AUTHOR: J.-Y. Prado, Sun, Heliosphere and Magnetospheres program scientist
CNES, 18 avenue Edouard Belin, 31401 Toulouse Cedex 9, France.

Sun, Heliosphere and Magnetospheres

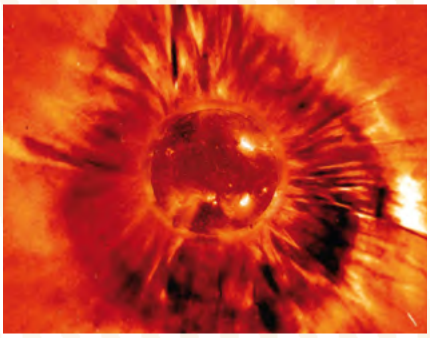

Fig. 1

Fig. 2

Fig. 3

The French solar and plasma physics community is presently deeply involved in the preparation of several missions: TARANIS (launch planned in 2017) is dedicated to the physics of atmosphere/ionosphere/magnetosphere couplings (Fig. 2), SOLAR ORBITER (2017) (Fig. 3), and a small contribution to NASA's SOLAR PROBE PLUS mission (2018). With the maturing of heliophysics science and the deeper understanding of its fundamental space plasma processes, we can not only establish new connections with other types of astrophysical plasmas, but also start forecasting some of the processes that represent a hazard to our technological society.
Two important directions for future research are a more systemic understanding of the impact of solar variability on the Earth and on other planets, and a deeper understanding of the fundamental physical processes that drives this variability.

At the beginning, there was SOHO

When it was launched in December 1995, SOHO was considered as a purely scientific mission. However, it rapidly became apparent that this spacecraft could do more than what it was designed for. SOHO actually paved the way for a new field of science: space weather.

Among the twelve instruments that are onboard SOHO, one still plays a unique role in monitoring the Sun. This instrument has been designed and operated by the US Naval Research Laboratory, and it is made of three coronagraphs with different fields of view. One of them, LASCO-C2, has been built by the Laboratoire d'Astrophysique de Marseille.

The LASCO-C2 coronagraph aboard SOHO has now completed 18 years (1996-2013) of quasi-continuous white-light imaging of the corona from 2.2 to 6.5 solar radii, thus providing an unprecedented view of evolution of the Sun over more than one solar cycle and a half, including the minima of solar cycles 22 and 23.

The global radiance of the K corona closely tracks the activity pattern of the Sun, including the prolonged cycle 23, and the subsequent anomalous minimum. The analysis of different coronal regions has uncovered a more complex behaviour, revealing a time lag between the northern and southern regions. The ARTEMIS (Automatic Recognition of Transient Events and Marseille Inventory from Synoptic maps) I and II catalogues of LASCO coronal mass ejections have reported over 20 000 events that are automatically detected from calibrated synoptic maps. Their statistical analysis has enabled a systematic study of the interactions between Coronal Mass Ejections (CMEs) and streamers. When a CME-streamer association occurs (in about half of the cases), approximately 95% of the streamers experience a change, either geometric or radiometric. The monthly rate of CMEs is known to follow the solar activity cycle, with for instance a strong correlation with the radio flux at 10.7 cm. However, the CME rate has been found to be relatively higher during the ascending phase of present cycle 24, as compared to the previous cycle. An unexpected bonus is offered by the detection of over 2 500 sungrazing and sunskirting comets whose study reveals their complex collisional history.

From the Sun to the Earth

The study of the solar variability and its impact on the Earth's magnetised environment has been one of the pillars of space exploration since the dawn of the space age. Numerous space missions have been dedicated to the understanding of the solar-terrestrial connection, with recent and noteworthy contributions from CLUSTER and SOHO in Europe, THEMIS,

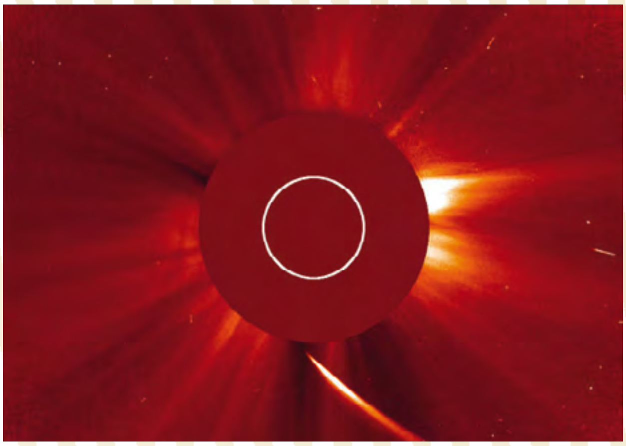
Fig. 4a

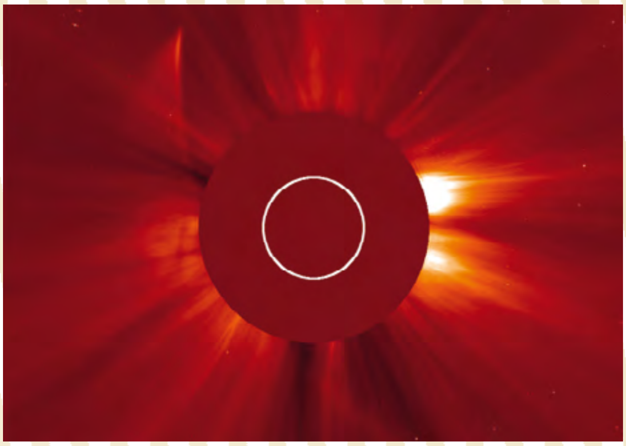
Fig. 4b

the VAN ALLEN probes and SOLAR DYNAMICS OBSERVATORY in the USA, and also GEOTAIL and HINODE in Japan. These missions were mostly addressing on one end of the connection, i.e. either the Sun or geospace. The launch of the NASA STEREO mission in 2006, with significant hardware contributions from Europe (e.g., heliospheric imagers, radio wave, electron and ion instruments), provided a significant step forward by opening up access to new vantage points from which both the Sun and the Earth could be observed from afar. The twin STEREO spacecraft were indeed launched on orbits similar to the terrestrial one, but just slightly off so that one spacecraft would drift ahead of the Earth and the other one trail it. In doing so, the spacecraft could drift apart and attain locations outside of the Sun-Earth line. STEREO's imagers had been designed specifically to track solar disturbances all the way from the Sun to the Earth. Observations from STEREO not only allowed for stereoscopic imaging of solar disturbances, but also provided multipoint *in situ* measurements of heliospheric perturbations one astronomical unit away from the Sun. In combining these observations with *in situ* measurements made by other spacecraft in the vicinity of the Earth, STEREO became the first mission to monitor the complete chain of processes from the Sun to the Earth, including propagation characteristics and the impact on geomagnetic activity. Two notable results are described, which focus on the tracking of coronal mass ejections as they propagate earthwards, and on their interaction with the ambient solar wind through magnetic reconnection processes.

Reconnection and turbulence

Shocks and turbulence are two major ingredients of astrophysical plasmas and are strongly interrelated. The microphysics of these plasmas, i.e. the physics at kinetic scales, is of key importance for understanding fundamental processes such as collisionless reconnection, energy dissipation, plasma transport and particle acceleration. Many aspects of the microphysics, however, are still poorly understood because their experimental study requires direct measurements of particle distribution functions, and electromagnetic field observations at high temporal resolution and down to the smallest spatial scales. At present, the best laboratory for addressing the microphysics of space plasmas is the near-Earth space, and foremost among the *in situ* diagnostics are the four CLUSTER spacecraft, allowing for disentangling spatial and temporal variations. Recent CLUSTER observations have revealed the turbulent cascade of electromagnetic energy down to electron scales, providing new constraints on possible dissipation mechanisms. Observations in reconnection regions, and at small scales, have shown how protons are accelerated to form reconnection jets. At higher energies, CLUSTER has provided the first evidence for very energetic electrons to be accelerated when reconnection is unsteady. CLUSTER observations have also greatly contributed to our understanding of the relationship between reconnection and turbulence/waves: the four spacecraft have provided the first direct evidence of reconnection in turbulent plasmas, and moreover allowed detailed observations of the different wave modes that are participating in this reconnection, e.g., by showing how ion-scale structures interact with electron-scale whistler waves during magnetospheric substorms. These results are highly relevant for understanding how these fundamental processes operate in other types of astrophysical plasmas, such as the solar corona or in astrophysical jets, where *in situ* measurements are not available. Future missions such as MMS (2015) and SOLAR ORBITER (2017) will further increase our understanding of reconnection and turbulence through measurements with improved resolution, and by visiting unexplored regions of the solar system, such as the near-Sun corona.

[Fig. 1]
An artistic look at a coronal mass ejection launched towards Earth.
© SOHO (ESA/NASA)/S.Hill

[Fig. 2]
Tests on the TARANIS satellite.
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[Fig. 3]
ESA's next generation Sun explorer SOLAR ORBITER.
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[Fig. 4a and 4b]
Comet ISON seen by the LASCO-C2 coronagraph before (Fig. 4a) and after (Fig. 4b) it passed closest to the Sun, in November 2013.
© ESA/NASA

AUTHOR: P. Lamy[(1)]

[(1)] LAM, UMR 7326, 38 rue Frédéric Joliot-Curie, 13388 Marseille Cedex 13, France.

Sun, Heliosphere and Magnetospheres

Eighteen years of white-light imaging of the solar corona with the LASCO-C2 coronagraph

Dix-huit années d'imagerie en lumière blanche de la couronne solaire avec le coronographe Lasco-C2

➔ **Abstract:** The LASCO-C2 coronagraph aboard SOHO has now completed 18 years (1996-2013) of quasi-continuous white-light imaging of the corona, thus allowing an unprecedented view of its evolution over more than a solar cycle and a half. The global radiance of the K corona and the monthly rate of coronal mass ejections (CMEs) follow very well the activity pattern of the Sun but distinct behaviors are observed in different regions. An unexpected bonus is offered by the detection of over 2 500 sungrazing and sunskirting comets.

➔ **Résumé :** Le coronographe Lasco-C2 à bord de SOHO a maintenant observé de façon quasi-continue la couronne solaire pendant 18 ans (1996-2013) offrant une vue sans précédent de son évolution sur plus d'un cycle solaire et demi. La radiance globale de la couronne K et le taux mensuel d'éjections coronales de masse (CMEs) reproduisent le cycle d'activité du soleil avec cependant des variations selon les régions de la couronne. Un bonus inattendu est offert par la détection de plus de 2 500 comètes rasantes.

The solar corona, the ionized gas comprising both protons and electrons forming the solar atmosphere, was first revealed and observed during total eclipses. The study of this so-called white-light corona resulting from Thomson-scattered sunlight from the free electrons in the coronal plasma led to the basic understanding of its physical properties. As observations accumulated, it became clear that it was closely associated to the magnetic activity of the Sun through its eleven-year cycle. The first spacecraft externally-occulted coronagraph OSO-7 followed by Skylab, P78-1 (Solwind) and SMM, revealed the existence of the coronal mass ejections (CMEs) and monitored the coronal activity during many years. The LASCO-C2 coronagraph built by the Laboratoire d'Astrophysique de Marseille and carried aboard the SOHO solar observatory launched in late 1995 has opened a new era in quantitative analysis of the white-light corona thanks to its superior sensitivity, excellent photometric performances and record longevity. LASCO-C2 has now completed 18 years (1996-2013) of quasi-continuous imaging of the corona from 2.2 to 6.5 solar radii, thus allowing an unprecedented view of its evolution over a period of time exceeding a solar cycle and a half.

The analysis of properly processed and calibrated LASCO-C2 images yields both quantitative results (radiance, polarized radiance and electron density) and spatially resolved information in regions inaccessible to *in situ* measurements (e.g., polar regions) giving a unique and broad insight on how the corona reacts to solar activity (Fig. 1). The global radiance of the K corona follows very well the activity pattern of the Sun as quantified by two standard indices, the sunspot number and the radio flux at 10.7 cm. It fully reflects the anomalously long cycle 23 estimated to 12 years and 3 months and the following deep minimum found to be 24% fainter than the previous one [1]. However, the two hemispheres experienced different reductions and this asymmetry supports the current view that solar maximum conditions have been reached in the northern region whereas the southern region is lagging with the rise of activity still on-going. The equatorial sector suffered a severe reduction of 44% in remarkable agreement with the *in situ* measurements of the proton density performed at 1 AU by WIND and ACE. The global radiance of the K corona exhibits quasi-periodic oscillations during the maximum phase of cycle 23 which are also seen in the temporal variation of the total solar irradiance and are part of several modes affecting the magnetic activity of the Sun. The increased coronal radiance during the maximum of a cycle is best explained by the increasing warping of the current sheet and by the emergence of high altitude "polar" streamers as well as pseudo streamers.

The ARTEMIS (Automatic Recognition of Transient Events and Marseille Inventory from Synoptic maps) I [2] and II [3] catalogs of LASCO coronal mass ejections rely on an original method of automated detection of these events on synoptic maps of the K corona built from the LASCO-C2 calibrated images. The catalogs list over 20 000 events and report their time of appearance, geometric parameters, and average velocity; ARTEMIS II further reports their mass and kinetic energy. These catalogs have allowed a first, global statistical study of the interaction between CMEs and streamers [4]. It has been found that about half of the global population of CMEs is not associated with streamers, whereas 93% of the 10% brightest CMEs are associated. A complete statistical analysis

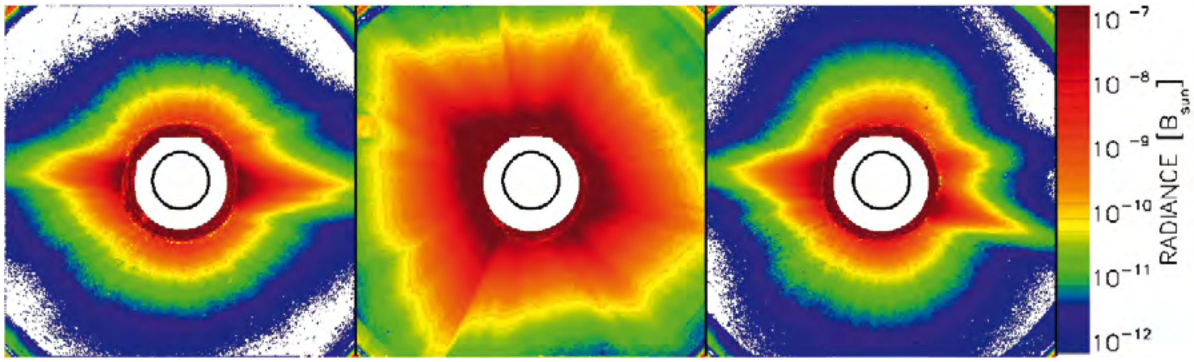

Fig. 1

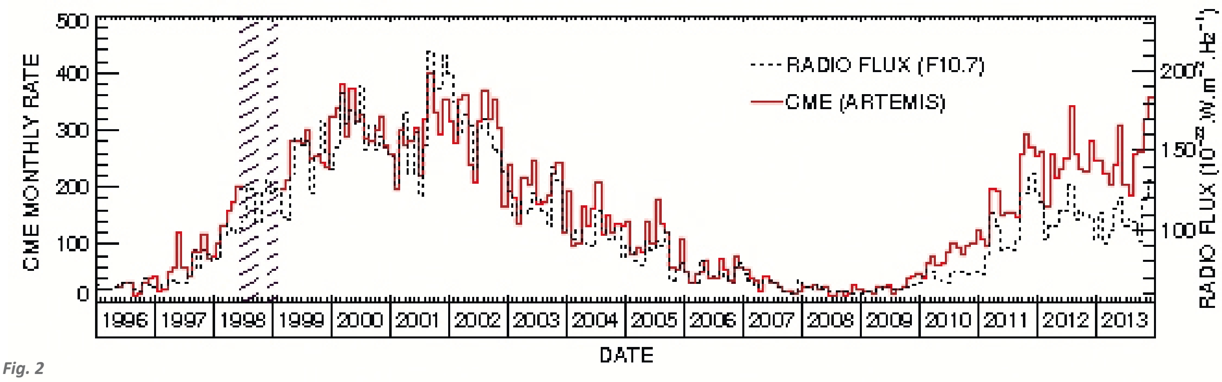

Fig. 2

of the properties of CMEs over 18 years is underway but it is already obvious that their monthly rate follows very well the solar activity cycle (Fig. 2). Note the quasi perfect correlation all over solar cycle 23 and also a tendency of a relative higher rate of CMEs during the ascending phase of cycle 24.

An unexpected bonus of the LASCO observations is the detection of over 2 500 comets as of today, an outstanding record for an instrument! The Kreutz sungrazing family, characterized by perihelion distances of two solar radii, represents about 90% of these discoveries and has long been considered unique. A new class of sunskirting comets has been discovered [5] organized in different groups: Meyer, Marsden, Kracht and sporadic. They all approach the Sun to 6-12 solar radii and contrary to the Kreutz family, many survive their perihelion passage. Two of them are definitively periodic with periods of 4 and 5.5 years. The sungrazing and sunskirting comets are all fragments of more massive parent comets that disrupted a long time ago, although cascade sub-fragmentation is still going on. The cumulative distribution functions of the peak brightness (used as the proxy to the size of the nucleus) allow tracking their fragmentation history and it has been established that, for instance, the Meyer group is more evolved than the other groups.

[Fig. 1]
Three images of the K corona obtained with the LASCO-C2 coronagraph on June 16, 1997 during the minimum of solar cycle 22 (left panel), on January 1, 2000 during the maximum of cycle 23 (central panel) and on December 21, 2008 during the minimum of solar cycle 23 (right panel). © From [1]

[Fig. 2]
Monthly rates of coronal mass ejections reported by the ARTEMIS-II catalog and the F10.7 radio flux. © From [1]

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AUTHORS: B. Lavraud[1], A. P. Rouillard[1], A. Ruffenach[1], J.-A. Sauvaud[1]
[1] IRAP, UMR 5277, 9 avenue du Colonel Roche, 31028 Toulouse Cedex 4, France.

Laboratory contribution

Sun, Heliosphere and Magnetospheres

Multi-satellite observation and tracking of CMEs from the Sun to the Earth

Observations multi-satellites et suivi des CMEs du Soleil à la Terre

➔ **Abstract:** Solar influence on the near-Earth environment has gained considerable interest in the last decades. This has come from the recognition that solar disturbances can strongly affect human activities. The STEREO mission was launched to augment our understanding of the fundamental processes that control these phenomena, as well as our ability to predict them. We present two important results that pertain to the interplanetary propagation of coronal mass ejections.

➔ **Résumé :** L'influence solaire sur l'environnement terrestre fait l'objet d'un intérêt croissant ces dernières décennies. Ceci résulte d'une meilleure appréciation de l'impact des perturbations solaires sur les activités humaines. La mission STEREO a été lancée afin d'approfondir notre compréhension des processus fondamentaux contrôlant ces phénomènes, ainsi que notre capacité à les prévoir. Deux résultats importants, portant sur la propagation d'éjections de masse coronales, sont présentés.

The Solar Terrestrial Relations Observatory (STEREO) NASA mission, launched in 2006, consists of two spacecraft that slowly drift ahead (ST-A) and behind (ST-B) the Earth on similar orbits around the Sun [1]. STEREO is the first mission to provide a complete set of both *in situ* and imaging instruments to study solar phenomena from two vantage points outside of the Sun-Earth line, as shown in the upper-right part of Fig. 1.

The STEREO Heliospheric Imagers (HI) can image directly the light scattered by solar disturbances propagating from the Sun to one AU, and even beyond. Each spacecraft also comprises a set of *in situ* plasma instruments, including the In-situ Measurements of Particles And CME Transients (IMPACT) suite. This suite comprises the Solar Wind Electron Analyzers (SWEA) that were designed and built at IRAP. These are dedicated to the *in situ* multipoint measurement of the interplanetary counterpart of solar disturbances such as coronal mass ejections (CME).

Using combined data from these imaging and *in situ* instruments, it has been possible to track solar disturbances all the way from the Sun to the Earth for the first time [2]. We show in Fig. 1 an example of a CME that was tracked in ST-B HI images in November 2007. As can be seen the fields-of-view (FOV) of STEREO are most appropriate to track disturbances all the way from Sun to Earth. At the time of Fig. 1, the disturbance had already propagated a significant distance and was just about to hit the Earth (e.g., ACE spacecraft) and the ST-A spacecraft. In ST-B images the CME is visible as the two black and white bands marking the locations of the leading and trailing edges of the CME that are impacting the Earth.

In the lower panels of Fig. 1, the *in situ* measurements near Earth show that the solar disturbance indeed impacted the Earth at the time observed by HI. The times of passage of the leading and rear black/white bands correspond, respectively, to the shocked plasma located ahead of the propagating CME and to its sunward edge [2]. Such unprecedented capability to track solar disturbances all the way from the Sun to the Earth allows space physicists to perform both fundamental science studies (e.g., propagation and *in situ* interaction of disturbances) and real-time monitoring of space weather near Earth's environment.

Detailed analysis of the STEREO *in situ* multipoint observations for this event further permitted the unambiguous demonstration of the occurrence of a fundamental process that at times can significantly alter the CME structure during its propagation: the erosion of magnetic flux by magnetic reconnection [3]. CMEs are magnetic structures that are typically characterized by a flux-rope topology, i.e. helical magnetic lines of force as illustrated in Fig. 2a. Thanks to this unprecedented multipoint, high-quality dataset, a careful determination of the CME axis orientation could be obtained. On this basis, the amount of magnetic flux erosion that occurred during propagation to Earth could be carefully quantified by analyzing the azimuthal magnetic flux imbalance during the multi-spacecraft sampling of the CME. The magnetic reconnection process that occurred at the front boundary of the CME is illustrated in Fig. 2b, where inferred changes in magnetic connectivity are displayed (by comparison to Fig. 2a). Consistent with this process, clear magnetic reconnection signatures were observed locally at the front boundary of the CME, as expected (not shown, cf. [3]). The occurrence of this process was also

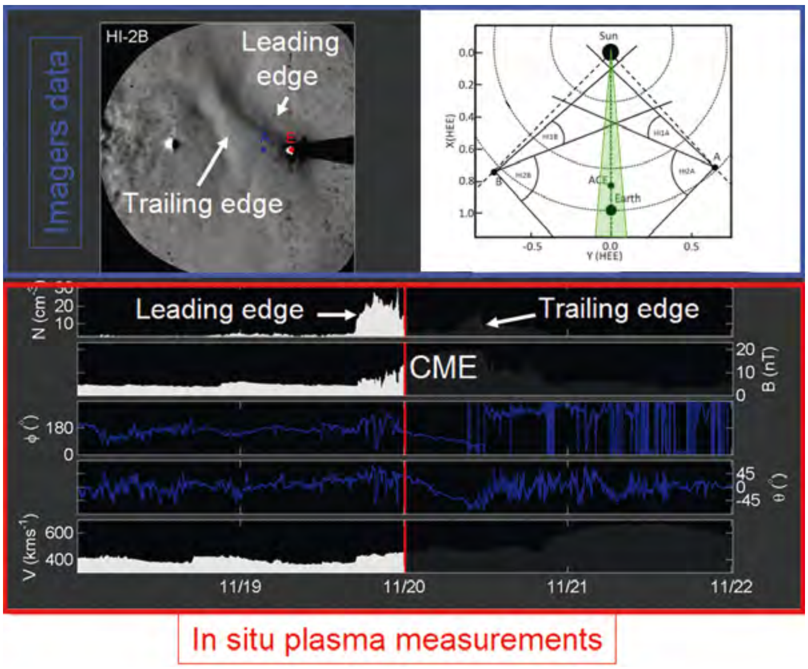

Fig. 1

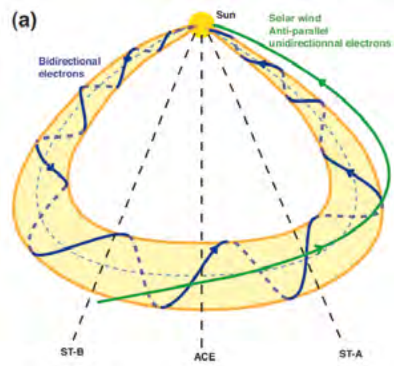

Fig. 2a

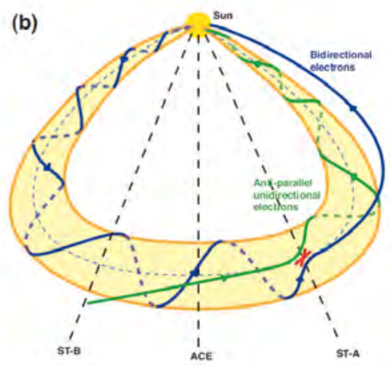

Fig. 2b

confirmed from suprathermal electron measurements within the CME. Such electrons travel very fast along magnetic field lines, and therefore signal the large-scale magnetic topology of both the CME and its surroundings. Changes in suprathermal electron properties were observed in the trailing part of the CME. This observation was interpreted as the result of the magnetic reconnection process occurring at the front of the CME. This is because the front part of a CME is magnetically connected to its trailing edge, where changes in electrons properties were found, owing to the helical nature of its magnetic field. A statistical analysis over the whole space era is underway to further quantify the importance of this process.

Finally, since this erosion mechanism can lead to the removal of part of the southward oriented magnetic field at the front of CMEs, the potential impact of this mechanism on the geo-effectiveness (i.e. the ability to drive geomagnetic storms) of CMEs was studied in [4]. It was shown to be very significant for amounts of magnetic flux erosion on the order of those inferred from the case studies [3-4]. The radial evolution of the magnetic erosion process in the inner heliosphere was also estimated based on simple theoretical models. This study concluded that most of the erosion is expected to occur within Mercury's orbit, paving the way for important contributions to this topic by the future ESA SOLAR ORBITER and NASA SOLAR PROBE PLUS missions, which will provide unprecedented high-quality measurements in the innermost parts of the Solar System.

[Fig. 1]
(Upper-right) ST-A and B locations with respect to Sun and Earth. The FOV of the two HI instruments are illustrated. (Upper left) HI image from ST-B at the time the disturbance hits the Earth. (Lower part) in situ observations near Earth showing density, magnetic field vector magnitude, azimuth and latitude, and ion speed.
© Adapted from [2].

[Fig. 2]
(a) Magnetic topology before reconnection at CME front.
(b) Changes in connectivity produced by reconnection. Blue lines are closed, with counterstreaming electrons. Green and red lines respectively correspond to open field lines with anti-parallel and parallel unidirectional electrons. Arrows show magnetic field orientation. © Adapted from [3].

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AUTHORS: A. Retinò[(1)], F. Sahraoui[(1)], O. Alexandrova[(2)], O. Le Contel[(1)], T. Chust[(1)], M. Berthomier[(1)]

[(1)] LPP, UMR 7648, Route de Saclay, 91128 Palaiseau Cedex, France.
[(2)] LESIA, UMR 8109, 5 place Jules Janssen, 92195 Meudon, France.

Laboratory contribution

Sun, Heliosphere and Magnetospheres

Magnetic reconnection and turbulence in near-Earth space plasmas

Reconnexion magnétique et turbulence dans les plasmas spatiaux autour de la Terre

➔ **Abstract:** The microphysics of reconnection and turbulence is a topic of key importance yet it is not fully understood. Recent CLUSTER observations in near-Earth space allowed determining the turbulent cascade down to electron scales, suggesting possible dissipation mechanisms. Observations showed how reconnection jets are formed and very energetic electrons are accelerated. CLUSTER also provided evidence of reconnection in turbulent plasma and measurements of wave modes at different scales during sub-storms.

➔ **Résumé :** La microphysique de la reconnexion et de la turbulence sont des sujets clés mal compris. Des observations faites par Cluster ont déterminé la cascade turbulente jusqu'aux échelles électroniques, suggérant les mécanismes de dissipation. D'autres observations ont expliqué la formation des jets de reconnexion et l'accélération des électrons très énergétiques. Cluster a fourni la preuve de la reconnexion turbulente ainsi que des mesures des ondes à différentes échelles lors des sous-orages.

The majority of visible matter in space is plasma. Plasma is ubiquitous in galaxies, in stars and within planetary systems. Important phenomena such as the acceleration of cosmic rays, stellar flares and planetary sub-storms are due to fundamental processes occurring in plasmas such as energy dissipation, plasma transport and particle acceleration.

Reconnection and turbulence are two key ingredients of such processes. Turbulent cascade allows the transfer of energy from very large scales, where energy is injected, to the smallest kinetic scales, where energy is eventually dissipated. Reconnection is a major mechanism to dissipate energy into particle heating and acceleration. The experimental investigation of reconnection and turbulence requires measurements of particles and fields *in situ*. At present, the best laboratory to study such processes is the Solar System where *in situ* measurements are available onboard spacecraft. In particular, recent multi-points observations from ESA/CLUSTER spacecraft [1] in the near-Earth space (solar wind, magnetosphere) revealed new physics of reconnection and turbulence down to the smallest scales.

Turbulence has been studied for decades in different regions of near-Earth space. The near-Earth solar wind, in particular, is a privileged laboratory and provides key information about turbulence in the near-Sun corona, where direct measurements are not yet available. While the properties at large-scales (the so-called MHD turbulence) were studied much in the past, key aspects of turbulence at kinetic scales (i.e. scales comparable to particle gyro-radii and below) were revealed only recently mostly thanks to CLUSTER measurements. One very important example is how energy is transferred and dissipated at kinetic scales, where particles are heated and accelerated. Observations from the STAFF magnetometer onboard CLUSTER allowed determining the behavior of energy cascade down to electron scales [2-3-4-5] (Fig. 1, left panel). Furthermore, the detailed analysis of STAFF data allowed to identify different wave modes in the turbulence (kinetic Alfven waves, whistler waves) [3] (Fig. 1, right panel) and to discuss dissipation mechanisms, such as Landau damping and gyro-resonance.

Magnetic reconnection has also been studied much in the near-Earth space [6]. Yet, its microphysics (i.e. the physics at kinetic scales where reconnection is initiated) could be studied in detail only recently mostly through CLUSTER multi-point measurements. One important example is to understand how particles are heated and accelerated in the very small-scale regions where reconnection occurs. Measurements in the magnetotail [7], combined with numerical simulations, allowed understanding how reconnection jets are formed. At higher energies, CLUSTER revealed that the production of energetic electrons occurs when reconnection is unsteady [8] (Fig. 2). These results highlighted basic properties of reconnection but are also important to understand reconnection in other astrophysical plasmas such as the solar corona or astrophysical jets, for which *in situ* measurements are not available.

Both being ubiquitous in astrophysical plasmas, reconnection and turbulence are strongly interrelated. Reconnection is efficient to dissipate turbulent energy while, in turns, turbulence strongly affects the conditions under which reconnection occurs. Despite this connection, however, the relationship

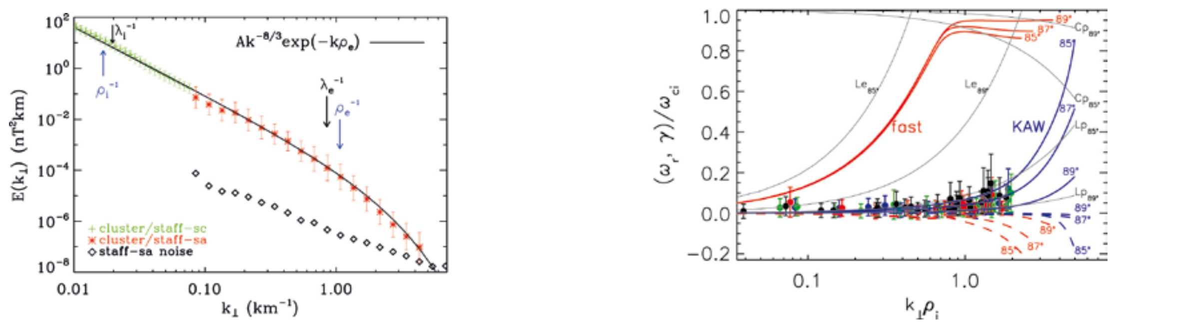

Fig. 1

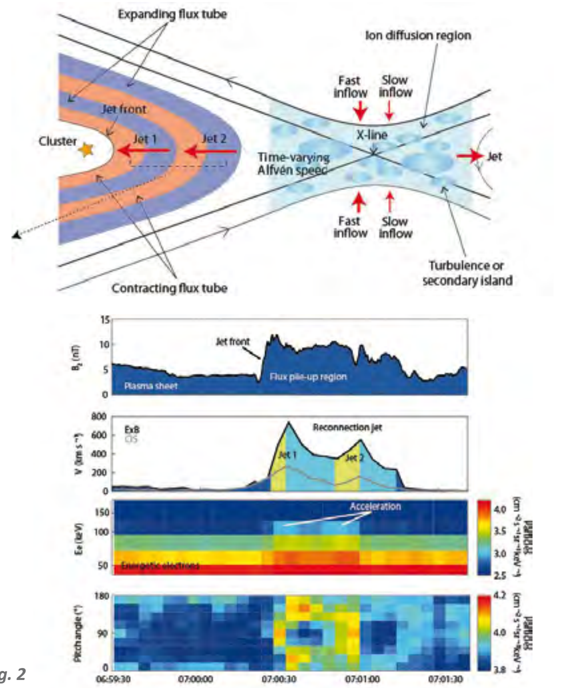

Fig. 2

[Fig. 1]
Left: spectrum of magnetic fluctuations in the solar wind measured by CLUSTER search coil magnetometer at sub-proton scales and compared with an exponential model. © Adapted from [4]
Right: observed dispersion relations (dots) compared to linear solutions of the Maxwell-Vlasov equations. © Adapted from [3] The observed wave modes are consistent with highly oblique kinetic Alfvén waves.

[Fig. 2]
Evidence of suprathermal electron acceleration during unsteady reconnection. Up: cartoon of the reconnection region in the magnetotail. Down: magnetic field, velocity and electron (~100 keV) CLUSTER measurements. The acceleration is due to betatron and Fermi mechanisms in reconnection jets, which are modulated during unsteady reconnection. © Adapted from [8].

between reconnection and turbulence was addressed only recently. CLUSTER provided for the first time evidence of reconnection in turbulent plasma, by using *in situ* measurements in the Earth's magnetosheath [9] and this motivated a number of other studies to understand the role of reconnection as a dissipation mechanism in turbulence. CLUSTER also improved our understanding of the role of different wave modes for the microphysics of reconnection [10]. As an example, observations [11] clearly indicate the strong coupling between ion and electron scales in the magnetotail current sheet during magnetospheric sub-storms, by showing that ion-scale structures can trap whistler waves and allow them to exist much longer than their characteristic electronic time scale. Whistlers [12] are crucial because they mediate the so-called "fast" reconnection occurring during sub-storms and flares.

Studying reconnection and turbulence at kinetic scales through *in situ* measurements is of pivotal importance to understand the basic physics of astrophysical plasmas, and to explain very energetic phenomena such as flares and sub-storms. CLUSTER recent measurements shed light on many aspects of the microphysics, but also showed the limitations of current spacecraft data and suggested new measurements. Future missions such as MMS (2015) and SOLAR ORBITER (2017) will increase our understanding of both processes by providing higher resolution measurements and flying in unexplored regions of the Solar System, such as the near-Sun corona.

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