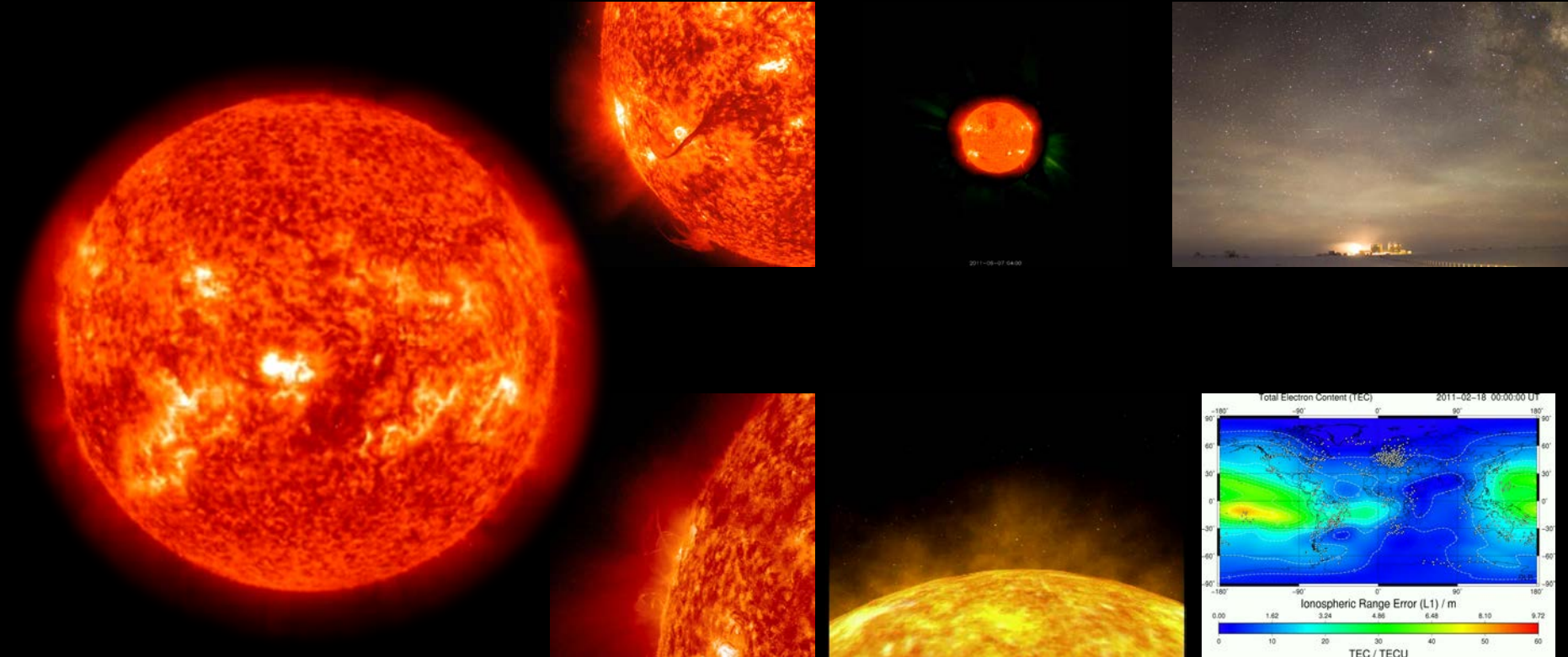


# ESA SSA Space Weather Network

Juha-Pekka Luntama, Alexi Glover, Stefan Kraft  
ESA SSA Programme Office

# What is "Space Weather"?

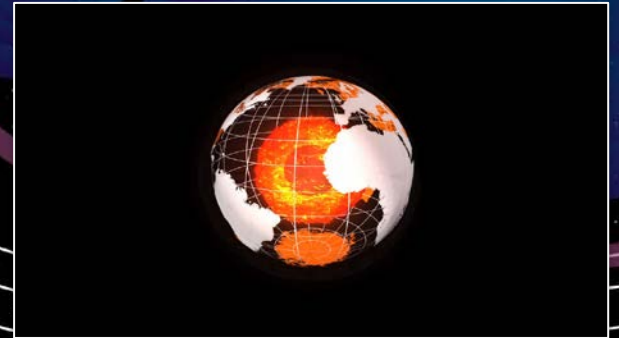


# Solar Wind

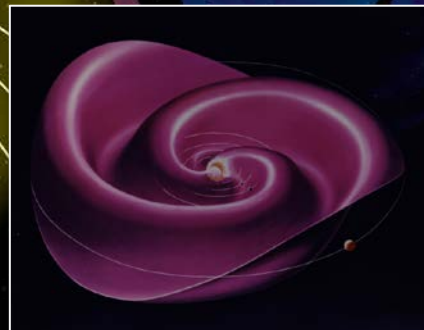
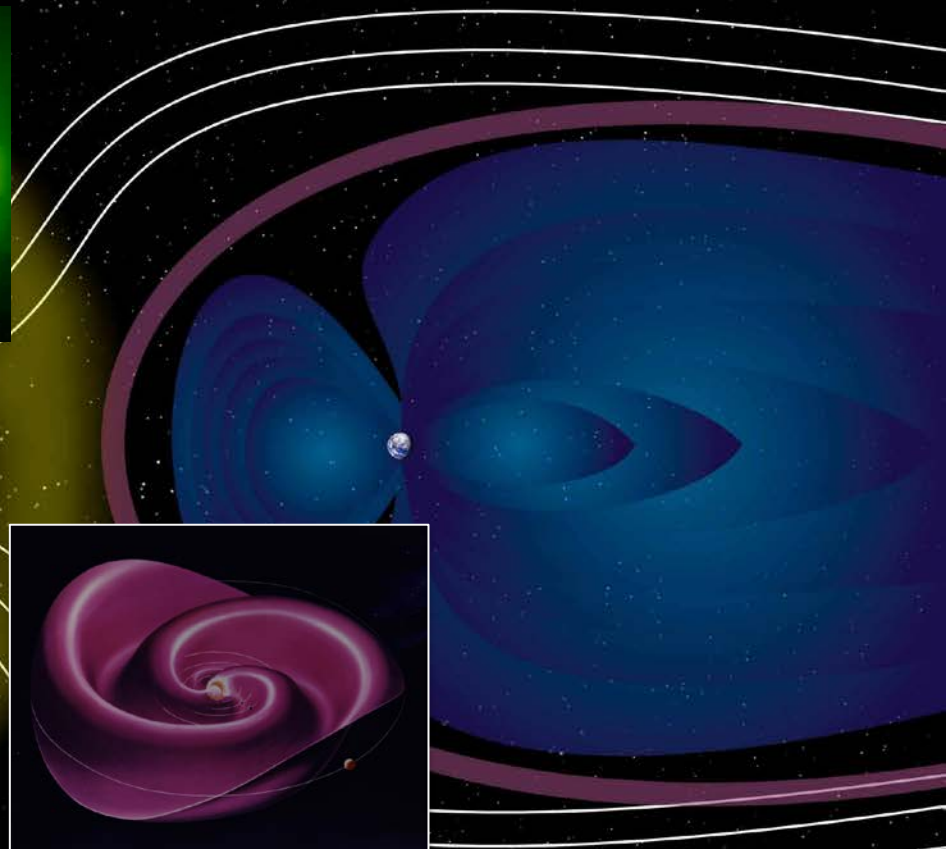
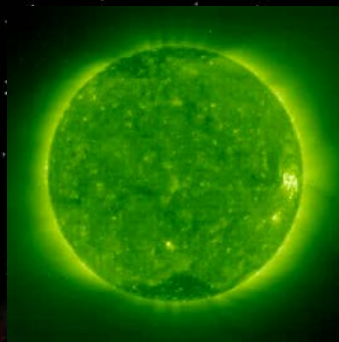
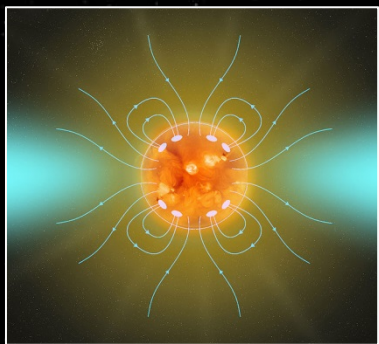
Solar Wind: constant emission of charged particles from the upper atmosphere of the Sun

Solar wind pressure shapes the magnetic field of the Earth: compressed day-side and tailed in the night side

Velocity of ambient, slow solar wind is around 400 km/s



# Interplanetary Magnetic Field (IMF)

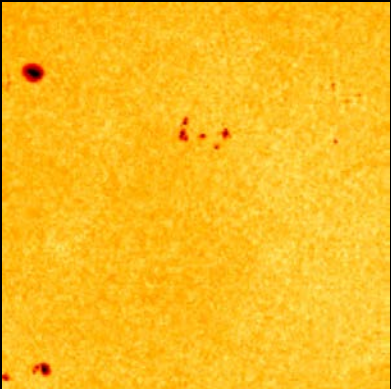
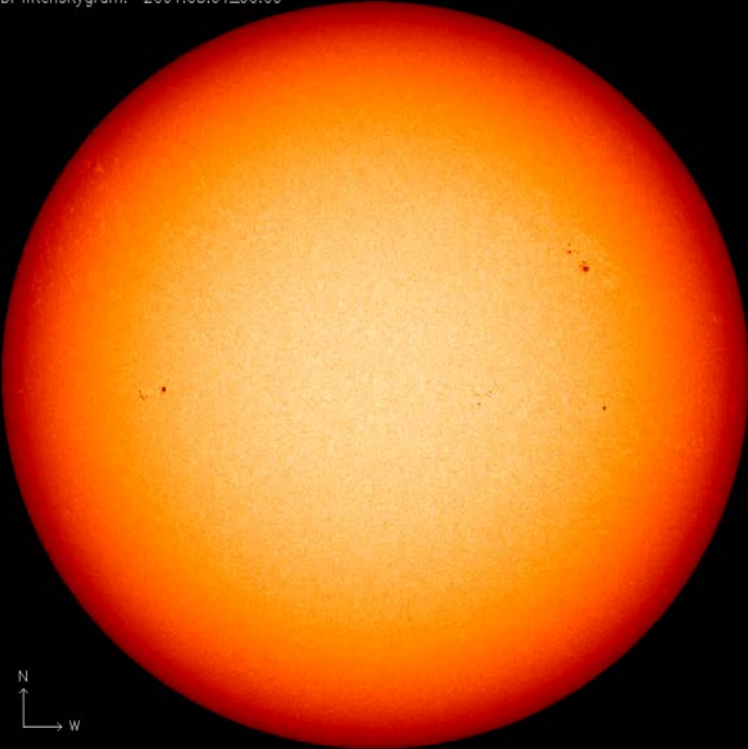


Fast solar wind from coronal holes can reach speeds over 800 km/s

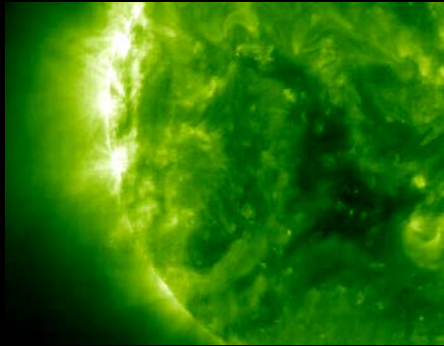
# Active Regions (Sunspots)



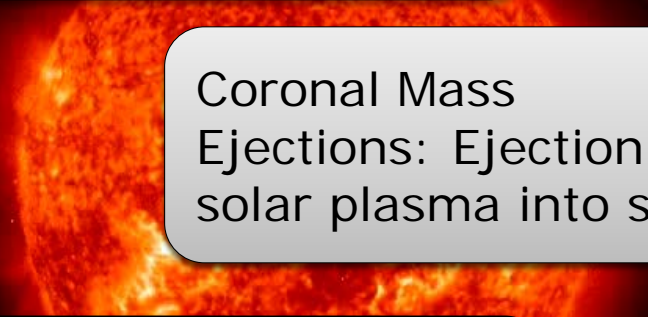
MDI Intensitygram: 2001.03.01\_00:00



# Solar activity from Active Regions



Solar flares: bursts of electromagnetic radiation



Coronal Mass Ejections: Ejection of solar plasma into space

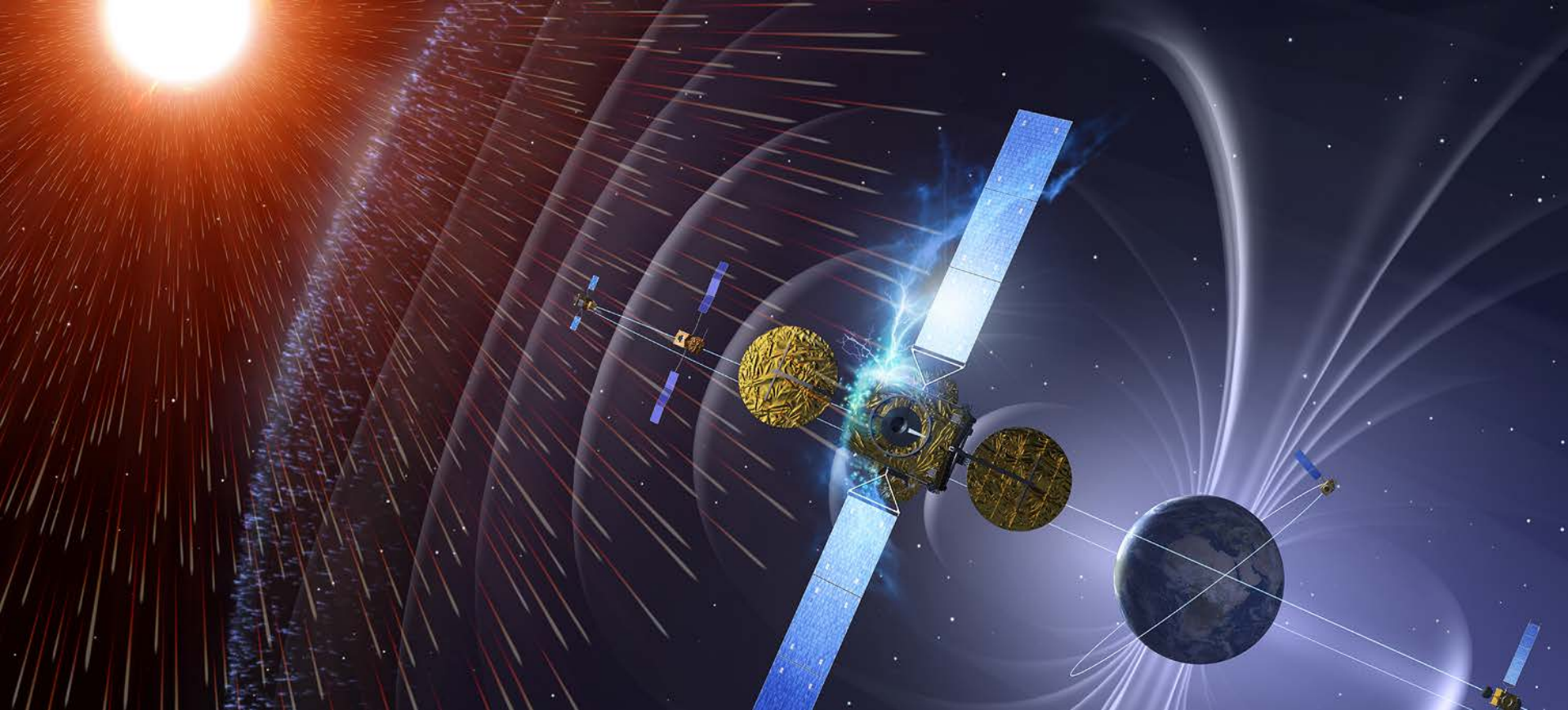


Solar Energetic Particles: protons and electrons accelerated to relativistic speeds

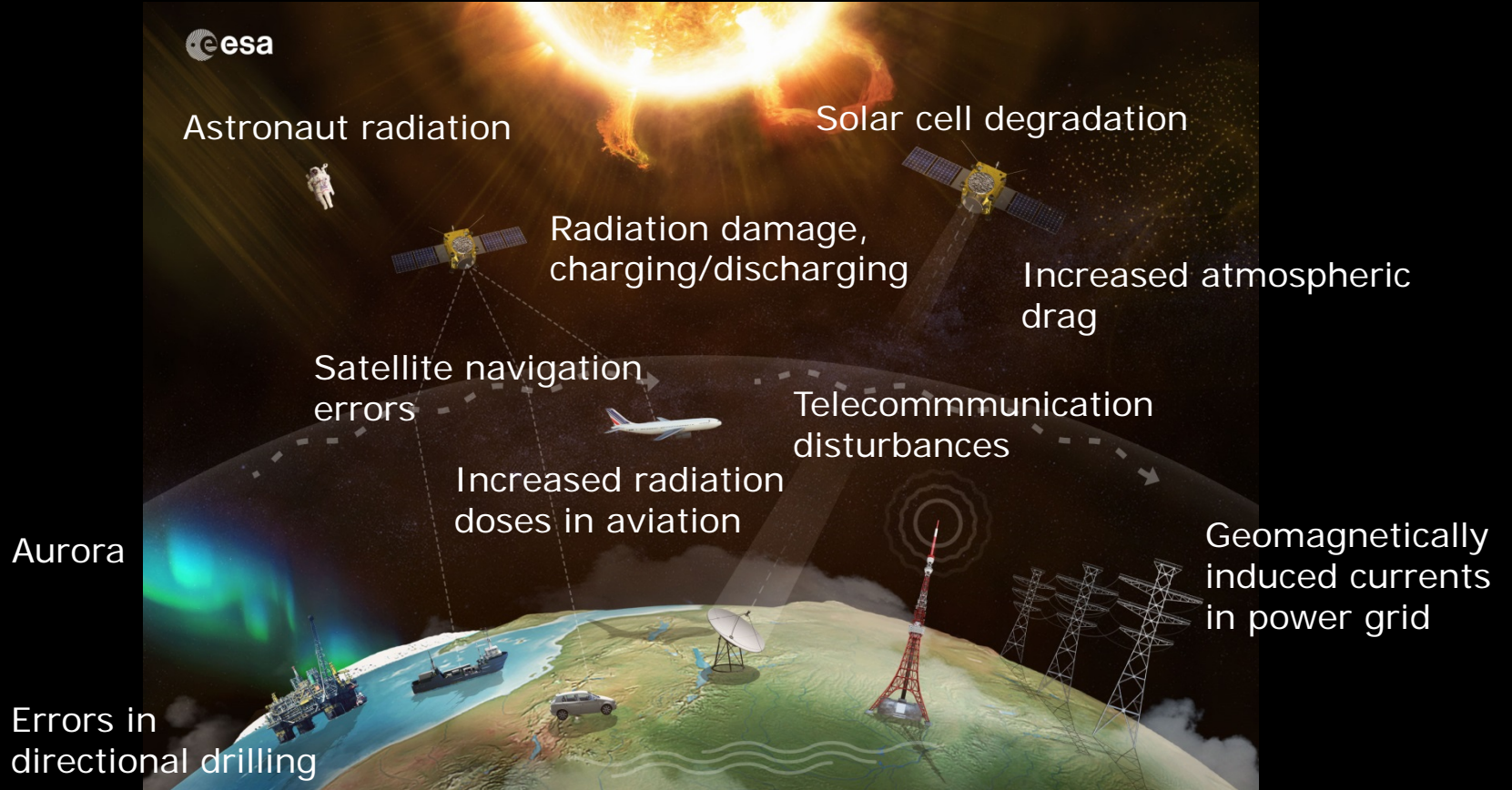
2003/05/26 00:00



# Why do we worry about space weather

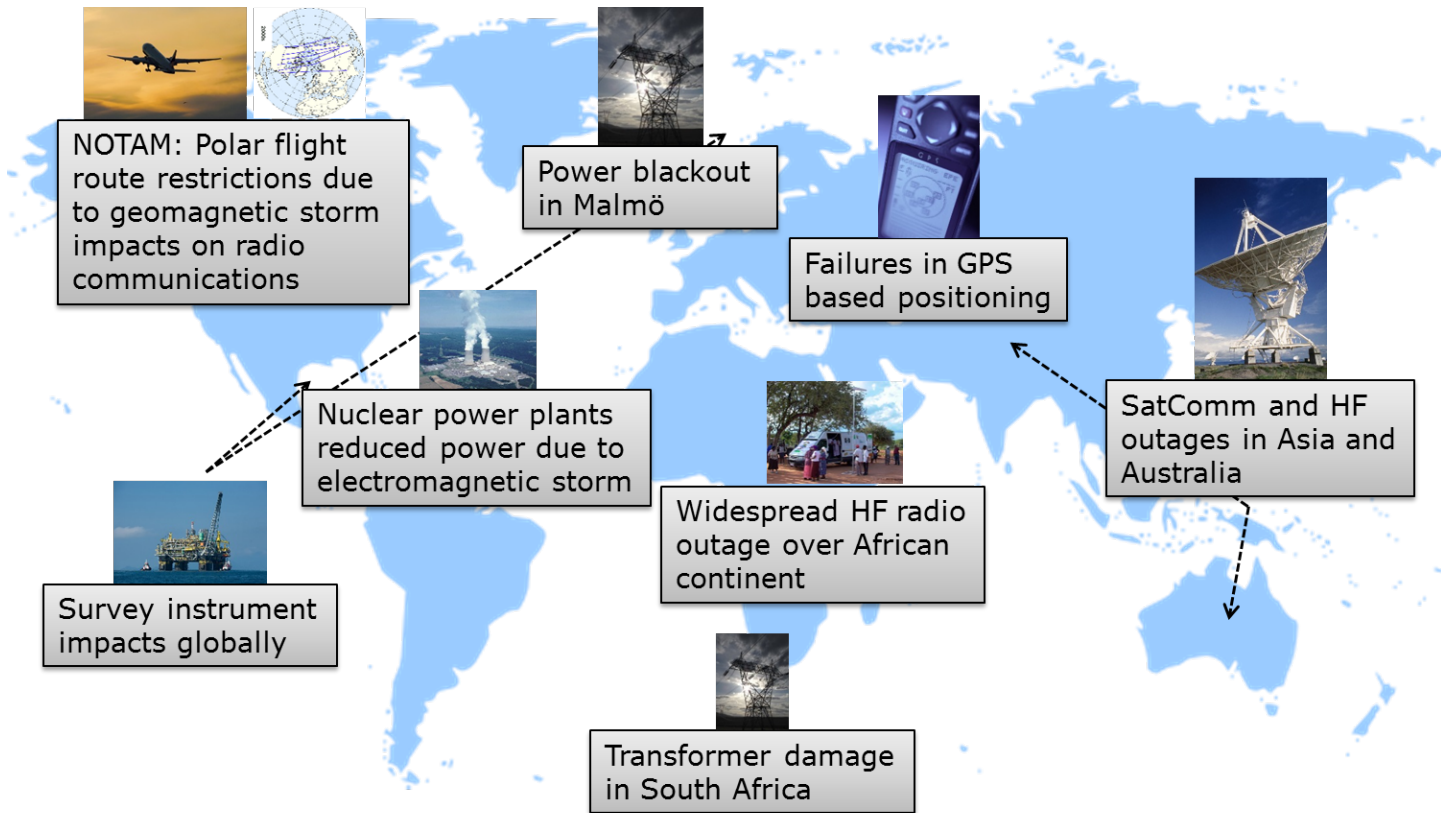


# Space Weather Hazards for Infrastructure





# Ground Effects of Space Weather during Halloween storm (Oct – Nov 2003)



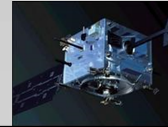
# Effects on Space Missions during the Halloween storm



Mars Odyssey mission:  
Safe mode during radiation storm.  
Memory error and loss of MARIE instrument



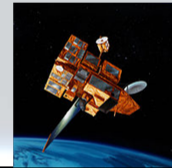
Mars Express star trackers blinded by particle radiation



Smart-1 spacecraft solar panels damaged



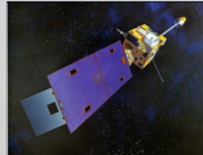
DMSP F16: SSIES sensor lost data twice, microwave sounder damaged



ADEOS-2  
Spacecraft lost



ACE: EPAM instrument permanently damaged



GOES-9, 10 and 12:  
High bit error rates (9,10),  
magnetic torquers disabled (12)



Multiple anomalies in GEO TV and Pay Radio satellites:  
Momentum wheels, CPU, service outages, ...

# Results of the CBA for the SWE segment

Cost/Benefit	Do nothing scenario	Do ESA scenario	Value added of ESA services
<b>User domain benefits</b>			
Satellite operations	- €293 M	- €267 M	€26 M
Launch operations	- €0.3 M	- €0.1 M	€0.2 M
Resource exploitation	- €327 M	- €135 M	€192 M
Power grids operations	- €5,771 M	- €4,546 M	€1,225 M
Aviation	- €3,312 M	- €3,066 M	€246 M
Logistic/Road transport	- €3,432 M	- €2,888 M	€544 M
<b>Investment benefits</b>			
GDP impact	None	€952 M	€952 M
<b>Total Benefits (b)</b>	- €13,135 M	-€9,950 M	<b>€3,185 M</b>
<b>Programme Costs (c)</b>	None	- €529 M	<b>- €529 M</b>
<b>Total Net Benefits</b>	- €13,135 M	- €10,479 M	<b>€ 2,656 M</b>
<b>Benefit / Cost ratio (b/c)</b>			<b>6</b>

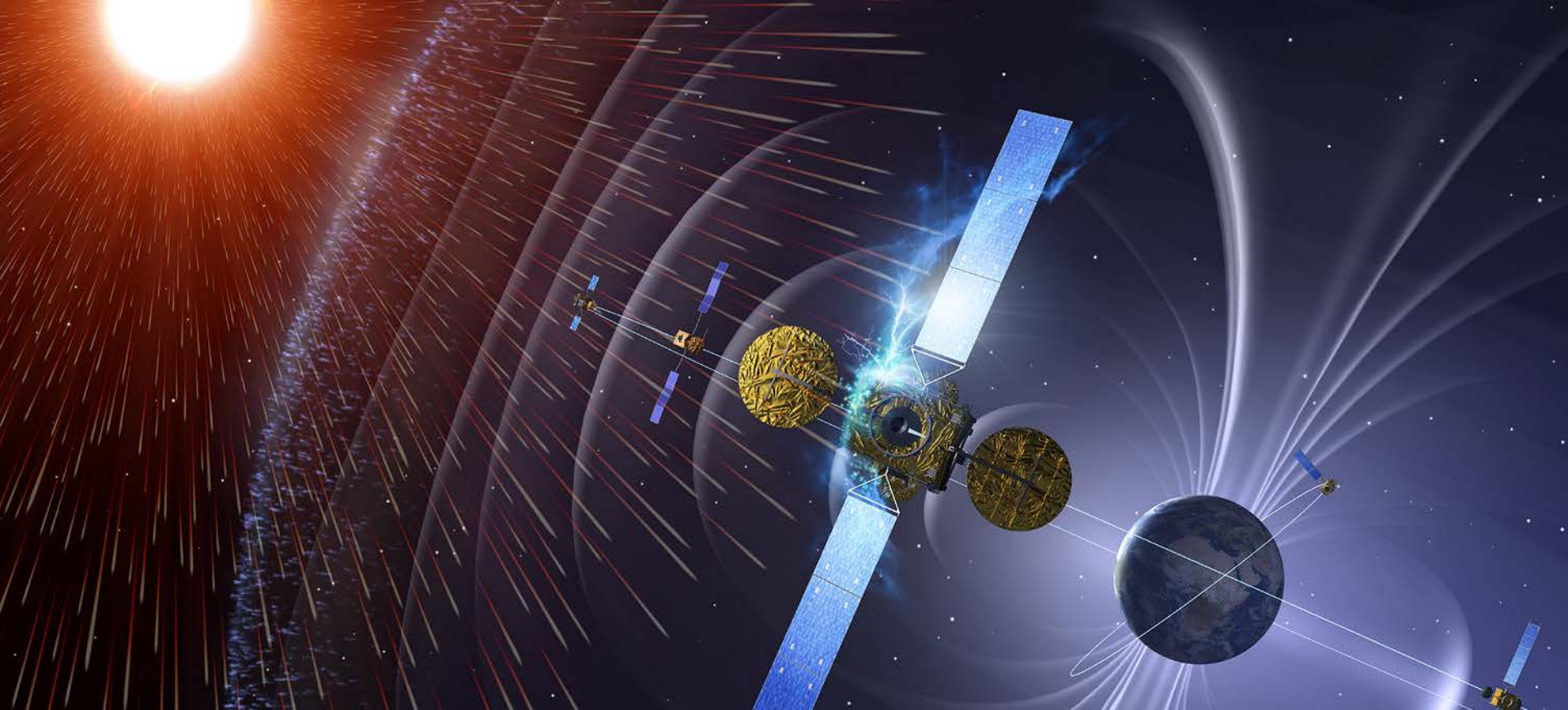
# Extreme SWE event impact estimates



Domain	2016 (year 1)	2024 (year 9)	2032 (year 17)
Spacecraft design and operations	- €912.9 M	- €1,123.2 M	- €1,389.4 M
Launch operations	- €0.008 M	- €0.037 M	- €0.051 M
Aviation	- €6,635.6 M	- €11,139.8 M	- €18,701.5 M
Resource exploitation	- €197.5 M	- €234.9 M	- €279.5 M
Power system operators	- €5,630.5 M	- €6,364 M	- €7,195.2 M
Road & Transportation	- €1,595.4 M	- €1,783 M	- €1,992.8 M
TOTAL	- €14,971.9 M	- €20,644.9 M	- €29,558.4 M
Estimated savings with ESA SSA SWE	2,500 M	3,500 M	5,000 M



# Protecting our Infrastructure



## Objective:

- Protection of space and ground assets against adverse effects from space

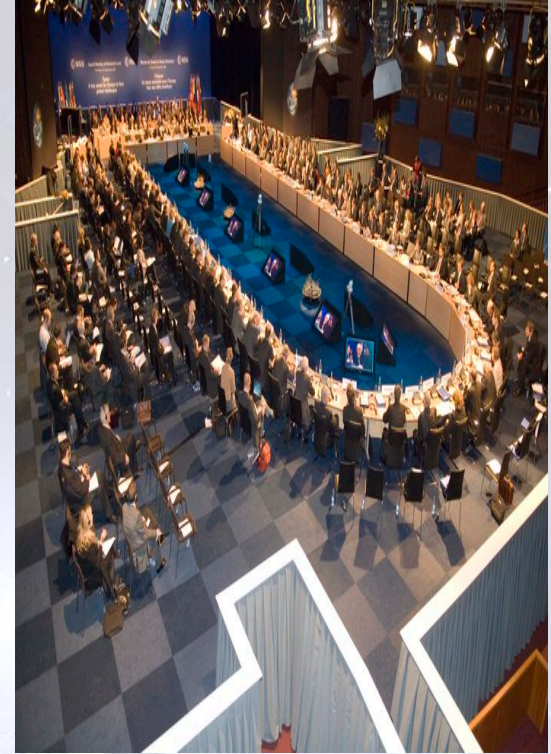
## Three main areas or segments:

- Space Weather (SWE)
- Near Earth Objects (NEO)
- Technology R&D for Space Surveillance and Tracking (SST)

**SSA Programme initiated in April 2008** (ESA Council, SSA Enabling Resolution)

## SSA Programme executed in Periods

- Period 1 decided at MC in November 2008 (Prep. Programme)
- Period 2 decided at MC12 in November 2012
- Period 3 decided in MC16 in December 2016



# Networking European Space Weather Expertise



## Data archives

- SSA SWE Data Centre (Redu)
- Federated data repositories

## SSA SWE Coordination Centre

- User Helpdesk
- Space Pole, Belgium

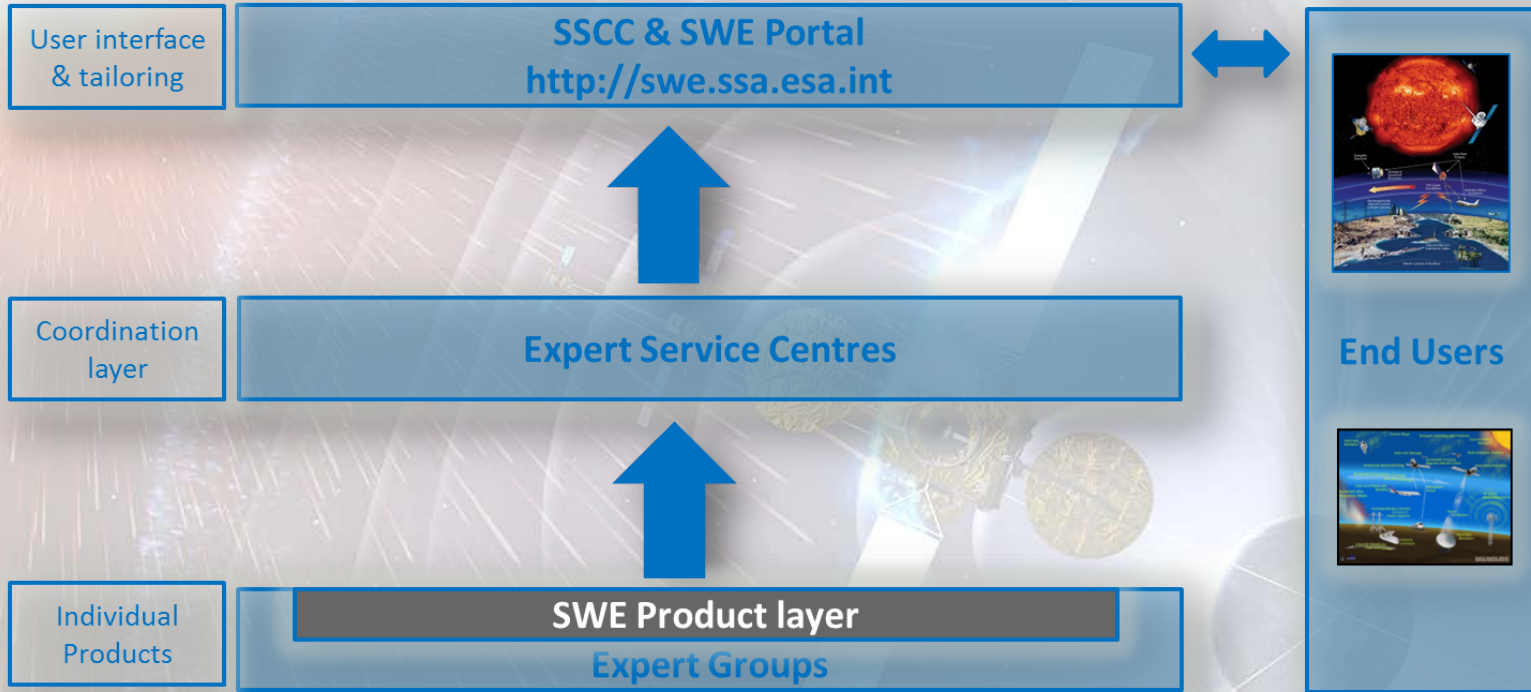
## SWE Expert Service Centres (ESCs)

<b>Solar Weather</b>	<b>Ionospheric Weather</b>	<b>Space Radiation</b>	<b>Geomagnetic Conditions</b>	<b>Heliospheric Weather</b>
European expert groups and centres of excellence				

## Sensor systems



# SWE Services Business Logic

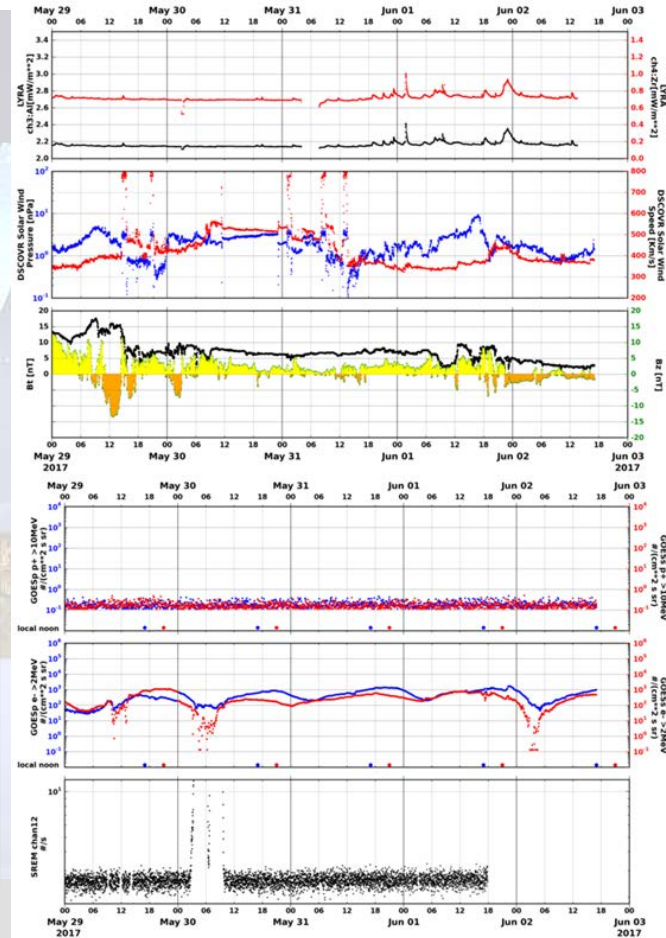
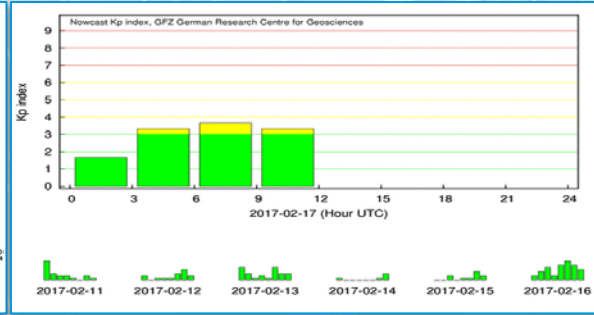
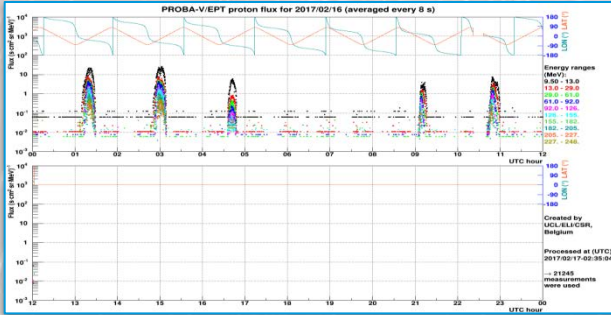




# SWE Service For Spacecraft Operators: In-orbit Environment and Effects Monitoring



- NRT estimate of space environment
- Effects experienced in spacecraft operations
- Geomagnetic storms, substorms, high-speed streams, solar energetic particle events & Earth-directed CMEs
- Training of mission operators
- New radiation environment forecast services under development => ESOC WS 14th June



# SWE Service For Spacecraft Operators: In-orbit Environment and Effects Monitoring




Met Office

Heliospheric Weather Expert Service Centre

Mercury Venus Earth Mars

## GEOMAGNETIC STORMS

Exceedance	Level	Past 24 h.	Day 1	Day 2	Day 3	Day 4
Minor or moderate	G1 to G2	No	10%	10%	5%	5%
Strong	G3	No	1%	1%	1%	1%
Severe	G4	No	1%	1%	1%	1%
Extreme	G5	No	1%	1%	1%	1%



### Alert Viewer

Current time: 02-06-2017 18:11

	Latest issued alert	Impact risk
Geomagnetic Storm Alert	No alert since 209 days	Nothing to report
SEP Proton Storm Alert > 10 MeV	No alert since 60 days	Nothing to report
SEP Proton Storm Alert > 60 MeV	No alert since 60 days	Nothing to report

Legend: ★ ... an alert has been issued  
 ...risk impact (timing and level, ● low, ● medium, ● high, ● extreme)

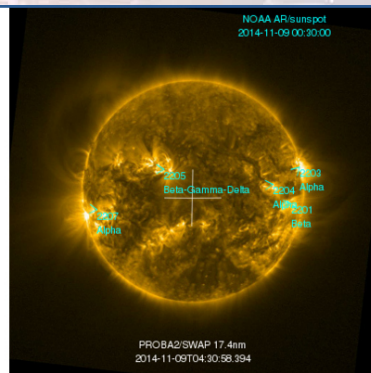
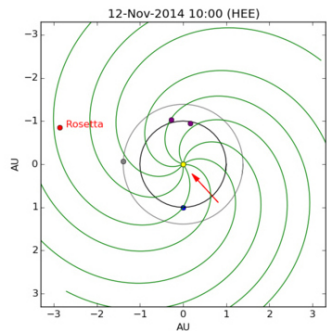
Click on the icons to see alert details

Mon 21 Dec 2015

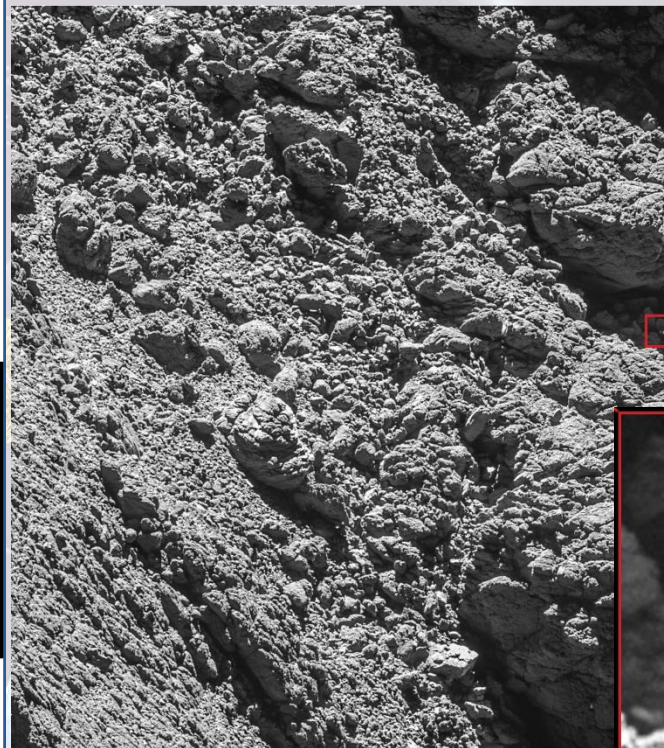
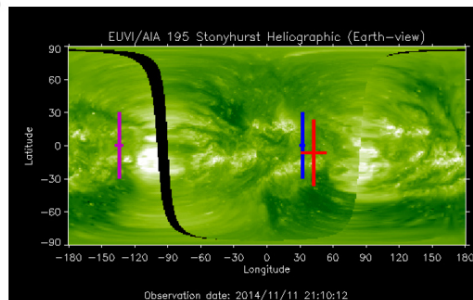
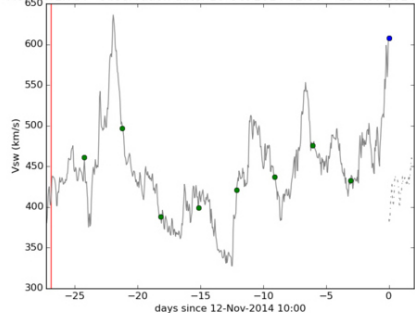
	18 DEC 12:00	19 DEC 12:00	20 DEC 12:00	21 DEC 12:00	22 DEC 12:00	23 DEC 12:00	24 DEC 12:00	25 DEC 12:00
Flare				★ ★ ★ ★ ★ ★	★ ★			
CME								
SEP				★ ★	★			
Geomagnetic activity				★			★	



# Tailored SWE Bulletins: Rosetta

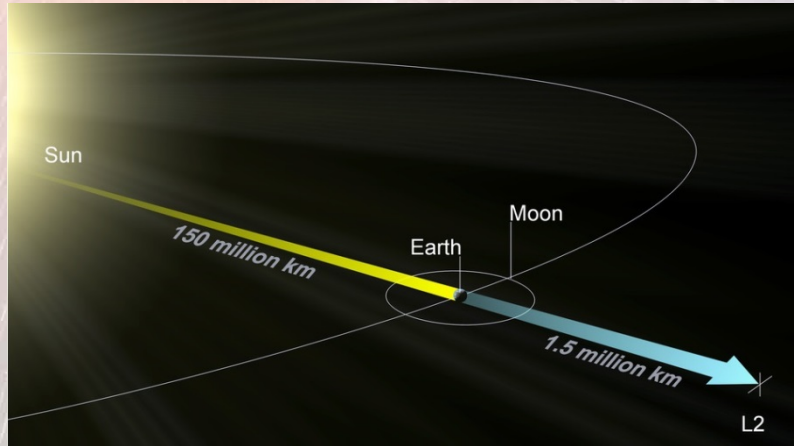


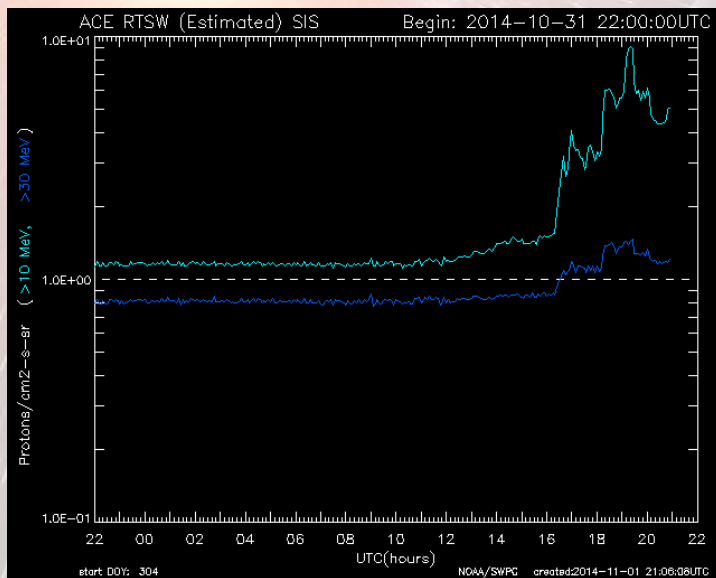
ACE/SWEPAM Observation date: 16-Oct-2014 02:00 -- 12-Nov-2014 10:00



Graphical overview of the solar and interplanetary conditions supporting the risk evaluation of high-energy proton events for the Rosetta mission, part of the tailored space weather bulletin provided by the SSA space weather service network.

# Tailored SWE Bulletins: GAIA





GAIA Flight Control Team,

An operator has replied to your support request, #605830 with the following response:

== Space Weather bulletin for GAIA spacecraft ==  
Extra bulletin prepared by Andy Devos (SSCC, SIDC forecaster) on November 1, 2014 at 21:30 UTC  
Valid until November 3, 2014 at 21:30 UTC

== Past hours ==

Earth and GAIA viewpoint:

A PRESTO message was sent on 21:19 UTC on a significant rise in the proton flux, reaching almost the event threshold (as seen in the attached figure). This rise is possibly related to flaring activity in the NOAA active region 2192.

== Next hours to days ==

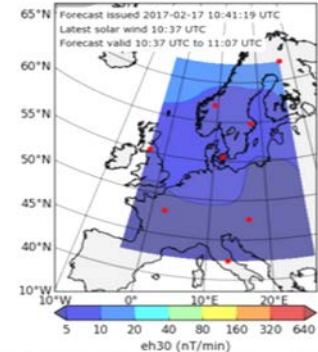
The proton flux has chances to rise again in case of an additional strong flares or a CME-driven shock.

Monitoring potential GIC levels in power systems using state of the art models and near real-time ground magnetic field recordings

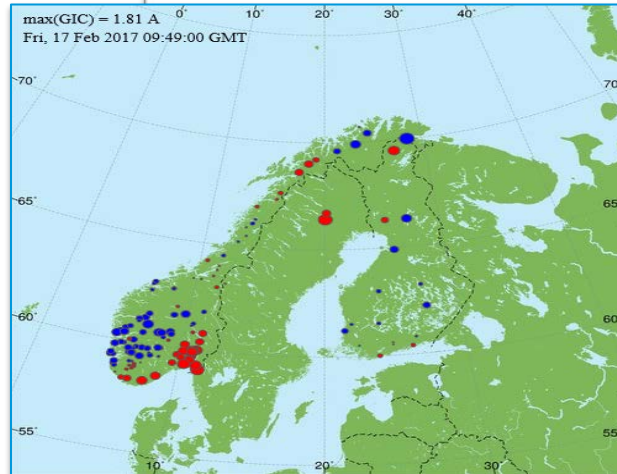
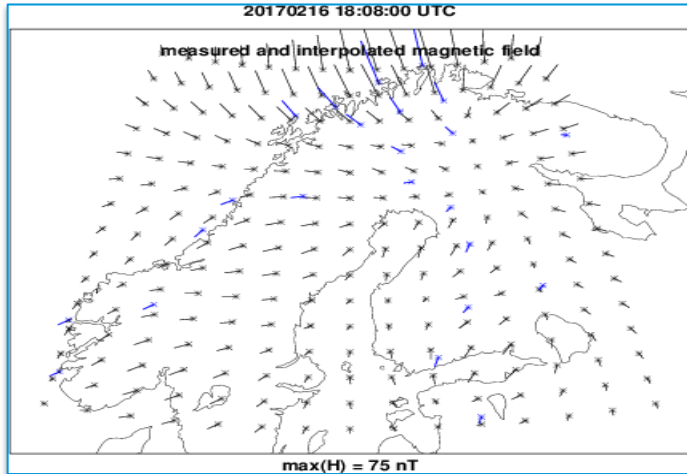
## Non-Space System Operation - Service to power systems operators

Service User Manual Products Tools Alerts Auxiliary Info

For power grid operators the major challenge caused by space weather is the geomagnetically induced currents (GIC). In technological conductor systems GIC are caused by rapid variations of the geomagnetic field (dB/dt). They can disturb the normal operation of the systems, for example, by creating transformer saturation in power grids. In the worst case, GIC can even lead to blackouts or transformer damages in high-voltage power grids. Real-time monitoring of GIC can be based on ground magnetic field recordings from which GIC can be modelled in power grids. Short-term forecast is based on the modelled rate of changes of the geomagnetic field (dB/dt), which is closely related to GIC.



Current image from the product dB/dt forecast. 30-minute maximum forecast for the rate of change of the magnetic field.



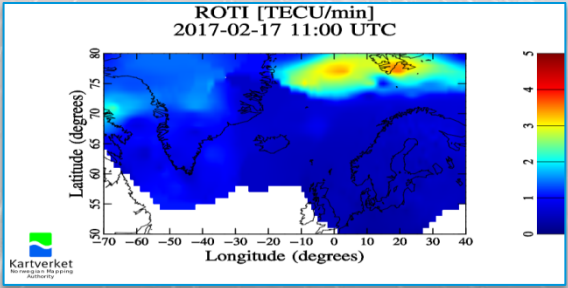
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netic Conditions. For further information, please

# SWE Service For Aviation



Near real-time assessment of cosmic radiation exposure at flight altitudes and timely information about potential space weather induced communication/navigation disturbances



### Non-Space Systems Operations – Service to airlines

Service
User Manual
Products
Tools
Alerts
Auxiliary Info

A range of space weather phenomena can affect both aircrew and aviation technical infrastructure. The health of aircrew can be affected due to elevated radiation exposure mainly caused by Galactic Cosmic Rays (GCR) and by occasional solar eruptions of energetic charged particles (Solar Energetic Particles - SEP). Technical infrastructure can suffer from degradation or loss of communication and navigation signals, as well as avionics errors. Such disruptions can be caused by both electromagnetic and charged particle radiation, as well as changes in the ionospheric conditions.

The service "Non-Space Systems Operations – Service to airlines" aims at provision of access to global information, data, models and tools addressing these issues to help pilots/airlines' dispatchers in flight planning, especially for flights affected by space weather effects.

This service is implemented through a combination of products, tools and alerts which can be found through the following tabs along with expert support provided by the teams constituting the SWE Network; should you require further guidance in the use of this service, or have specific questions about any aspects of the service presented here, don't hesitate to contact the Helpdesk.

A number of tools and products are available through this service, such as:

- the Aviation Dosimetry (AVIDOS) tools providing a real-time assessment of cosmic radiation exposure at flight altitudes;
- the Athens Neutron Monitoring Station (ANEMOS) providing tools like a real time GLE alerting system and access to multi-station neutron monitor data;
- the RadSEP product providing an SEP post-event analysis for aviation radiation exposure;
- the Ionosphere Monitoring and Prediction Center (IMPC) providing TEC maps and local scintillation indices;
- the Real-Time Ionosphere Monitor (RTIM) providing VTEC, GIVE, S4 and  $f_{min}$  maps;
- the European Ionosonde Service (EIS) providing TEC and foF2 maps, and ionospheric condition at several locations;
- the Ionosphere Monitoring Facility (IONMON) providing TEC maps;
- the Space Weather Data Browsing and Analysis (SWE Data) provides access to space weather environment data.

This service page is curated by the ESC Space Radiation. For further information, please contact **SSCC Help desk**.

# Next Steps in SSA Period 3





# SSA SWE System Objectives in P3

Mature elements of the SSA SWE system

Develop and validate improved services for key users

Establish robust R2O process for models and tools

Continue development of the SWE mission to L1/L5

Develop Distributed SWE Sensor System (D3S)

Develop SWE instruments for L5 mission and D3S

Reinforce and mature SWE system

Reduce dependence on non-European systems

Begin transition towards operational system

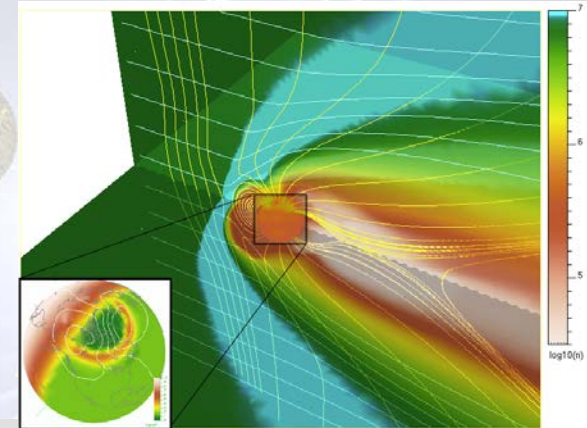
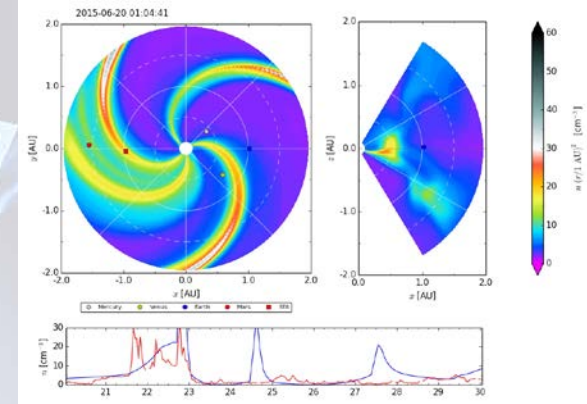
# Capability Assessment

- Measure maturity of services and constituent elements
- Provide accuracy and reliability information to SWE users
- Product maturity
  - How well does the product match the target requirement? Scope... accuracy...timeliness
- Service maturity
  - Combination of available product maturity + operational implementation
- Collaboration with international partners
  - Formats, metrics, validation, ...



# SWE Service Enhancements

- Target: protection of sensitive infrastructure and human life
- Improved SWE forecasting capability:
  - Physics based models
  - Utilisation of new data: L1 + L5, D3S
- Focussed target domains including e.g.
  - Power grid operation
  - Aviation
  - Satellite operation
  - Arctic region
- Enhancement of SWE monitoring capability



# Ground based Space Weather Measurements



Measurement	Existing Assets
<b>Solar images: H-alpha, white-light</b>	Solar telescopes (e.g. Kanzelhoehe Solar Observatory)
<b>Solar Magnetogram images</b>	Solar telescopes (e.g. IAC contribution to GONG network)
<b>Solar indices: F10.7</b>	Solar radiometer. Currently only DRAO Penticton (Canada)
<b>Solar Radio Bursts</b>	Solar radio spectrograph network (e.g. eCALLISTO network)
<b>Cosmic Ray Neutron Flux</b>	Existing neutron monitor network (e.g. <a href="http://www.nmdb.eu/">http://www.nmdb.eu/</a> )
<b>Earth surface vector magnetic field</b>	Vector magnetometers in existing networks (additional stations particular in arctic region would be needed). Global coverage through agreement (e.g. INTERMAGNET).
<b>TEC maps</b>	Existing GNSS receiver networks (e.g. IGS, EUREF)
<b>Auroral visible imaging</b>	All-sky imagers (e.g. FMI real-time auroral cameras)
<b>Ionosphere: URSI parameters</b>	Ionospheric sounders: Digisonde/ionosonde networks (e.g. DIAS network). Completion of global coverage through international cooperation agreements.
<b>Ionospheric Scintillation: S4 and Sigma_Phi</b>	Dedicated GNSS receivers for scintillation monitoring (e.g. ESA Monitor network). Deployment of further sensors should be considered.
<b>Ionospheric Electric Field</b>	Incoherent/coherent radar network (e.g. SuperDARN and EISCAT). Current assets not suitable for continuous monitoring => EISCAT_3D
<b>Ionospheric Radio Absorption</b>	Riometer network (e.g. AAR/AIRS (Nor), IRIS (Fin), Svalbard (Nor), NORSTAR (Can)).
<b>CME detection through cosmic ray anisotropy</b>	Muon telescope network (e.g. MuSTanG). European element of the network in prototype status and would require upgrade.

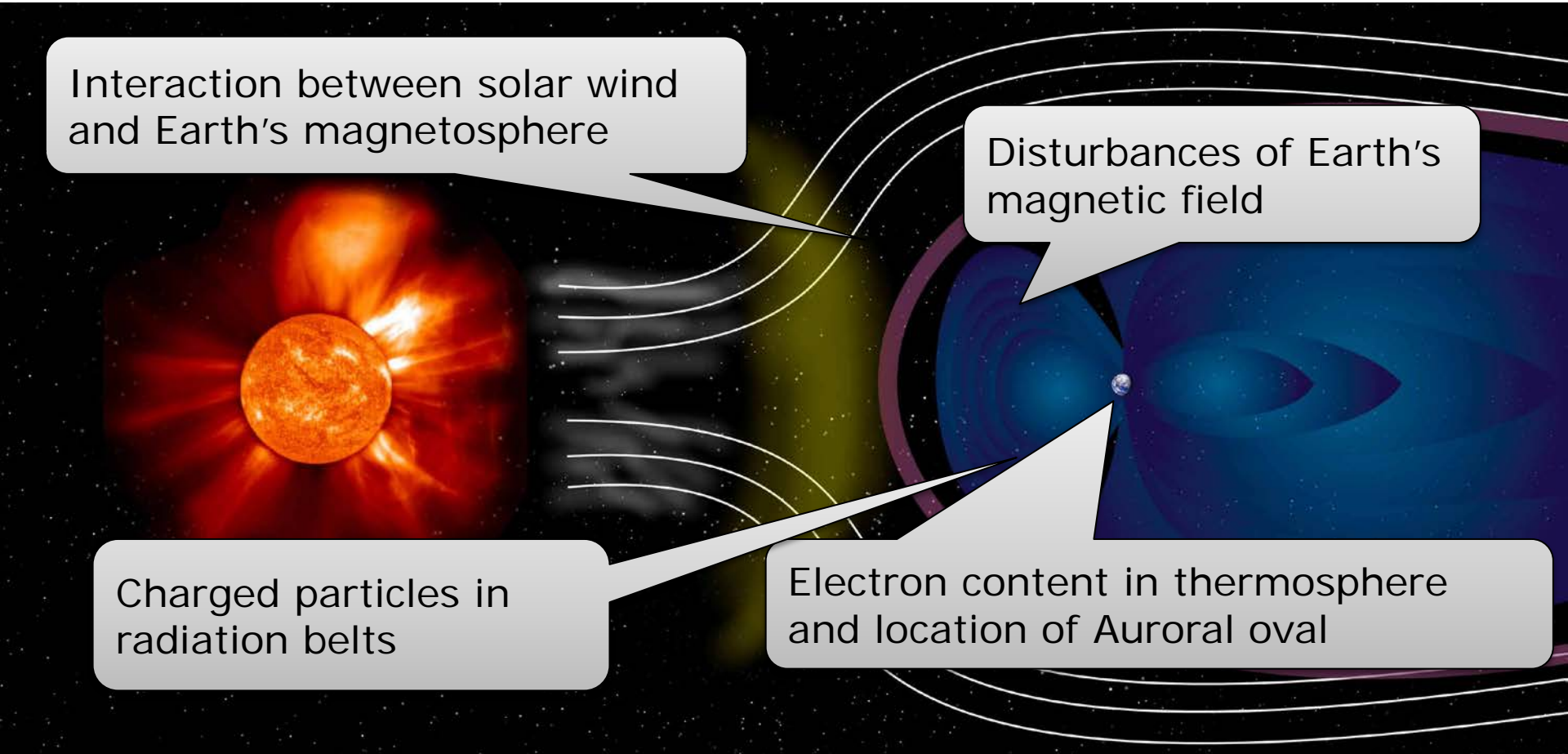


Interaction between solar wind and Earth's magnetosphere

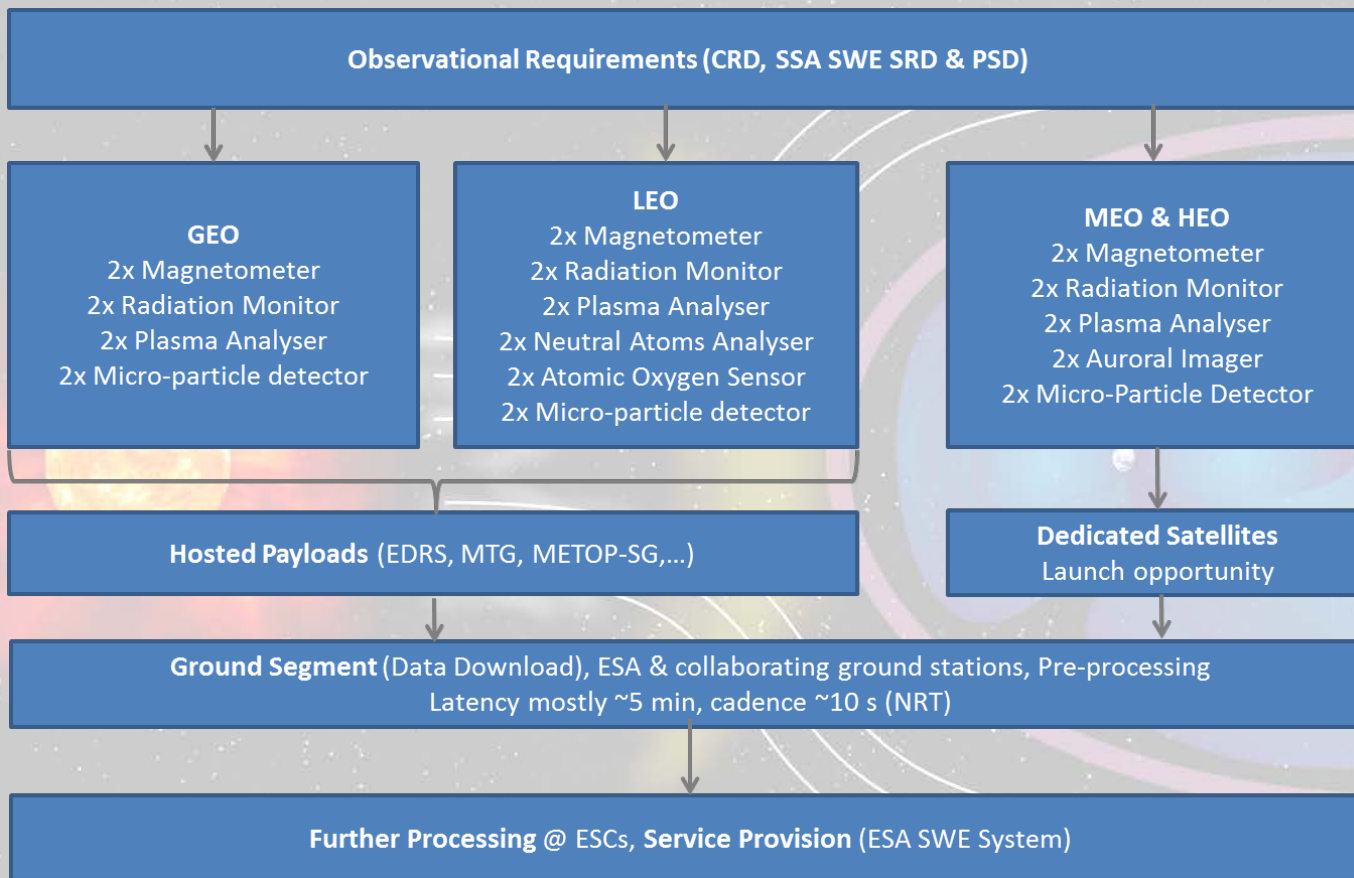
Disturbances of Earth's magnetic field

Charged particles in radiation belts

Electron content in thermosphere and location of Auroral oval

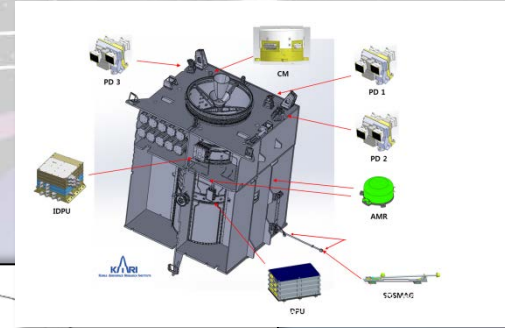
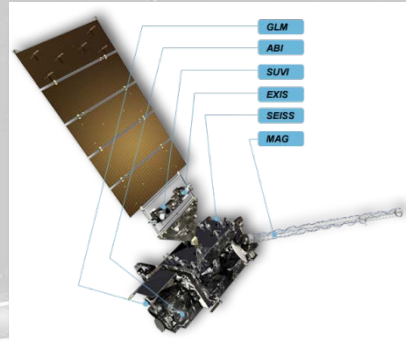


# Distributed SWE Sensor System (D3S)



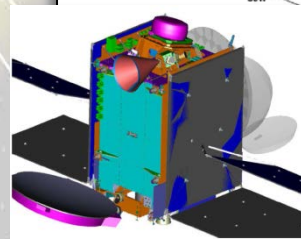
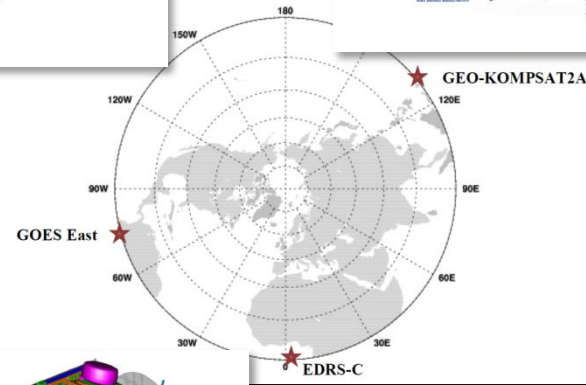
## Next Generation Radiation Monitor (NGRM)

→ ARTES 7, EDRS-C (2018)



## Service Oriented Spacecraft Magnetometer (SOSMAG)

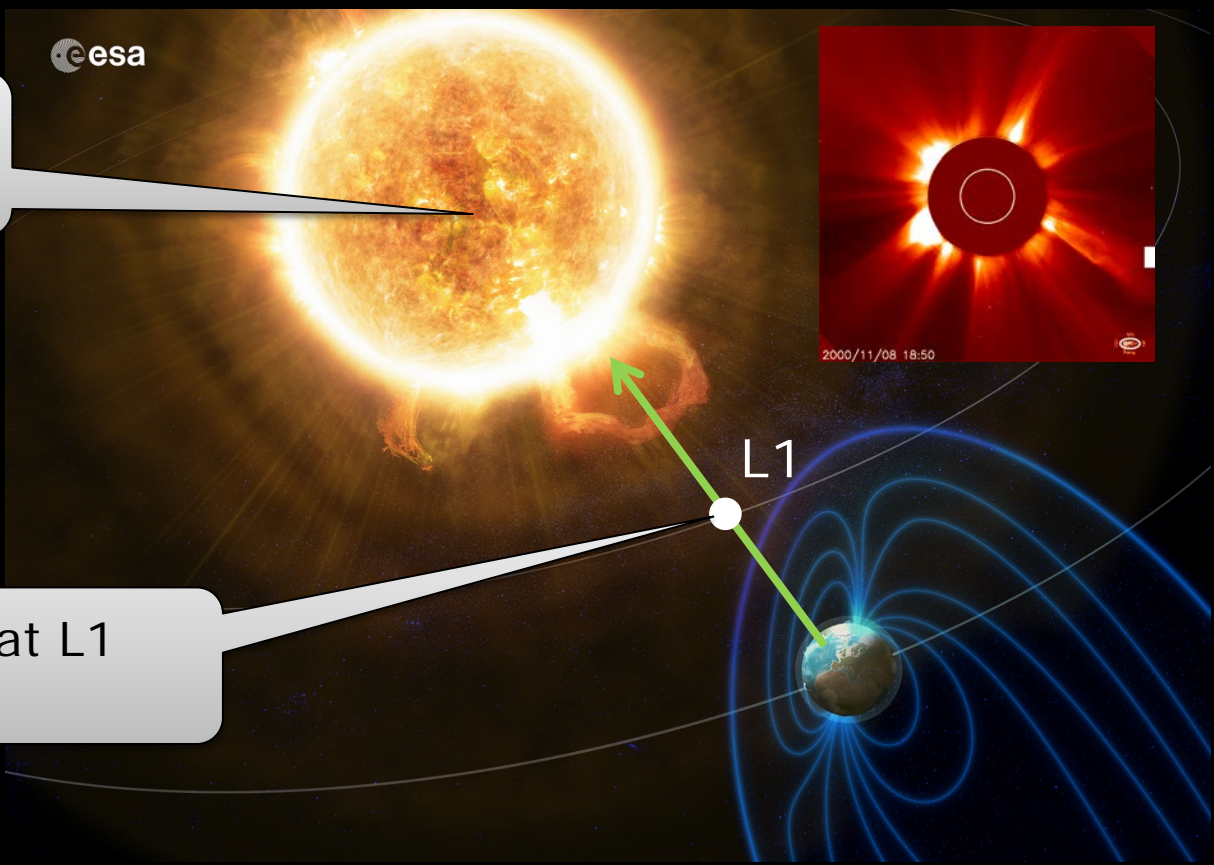
→ Korean GEO-KOMPSAT-2A (2018)



# Monitoring the Sun-Earth line

Monitoring of solar disc and corona on Sun-Earth line

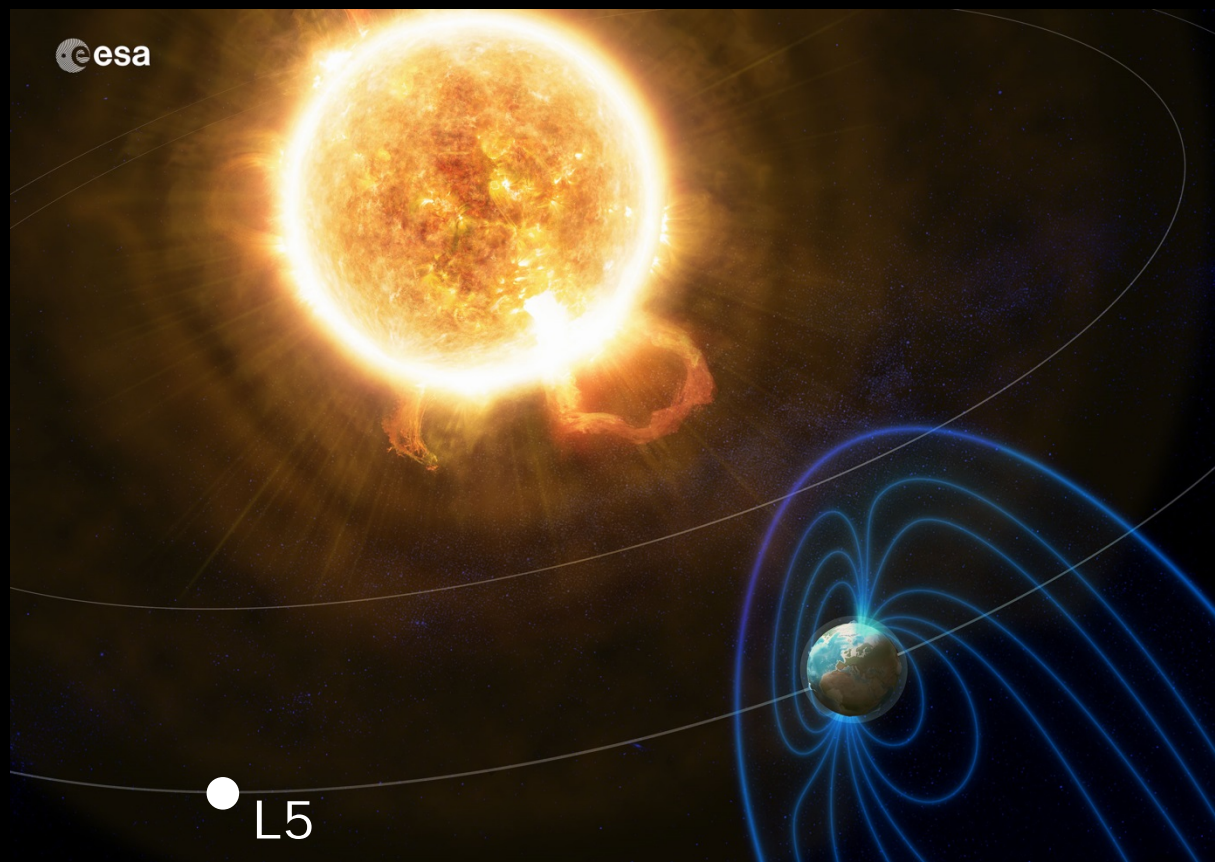
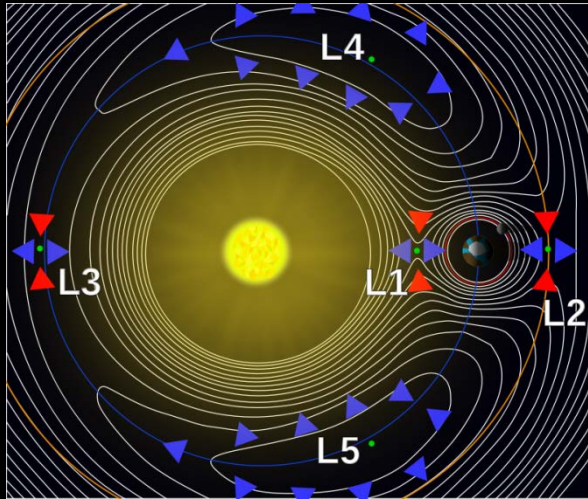
esa



In-situ measurements at L1 point

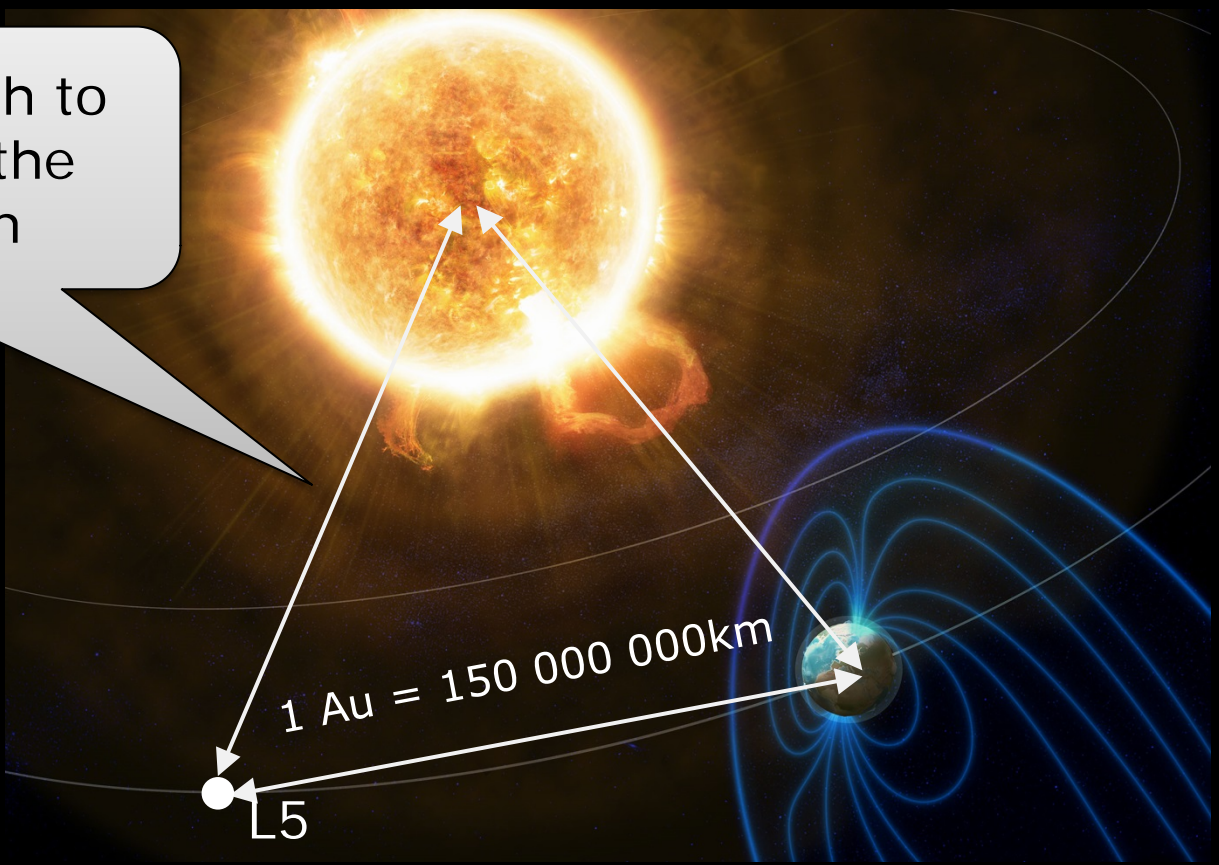
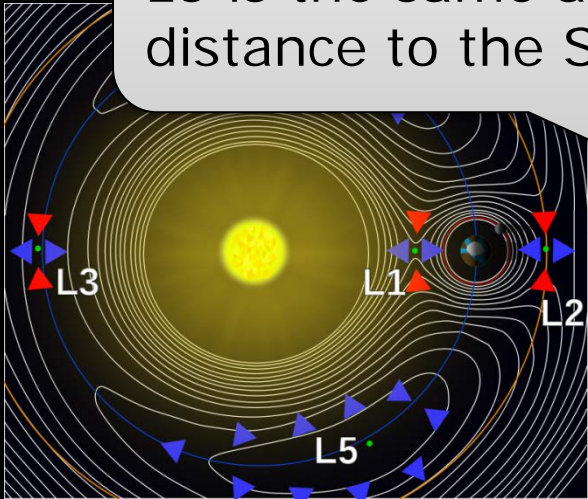


# Measurements from L5 point



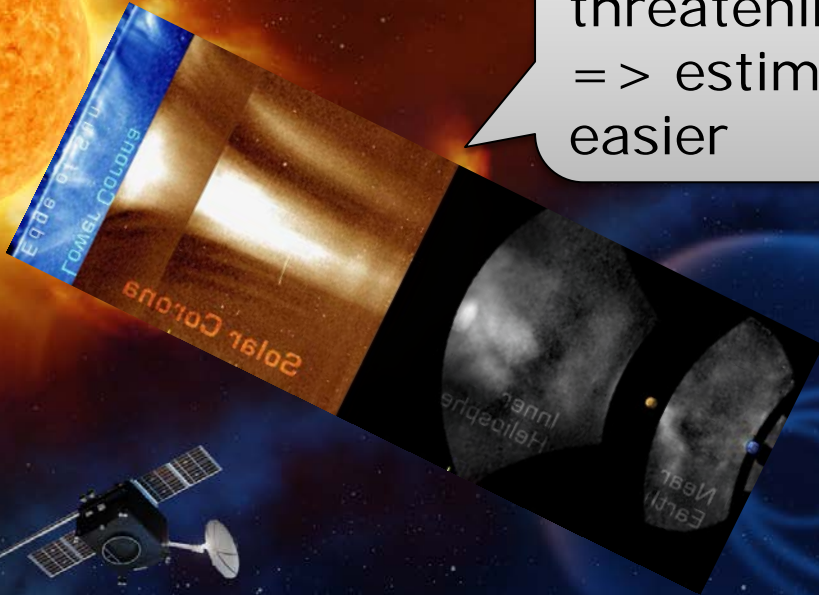
# Measurements from L5 point

Distance from Earth to L5 is the same as the distance to the Sun

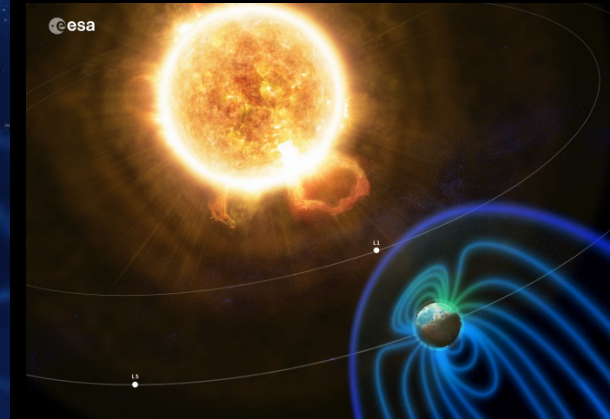


# Benefits of L5 Measurements

Spacecraft in L5 can see Earth threatening CMEs from the side  
=> estimation of speed and direction easier

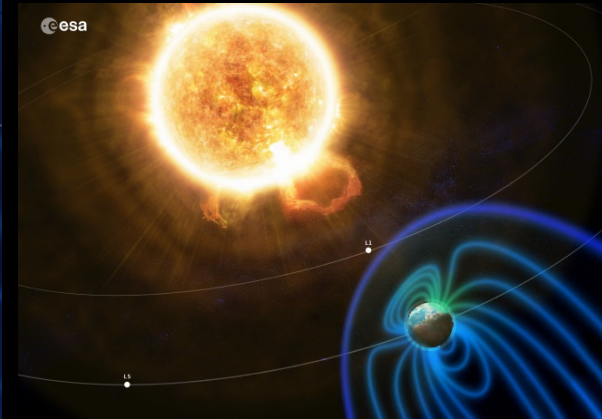
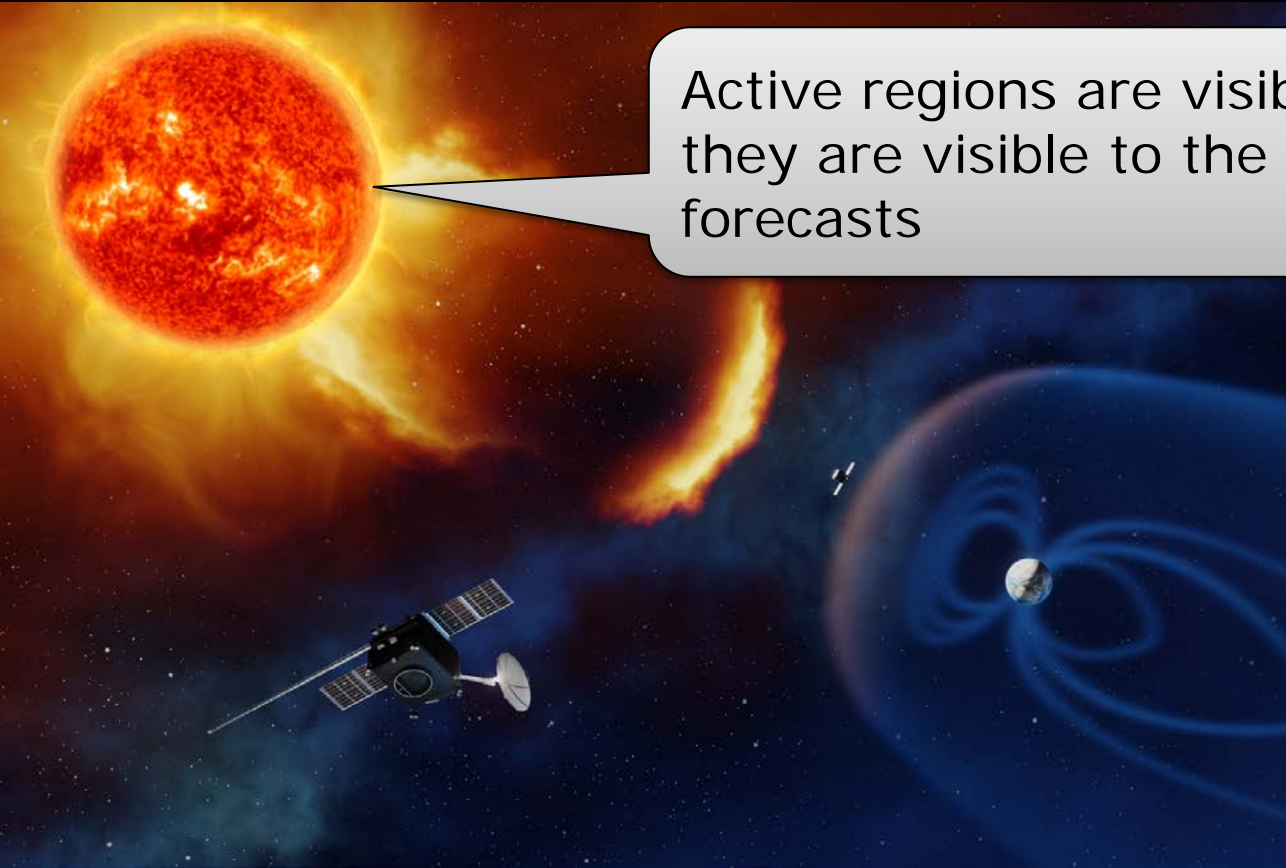


Video: NASA



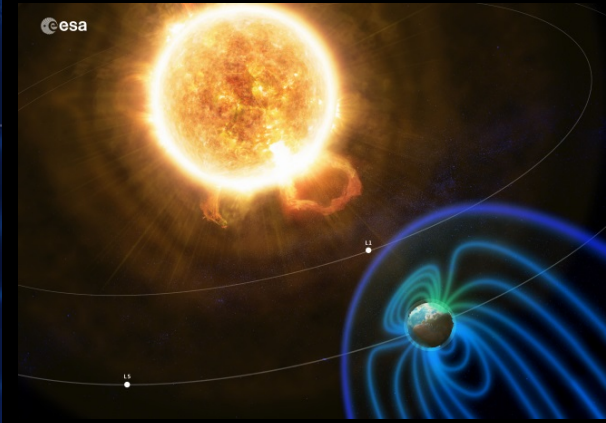
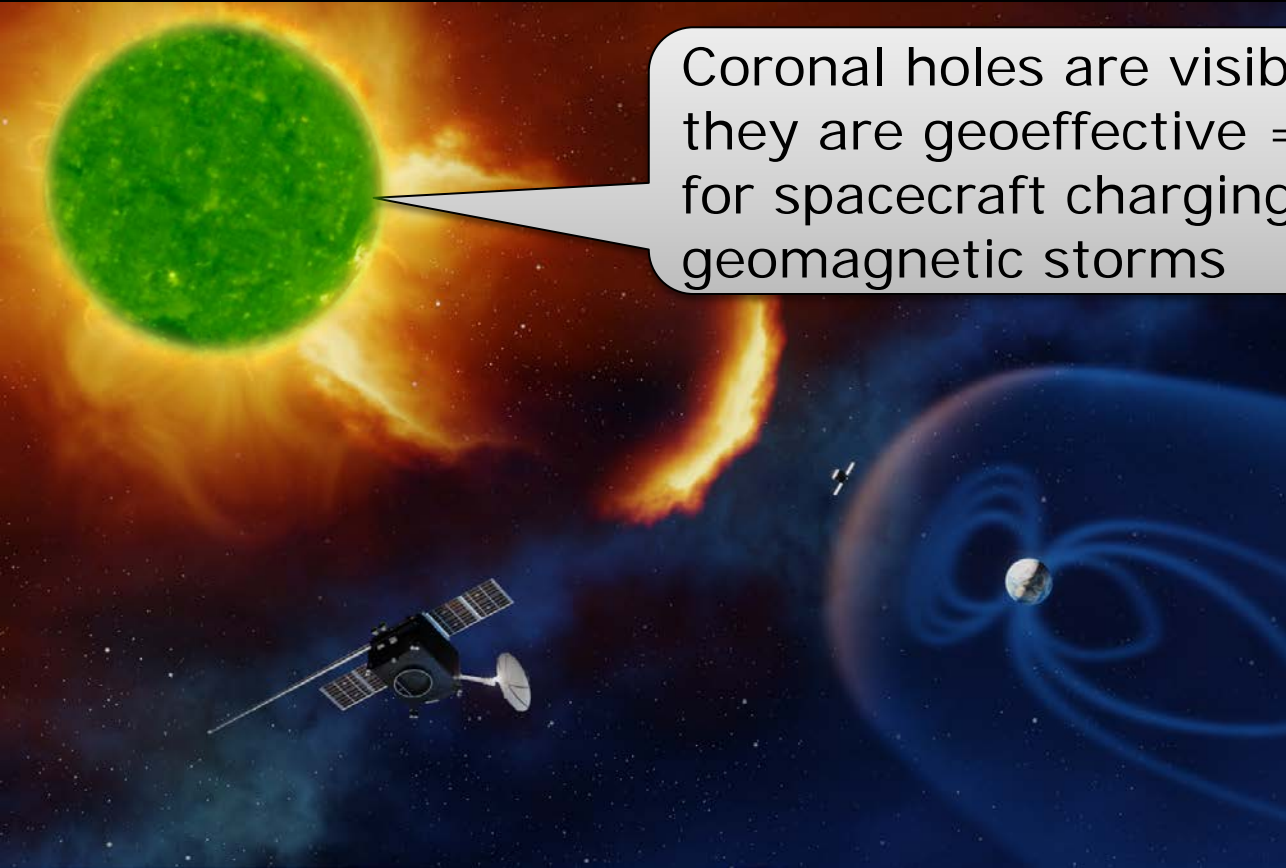
# Benefits of L5 Measurements

Active regions are visible 4-5 days before they are visible to the earth => better forecasts



# Benefits of L5 Measurements

Coronal holes are visible 4-5 days before they are geoeffective => advance warnings for spacecraft charging conditions and geomagnetic storms



# ESA L1/L5 Observations and Instruments



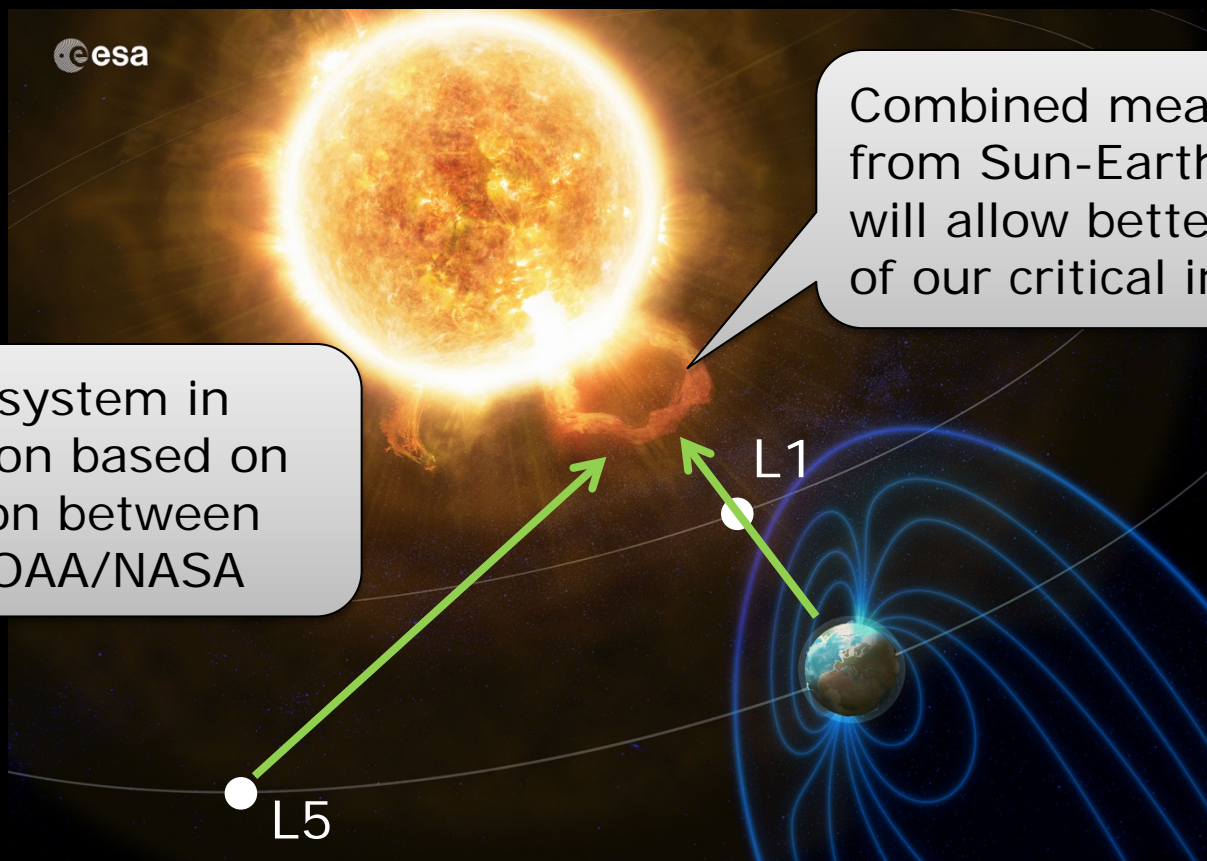
#	Product Name	Observation / measurement	Classification	Instrument
1	Interplanetary Magnetic-Field (IMF)	IMF properties and dynamics	High priority	<a href="#">Magnetometer</a>
2	Solar-Wind Properties	Solar-wind velocity, bulk-density and temperature	High priority	<a href="#">Plasma Analyser</a>
3	Photospheric Solar Disk Magnetic Field	Magnetic-field mapping of the photosphere	High priority	<a href="#">Magnetograph</a>
4	White-light wide-angle Coronagraph Images	Intensity Mapping of outer corona	High priority	<a href="#">Coronagraph</a>
5	Coronal EUV Images of the Sun	Intensity mapping of the low Corona	High priority	<a href="#">EUV imager</a>
6	Heliospheric Images	Intensity Mapping of Heliosphere	High priority	<a href="#">Heliospheric Imager</a>
7	Solar X-ray flux	X-ray flux monitoring	High priority	<a href="#">X-ray monitor</a>
8	High Energy Protons	Energy distribution and flux dynamics with $E > 10$ MeV	High priority (L1) Enhancing (L5)	<a href="#">Radiation monitor</a>
9	Medium-Energy ions	Detection of Solar-Wind Ions with $E = 30\text{keV/nuc}$ to $1$ MeV/nuc	High priority (L1) Enhancing (L5)	<a href="#">Medium Energy Particle Spectrometer</a>
10	Medium-Energy electrons	Solar-Wind Electron flux and energy distribution with $E = 30$ keV to $8$ MeV	High priority (L1) Enhancing (L5)	<a href="#">Medium Energy Particle Spectrometer</a>
11	Solar radio-spectrographic emissions	Detection of radio burst/flare signatures and associated outward expanding shocks	Enhancing	<a href="#">Radio burst spectrograph</a>
12	Medium-Energy Ions	Solar-Wind Ion flux and energy distribution with $E = 1$ to $10$ MeV/nuc	Enhancing	<a href="#">Medium Energy Particle Spectrometer</a>
13	High-Energy Ions	Solar-Wind Ion flux and energy distribution with $E > 10$ MeV/nuc	Enhancing	<a href="#">Radiation monitor</a>



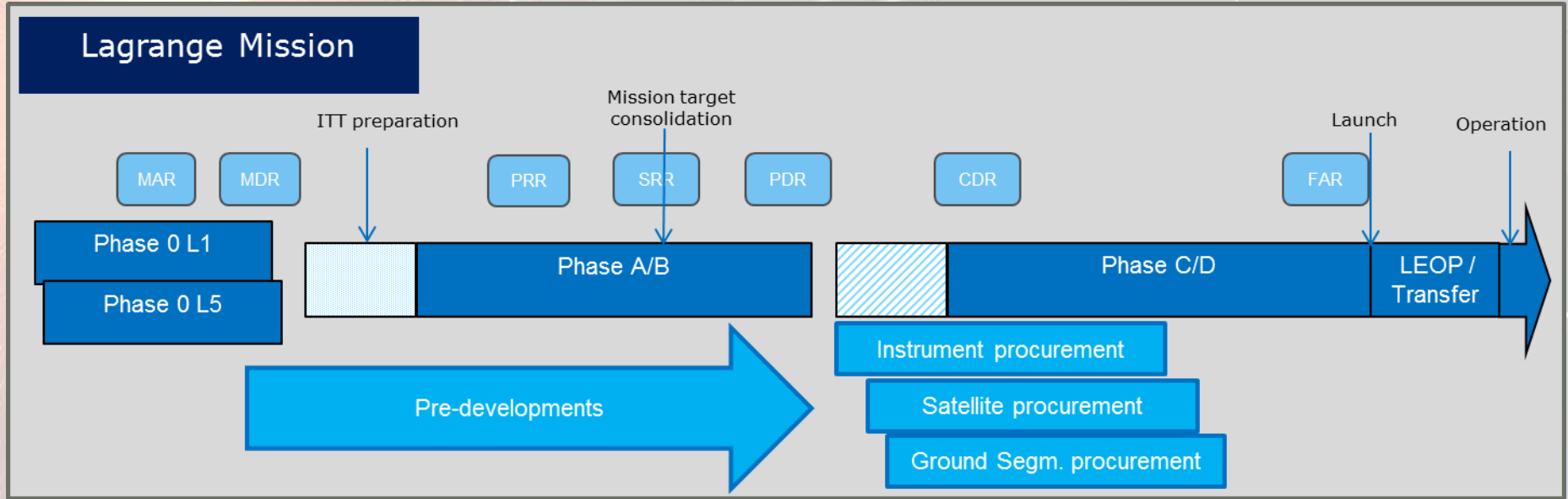
# Joint L5 and L1 measurement system

Combined measurements from Sun-Earth line and L5 will allow better protection of our critical infrastructure

Join L5/L1 system in consideration based on collaboration between ESA and NOAA/NASA



# SSA SWE Lagrange Mission Roadmap





For more information:

[swe.ssa.esa.int](http://swe.ssa.esa.int)

[www.esa.int](http://www.esa.int)