Deep Space Satellites for Space Weather Forecasting

Science and Technology Challenges

Dr. Thomas Berger Space Weather Prediction Center Boulder, CO



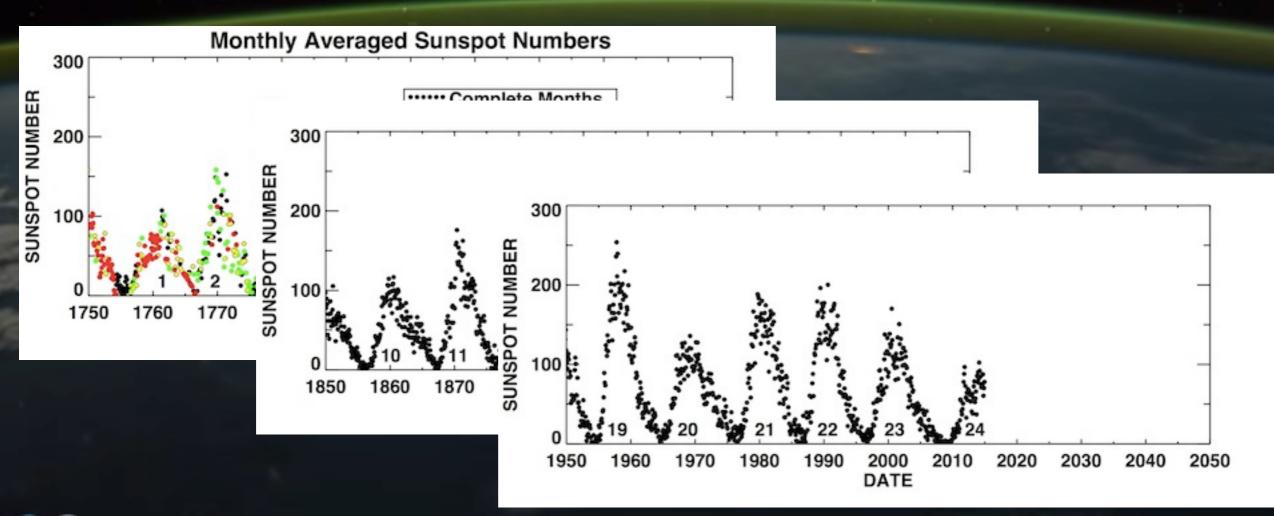
National Weather Service



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

- 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.



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

2003 Oct 30 15:00:12

2003 Oct 30 15:00:12

Magnetic Field



White Light

Sunspots are dynamic convective structures...

Solar Dynamics Observatory/HMI Courtesy Phil Scherrer, Stanford

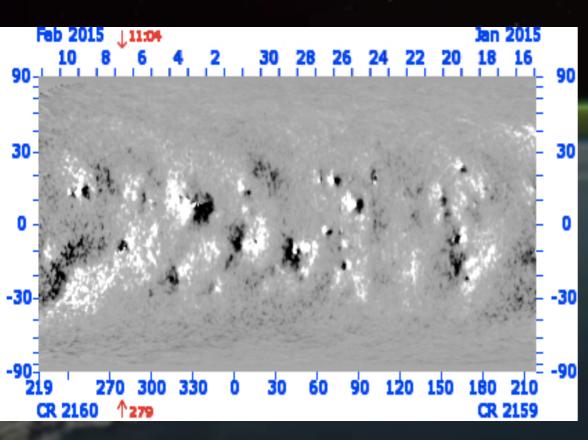
 The Sun's outer atmosphere or "corona" is heated to >10⁶ K by this "magnetohydrodynamic" activity.



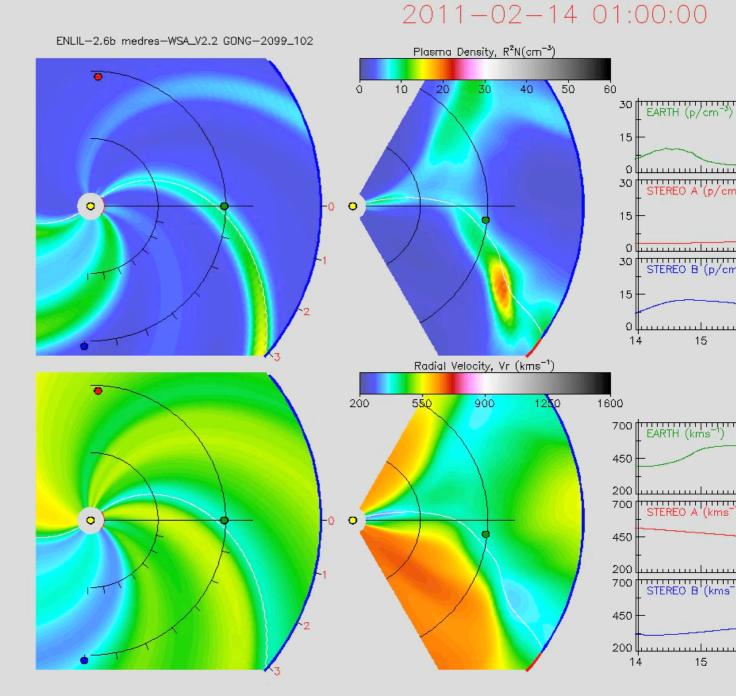
12 November 1966 Solar Eclipse at Pulacayo, Bolivia Courtesy NCAR/HAO

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

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



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GONG Solar magnetic field map
Courtesy of National Solar Observatory
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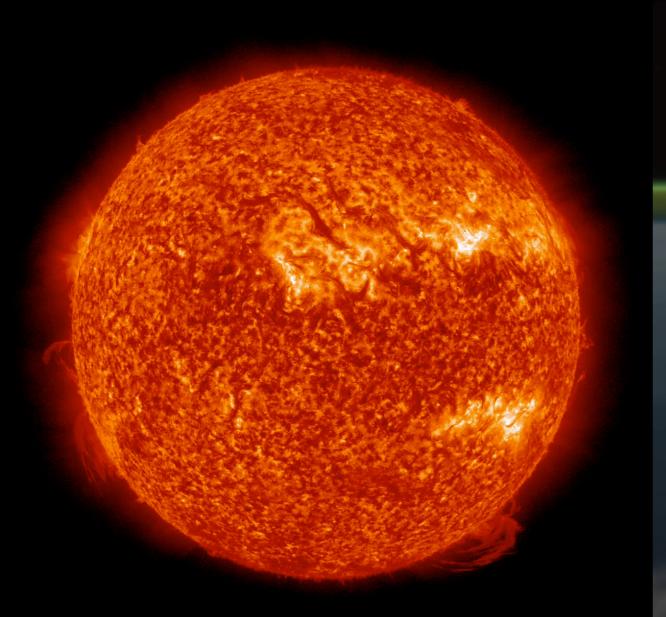


National Weather Service

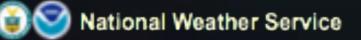
Sunspots occasionally "flare" due to "magnetic reconnection".

Hinode/SOT 396.8 nm Ca H-line

 The same reconnection can lead to "coronal mass ejections" (CMEs).

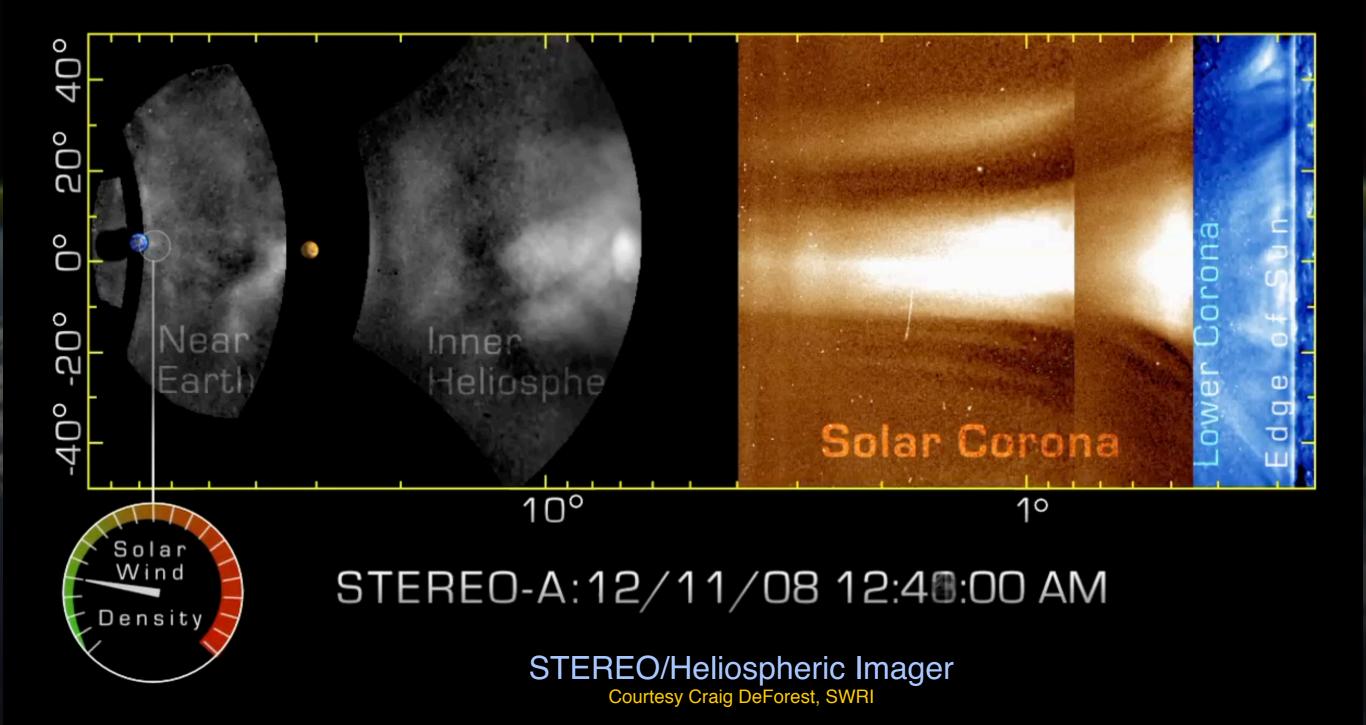


NASA Solar Dynamics Observatory

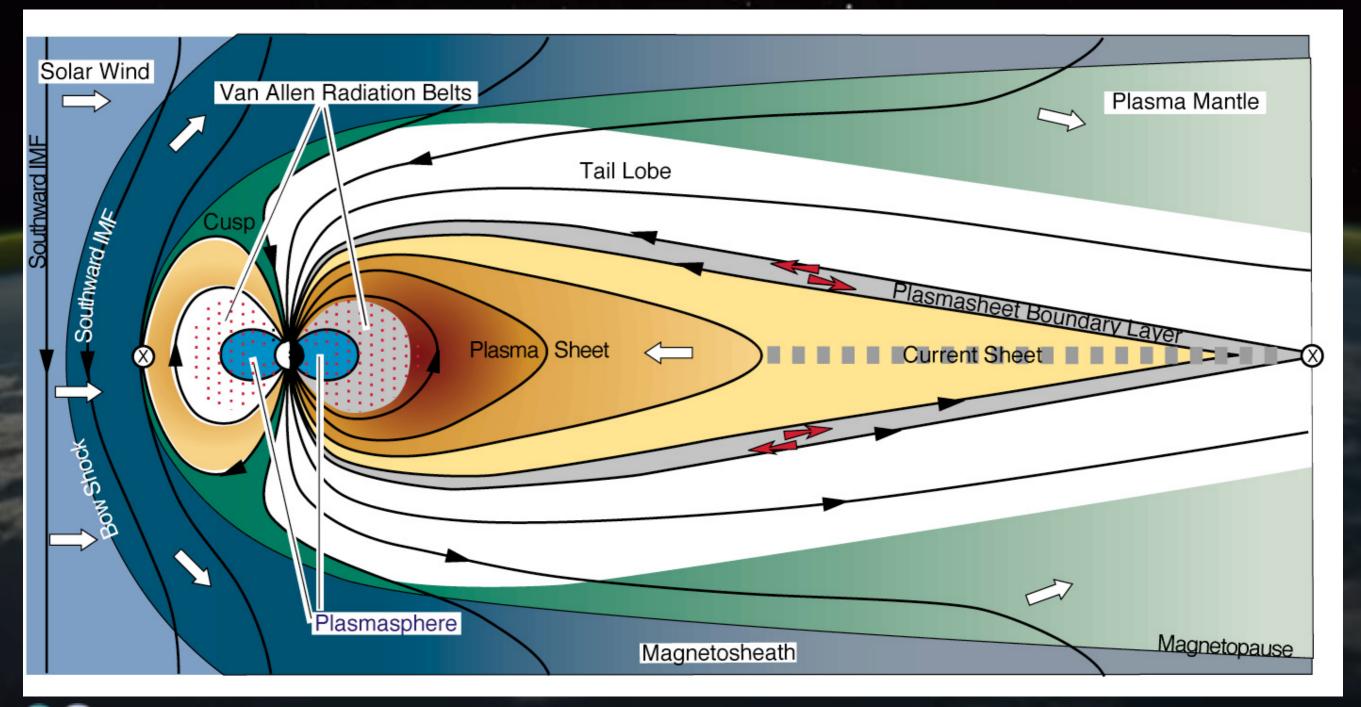


C2: 2011/06/07 09:04 AIA 193: 06/07 09:04 SOHO/LASCO Coronagraph + SDO

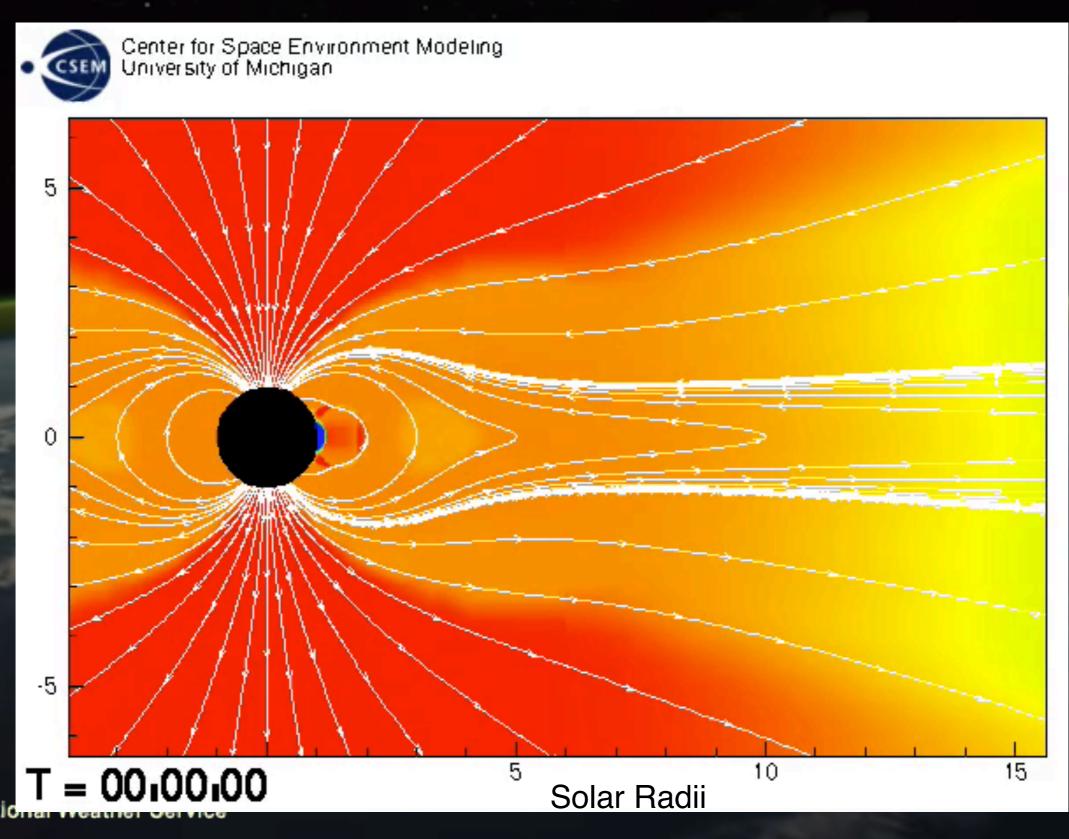
 Both the solar wind and CMEs transport coronal plasma and magnetic field into interplanetary space.



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



The scale of solar eruptions is enormous



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

University of Oslo, Dept. of Physics

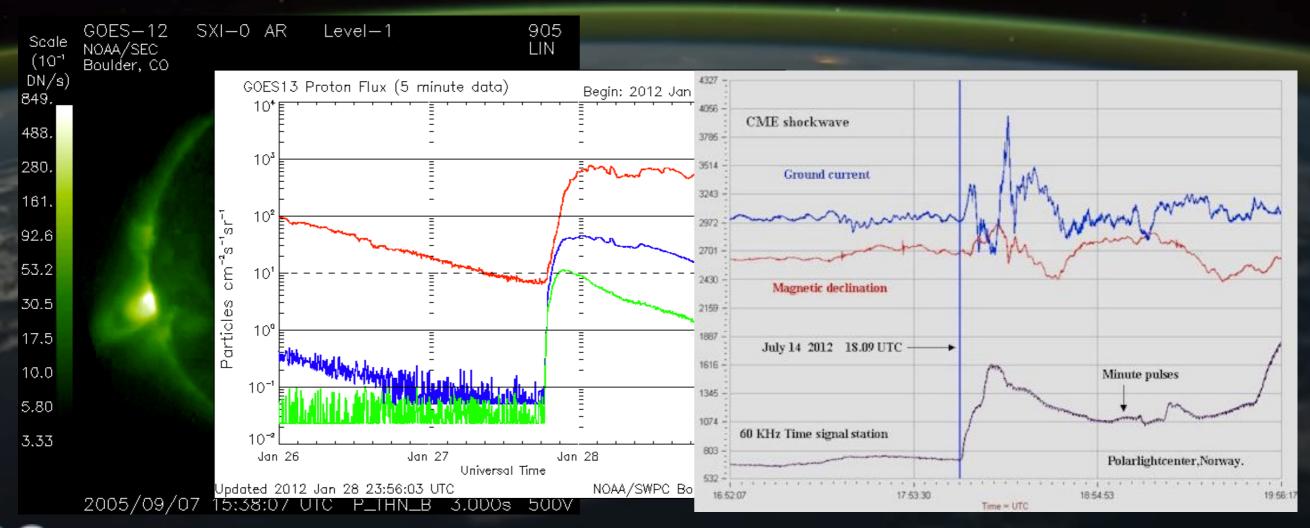
 Van Allen radiation belts change in response to geomagnetic field



Van Allen Probes Data Courtesy of Johns Hopkins Applied Physics Lab

- The main space weather phases of a solar eruption
 - Solar flare → Upper atmospheric ionization
 - Interplanetary shock → Energetic particle radiation
 - CME arrival at Earth → Geomagnetic storm

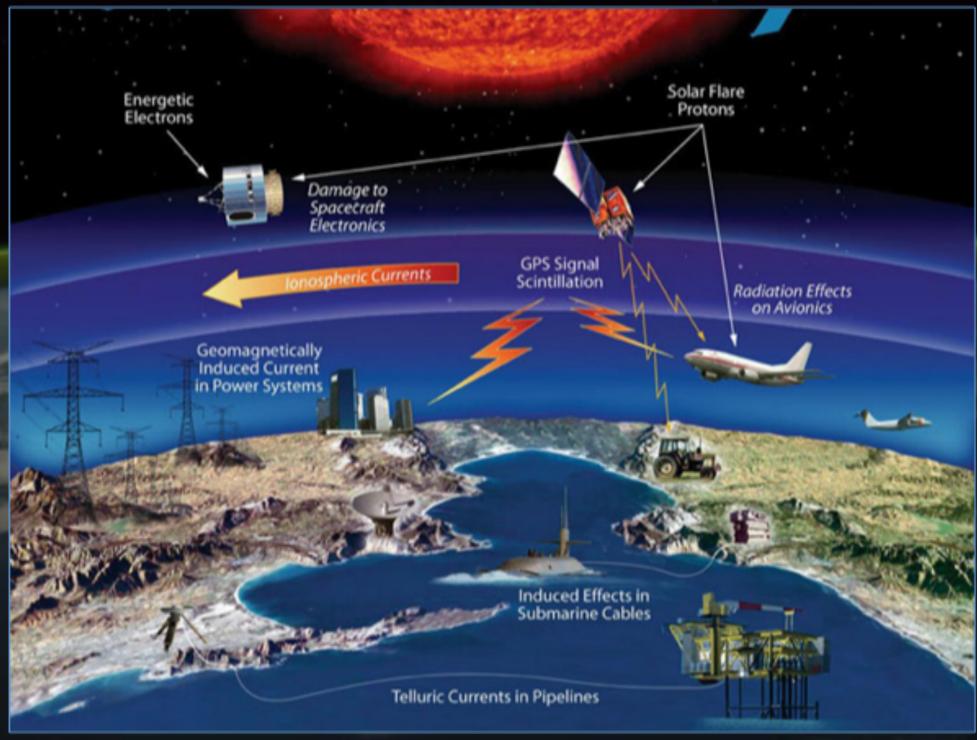
immediate 10s of minutes 12 — 72 hours



NOAA/SWPC has scales for each phase

Radio BlackoutsLead time: 0GOES X-ray peak brightness by class and by flux*						tness flux d by (nur	Number of events when flux level was met; (number of storm days)	
R 5		Solar Radiation Storms Lead time: minutes				Flux level o 10 MeV particles (ior 10 ⁵	flux le	er of events when vel was met**
R4	S 5	G	eomagnetic Storms Lead time: 12 – 72 hrs			Kp dete eve	values* ermined ry 3 hours	Number of storm events when Kp level was met; (number of storm days)
R3			-	<u>Power systems</u> : widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. <u>Spacecraft operations</u> : may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. <u>Other systems</u> : 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.).**			=9	4 per cycle (4 days per cycle)
R 2	S 4	G	5 Extreme					
R1	S 3	G	4 Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Kp=8 100 per cycle (60 days per cycle) Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Kp=8 100 per cycle 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.).** Mathematical contents affect preventive lat.)				
	S 2	G	3 Strong	<u>Power systems</u> : voltage corrections may be required, false alarms triggered on some protection devices. <u>Spacecraft operations</u> : surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. <u>Other systems</u> : 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.).**				200 per cycle (130 days per cycle)
	S1	G	2 Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration stor transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; pos drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as I and Idaho (typically 55° geomagnetic lat.).**	sible change	s in	-6	600 per cycle (360 days per cycle)
		G	1 Minor	Power systems: weak power grid fluctuations can occur. <u>Spacecraft operations</u> : minor impact on satellite operations possible. <u>Other systems</u> : migratory animals are affected at this and higher levels; aurora is commonly vis latitudes (northern Michigan and Maine).**	ible at high	Кр	-5	1700 per cycle (900 days per cycle)

Impacts to terrestrial technology are many...





Global Positioning System (GPS)

Geomagnetic storms can impact the accuracy and availability of GPS by changing the ionosphere, the electrically charged layer of the atmosphere a GPS signal must pass through from satellite to ground receiver. The ionosphere is the largest source of error in GPS positioning and navigation. These ionospheric disturbances are ever-present but can

become severe during geomagnetic storms, resulting in range errors in excess of 100 feet, or even resulting in loss of lock on the GPS signal entirely. These errors can have significant impacts on precision uses of GPS such as navigation, agriculture, oil drilling, surveying, and timing.



Satellite Operations

There are thousands of satellites in orbit around Earth with applications in television and radio, communications, meteorology, national defense, and much more. Space weather can affect these satellites in many ways. Solar radiation storms can cause spacecraft orientation problems by interfering with star trackers and by causing errors or damage in electronic devices. Geomagnetic storms can create a hazardous charging environment for satellites resulting in damaging electrostatic discharge, much like touching a door knob and getting that spark on a dry winter day. Geomagnetic storms also cause heating of the atmosphere, essentially causing it to expand, which results in more drag or slowing down of an orbiting satellite. In a worst case, space weather can cause the satellite to fail.

Space Operations

Astronauts and their equipment in space are bombarded with charged particle radiation. This radiation causes tissue or cell damage in humans. Space weather and solar radiation storms are of particular concern for activities outside the protection of Earth's atmosphere and magnetic field.

Space Weather Impacts on Eart

Electrons collide with the upper mosphere 50 to 300 miles above Earth.

magnetic field lines.

Electrons exchange energy with the atmosphere exciting the atmospheric atoms and molecules to higher energy levels. When the atoms and molecules relax back to lower energy levels, they release their energy in the form of light.



Auron

Aurora

The Aurora Borealis (Northern Lights) and Aurora Australis (Southern Lights) are the result of electrons colliding with Earth's upper atmosphere. The electrons are energized through acceleration processes in the downwind tail (nightside) of the magnetosphere. The accelerated electrons follow the magnetic field of Earth down to the polar regions where they collide with oxygen and nitrogen atoms and molecules in Earth's upper atmosphere. In these collisions, the electrons transfer their energy to the atmosphere, thus exciting the atoms and molecules to higher energy states. When they relax back to lower energy states, they release their energy in the form of light. The aurora typically forms 50 to 300 miles above the ground. Earth's magnetic field guides the electrons such that the aurora forms two ovals approximately centered at each magnetic pole.

THE COLORS OF THE AURORA

Deep red from high altitude atomic nitrogen

Magenta from high altitude molecular nitrogen in sunlight

 Greenish yellow from lower altitude atomic oxygen

Magenta from low altitude molecular nitrogen (not shown in the picture)

Aviation

Aircraft use High Frequency (HF) radio communication to stay in touch with ground controllers in remote areas such as over the oceans or over the poles. Solar flares can "black out" the use of HF on the dayside of Earth and solar radiation storms can "black out" use of HF near the poles, impacting the aircraft's ability to stay in touch with the ground. Impacts to GPS systems can also significantly affect airline operations.

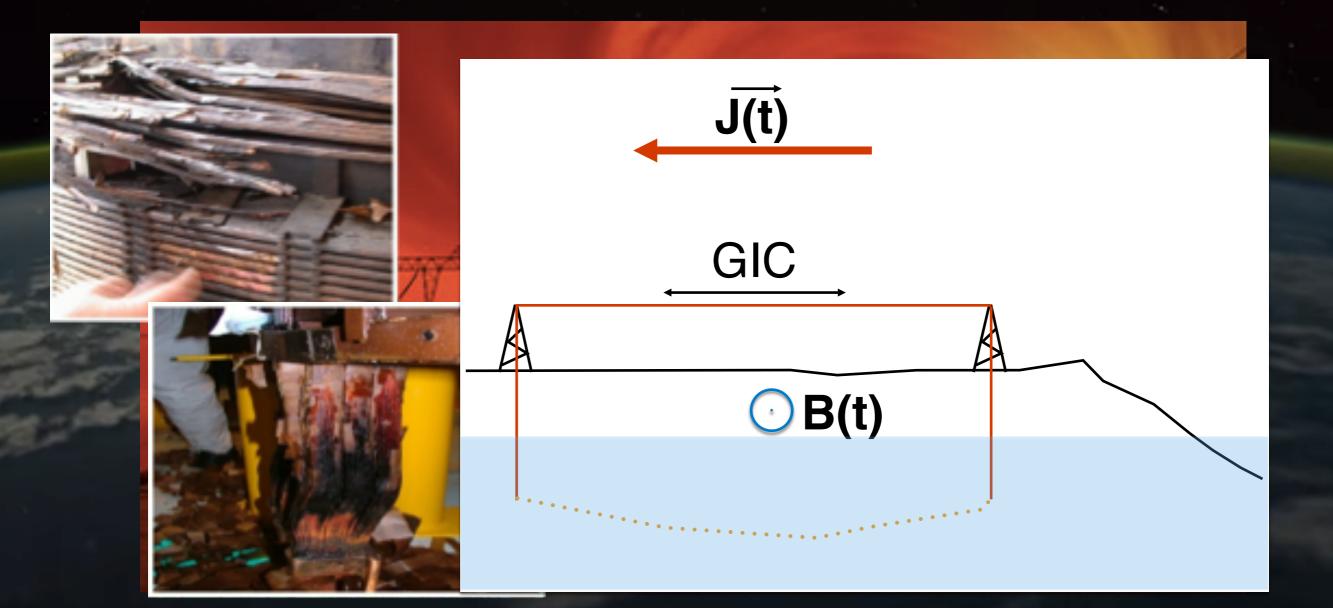
Power Grids

Geomagnetic storms result in electric currents in the magnetosphere and ionosphere as the area shaped by Earth's magnetic field is compressed and disturbed. The disturbed conditions create additional currents in long conductors on the ground such as overhead transmission lines or long pipelines. In the most extreme cases, these currents can cause voltage instability or damage to power system components, potentially resulting in temporary service disruptions, or even a widespread power outage.

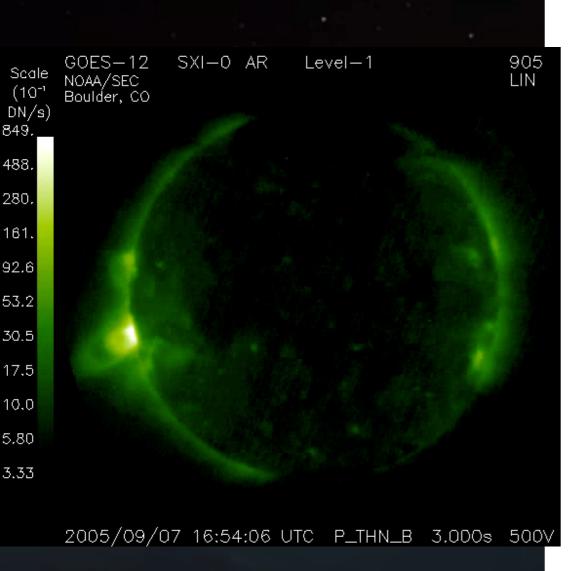
NOAA Education www.education.noaa.gov NOAA Space Weather Prediction Center www.spaceweather.gov

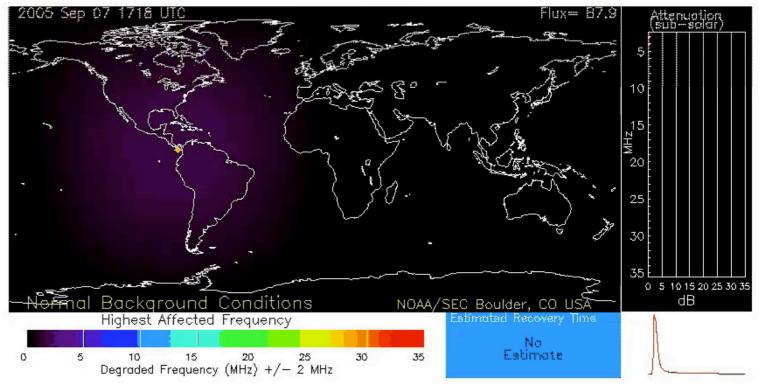


- Currents in the ionosphere create time-varying magnetic flux.
- These "Geomagnetically Induced Currents" (GIC) are picked up by long conductors such as EHV power lines.



Space Weather 101 Impact example: solar flare → radio blackout





Sational Weather Service

Only visible manifestation of Space Weather: the Aurora *

🔊 🞯 National Weather Service

* Astronauts in orbit report retinal proton "fireflies"

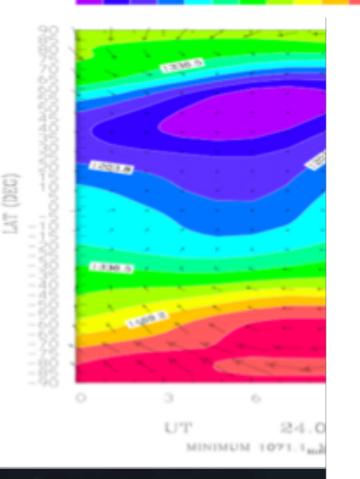
Only visible manifestation of Space Weather: the Aurora *

22-January-2012

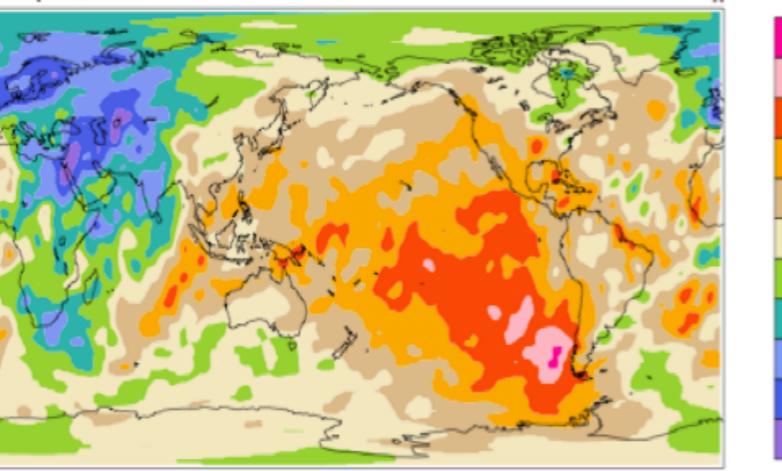
* Astronauts in orbit report retinal proton "fireflies"

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

CTIP NEUTRAL TEMPERATURE (DEG. K) M20031027



Temperature



1040

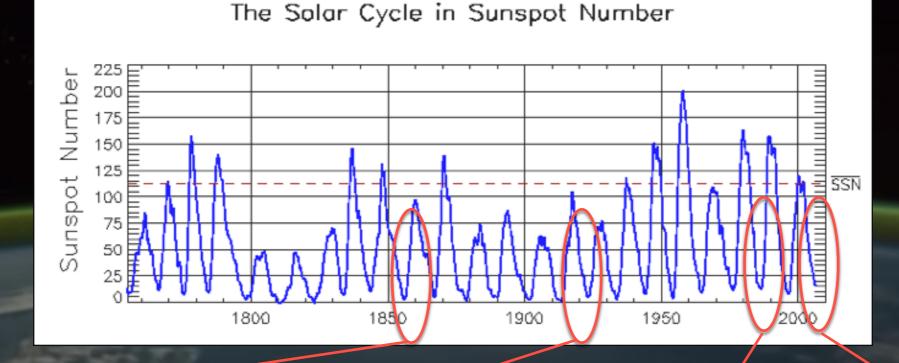
1000

960

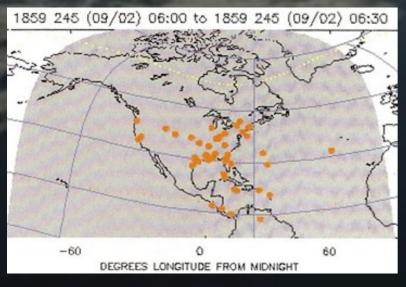
920

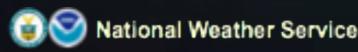
880

 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 borealls 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 sunspol has been blamed for such a piece of mischief. From other accounts it appeared

> Ehr New Hork Eimes Published: May 16, 1921

1989 Storm

HYDRO-QUEBEC PRESS RELEASE

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

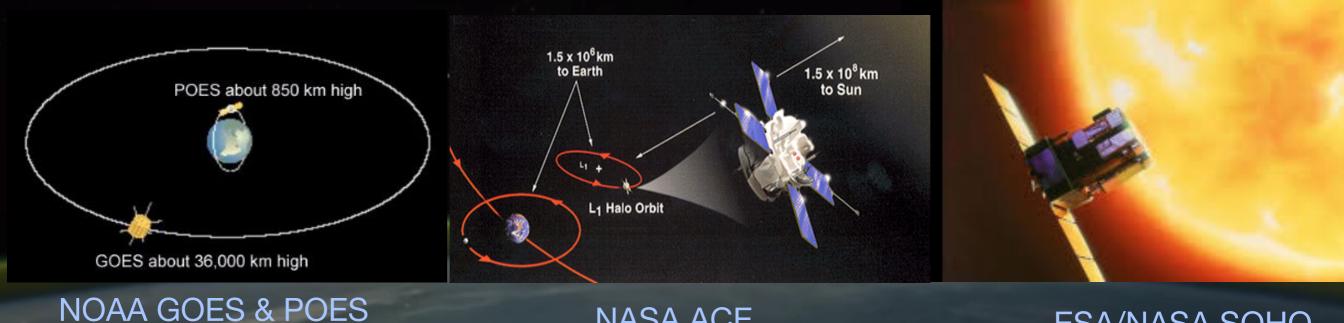
An hour-long power outage that affected 20,000 homes in Sweden's southern city of Malmoe on Thursday was probably caused by a powerful



geomagnetic storm that hit the Earth, power company Sydkraft said.

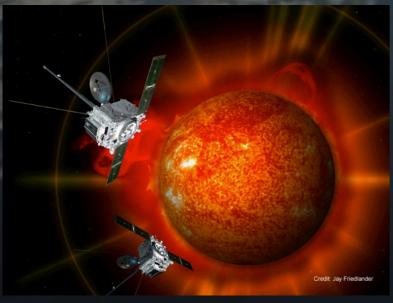


Current NOAA Space Weather observations •



NASA ACE

ESA/NASA SOHO



NASA STEREO National Weather Service



NASA Solar Dynamics Observatory

Current NOAA Space Weather observations



USGS Magnetometers



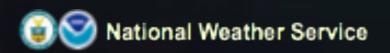
Air Force SEON Network



NOAA CORS Network



NSF GONG Network



NOAA SWx forecast models.

Solar Wind source WSA (AFRL) Operational

> Solar Wind heliosphere Enlil (George Mason) Operationa

Magnetosphere (U. Michigan) SWMF Operational in 2016

Ionosphere IPE (U. Colorado) Operational in 2017

> **Thermosphere** WAM (NOAA) Operational in 2018

Aurora

OVATION (Johns Hopkins)

Ground E-Field (USGS) Operational in 2016

- 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).

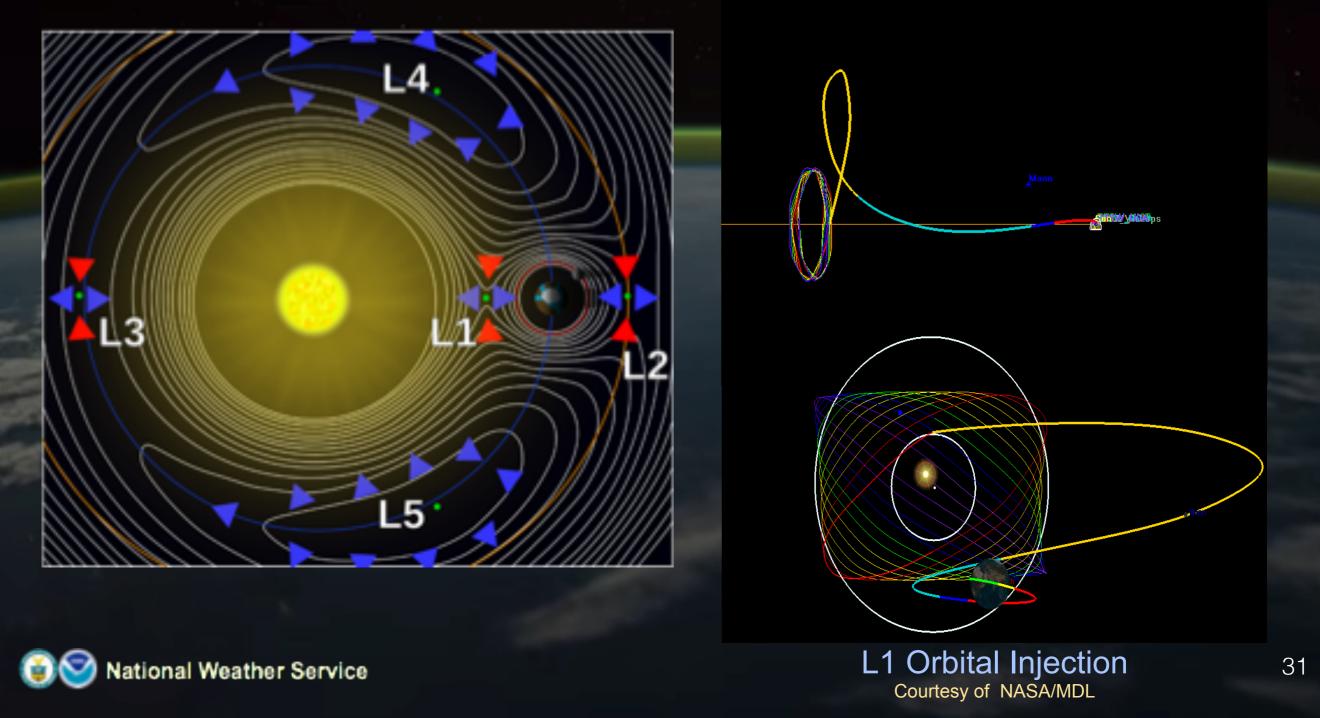
- What we need to (better) forecast geomagnetic storms:
 - Observations and models of the solar magnetic field (sunspots).
 - Observations and models of the solar corona (esp. flares and CMEs).
 - Measurements of the solar wind heading to Earth (speed and magnetic field).
 - Models of the "heliosphere" 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.

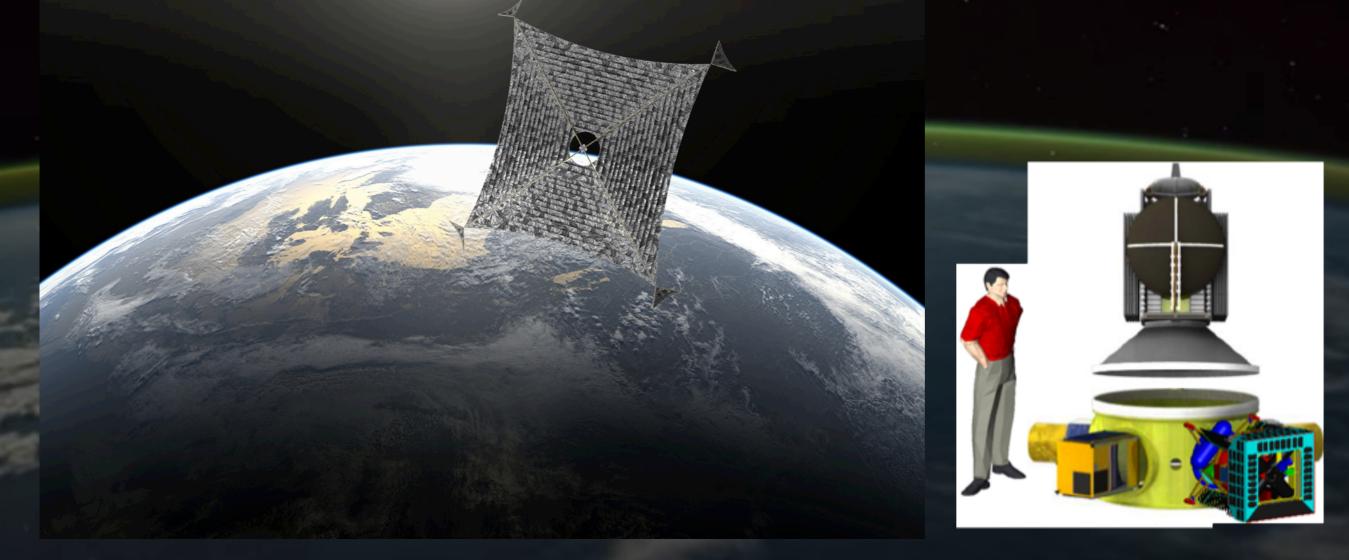
Deep space orbits

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



Deep space orbits

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



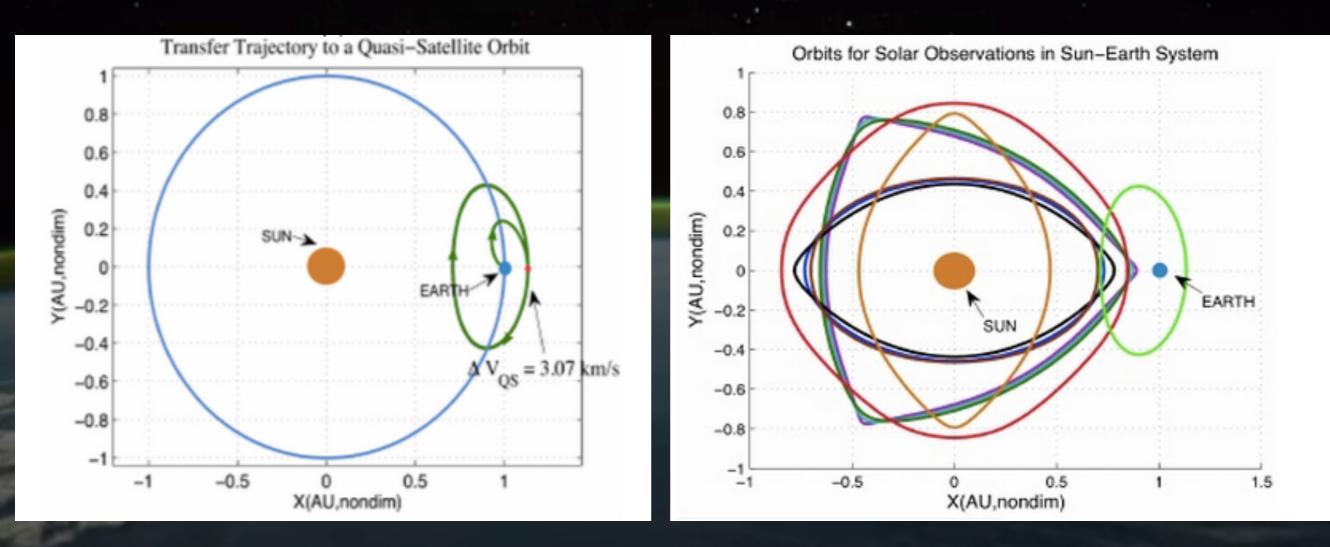
Sunjammer mission concept

<u>vww.sunjammermission.com</u>



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.

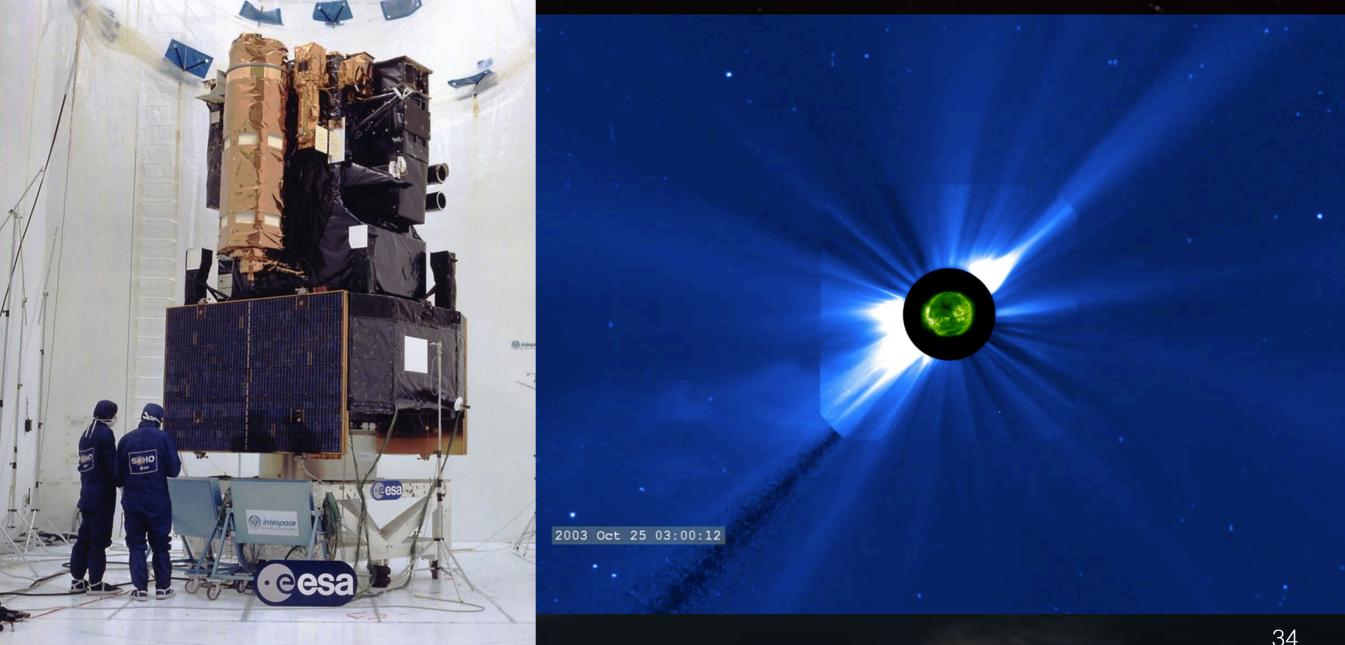


Deep space missions: SOHO

Solar and Heliospheric Observatory

Launched 1995

- NASA/ESA flagship mission. •
- L1 orbit.



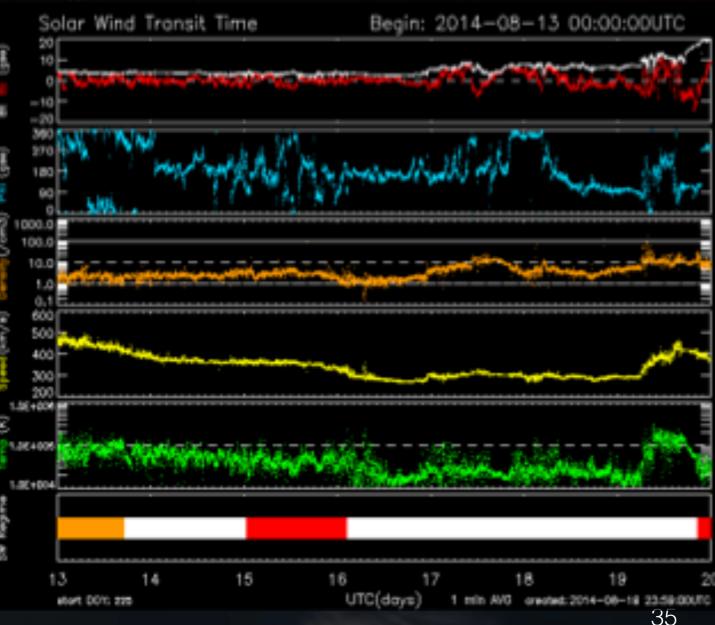
Deep space missions: ACE

Advance Composition Explorer

Launched 1997

- NASA Small Explorer mission.
- L1 Orbit.
- Real-time "beacon" transmitter and antenna network supplied by NOAA.

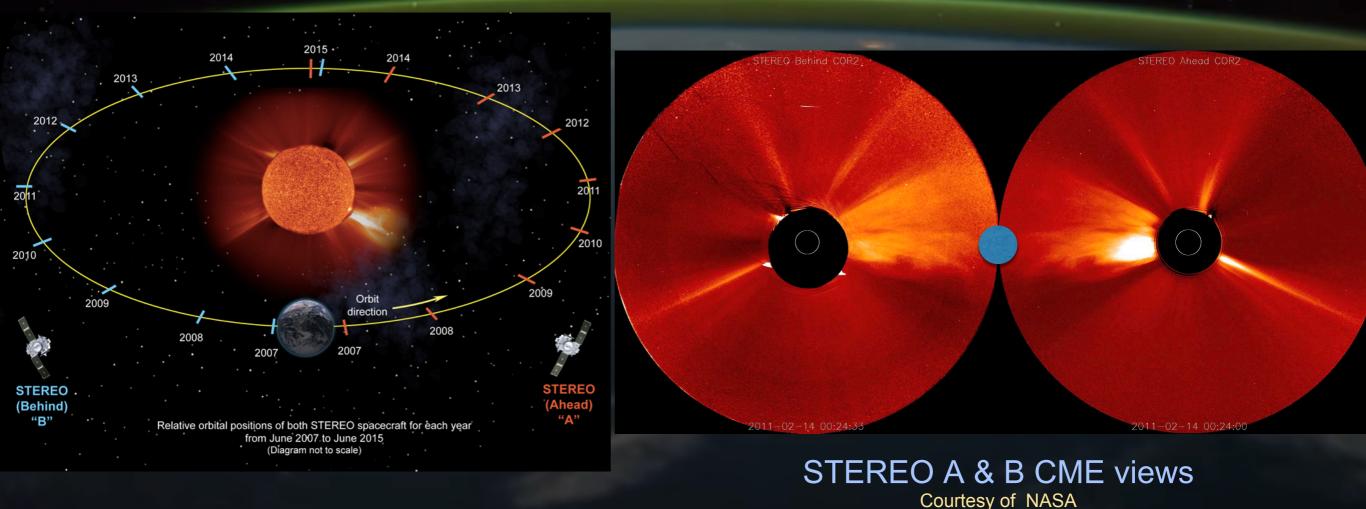


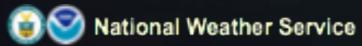


Deep space missions: STEREO

- Solar Terrestrial Relations Observatory
- Two satellites: "Ahead" and "Behind".
- NASA Solar Terrestrial Probes mission.
- Heliocentric leading and trailing orbits.

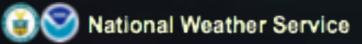
Launched 2006





Deep space missions: DSCOVR



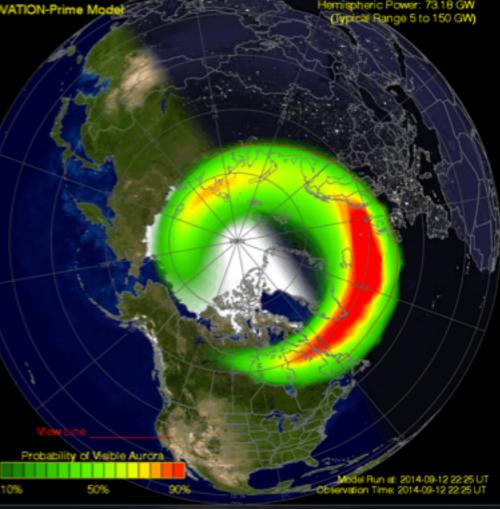


Falcon 9 Launch, 11-Feb-2015 Courtesy of SpaceX

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

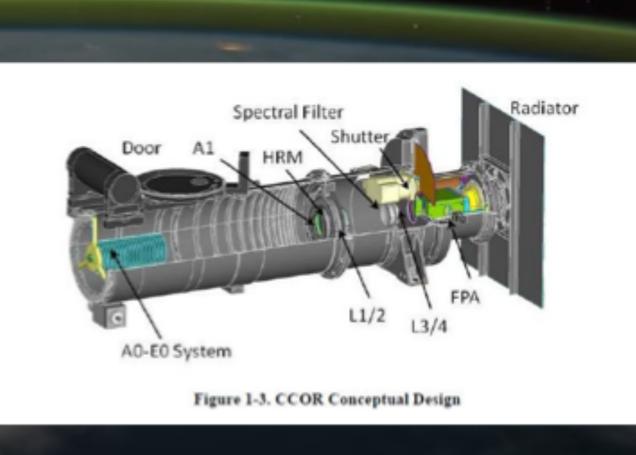
Real-Time Solar Wind Network Air Force Space Command Network



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.

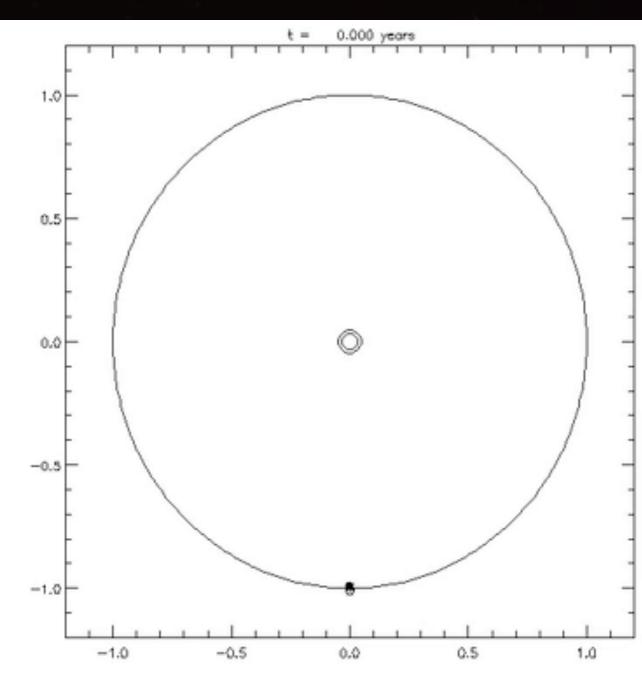




Compact Coronagraph Courtesy of NRL

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.



Sational Weather Service

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!