribution functions of multiple ion populations and electrons. This project will benefit of the recent launch of two missions to study the solar wind: Parker Solar Probe and Solar Orbiter. Parker Solar Probe has encountered the Sun at distances down to 30 R_S, a region never visited before, which features strong magnetic fields and dense coronal plasma, and a lot of unexpected microstructures. Solar Orbiter carries very powerful electron and ion detectors, including heavy ion sensors, that will constitute a unique dataset to study the effect of multiple ion populations in the inner heliosphere. In relation to Objective 1, we will do an automatic search of current sheets in the solar wind data, down to ion scales, and classify them as a function of solar wind type (slow and fast) and heliocentric distance. We will then search for reconnection signatures, namely bifurcated current sheets plus reconnection jets (e.g., Phan et al. 2020). The solar wind current sheet database will be the main dataset that we will use for completion of Objective 1. We have also implemented an automatic EMIC wave detection algorithm based in Bortnik et al. (2007) in the magnetosphere, that will be adapted for detecting EMIC waves in the solar wind data and will a catalogue of observations. This dataset will be key for comparison with numerical simulations and addressing Objective 2.

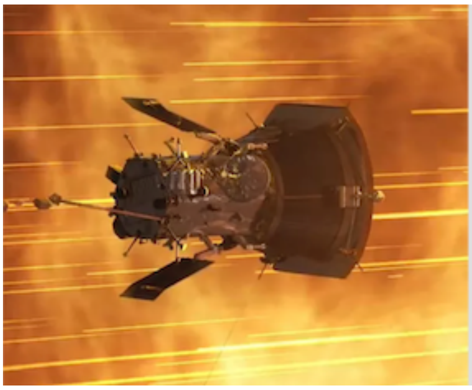
In addition, we will use the Magnetospheric Multiscale mission to study the generation and propagation of EMIC waves in the magnetosphere at higher time and space resolution than what can be achieved by the solar wind missions. One of the key features of the Magnetospheric Multiscale of direct relevance to Objective 2 is that the mission is composed of four spacecraft that sample the plasma in tetrahedron formation. This allows for unambiguous determination of the wave **K** vector under certain conditions (Bellan, 2016). These observations will be compared to numerical simulations (see below) and will be a key methodology for completion of Objective 2.

Spacecraft missions

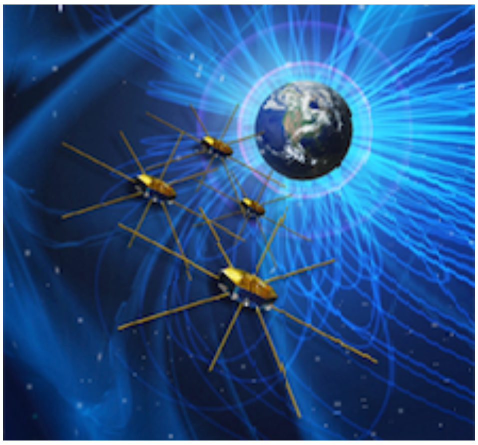
The key methodology that will be used to execute this project is direct observations of space plasmas by satellite missions. All the data of the missions involved becomes public after a short proprietary period (few to several months). In addition, the PI has privileged access to some of the datasets owing to his direct involvement in two of the key missions: Solar orbiter and MMS.



Solar Orbiter (SolO). It was launched in February 2020 by the European Space Agency (ESA) to study the connections between the Sun's atmosphere and the solar wind. It is composed of various in-situ and remote instruments to measure the properties of the Sun's plasma. It will measure the plasma electromagnetic fields and particles at high cadence at various heliocentric distances, from 1 AU down to 60 R_S. Of particular interest for this project are the Proton-Alpha Sensor (PAS), which measures H^+ and He^{2+} particle distribution functions, and the Heavy Ion Sensor (HIS), which measures particle distribution functions of the minor heavy ion species. The mission is in its cruise phase but has already provided solar wind data at 0.5 – 1 AU. The PI is part of the science working team and was collocated during 3 years (2015 – 2018) with the science operations team at ESAC, Madrid. He is also collaborator of various instrument teams and has privileged access to their datasets. Dr. Zouganelis, member of the work team, is the Deputy project scientist of the mission and will provide continuous advice on the use of the datasets.



Parker Solar Probe (PSP). It was launched in 2018 by NASA to study the plasma dynamics of the outer Sun's corona. So far, it has encountered the Sun as close as 30 R_S, and future encounters plan to shorten this distance down to 10 R_S. It is the first spacecraft that has ever sampled the Sun's environment at such short distances. The payload is composed mainly of in-situ detectors, plus one telescope. Of particular interest for this project are the Solar Probe Faraday cup and the Electrostatic analyzers, which measure the moments and particle distribution functions of electrons, H^+ and He^{2+}. Dr. Lavraud and Dr. Phan are members of science working team of the mission and will serve as a bridge between this project and the mission.



Magnetospheric Multiscale (MMS). It was launched in 2015 by NASA and inserted into a high-elliptical equatorial orbit around the Earth to study magnetic reconnection in the magnetosphere. It is composed of four identical satellites flying in close tetrahedron formation, that allow to disentangle spatial from temporal variations in the plasma. Owing to its apogee raise in 2017, MMS spends long periods in the solar wind at 1 AU. A specific campaign was conducted in 2019 to study turbulence in the solar wind, where the PI was involved in the data selection for downlink. The instrument operations and constellation formation were changed to favor the study of the solar wind. The resulting dataset has the highest cadence ever recorded in the solar wind. The PI is part of the science working team of the mission, together with Dr. Lavraud and Dr. Phan, members of the work team of this project.

Waves in Anisotropic Homogeneous Media in Plasmas (WHAMP) simulations

WHAMP is a numerical solver of the dispersion relation in plasmas, including hot plasmas (Roenmark, 1982). It allows to include multiple particle populations with varying mass to charge ratio, drift velocity, and parallel and perpendicular temperatures. It will be used in the frame of this project to study under which conditions the magnetospheric and solar wind plasmas become unstable and generate EMIC waves, which are the properties of these newly generated waves (frequency, wave normal angle, ellipticity, etc.) as a function of ion composition. This software will be key for understanding the preferred source regions of EMIC waves in the Earth's magnetosphere and inner heliosphere (related to Objectives O2.1 and O2.2).

Finite Differences in Time Domain (FDTD) and Transmission Line Matrix (TLM) methods

FDTD is a very powerful tool to study the propagation of electromagnetic waves in complex heterogenous media in the time domain, is a very mature method, and is currently used in many applied fields. TLM is essentially different from other existing time domain methods. It is a relatively new method which is based on establishing analogies with a transmission line circuit, while methods such as FDTD are purely numerical methods based on the approximate solution of partial differential equations. However, the applicability of the two methods is quite similar and a parallel development of both methods is a powerful strategy. Both methods can solve the Maxwell equations in the time domain, and can account for dispersive, anisotropic heterogenous media, although practical implementations in these fields are scarce, to date (cf. Section 1.2). Some of the advantages of TLM versus FDTD are its inherent stability and that magnetic and electric fields are resolved at the same spatial locations. On the other hand, TLM is more difficult to implement, owing to its conceptual approach. This project will make intensive use of both methods in parallel. The more novel TLM approach will be emphasized with respect to FDTD, but the concurrent use of both brings the advantage of obtaining independent solutions to the same problem, which is key for validation, and more importantly, enables to complement solutions for cases where one of the methods is more robust.

The TLM method allows to treat independently wave propagation and wave dispersion. Contrary to FDTD, which uses the leapfrog approach, in TLM the electric and magnetic fields are computed at the same spatial location at time step. Dispersion can be achieved by using the Z-transform approximation (Paul et al., 1999a), while anisotropy is achieved incorporating different line stubs for each direction (Paul et al., 1999b). The recent formulation provided by team members (Salinas et al., 2015), allows for the inclusion of these two effects, plus a direct coupling to the fluid or kinetic particle effects that will impose currents and voltages to the individual TLM nodes.

The plasma will be initially self-consistently modelled using the cold plasma approximation, i.e., neglecting the effects of particle pressure terms, which results in a medium that can be described by a time varying, anisotropic and dispersive dielectric tensor (Stix, 1992). This formalism allows to easily include the effect of heavy ion populations. Opposed to WHAMP, which assumes homogeneous media, FDTD allows to model spatial variations of the background plasma, such as for instance the non-adiabatic expansion of the solar wind in the heliosphere, or closed and open magnetic field lines of the magnetosphere. Further improvements, such as solving the particle momentum equations including the pressure terms, will be applied in a second step, where the medium variations set by the evolving electron and ion fluids are coupled to the Maxwell's equations via the current in the Ampere's law. The formalism that will be employed to model the transport of waves in the inner heliosphere in analogous to multi-fluid MHD, and therefore cannot capture kinetic interactions between the waves and the particles. These interactions will be studied using the WHAMP code, which solves the Vlasov equation for homogeneous plasmas, and direct spacecraft observations of the ion and electron dynamics. Using the multi-fluid codes that will be developed, it will be possible to assess under which propagation conditions the kinetic effects will arise and become important, but we will not be able to characterize them. Coupling the solution of the electromagnetic fields to a Vlasov solver or including macro-particles to the model to study the kinetic interactions in detail is foreseen, but may go beyond the time frame of this project. The parallel use and development of both numerical methods, TLM and FDTD, will be used to attain Objectives O2.1 and O2.2.

1.6 Work plan

The work plan has been carefully designed and it corresponds to an ambitious but feasible plan. We briefly describe the specific Work Packages (WP) that will allow us to tackle the scientific objectives described in Section 1.4. We include a WP for project management (WP0), a WP for dissemination and outreach (WP3), and another for training of the PhD student training (WP4). Table 2 shows the time line of the project and the interrelations between the work packages.

WP0 Management

Includes team coordination, evaluation of the action, risk management, decision taking, regular monitoring and progress meetings. Carried out by S. Toledo.

WP1.1 Build a database of reconnecting current sheets

An automatic detection algorithm of reconnecting current sheets will be implemented, down to ion-scale structures, which are difficult to detect manually. The required input data is magnetic field and ion velocity vectors (e.g., Phan et al. 2020). The algorithm will correlate these two vectors to search for reconnection jets embedded in current sheets. The algorithm will then be applied to all available data of PSP and SolO missions. This WP is required for WP1.2, WP1.3 and WP1.4. Carried out by S. Toledo, T. Phan and PhD student.

WP1.2 Statistical study of magnetic reconnection in the young solar wind

We will perform an independent study of reconnecting CS below 50 R_S, taking advantage of the database built in WP1.1. We will assess the prevalence of magnetic reconnection at ion scales in the outer solar corona and surroundings, study which are the most favorable conditions for this dissipation mechanism to be at work and quantify the amount of dissipation achieved. This WP addresses Objective 1.1. Writing of articles 1 and 2 is included. Carried out by S. Toledo, T. Phan and PhD student.

WP1.3 Statistical study of magnetic reconnection in the HCS

We will identify reconnection events in the database of WP1.1 that are in association with the spacecraft crossing the heliocentric current sheet. Preliminary results indicate that this is the region where reconnection takes place more commonly. Based on the statistical observations, we will stablish whether magnetic reconnection is a major process in shaping the HCS. This WP addresses Objective 1.1. Writing of article 3 is included. Carried out by S. Toledo, B. Lavraud, Y. Zouganelis and PhD student.

WP1.4 Study energization of ion populations by magnetic reconnection

For each element of the database of WP1.1, we will compute the temperature difference of each ion population in the inflow (before entraining reconnection) and outflow (after entraining reconnection) regions. This will allow us to estimate the energy budget of magnetic reconnection, since ion energization takes most of the magnetic field energy conversion. We anticipate differential heating and temperature anisotropy depending on ion mass and charge. Of particular interest for this WP is to investigate the heating of minor heavy ions, that will provide hints on the steadiness of magnetic reconnection at larger time scales (heavy ion scales) and the heating mechanisms at work in magnetic reconnection. This WP addresses Objective 1.2. Writing of articles 4 and 5 is included. Carried out by A. Salinas, S. Toledo, Y. Zouganelis, T. Phan and B. Lavraud.

WP2.1 Classification of EMIC waves in the Earth's magnetosphere

The PI has developed, in the frame of a Master thesis (Pablo García, 2018), an algorithm for automatic detection and K vector estimation of EMIC waves in the Earth's magnetosphere using MMS. This algorithm will be run on the entire MMS dataset (5 years of data) to study the properties of the EMIC waves. Unambiguous detection of the K vector can be achieved using 4-spacecraft techniques (e.g., Bellan 2016), and will provide details on EMIC wave propagation. EMIC waves are believed to be generated at small wave normal angles, according to basic linear theory, but this is contrast with frequent observations of EMIC waves propagating at large angles in the Earth's magnetosphere. Whether the oblique angles are set in the generation region or the waves becomes oblique as they propagate is not well understood. This WP addresses Objective 2.1. Writing of article 6 is included. Carried out by S. Toledo, PhD student, and B. Lavraud.

WP2.2 Classification of EMIC waves in the Solar wind

We will adapt the algorithm for automatic EMIC wave detection to work in the solar wind, where doppler shift effects become important owing to the relative velocity between the spacecraft and the plasma. A large survey on the occurrence and properties of EMIC waves, using all available PSP and SolO data, will be conducted. We aim to understand the role of EMIC waves in transporting and dissipating energy across the heliosphere from an observational perspective, based on their prevalence in the various heliosphere regions and types of solar wind. This work will also benefit of the findings of numerical simulations carried out in the Frame of WP2.4 and WP2.5. This WP addresses Objective 2.1. Writing of articles 7 and 8 is included. Carried out by A. Salinas, PhD student, J. Portí, E. Navarro, S. Toledo, Y. Zouganelis, B. Lavraud.

WP2.3 Implementation of anisotropic, dispersive FDTD/TLM algorithms (1D problem)

The transport of EMIC waves in space plasmas can be modelled considering the plasma as a dispersive, anisotropic medium. There are some proofs of concept published in the literature for modeling such media using TLM and FDTD (Paul et al., 1999ab, 2002, Salinas et al., 2015, Elkalsh et al., 2017) but to our knowledge, there have been only few attempts to model realistic problems of wave propagation in plasmas using this approach. The cited studies stablish the foundations for modelling anisotropic or dispersive media using TLM. We will adapt the described techniques to self-consistently model the propagation of EMIC waves in cold plasmas. We will first model parallel propagation along an open field line. This is essentially a 1D problem, that has direct applications to model field lines of the solar wind and the cusp magnetosphere, and we will be the first step towards implementing a more complex model of plasma wave transport. We will explore the feasibility and stability of the TLM and FDTD methods to model dispersive media near the cutoff frequency. This WP addresses Objective 2.1 and is required to complete WP2.4 and WP2.5. Carried out by J. Portí and E. Navarro.

WP2.4 Transport of EMIC waves in arbitrary directions (2D and 3D problems)

Next, we will extend the TLM/FDTD models to 2D problems. This will allow us to model plasma structures, such as current sheets, density depletions, etc., and more importantly, oblique wave propagation. This is of direct interest to understand under which conditions EMIC waves can be transported efficiently across magnetic field lines. Extension of the model to solve 3D problems is foreseen as an additional output of this objective, although the 2D solution (3D nodes with periodic boundary conditions in one direction) is sufficient for tackling the scientific objectives related to EMIC wave propagation in the heliosphere. This WP addresses Objective 2.1. Writing of article 9 is included. Carried out by E. Navarro, J. Portí and A. Salinas.

WP2.5 Thermal effects and multiple ions in EMIC waves

As a final step in the timeframe of this project, we plan to extend our algorithms to include multiple ion populations, which are often present in the Earth's magnetosphere and solar wind, and account for the pressure term in the momentum conservation equation. We will also explore the possibility of coupling our methods to a Vlasov solver, to account for non-Mawellian particle distribution functions. This WP addresses Objective 2.2. Writing of article 10 is included. Carried out by J. Portí, E. Navarro, A. Salinas and S. Toledo.

WP3 Dissemination of results and outreach activities.

Present project findings at conferences and international networks: European Geosciences Union, American Geophysical Union, Solar Orbiter Science Working teams and ISSI (see section 2.2 for details). Outreach activities to promote my research to broad audiences, in the form of talks and social networking (see section 2.3). Carried out by all research and work team members.

WP4 PhD training

The PhD student of this project will be focused in analyzing spacecraft data for completion of objectives 1 and 2. He will be key at carrying out WP1.1, 2.1 and 2.2. A specific WP is devoted to the training of the student, and includes various short (few weeks) and long (few months) visits to the different institutions involved in the project, plus specific training in kinetic plasma physics and spacecraft instrumentation by the team members. He is also expected to participate in the Solar Orbiter working groups. See Section 3 for more details. Carried out by all research and work team members, coordinated by S. Toledo (PI).

Year 1				Year 2				Year 3			
Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
WP0 Management											
WP1.1 Reconnection database											
			WP1.2 Reconnection in the young solar wind								
			WP1.3 Reconnection in the Heliocentric Current Sheet								
					WP1.4 Multiple ion populations in solar wind reconnection						
WP2.1 EMIC waves in the magnetosphere											
			WP2.2 EMIC waves in the solar wind								
WP2.3 TLM and FDTD 1D models											
		WP2.4 TLM and FDTD 2D and 3D models									
		WP2.5 TLM and FDTD multi ion nodes									
	WP3 Dissemination and outreach										
WP4 Training of the PhD student											

Table 2. Time planning of the project.

Risk management and contingency plan

Risk 1. Number of reconnecting current sheets in the database

There is not much information in the literature about the prevalence of magnetic reconnection in the inner heliosphere. Phan et al. (2020) has recently suggested that large-scale magnetic reconnection may be less frequent than expected near the Sun's corona. The particle instruments onboard SolO and PSP can achieve time resolutions of ~1 Hz, and this limits the spatial scales that can be resolved, which will ultimately depend on the solar wind speed and the orientation of the structure with respect to the solar wind flow. It is hard to estimate how many reconnecting events we will find in the range of scales that can be resolved and below the large scales treated by Phan et al. (2020). We expect to find hundred to thousands of current sheets, but there is a risk that a fraction of these events cannot be well resolved by the ion instruments, and it is unclear how many of these will show reconnection signatures. There exists a low risk of having a small number of events (less than hundred). Statistics will be less reliable under this scenario, but the scientific Objectives 1.1 and 1.2 can still be partially addressed with such a number of events, implying that the role of magnetic reconnection is less important than expected or that it proceeds at very small scales, not resolvable with current, state-of-the-art instrumentation.

Risk 2. Stability of dispersive media in TLM and FDTD

Another potential risk we may encounter is related to the innovative approach proposed here to model the transport of waves in plasmas (WP2.3). These problems are usually tackled using MHD and PIC multi-purpose implementations, which often result in very resource-consuming simulations. The approach proposed here is light-weight and elegant, with specific methods tailored to model only the relevant physics of each problem. Our approach will initially make use of the cold plasma approximation for modelling wave transport, simplifying the calculus of the particle evolution and treating the plasma as an anisotropic and dispersive media. There exist proofs of concept for using FDTD and TLM in anisotropic or dispersive media, but the implementation of all the features required to model the transport of EMIC waves has not been tested, to our knowledge. The main risk is related to the implementation of the dispersive nature of the dielectric tensor, which is frequency dependent and presents an indetermination (cutoff) at the cyclotron frequency. Implementing the model for frequencies not close to the cutoff is OK, but the numerical behavior near the cutoff frequency is a challenge still to be studied. Should the method become unstable near the cutoff, we will assess how close to the cutoff the method provides reliable solutions, and use these partial solutions to provide insights to the propagation of the waves.

Risk 3. Dissemination and outreach during the pandemic.

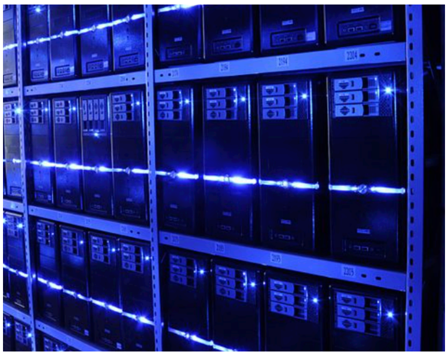
A potential risk that is foreseen to implement the project is the COVID-19 world pandemic that we are facing. The space agencies have guaranteed so far mission operations, although some delays in the launch and commissioning of Solar Orbiter have occurred in 2020, which do affect the plan of this project. The three key missions involved in this project are either in its nominal science phase or cruise, and we do not foresee problems in observations. The main risk for this project related to the pandemic is the mobility restriction, that will difficult both the interactions between the research team members, since various national and foreign institutions are involved, and dissemination and outreach activities. In case that mobility restrictions remain during the execution of the project, the team members will have online meetings to follow up the development of the project. Part of the dissemination activities within the scientific community is foreseen to take place during international conferences. Fortunately, all the major conferences of our field (e.g., EGU and AGU) are finding online solutions to keep our communities in contact, and we would disseminate our results using the online formats if required. Another threat is posed to outreach activities, which are planned to be carried out during social events at universities and other institutions. Most social events have now strong restrictions on the number of attendees or are directly cancelled. We will reorient our outreach activities towards the university communities if these restrictions are in place. The Universities in Spain have quickly adapted to online formats, and many talks, round-tables, etc. are being carried out fully online.

Data management plan

All the scientific data of the spacecraft missions involved in this project becomes public after a short (few months) proprietary period and can be accessed via the mission science gateways. We will build a number of databases containing information of reconnecting current sheets and EMIC wave observations by MMS, PSP, and Solar Orbiter. These databases will be made public and under Creative Commons License. With respect to TLM and FDTD simulations, their output will be also made public under the same License. We will use the repository digibug.ugr.es for that purpose, as we have been doing previously.

1.7 Equipment and infrastructures

Computing and mirroring infrastructures



All the spacecraft missions involved in this project produce very large datasets and require intense computing and storage capabilities for data analysis. A dedicated server will be deployed at the host institution to mirror and provide fast access to mine the various spacecraft mission datasets, which will be used by the scientific team members and the students involved, linked to Objectives 1 and 2.

The computational part of the project, i.e., WP2.3-5, linked to Objectives 2.1 and 2.2, may require of intensive computations. The members of the science team at University of Granada already have dedicated servers for High-Performance Computations (HPC) from previous projects. In addition, they have access to UGRgrid, if additional resources are needed. HPC computations are foreseen for implementation of 3D models.

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Team members are highlighted in green.

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2. EXPECTED RESULTS IMPACT

2.1 Scientific impact and significance

There are various reasons for studying the plasma processes that take place in the solar wind and the solar system magnetospheres. First of all, they constitute a natural laboratory that is accessible by satellite missions, allowing in-situ measurements of their electromagnetic fields, waves, and particle distribution functions. A main advantage of this natural laboratory is that spatial scales of space plasmas are much larger that the size of satellites, allowing for detailed measurements of particle distribution functions that are simply not possible in laboratory plasmas. Therefore, placing spacecraft in the solar wind at various heliocentric distances, or inside planetary magnetospheres, provides invaluable datasets of the internal structure and nature of plasma processes. These direct observations validate and extend current analytical and numerical models of plasmas, in an iterative way, that allow then to extrapolate the observations to other plasmas not directly accessible to humanity, such as magnetars, stellar accretion disks, stellar winds or exoplanet magnetospheres, to name a few.

Another strong motivation for studying the plasmas of our solar system, and in particular the solar wind and the near-Earth's space environment, is to understand, and eventually predict, Space Weather events. Space Weather refers to a variety of plasma processes that ultimately end up in damaging or disrupting human infrastructures that rely on space assets or that are placed in polar regions. Energetic particles coming from the radiation belts, the Sun and the interstellar medium pose a major risk for astronauts and satellites. GPS signals are often affected by plasma irregularities in the ionosphere, referred as scintillations, which can result in service disruption and pose a serious risk for aviation, for instance. On Earth, power transmission lines placed in polar regions induce large currents during geomagnetic storms that can result in damaging of the transformers.

Scientific satellite missions visiting the solar wind and the solar system planets constitute a major driver of space technology and space exploration. This kind of endeavors involve launch vehicles, complex orbital mechanic calculations, deep-space network communications, space instrumentation, or data science, to name a few technologies that are benefitted by space plasma missions.

Finally, we note that Astrophysics and Space Physics are of great interest for students and the general public, and enlightening new generations is one of the aims of the space agencies. This project, carried out at the University of Murcia, University of Granada and University of Valencia, will involve several students at different levels (undergraduate, MSc, and PhD), who will benefit of the infrastructures requested, i.e., servers for mirroring and data mining the spacecraft mission databases.

2.2 Dissemination plan

The results of this project will be disseminated among the scientific community in four different ways:

1. **Scientific articles**. We foresee the publication of ~10 articles (cf. section 1.6), that constitute the main scientific legacy of this project. Thanks to the timeliness of this project, which benefits of recently launched spacecraft missions, we anticipate that high-impact journals will be interested in publishing our research.
2. **Scientific conferences**. The results will be presented at the major international conferences in our field: the European Geosciences Union General Assemblies and the American Geophysical Union Fall meetings. In addition, the project results will be disseminated at more specific conferences and workshops, including the mission SWTs.
3. **International team networking**. The PI is co-leader of a recently-launched ISSI team composed of 12 international scientists plus 3 young scientists, whose activities are of direct

interest to this research project. The ISSI team will constitute a major hub for dissemination of these activities. In addition, international members of the work team will also disseminate the results at their institutions (European Space Agency, CNRS France, University of California, Berkeley). It is foreseen that the PI and research team members of the project will impart seminars at foreign institutions.
4. **PhDs, MScs, TFGs**. The team members have extensive experience in mentoring students. These students will have great opportunities to disseminate their actions at national and international conferences and workshops. This project can also serve them as a boost for their careers.
5. **Social media**. The PI regularly posts content on LinkedIn, and will use his contact network to disseminate the project results.

2.2 Outreach plan

It is very important to present the project results not only to the scientific community, but also to a broad audience. We plan the following actions related to outreach:

1. **Seminars and talks at host universities.** The students from the universities involved will have the opportunity to attend talks that will be imparted by the research team members.
2. **Aula Senior.** The PI will collaborate with courses at the host institution that are aimed at elder people, presenting the project findings there.
3. **Project website.** We will set a website including the major findings of the project.
4. **Outreach through the European Space Agency.** Dr. Zouganelis (deputy project scientist of SolO at ESA) is member of the work team. One of his tasks is to coordinate dissemination and outreach of the mission results. We expect that some of the results of this project can be part of these ESA activities (including conferences, press releases, etc.).
5. The team members at University of Granada participate in the programs **PIISA**, ***Semana de la Ciencia, la Noche de los investigadores*** and the program ***Ciencia y Sociedad*** of the Science Faculty. They will make the results of this project accessible to the public during these events.
6. Program ***Quiero ser ingeniera***. This is a program to promote gender equality in science and technical disciplines. A workshop to model complex materials will be carried out in the frame of this program.

3. TRAINING CAPACITY

3.1 Summary of training plan

The PhD candidate will carry out the studies in the frame of the International Doctoral School of the University of Murcia. The trainee will also have the opportunity of participating in short courses imparted at the University of Uppsala, Sweden, and the Swedish Institute of Space Physics. Few long stays (~3 months each) are foreseen in the time frame of the training, at prestigious international institutions such as the European Space Agency, the Swedish Institute of Space Physics or *Institut de la Recherche en Astrophysique et Planétologie* (IRAP) in Toulouse, France, plus a number of short visits to University of Granada and University of Valencia. The research and work group members will contribute to the training of the student, in a variety of topics, including kinetic plasma physics, magnetic reconnection, plasma waves, spacecraft instrumentation, science operations and numerical simulations.

3.2 Previous training experience within the research team

The research team in Spain is composed of 4 permanent researchers, including 3 full professors, at three different institutions: University of Murcia, University of Granada and University of Valencia. 5 PhD thesis have been mentored by the team members. International collaborators of this project (work team) have also long-standing experience in mentoring PhDs and Postdocs, that will be of benefit for internationalization of the PhD student.

3.3 Situation of previous PhDs within the team

The following PhDs have been mentored in the last years by the research team members:

- Benlloch Casabán, M. A., currently teaching mathematics at high-school in Valencia, Spain
- Blanchard, C.. currently lecturer at the University of Órleans, France.
- García Alarcón, I., currently working at the Spanish Embassy in Paris, France.
- Rodríguez Camacho, J., PhD Ongoing.
- Toledo Redondo. currently lecturer at the University of Murcia.

3.4 Context for the PhD student

The trainee is expected to develop a strong background in plasma physics, including statistical mechanics (kinetic theory), of direct applicability to electromagnetism and hydrodynamics, the two Physics theories that describe the behavior of plasmas. In addition to that, the trainee will carry out extensive data analysis of state-of-the-art satellite missions. The trainee will therefore acquire strong competences in engineering, owing to the complex instrumentation involved, including magnetometers, langmuir probes, antennas, or electrostatic analyzers, to name a few. Additionally, the trainee will gain strong competences in data analysis and data mining, owing to the large size of the datasets involved in this project. Finally, the PhD student will also learn how to perform complex electromagnetic numerical simulations, as part of Objective 2.

The PI is member of the science working team of two satellite missions, MMS (NASA) and Solar Orbiter (ESA). This constitutes an excellent forum for students, with few hundred collaborators on each mission all over the world, including a significant fraction of students. The trainee will participate of these team activities, including weekly teleconferences and international team meetings.

The PI has a long-standing relationship with the International Space Science Institute in Bern, Switzerland, where he has led and co-led three international teams. The trainee will benefit of this international network and will participate in ISSI international team activities.

The PI also has an extended network of collaborators, owing to his previous positions at the European Space Agency, *Centre National d'Études Spatiales*, and Swedish Institute of Space Physics. Doctoral stays at these institutions are foreseen.