Deep Space Satellites for Space Weather Forecasting

Science and Technology Challenges

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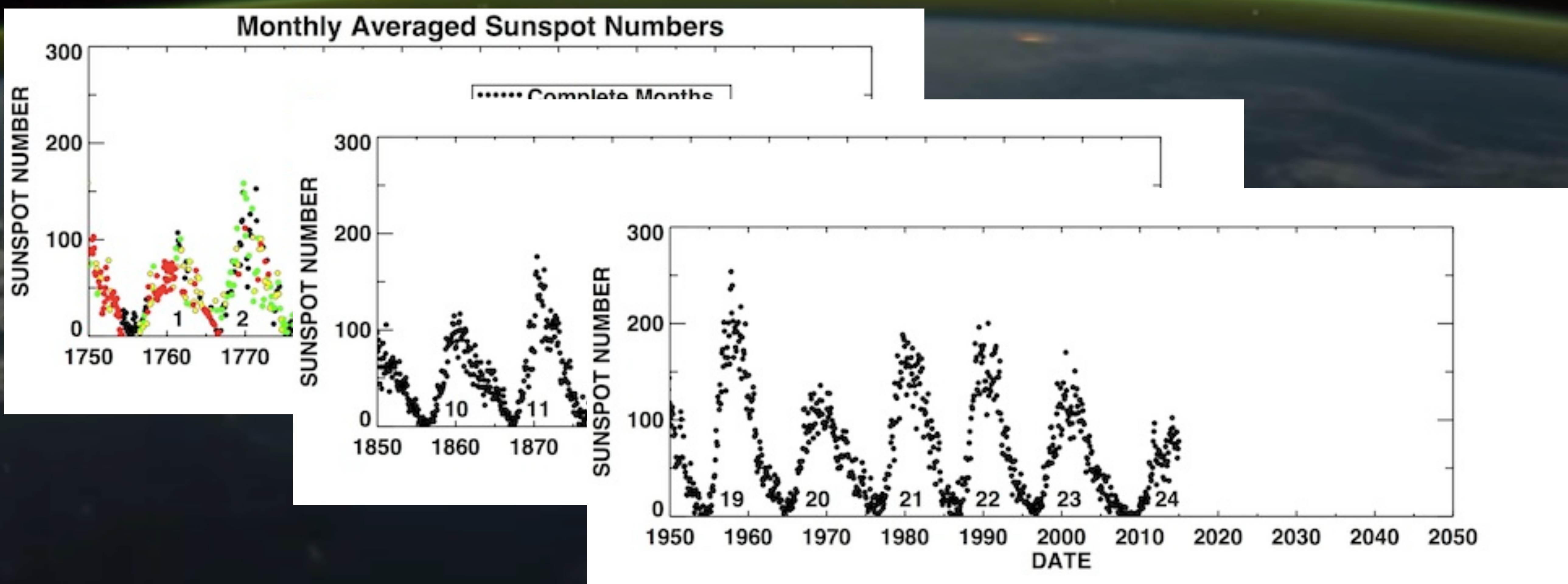
National Weather Service

Outline

- Space Weather 101
- Current Deep Space Missions
  - NASA/SOHO
  - NASA/ACE
  - NASA/ STEREO
  - NOAA/DSCOVR
- Future Deep Space Missions
  - Science Challenges
  - Technology challenges
- Conclusions

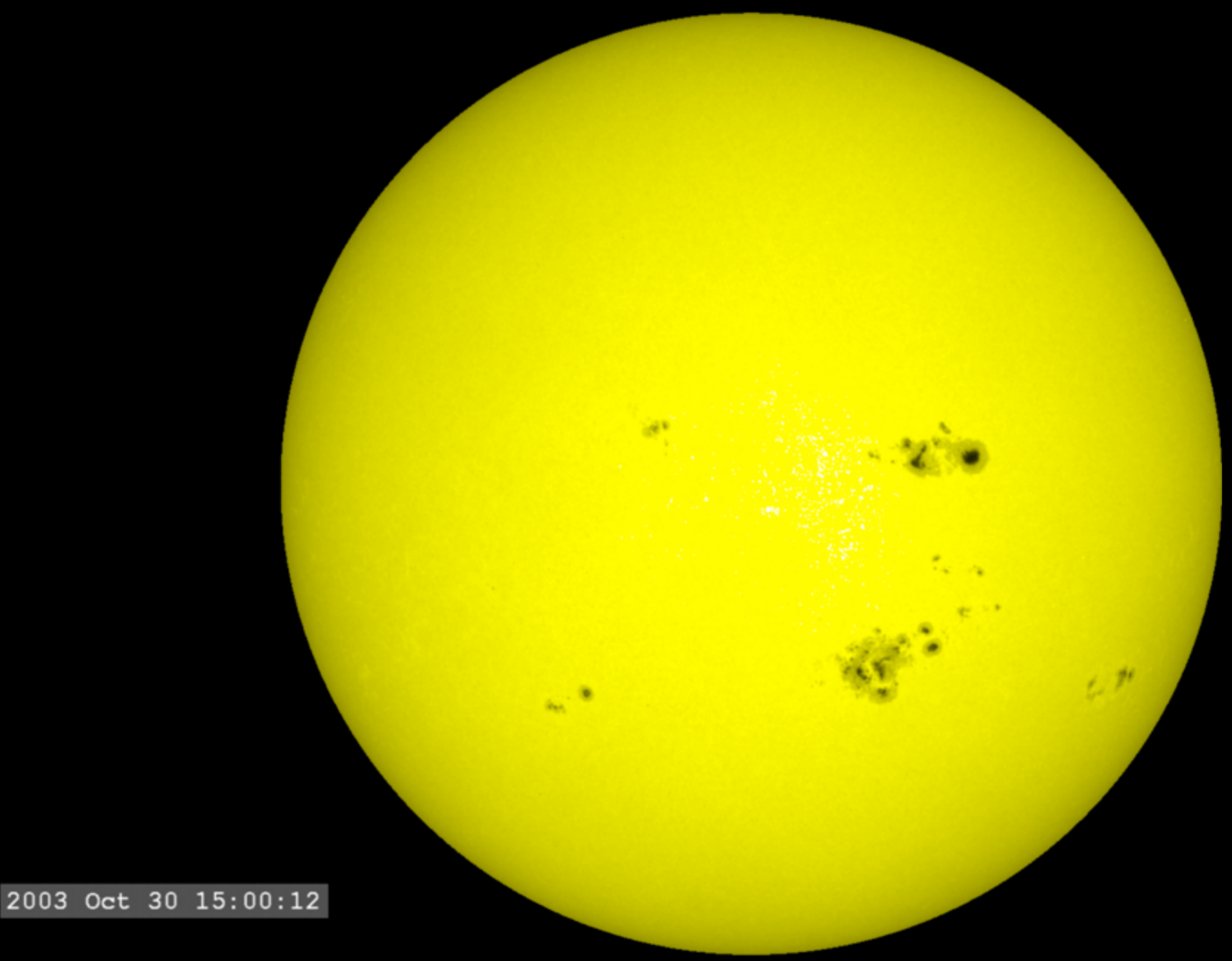
Space Weather 101

- We live in the outer atmosphere of a magnetically active G2V star we call the Sun.
  - The global solar magnetic field cycles every ~22 years.
  - The number of sunspots (“magnetic storms on the Sun”) peaks every ~11 years.



Space Weather 101

- Sunspots show where the magnetic field is concentrated into "Active Regions"

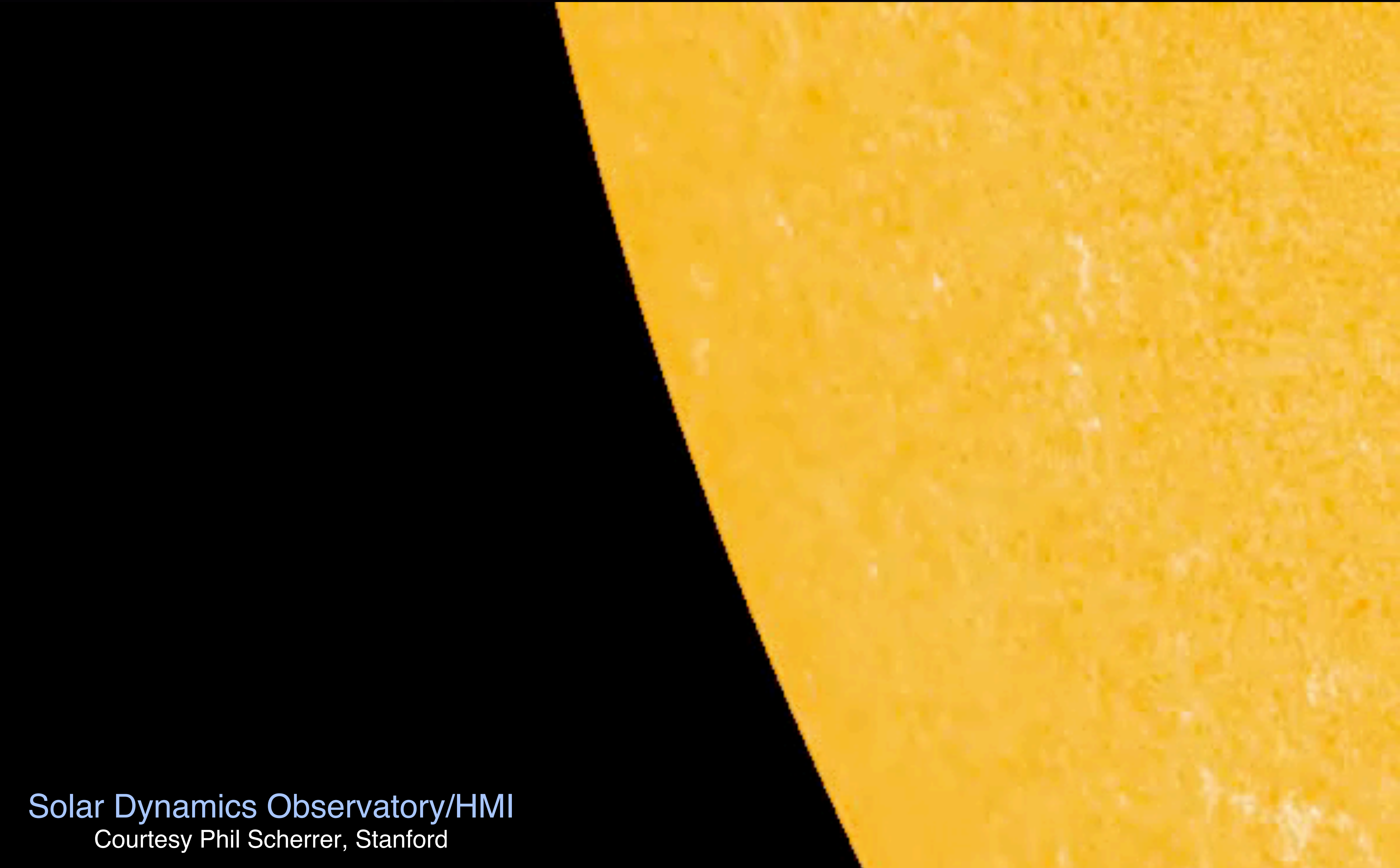


White Light

Magnetic Field

Space Weather 101

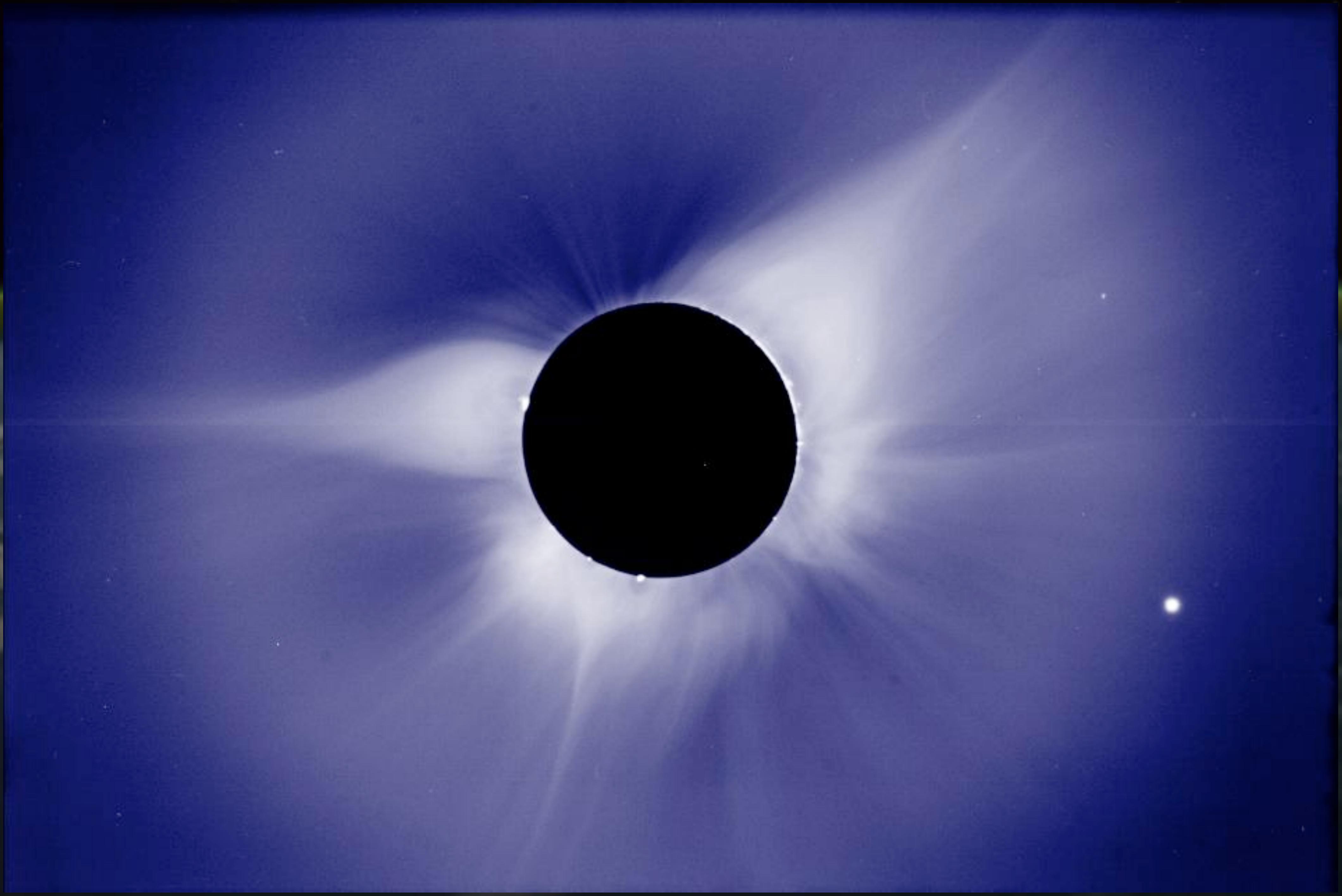
- Sunspots are dynamic convective structures…



Solar Dynamics Observatory/HMI
Courtesy Phil Scherrer, Stanford

Space Weather 101

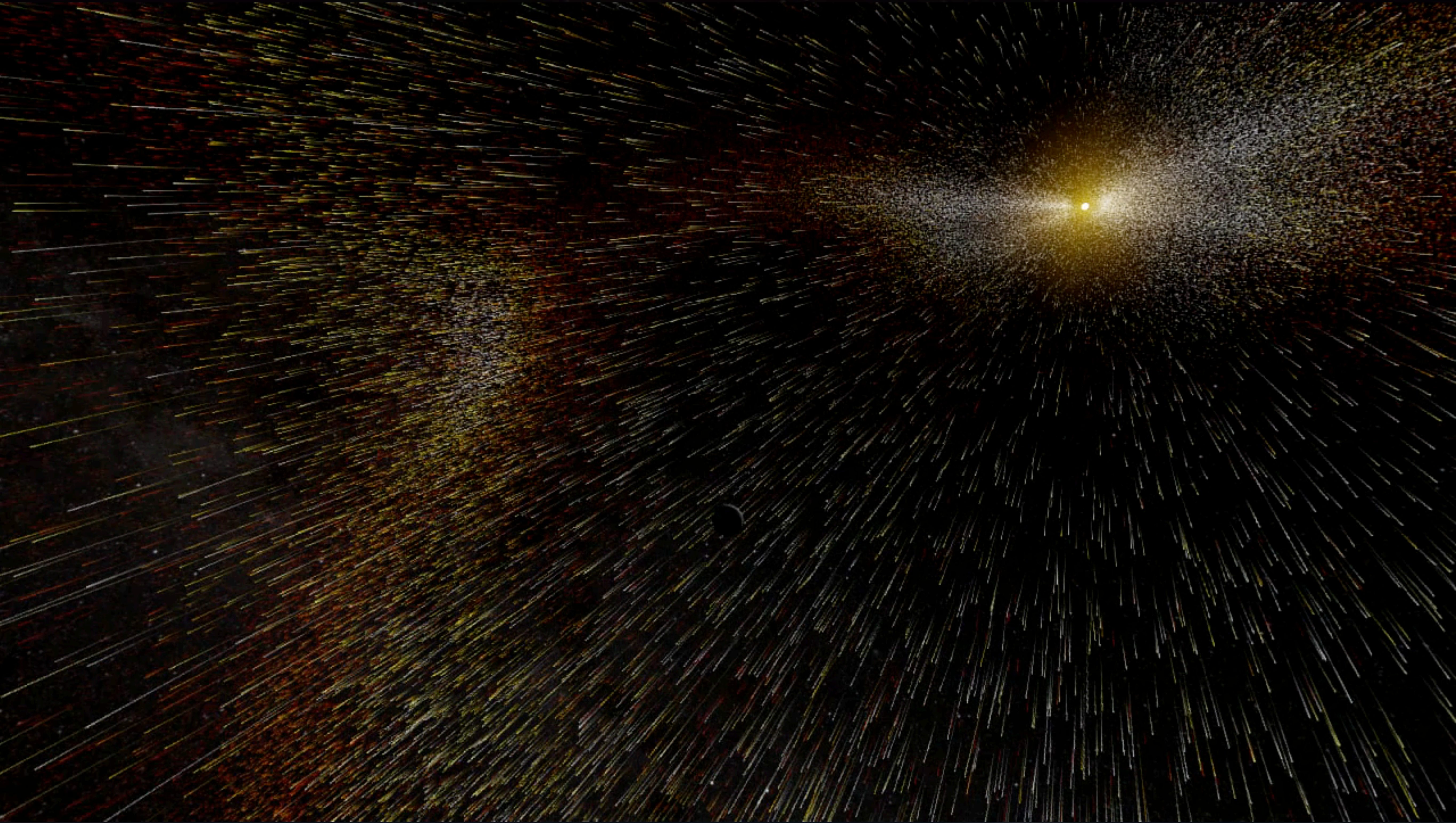
- The Sun's outer atmosphere or "corona" is heated to $>10^6$ K by this "magnetohydrodynamic" activity.



12 November 1966 Solar Eclipse at Pulacayo, Bolivia
Courtesy NCAR/HAO

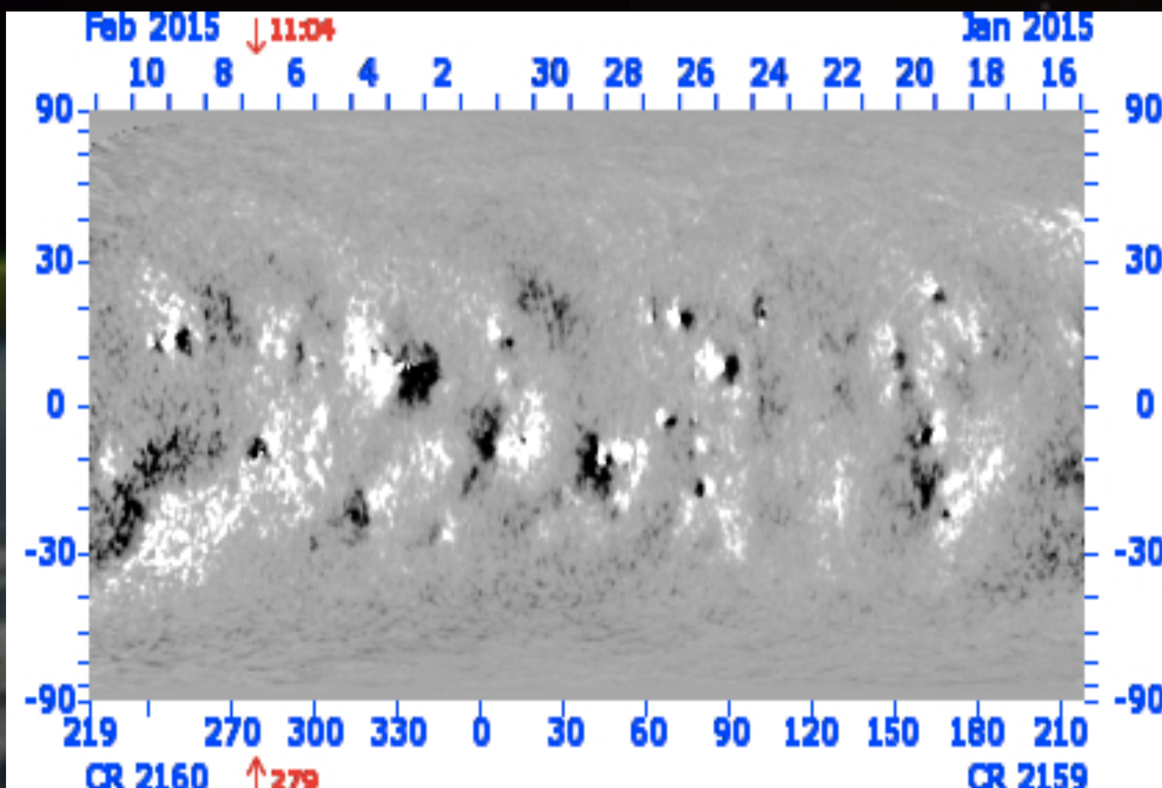
Space Weather 101

- The magnetically heated corona expands into space to form a supersonic time varying "solar wind".



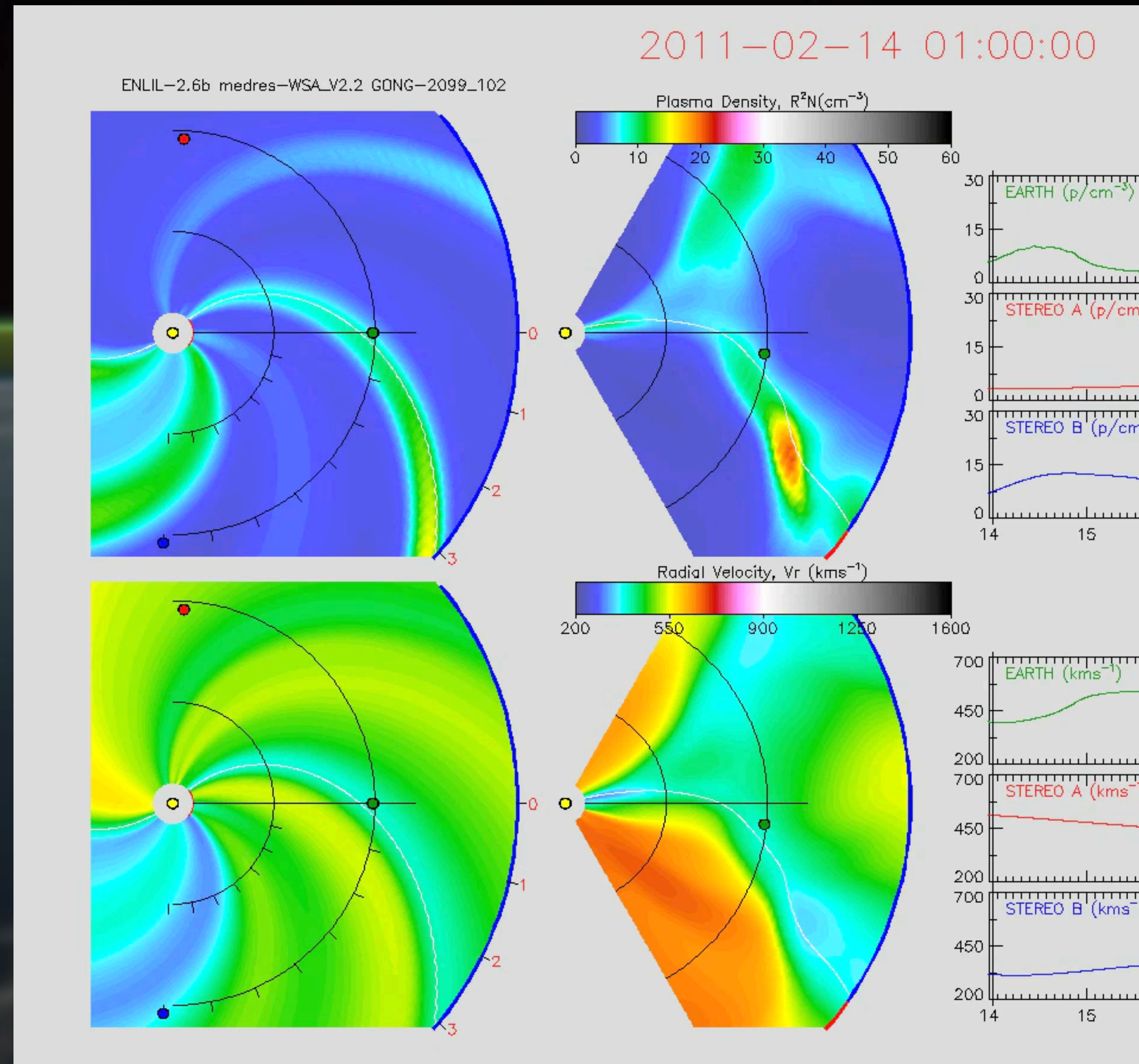
Space Weather 101

- Solar rotation results in a "Parker Spiral" of solar wind.



GONG Solar magnetic field map

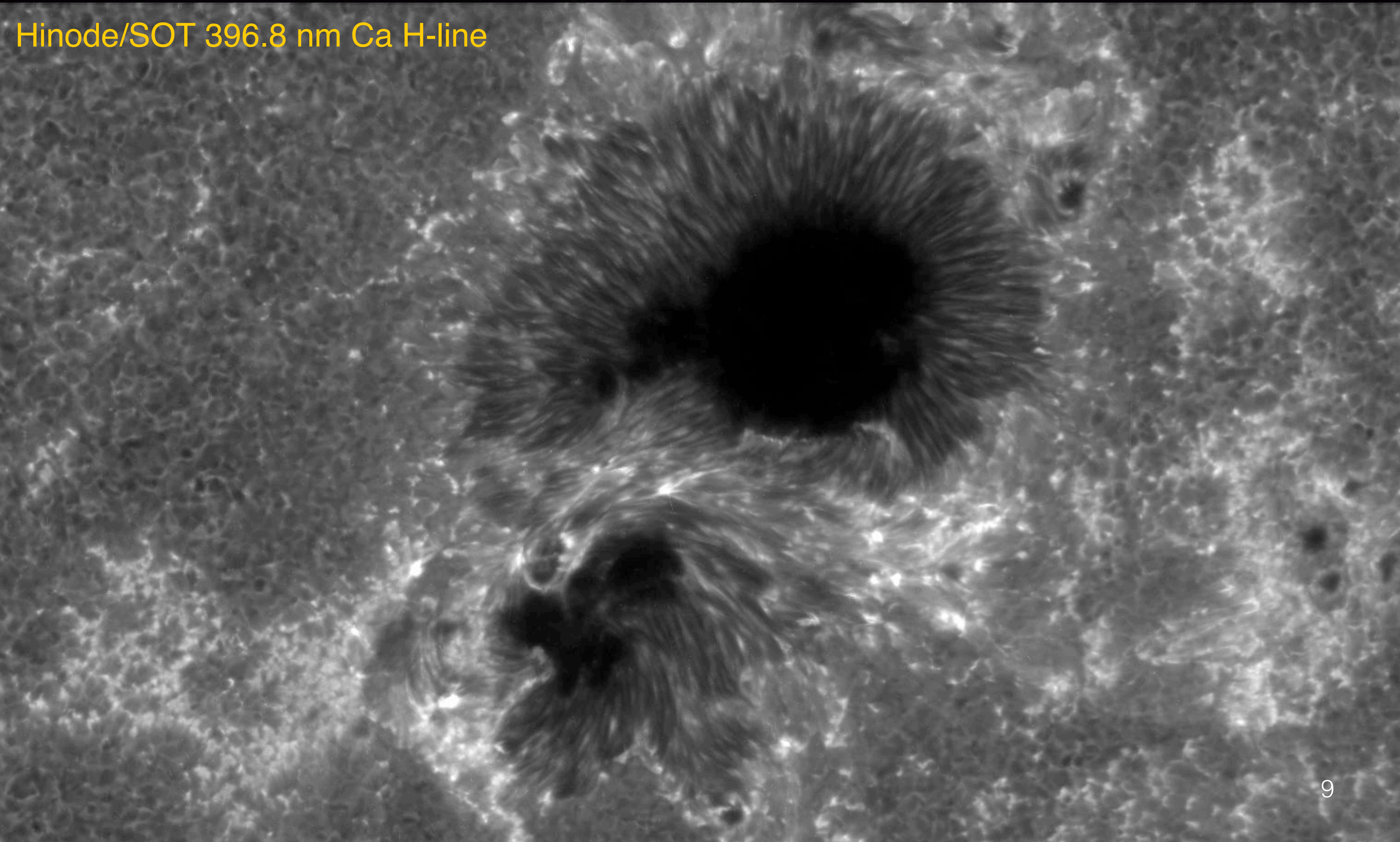
Courtesy of National Solar Observatory



Enlil Solar Wind Model

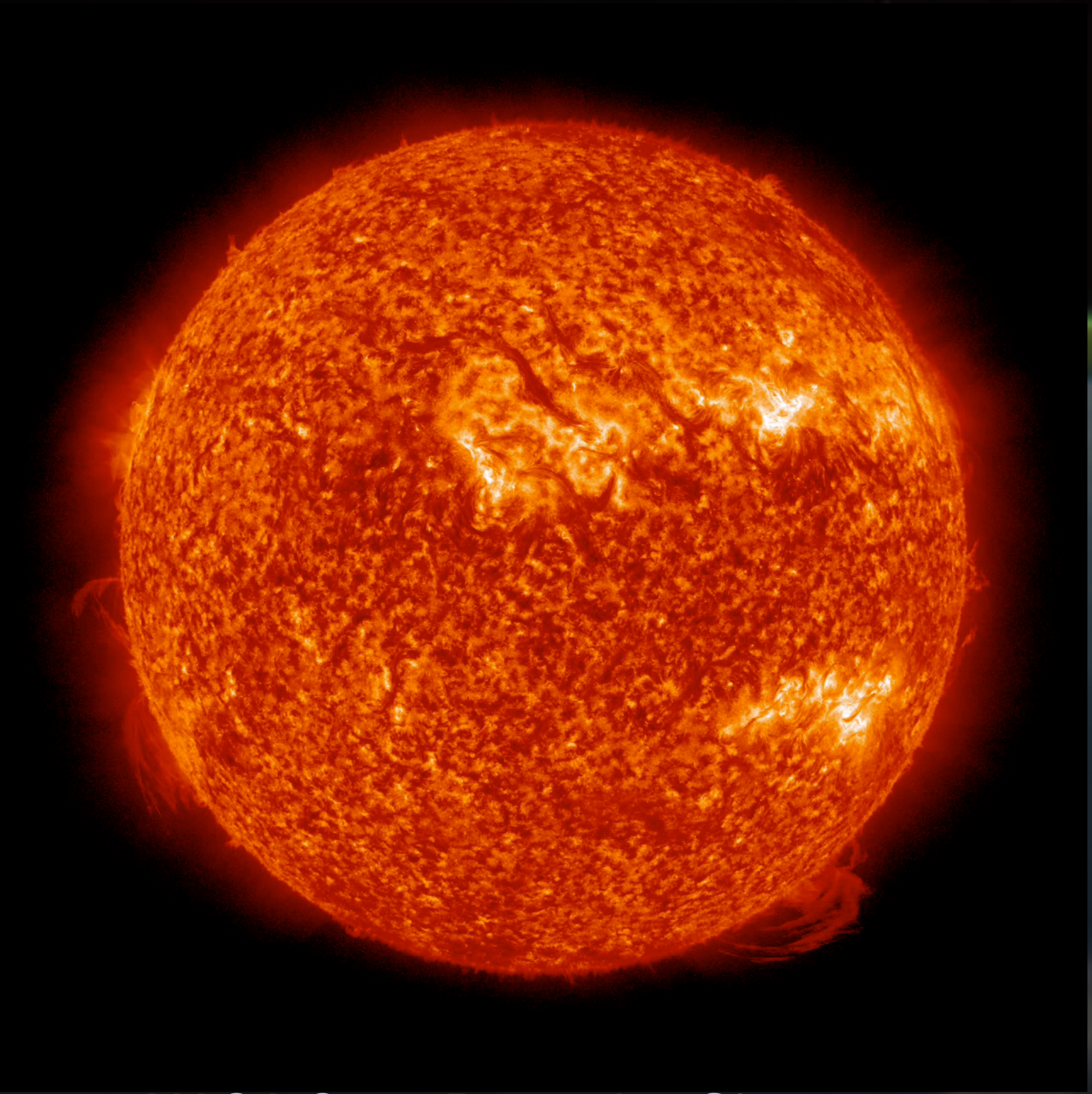
Space Weather 101

- Sunspots occasionally “flare” due to “magnetic reconnection”.

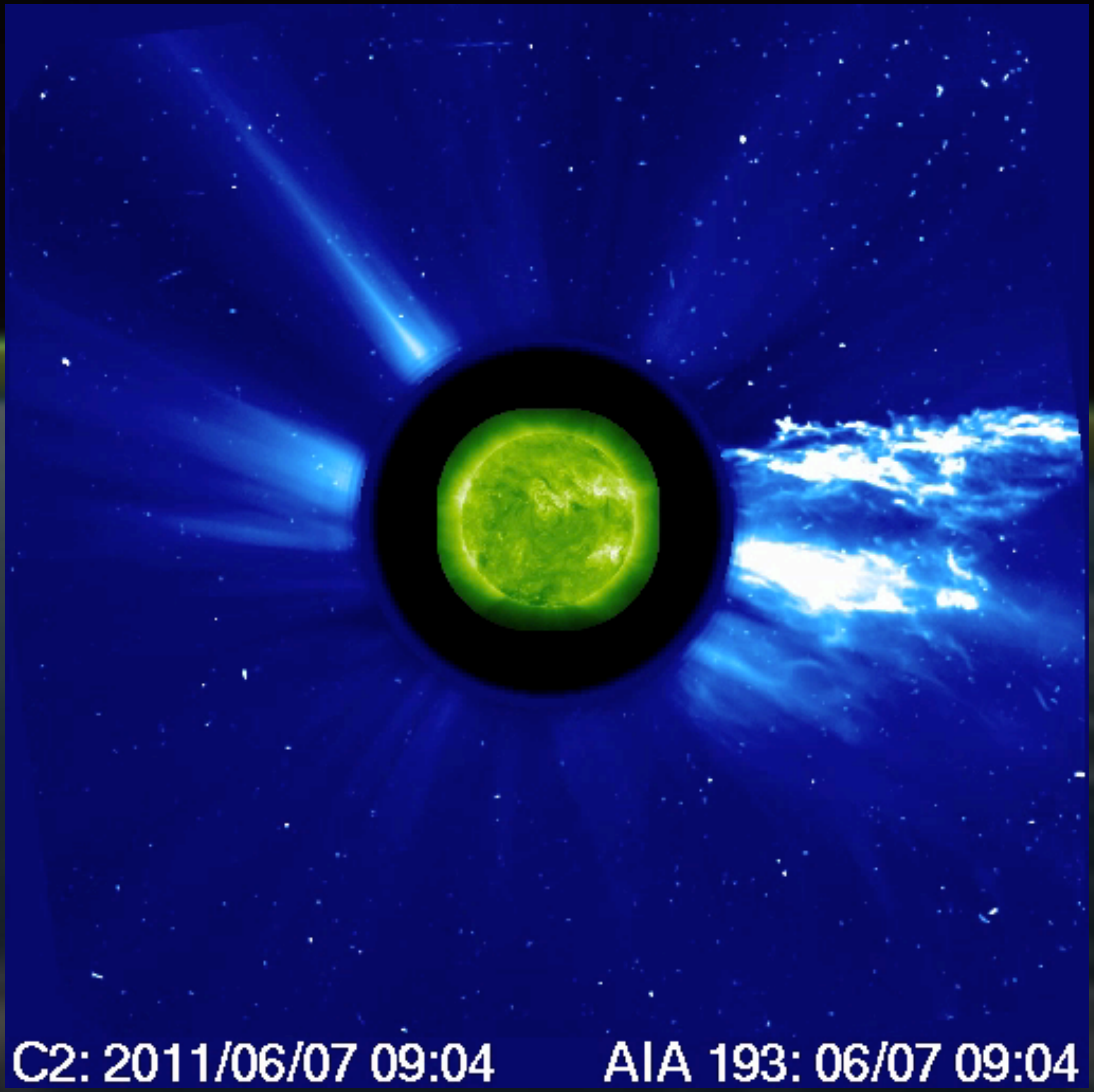


Space Weather 101

- The same reconnection can lead to “coronal mass ejections” (CMEs).



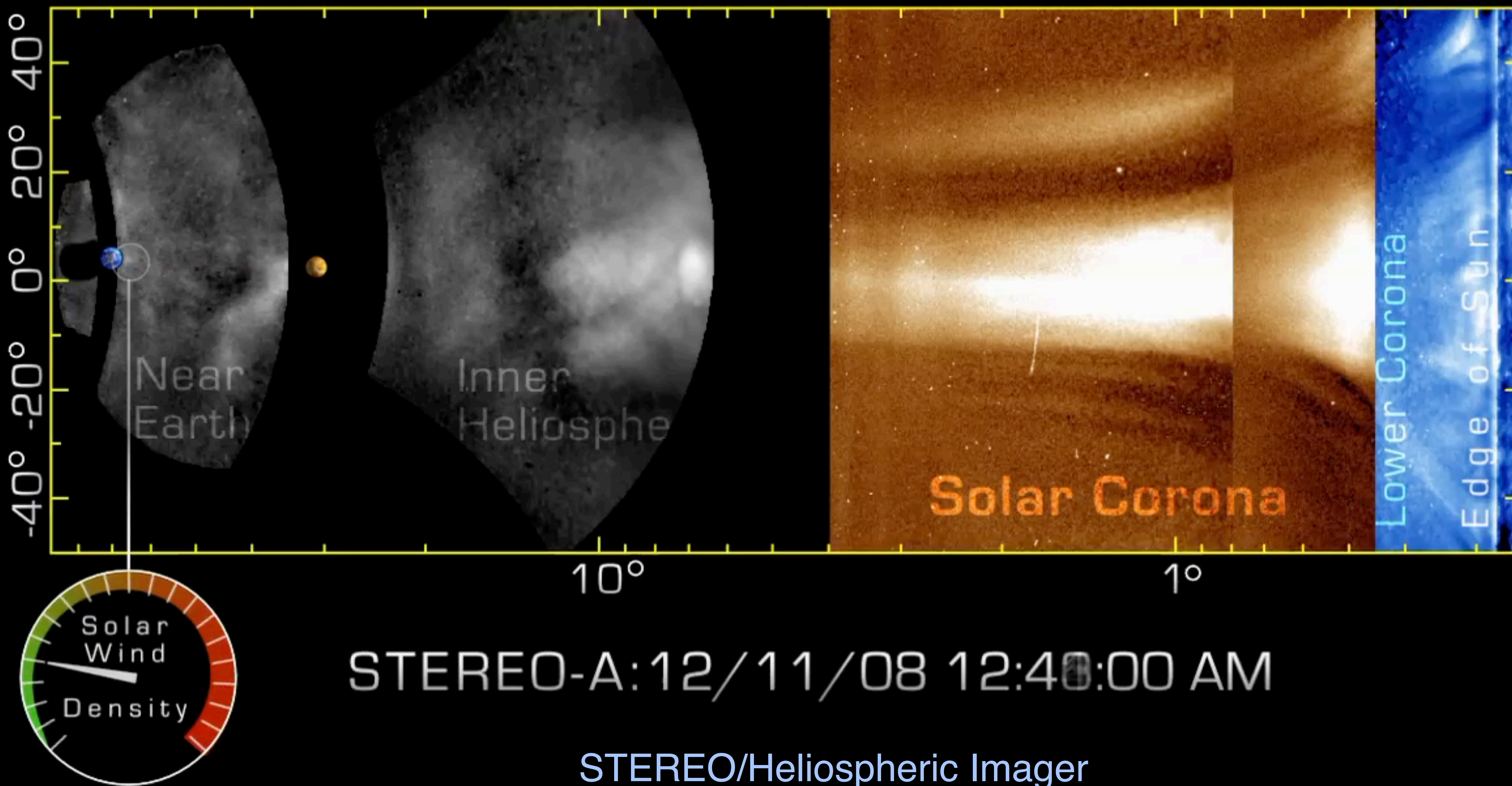
NASA Solar Dynamics Observatory



SOHO/LASCO Coronagraph + SDO

Space Weather 101

- Both the solar wind and CMEs transport coronal plasma and magnetic field into interplanetary space.

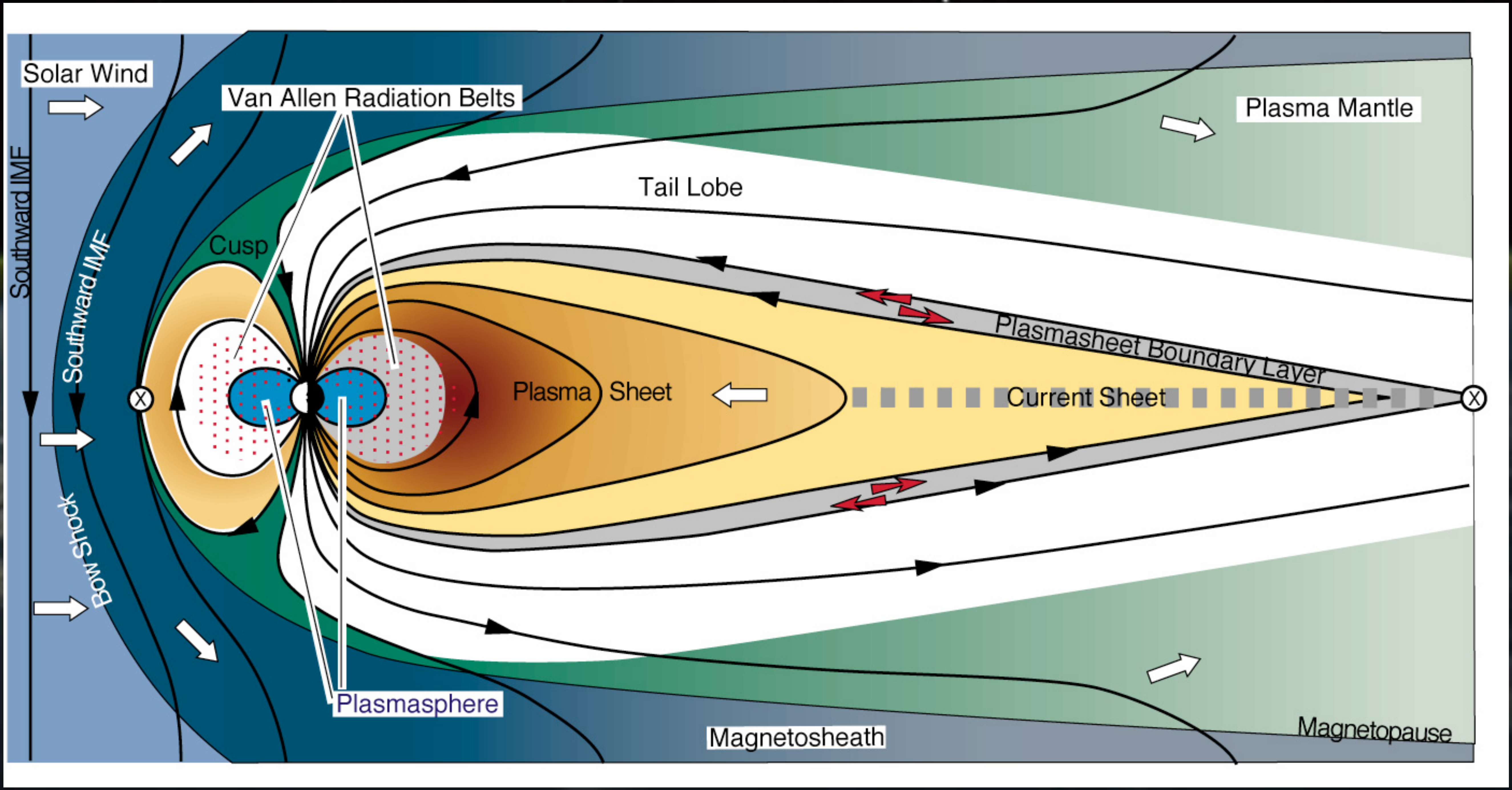


STEREO/Heliospheric Imager

Courtesy Craig DeForest, SWRI

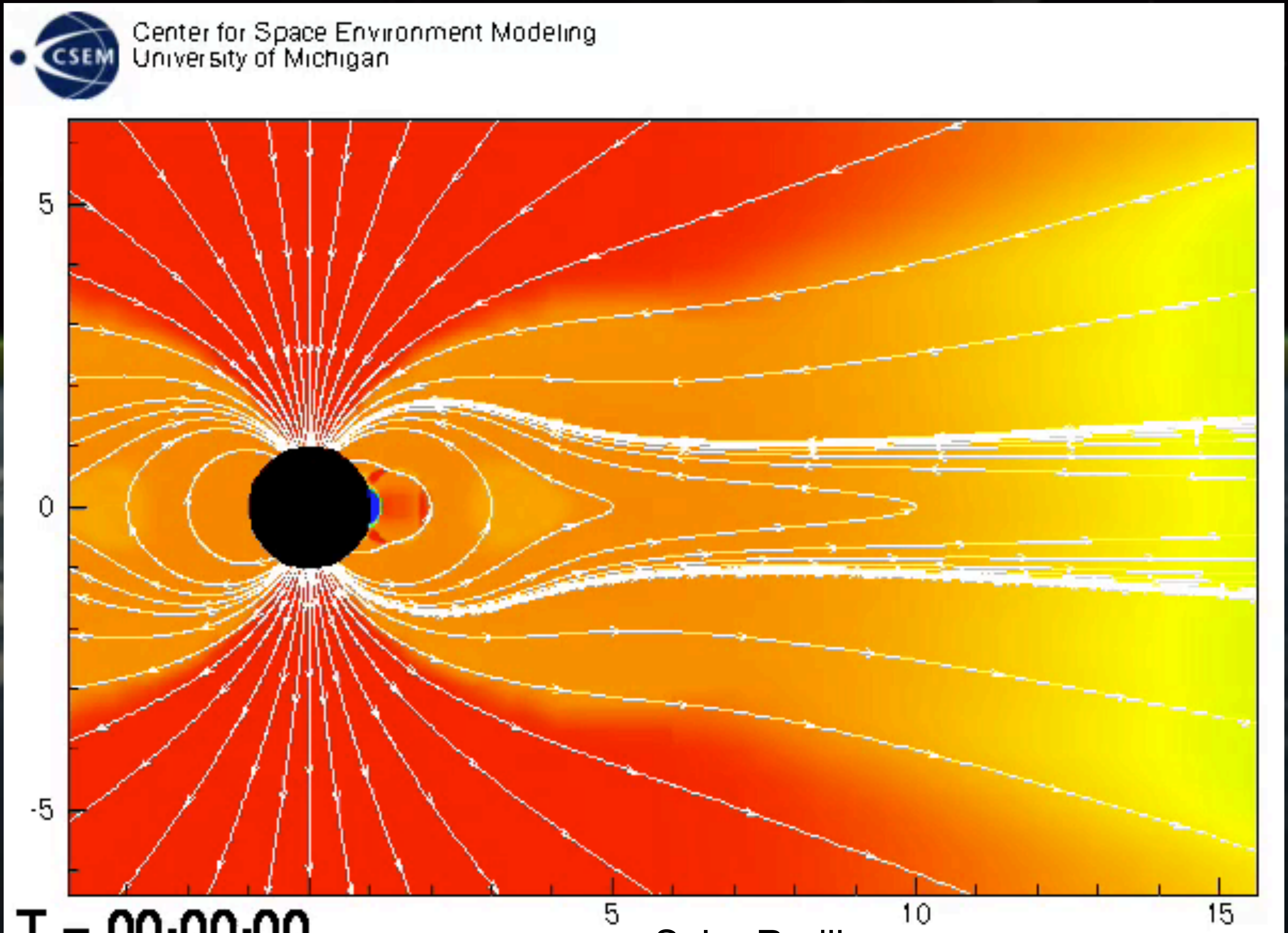
Space Weather 101

- The solar magnetic fields interaction with the Earth's "magnetosphere"



Space Weather 101

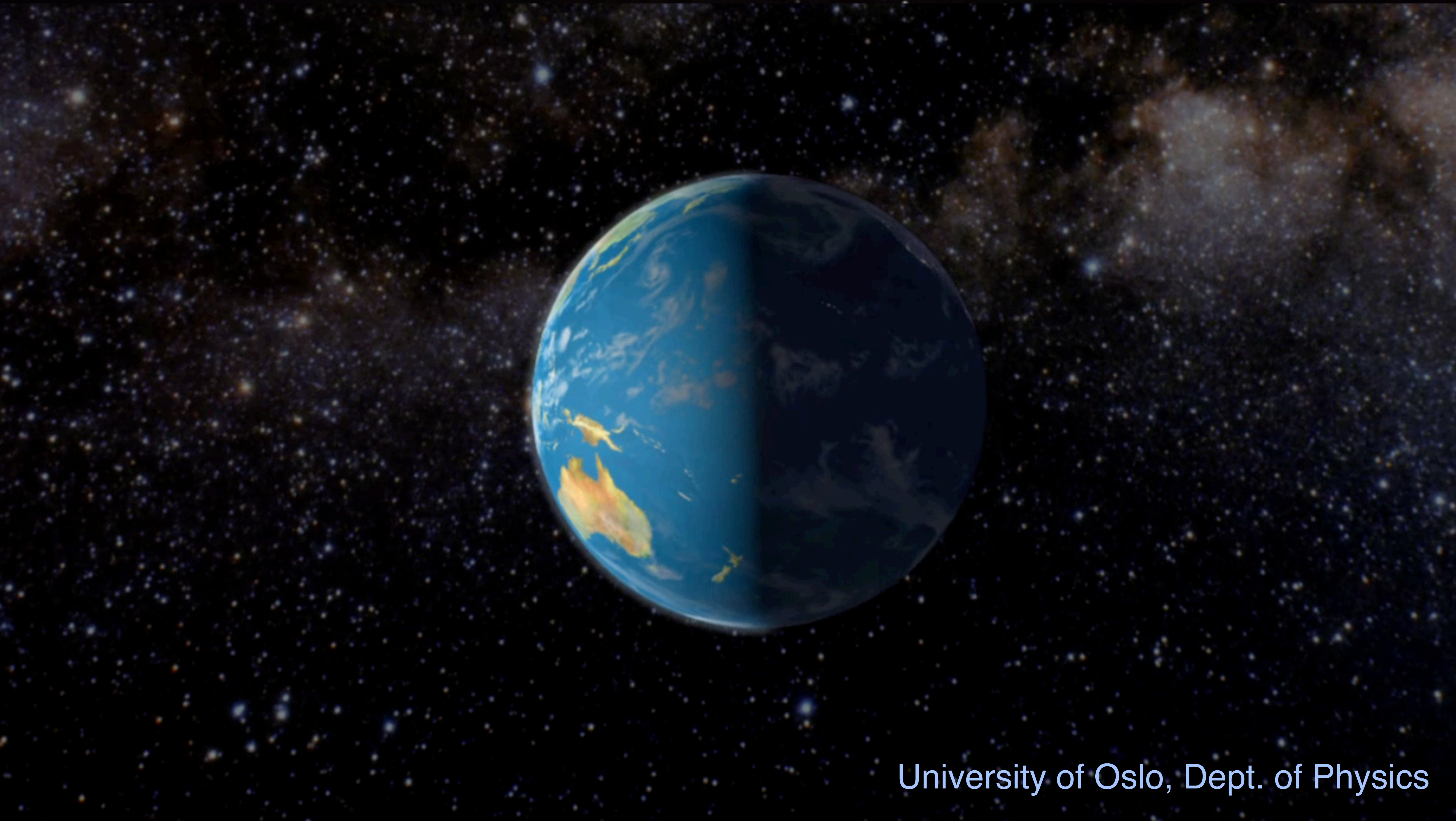
- The scale of solar eruptions is enormous



Solar Radii

Space Weather 101

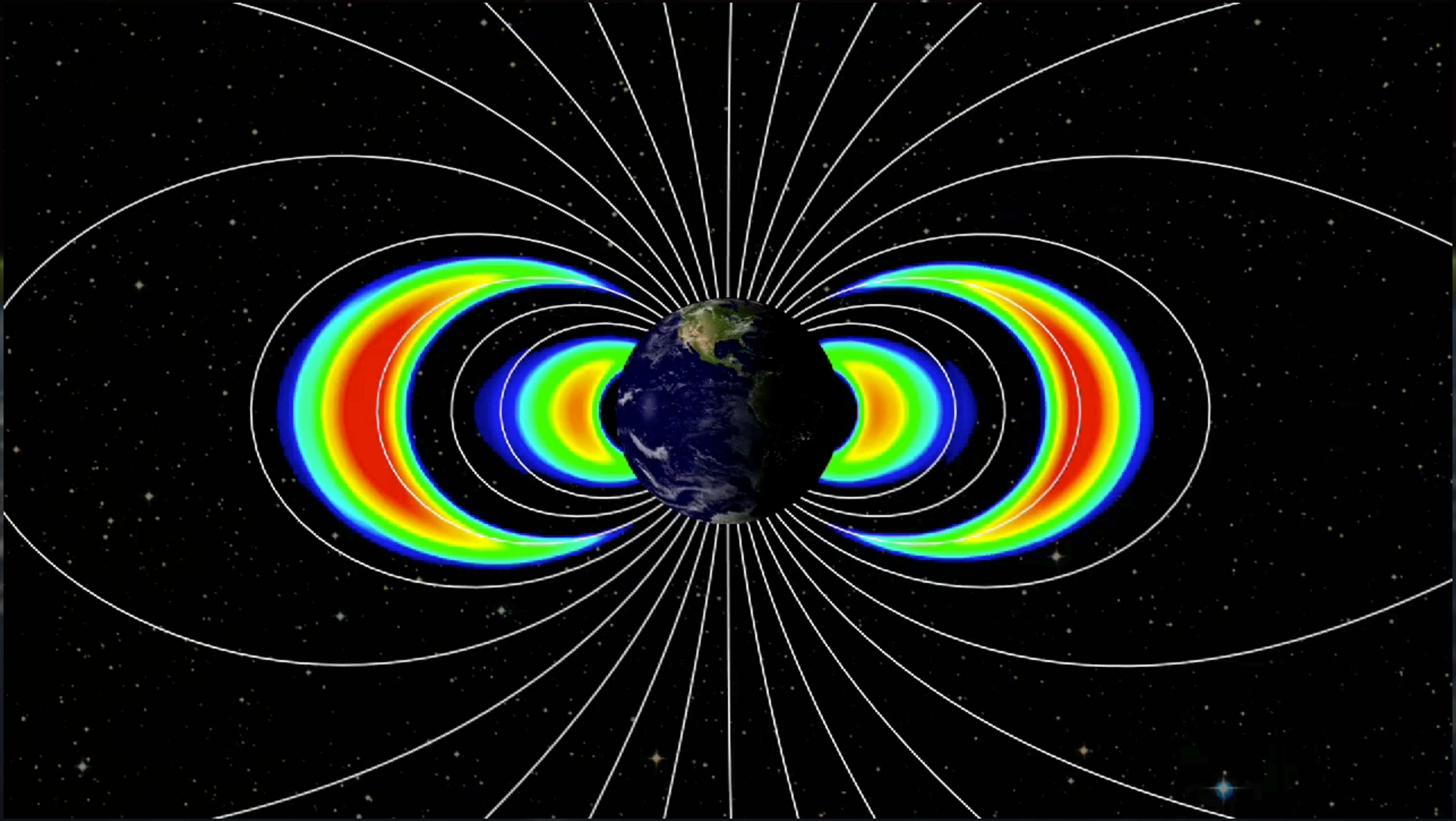
- The directionality of the solar field relative to Earth's determines the "geo-effectiveness" of the event



University of Oslo, Dept. of Physics

Space Weather 101

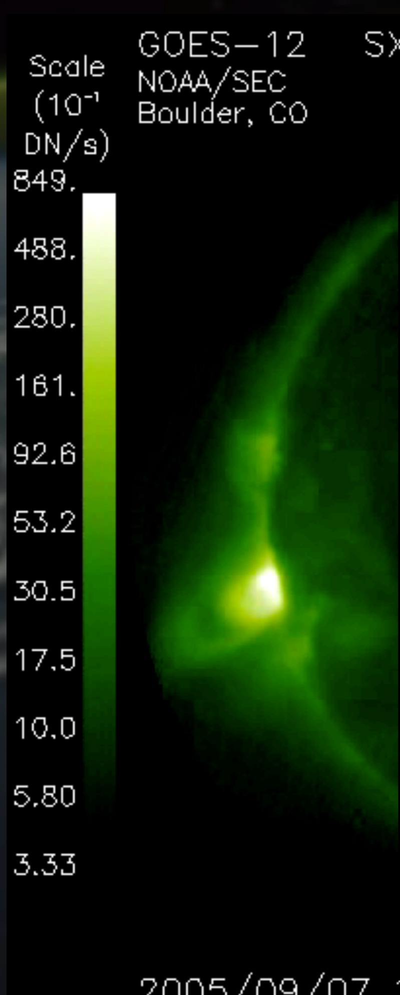
- Van Allen radiation belts change in response to geomagnetic field

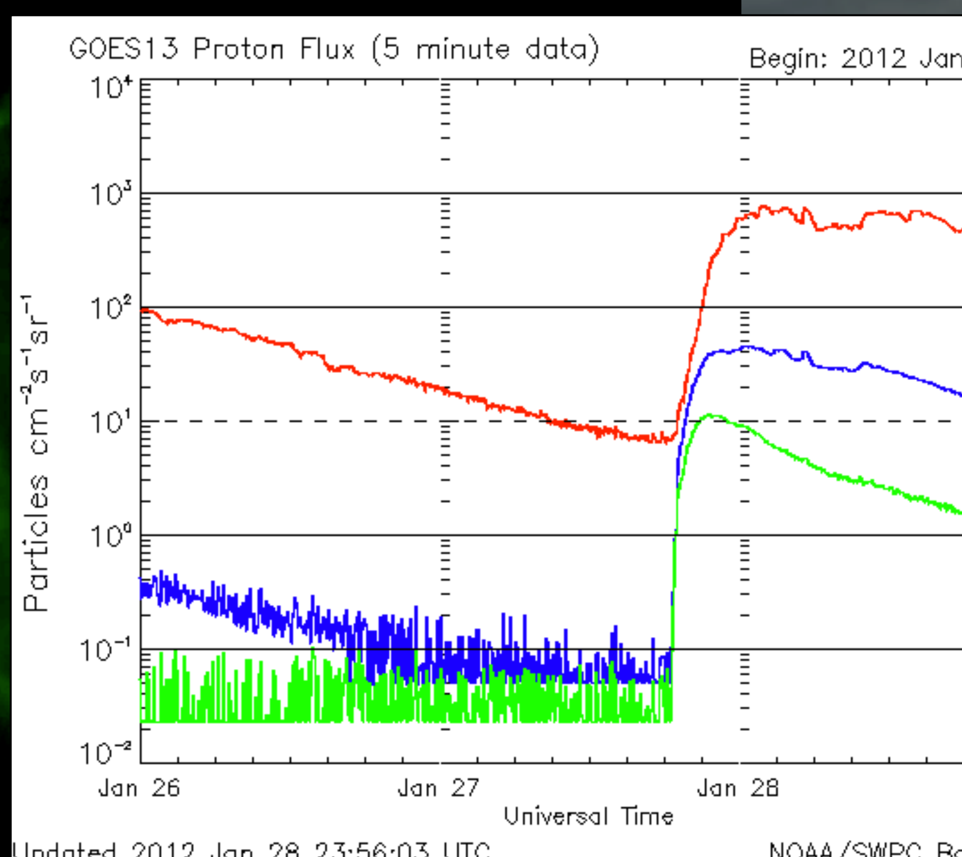


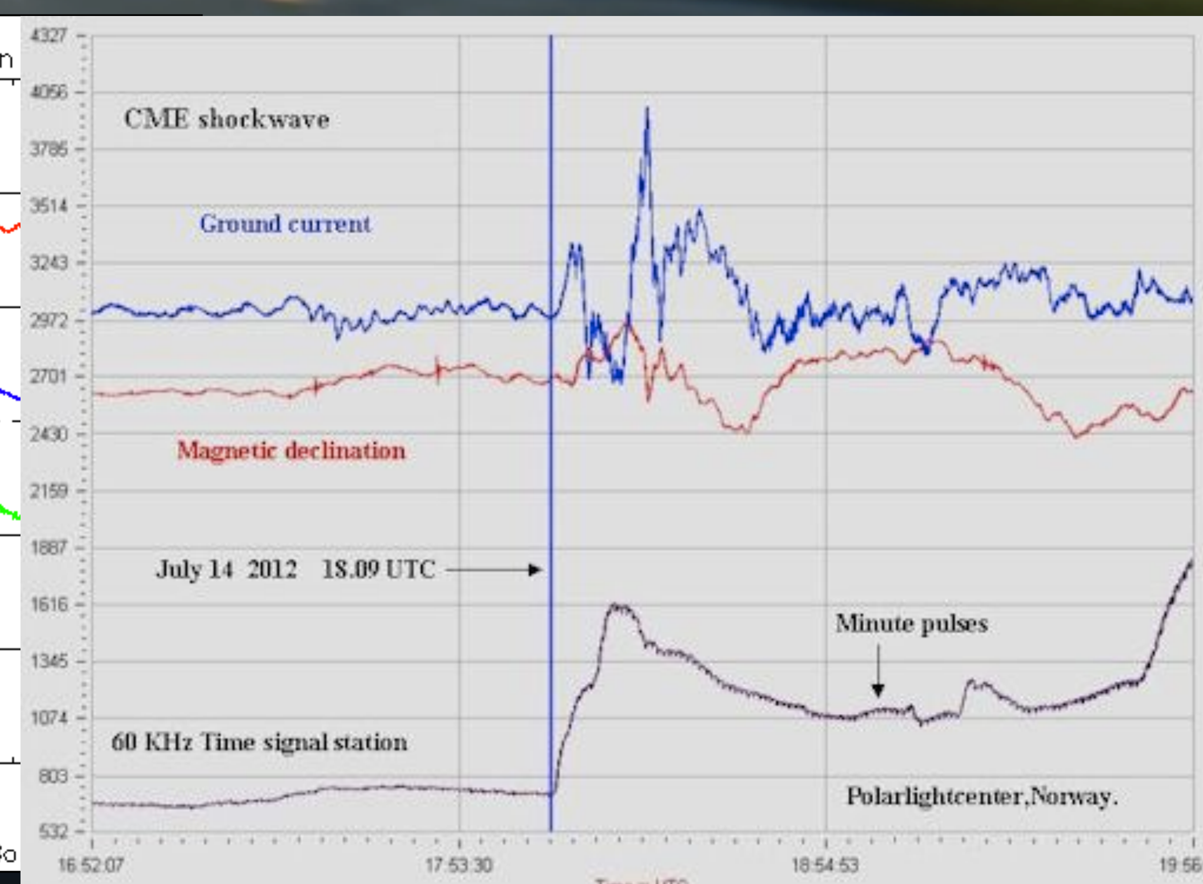
Van Allen Probes Data
Courtesy of Johns Hopkins Applied Physics Lab

Space Weather 101

- The main space weather phases of a solar eruption
  - Solar flare → Upper atmospheric ionization — immediate
  - Interplanetary shock → Energetic particle radiation — 10s of minutes
  - CME arrival at Earth → Geomagnetic storm — 12 — 72 hours







Space Weather 101

- NOAA/SWPC has scales for each phase

Radio Blackouts

Lead time: 0

			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5		HF Radio: Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a …	X20	Fewer than 1 per cycle
R 4				
R 3				
R 2				
R 1				

Solar Radiation Storms

Lead time: minutes

			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5		Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and …	10^5	Fewer than 1 per cycle
S 4				
S 3				
S 2				
S1				

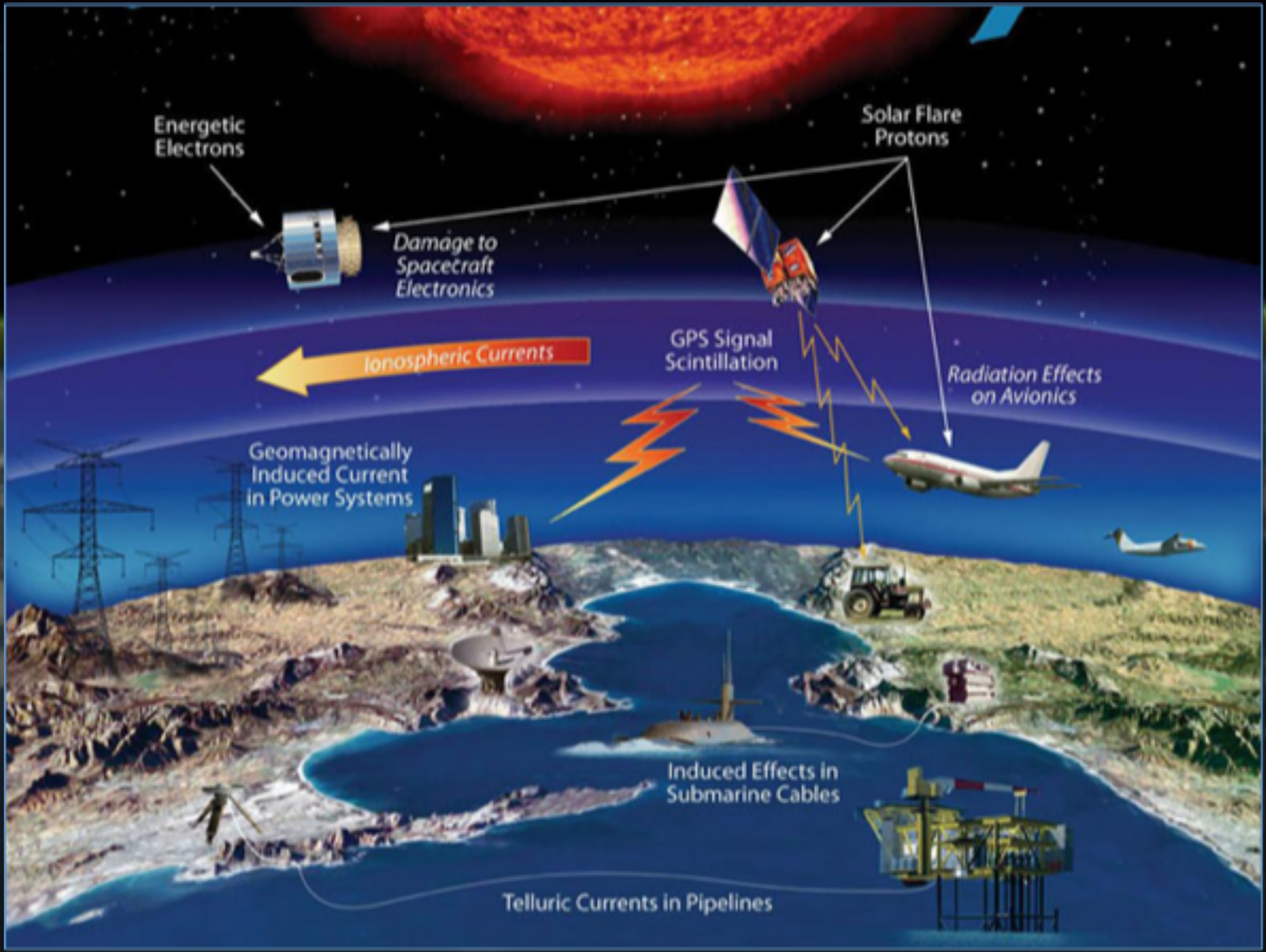
Geomagnetic Storms

Lead time: 12 — 72 hrs

			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).**	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).**	Kp=8	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).**	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).**	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).**	Kp=5	1700 per cycle (900 days per cycle)

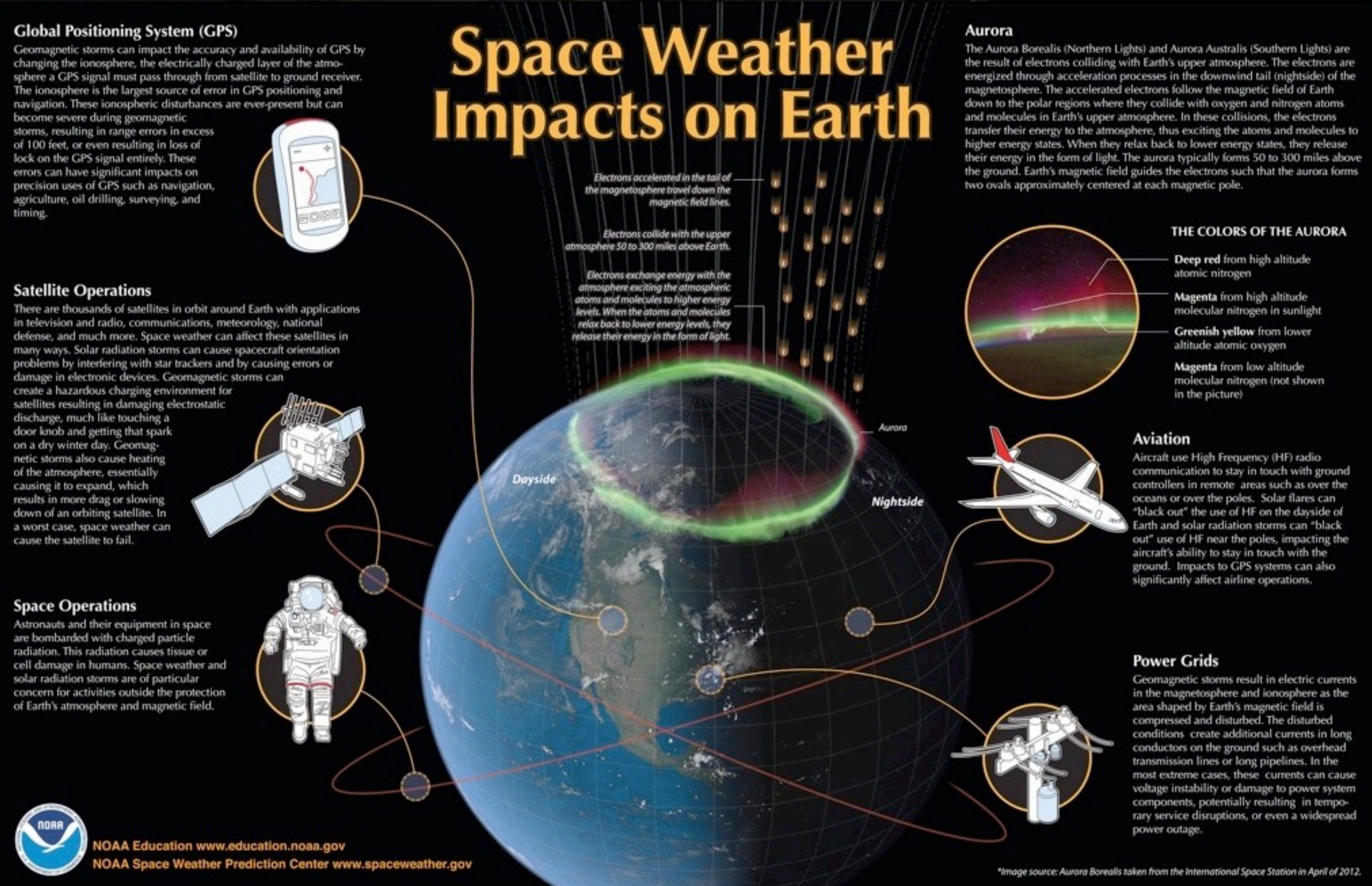
Space Weather 101

- Impacts to terrestrial technology are many…



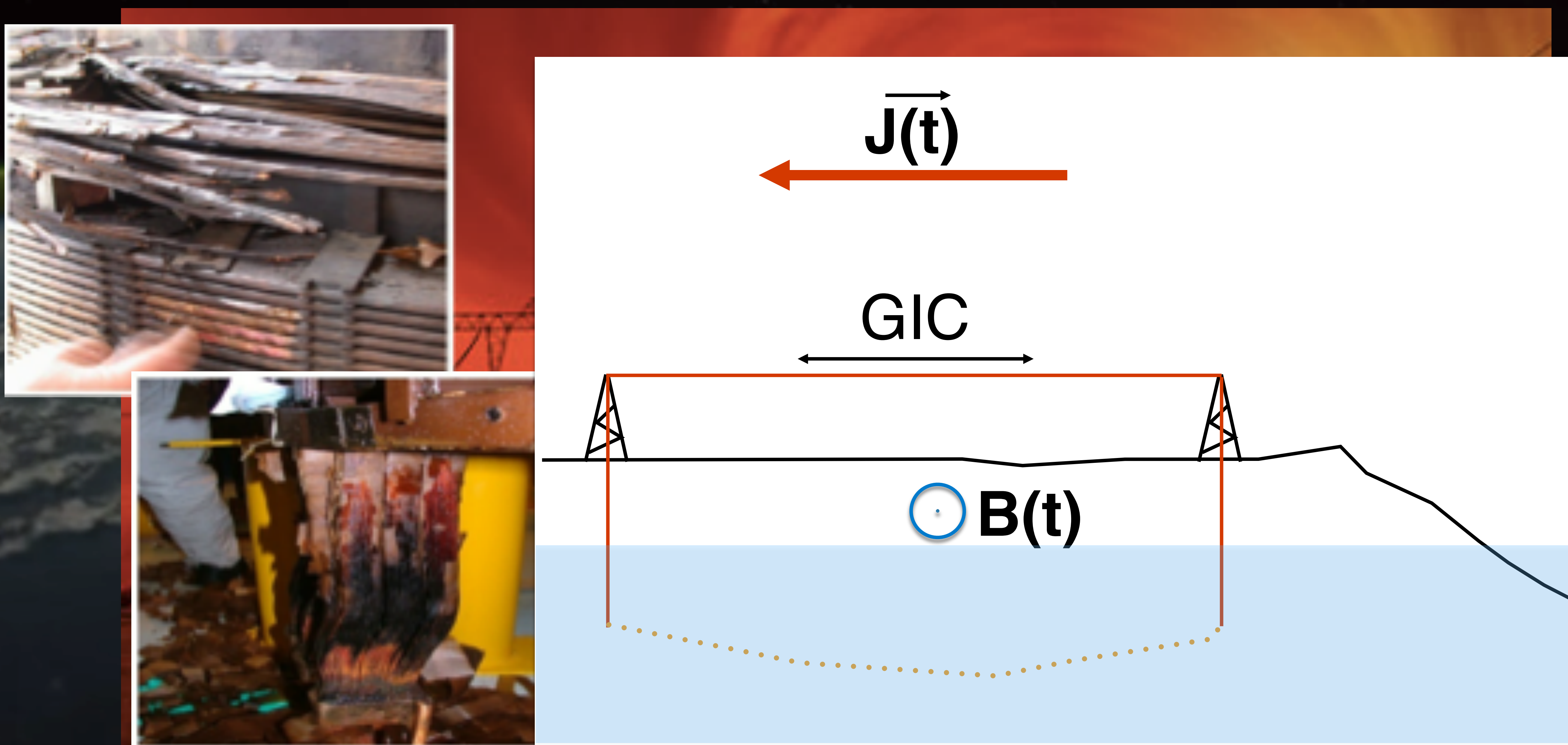
Courtesy NASA

Space Weather 101



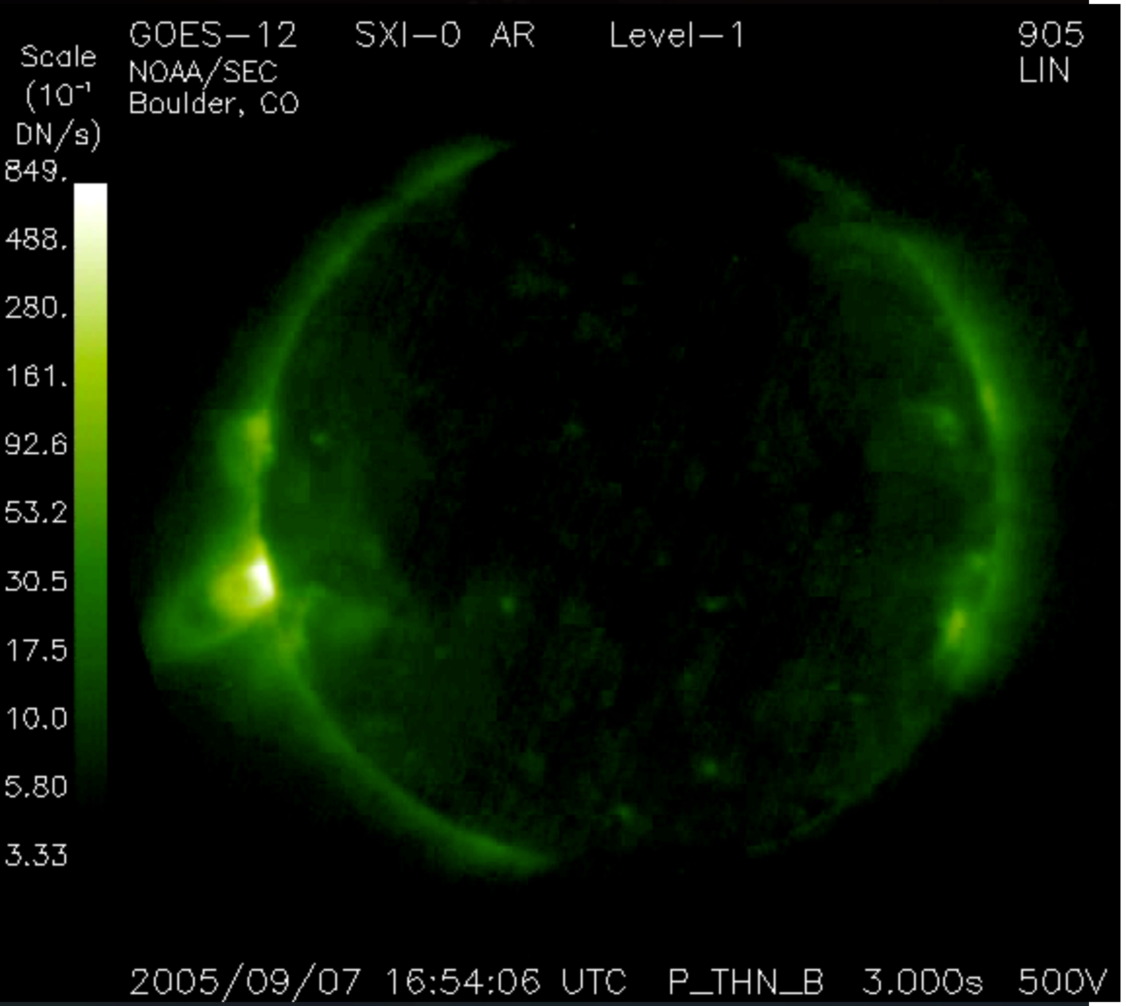
Space Weather 101

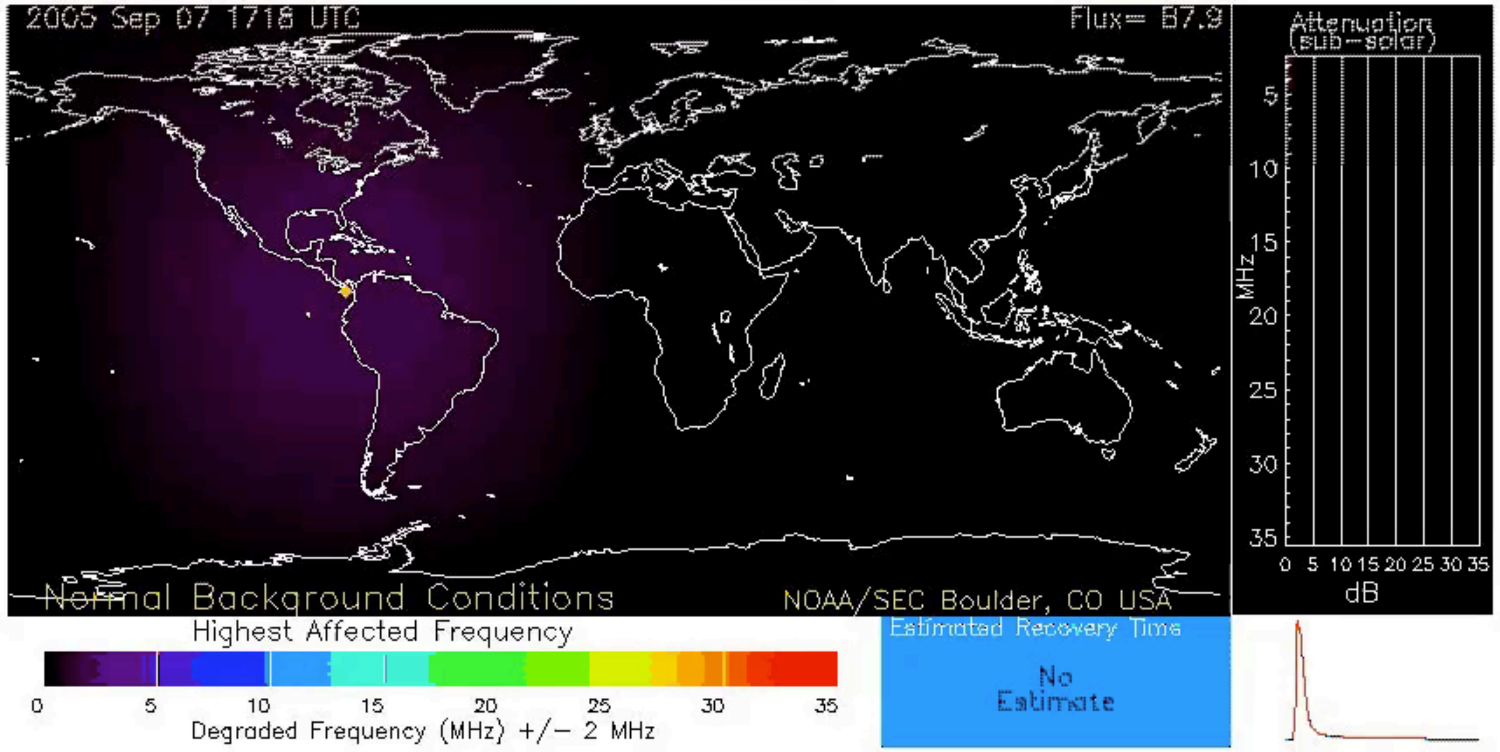
- Currents in the ionosphere create time-varying magnetic flux.
- These “Geomagnetically Induced Currents” (GIC) are picked up by long conductors such as EHV power lines.



Space Weather 101

- Impact example: solar flare→radio blackout





Space Weather 101

- Only visible manifestation of Space Weather: the Aurora *

* Astronauts in orbit report retinal proton “fireflies”

Space Weather 101

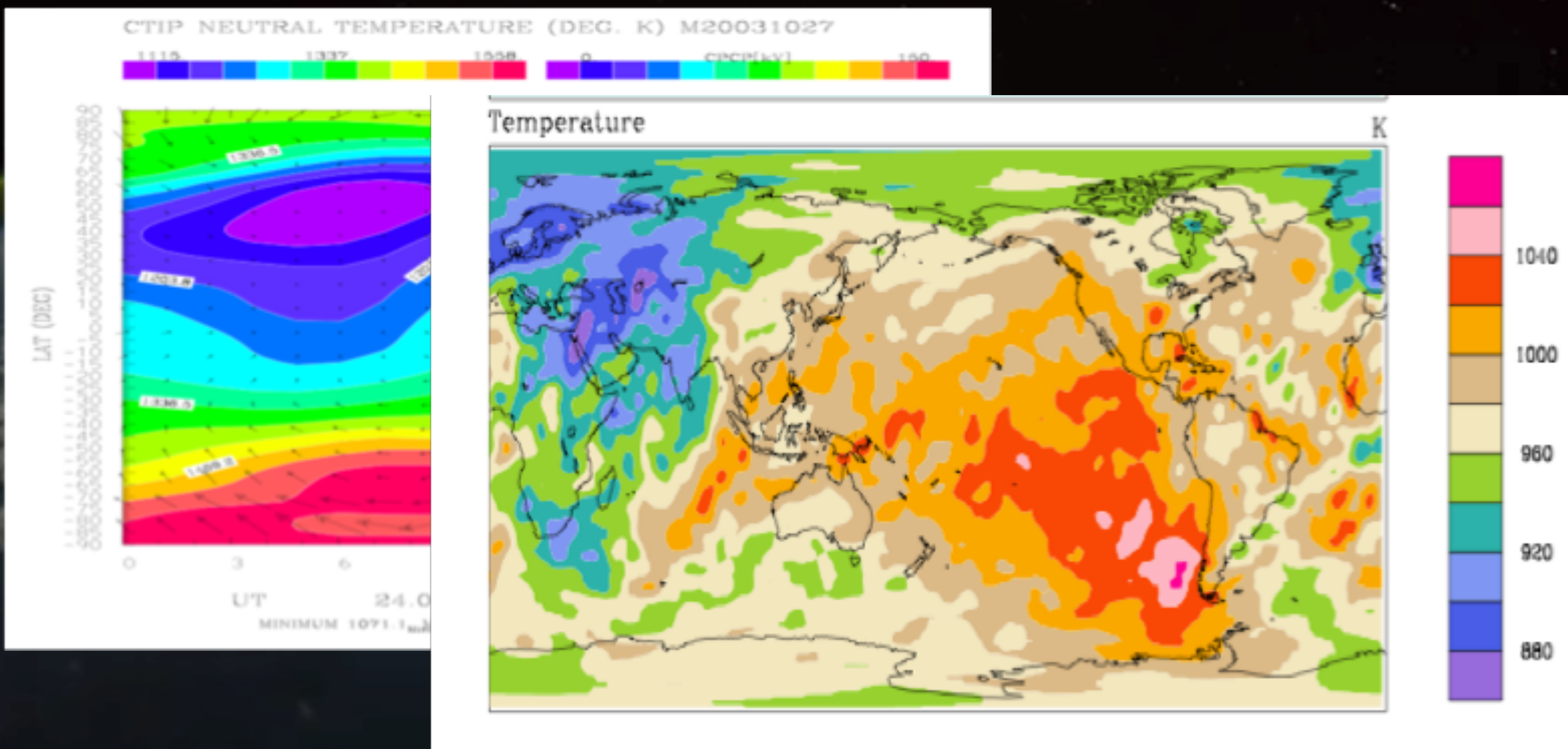
- Only visible manifestation of Space Weather: the Aurora *

22-January-2012

* Astronauts in orbit report retinal proton “fireflies”

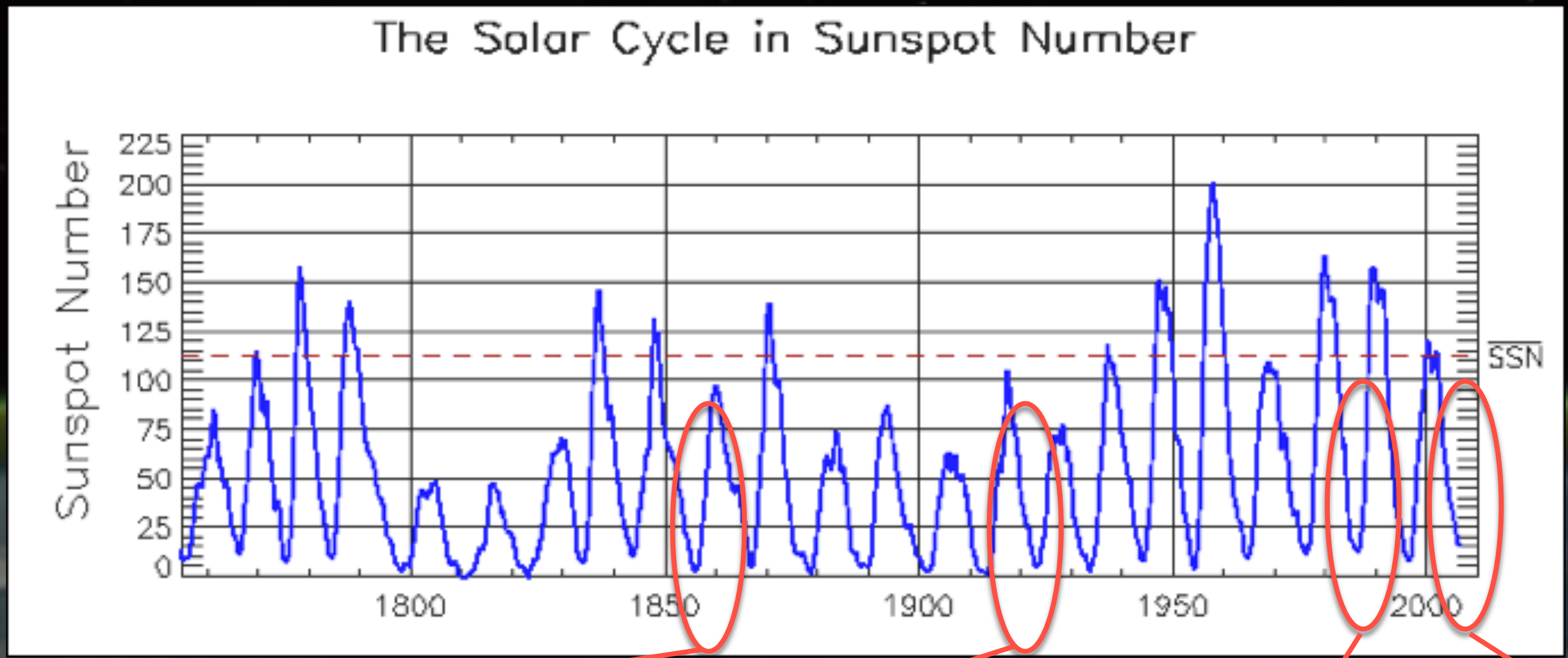
Space Weather 101

- Space Weather does not just come from the Sun: the troposphere can significantly influence the ionosphere.
- “Whole Atmosphere Models” are needed.

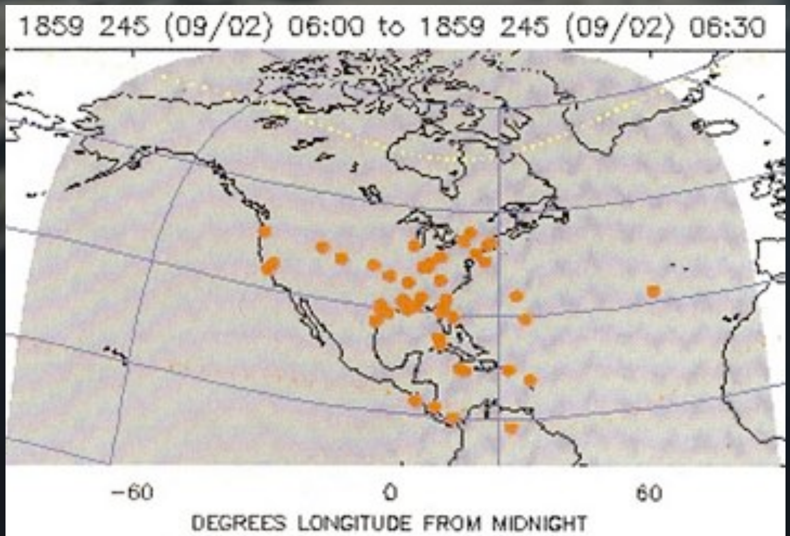


Space Weather 101

- Why worry? Extreme geomagnetic storms can occur in any solar cycle.



1859 Storm



1921 Storm

SUNSPOT CREDITED WITH RAIL TIE-UP

New York Central Signal System Put Out of Service by Play of Northern Lights.

The sunspot which caused the brilliant aurora borealis on Saturday night and the worst electrical disturbance in memory on the telegraph systems was credited with an unprecedented thing at 7:04 o'clock yesterday morning, when the entire signal and switching system of the New York Central Railroad below 125th Street was put out of operation, followed by a fire in the control tower at Fifty-seventh Street and Park Avenue.

This is the first time that a sunspot has been blamed for such a piece of mischief. From other accounts it appeared

The New York Times
Published: May 16, 1921

1989 Storm

HYDRO-QUEBEC PRESS RELEASE

Direction Relations Publiques
HYDRO-QUEBEC
MONTREAL, CANADA

MARCH 13 BLACKOUT CAUSED BY AN EXCEPTIONALLY STRONG MAGNETIC STORM

Montreal, March 15, 1989 - Hydro-Quebec confirms that the March 13 blackout was caused by the strongest magnetic storm ever recorded since the 735-kv power system was commissioned. At 2:45 AM the storm, which resulted from a solar flare, tripped five lines from James Bay and caused a generation loss of 9,450 MW. With a load of some 21,350 MW at that moment, the system was unable to withstand this sudden loss and collapsed within seconds, thereby causing the further loss of generation from Churchill Falls and Manio-Outardes.

2003 Storms

Solar eruption likely cause of power outage in Sweden

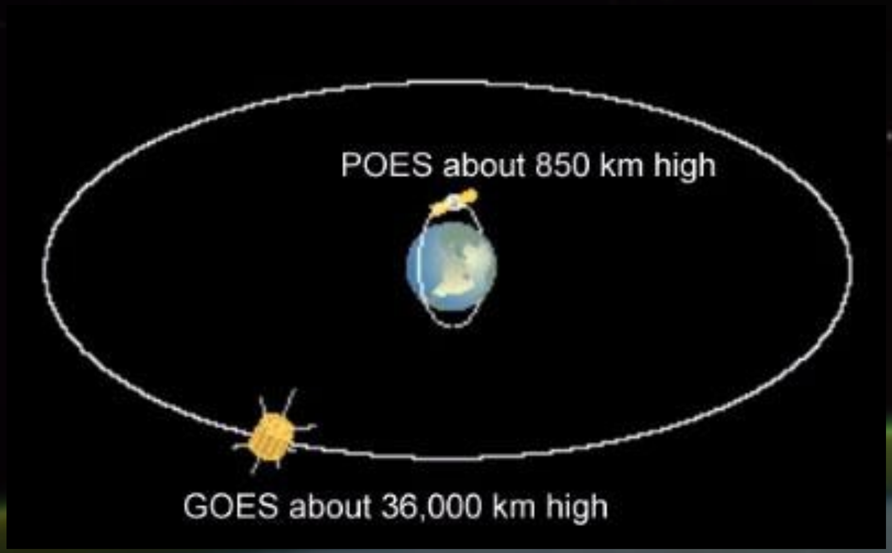
MALMOE, Sweden (AFP) Oct 31, 2003

An hour-long power outage that affected 20,000 homes in Sweden's southern city of Malmoe on Thursday was probably caused by a powerful geomagnetic storm that hit the Earth, power company Sydkraft said.

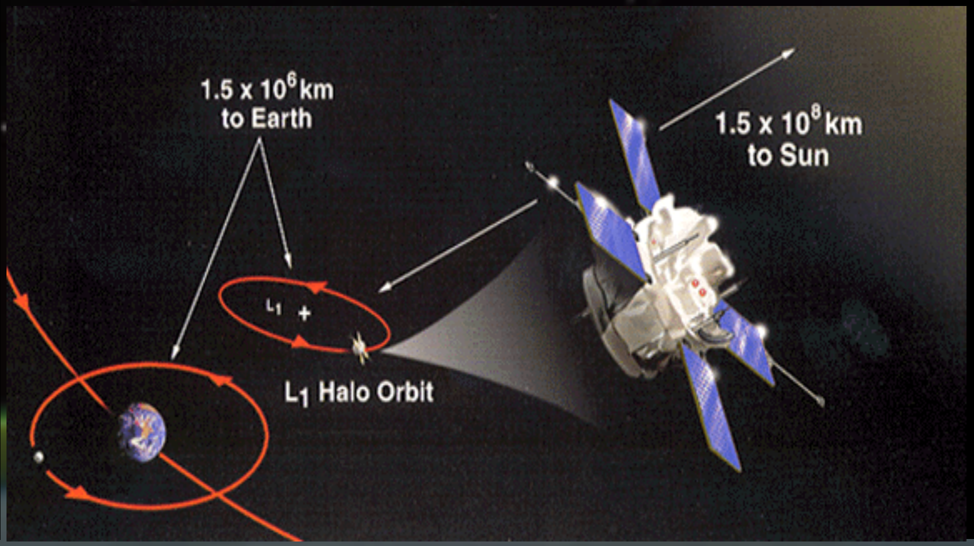
National Weather Service

Space Weather 101

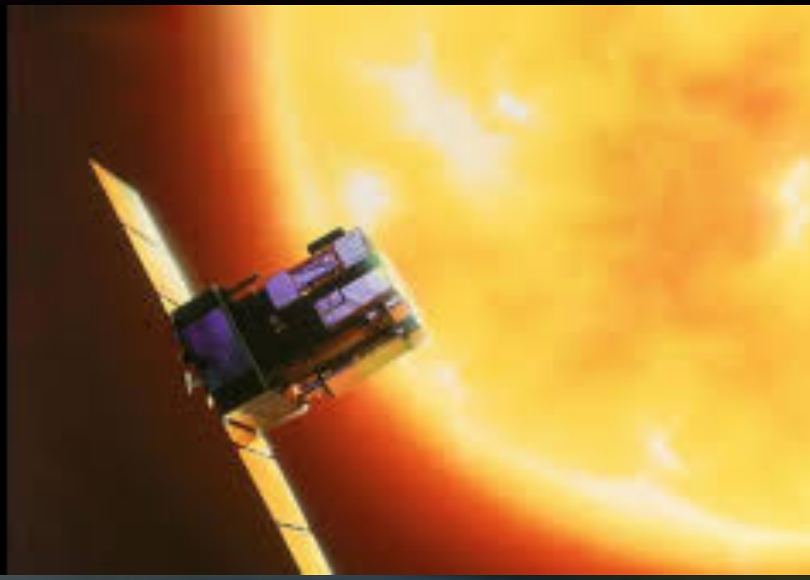
- Current NOAA Space Weather observations



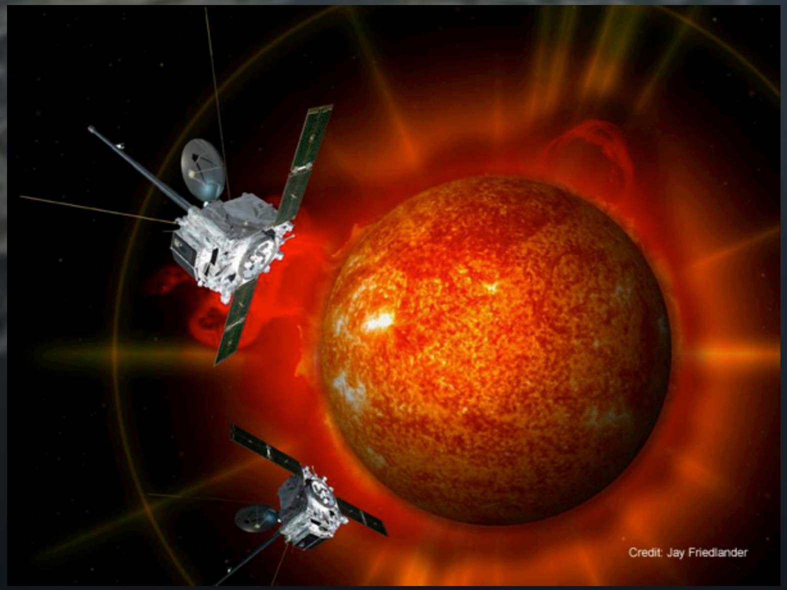
NOAA GOES & POES



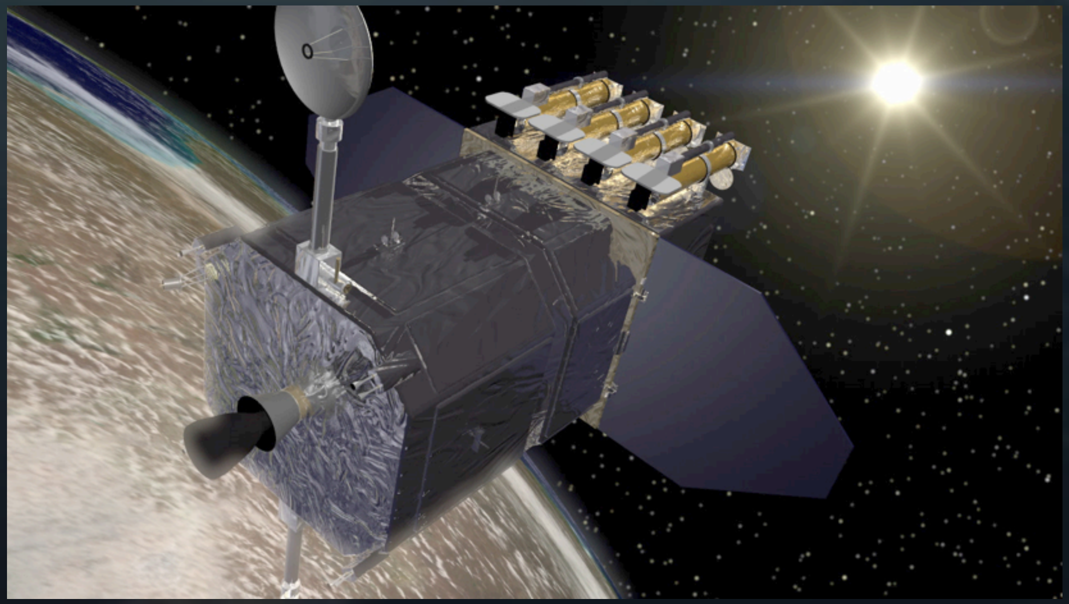
NASA ACE



ESA/NASA SOHO



NASA STEREO



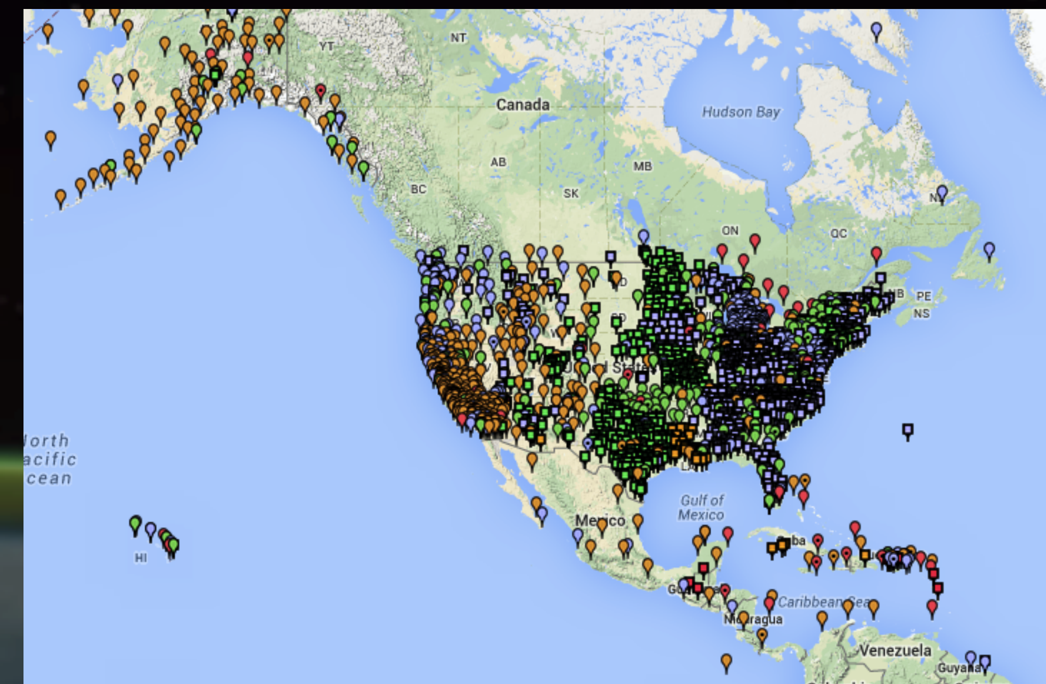
NASA Solar Dynamics Observatory

Space Weather 101

- Current NOAA Space Weather observations

USGS Magnetometers

Air Force SEON Network

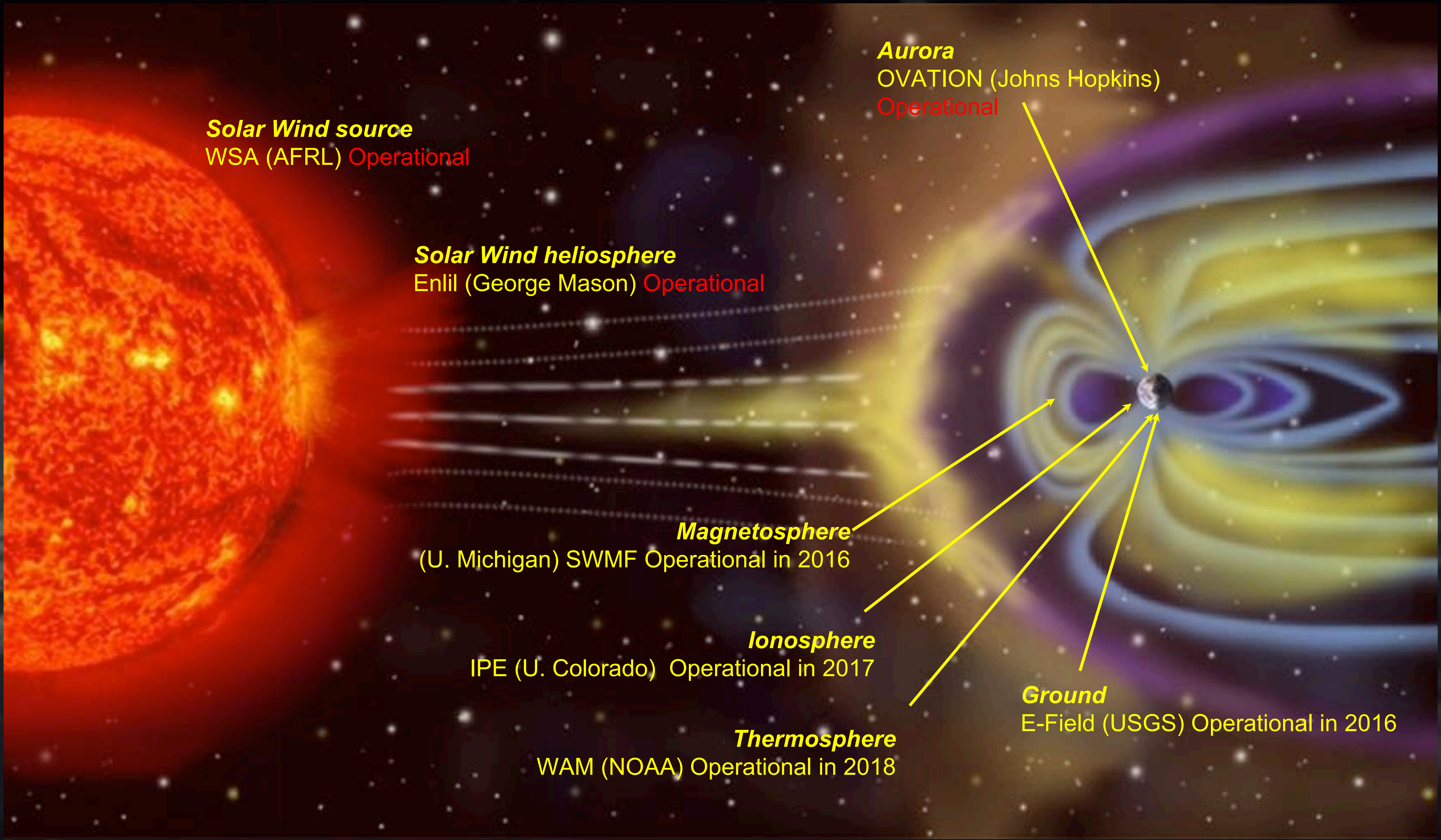


NOAA CORS Network

NSF GONG Network

Space Weather 101

- NOAA SWx forecast models.



Space Weather 101

- Major science challenges
  - Prediction of solar eruptions and better prediction of arrival time.
  - Prediction of solar magnetic field direction “Bz”.
  - Prediction of Flares.
  - Prediction of SEPs.
  - Prediction of magnetospheric and GIC response.

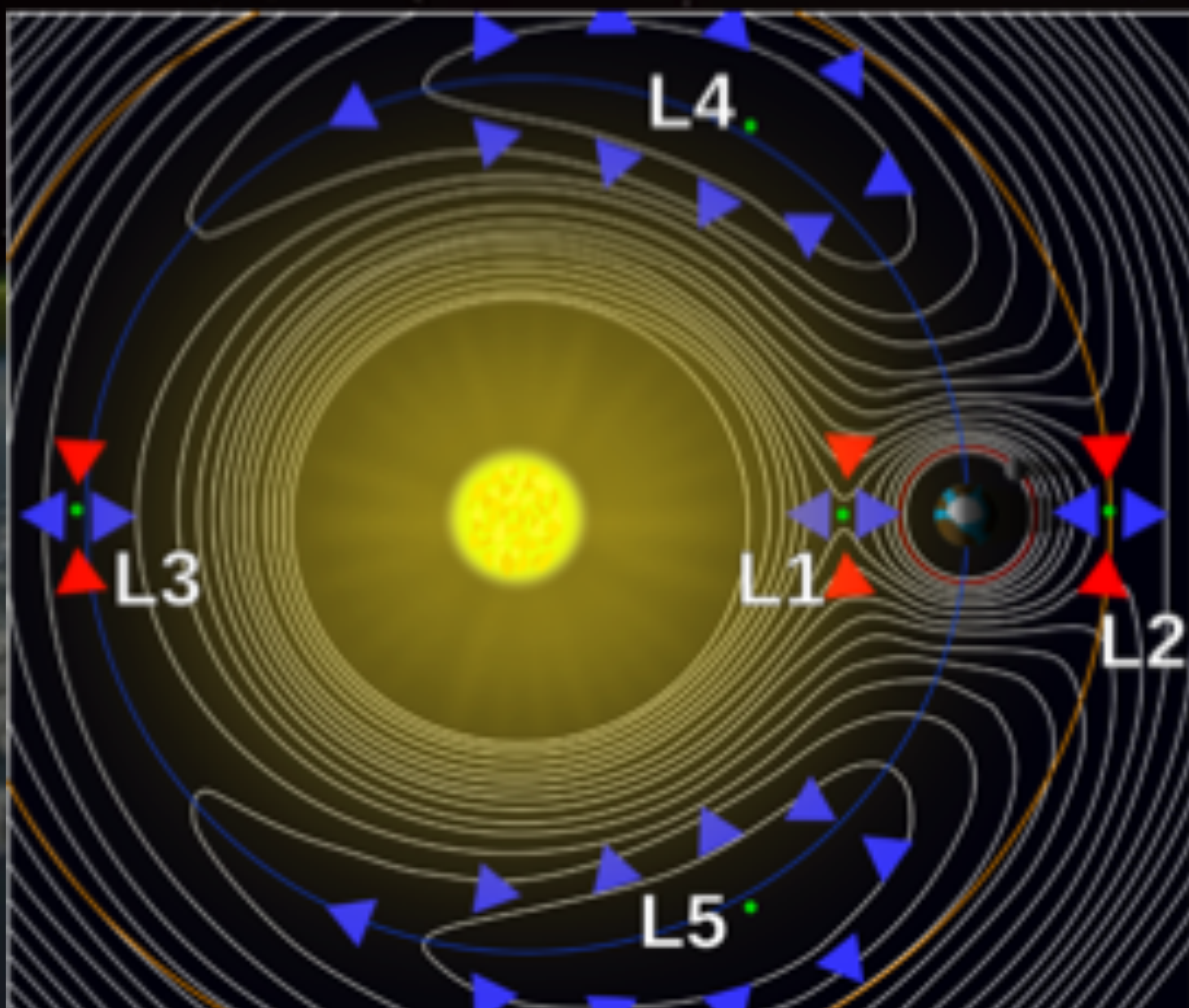
- Major operational challenges
  - Currently only one coronagraph for CME imaging (SOHO/LASCO).
  - No operational off Sun-Earth line platforms.
  - Only 15—60 minutes lead time on Geomagnetic storm severity.
  - Limited operational magnetospheric platforms (GOES).

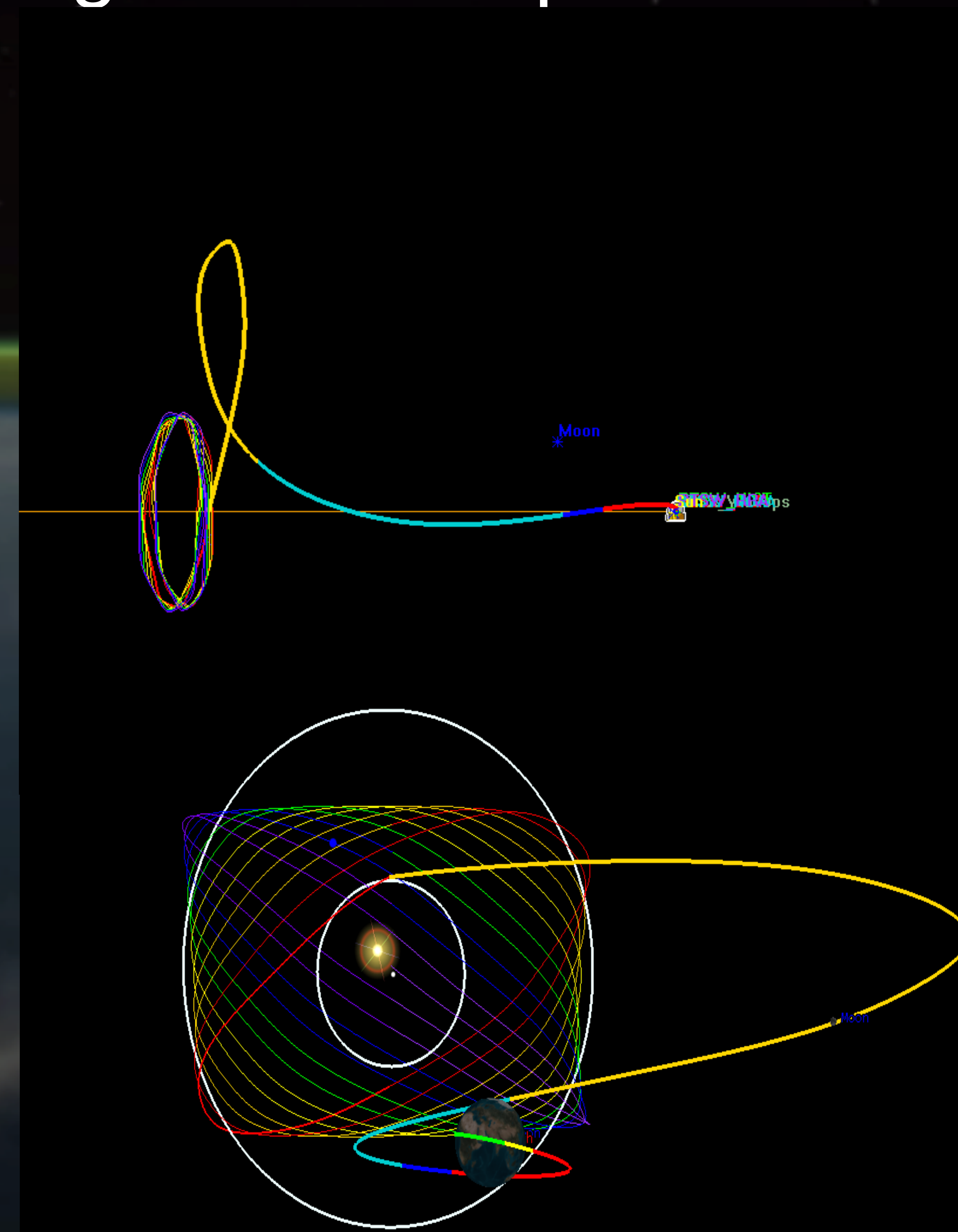
Space Weather 101

- What we need to (better) forecast geomagnetic storms:
  - Observations and models of the solar magnetic field (sunspots).
  - Observations and models of the solar corona (esp. flares and CMEs).
  - Measurements of the solar wind heading to Earth (speed and magnetic field).
  - Models of the “heliosphere” to predict solar wind and CME arrivals at Earth, and of the geomagnetic field to predict storm severity.
- Nowcasting is also critical:
  - Measurements of solar X-ray input to Earth’s atmosphere.
  - Measurements of geomagnetic field during storms.
  - Measurements of the ionospheric disturbances during storms.
  - Measurements of particle radiation incident at Earth.

Deep space orbits

- Stable locations at “Lagrangian Points”.
- L1 gives 15—60 minutes warning of CME impact.

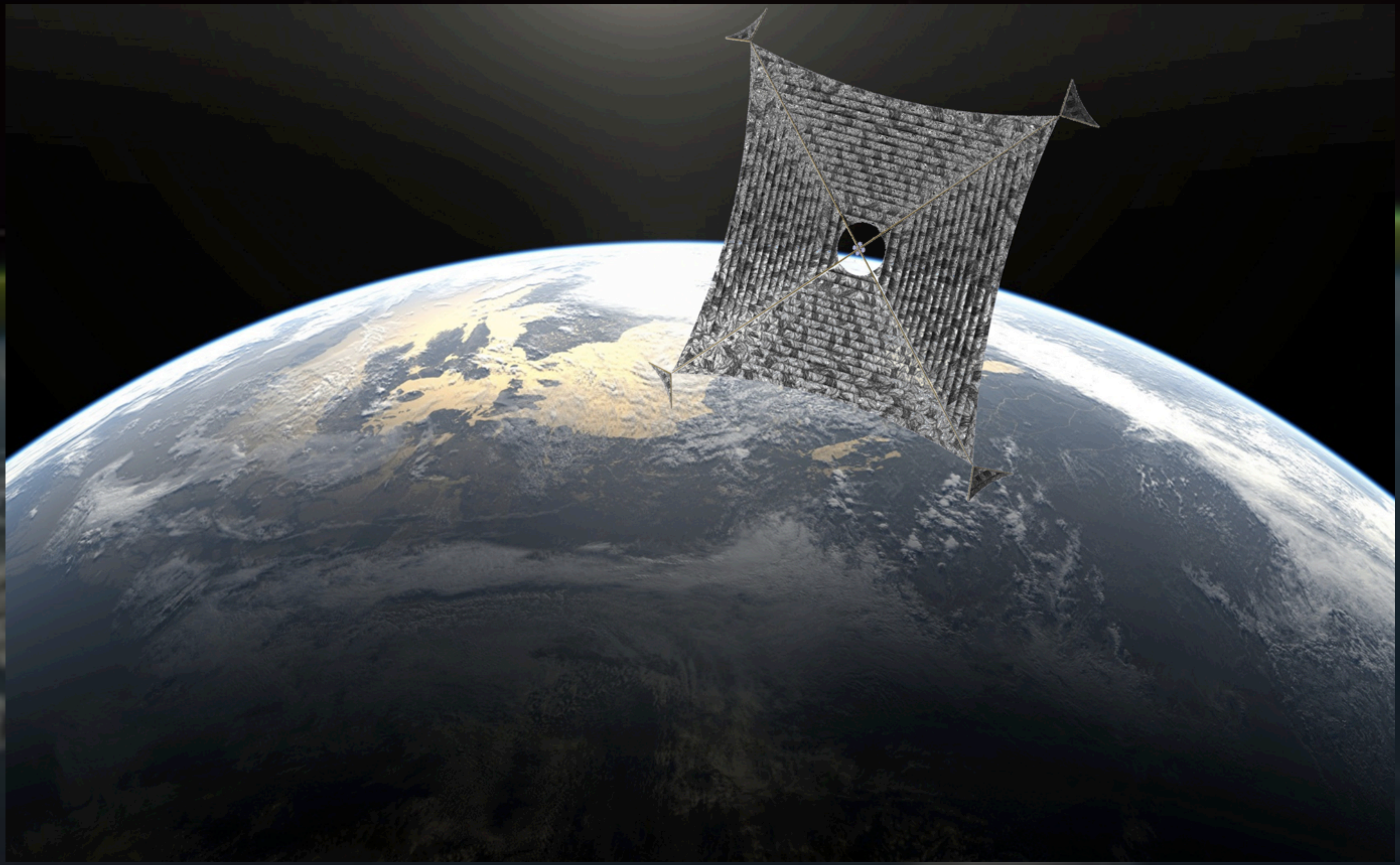


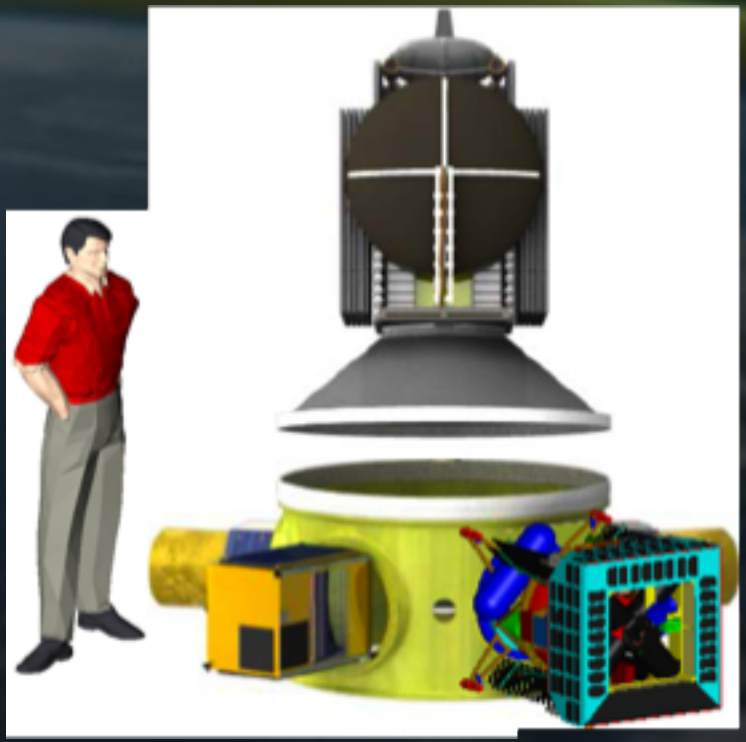


L1 Orbital Injection
Courtesy of NASA/MDL

Deep space orbits

- Solar Sail technology could make "inside L1" accessible.
- More than 60 minutes warning of CME impact.

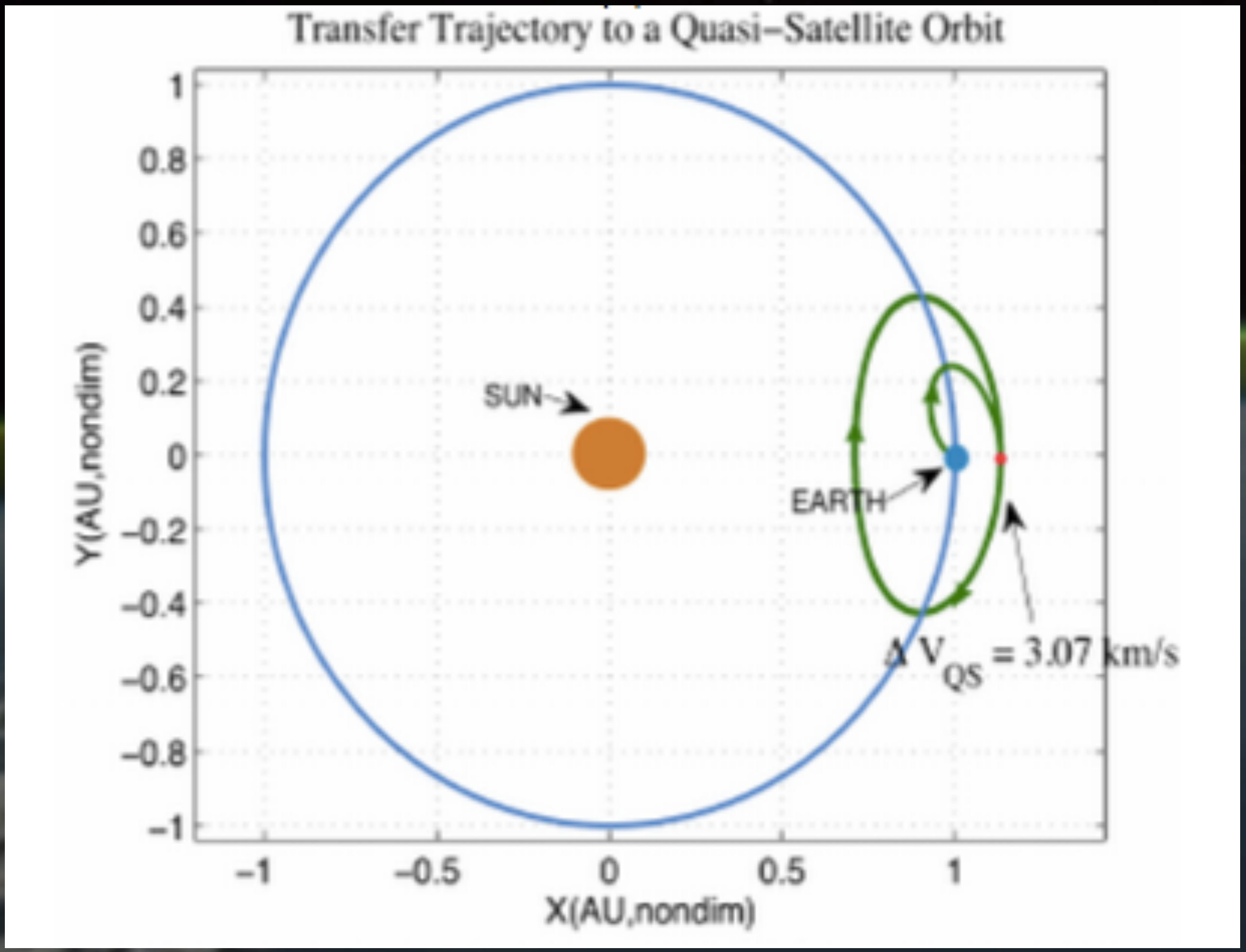


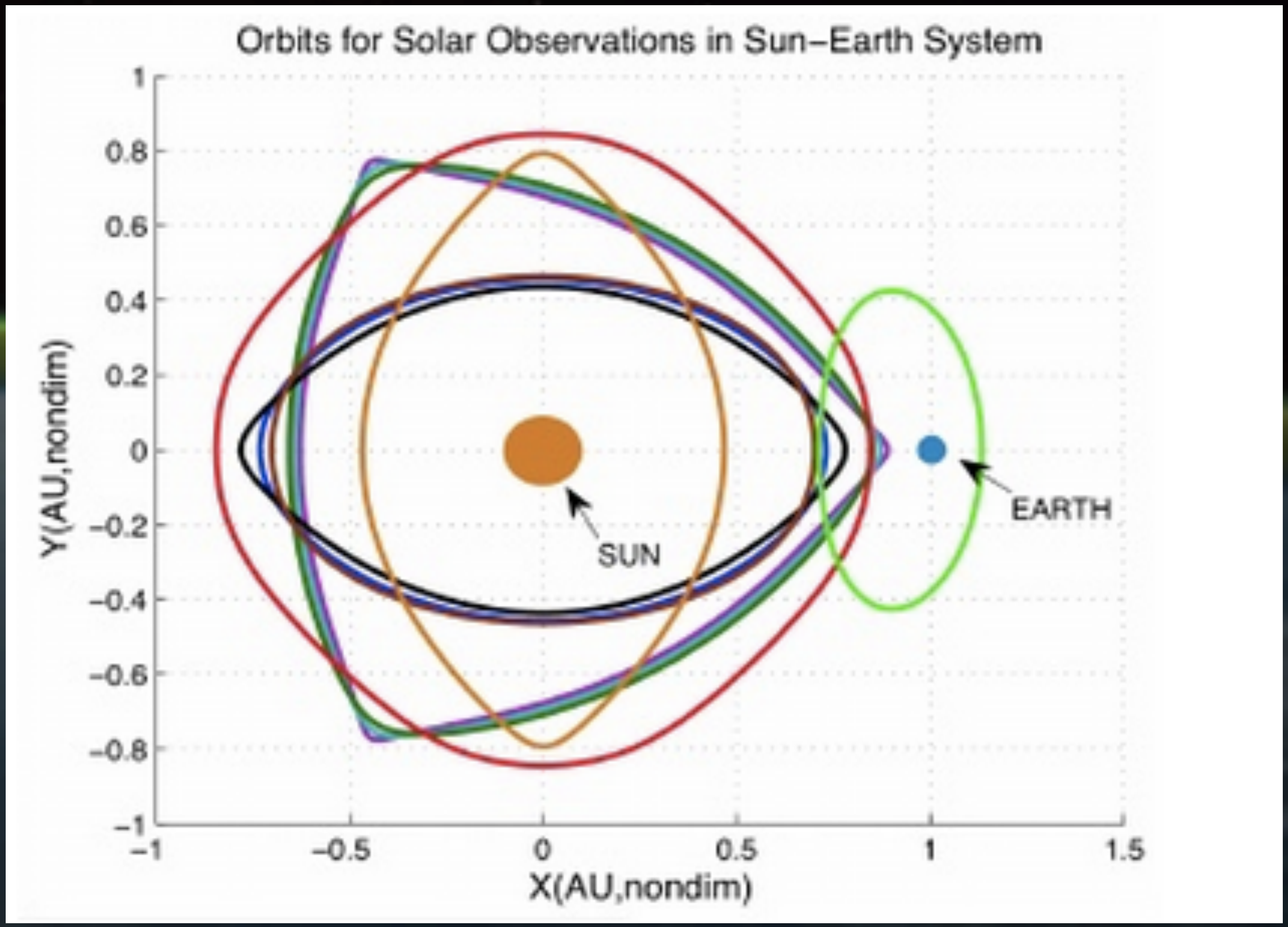


Sunjammer mission concept
www.sunjammermission.com

Deep space orbits

- “Quasi-satellite” orbits for off-Sun-Earth line observations.

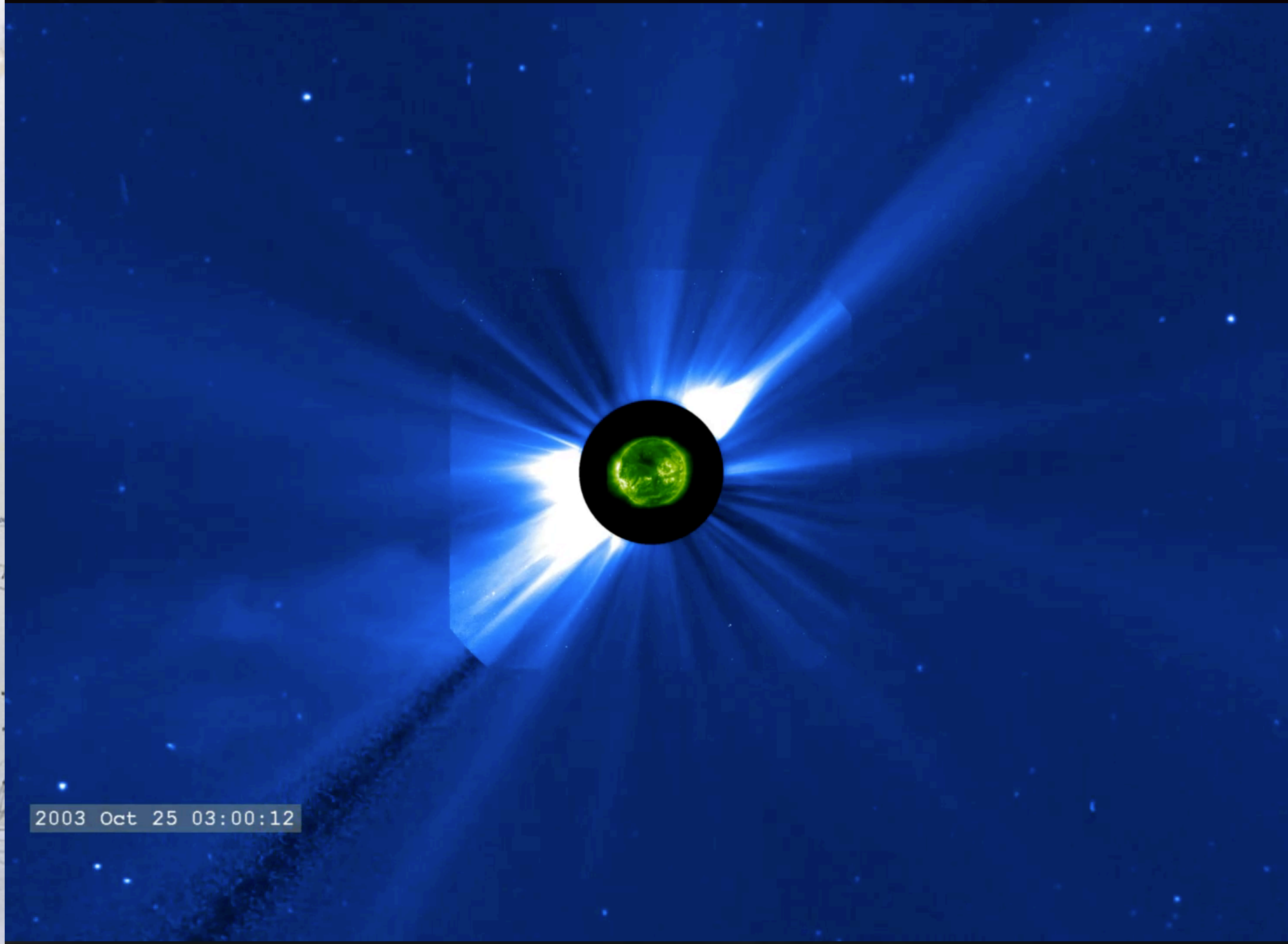




Llanos, Hintz, Lo, Miller, Journal of Earth Science and Engineering, **3**, 2013, 515.

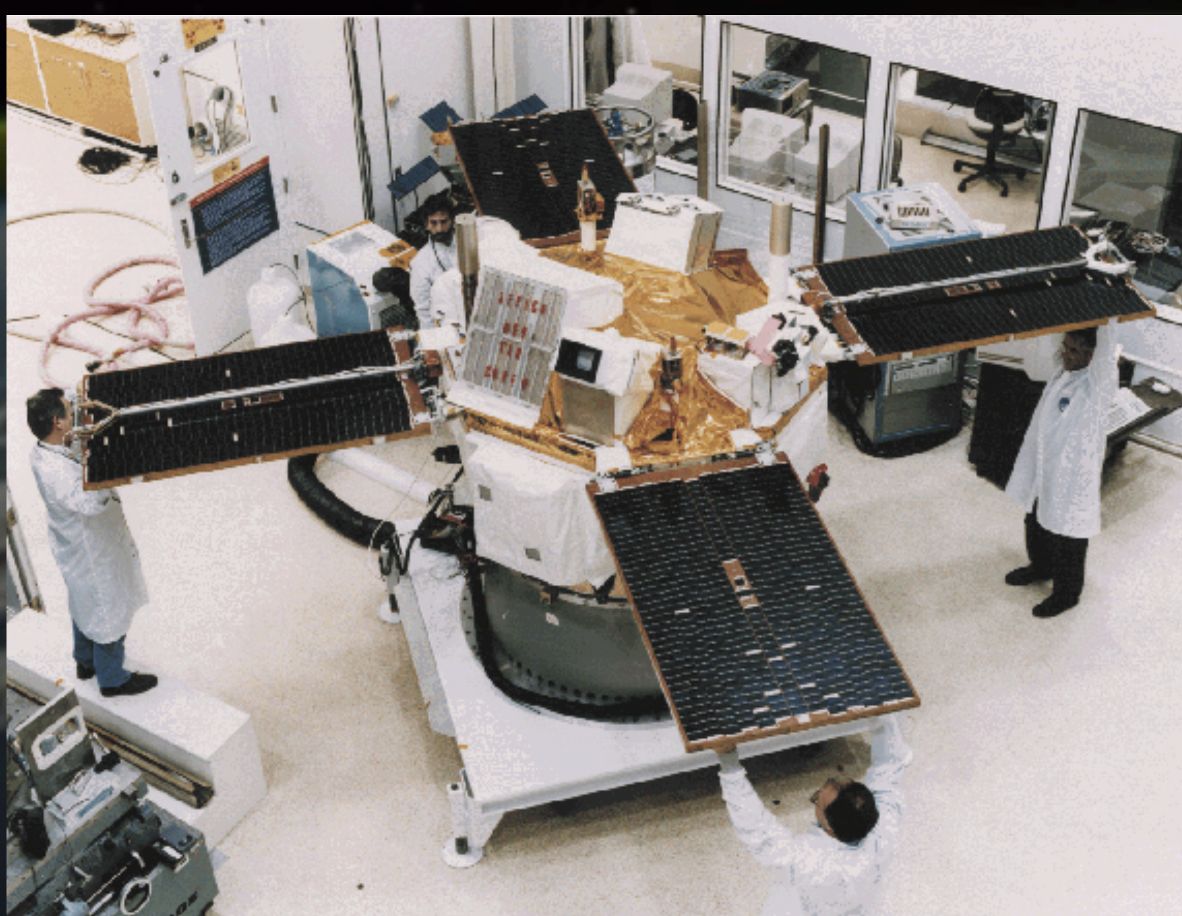
Deep space missions: SOHO

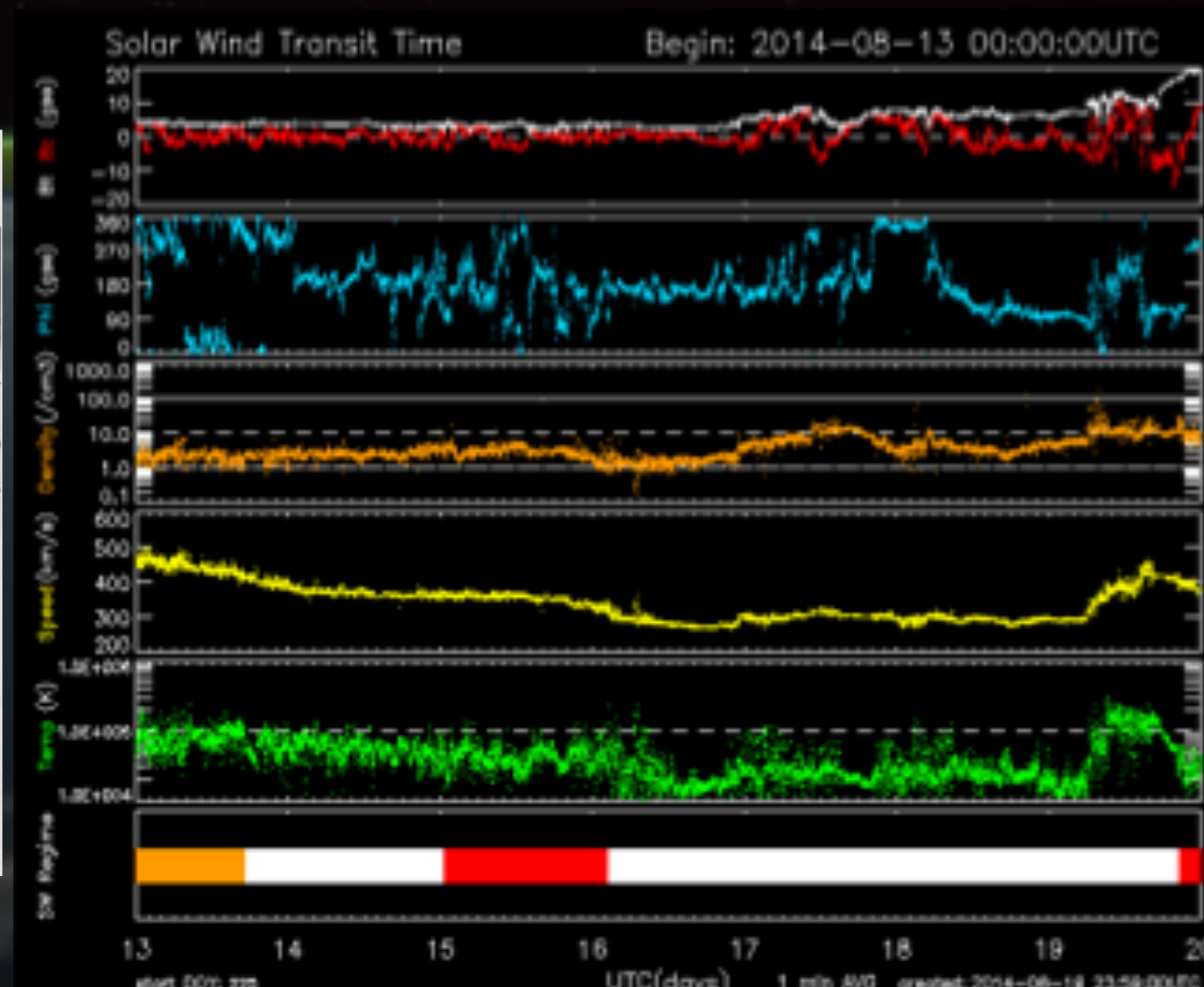
- Solar and Heliospheric Observatory Launched 1995
- NASA/ESA flagship mission.
- L1 orbit.



Deep space missions: ACE

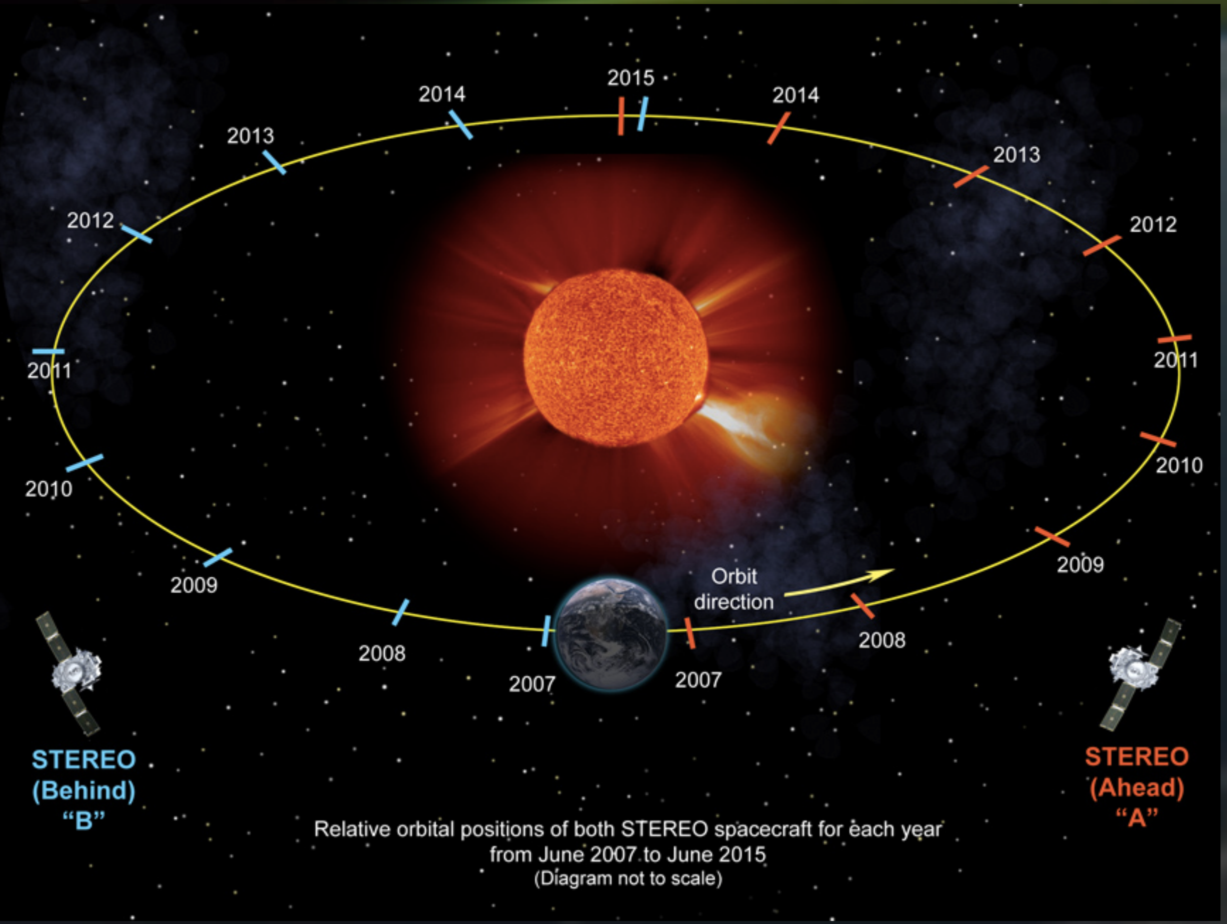
- Advance Composition Explorer Launched 1997
- NASA Small Explorer mission.
- L1 Orbit.
- Real-time “beacon” transmitter and antenna network supplied by NOAA.

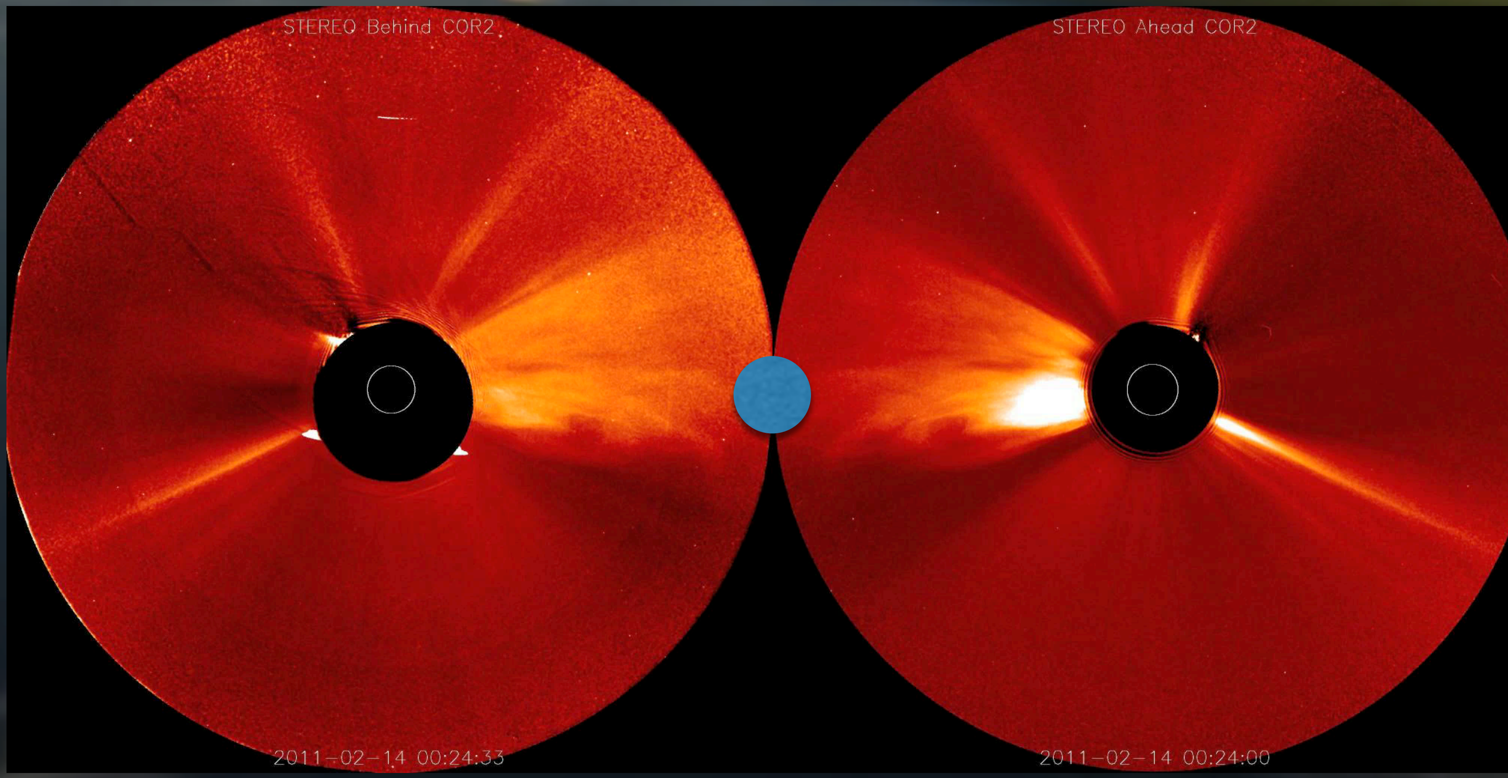




Deep space missions: STEREO

- Solar Terrestrial Relations Observatory — Launched 2006
- Two satellites: “Ahead” and “Behind”.
- NASA Solar Terrestrial Probes mission.
- Heliocentric leading and trailing orbits.





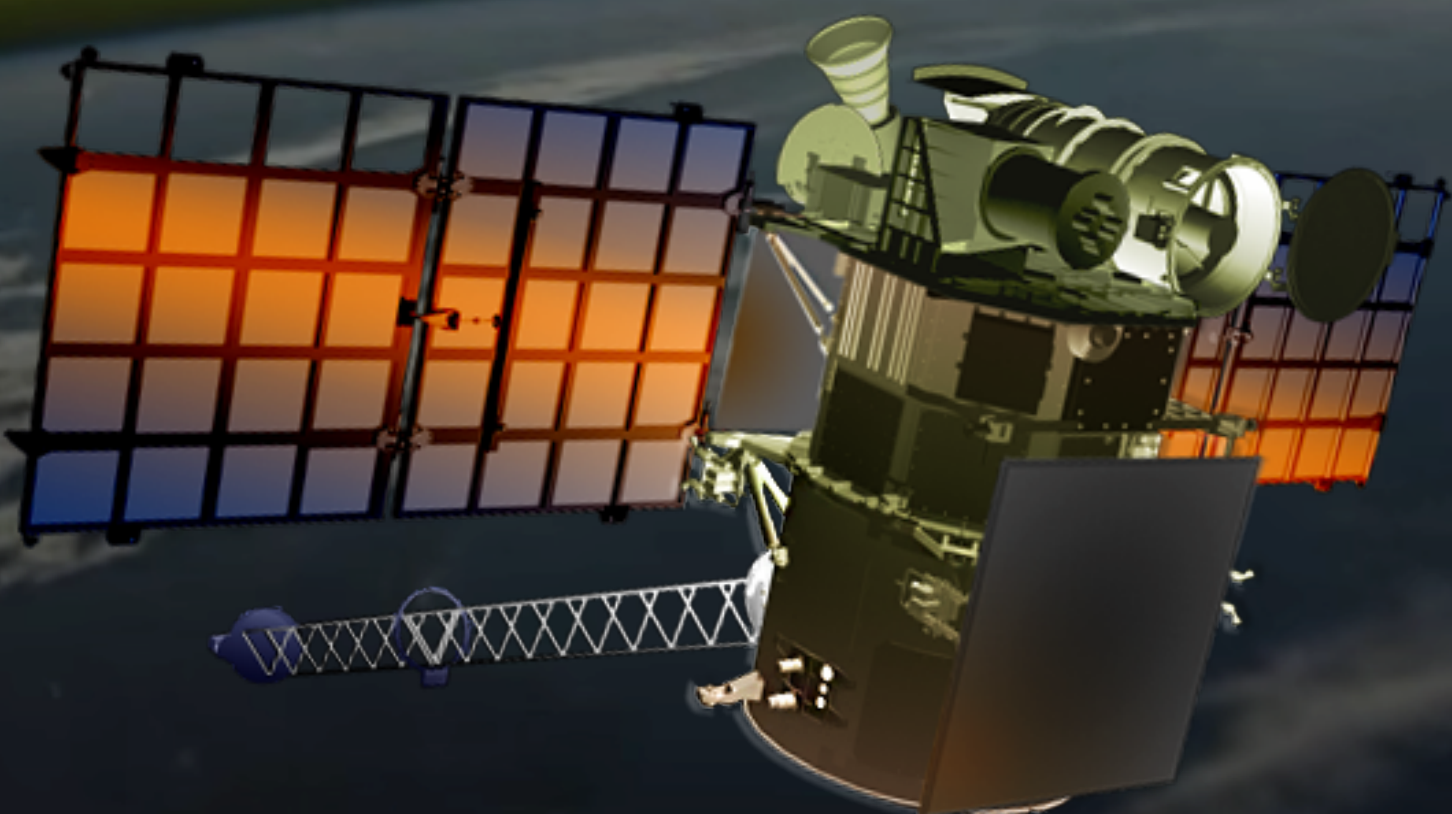
STEREO A & B CME views
Courtesy of NASA

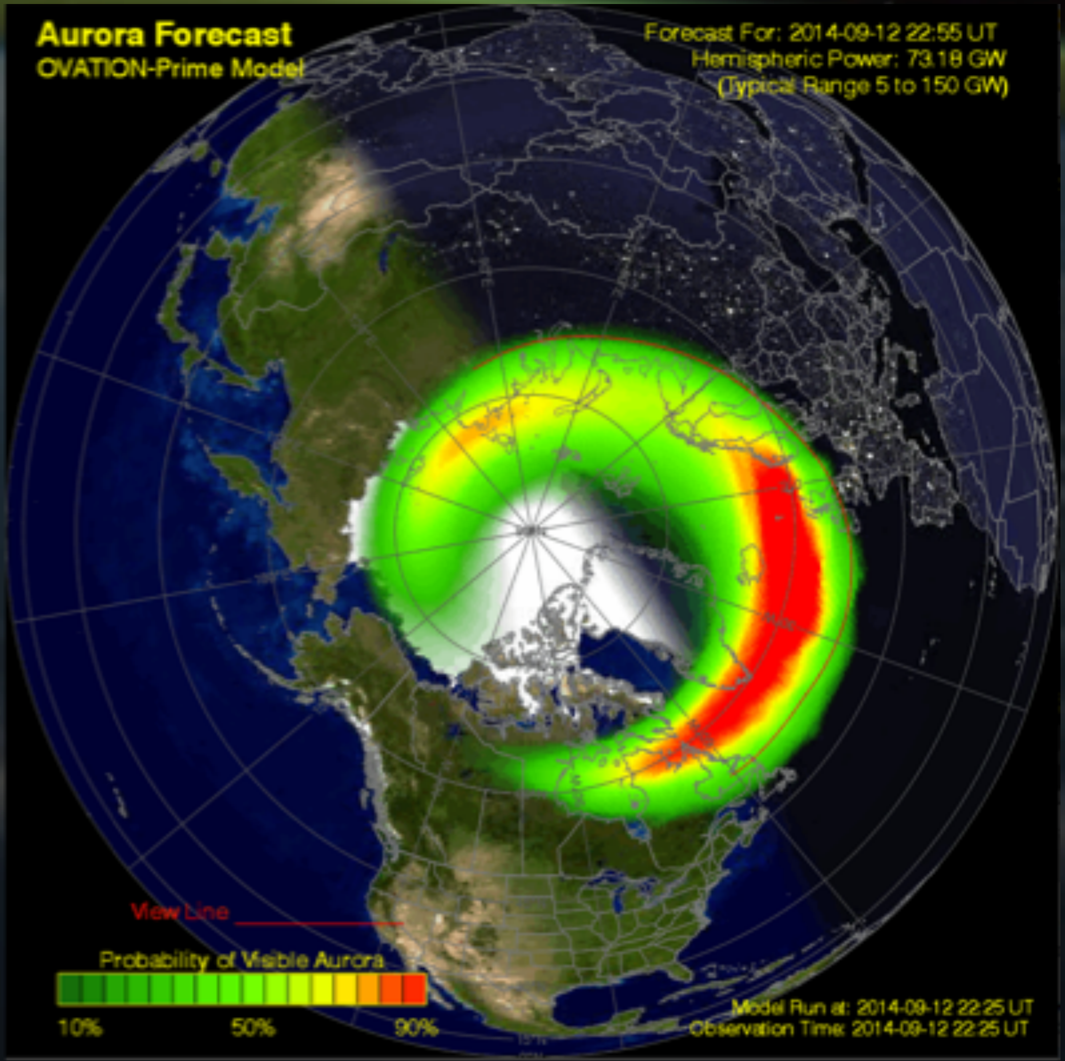
Deep space missions: DSCOVR

Falcon 9 Launch, 11-Feb-2015
Courtesy of SpaceX

Deep space missions: DSCOVR

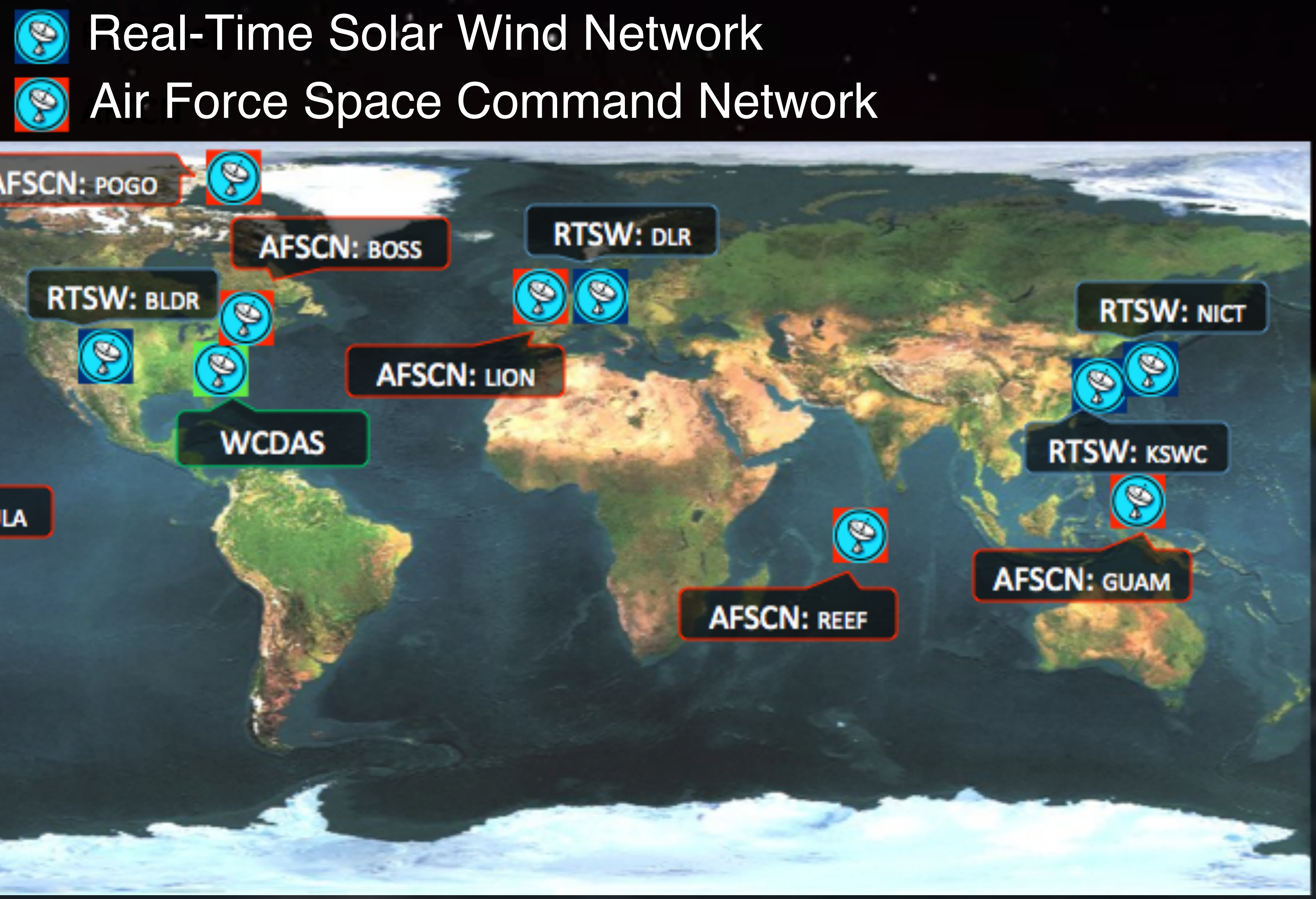
- Deep Space Climate Observatory   Launched 11-Feb-2015!
- NOAA's first deep space weather satellite.
- Primary mission: NOAA solar wind and **B** measurements.
- Secondary mission: NASA Earth science observations.





Operational deep space receiving networks

- National Institute of Information and Communications Technology **(NICT)** in Tokyo, **Japan**
- Korean Space Weather Center **(KSWC)** in Jeju, **Korea**
- German Aerospace Center **(DLR)** in Neustrelitz, **Germany**
- Wallops Command and Data Acquisition Station **(WCDAS)** in Virginia
- Space Weather Prediction Center **(SWPC)** in Boulder



Future deep space missions

- NOAA "Space Weather Follow-on"
- Launch: ~2020
- Primary mission: operational (real-time) coronagraph at L1 to replace SOHO/LASCO.
- Mission studies currently being conducted.

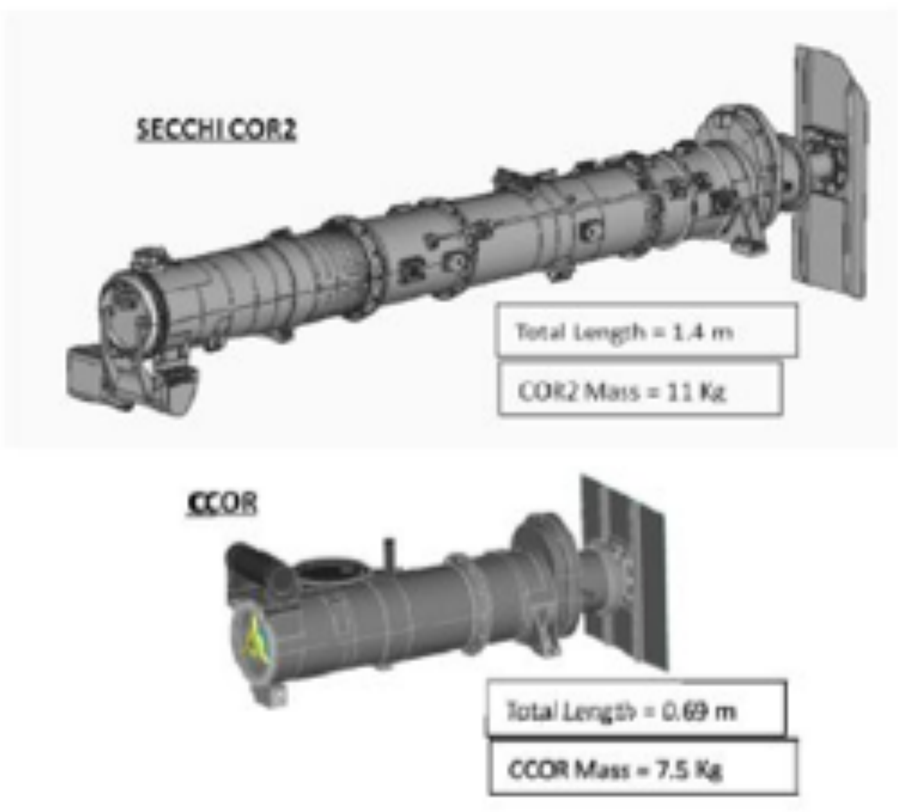


Figure 1-4. CCOR Comparison to Heritage SECCHI/COR2 Design

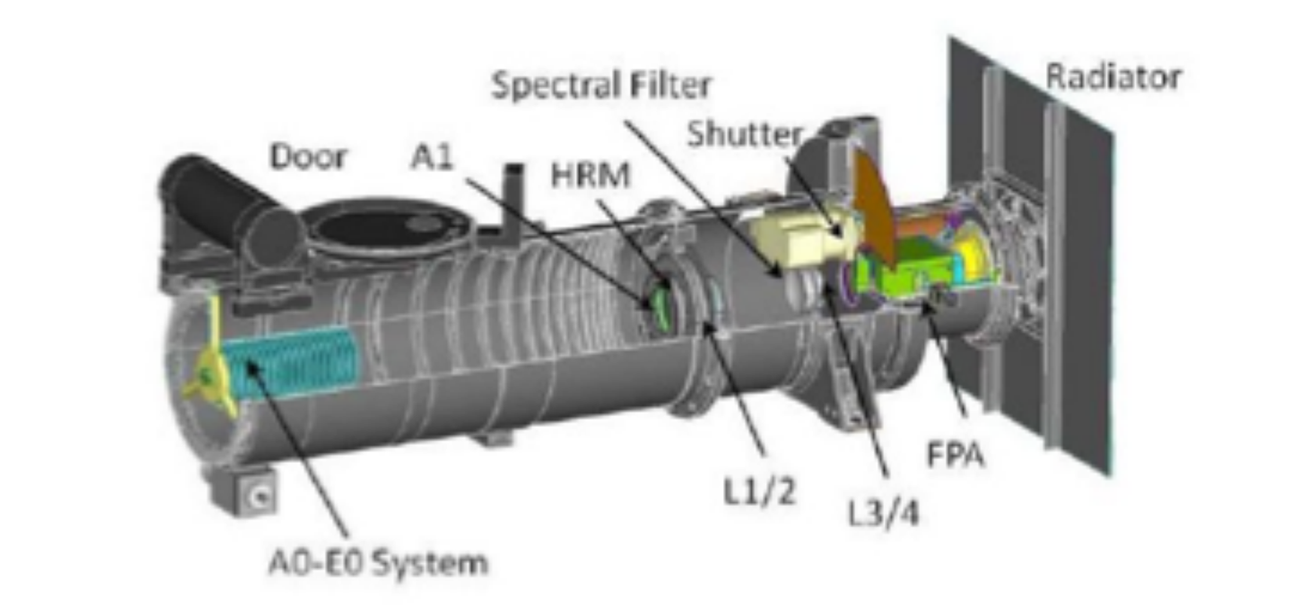
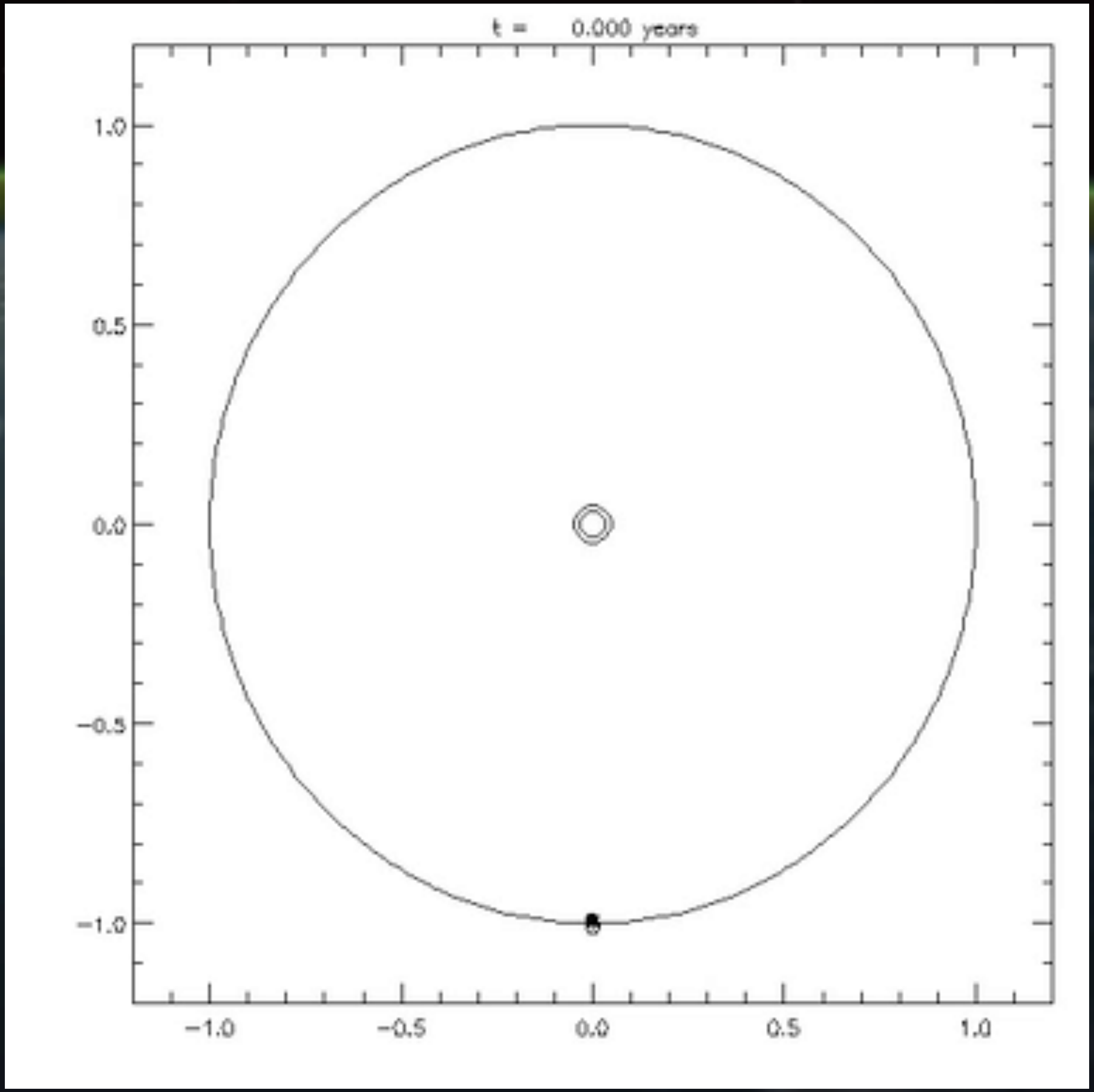


Figure 1-3. CCOR Conceptual Design

Compact Coronagraph
Courtesy of NRL

Future deep space missions

- On-going series of “STEREO” pairs in heliocentric orbit.
- Full-Sun view at all times: *all* CMEs and *all* flux emergence.
- Real-time communications network is a challenge.



Conclusions

- Real-time operational deep space missions are crucial to early lead-time Space Weather forecasting.
- Lagrange points offer stable low-fuel orbits, but are limited in solar viewpoints.
- Eccentric Earth-orbit constellations offer multi-angle views of the Sun, but lack far-side observing.
- Solar sail technology is promising for orbits inside L1 but remains unproven.
- Observing the entire solar globe at all times is the only way to supply data assimilative models of solar activity.

Deep space is here to stay!