A short introduction to Space Weather

(...and opportunities for small satellites)

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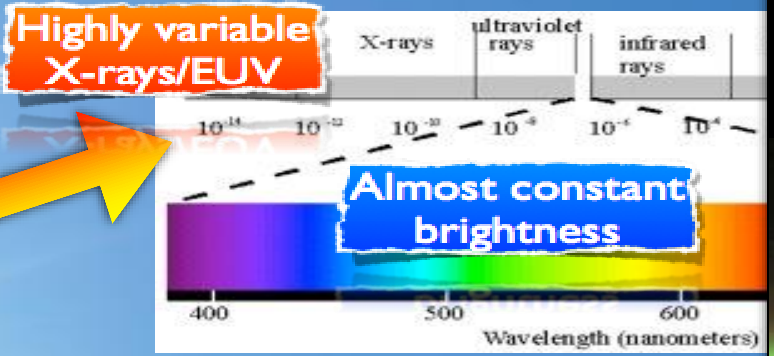
for the

COSPAR Space Weather Panel
&
European Space Weather Assessment and Consolidation Committee of the ESSC

What the Sun sends our way

Light
(X-ray to radio)



Magnetized wind

Particle radiation

Geomagnetic storms:
couple into power grids, cause ionospheric disturbances affecting satellite-based navigation.

Aurorae

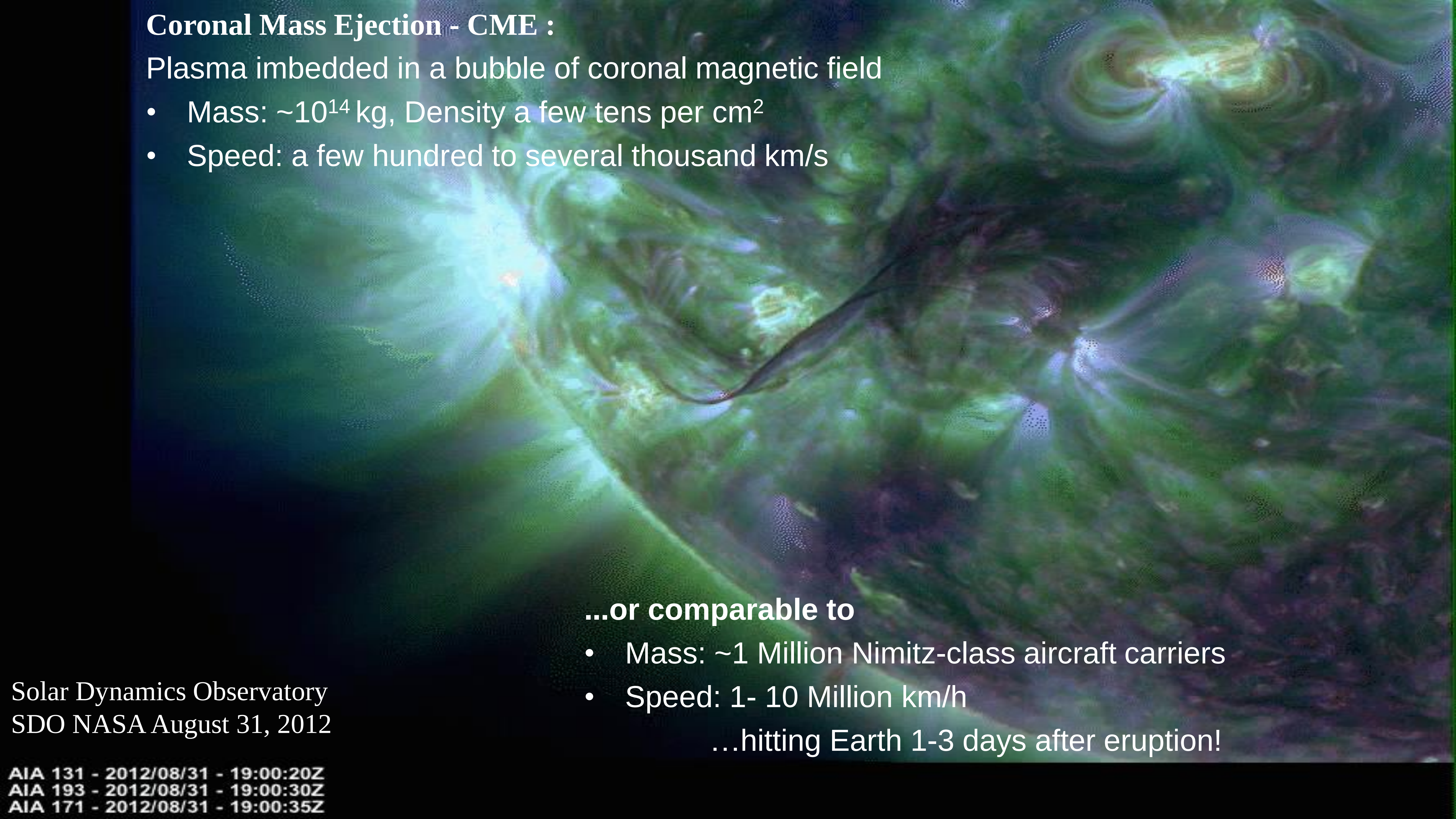
Radiation storms:
hazard to astronaut health and satellite function;
affect high-latitude radio ommunication; position errors on navigation.

Ionospheric storms:
Scintillations and GPS signal loss,
time stamp problems,
radio blackouts.
Satellite drag affecting orbits and re-entry.

Coronal Mass Ejection - CME :

Plasma imbedded in a bubble of coronal magnetic field

- Mass: ~10^{14} kg, Density a few tens per cm^2
- Speed: a few hundred to several thousand km/s



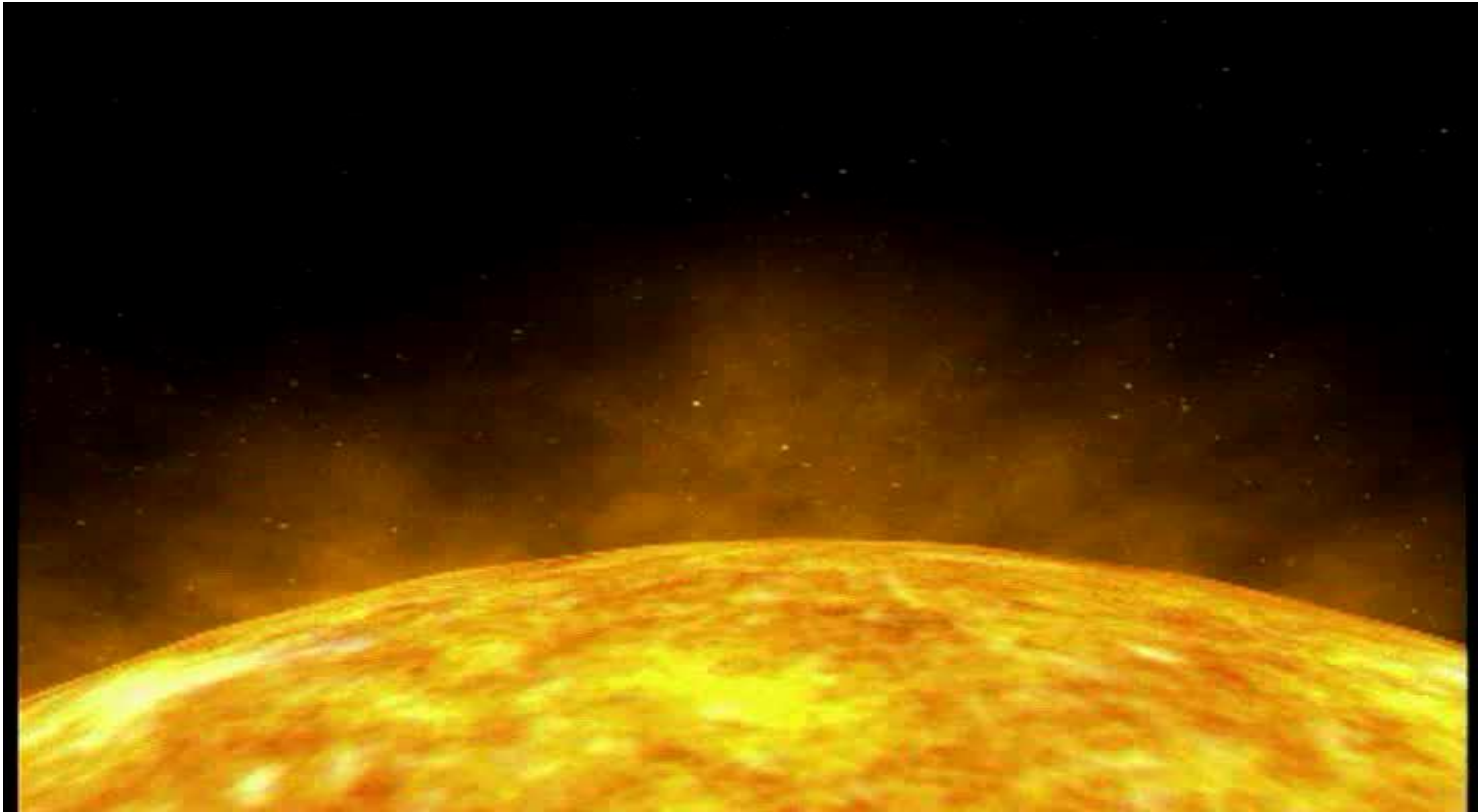
Solar Dynamics Observatory
SDO NASA August 31, 2012

...or comparable to

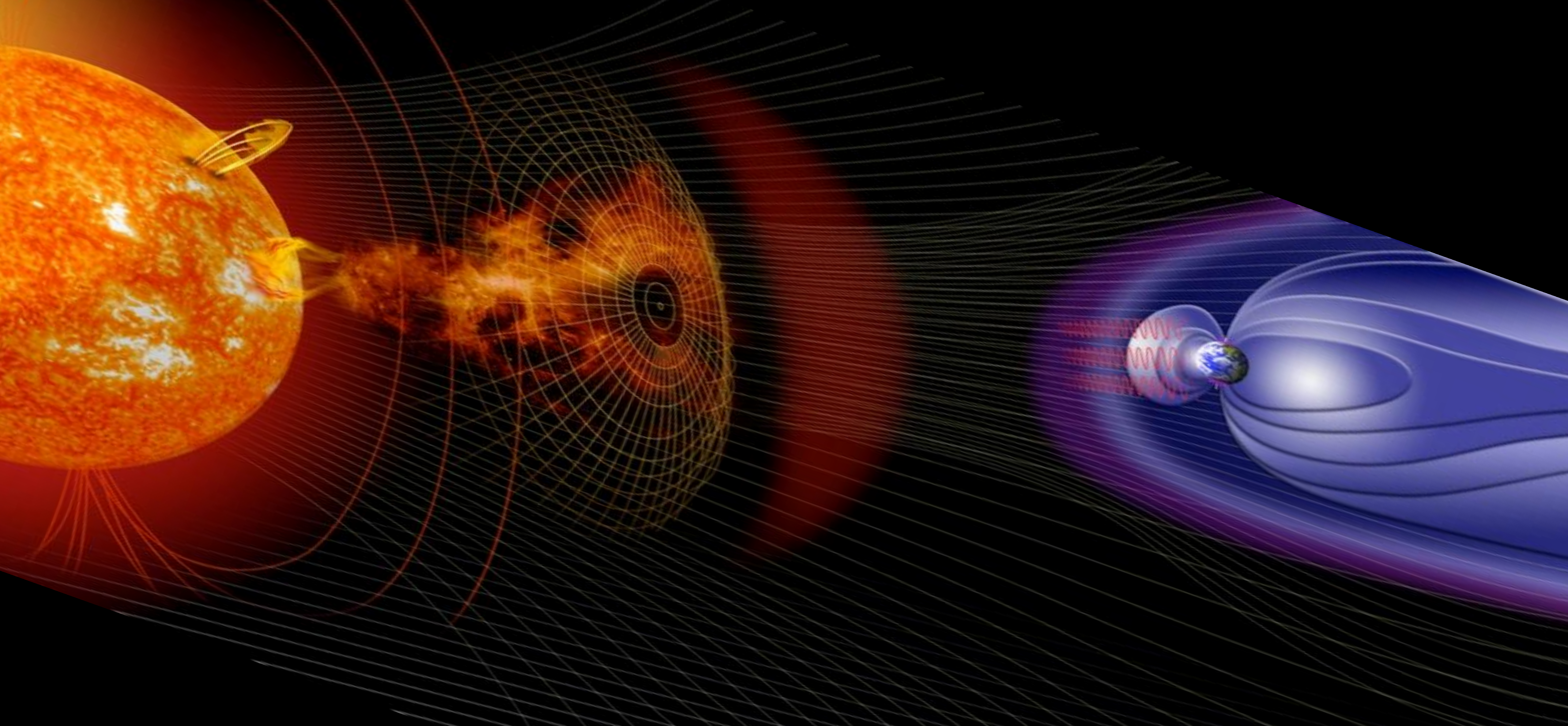
- Mass: ~1 Million Nimitz-class aircraft carriers
- Speed: 1- 10 Million km/h

…hitting Earth 1-3 days after eruption!

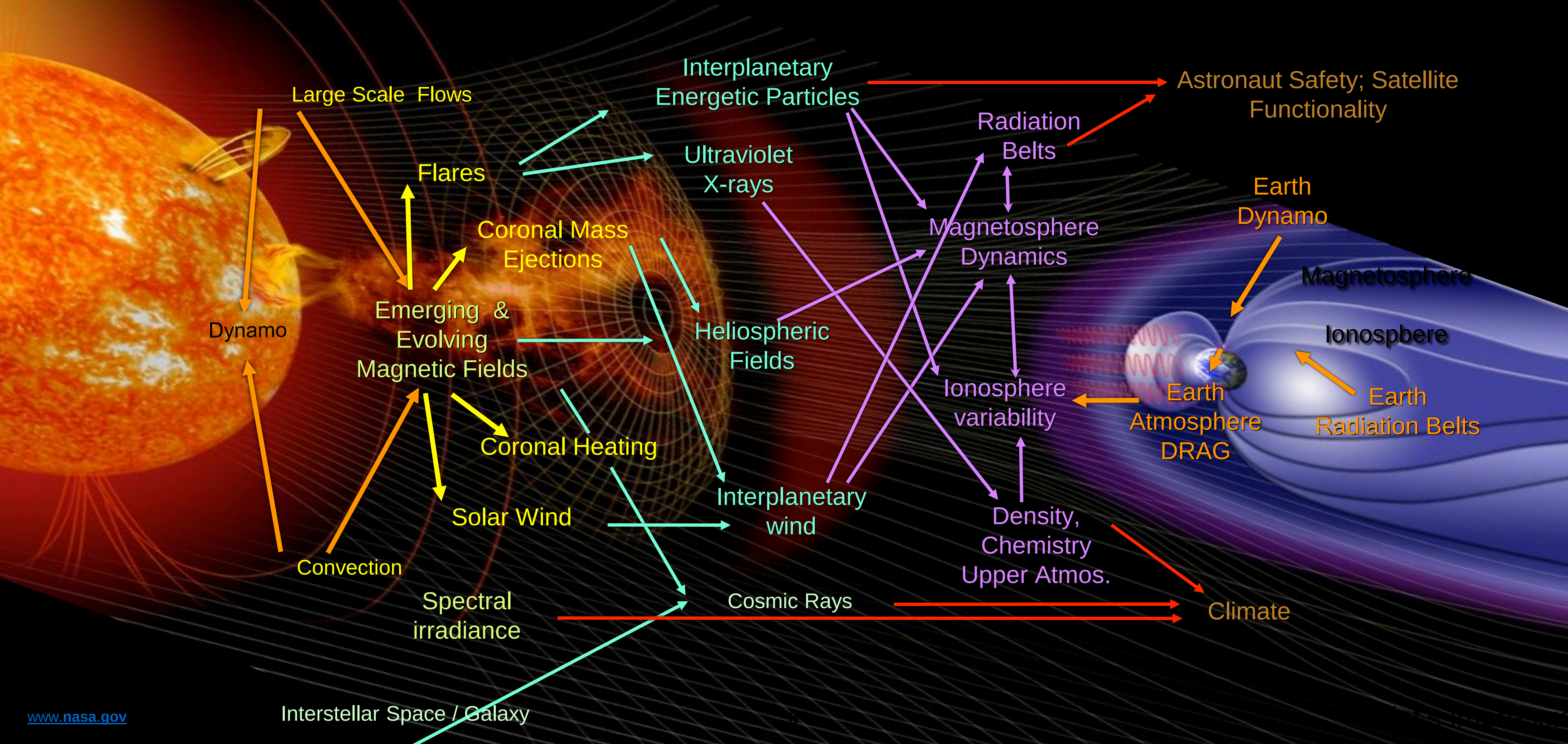
CME-Earth Interaction



It all looks so nice and simple – but…



Sun-Earth Space : a complex system of coupled processes and phenomena



Six Important Areas of ESWACC Findings and Recommendations

as presented to ESA DG J. Wörner, Febr.5, 2019 in Paris

- (1) Critical science
- (2) Coupled Models
- (3) Risk Assessment
- (4) User Requirements
- (5) Research 2 Operation
- (6) Observational Networks

(1) Imminent Need for Critical Research with Dedication to Enable Space Weather Understanding and Prediction (General)

E S W A C C

- A **unique fleet of spacecraft is now observing** the sun, the solar wind and the near Earth environment
- Such an **opportunity for ground-breaking science** including several multi-spacecraft missions, and well developed ground-based networks **will not re-occur within the foreseeable future of SWx observations**
- While we do understand the underlying principles and most of the causal relations between the elements of the Sun-Earth chain, **we still lack some critical scientific understanding of:**
  - **the solar activity cycle itself**
  - **the origin of solar eruptions,**
  - **SIR, CIR and CME interaction with and propagation in the solar wind,**
  - **detailed mechanisms of energy storage, transformation and release in the magnetosphere/ionosphere system,**
  - **and its propagation into the atmosphere and the Earth's conducting crust**

  to improve the value of space weather forecasts to the degree required to meet the expectations emerging from most present – and still increasing - user requirement
- **We also lack a coordinated science effort** to combine the results of such increased SWx-enabling research for prediction purpose **…like e.g. the COSPAR I-SWAT initiative**

Panel on Space Weather

COSPAR ISWAT International Space Weather Action Teams: A bottom-up component of global coordination in space weather

M. Kuznetsova[1], *H. Opgenoorth[2], A. Belehaki[3], M. Bisi[4], S. Bruinsma[5], A. Glover[6], M. Grande[7], D. Heynderickx[8], J. Linker[9], I. Mann[10],D.Nandi[11], M. Temmer[12], R. Wimmer- Schweingruber[13], Sharafat Gadimova [14]*

[1]NASA GSFC, [2] Univ. of Umeå, Sweden, and Leicester, UK, [3]NOA, [4] UKRI STFC, [5]CNES, [6]ESA, [7] Aberystwyth University, [8]DH Consultancy, [9]PSI, [10]University of Alberta, [11] Center of Excellence in Space Sciences India, [12] University of Graz, [13]University of Kiel, [14] UNOOSA

COSPAR Symposium
UNOOSA, 2019

GLOBAL COMMUNITY FORUM

GLOBAL COMMUNITY VOICE

A Global Space Weather Roadmap 2015-2025

commissioned by COSPAR and ILWS

Understanding space weather to shield society *[Schrijver et al., 2015]:*

Performed gap and feasibility analysis. Identified research priorities in theory, modeling and observations. Analyzed opportunities for improvement.

Key challenges identified in the Roadmap:

- **Understand and quantify key aspects of space weather:** *physical processes, impact on technology & society.*
- **Address the Research-2-Operations (R2O) problem:** *establish mechanism for rapid implementation of latest advances in SWx research into applications,* *targeting improvement of resilience to space weather impacts.*
- ***Facilitate transition to a collaborative, information-sharing and effectively functioning global space weather community.***

COSPAR Panel on Space Weather:

Top-Down & Bottom-Up Approaches

COSPAR PSW updated Its Terms of Reference On July 19th, 2018

- **Top-Down approach:**
  - Actively contribute to global coordination of space weather efforts.

UN COPOUS Expert Group on Space Weather

International space weather stakeholders	National Regional Agencies
URSI SCOSTEP	

- **Bottom-Up approach:**
  - Facilitate the establishment and coordinate an active network of topical scientific action teams: ***International Space Weather Action Teams – "I-SWAT"***
  - Evolve the current SW **Roadmap** into a regularly updated **living document.**
  - Organize *task oriented* ***Community-wide Campaigns*** & ***Working Meetings.***
  - Create a dynamic environment that encourages active participation, emergence of new leads and innovative ideas.

What is a topical action team ?

- An **action team**
  - provides a **building block of the ISWAT initiative.**
  - choses to address a **specific focused task** relevant to roadmap goals.

    All teams work in a coordinated effort towards:

    a) the realization of global roadmap goals

    b) the generation of inputs for roadmap updates
- Focused tasks can address different aspects of SW capabilities:
  - advancing **understanding**,
  - improving **modeling** capabilities,
  - transition of advances in **research to operations,**
  - utilization of **available observations,**
  - recommendations for **future mission** planning.
- Team’s work is organized by action team leads/co-leads.

  “**Leaders are not appointed, they emerge**”

What is an I-SWAT Cluster?

- **Action teams** are organized into **I-SWAT Clusters** grouped by **domain** (e.g., Sun, Heliosphere, Geospace), **phenomenon** (e.g., SEP, CME, irradiance), **driver** (input to heliosphere/geospace) or **impact** (e.g., GICs).
- Activities of action teams in topical cluster are coordinated by **Cluster moderators.**
- The Cluster concept will allow to **engage existing international teams** and to **build upon established efforts.**
- Advantages of **Cluster of multiple teams vs. one big topical team**
  - Small teams are typically more efficient.
  - It may always be an option to have only one team within a topical cluster, but the Cluster concept will allow expansion.
  - Team merging may be encouraged by moderators, but not enforced.

S: Space weather origins at the Sun

Solar output
Input to heliosphere and geospace

S1: Long-term solar variability.

S2: Solar magnetic field, heating & spectral irradiance.

S3: Solar eruptions:
(a) flares and enhanced electromagnetic emissions;
(b) high energy particle fluxes;
(c) CMEs

H: Propagation of transient through evolving ambient heliosphere

input to geospace

H1: Evolving ambient heliosphere.

H2. CME structure, evolution and propagation through heliosphere.

H3. SEP in heliosphere.

G: Coupled magnetosphere Ionosphere-atmosphere (geospace) system

response to solar drivers

G1: Geomagnetic environment.

G2a: Atmosphere variability.

G2b: Ionosphere variability.

G3: Near-Earth plasma (a) & radiation (b) environment.

Impacts and primary user groups

Climate

Electric power systems, GICs

Satellite/debris drag

Navigation Communications

(Aero)space assets functions

Human exploration

Overarching Activities: EO: Education and Outreach

TE: Testing and Evaluation IA: Information Architecture DU: Optimized Data Utilization

Who are moderating ISWAT Clusters? – at present

See http://ccmc.gsfc.nasa.gov/iswat for details… - and updates!

S: Space weather origins at the Sun - Input to heliosphere and geospace.

- S1: Long term solar variability and impact on Earth's climate. **D. Nandi**
- S2: Solar magnetic field, heating, spectral irradiance. Input to ambient heliosphere, **J. Linker**
- S3: Solar eruptions: (a) flares and enhanced electromagnetic emission; (b) SEPs; (c) CMEs. **TBD**

H: Propagation of transients through evolving ambient heliosphere - Input to geospace.

- H1: Evolving ambient heliosphere. **M. Bisi**
- H2: CME structure, evolution and propagation through heliosphere, **M. Temmer**
- H3: SEP and GCR in heliosphere. **R. Wimmer-Schweingruber**

G: Coupled geospace system response to drivers.

- G1: Geomagnetic environment. **H. Opgenoorth**
- G2A: Atmosphere variability. **S. Bruinsma**
- G2B: Ionosphere variability. **A. Belehaki**
- G3: Near-earth radiation and plasma environment, **I. Mann**

O: Overarching activities:

- TE: Testing and evaluation. **M. Kuznetsova, A. Glover**
- DU: Optimized data utilization, **TBD**
- IA: Information architecture. **D. Heynderickx**
- EO: Education and outreach. **D. Nandi**

ISWAT Pre-cursor: International Forum on Space Weather Capabilities Assessment:

SOLAR
CCMC facilitator(s): P. Macneice

- Solar Flare Prediction (Leads: S. Murray, M. Georgoulis, S. Bloomfield, K.D. Leka
  Scoreboard Leads: S. Murray, M.L Mays) SSA-0,SSA-6
- Coronal & Solar Wind Structure
  Coronal & SW Structure; Ambient SW; Coronal Hole Boundaries
  (Leads: P. Macneice, L. Jian) SSA-?
- 3D CME kinematics and topology (Leads: B.Thompson, C.Moestl, D.Barnes)
- Solar Indices and Irradiance (Leads: J. Klenzing, C. Henney, K. Muglach) SSA-0

GEOSPACE: Geomagnetic Environment
CCMC facilitator(s): L.Rastaetter

- Ground Magnetic Perturbations: dBdt, delta-B, GI
  (Leads: D. Welling, H. Opgenoorth, C. Ngwira) SSA-1
- Geomagnetic Indices (Leads: M. Liemohn) SSA-1
- Magnetopause location and geosync. orbit crossir
  (Leads: Y. Collado-Vega, S. Merkin) SSA-1

HELIOSPHERE
CCMC facilitator(s): M.L. Mays, A. Taktakishvili, P. Macneice

- CME Arrival Time (Leads: C. Verbeke, M.L. Mays, A. Taktakishvili) SSA-1
- IMF Bz at L1 (Leads: N. Savani, P. Riley) SSA-1
- SEPs (Leads: I.G. Richardson. P. Quinn, M. Marsh, M.L. Mays
  Scoreboard Leads: M. Dierckxsens, M. Marsh) SSA-3,SSA-6

GEOSPACE: Auroral Region
CCMC facilitator(s): M.Kuznetsova

- Auroral precipitation and high latitude ionosphere
  (Leads: R. Robinson, Y. Zhang, B. Kosar)

RADIATION and PLASMA EFFECTS Scope of work
CCMC facilitator(s): Y. Zheng, M. Kuznetsova

- Surface Charging *few eV - keV electrons, plasma density*
  (Leads: J. Minow, D. Pitchford, N. Ganushkina) SSA-6
- Internal Charging *keV–MeV electrons*
  (Leads: P. O'Brien, Y. Shprits) SSA-6
- Single Event Effects *MeV–GeV-TeV protons, ions*
  (Leads: M. Xapsos, J. Mazur, P. Jiggens) SSA-3,SSA-6
- Total Ionizing Dose *keV–MeV electrons, keV–GeV protons,ions*
  (Leads: I. Jun, T. Guild, M. Xapsos) SSA-6
- Radiation effects for aviation (Leads: K. Tobiska, M. Meier) SSA-6

IONOSPHERE
CCMC facilitator(s): J. Shim, M. Kuznetsova

- Neutral Density and Orbit Determination at LEO
  (Leads: S. Solomon, T. Fuller-Rowell, S. Bruinsma, E. Sutton) SSA-2
- Global & Regional TEC (Leads: L. Scherliess, R. Calfas) SSA-4
- Ionosphere Plasma D
  (Leads: I. Tsagouri, M. An
- Ionosphere Scintillati

Forum working teams are focused on different **evaluation topics**.

Historic **event-based** evaluations

Pre-event forecast **Scoreboards**

Cross-team interactions

- **International CCMC-LWS Working Meeting** (April 2017) to kick-off activities.
- AGU SWJ Special Issue (> 25 paper accepted),

Recent Successes: Forecasting Scoreboards

https://ccmc.gsfc.nasa.gov/challenges/

TRINITY COLLEGE DUBLIN

Royal Observatory of Belgium

Flare Scoreboard

Upload your Flare Predictions for Full Disk and/or Active Regions.

Leads: **Trinity College Dublin** (S. Murray), **ROB** (J. Andries)

Met Office

BIRA-IASB

SEP Scoreboard

Under development
Help us plan and design.

Leads: **BIRA-IASB** (M. Dierckxsens, N. Crosby), **GSFC** (I. Richardson), **UK Met Office** (M. Marsh)

Met Office

CME Scoreboard

Submit your CME arrivable time predictions and compare with others.

Leads: **CCMC** (L. Mays), **UK Met Office**

IMF Bz Scoreboard

Leads: **PredSci** (P. Riley)

- Scoreboards collect forecast before event is observed
- Allow a consistent **real-time** comparison of various operational and research forecasts. Complementary to non-real time model assessments.
- Riley et al. (2018), **Forecasting the arrival time of coronal mass ejections: Analysis of the CCMC CME scoreboard,** *Space Weather.*

Near-Term Projects

- ***S2, H1:*** Ambient corona and solar wind modeling challenge. Uncertainty assessment of magnetic connectivity spacecraft mapping. Comparison of different coronal holes detection schemes.
- ***H1, H2:*** 3D structure of Coronal Mass Ejections (CME). CME propagation through ambient heliosphere and parameters at L1.
- ***H3***: *Community-wide* Solar Energetic Particle Scoreboard to address human exploration needs (encouraged by NASA Space Radiation Analysis Group).
- ***G1*****:** Role of drivers and coupling on GICs. Assessment of GIC spikes modeling capabilities for different stages of geomagnetic storms: *sudden commencement, substorm, ring current intensification.*
- ***G2B:*** Traveling ionosphere disturbances & scintillations - assessment of predictive capabilities. Ionosphere activity indices based on user needs.
- ***G2A:*** Neutral density and satellite drag - a new component of the updated Roadmap
- ***G3:*** Design and develop Essential Space Environment Quantities (ESEQ) for near-Earth radiation and plasma environment based on user needs.

Topical Sessions and Working Meetings

- **Mini-ISWAT** sessions and mini-workhops (1-2 hours/days)
  - Organized by action team leads and/or cluster moderators
  - Utilize all opportunities to meet
  - Take advantage of opportunities at national/international space weather forums, e.g., ESWW, EGU, GEM, CEDAR, COSPAR Assemblies & Symposiums
- **Biennial ISWAT Working Meeting** (between COSPAR Assemblies)
  - **2017** (April): International CCMC-LWS Forum on Space Weather Capabilities Assessment (ISWAT pre-cursor), Florida, USA
  - **2019** (TBD), Europe, TBD
  - **2021** (TBD) Asia, TBD

Understanding and predicting space weather
is a global challenge.

Unite as a SW Community: Join ISWAT

The ISWAT initiative is **open to all** individuals or groups committed to active participation.

- To join an already registered action team: contact team leads.
- To register a new topical action team: contact topical cluster moderator

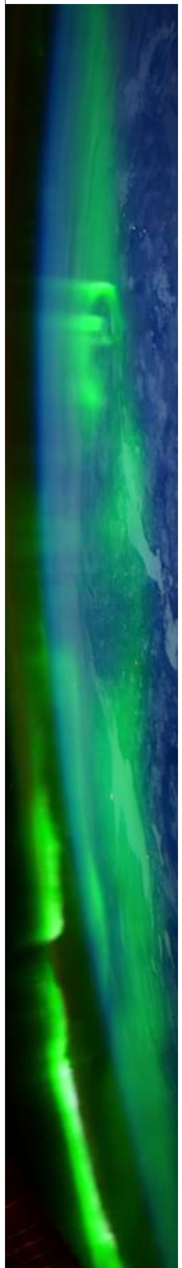
***GLOBAL COMMUNITY* HUB**

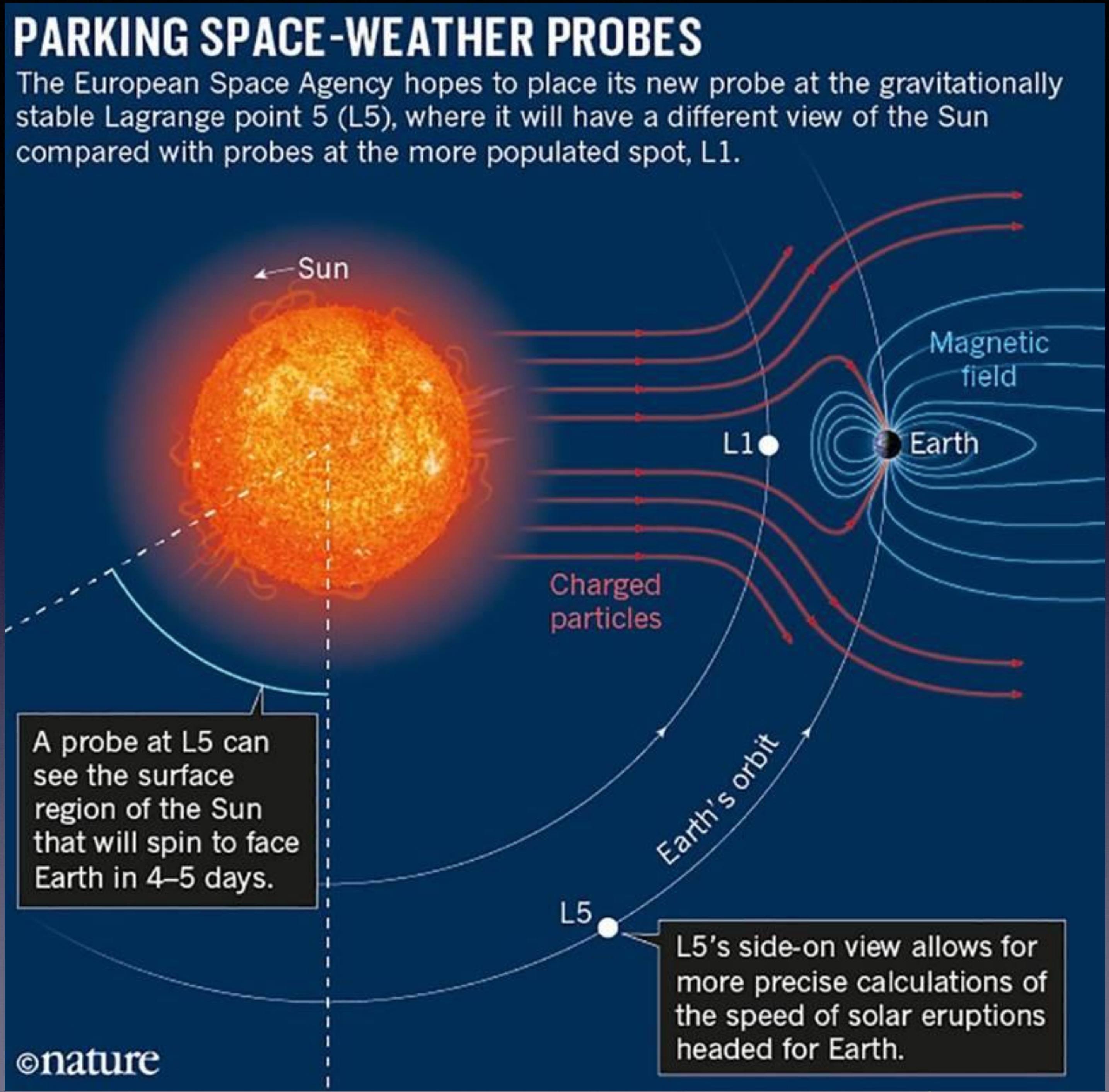
http://ccmc.gsfc.nasa.gov/iswat

***GLOBAL COMMUNITY* VOICE**

(6) Define and implement an operational network for future SWx observations

- Based on the emerging scientific understanding of space weather events and processes scientists and space agencies together will have to define a **baseline and optimum set of observable parameters** at the Sun and in the heliospheric/magnetospheric/ionospheric/atmospheric/solid Earth system, which are needed **to characterise the energetic and dynamical state of the most important elements of the Sun—Earth coupled plasma regimes (characteristic “Proxies”)** and to drive the required forecasts of the expected response of the system as a whole.
- Based on such required sets of observables one will have to define a both a **baseline and an optimum network of space and ground-based instrumentation,** which could monitor such variables with sufficient accuracy and in real-time.
- **NOTE: Any future observational network should be able to do a little better than the bare minimum requirement and - out of principle - always also allow for new science emergence, to prepare for potentially growing future SWx user requirements**.
- Any European network for space weather observations in space and on the ground should be embedded in and **coordinated with a global effort of other agencies and nations** - coordination implies both complementarity and comparability in terms of location, type of measurement, and intercalibration!
- The planned **ESA Lagrange mission to L5 for improved solar and solar wind monitoring** in concert with other international efforts at L1 is one **perfect example for such coordination.**

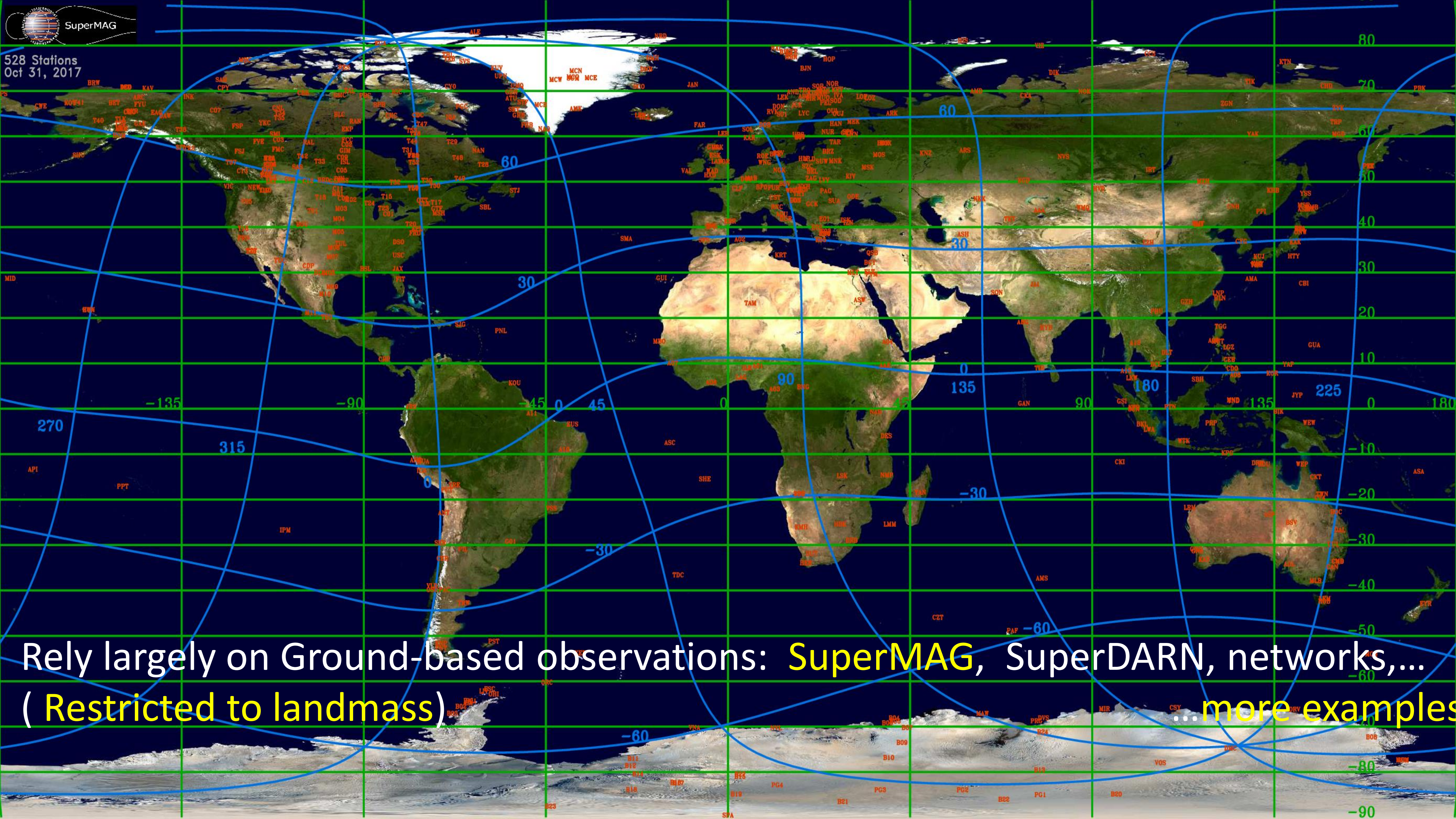




Future Space Weather Services and Science will always have to rely on major missions, in particular with respect to the Sun and Heliosphere

The combined upstream Observatories at L1 (NASA) and L5 (ESA) are excellent examples how to satisfy such needs…

GEOSPACE is different !
We cannot have " 24/7 " Themis or Cluster missions…


SuperMAG
528 Stations
Oct 31, 2017
Rely largely on Ground-based observations: SuperMAG, SuperDARN, networks,…
(Restricted to landmass)
…more examples

AMPERE : A good example of a fleet of small S/C used for SWx purposes…

other examples: ESA-Swarm, Formosat TEC sounders, TEC Beacons…

…more examples in this Symposium