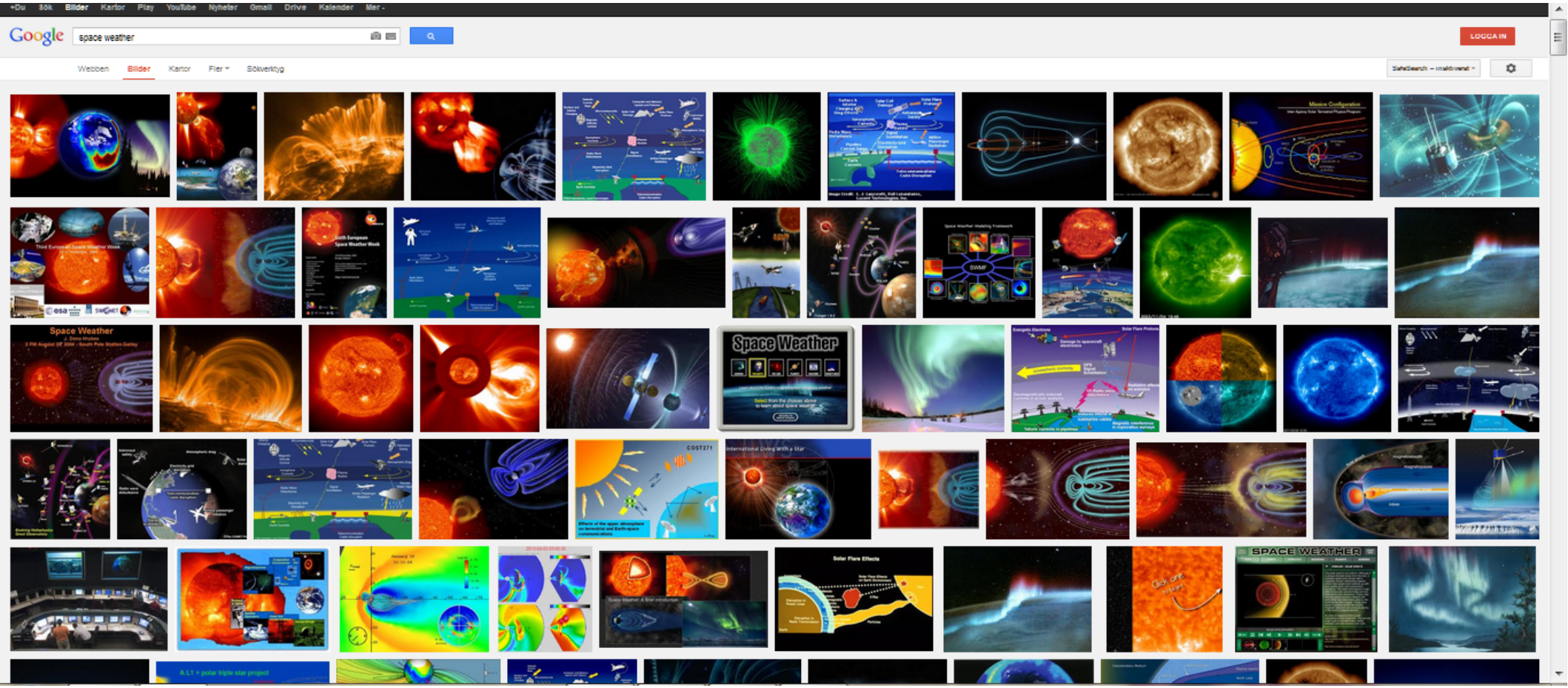
Space Weather

Anders Tjulin
EISCAT Scientific Association

Kiruna, 2013-05-13

What is space weather?

- Google Images says:

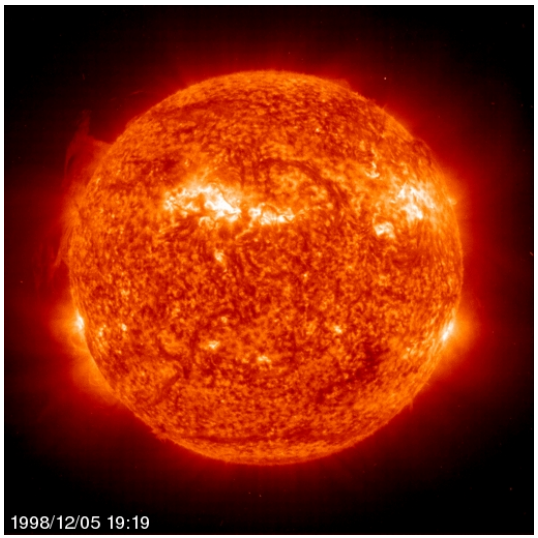


What is space weather?

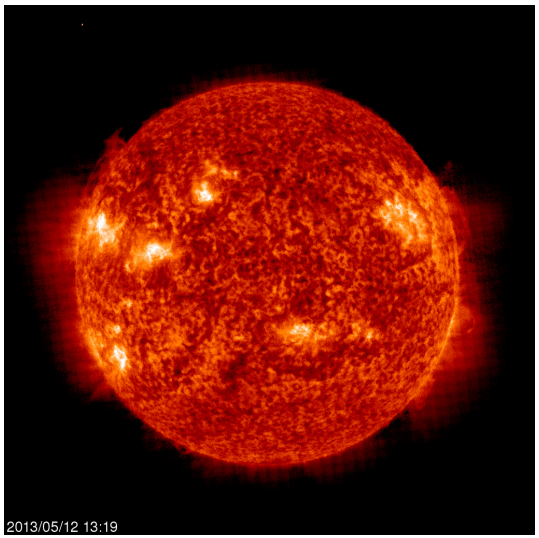
- “The conditions on the Sun and in the solar wind, Earth's magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and endanger human life or health” *(Eastwood, Phil. Trans. R. Soc. A 2008)*

The source of space weather

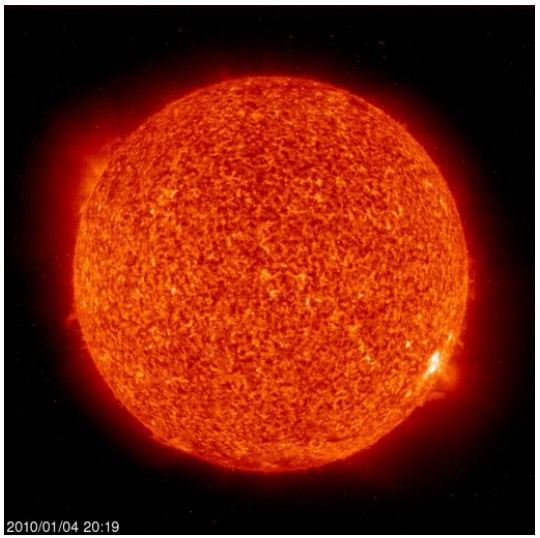
- The sun is the energy source for all weather, including space weather
- The activity of the sun varies with roughly a period of 11 years between successive activity maxima



High Activity



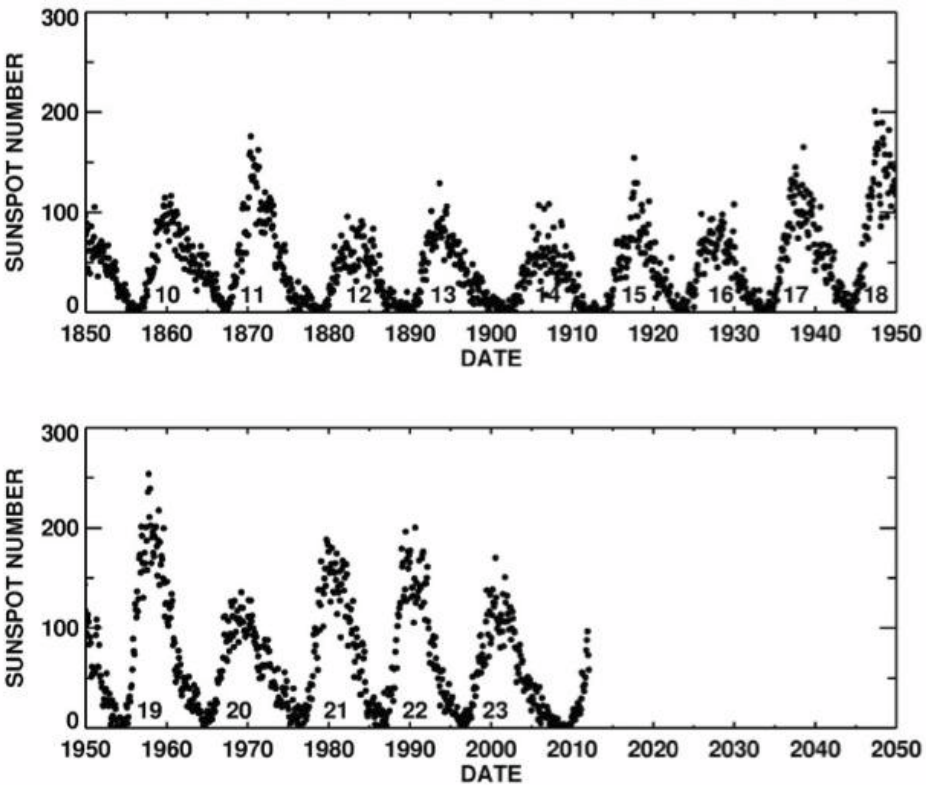
Now



Low Activity

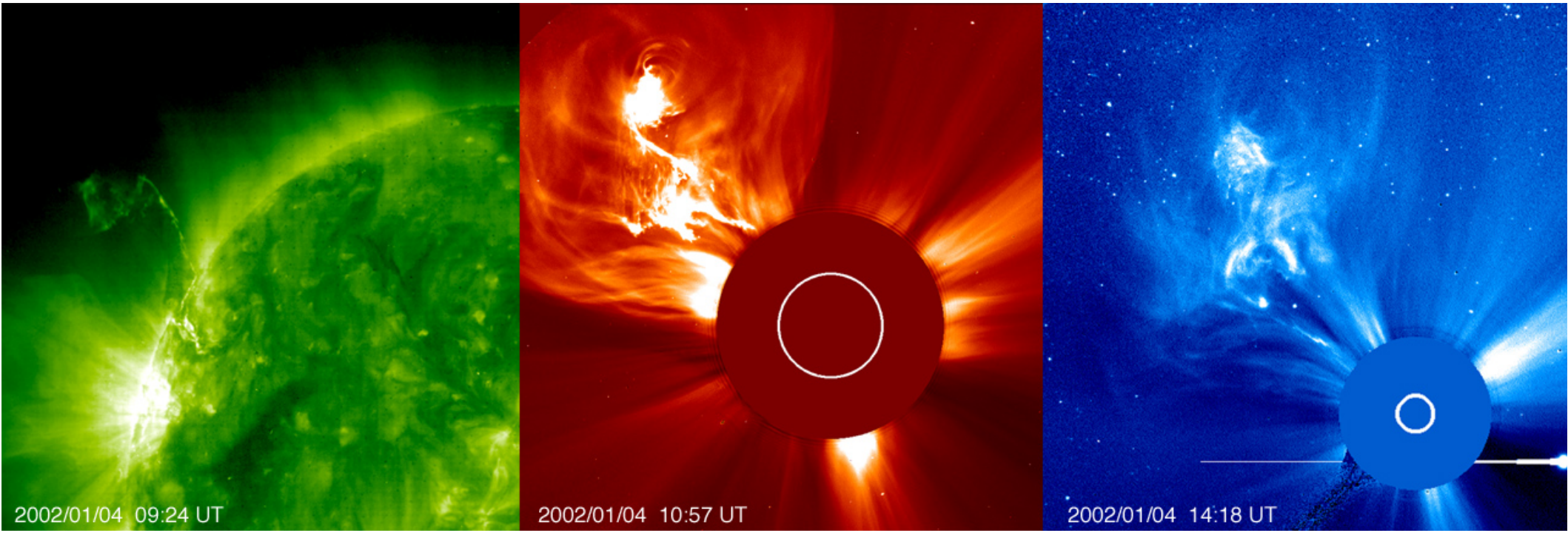
Source: The Sun

- The solar activity cycle corresponds to reversals of its dipole magnetic field
  - Low activity when the field is stable – dipole-like field
  - High activity during the reversal – complicated field
- One simple measure of the activity is the number of sun-spots



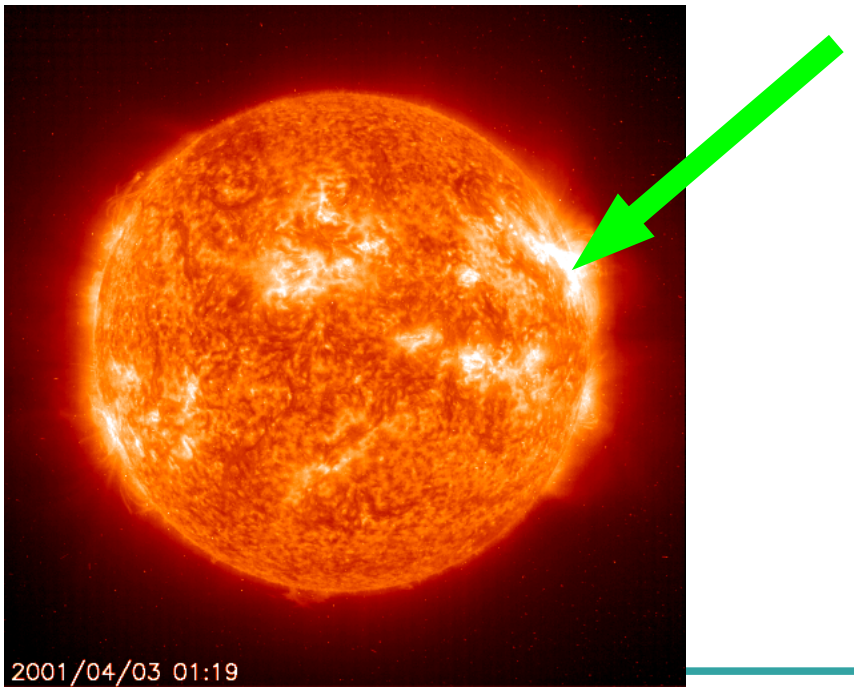
Source: Coronal Mass Ejections (CMEs)

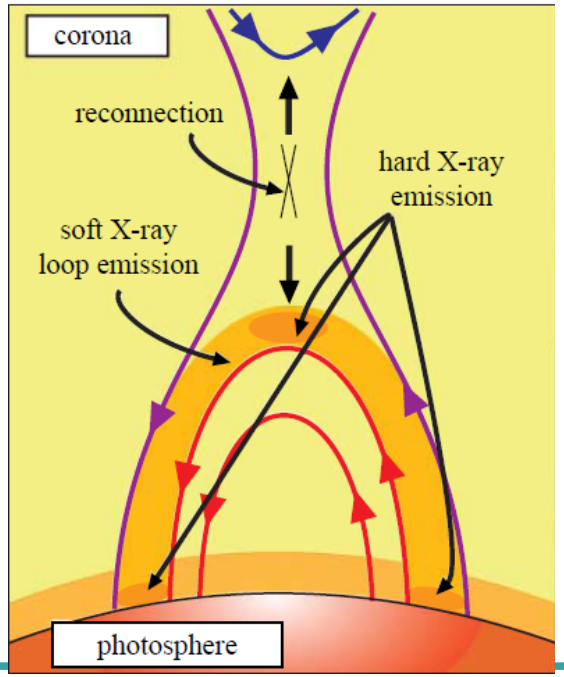
- Large eruptions of solar coronal material into space
  - Most common at solar maximum



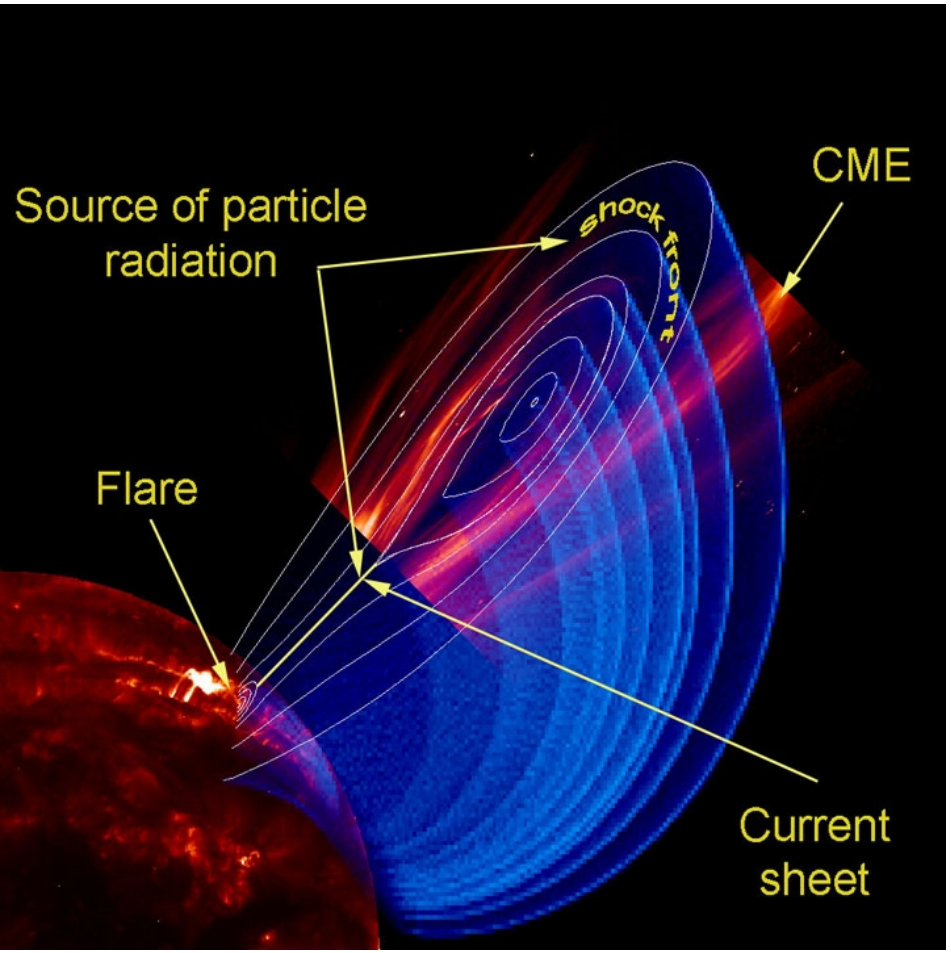
Source: Solar Flares

- Rapid release of the energy in the magnetic field of the solar corona
  - Reconnection plays an important role
  - Bright X-ray and UV emissions





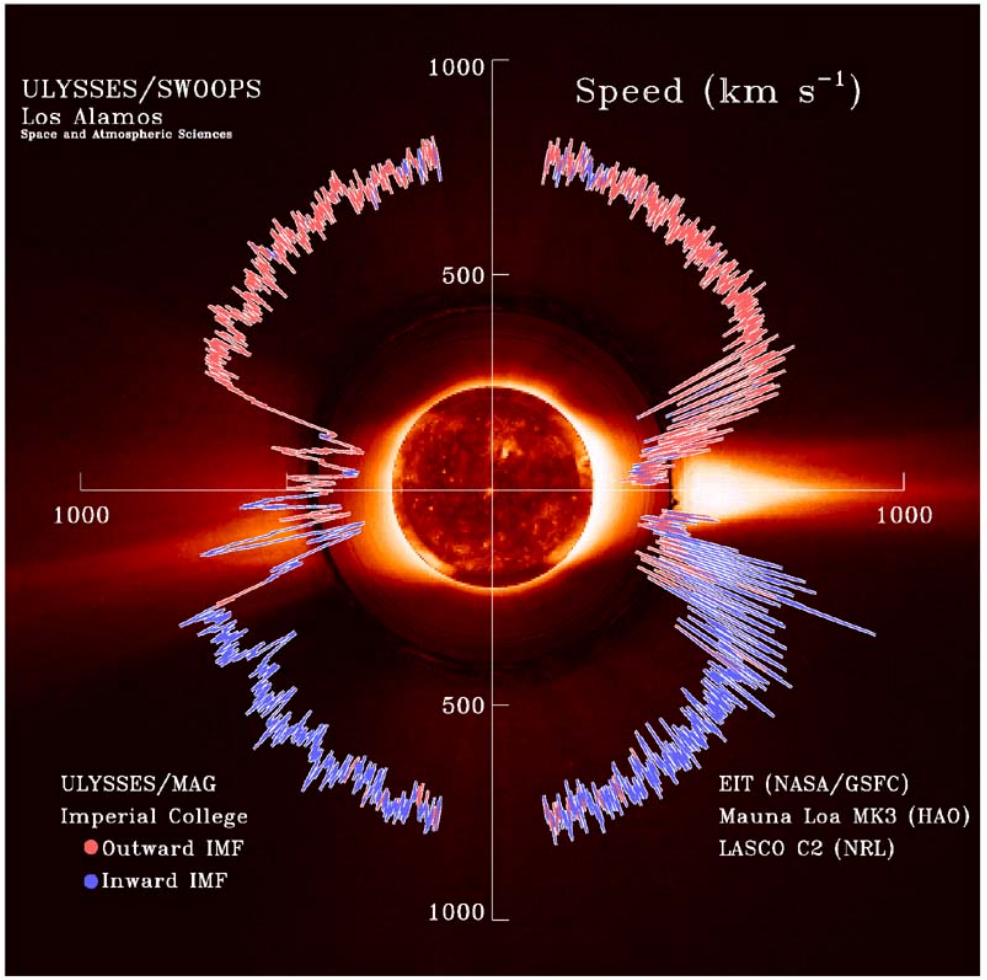
Source: Solar Energetic Particles (SEPs)



- Protons and electrons travelling with relativistic energies
  - Sometimes with velocity up to 0.8c
- Comes from CMEs and solar flares
  - Shock acceleration at CME
  - Reconnection at solar flares

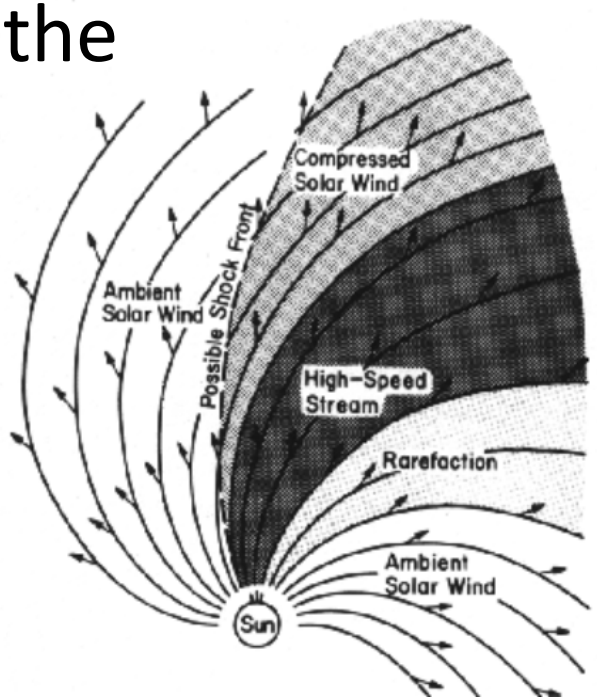
Source: Corotating Interaction Regions (CIRs)

- Solar wind has two typical velocities
  - Fast wind close to the solar poles
  - Slow wind close to the solar equator



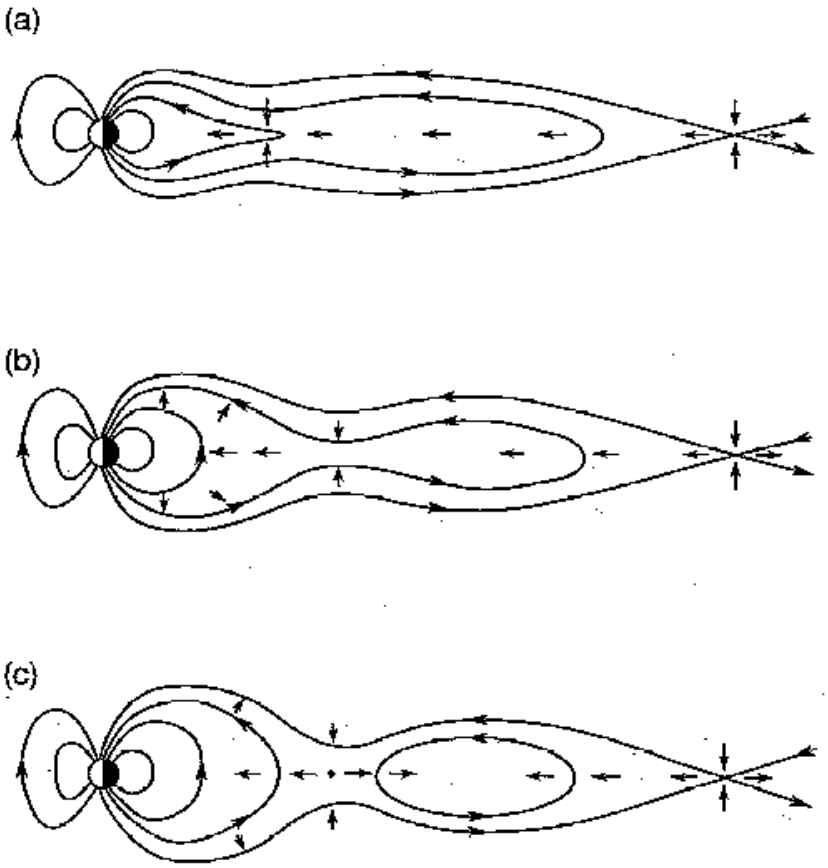
Source: CIRs

- Tilt, and irregularity of the solar dipole can make the fast wind catch up with the slow wind
  - Leads to compressed plasma regions
- Effects on the space weather when interacting with the Earth's magnetosphere
- Most common at solar minimum
  - More stable conditions at the sun enhances the effect



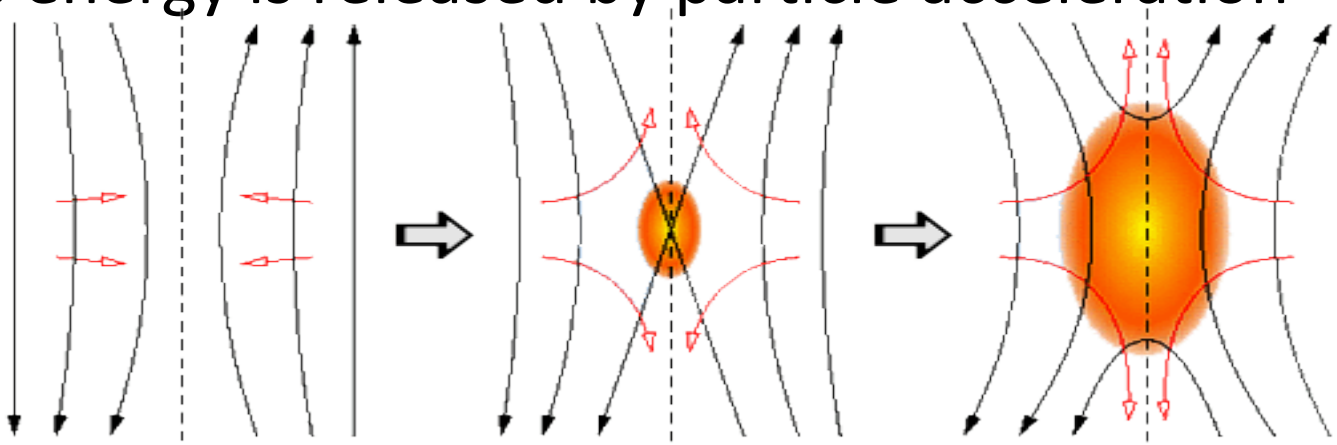
Source: Magnetic Substorms

- Explosive release of stored magnetic energy in the magnetotail
  - Occurs at southward Interplanetary Magnetic Field (IMF)
  - The build-up (the storage of energy) do not occur for northward IMF



Source: Magnetic Substorms

- Accelerates particles towards the Earth
- Magnetic reconnection is the means of the acceleration
  - Changing the topology of the magnetic field to minimise the magnetic energy
  - The energy is released by particle acceleration



Geomagnetic Storms

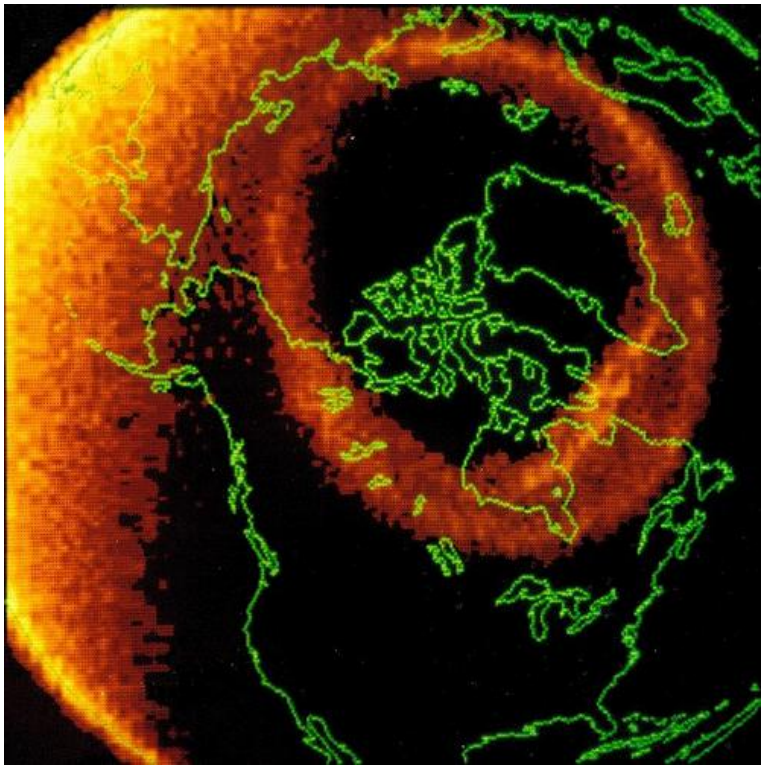
- Temporary large-scale disturbance of the Earth's magnetosphere
  - Often caused by one, or a combination, of the previously mentioned sources
- Typically lasts for 24 to 48 hours
- Important facet of what we call space weather

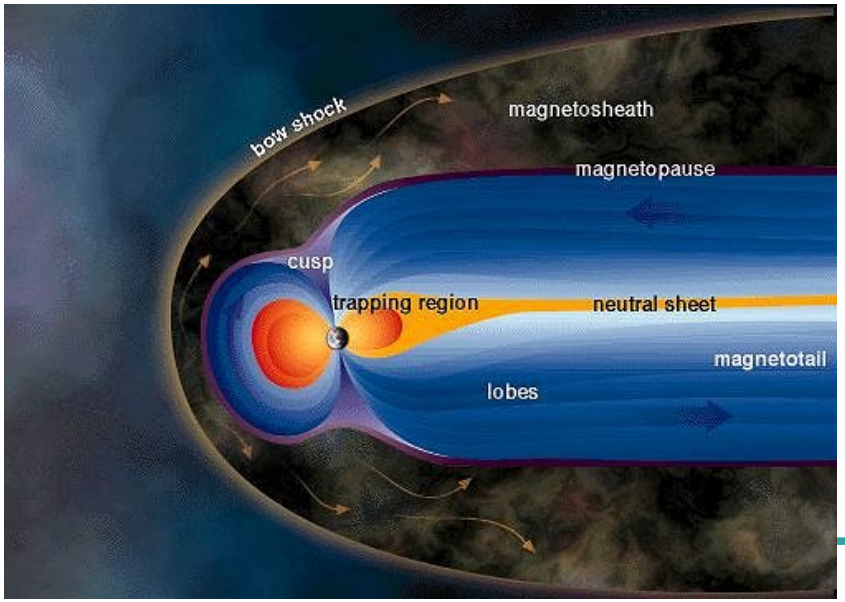
Effects: Aurora

- Photon emissions from oxygen and nitrogen in the upper atmosphere
  - Atoms excited by collisions with accelerated ions and electrons
  - Emitting photons when returning to ground state

Effects: Aurora

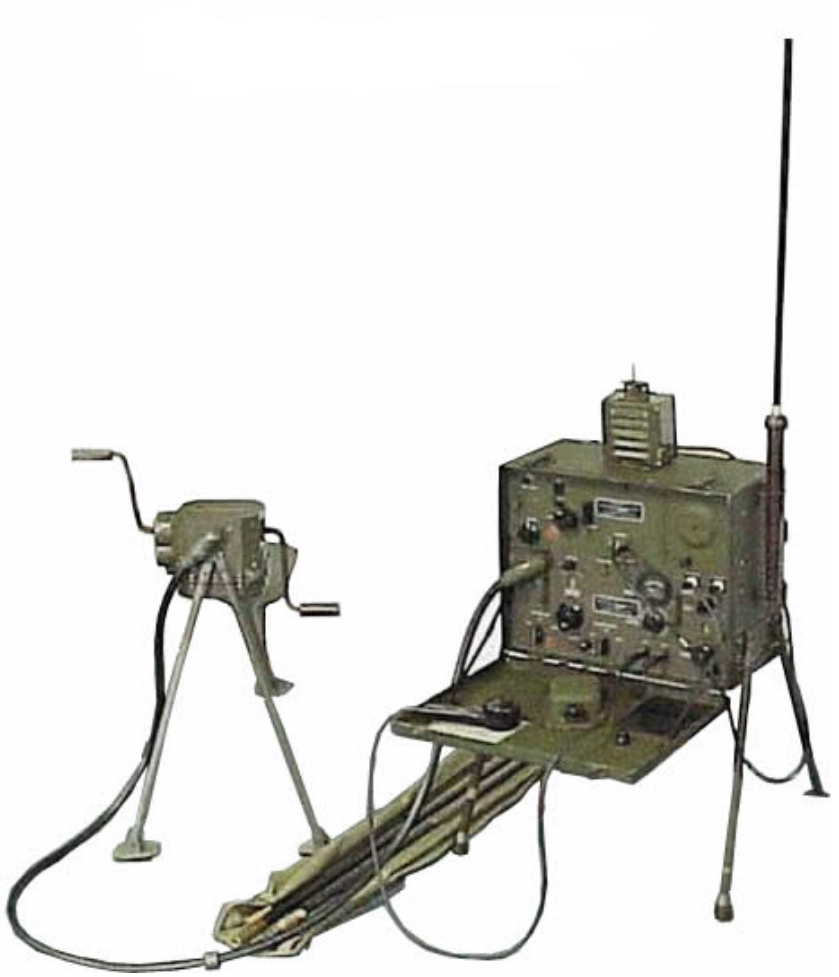
- The accelerated particles follow magnetic field lines
  - Thus, the aurora occurs where these field lines reach the Earth: The Auroral Oval





Effects: Radio communication

- Changing ionospheric conditions has effects on HF radio
  - HF radio signals may be lost or absorbed, bounce and miss the receivers
  - Communication over the poles at certain frequencies can be completely blacked out

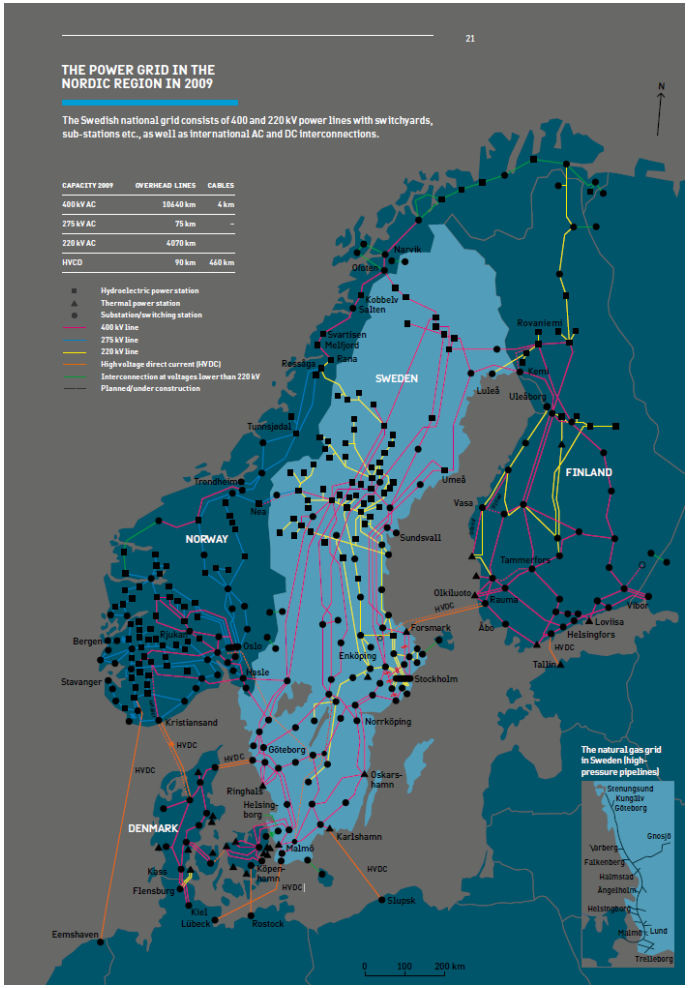


Effects: Air travel

- On polar routes, HF radio is used
  - Geostationary com-satellites cannot be used
- Disrupted radio means re-routing
  - Expensive: ~ $100,000 per flight
- Also, exposure to SEPs on high altitudes and latitudes
  - Risk for human health
  - Risk for vital electronics

Effects: Electric power

- Variations in magnetic field induce electric fields
  - Faraday's law: $\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E}$
- Drives Geomagnetic Induced Currents (GICs) in conducting networks
- Power transformer cores may saturate: Blackouts
- Cascading effects from failures in grids



Effects: Electric power

- Famous large blackouts from space weather:
  - Québec, 13 March 1989
    - Large geomagnetic storm following a CME
    - Large transmission line loops, and poor conduction in the ground
    - Circuit breakers tripped on Hydro-Québec's power grid
    - Power failure lasted 9 hours, 6,000,000 people affected
  - Malmö/Copenhagen, 30 October 2003
    - Very powerful geomagnetic storm following a CME
    - Resonance of the magnetic fluctuations in the power grid
    - Lasted 1 hour, 50,000 people affected
  - These events lead to changed mitigation strategies

Effects: Pipeline corrosion

- GIC may lead to a potential difference between the pipeline and the soil
  - Enhanced corrosion of the pipes
  - May lead to severe leaks and damage to the environment (and the owner's economy)
- Long pipes at high latitudes most sensitive

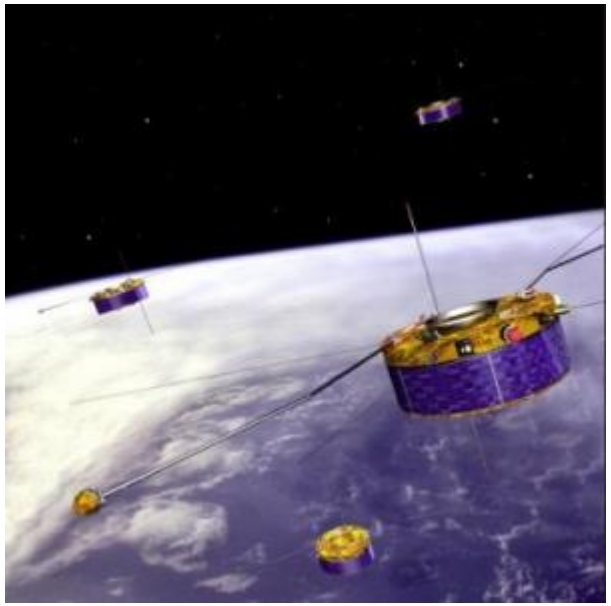
Effects: Navigation

- Global Navigation Satellite Systems (GNSS) receivers determines position using signals from satellites
  - Irregularities in the ionosphere may lead to diffraction and refraction of the signals
    - Errors in position
  - Signals may be drowned in the radio emissions following solar flares
  - Solar flare events may last for hours
- Navigation errors for ships can lead to wasted fuel, groundings, and spoiled cargo

GPS
GLONASS
BeiDou
Galileo

Effects: Satellites

- Satellites experience several effects from space weather:
  - Surface charging
  - Surface damage
  - Solar panel degradation
  - Spurious sensor data
  - Satellite orientation anomalies
    - Many uses magnetic field for orientation
  - Extra atmospheric drag
    - Earth's atmosphere expands when heated during SEP-events
  - Effects can be avoided with a timely alert

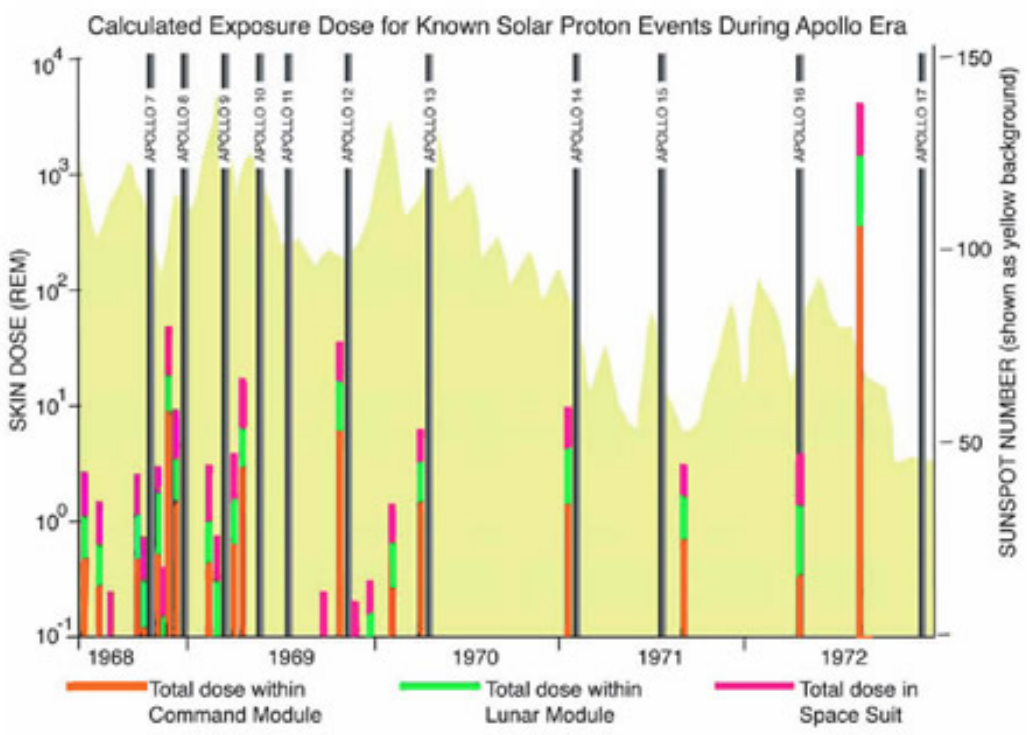


Effects: Spaceflight

- Very dangerous for astronauts during certain space weather events
  - The Apollo astronauts were extremely lucky
  - Advance warning systems important for longer manned space missions

(1 rem = 0.01 Sv)

50 rem → illness
200 rem → severe illness
1000 rem → death



Effects: Climate

- The solar variability is certainly connected to variations in the climate on Earth
- The extent of this connection is highly debated

Predicting Space Weather

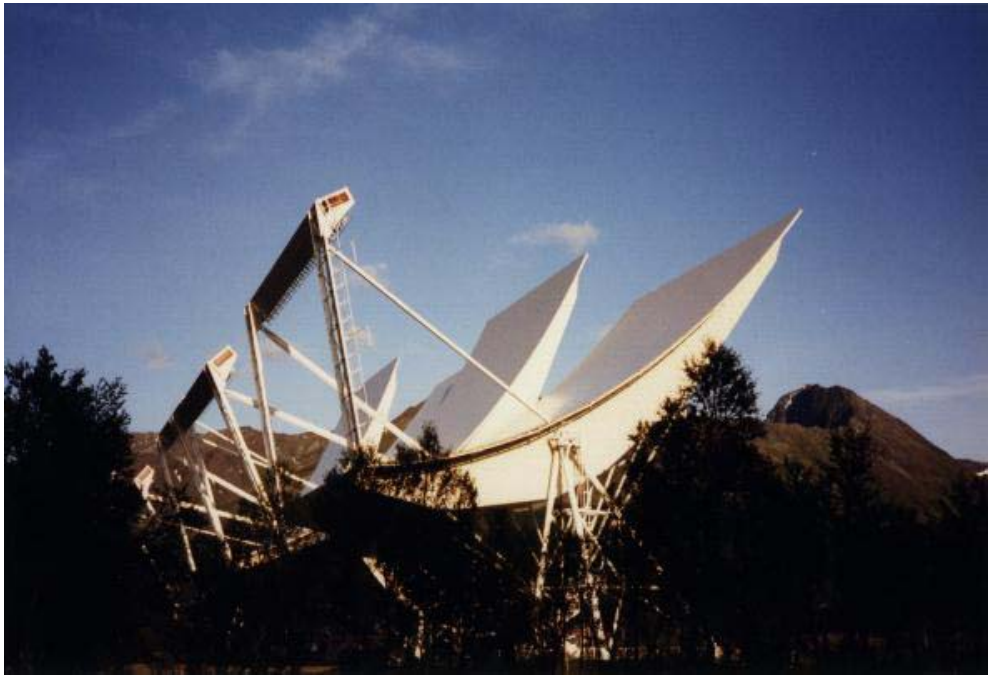
- Space weather predictions are needed to minimise the effects of large space weather events
- Advanced computer models are used
- Observations are also needed
  - Input to the models
  - Correction of the models
  - Understanding the physics behind the models

Space weather warnings

- NOAA (National Oceanic and Atmospheric Administration) has introduced space weather scales to describe space weather conditions and possible effects
  www.swpc.noaa.gov/NOAAscales
- Three space weather aspects in the warnings:
  - Geomagnetic storms
    - Disturbances in the geomagnetic field
  - Solar radiation storms
    - Elevated levels of energetic particle radiation
  - Radio blackouts
    - Ionospheric disturbances caused by solar X-ray emissions

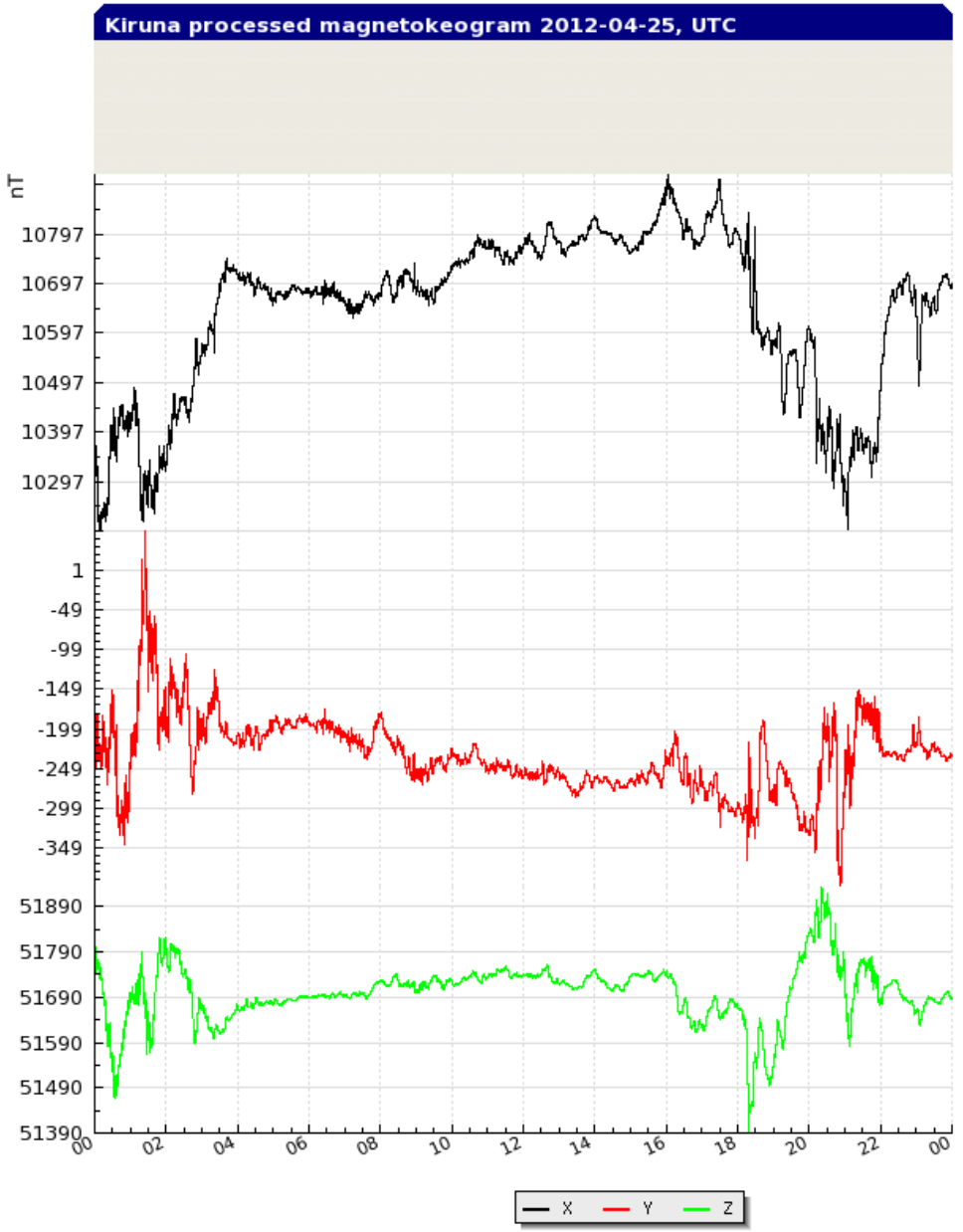
Monitoring the Space Weather

- There are many ways to monitor the space weather
  - On spacecraft
  - On the ground
- Many things to measure
  - Density
  - Temperature
  - Magnetic field
  - …



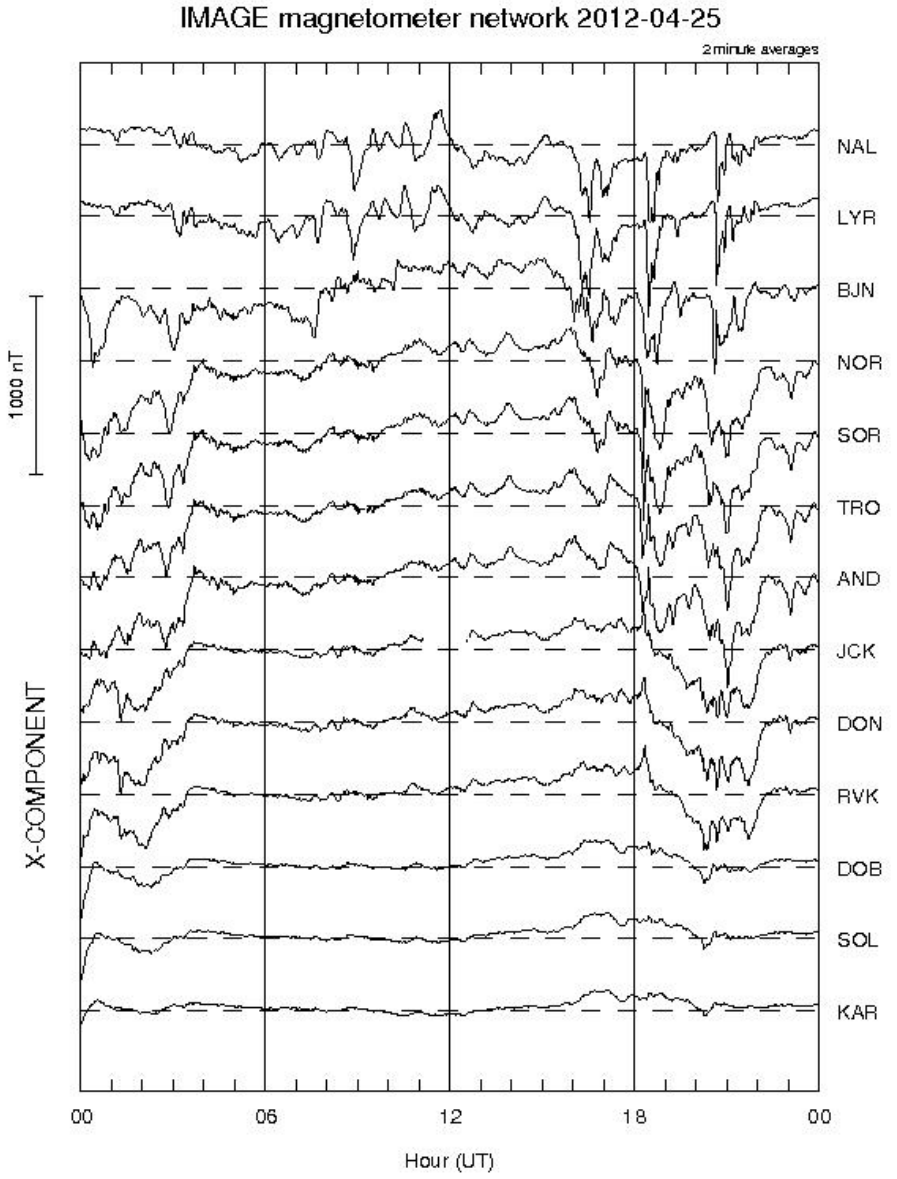
Magnetometers

- There are many magnetometers observing the local geomagnetic field
- They typically produce time series of three magnetic field components



Chain of magnetometers

- By combining magnetograms from several places we get a more complete view of the situation
  - Different magnetometers plotted on top of each other
  - The top one is the northernmost
  - This example is from the IMAGE network



Geomagnetic Indices

- K-index is related to the maximum fluctuations of horizontal components observed on a magnetometer relative to a quiet day, during a three-hour interval
  - Integer value from 0 to 9
  - Translation from nT to K-index dependent on observatory
- Kp-index is a weighted average of K-indices from a network of geomagnetic observatories
  - One number for the whole planet
- The Dst (disturbance storm time) index is based on the average value of the horizontal component of the Earth's magnetic field measured hourly at four near-equatorial geomagnetic observatories
  - Measured in nT
  - Large negative values indicate geomagnetic storm

Total Electron Content (TEC)

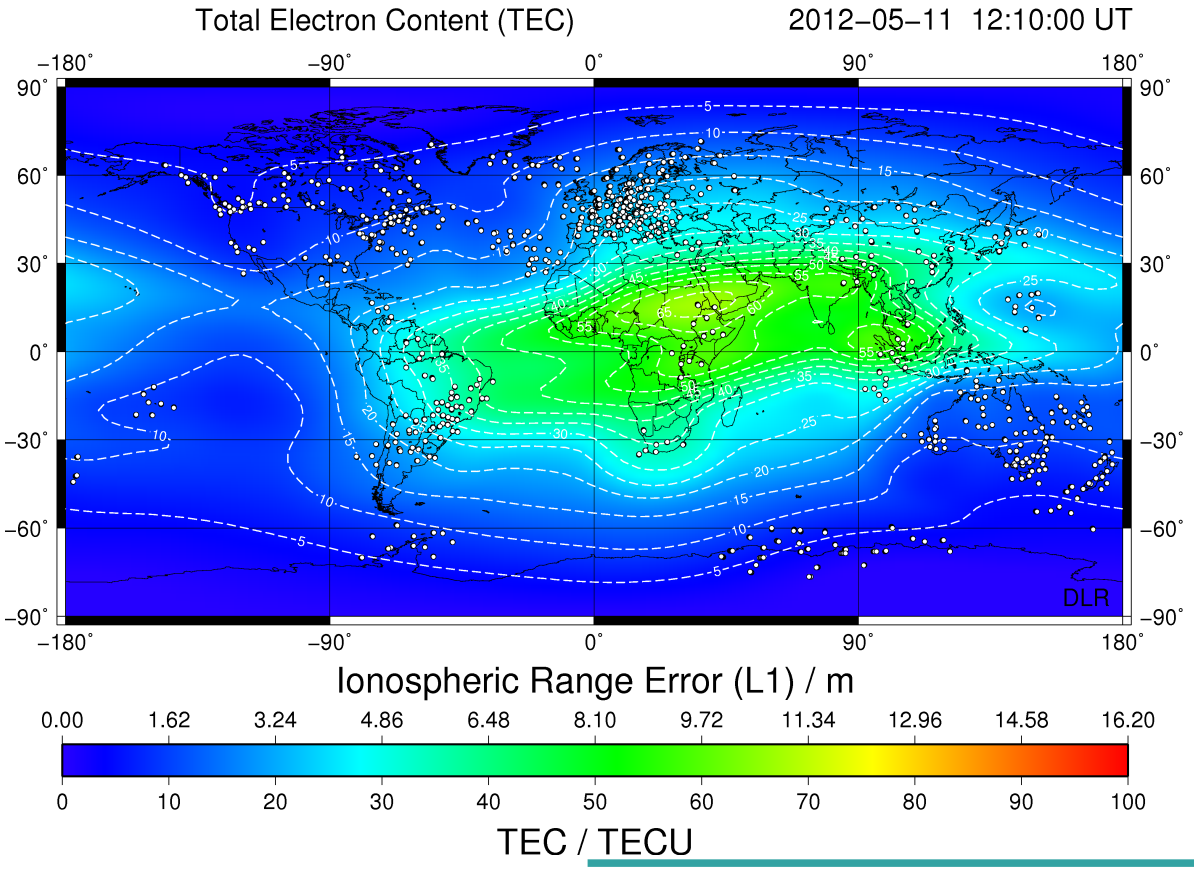
- TEC describes the overall ionisation level of the ionosphere
  - Estimated using calibration data from GNSS satellites
  - Number of electrons found in a column in a with a cross section area of 1 m² between receiver and satellite

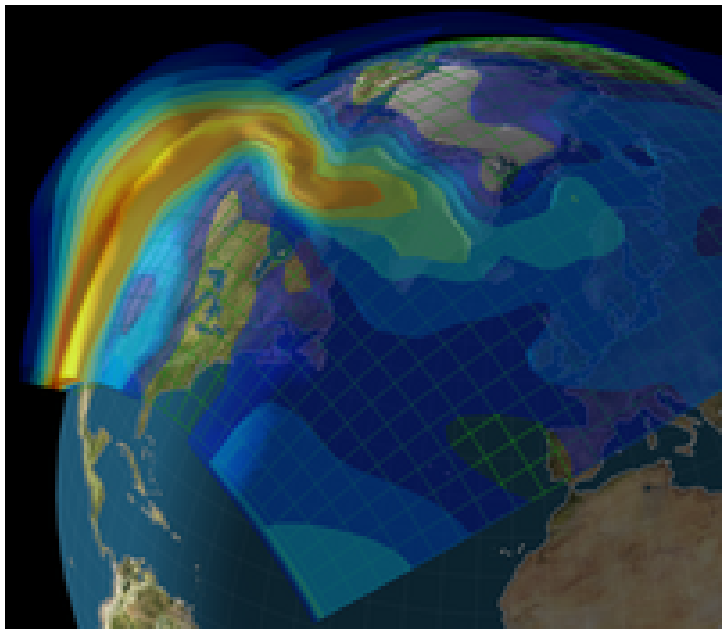
$$TEC = \int_{x_{obs}}^{x_{sat}} n_e(x)\,dx$$

- Depends on latitude, space weather conditions, time of day…

TEC

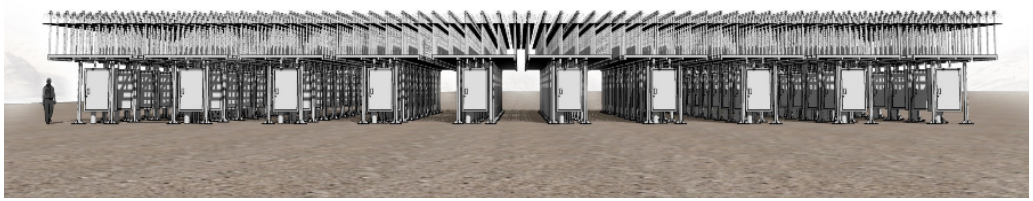
- TEC data can be combined into maps of the ionospheric ionisation level
- Even 3D pictures are possible (tomography)





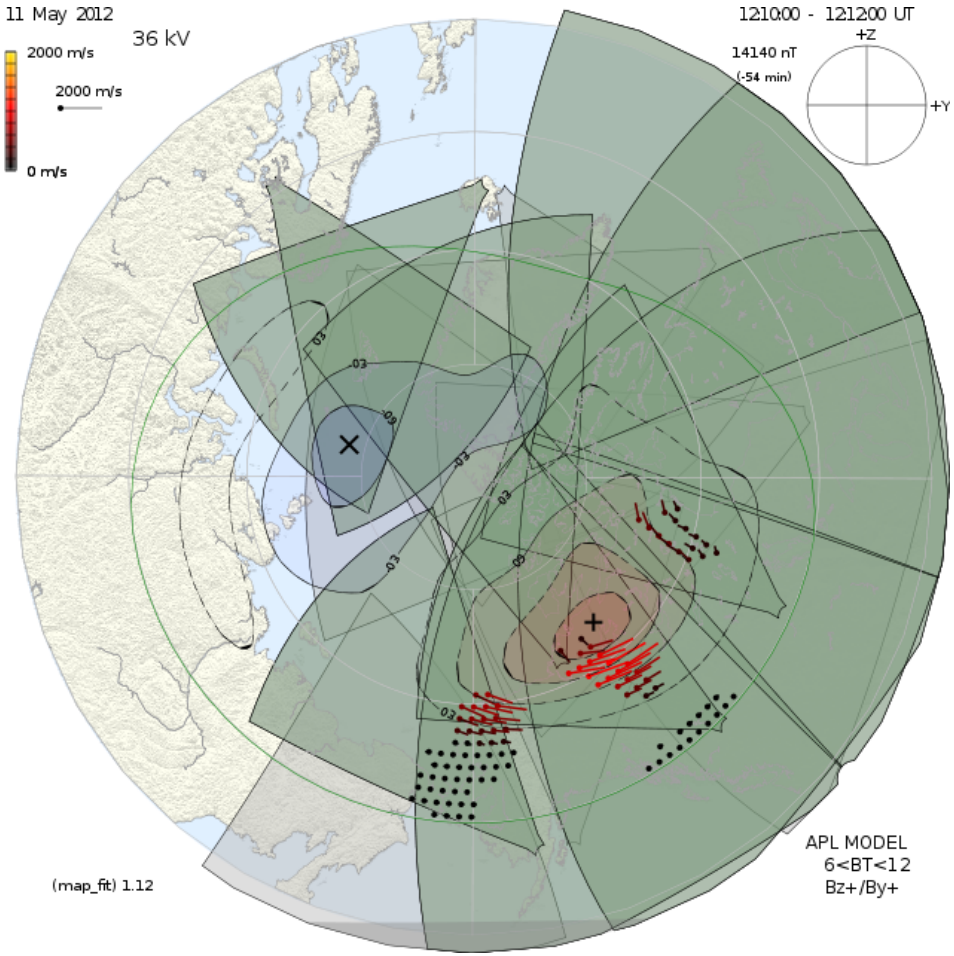
Incoherent Scattering Radars (ISRs)

- EISCAT is an example
- Measures as function of height:
  - Electron density
  - Ion and electron temperatures
  - Ion drift velocity
  - Plasma composition
- EISCAT upgrade in the works



Super Dual Auroral Radar Network (SuperDARN)

- International network of more than 20 HF radars
- Measures the Doppler velocity of plasma density irregularities in the ionosphere
- Produces maps of plasma convection near the poles

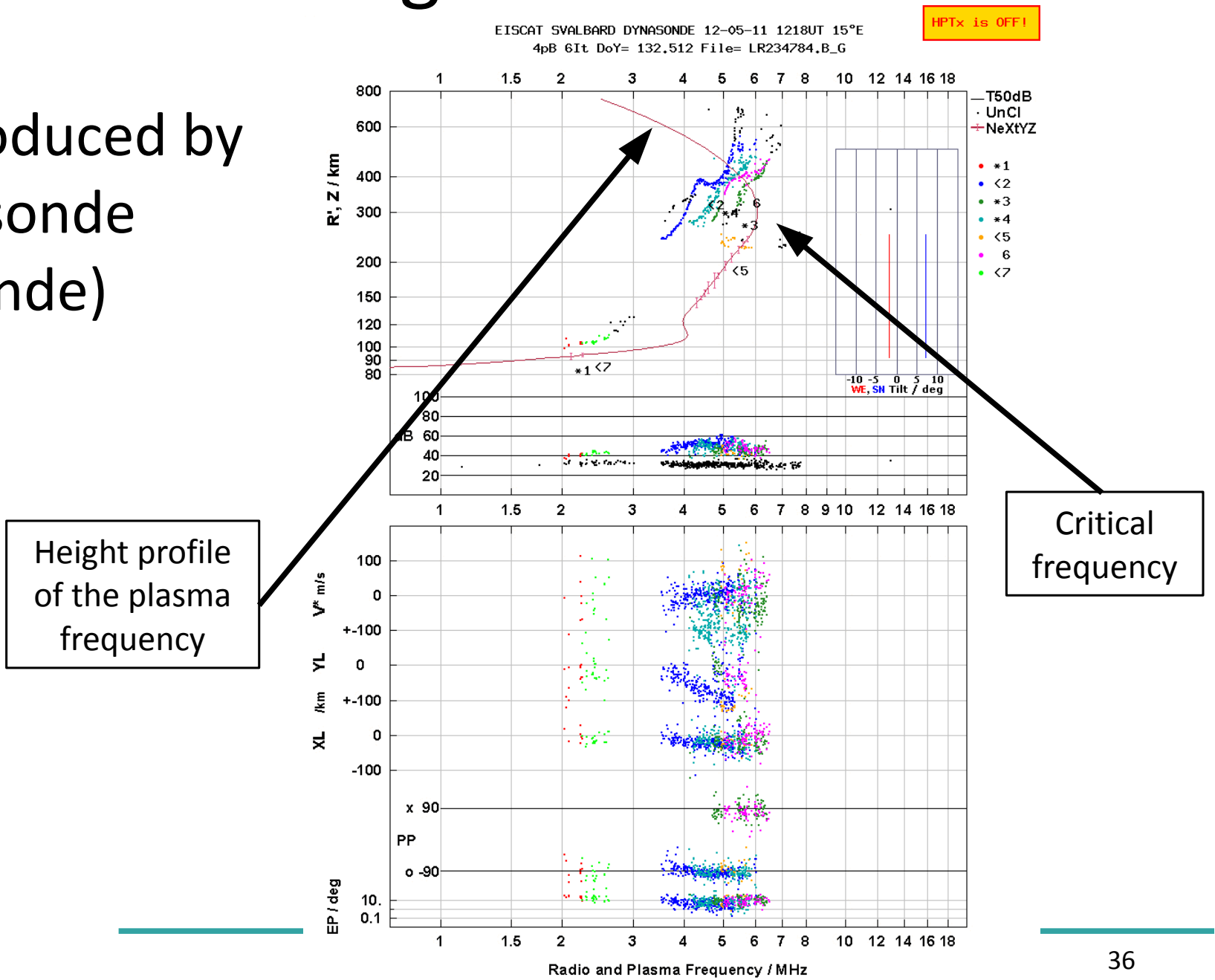


Ionosondes

- Simple measurement principle
  - Transmitter sends pulses of varying frequency
  - The signal reflects at the ionosphere
    - Different frequencies and wave modes reflect at different heights, depending on the electron density
  - System measures time it takes before receiving the reflected signal
  - Translates into plasma frequency (electron density) as function of height

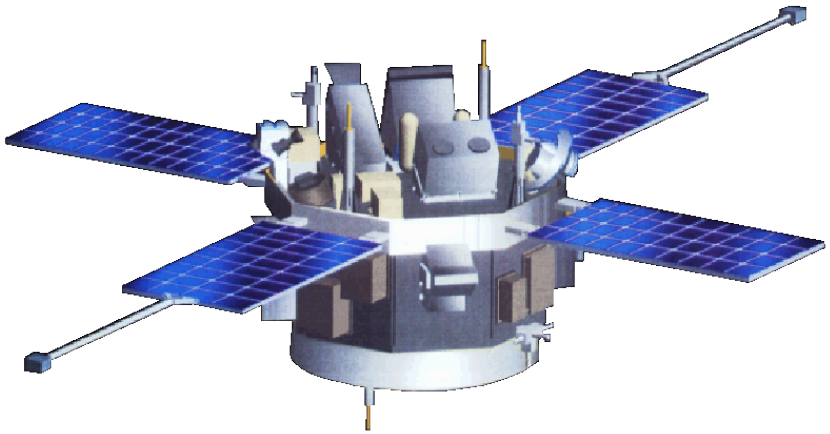
Ionograms

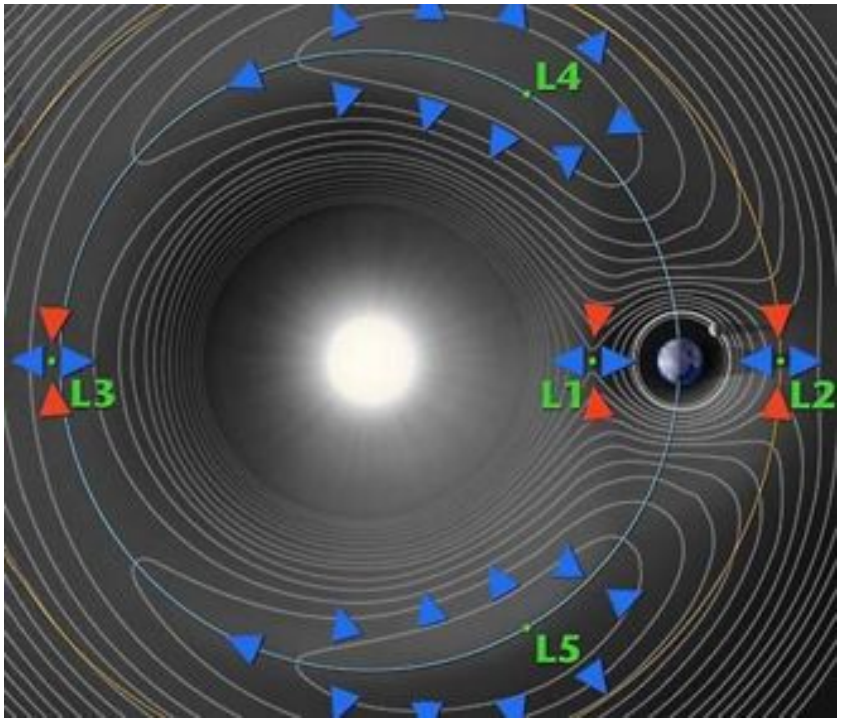
- Data produced by an ionosonde (dynasonde)



ACE

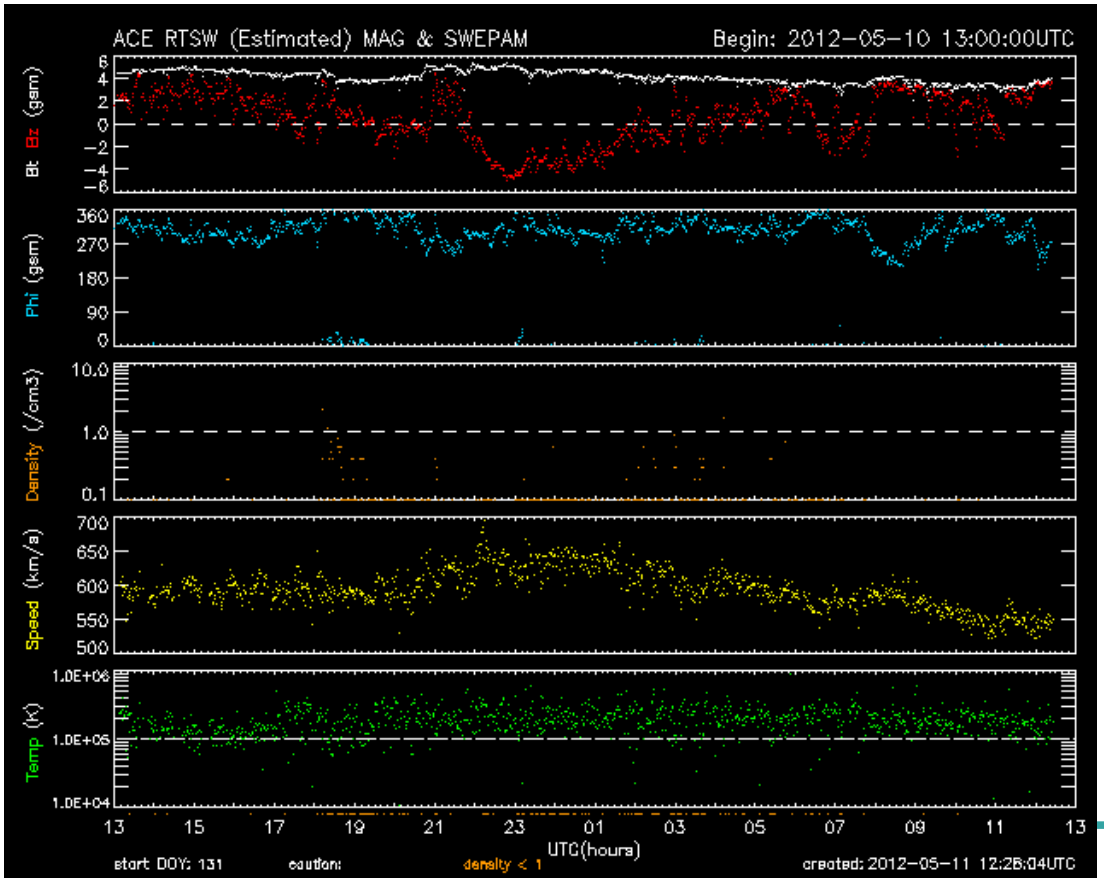
- The Advanced Composition Explorer (ACE)
  - Spacecraft at the L1 Lagrange point between the Earth and the Sun
    - About 1.5×10^6 km upstream of the Earth (roughly an hour of solar wind travel)





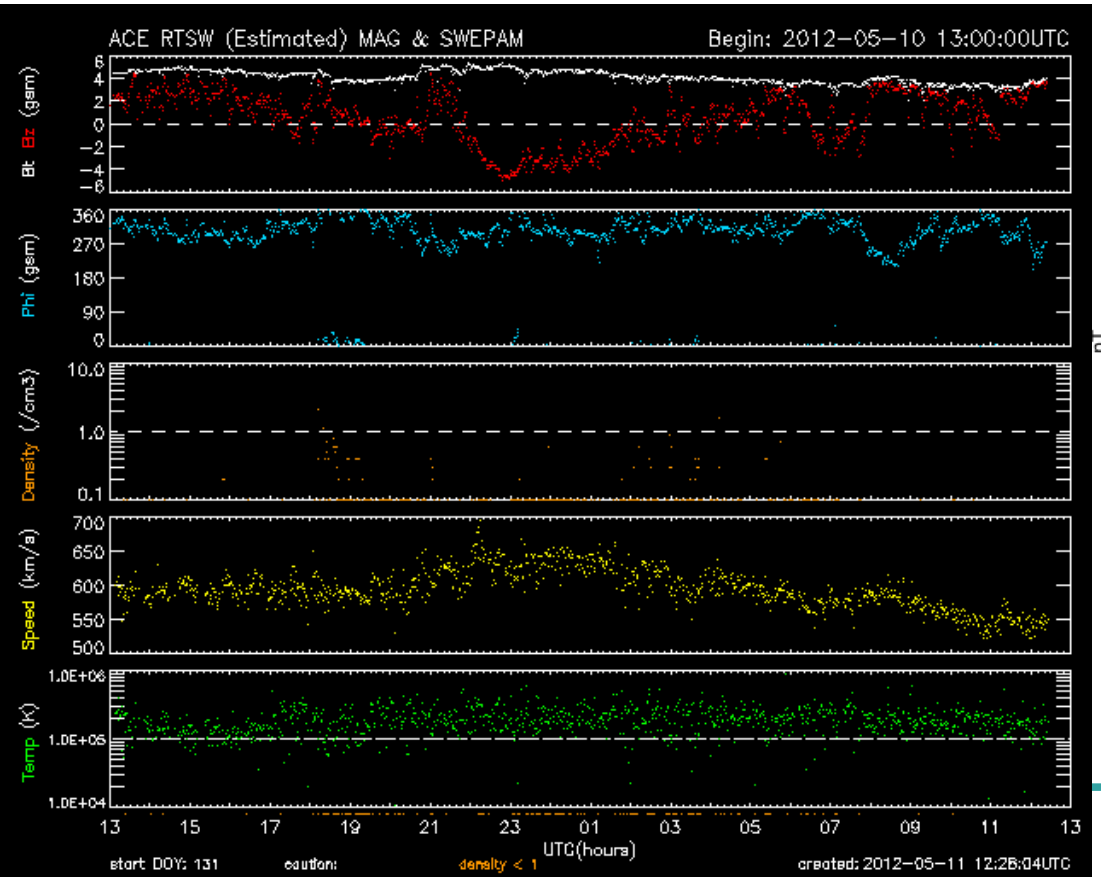
ACE

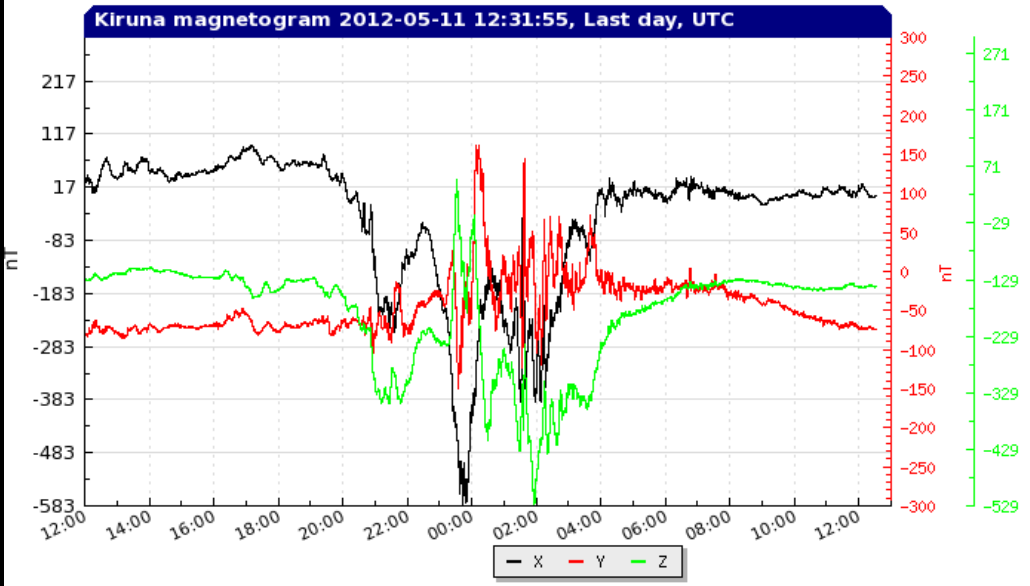
- Measures the magnetic field and the density, radial speed and temperature of the solar wind
- Almost real time data access
- Data from ACE is used to improve space weather forecasting and warning systems



ACE

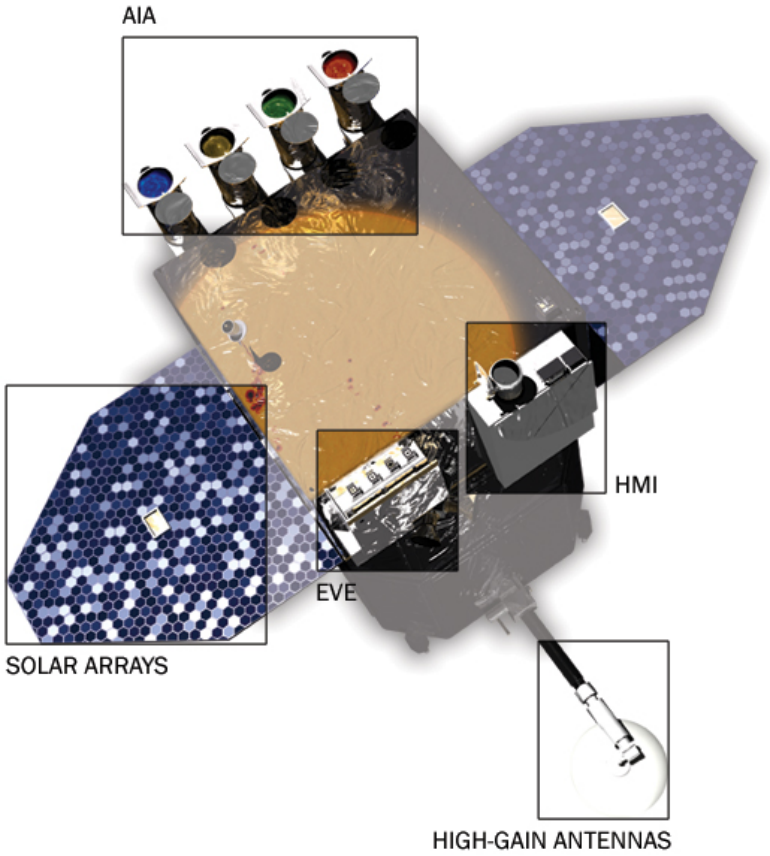
- Measures the magnetic field and the density, radial speed and temperature of the solar wind
- Almost real time data access
- Data from ACE is used to improve space weather forecasting and warning systems





SDO

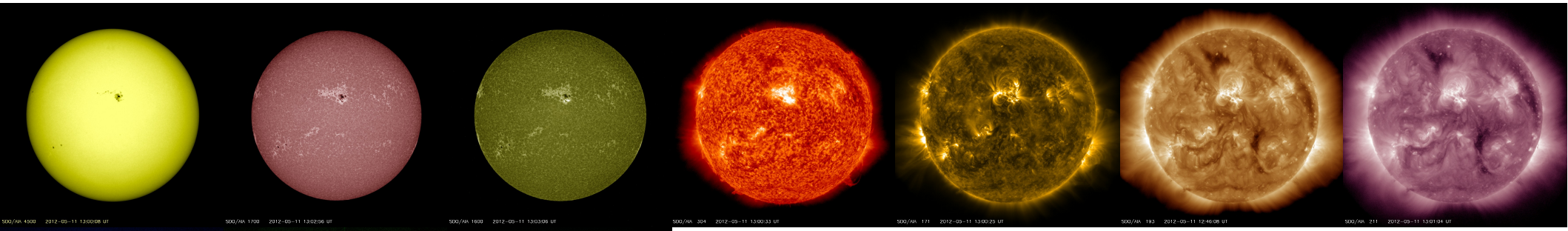
- Solar Dynamics Observatory
  - Geosynchronous orbit
  - Studies the Sun
    - HMI (Helioseismic and Magnetic Imager)
    - AIA (Atmospheric Imaging Assembly)
    - EVE (Extreme Ultraviolet Variability Experiment)

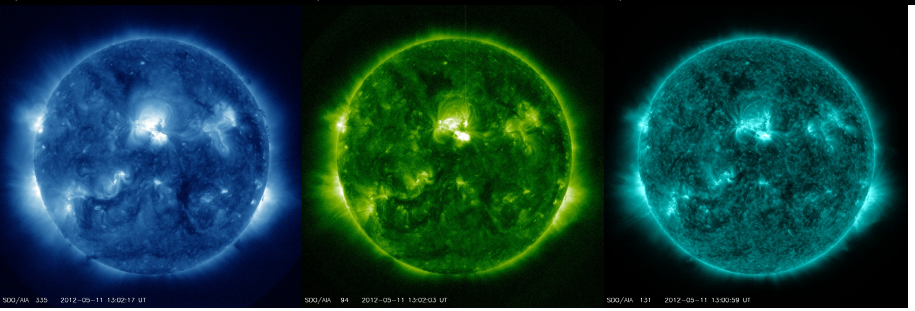


SDO

- All images from 2012-05-11, 12:40 – 13:00 UTC

AIA 4500 AIA 1700 AIA 1600 AIA 304 AIA 171 AIA 193 AIA 211

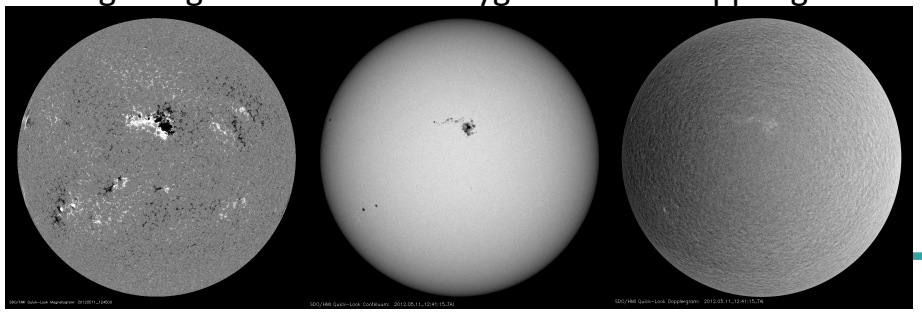




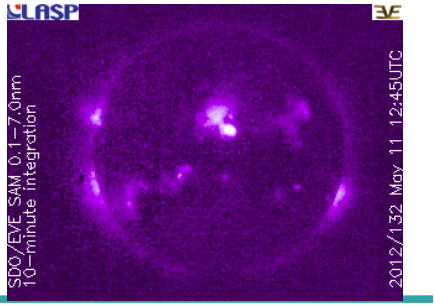
AIA 335 AIA 094 AIA 131

Images at different wavelengths
=
Images of different temperatures

HMI Magnetogram HMI Intensitygram HMI Dopplergram



EVE
Soft X-Ray

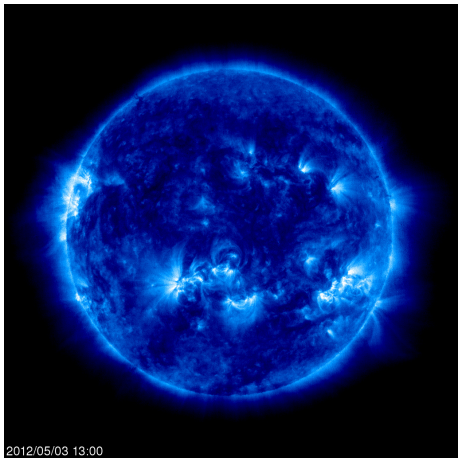


SOHO

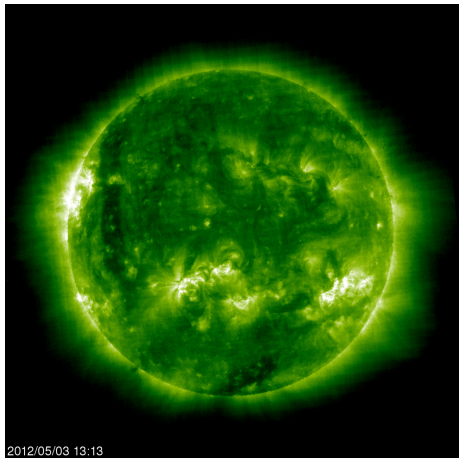
- SOHO (the Solar and Heliospheric Observatory) is a spacecraft that studies the Sun and the solar wind
- Produces images of the sun of different types
  - EIT (Extreme ultraviolet Imaging Telescope)
    - Images at different wavelengths (different temperatures, different heights)
  - MDI (Michelson Doppler Imager)
    - Images from the visible range of the spectrum
    - Magnetogram images
  - LASCO (Large Angle Spectrometric Coronagraph)
    - Pictures of the solar corona
- Positioned at the L1 Lagrange point

SOHO

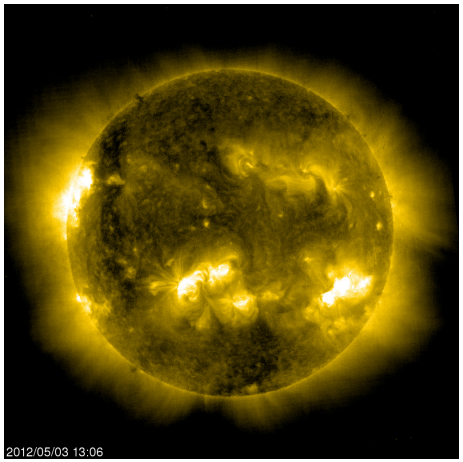
- Examples of EIT images
  - Images from 3 May 2012



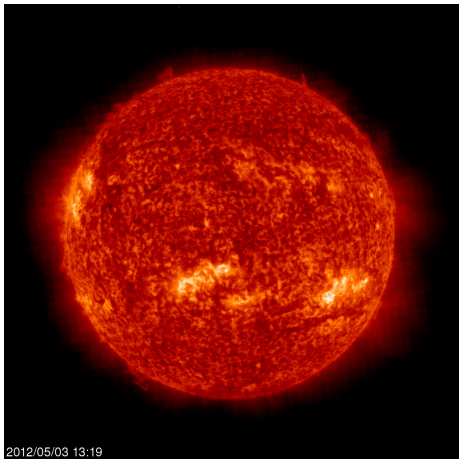
EIT171
171 Å
1×10^6 K
Fe IX/X



EIT195
195 Å
1.5×10^6 K
Fe XII



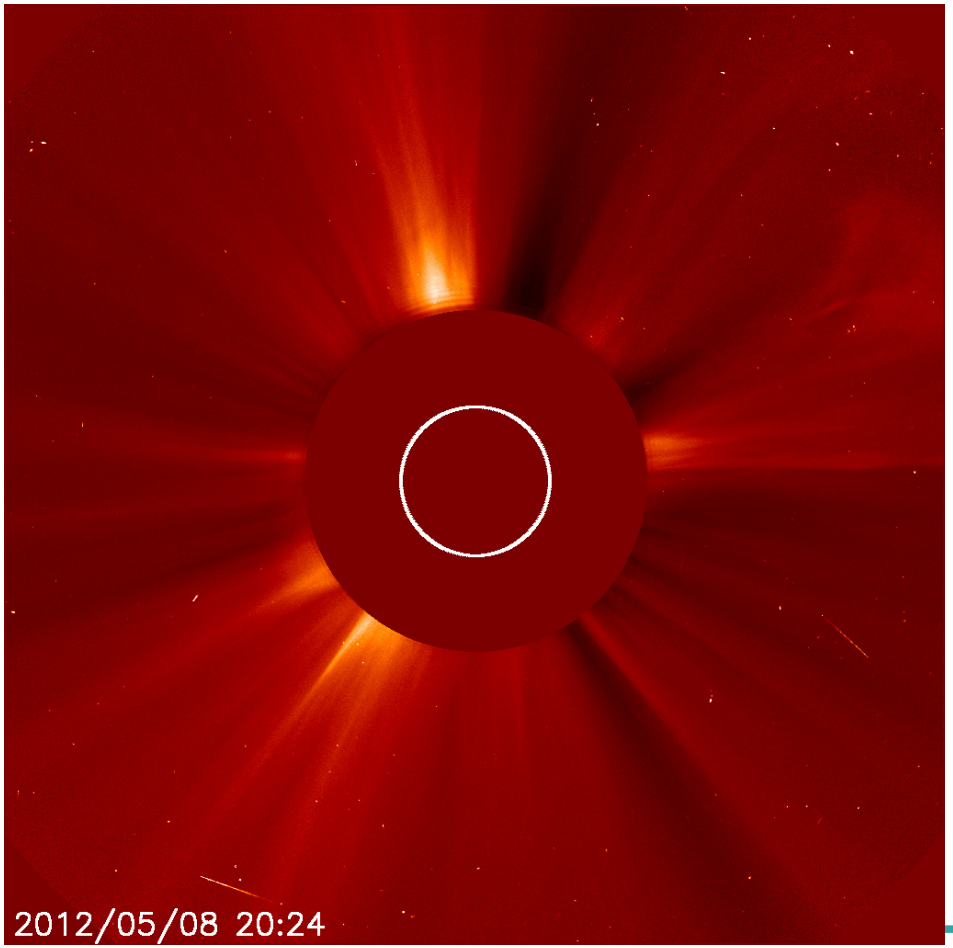
EIT284
284 Å
2×10^6 K
Fe XV



EIT304
304 Å
~70,000 K
He II

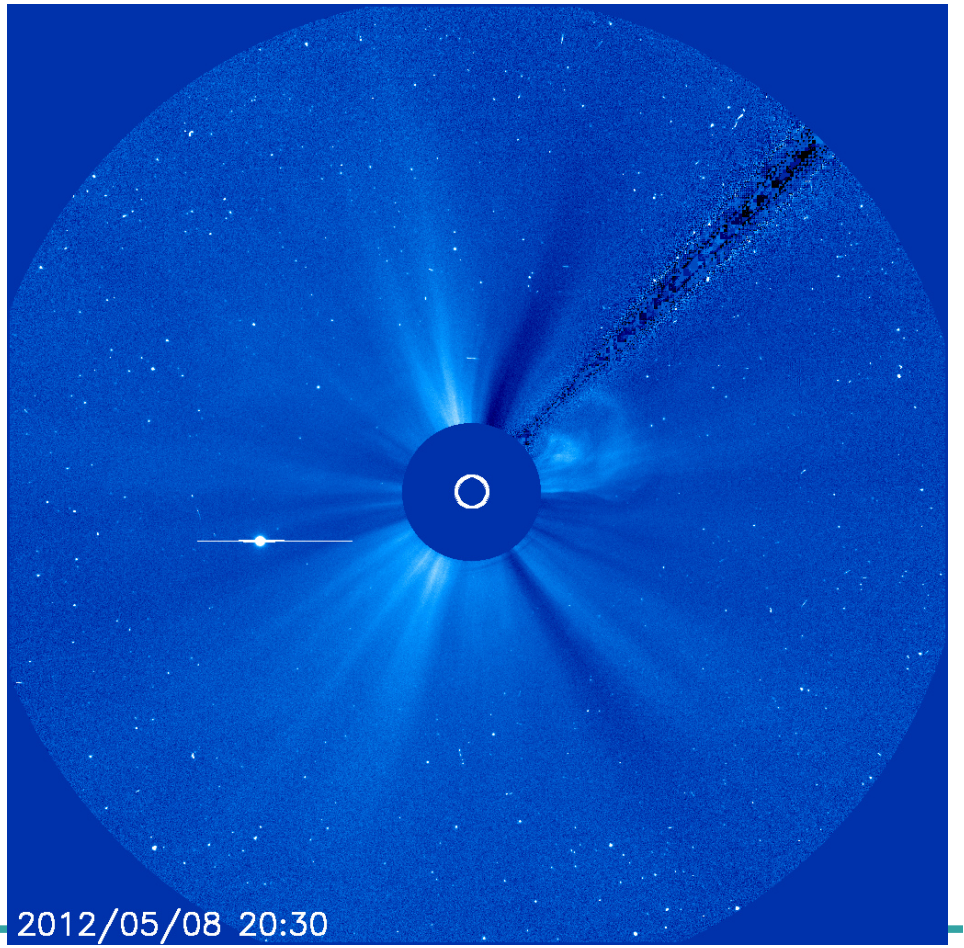
SOHO

- Examples of images from MDI and LASCO
  - Images from 8 May 2012



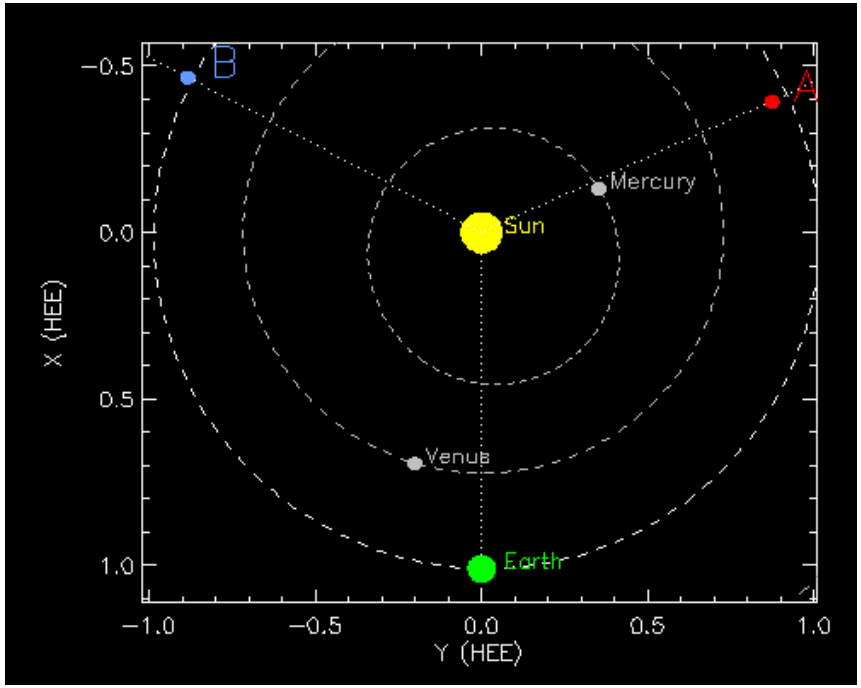
LASCO C2

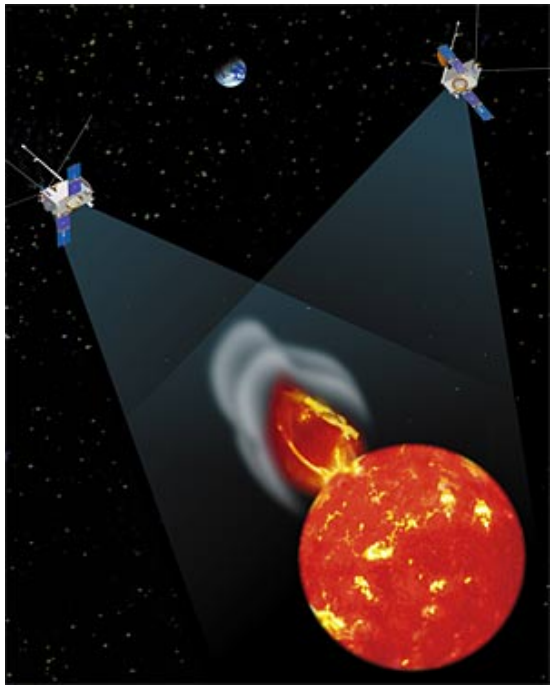
LASCO C3



STEREO

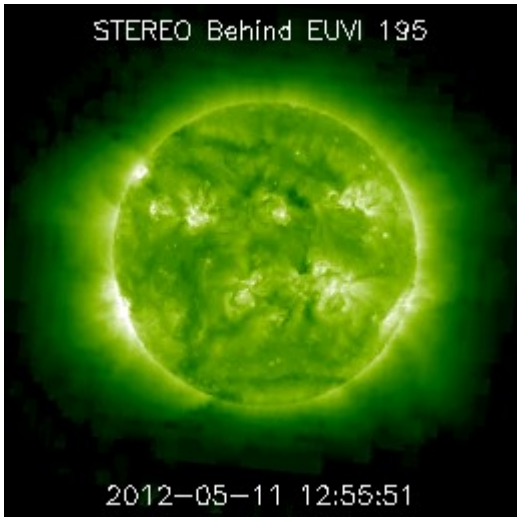
- Two identical spacecraft observing the sun and the solar wind
  - STEREO A (Ahead) in orbit ahead of the Earth
  - STEREO B (Behind) in orbit behind the Earth



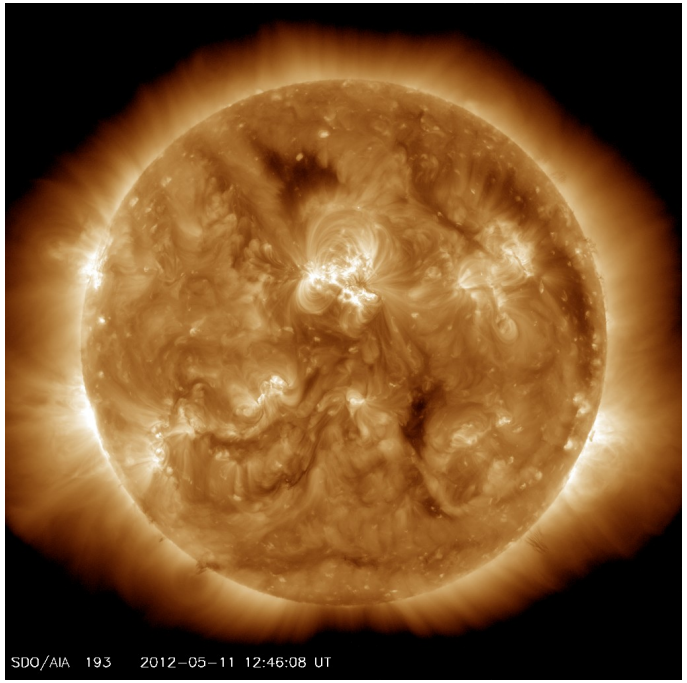


STEREO

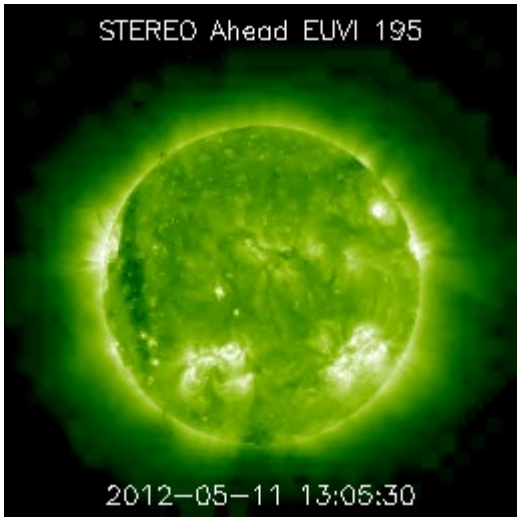
- The STEREO data complement SDO and SOHO data in many ways



STEREO B EUVI 195

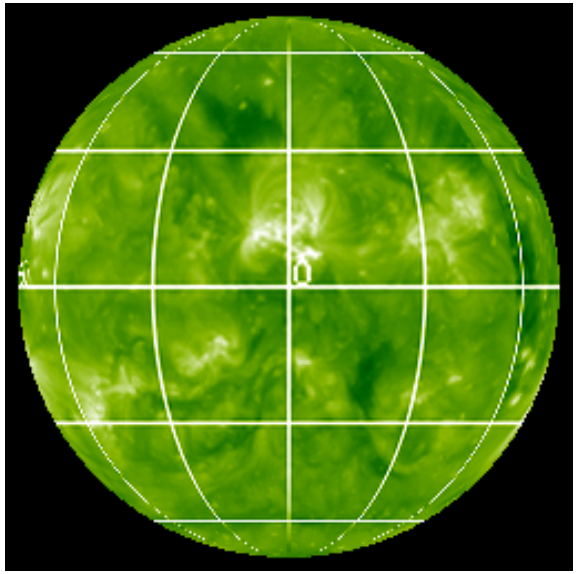


SDO AIA 193



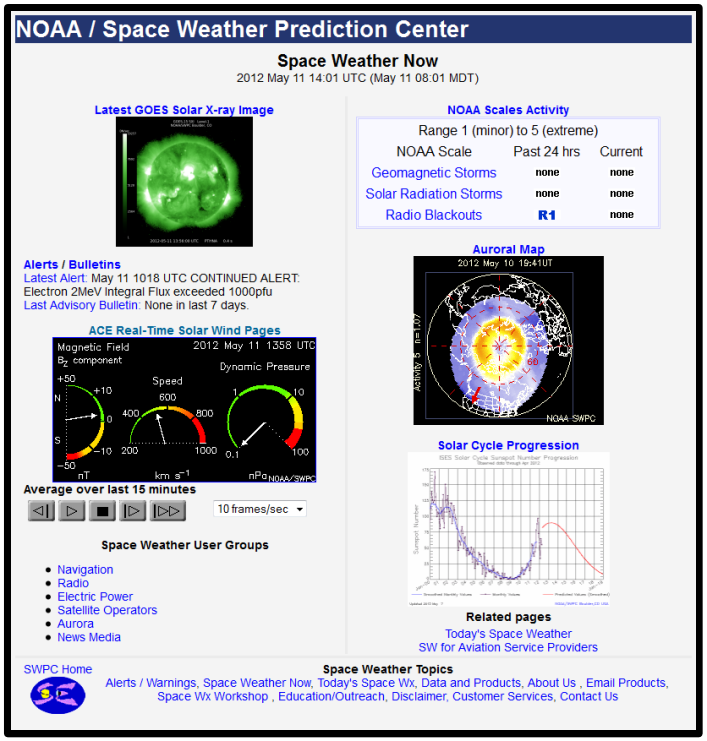
STEREO A EUVI 195

Combined STEREO and SDO



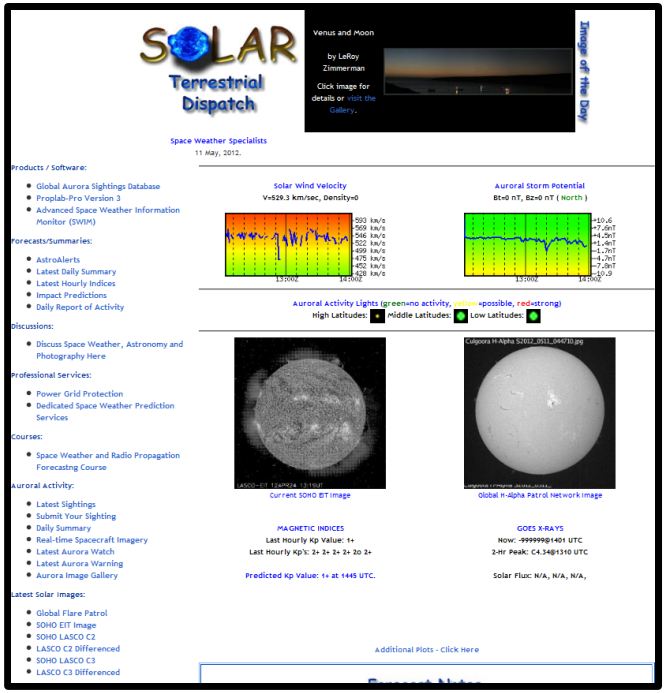
Many space weather web-sites

- Contain many links to space weather data
- Good places to start exploring the space weather



www.swpc.noaa.gov/SWN

www.spaceweather.com



www.spacew.com

Good luck
exploring and observing
the
Space Weather