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Sun, Heliosphere, Magnetospheres

The SHM community is strongly involved in several projects which cover the wide domain of heliosphere including solar physics, Earth magnetosphere, Earth environment but also couplings between the Sun, the solar wind, the magnetosphere, the ionosphere and the thermosphere. It also studies space meteorology.

Sun and Solar physics

- Launched on December 2, 1995, SOHO continues its harvest of data. The mission is likely to be extended.
- SOLAR ORBITER is scheduled for launch in October 2018. France is involved in the development of six instruments among the 10 selected by ESA. In December 2015, CNES decided to support the French leadership for the SPICE instrument, thus placing the French teams at the core of the SOLAR ORBITER activity. SPICE will be the only instrument able of remotely determining plasma properties.
- Launched in 2006, STEREO is still orbiting around the Sun. One of its twin satellites precedes the Earth in its revolution around our star (STEREO A) and the other one follows it (STEREO B). They are currently on the other side of the Sun with respect to Earth.
- SOLAR PROBE PLUS, due for launch in 2018, has the ambitious goal to go into our star's outer atmosphere.

Earth's magnetosphere

- CLUSTER: the four satellites launched in 2000 are still operating. The mission is likely to be extended.
- MMS: four identical satellites were launched on March 12, 2015, and placed into an equatorial orbit. The mission has been in science analysis phase since September 1, 2015, and the temporal resolution data are extremely promising (*cf.* article on the MMS project).

Earth's environment

TARANIS is the first space mission dedicated to the observation of lightning above storm clouds at altitudes between 20 and 100 km. It will study the mechanisms at the origin of the gigantic energy transfers just after intense lightning flashes between the atmosphere, the ionosphere and the magnetosphere, as well as their possible impacts on the Earth's environment. The launch is scheduled for 2018.

Magnetospheric planetary missions

The French SHM community is also increasingly involved in missions such as BEPI-COLOMBO, which is planned to be launched in April, 2018, and to arrive to Mercury in December, 2024. JUICE, a mission to Jupiter and its satellites, is scheduled for launch in 2022.

Projects under study

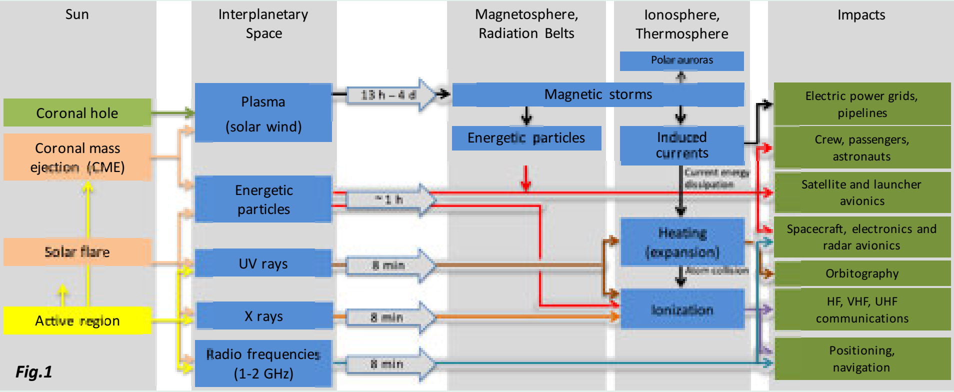
The following projects are under investigation:

- THOR: pre-selected by ESA to fill the M4 opportunity, this mission will address the mechanisms of heating and particle acceleration linked to electromagnetic energy dissipation in turbulent plasmas at kinetic scales.
- NANOMAGSAT for magnetic measurements; NOIRE Nanosats for a Radio Interferometer Observatory in Space.
- NOBLE plans to study the mechanisms of nitrogen and oxygen escape from terrestrial and planetary atmospheres. ALFVEN plans to study the acceleration mechanisms in the Earth's auroral zones, which will be proposed as part of the ESA M5 call.

Space weather

This multidisciplinary topic requires a better understanding of the couplings of the regions from the Sun to the Earth, as well as the monitoring of the solar activity's impact on the Earth as illustrated in Fig. 1.

Our current understanding of the physics of the Sun-Earth system is not enough to plan the disturbances of the Earth's space environment with sufficient reliability. However, data-based physical models and digital simulations, observation instruments and interpretation tools from the contribution of the SHM scientific community lead to the understanding of some mechanisms on the Sun/solar wind/magnetosphere/ionosphere/thermosphere coupling thanks to which we could plan solar phenomena and their impacts on operational systems.



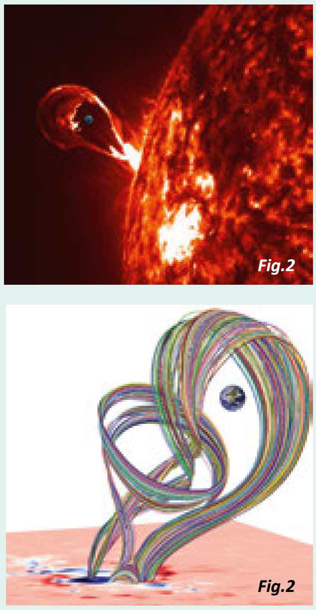


Fig. 1: The colors in the first column show phenomena that vary on several timescales: the coronal holes are stable on several solar rotations (27 days). The active regions vary on the solar rotation scale, whereas flares and mass ejections are explosive phenomena. Sun-Earth propagation times are indicated in the grey arrows. All these events vary according to the 11-year activity cycle. GTME Report.

Fig. 2: Top right: A typical solar flare. Bottom right: Model of the magnetic rope during the flare. The Earth has been superimposed on both images to illustrate the huge scale of the phenomenon. *© Tahar Amari/Centre de physique théorique*

For example:
- Sun: the source of solar magnetism is a nonlinear dynamo operating at the base of the convection zone via the joint effect of a cyclonic turbulence and large scale cuts regenerating the toroidal field. This magnetic activity is cyclic and lasts about 11 years (± three years). It is difficult to anticipate owing to the turbulent nature of the dynamo. The topology of the Sun's global magnetic field follows the cycle; by going from a simple dipolar configuration to a complex multipolar configuration, the topology causes significant changes to the corona and the solar wind [1], which impact the Earth's space environment. The same applies to eruptions and coronal mass ejections which are more common at solar maximum.
- Solar wind: since the increase in solar activity in 2010, numerous solar thunderstorms were simultaneously observed from several sites by the NASA STEREO probes. Using these data, IRAP(1) researchers developed new techniques to rebuild the temporal evolution of these thunderstorms' internal magnetic field as well as the shocks that form during the expansion of these structures. Thanks to this work, researchers gained a better understanding of the evolution of thunderstorms as well as high-energy particle acceleration [2].
- Earth's ionosphere: ONERA has been working for several years on a data assimilation tool applied to the Earth's radiation belts. The aim is to restore in an optimal way the behavior of the electron belts after a solar thunderstorm. The results obtained open the way towards an operational service for space weather. Moreover, several laboratories in France (the IPGS(2), the IPGP(3), the LPC2E(4), IPAG(5), IRAP(1) and LATMOS(6)) are working on tools to model the Earth's ionosphere in order to predict and measure the disturbances (which are essential for ground communications) caused by our Sun to this environment.
- Numerical simulations: we may also mention modeling works which aim to study the solar environment continuously and characterize the evolution of the environment leading to a flare (warning). For example, the work led by the CPT(7) and AIM(8) laboratories enabled the identification of a key-phenomenon in the solar flare trigger mechanism [3] and the explanation of why the Sun's atmosphere is much hotter than its surface [4].

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Sun, Heliosphere, Magnetospheres

First results of the Magnetospheric MultiScale mission (MMS)

The French contribution to the MMS mission

On March 12, 2015, NASA's MMS mission was successfully launched by an Atlas V rocket from the Cape Canaveral station. It consists of four identical satellites placed into an Equatorial orbit. As of September 1, 2015, the mission entered the scientific analysis phase to explore the key regions of the Earth's magnetosphere. It is divided into two main orbital phases: phase 1 is dedicated to the study of the dayside magnetopause, the flanks and the near-Earth magnetotail (apogee of 12 Earth radii, R_E); phase 2 focuses on the study of the geomagnetic tail at average distance from Earth (apogee 25 R_E). Its main goals are to study magnetic reconnection, particle acceleration and the role of turbulence in plasmas, especially in the context of magnetic reconnection. [1] Its next-generation instruments and inter-satellite distances aim to study these physical processes at the scale of electron dynamics. The average inter-satellite distance of the tetrahedral configuration varies from 160 km to 10 km complementing the scales studied by Cluster (10 000 km to 100 km). In addition, particle measurements are freed from the limitation linked to satellite rotation (4 s on Cluster) by increasing the number of sensors. Electron distribution functions are thus measured with a temporal resolution of 30 ms and of 150 ms for ions. The strategy for managing telemetry data volume is to configure the instrument into the burst mode when the spacecraft crosses the targeted region, to store data in the onboard memory and to select, from the low time resolution data downlinked to the ground, high time resolution periods to transmit first. The level-2 database (physical quantities) has been open to the public since March 1, 2016, and the data must be continuously produced within one month of receipt.

The French contribution includes the search coil magnetometer (SCM) – which was designed, built and calibrated by the LPP [2] within the "FIELDS" consortium [3] – and the supply and calibration of micro-channel plates (MCP) by IRAP for the dual ion spectrometer (DIS) of the Fast Plasma Investigation (FPI). [4]

The magnetopause at ion and electron scales

On October 16, 2015, at 10:33:30 UT, MMS crossed the magnetopause while the satellites were within 10 km of each other. A plasma jet heading south along the magnetopause was detected in accordance with the formation of a magnetic reconnection region located north of MMS. In Fig. 1 (left), the satellites' trajectory is superimposed on the results of a numerical simulation using the "Particle-in-cell" (PIC)-type SMILEI code for a case of asymmetric magnetic reconnection. Electron pitch angle(1) distributions (PADs) measured by MMS (Fig. 1, right) indicate that as the satellites approach regions of high magnetic field line curvature, electron gyration around the magnetic field is disrupted and their PADs become isotropic. [5]

MMS crossed the magnetopause again at 1:05:40 p.m. UT and a plasma jet heading south was also detected. Before it crossed the magnetopause, a nearly stationary whistler mode wave emission propagating oblique to the north was identified thanks to a polarization analysis using SCM measurements [6]. These whistler mode waves have a parallel electric field component capable of accelerating resonant electrons into the ionosphere. This emission is interrupted just before magnetic field lines open and the Hall electric field (jx**B**/(qe ne)) appears, leading to ion-electron decoupling with magnetic field lines and electrons. The Hall electric field is obtained by calculating the electric current thanks to as on the CLUSTER mission four-point-measurements of the magnetic field. The good agreement between this current and that obtained independently from particle measurements rules out artifacts. Open magnetic field lines are deduced from the disappearance of energetic electrons in the direction antiparallel to the magnetic field.

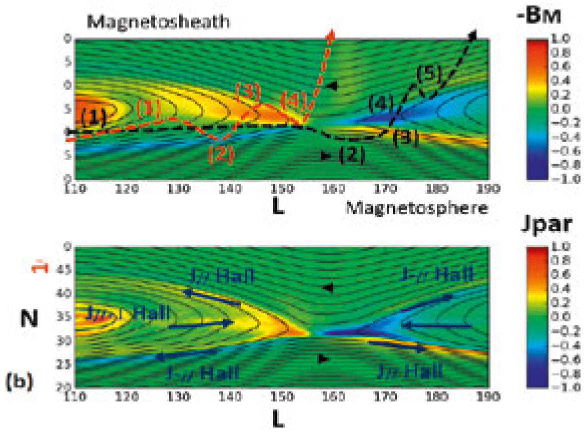

Fig.1

Fig. 1: Left: representations of the “Hall” magnetic field (top panel) and of the parallel current (lower panel) superimposed on the magnetic field lines in black obtained from the SMILEI numerical simulation code. The L direction corresponds to the vertical direction towards the North and tangent to the magnetopause. The N direction corresponds to the outward normal to the magnetopause toward the Sun.

Right: Module of the magnetic field (a) and pitch angle distribution (PAD) (b) for <200 eV electrons. The (c), (d), (e) and (f) panels have a PAD expansion for energies of 600 eV, 400 eV, 100 eV and 20 eV. The magnetic field line curvature radius is shown in panel (g), the error in its determination is in panel (h) and χ^2 parameter is defined as the ratio between the radius of curvature and the gyration radius of electrons of different energies indicating the transition to a stochastic dynamics for a value close to 25. © *Figure from Lavraud et al. (2016) [5]*

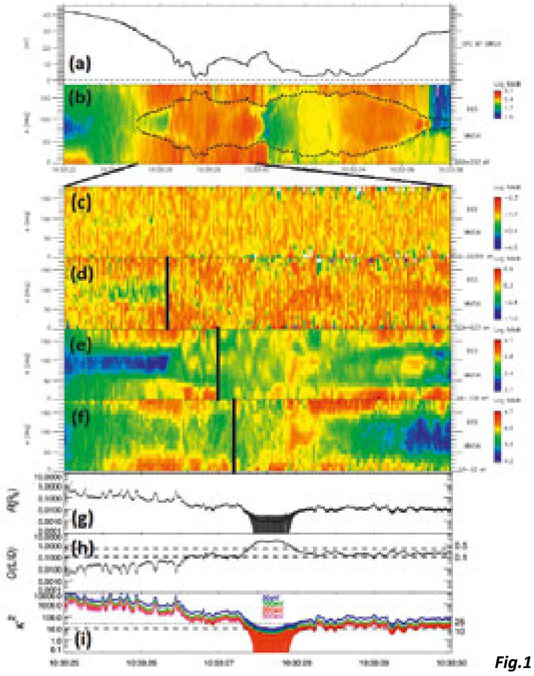

Fig.1

The first results delivered by the MMS mission demonstrate the need for a very high temporal resolution of wave and particle instruments as well as a fine spatial resolution (small inter-satellite distance <100 km) in order to understand the physical processes that occur at the interface between two plasmas such as in the terrestrial magnetopause, or in a turbulent plasma such as in the magnetosheath. The future phases of the mission in the close and distant tail as well as in the magnetopause will provide the international community with a comprehensive set of measurements at the scale of electron dynamics in all key regions of the Earth’s magnetosphere.

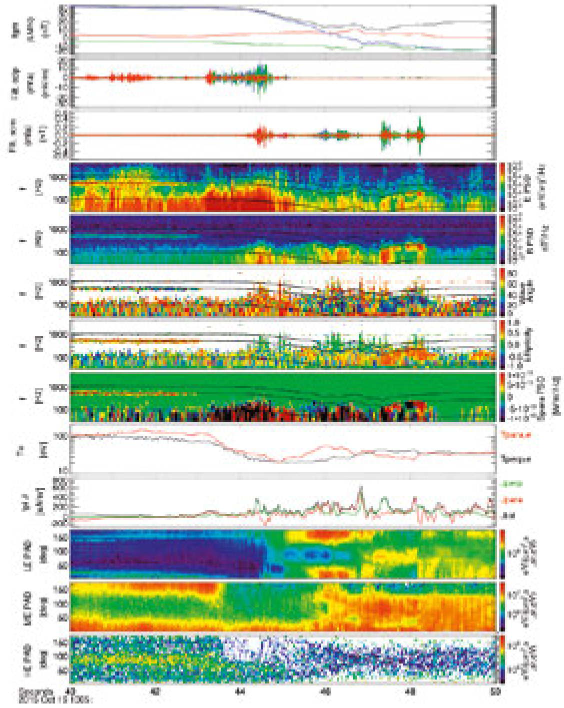

Fig.2

Fig. 2: Magnetic field components in the LMN frame linked to the magnetopause. L is directed toward the North, N toward the Sun and M completes the triad. Electric and magnetic fluctuations are filtered between 32 and 4096 Hz. Power spectral densities of electric and magnetic fluctuations. The black lines indicate 0.1 fce, 0.5 fce, where fce is the electron gyration frequency. The following panels show the propagation angle and the ellipticity provided by the polarization analysis. The component of the Poynting vector; electron parallel and perpendicular temperatures; the parallel, perpendicular and total flows obtained from particle measurements; electron PAD at three energy ranges (LE = [0.200 eV] ME = [200 eV, 2 keV] HE = [2 keV, 30 keV]). ©*Figure from Le Contel et al. (2016) [6]*

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(1) *The pitch angle of a particle is the angle between the direction of its velocity vector and of the magnetic field.*

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Sun, Heliosphere, Magnetospheres

CDPP & MEDOC data centers

Although the variability of the Earth's atmosphere affects our everyday lives more than that of the Sun, the latter has a significant impact on the heliosphere, on the space environment of Earth and other planets, and even on Earth itself. Numerous instruments were designed and built to understand this influence and anticipate its consequences. They are placed both on Earth and in its close environment, or aboard probes which travel great distances in the heliosphere.

Each instrument produces data that are characterized by measured parameters (magnetic field, luminous intensity, etc.) and by parameters of the measure itself (position, direction, duration, sensitivity, resolution, etc.) – every dataset is different.

To optimize data exploitation, they must be stored in the long term and easily accessible and usable by the scientific community, as widely as possible. To pool data management resources and skills between various instruments and to ensure an increased simplicity for the users, the data should be gathered in data centers, rather than distributed only by the teams in charge of each instrument.

CNES has adopted this approach and supports the MEDOC(1) and CDPP(4) data centers, after having participated in their creation. MEDOC was created in 1996 by CNES, INSU/CNRS and University Paris-Sud to be Europe's data and operations center for the scientific instruments of ESA's SOHO mission. Since then, MEDOC has gained many other datasets from Sun-observing space instruments, including the STEREO, SDO and PICARD missions, as well as from value-added products such as UV synoptic maps or maps representing the distribution of solar coronal plasma according to temperature and density. In 1998, CNES and INSU created the CDPP(2), the national data archive for all experiments in which France has participated linked to natural plasma physics in the Solar System.

Both centers ensure the archiving, redistribution and valorization of many complementary datasets from space instruments, relating to the heliosphere, the Sun, the interplanetary medium and the planetary magnetospheres. To this end, the data centers must first acquire data from the team in charge of each instrument, and archive them with their metadata and associated descriptive documents. The structure of each dataset must be taken into account, and some procedures – determined in association with CNES's Service for Referencing and Archiving Data (SERAD) – must be followed to ensure data access and usability in the long term, including by non-specialists.

The data is redistributed to the users through web interfaces and web services – interfaces on which web-based requests can be made from computer programs. Both are provided by the same system, namely SIPAD-NG at the CDPP and SiTools2 at MEDOC. CNES is responsible for the maintenance of these software programs, which are the result of a standardization effort with the data centers. They communicate with databases and third party tools, as well as with the users.

In addition to these interfaces, MEDOC and the CDPP have designed services to make the use of data easier. MEDOC's FESTIVAL software program enables solar and heliospheric data image visualization and analysis. To browse easily these images, MEDOC provides the HelioViewer server – designed by ESA and NASA – with the only complete mirror database of the American server. To help interpret the data, radiative transfer codes and solar flare and wind simulation results are also avail-able. For heliospheric plasma measurements, the CDPP has been improving for 10 years the AMDA service (Automated Multi-Dataset Analysis), thanks to which users can interactively handle online data, combine various physical parameters, conduct conditional researches and organize, track and interface data with other community tools, and eventually

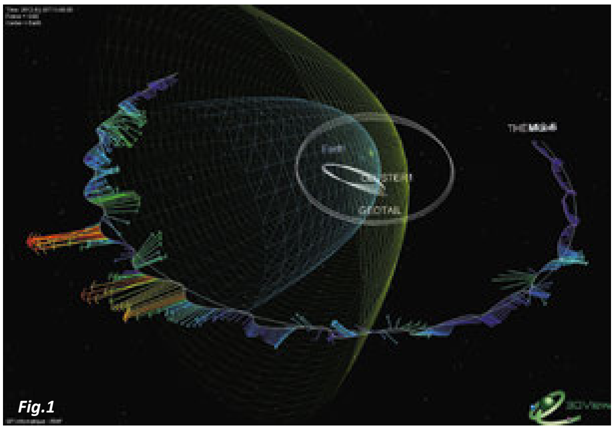
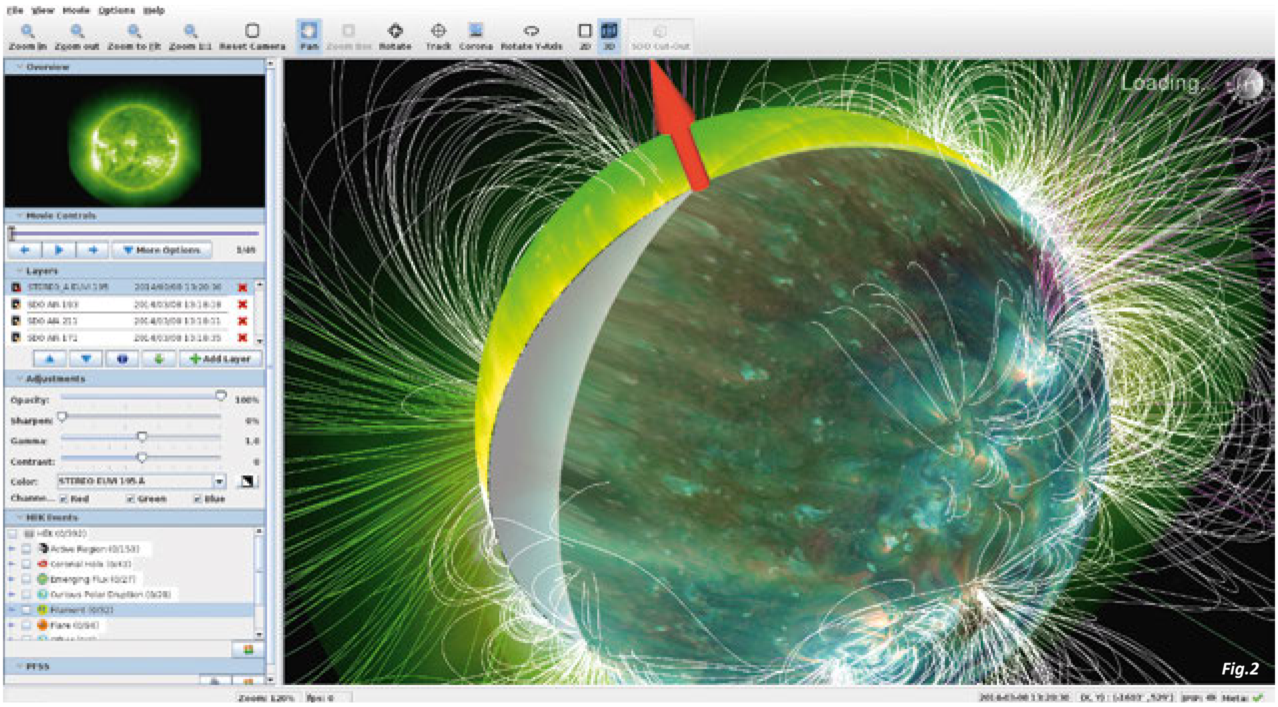


Fig. 1: Models and data observed in the Earth's magnetosphere and the solar wind during ~ 3 weeks. The yellow and blue lines are respectively shock and magnetopause models. The Cluster 1 satellite explores the magnetosphere, Geotail ventures in the solar wind and the Themis B satellite is orbiting the Moon. This figure was made with 3DView connected to AMDA's in situ data.

Fig. 2: Data from SDO/AIA, Stereo/Secchi and a reconstruction of the magnetic field, displayed in the 3D version of HelioViewer's Java client, using data from the MEDOC server.



obtain them in different formats. This tool is increasingly used for teaching or for thematic schools. Thanks to the 3DView tool, it is also possible to display the orbits of Solar System objects and space missions in 3D as well as the data simulated or measured by the instruments.

As data centers, the CDPP and MEDOC also support space missions (archiving, distribution and valorization service for the instruments, including SOLAR ORBITER/SWA and JUICE/RPWI at the CDPP, and PICARD at MEDOC), and can be used as operations center. Moreover, the CDPP's AMDA is available for the analysis of ROSETTA's plasma data, and the CDPP offers its expertise for the characterization of the space environment of the ATHENA mission (in the second Lagrangian point L2).

The complementarity between MEDOC and the CDPP, already present for the datasets, is particularly used by the PropagationTool, which calculates the trajectory of solar disturbances (such as coronal mass ejections) and energy particles, and highlights the link between solar and heliospheric events. The tool can also be used for heliospheric studies: for a given observation date of the Sun, the user obtains the estimated dates of the in situ observations. He is then automatically directed either towards MEDOC movies and observations, either towards the in situ measurements hosted on the AMDA. The tool will be extremely valuable in the synergy between remote observations and in situ measurements which the SOLAR ORBITER instrumentation will enable.

The tools provided by MEDOC and the CDPP are essential to understanding the Sun's influence on the heliosphere, especially Earth-Sun relationships. MEDOC and the CDPP provide services for the study of space weather events having affected the systems which are sensitive to it. They can provide operational services to characterize the space environment of these systems in near-real time.

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