Accordo ASI - INAF n. 2020-35-HH.Oi

30/11/2022 **Tor Vergata Astrophysics Seminar**

The CAESAR project: Comprehensive spAce wEather Studies for the ASPIS prototype Realization

Monica Laurenza

Project Prime:

INAF Istituto Nazionale di Astrofisica – National Institute for Astrophysics

Project Partners:

INFN Istituto Nazionale di Fisica Nucleare; Istituto Nazionale di Geofisica e Vulcanologia; Tor Vergata Università degli Studi di Roma; unipg Università degli Studi di Perugia; Università di Genova; Università degli Studi dell'Aquila; Università della Calabria; Università di Catania; Università di Trento

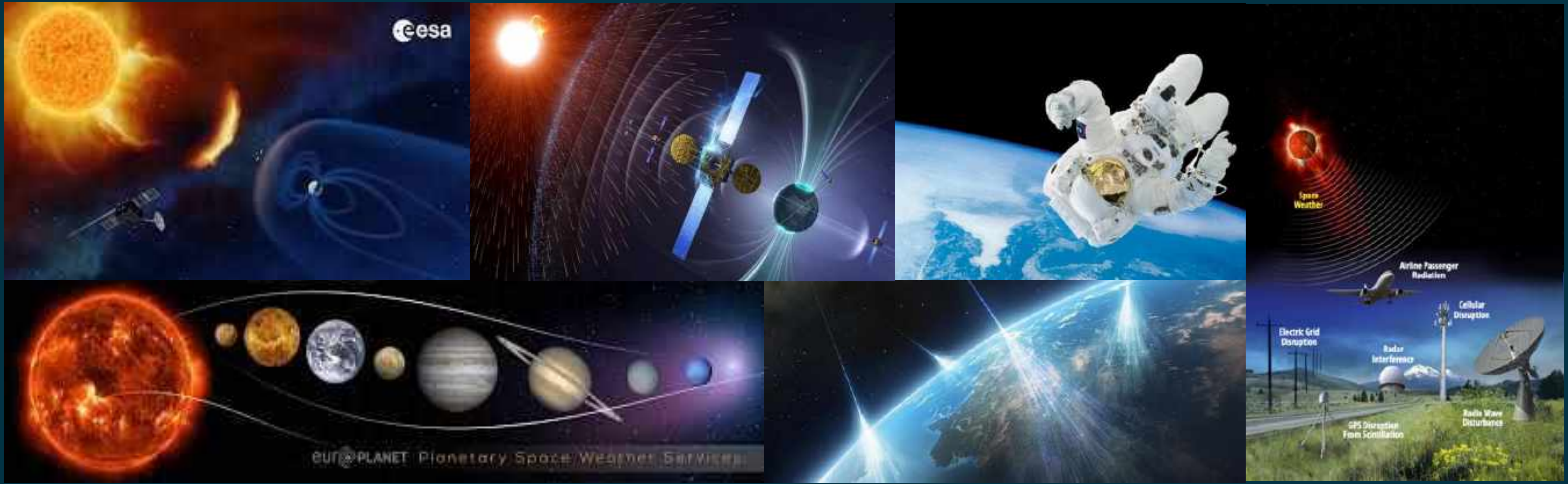
Scientific Context

Understanding of processes of plasma physics from the Sun to the Earth and planets at the base of Space Weather (SWE) is an unanimously recognized primary interest both for making significant advances in SWE Science and for realising a quality leap in our capabilities to predict SWE effects and ensure effective mitigation.

- Fundamental scientific questions remain open
- The scientific community has so far suffered from a fragmented scientific approach
- Urgent need to reinforce the interactions and synergies among the SWE Italian groups and unify Italian resources (ASI roadmap, Plainaki et al., 2020)

CAESAR overview

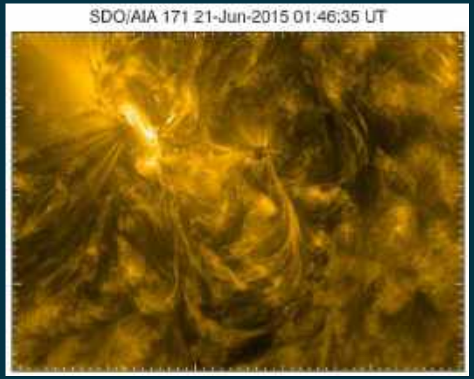
CAESAR rallies a great part of the Space Weather (SWE) Italian community and tackles **the main relevant aspects of SWE science.** It will realize the **prototype** of the scientific data centre for Space Weather of the Italian Space Agency (ASI) called **ASPIS** (ASI SPace Weather InfraStructure).

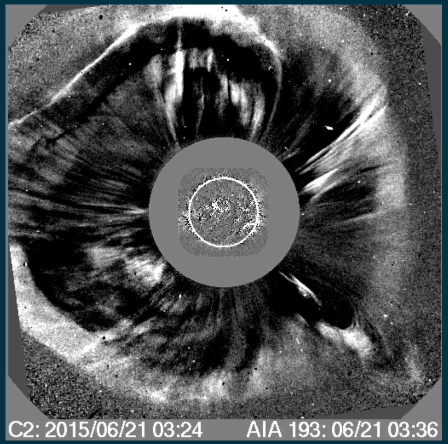


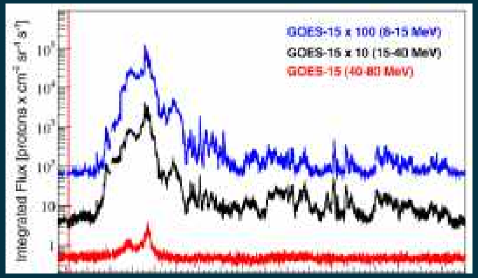
CAESAR approach

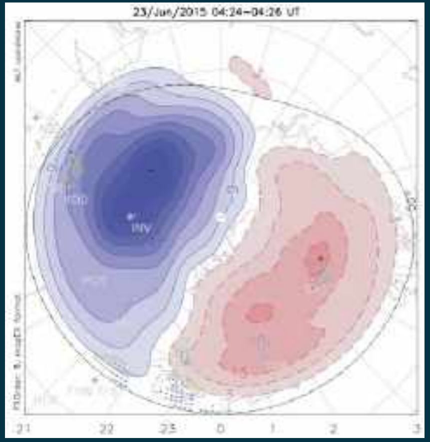
CAESAR adopts an unprecedented, comprehensive, multidisciplinary and integrated approach, encompassing the **whole chain of phenomena from the Sun to the Earth up to planetary environments.**

Geoeffective event

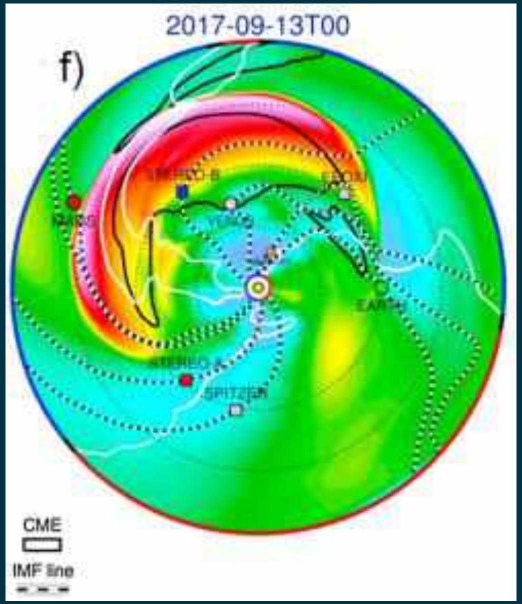








Widespread event



CAESAR investigates a number of well-observed "**target SWE events**" (geoeffective, widespread), exhibiting moderate to extreme SWE characteristics from several perspectives, for detailed case studies.

CAESAR investigations synergistically exploit different products, that will be made available in ASPIS.

CÆSAR

CAESAR objectives

1) Advance the understanding of the origin and evolution of SWE phenomena;

2) provide novel and longstanding data, codes and models;

3) design, implement and populate with such products the ASPIS prototype in a flexible user-friendly infrastructure;

4) pave the way to future advanced SWE forecasting capabilities;

5) ensure efficient dissemination and foster future studies.

CAESAR team

CAESAR brings together **10 Italian institutions as partners**, with complementary recognised expertise

Executive board: A. Milillo (INAF), C. Plainaki (ASI), G. Sindoni (ASI), M. Giardino (ASI), G Polenta (ASI)

92
researchers

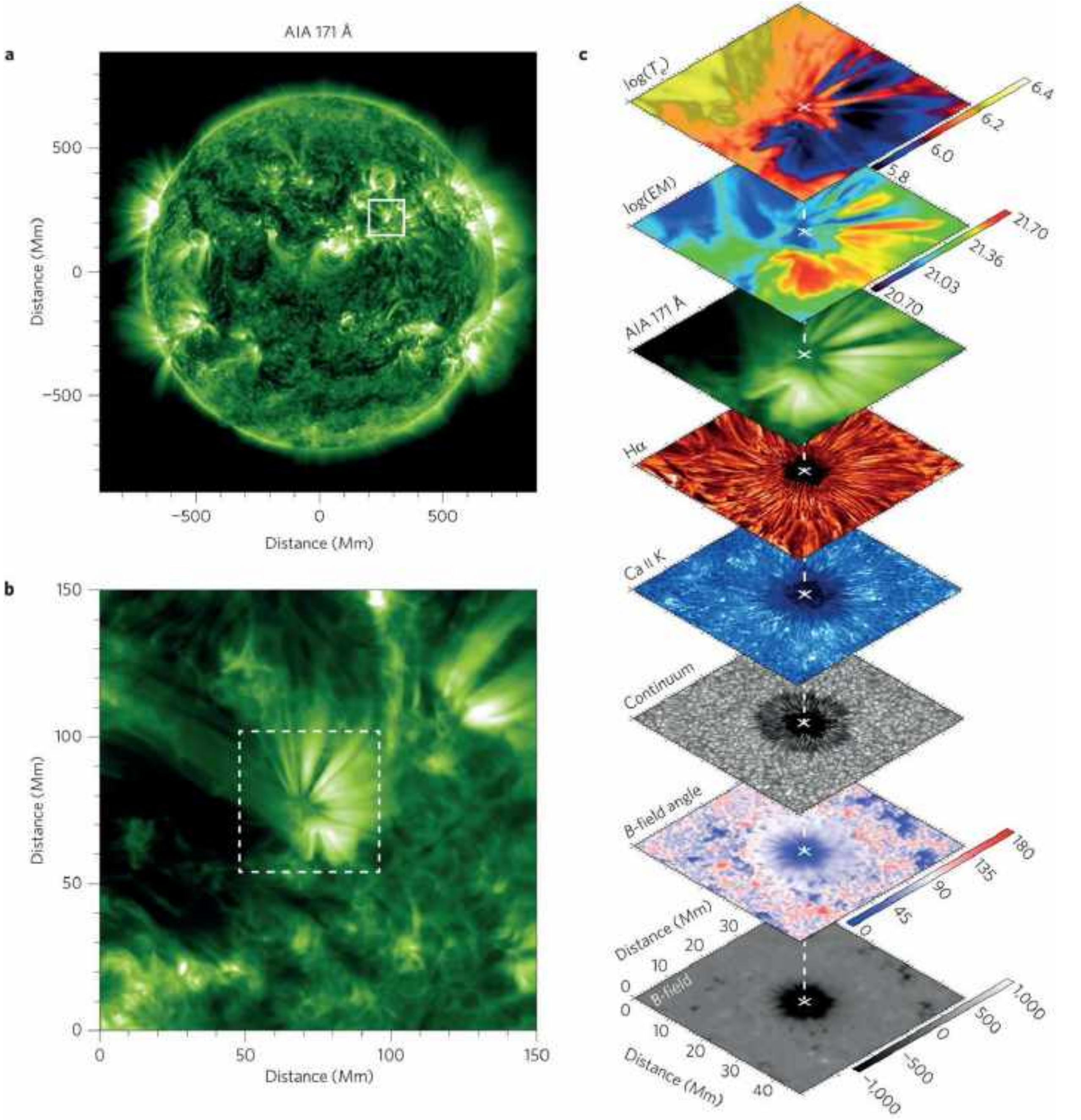
Istitution	Leader	N° partecipants
INAF (prime)	Monica Laurenza (PI)	24
INGV	Fabio Giannattasio	8
INFN	Valeria Di Felice	3
UNIAQ	Ermanno Pietropaolo	6
UNICAL	Fabio Lepreti	7
UNICT	Francesca Zuccarello	3
UNIGE	Cristina Campi	2
UNIPG	Bruna Bertucci	5
UNITOV	Dario Del Moro (Deputy PI)	15
UNITN	Roberto Battiston	2
ASI e other institutions		8

Active Sun

The purpose is to better understand the link between solar magnetism and features in the layers of the solar atmosphere (photosphere, chromosphere, and corona) associated with the occurrence of the SWE drivers, i.e., what physical conditions on the Sun generate SWE events.

- Characterization of solar eruptions and evolution in the solar atmosphere of the main drivers of SWE phenomena

- Assessment of the eruptive capability of solar active regions



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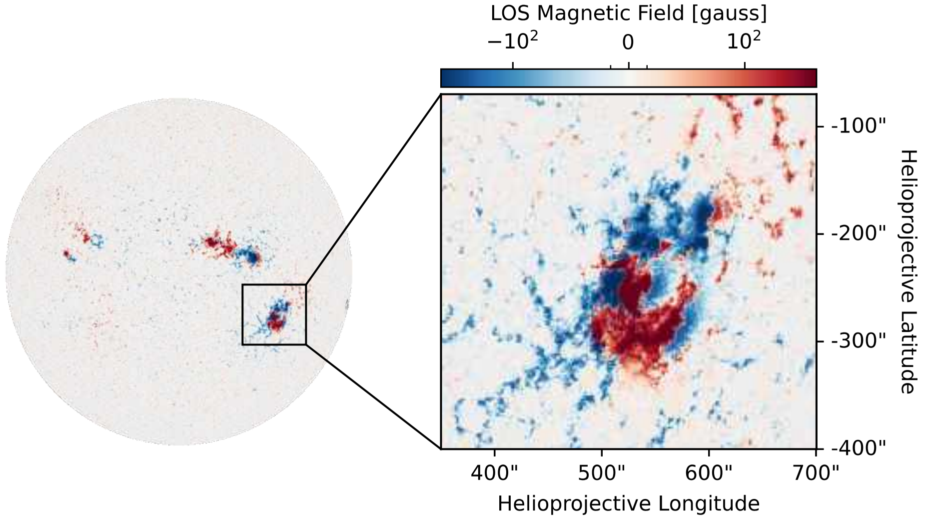
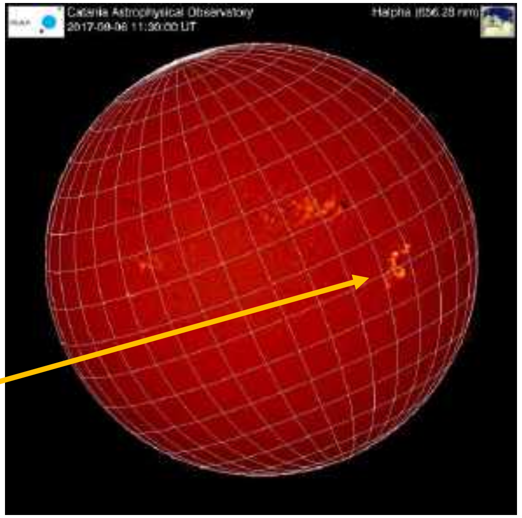
Active Sun

Full disk HMI LoS magnetogram on 09/06/2017 with zoom on NOAA 12673, showing the configuration of the AR located at S09W42.

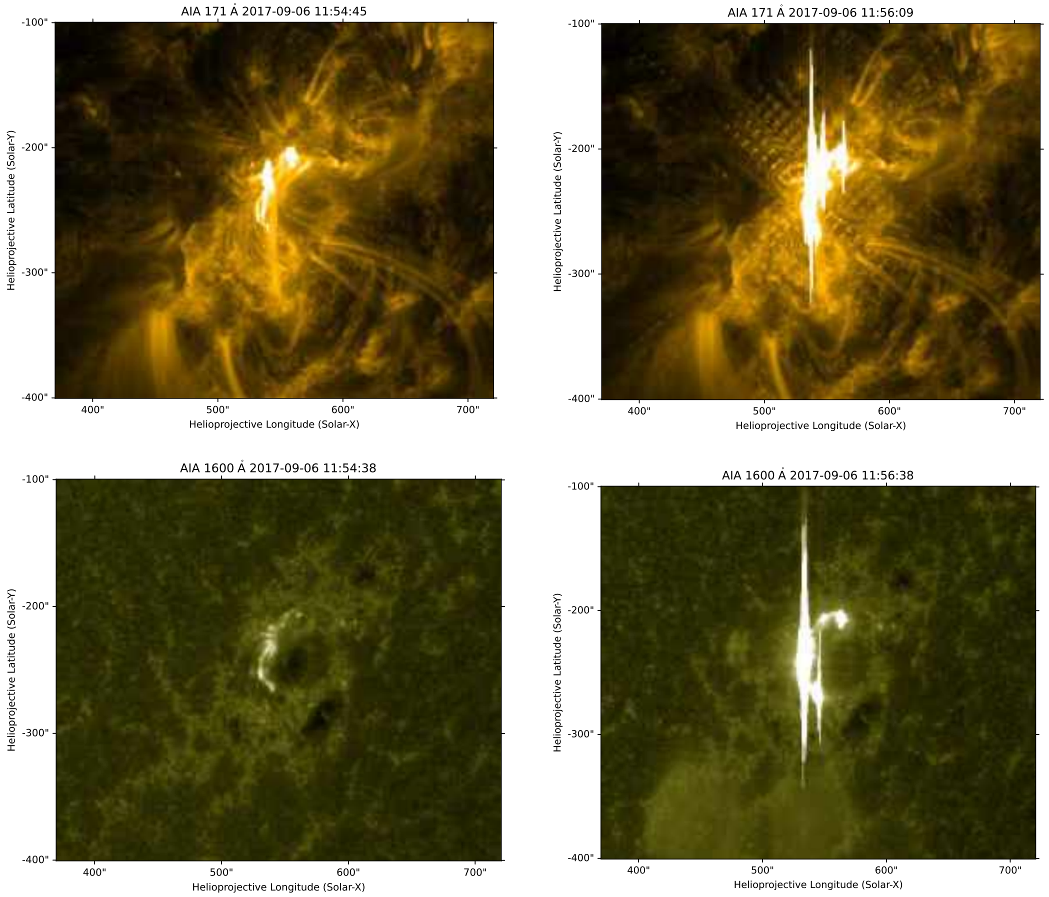


Full disk Chromospheric image acquired at INAF – Catania Astrophysical Observatory on 09/06/2017 at 11:30 UT.

A facular region is present in NOAA 12673, few minutes before the beginning of the flare.

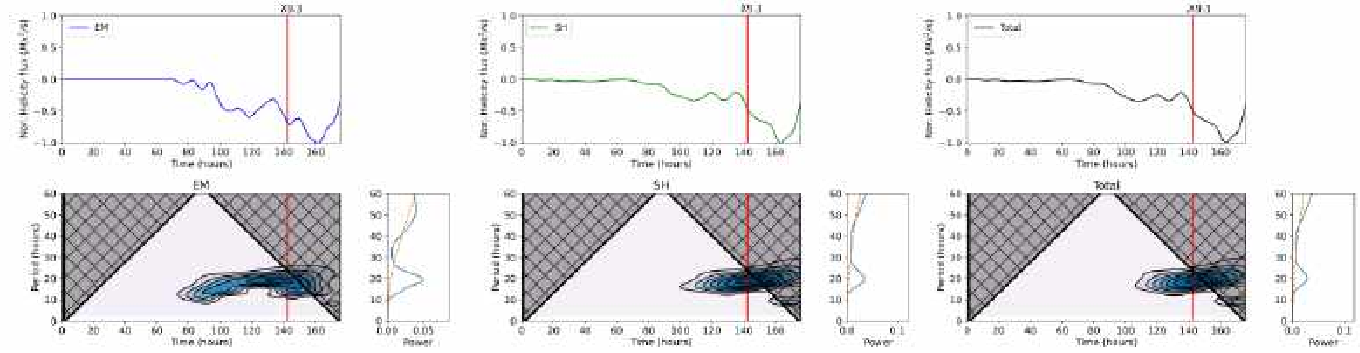


On 6 September 2017 an **X9.3** flare took place in AR NOAA 12673. The flare started at 11:53 UT, peaked at 12:02 UT, ended at 12:10 UT.



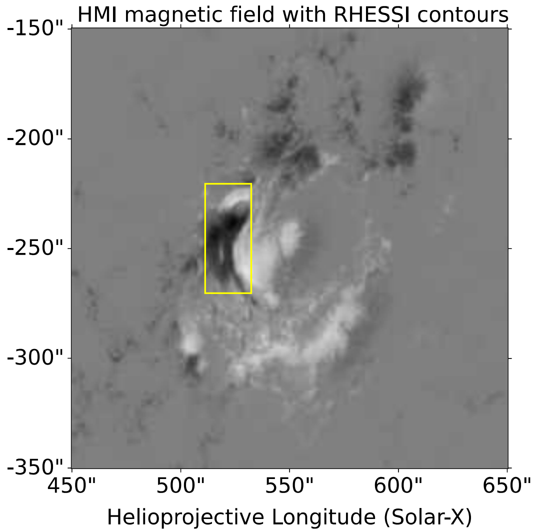
AIA images acquired at two different times during the flare evolution. Top: 171 Å; Bottom: 1600 Å

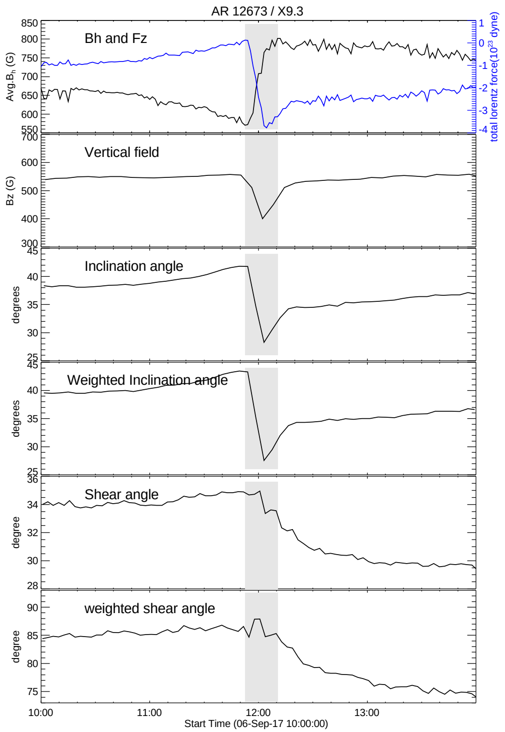
Active Sun



Top panels: time-series of the normalised emergence EM (left), shearing SH (middle), and total T (right) helicity fluxes. The red vertical lines mark the onset time of the X9.3 flare. The 2*nd* row show the wavelet power spectrum (WPS) and the associated global power spectrum (GPS) of the EM/SH/T.

A strong oscillation with a 18.9-hr period is found in the evolution of the magnetic emergence component. Based on Wavelet Power Spectrum analyses, this oscillation first developed 68 hrs before the X-class flare. Moreover, the Shearing and Total helicity fluxes have oscillations with 18.3-hr periods that start to develop about 40 hrs before the flare.





Left: HMI LoS magnetogram with overplotted RHESSI 6 - 12 keV isocontours (color refer to different times). The yellow box indicates the FoV used to determine the evolution of the parameters shown in the right panel. Right: from top to bottom: evolution of several obtained parameters, The gray area indicates the time of the X9.3 flare occurrence.

The vertical field remains almost constant throughout +/-2 hr from flare peak time, whereas the horizontal magnetic field, total downward Lorentz force, inclination and shear angles show step-wise irreversible changes during the flare.

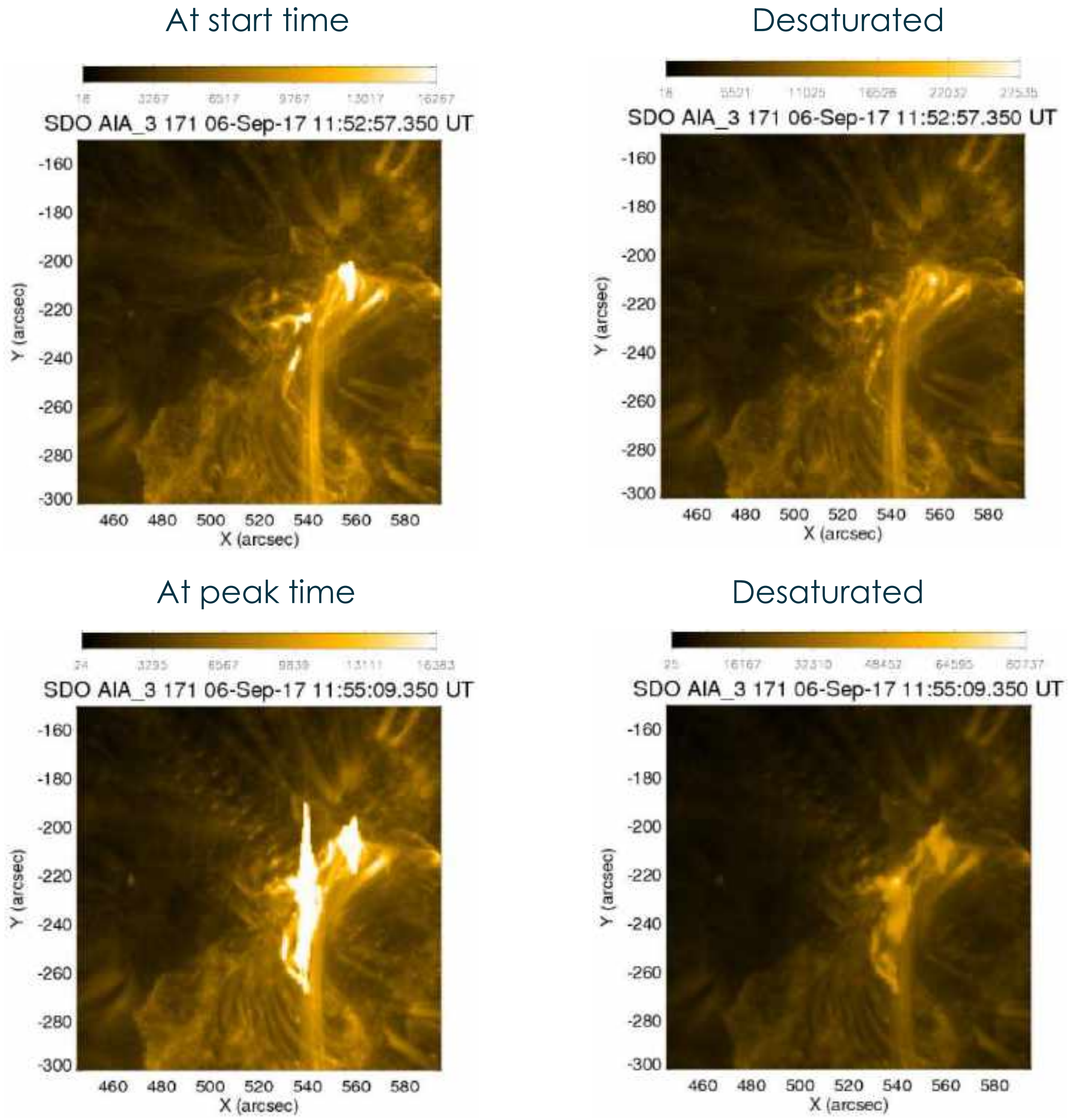
Active Sun

- Computational methods for desaturation of EUV images

- Computational method for image reconstruction from Fourier X-ray data

- AI methods for flare prediction

- Computational methods for detection and tracking of global EUV waves



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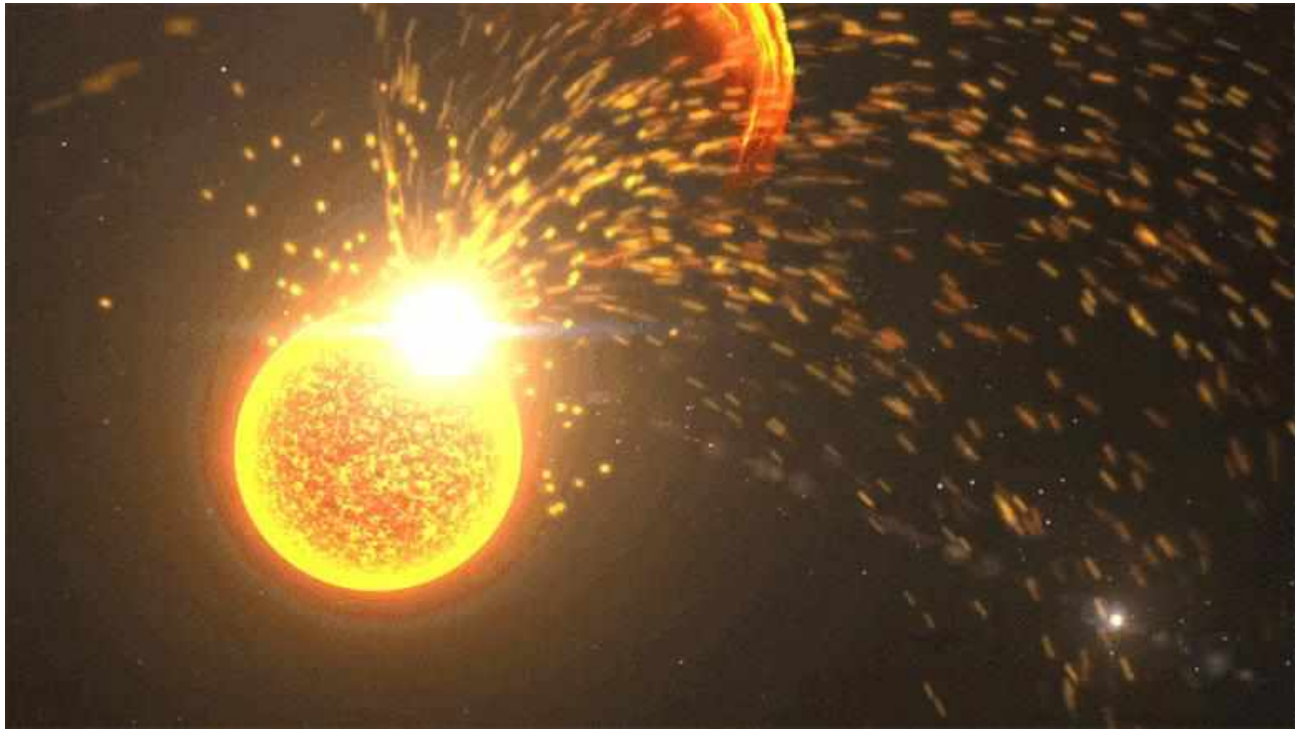
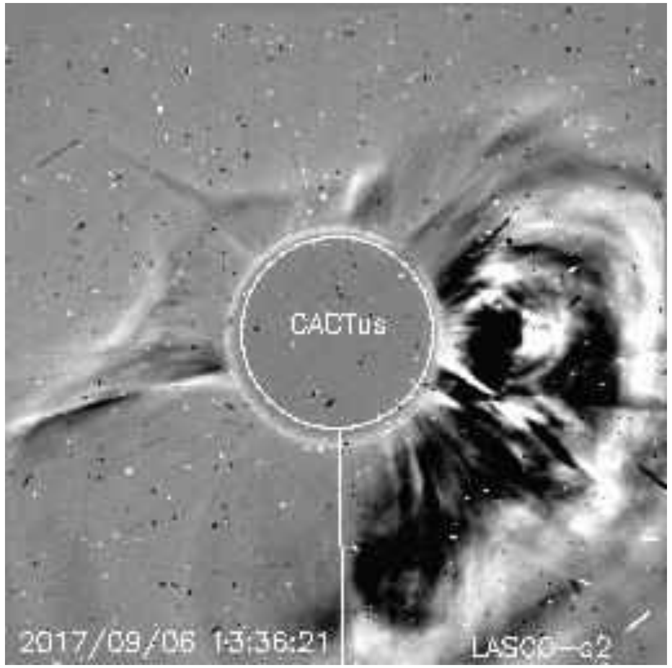
Interplanetary Space

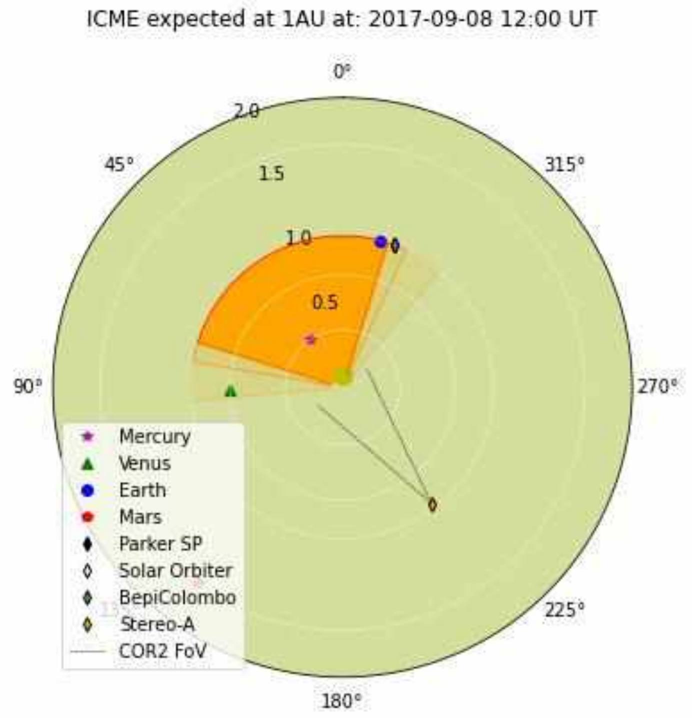
The purpose is to shed light on the mechanisms leading to the acceleration and transport of energetic particles during solar energetic particle (SEP) and energetic storm particle (ESP) events and to investigate the physical conditions produced in the interplanetary (IP) space by the emission of Space Weather (SWE) drivers at the Sun.



Interplanetary Space

- Modelling of the propagation of coronal mass ejections (CMEs) in the IP space and characteristics at arrival at Earth and other planetary environments.
- Evaluation of the large-scale magnetic structure from in situ solar wind parameters and magnetic field measurements





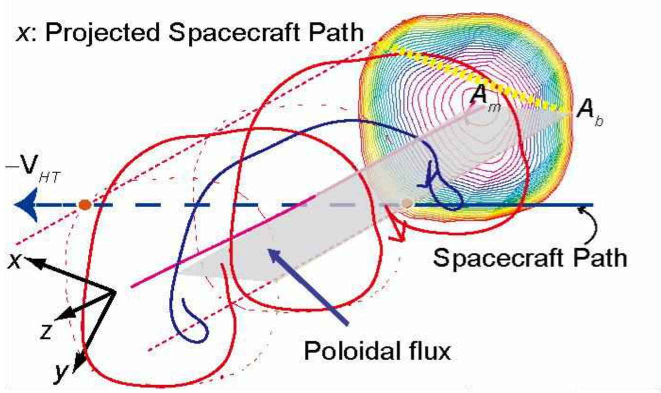
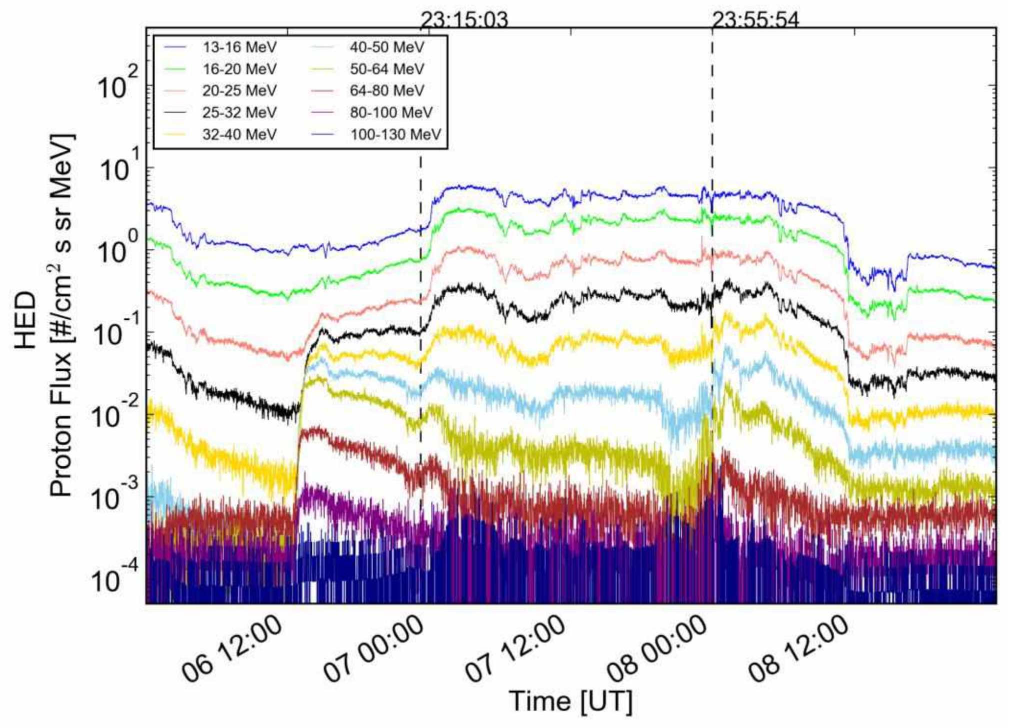
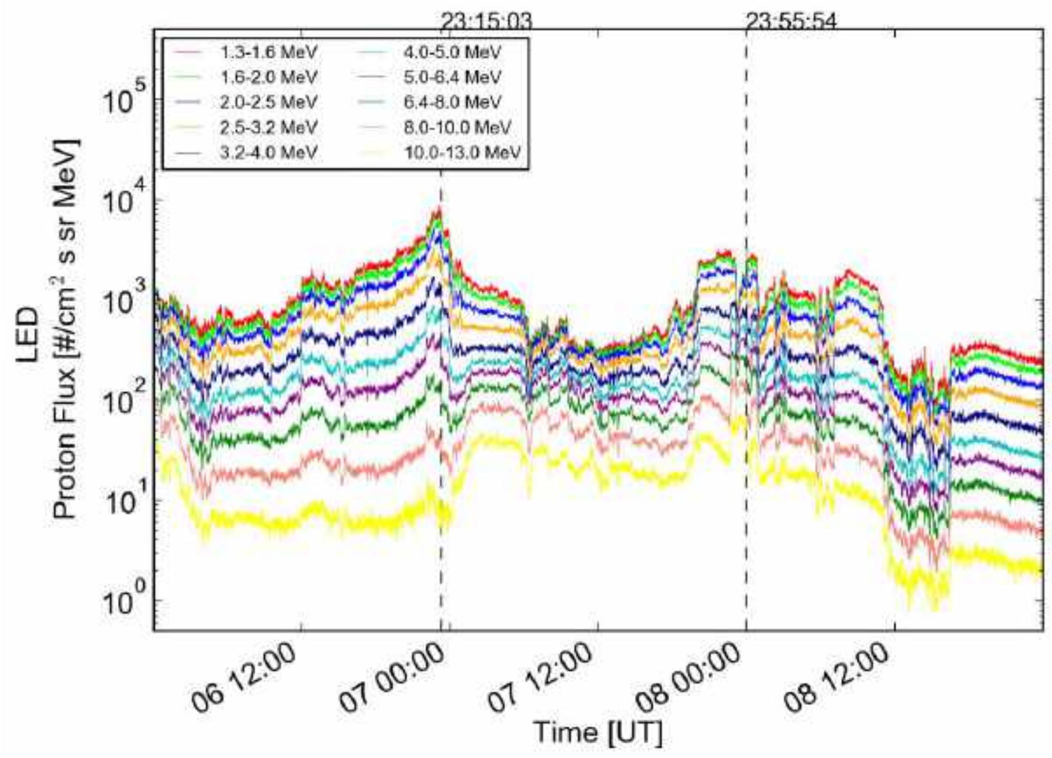


Figure 5 A typical GS reconstruction result in 3D view of an interplanetary magnetic flux rope. The flux function values at the center and boundary of the flux rope are marked A_m and A_b, respectively.

Interplanetary Space

- Derivation of properties of SEP and ESP events
- Modelling of the high energy SEP spectrum
- Comparison of the obtained SEP and ESP spectra with expectations of acceleration/transport models

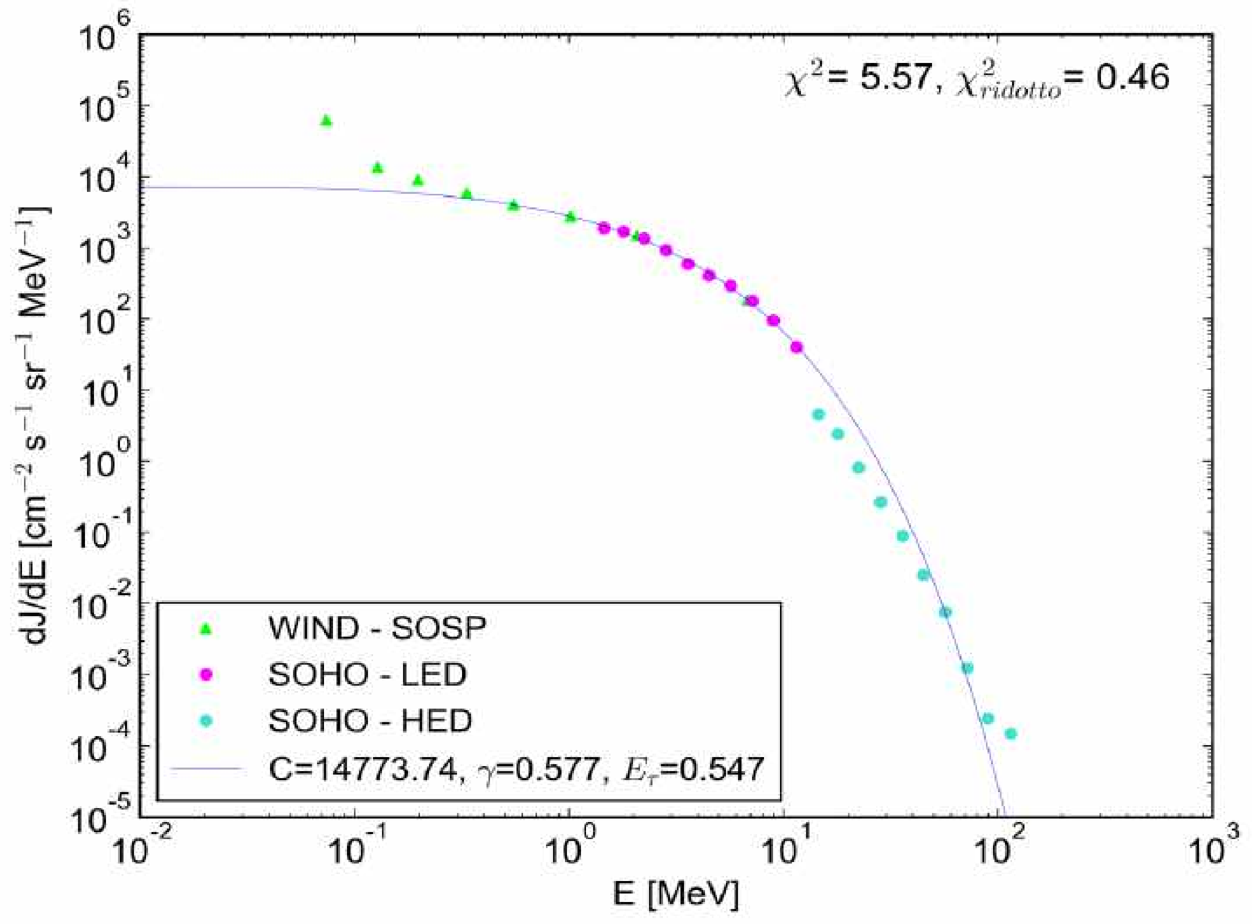




- Shock passages at L1: 6 Sept 23:02 UT and 7 Sept 22:28 UT

Interplanetary Space

7 September 2017 ESP spectrum



Shock parameters

$M_{ms} \cong 1.86$ $\vartheta_{Bn} \cong 57^\circ$

$\beta \cong 0.038$ $r \cong 2.5$

- Average differential flux calculated over three hours around the shock arrival
- Best-fit obtained with the Weibull function

$$\frac{dJ}{dE} = C\left(\frac{E}{E_\tau}\right)^{\gamma-1} E^{1/2} e^{-\left(\frac{E}{E_\tau}\right)^\gamma}$$

theoretically derived in the framework of stochastic acceleration

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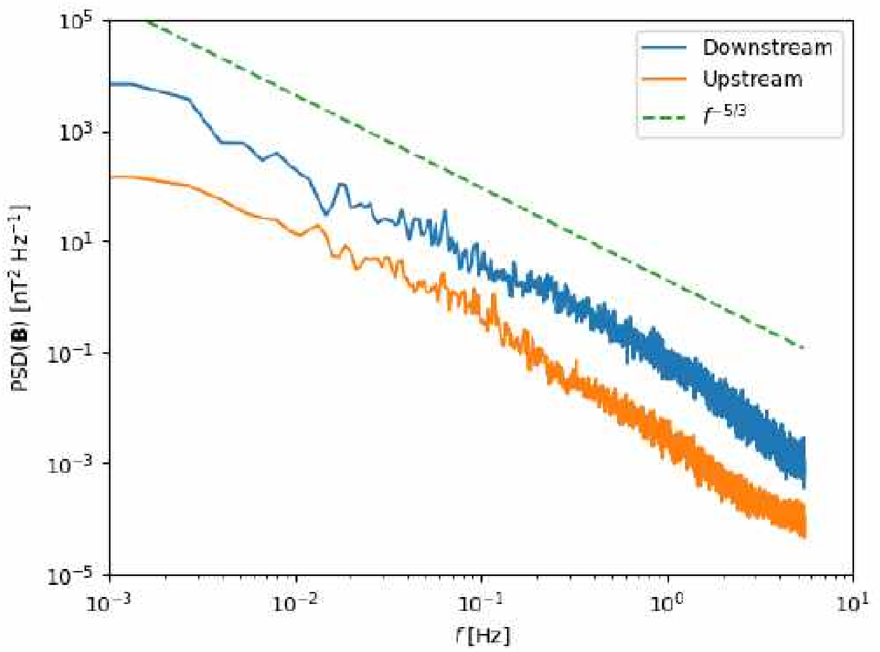
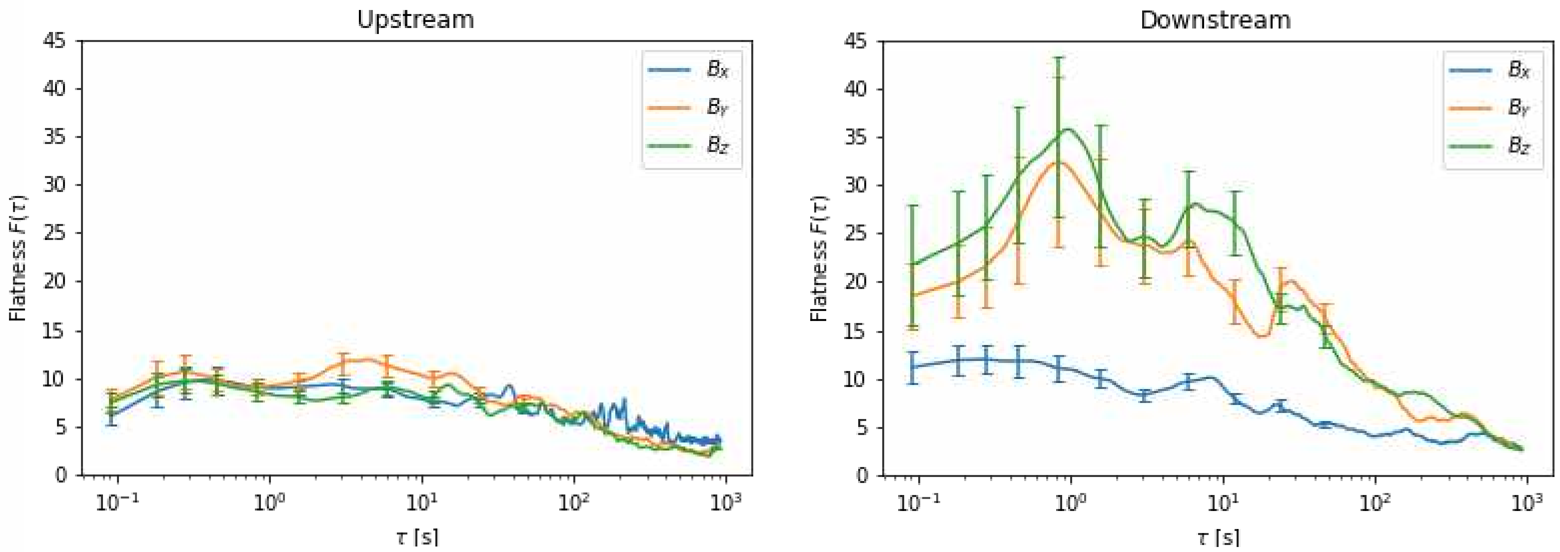
Interplanetary Space

7 September 2017 ESP related shock



PSD trace of the magnetic field upstream and downstream of the shock. Intervals with length 50 min (0.092 s resol.) were used, avoiding a 5 min interval around the shock. The $f^{-5/3}$ dashed line is shown as a reference.

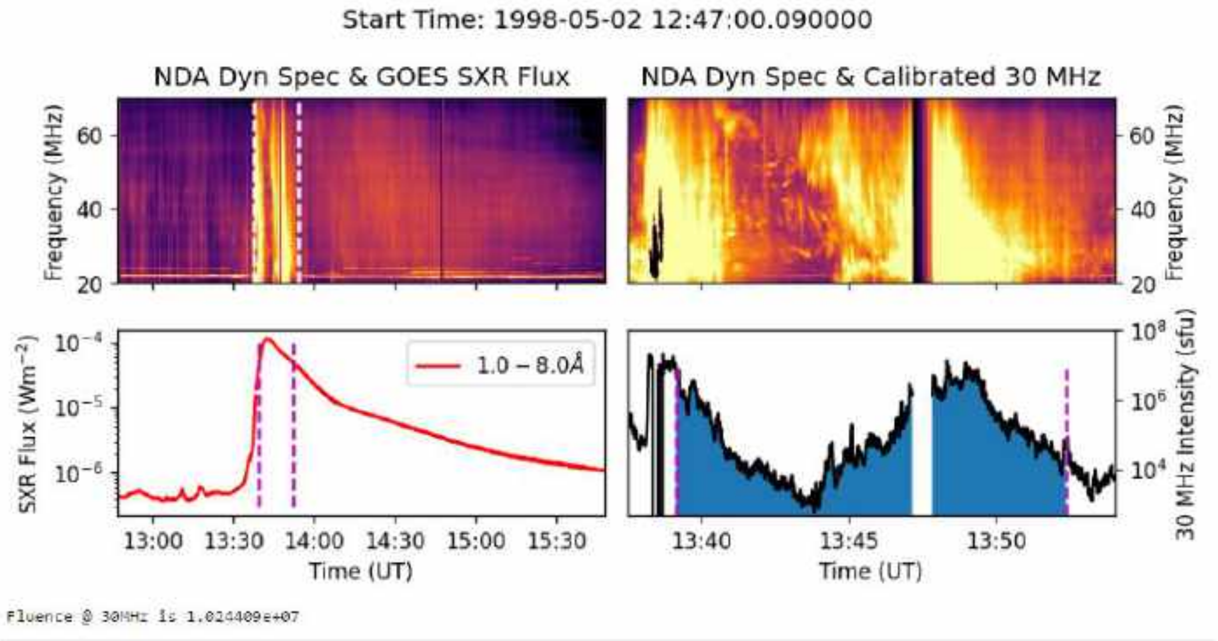


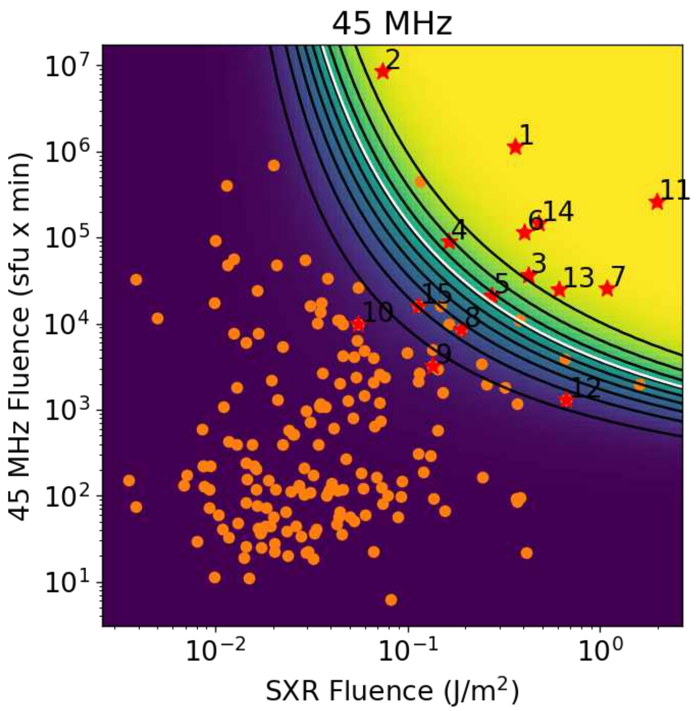
Flatness $F_i(\tau) = S^{(i)}{}_4(\tau) \;/\; [\, S^{(i)}{}_2(\tau)]^2$ (where $S^{(i)}{}_p(\tau)$ are the p-th order structure functions of the i-th component) of the increments of the magnetic field components (GSE system) upstream and downstream of the shock. Same intervals as for the PSD.

The downstream region is characterized by a higher level of magnetic fluctuations $\delta B/B_0$ (~0.25 vs ~0.13) and intermittency.

Interplanetary Space

Validation of the ESPERTA SEP forecasting model

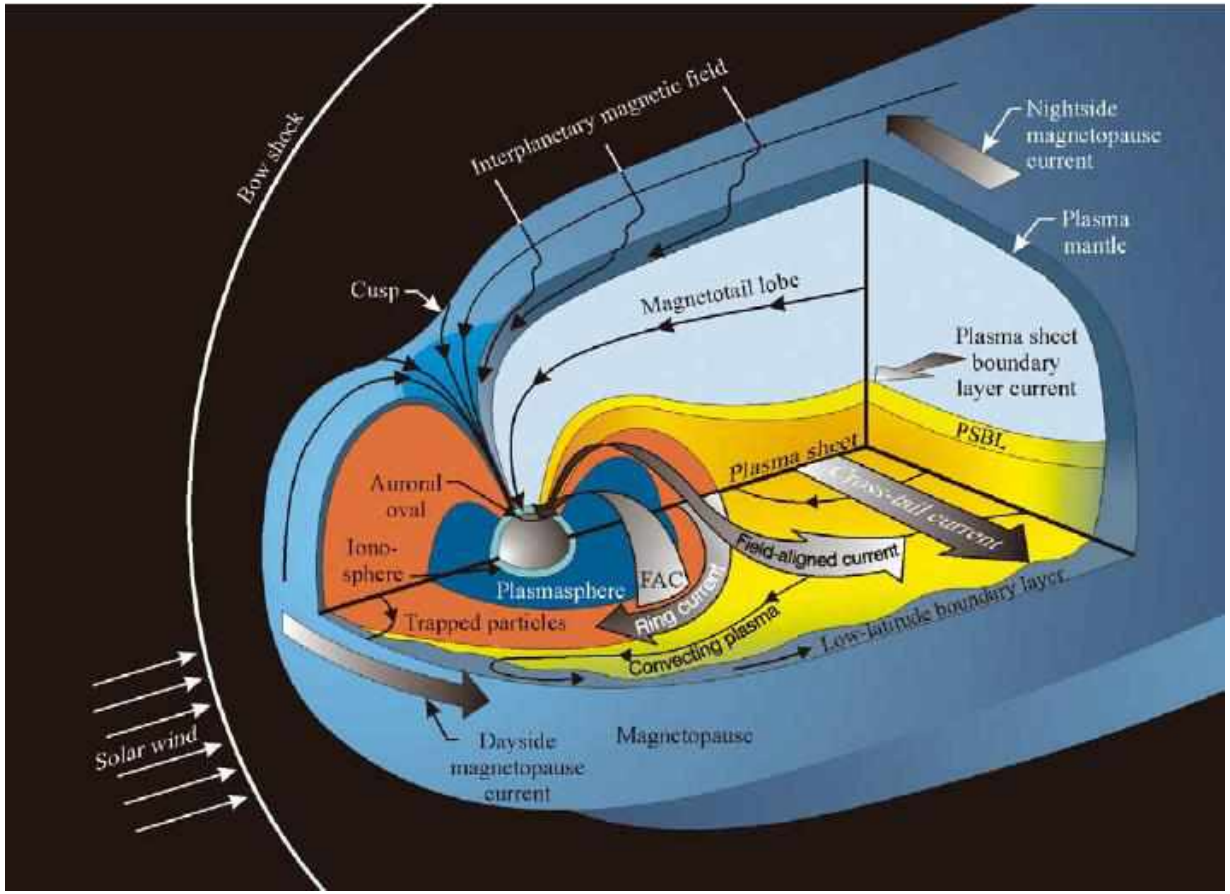




Validation of ESPERTA SEP probability based of X-ray and radio data (1MHz) to work with LOFAR data.
Such real time radio data may be added to provide alerts.

Solar Wind-Magnetosphere Coupling

The coordinated study of in situ plasma and fields measurements and of ground-based observations of geospace parameters are used to improve our knowledge of the magnetospheric response during SWE events with regard to the magnetosphere structure and dynamics within its different plasma regions, pervaded by large scale currents systems.



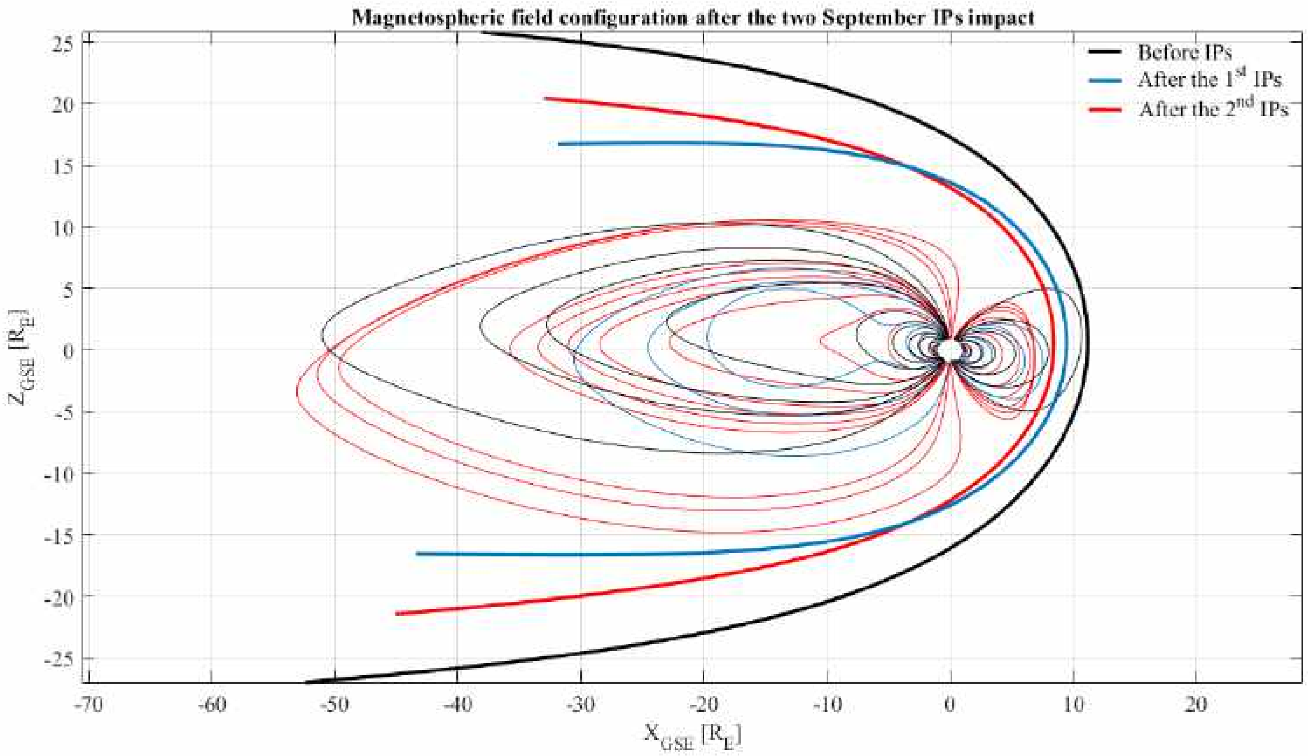
Solar Wind-Magnetosphere Coupling

- Analysis of CLUSTER, THEMIS and MMS plasma and magnetic field data in order to study the occurrence of reconnection at the magnetospheric boundaries

- Characterization of the energy and plasma transfer from the solar wind into the magnetosphere

- Modelling of the magnetosheath parameters at the magnetospheric nose and flanks

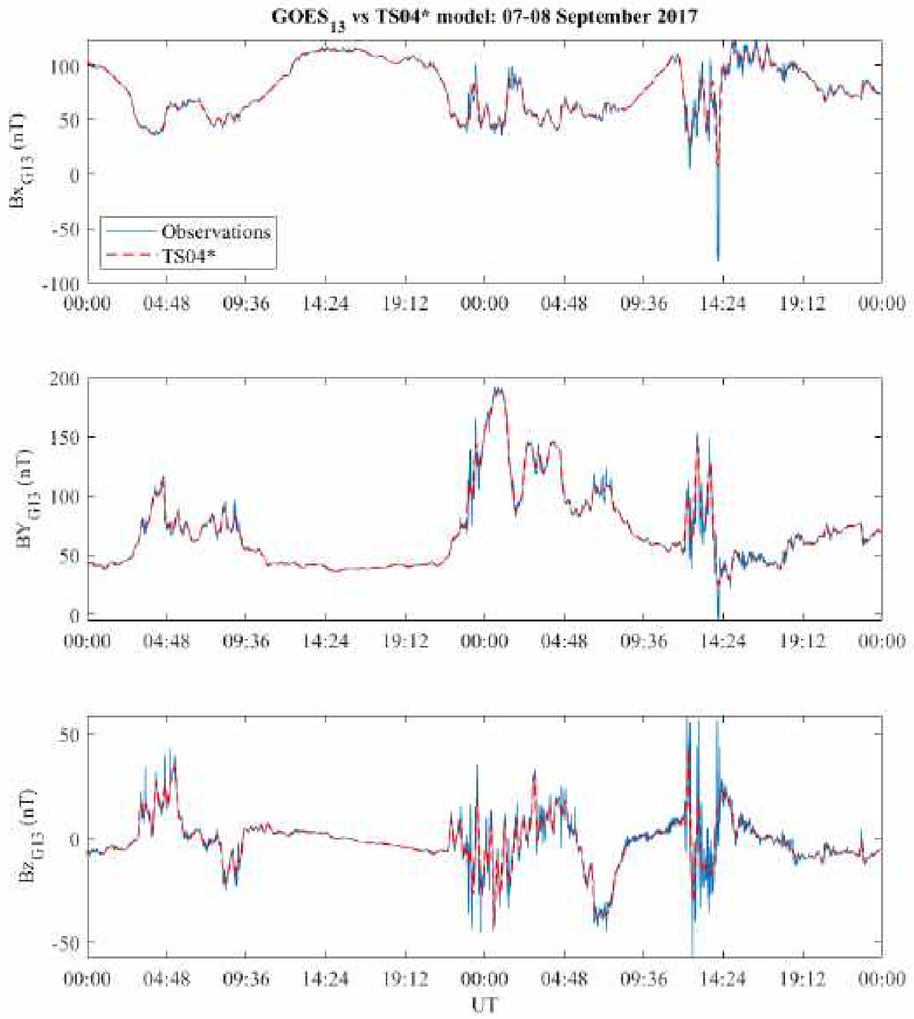
- Estimation of the magnetopause compression



Solar Wind-Magnetosphere Coupling

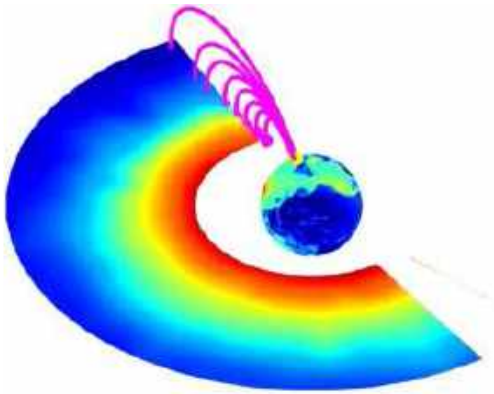
- Evaluation of magnetospheric current systems

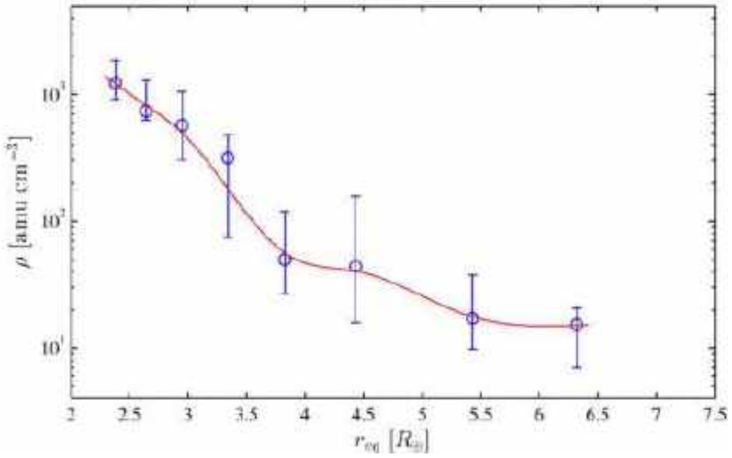
- Comparison between the model prediction and GOES satellites G13

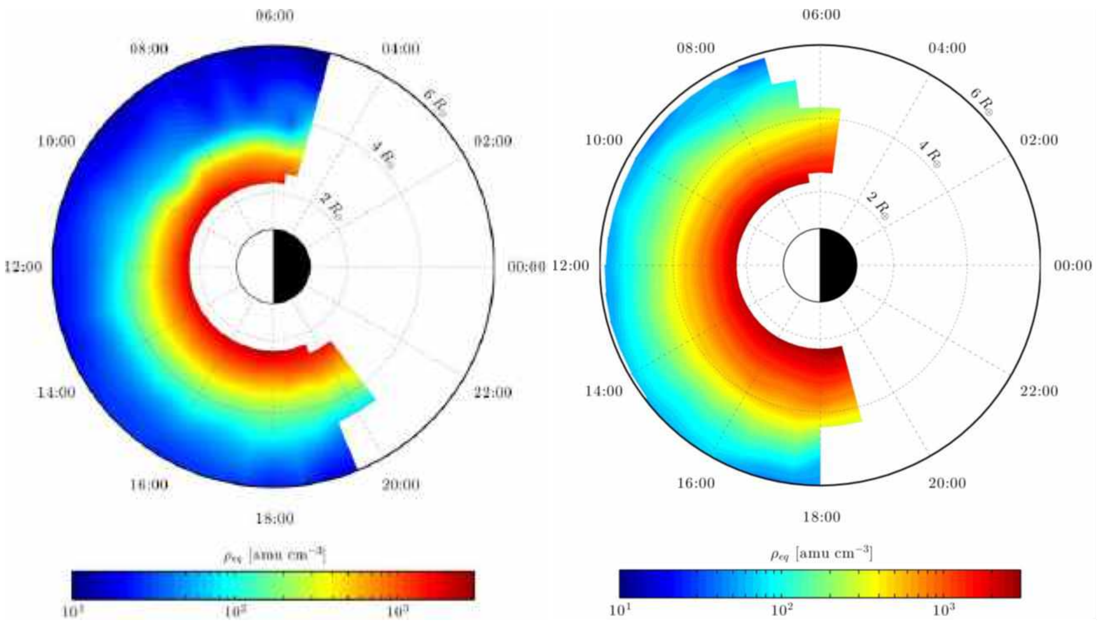


Solar Wind-Magnetosphere Coupling

- Estimation of near real-time values of the equatorial plasma mass density in the inner magnetosphere updated every 15 min.







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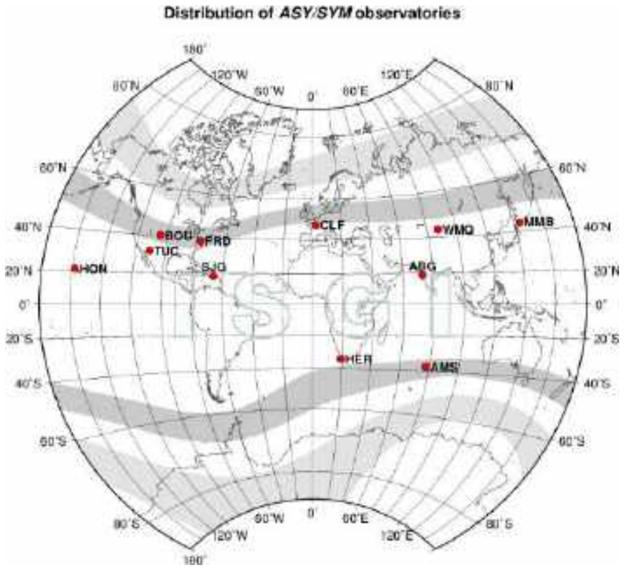
Solar Wind-Magnetosphere Coupling

Development of a model for predicting the Sym-H index one hour in advance

SYM-H index: derived as the Dst index with a higher resolution (1 minute)



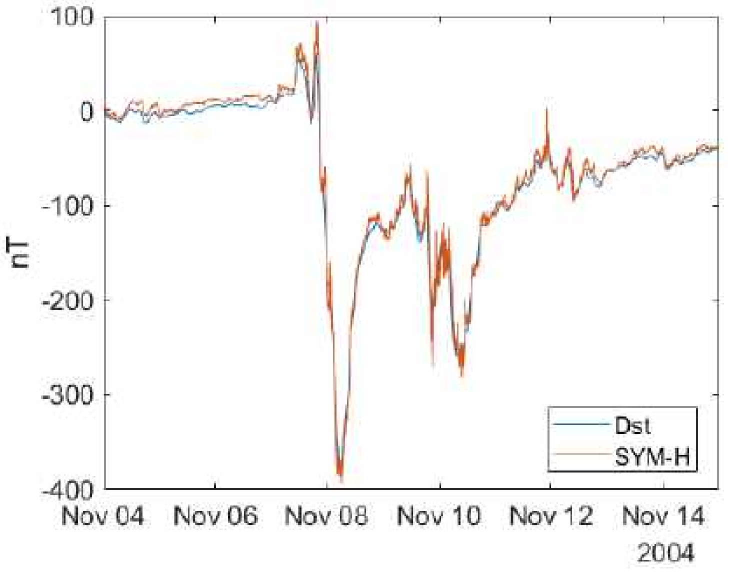
Adopted method: two different ANN

Long Short-Term Memory (LSTM)

- A type of Recurrent Neural Network
- Designed for sequence prediction problems

Convolutional Neural Network (CNN)

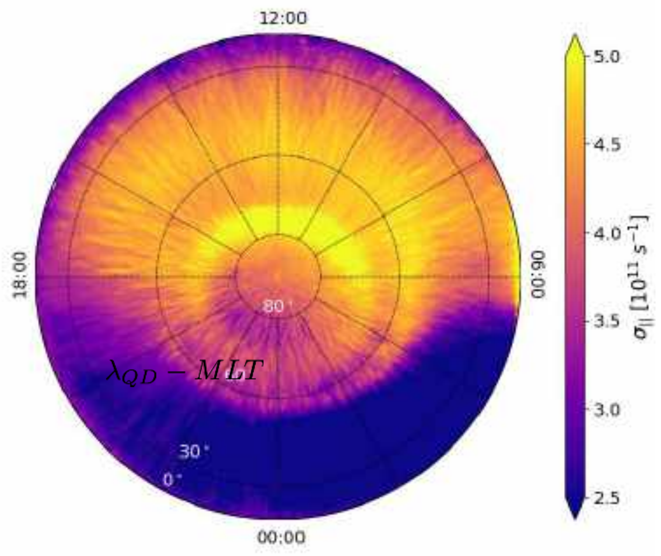
- Commonly applied to image analysis



Magnetosphere-Ionosphere Coupling

Magnetosphere-Ionosphere coupling is at the base of many phenomena relevant to Space Weather, as it drives the exchange of energy and momentum and crucially contributes to the energy budget of the ionosphere.

- Characterisation of the physical state of the topside (electron density and temperature, vector magnetic field and electrical conductivity) by using in situ measurements from the Swarm and Limadou/CSES missions



- The observed physical parameters can be studied in dependence on seasonal variations and at different solar and geomagnetic activity conditions
- Example of parallel electrical conductivity during disturbed (AE > 150 nT) conditions

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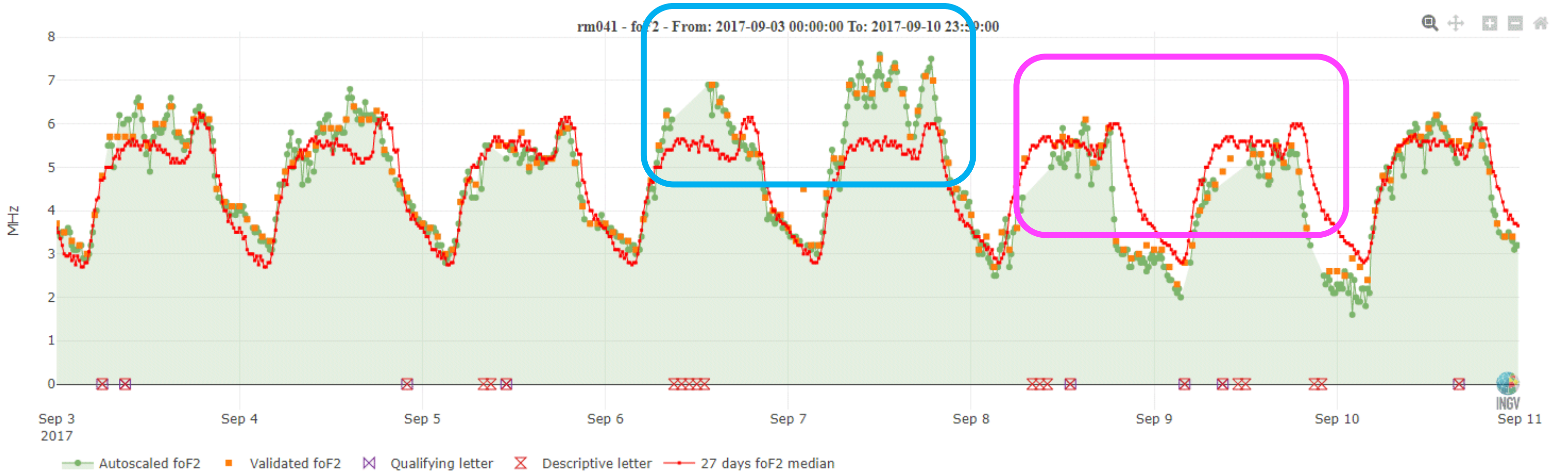
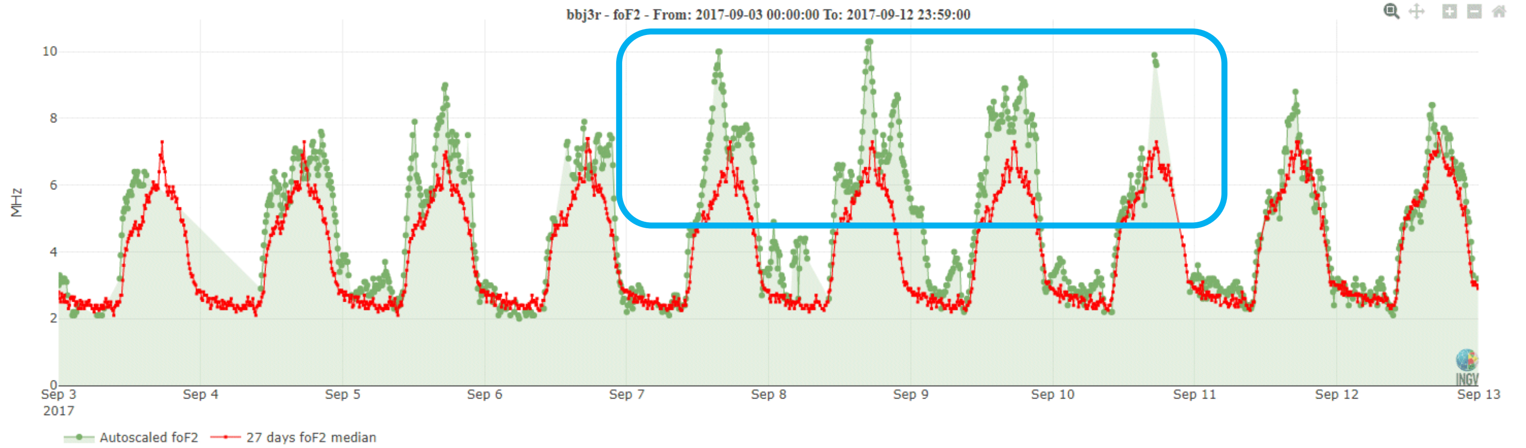
Magnetosphere-Ionosphere Coupling





http://www.eswua.ingv.it

Ionosonde observations

Rome

- Positive ionospheric storm on 6th and 7th September
- Negative ionospheric storm on 8th and 9th September

Bahia Blanca (ARG)

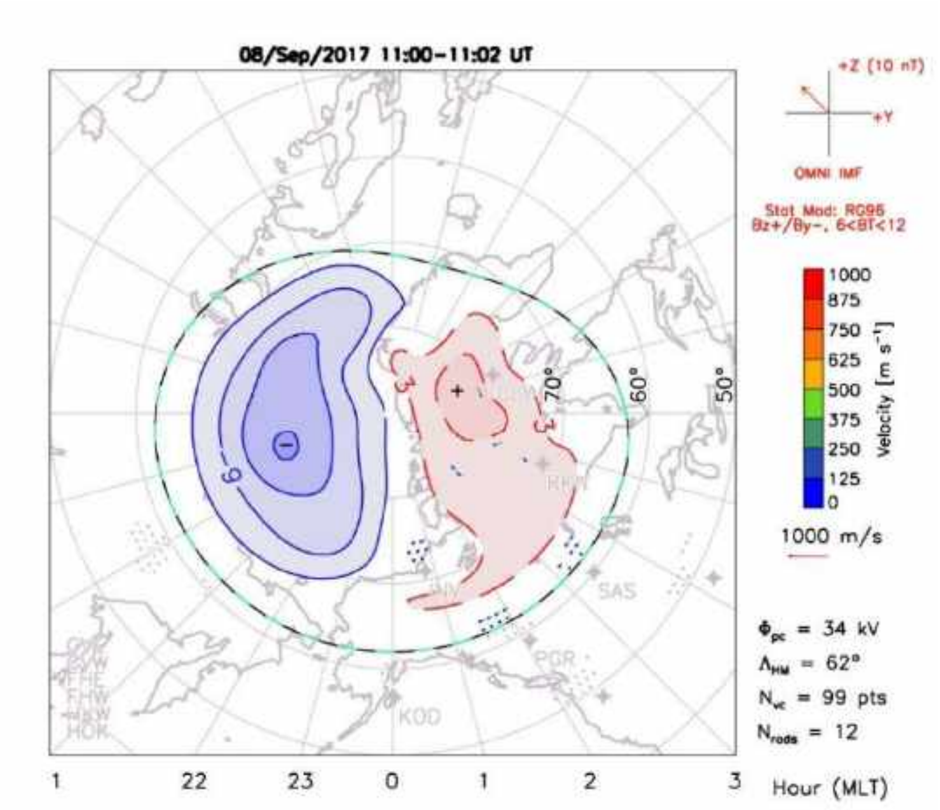
- Positive ionospheric storm from 7th to 10th September

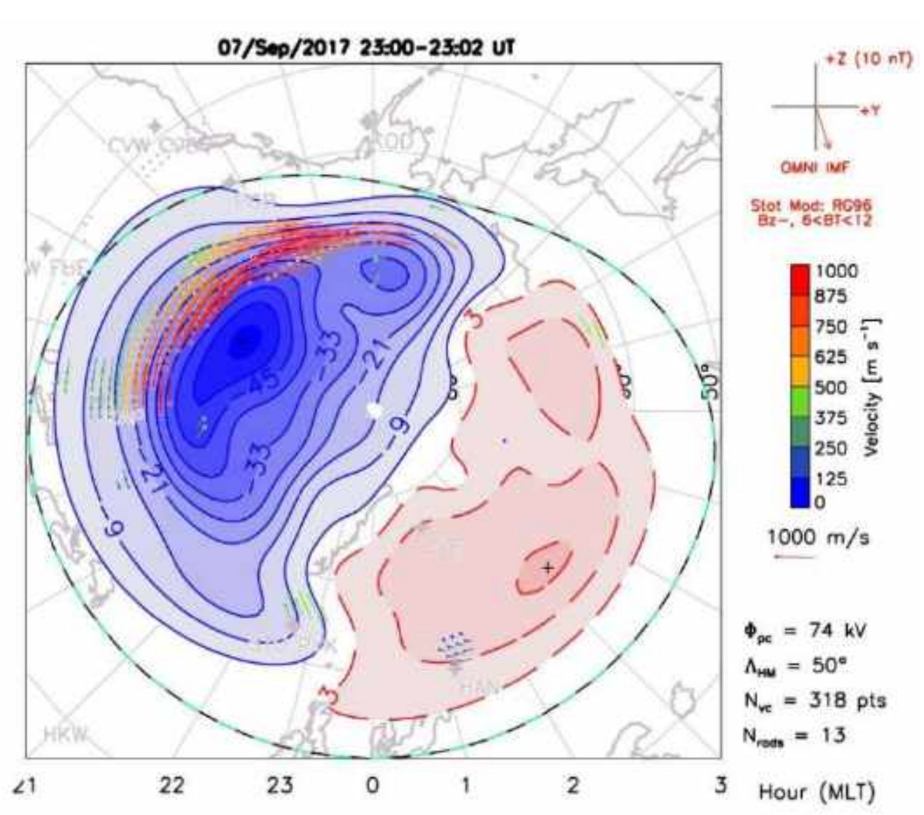
↓

Dependence of ionospheric plasma dynamics on solar and geomagnetic **activity**, latitude and **longitude**

Magnetosphere-Ionosphere Coupling

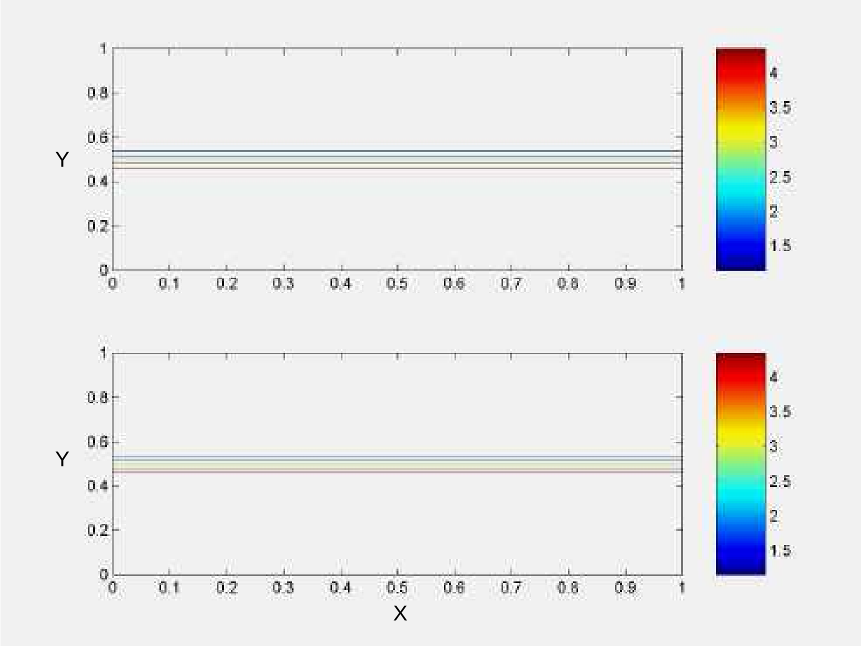
Reconstruction of the large-scale convection pattern of ionospheric plasma and the cross polar cap potential by using radar measurements from the SuperDARN network



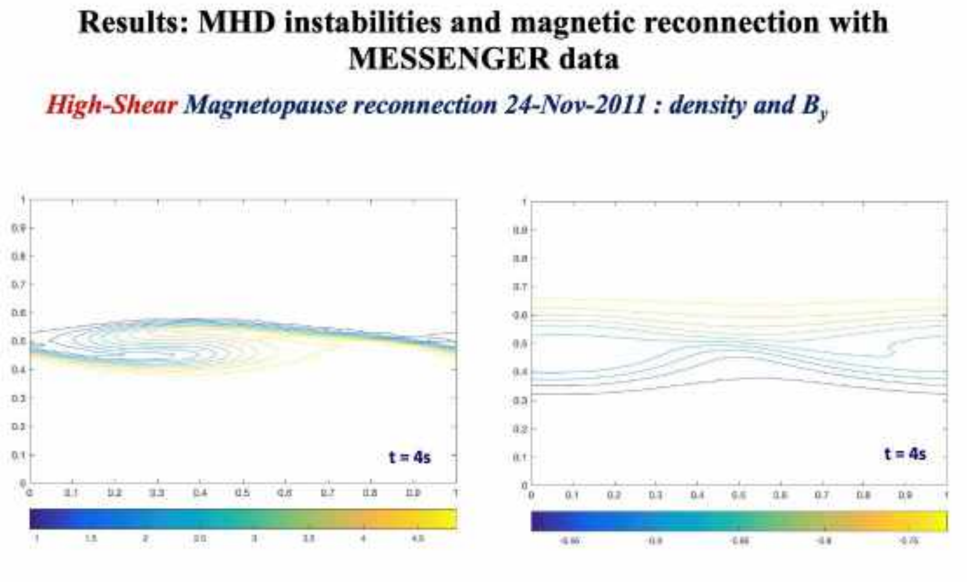


Planetary Space Weather

MAGNETOSPHERIC SIMULATIONS: The Magnetospheric Instability Model (MIM) is utilized for studying observed asymmetries and generally the coupling between external and internal layers after the impact of SWE events. MIM runs for different solar wind parameters (velocity, density and IMF) to study KH and TM instabilities. Earth's and Mercury's magnetopause will be investigated for the target SWE events.



Earth's case



Mercury's case

Comparison between cases with different velocity on the boundary (for developed instability of the density) for period of time *t=9*. In case A - $V^{sh}=0.5$, and in case B – $V^{sh}=1.0$.

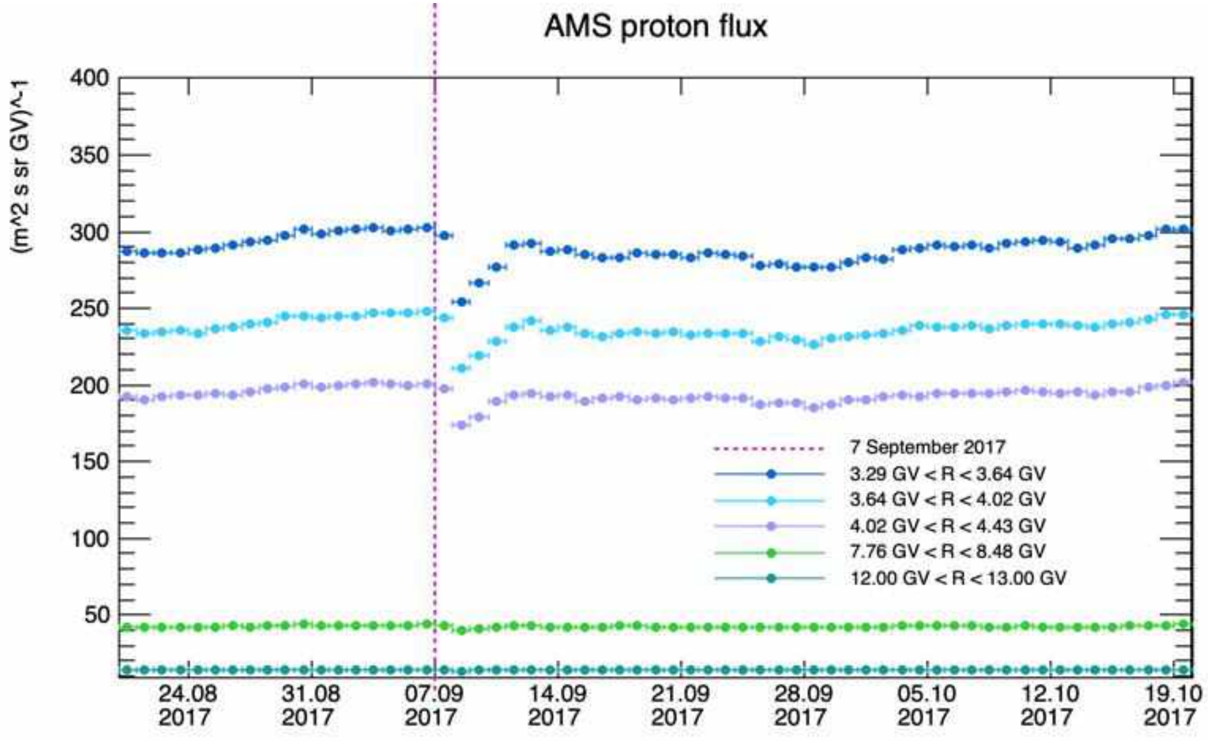
Galactic Cosmic Rays

GCRs are an important source of SWE and constitute a proxy of interplanetary perturbations in the whole Heliosphere.

- Exploitation of data from space and ground-based missions (e.g., PAMELA, AMS, CSES, SolO NMs as Rome and Testa Grigia)

Phys. Rev. Lett. **127**, 271102 (2021)
The daily AMS proton fluxes for ix typical rigidity bins from 1.00 to 10.10 GV measured from May 20, 2011 to October 29, 2019

- Study of transient and recurrent GCR variations (e.g, Forbush Decreases, high speed streams associated depressions)



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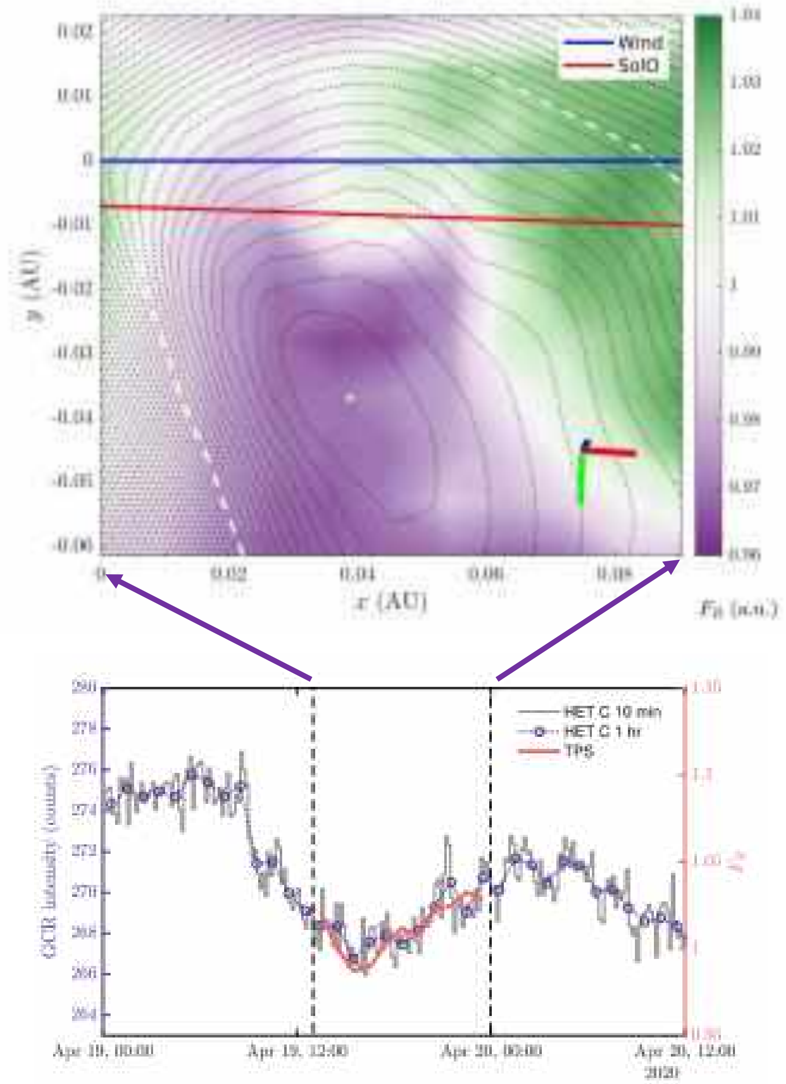
Galactic Cosmic Rays

FD observed on board Solar Orbiter on 2020 April 19

- Modeling of transient GCR depressions, Forbush decreases (FDs), due to the interaction with solar wind disturbances such as flux rope/magnetic cloud structures

Test-particle simulations on the background MC field, which consists of a GS reconstruction

- Full-orbit integration of the particle motion
- Computation of particle trajectories
- Energy dependence of FDs: comparison with space- and ground-based neutron monitor observations



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Space Weather Hazards

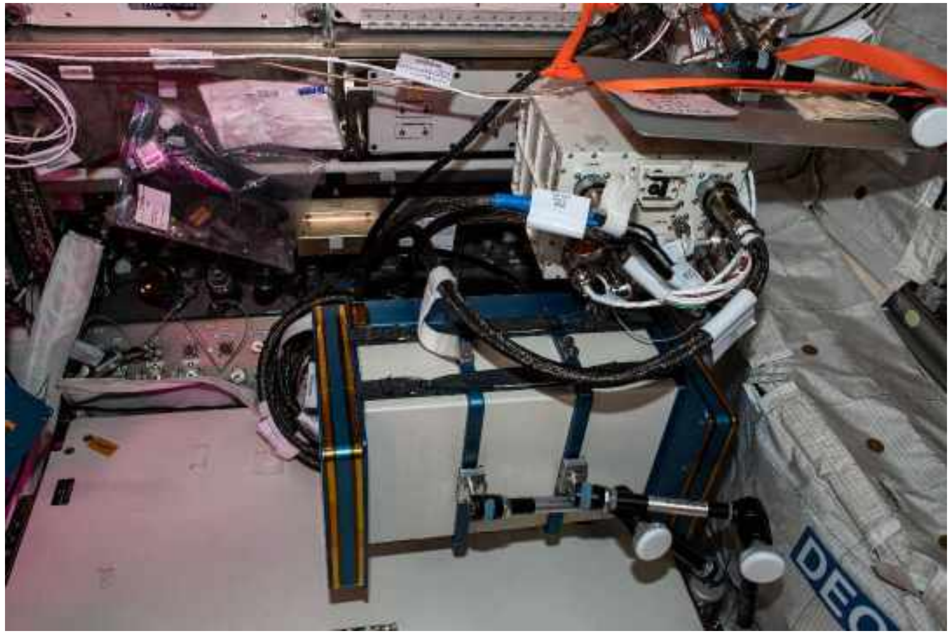
Assessment of the SWE hazards for technological systems and for the human body in space.

- characterise the SEP radiation environment onboard the ISS and derive radiation dose rates measuring charged particle fluxes.

LIDAL is operating on the ISS from January 19th 2019, in three different orientations inside the Columbus module.

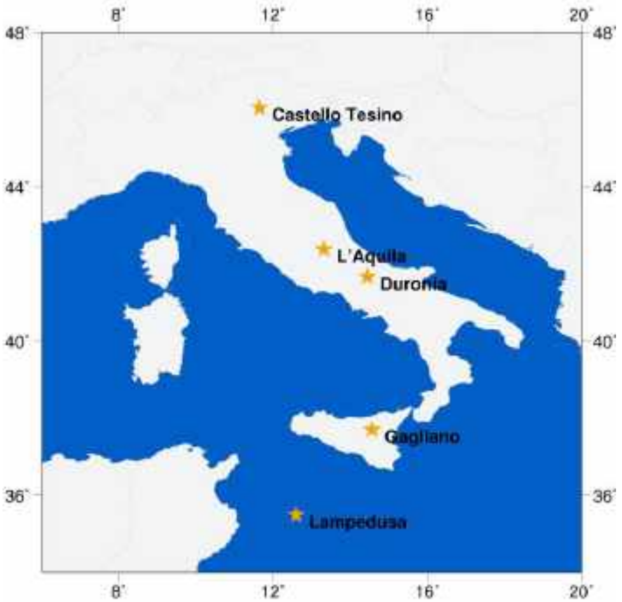
Retrieve and format data from the archives

LIDAL sends continuous data to the ground. A near real time analysis and visualization tool is under development.

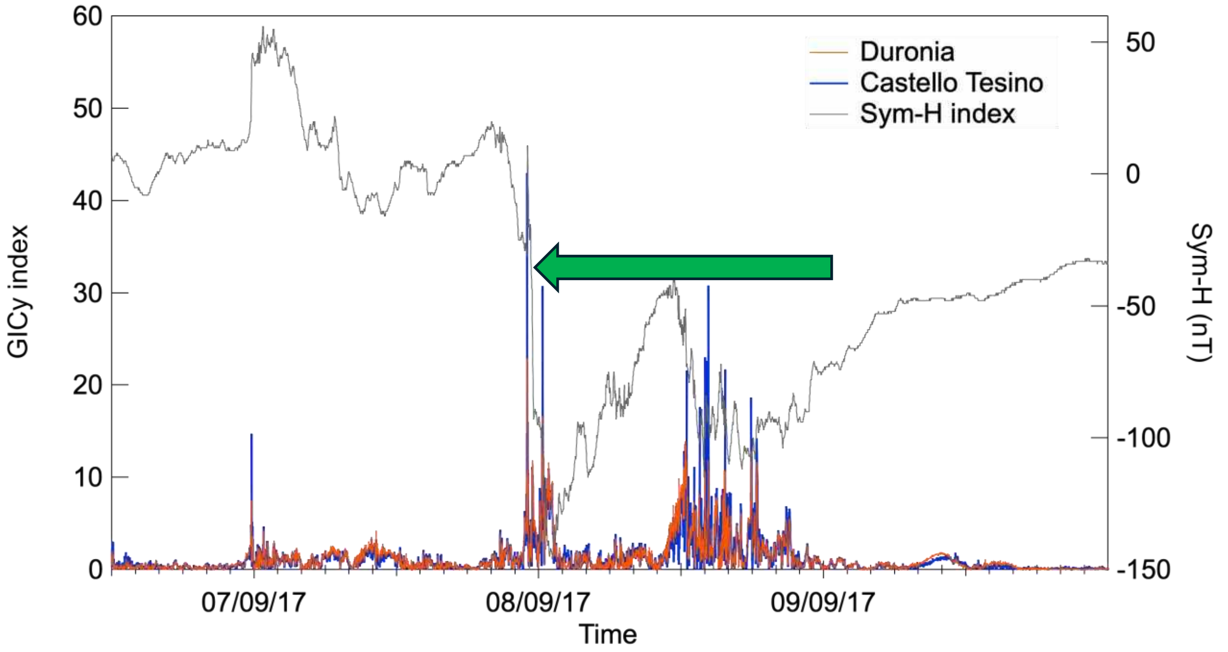


Space Weather Hazards

- Characterisation of the Geomagnetically Induced Currents (GICs) and loss of lock (LoL) events so to investigate the SWE impact on critical infrastructures as power grids and Global Navigation and Satellites Systems (GNSS), respectively



Risk	Probability
Extreme	>95%
High	65-95%
Moderate	35-65%
Low	5-35%
Very Low	<5%



Due to the moderate intensity of the magnetic storm that began on the 7th, maximum values reached by the GIC index correspond to the risk level "very low" at both observatories

ASPIS Prototype

- ASPIS Prototype will be deployed in ASI SSDC:
  - More than 100 products
  - Ready to ingest new additional product types
  - Real-time monitoring
  - Two differentiated access interfaces (Gui and ASPIS.py Module) to ease the use of the ASPIS products

ASPIS
ASI SPACE WEATHER INFRASTRUCTURE

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