Space!!!! Weather!!!!

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Astronomy 253: Plasma Astrophysics

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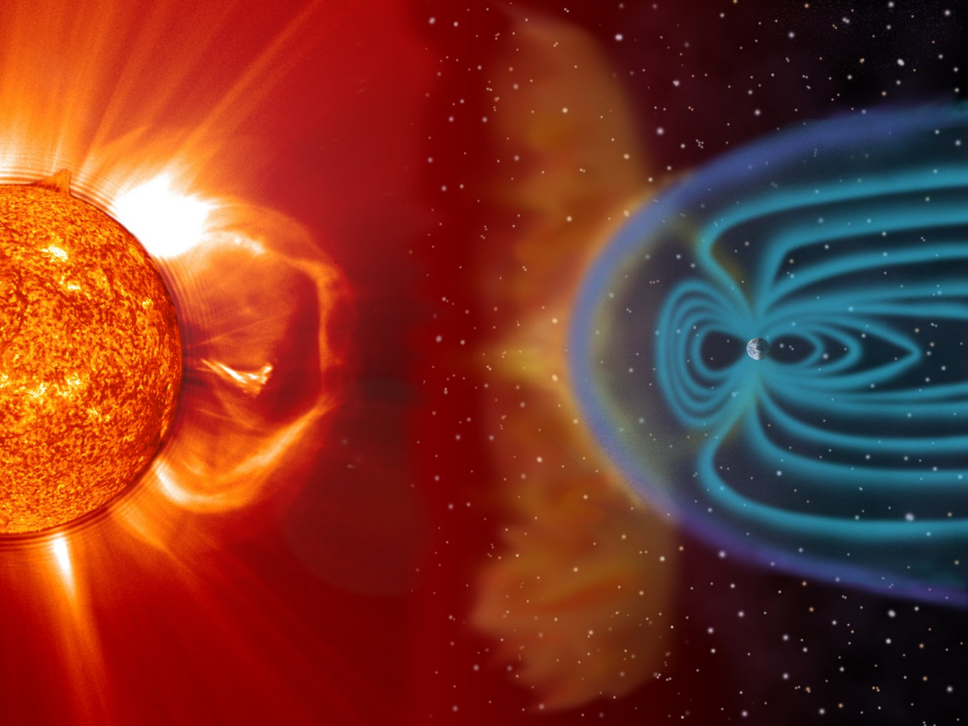
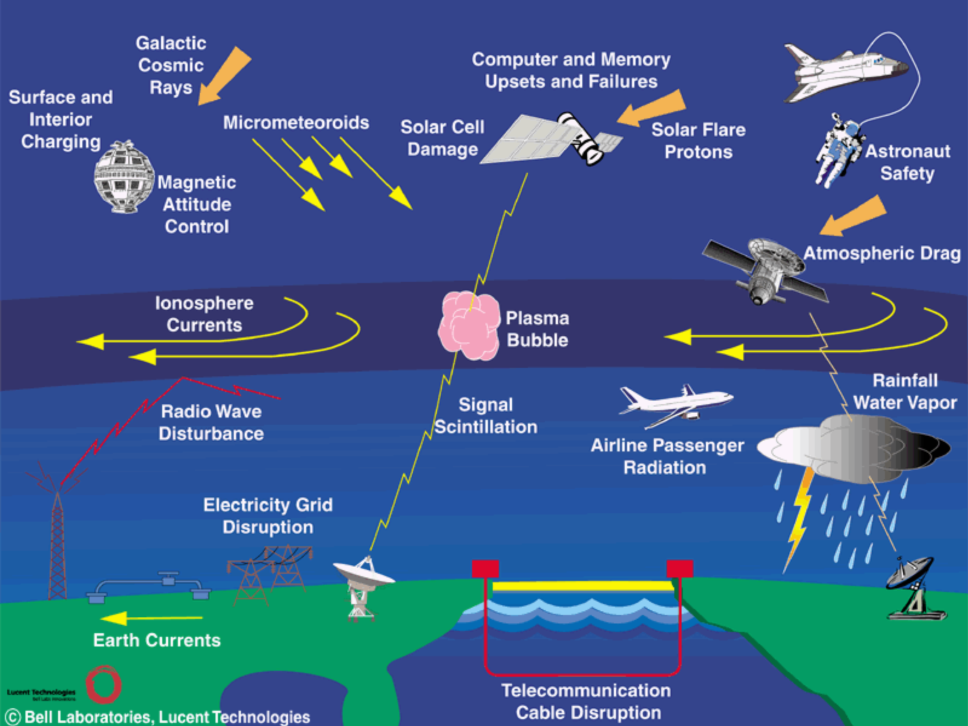
These slides are based off of presentations by Kelly Korreck and Mike Stevens and numerous other resources.



Societal impacts of space weather

- Power grid failures
  - Transformer meltdowns, etc.
- Disruption to spacecraft operations
  - Energetic particles disrupt electronics
- Diversion of airplanes from poles
- Radio interference
- Reduced accuracy of Global Positioning System (GPS)
  - Radio emission during flares reduces signal-to-noise
- Radiation danger to astronauts
- Disruption of telegraph services
- Reduced efficacy of space wombat echolocation



Galactic Cosmic Rays
Surface and Interior Charging
Micrometeoroids
Magnetic Attitude Control
Computer and Memory Upsets and Failures
Solar Cell Damage
Solar Flare Protons
Astronaut Safety
Atmospheric Drag
Ionosphere Currents
Plasma Bubble
Radio Wave Disturbance
Signal Scintillation
Airline Passenger Radiation
Rainfall Water Vapor
Electricity Grid Disruption
Earth Currents
Telecommunication Cable Disruption
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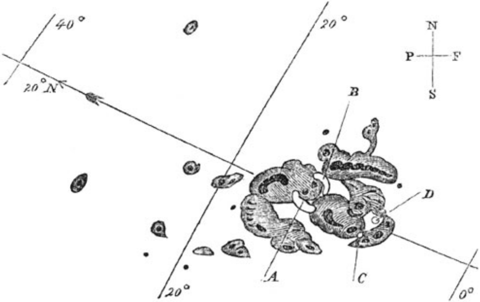
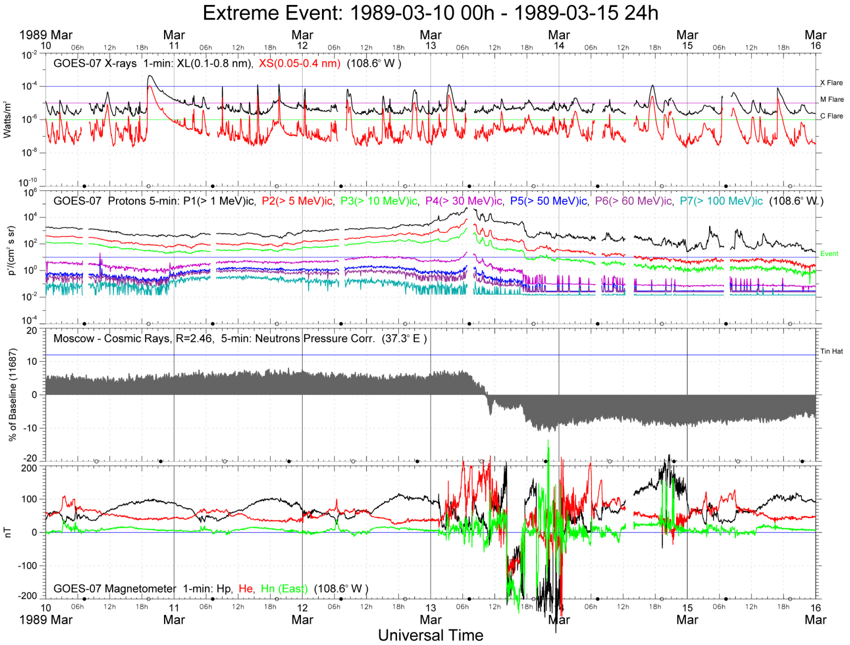
The Carrington Event of 1859

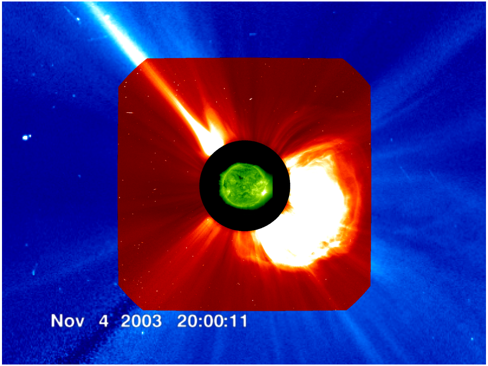


- First observed solar flare
- The associated coronal mass ejection (CME) took just 17.6 hours to reach Earth
  - Usually takes several days
  - Previous CME cleared the way
- Global effects
  - Aurora observed at low latitudes
  - Telegraph messages could be sent without a power supply
- Potential trillion dollar costs were it to happen today

1989 geomagnetic storm caused 9 hour blackout in Quebec

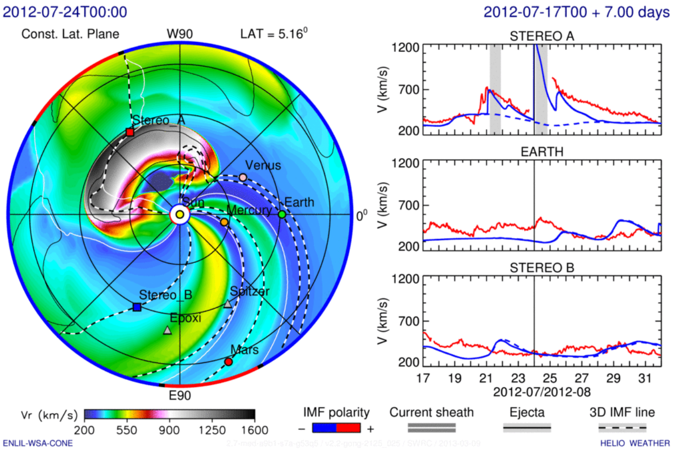


Halloween storms of 2003



- Series of ∼17 major flares
- Biggest X-ray flare observed (at least X28, maybe X45)
- ∼2–3 years after solar maximum
- Power outage in Sweden
- Aircraft re-routed
- Detected by Voyager 2 in April 2004!

A near miss in July 2012



- A Carrington-scale event passed STEREO-A which is in an Earth-leading orbit
- Several prior CMEs cleared the way
- Could have caused major disruptions to power grids

Why should astronomers care about space weather?

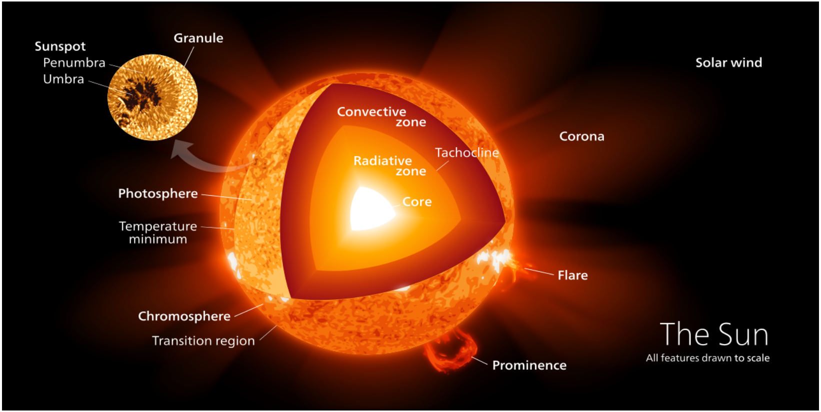
- In situ[1] measurements allow greater understanding of fundamental processes in plasma astrophysics
- Planning and operating observatories in space
- The Sun and heliosphere provide test/limiting cases for astrophysics
  - Stellar accretion (e.g., failed eruption on 2011 June 7)
  - Stellar dynamos
  - Particle acceleration (CME shocks, reconnection)
  - Space environment and habitability of exoplanets
- Need improved communication between astrophysicists, solar physicists, and space physicists!
- Education and public outreach opportunity

[1] Here "in situ" means that measurements of particles and electromagnetic fields are taken locally by a spacecraft embedded in the space plasma environment.

Plasma processes in the heliosphere

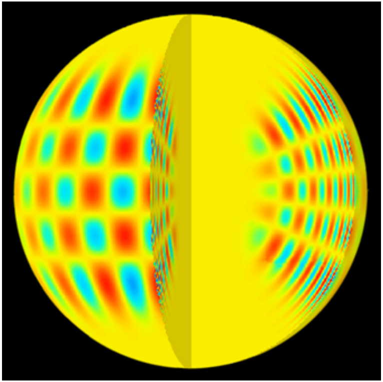
- Dynamo
- Radiative transfer
- Ionization and recombination
- Ambipolar diffusion (in partially ionized plasmas)
- Collisional effects
- Kinetic effects
- Waves, shocks, and instabilities
- Particle acceleration
- Turbulence
- Magnetic reconnection

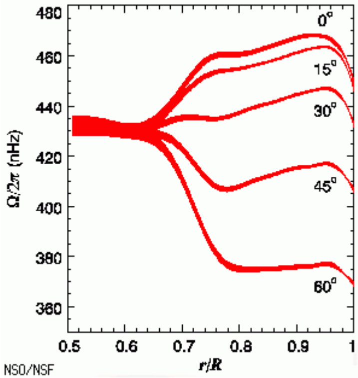
Solar structure ($\beta \gg 1$)



- Fusion dominated by proton-proton chain in core
- Inner radiative zone
- Tachocline: thin shear layer boundary
- Outer convective zone: vital for solar dynamo

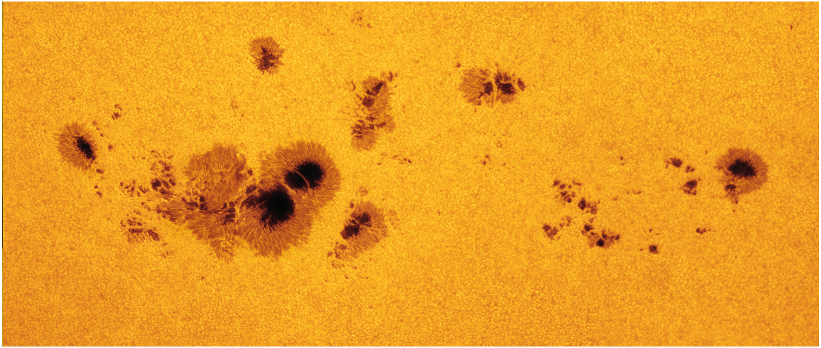
Helioseismology





- Solar oscillations (acoustic modes, gravity modes)
- Observed using Doppler shift of photospheric spectral lines
- Right: The angular velocity of the solar interior as a function of radius and latitude
  - Radiative zone: ∼solid body rotation
  - Convective zone: differential rotation

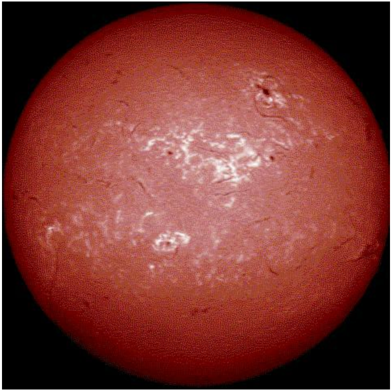
The solar photosphere ($\beta \gg 1$)



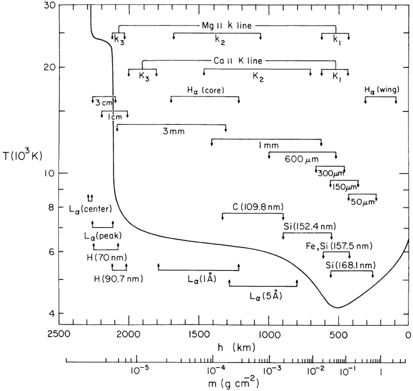
- $T \sim 5800K$, partially ionized
- Granulation is a signature of convection
- Sunspots are cooler regions where strong magnetic fields suppress convection
  - Result from large-scale flux emergence
  - Usually associated with active regions and solar activity

The chromosphere is a thin, dynamical layer where many simplifying assumptions break down

Full disk Hα observation

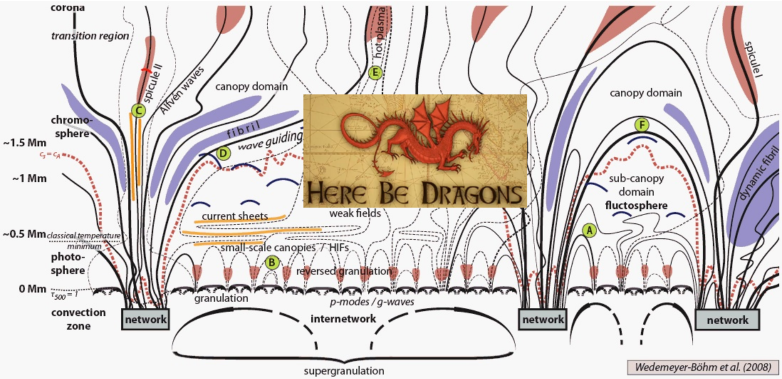


Temperature structure and line formation regions in the 1D VAL C model



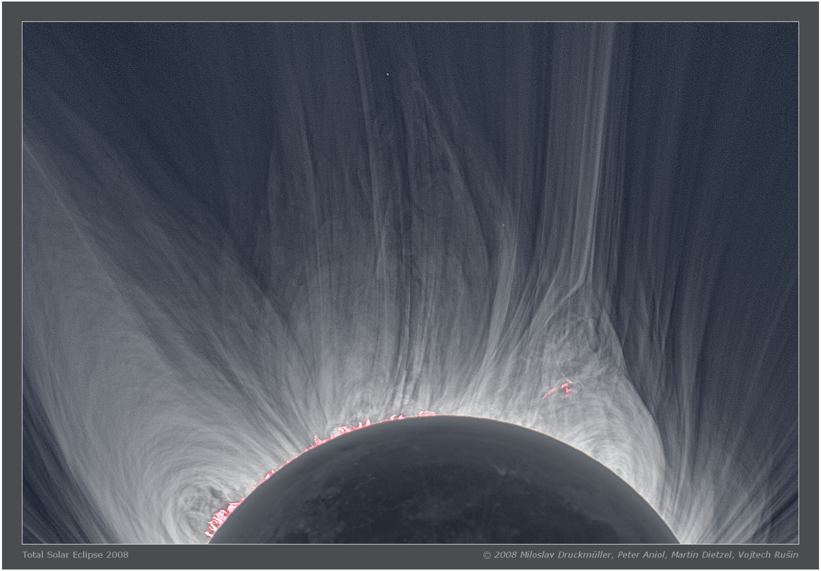
- Non-LTE radiative transfer, partially ionized, $\beta \sim 1$
- Mass and energy must pass through the chromosphere to reach the corona

The chromosphere is the least understood part of the Sun

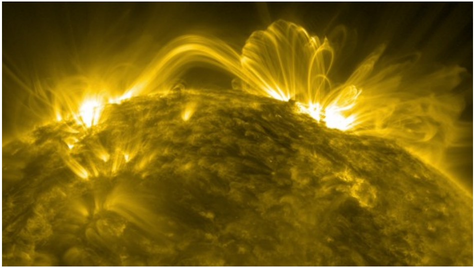


- Why does the chromosphere exist?
- How are mass and energy transported from the photosphere to the corona?
- How is the chromosphere heated?
- How does the chromosphere respond to flares?
- How can we diagnose chromospheric magnetic fields?

The solar corona during an eclipse



Properties of the highly dynamical solar corona

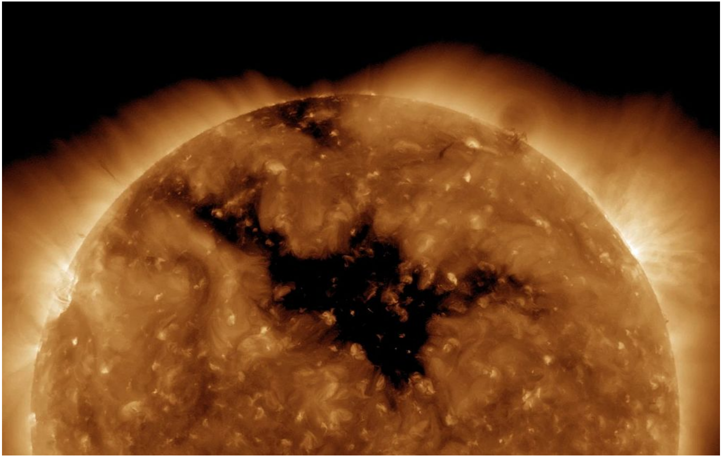


SDO/AIA 171 Angstrom channel (Fe IX)

- Key player in space weather
- Magnetically dominated ($\beta \ll 1$); full of loops
- Solar activity often occurs in or near active regions
- $T \sim 10^6$ K; heating mechanisms may include
  - Wave damping
  - Reconnection (e.g., nanoflares)
- Enhanced abundances for elements with a first ionization potential (FIP) $\lesssim 10$ eV (e.g., Fe, Si, Ca, Mg, Na)
  - Cause unknown (ponderomotive forces in chromosphere?)
  - Plasma can sometimes be traced back to source regions

The fast solar wind: $V \sim 750$ km s^{-1}

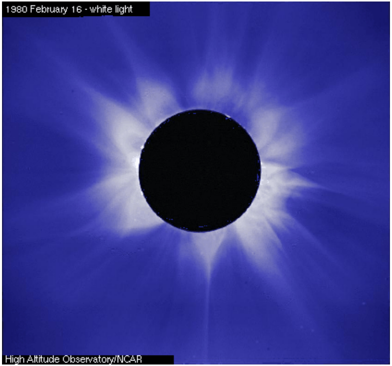
SDO/AIA 193 Angstrom channel (Fe XII, XXIV)



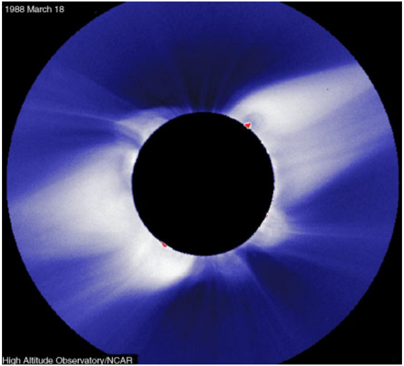
- Hot, low density, steady
- Source: open field regions called coronal holes
- Photospheric elemental abundances

The slow solar wind: $V \sim 300$ to 400 km s^{-1}

Solar maximum

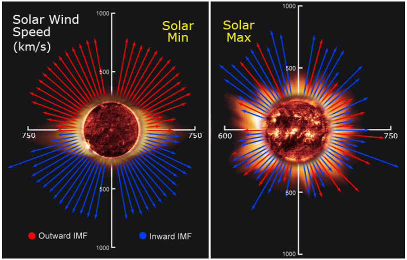


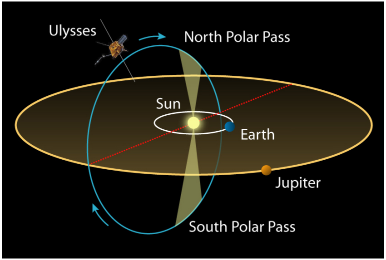
Solar minimum



- Cool, dense, variable
- Source: closed field regions such as streamers
  - Boundaries between open & closed field regions?
- Coronal abundances (overabundance of low-FIP elements)

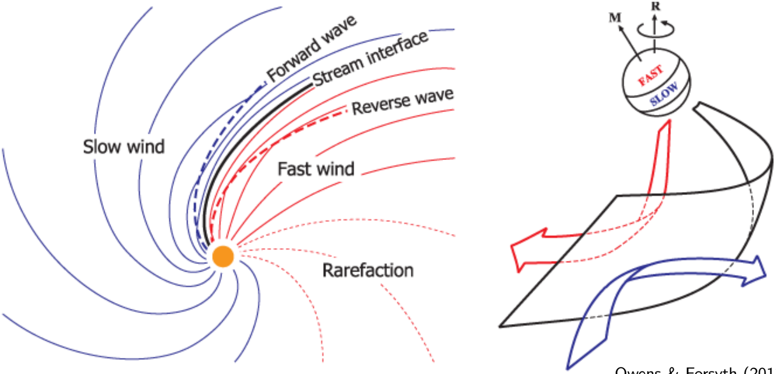
The speed and magnetic polarity of the solar wind depends on latitude and solar cycle (observed by Ulysses)





- Solar minimum
  - Fast solar wind: prevalent at high latitudes
  - Slow solar wind: prevalent at low latitudes
- Solar maximum
  - Significant variability with latitude

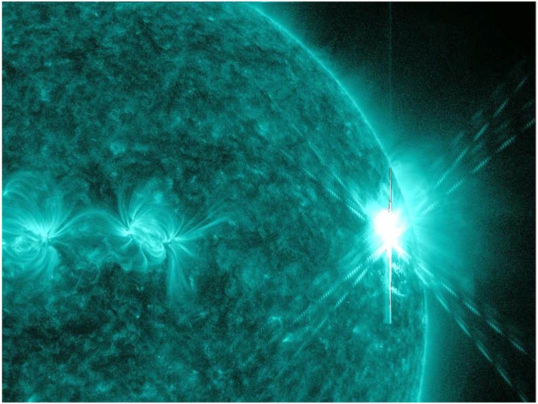
Corotating interaction regions (CIRs)



Owens & Forsyth (2013)

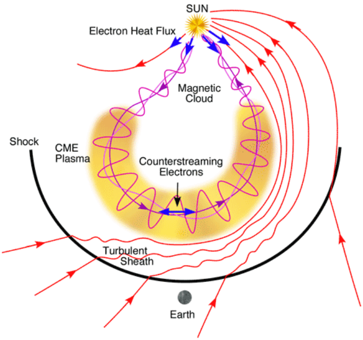
- Compression/shock where fast wind overtakes slow wind
- Rarefaction where slow wind is unable to catch up to fast wind
- In reference frame of CIR (right), both the slow and fast winds approach the interface
- Frequently geoeffective

Solar flares



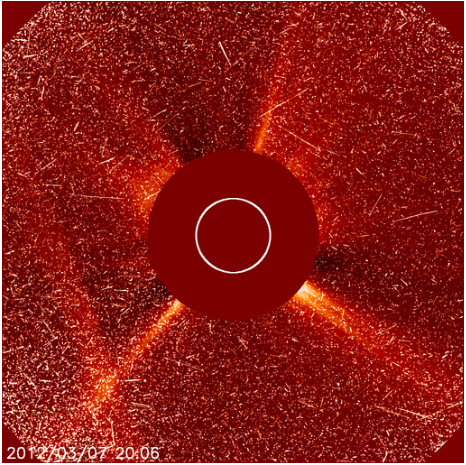
- Magnetic energy released by reconnection
- Efficient plasma heating and particle acceleration
- Energy transport downward into chromosphere
    - Energetic particle beams and/or thermal conduction fronts
- Radiation emitted from radio to gamma rays

Coronal mass ejections (CMEs)



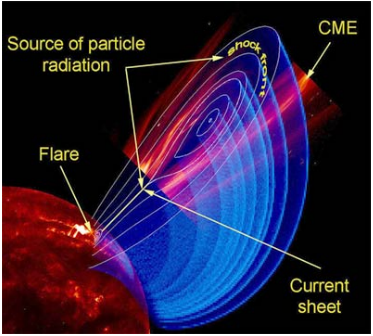
- Expulsion of magnetized plasma into the solar wind
- Velocities of hundreds to thousands of km s^{-1}
- Usually contain a magnetic flux rope
- A shock preceding the flux rope can accelerate particles
- CMEs are the main driver of geomagnetic storms

Solar energetic particle (SEP) events



- Protons, electrons, and ions
- $\sim$10 keV to $\sim$1 GeV (Velocities up to $\sim 0.8c$)
- Only $\sim$1% of CMEs produce strong SEP events

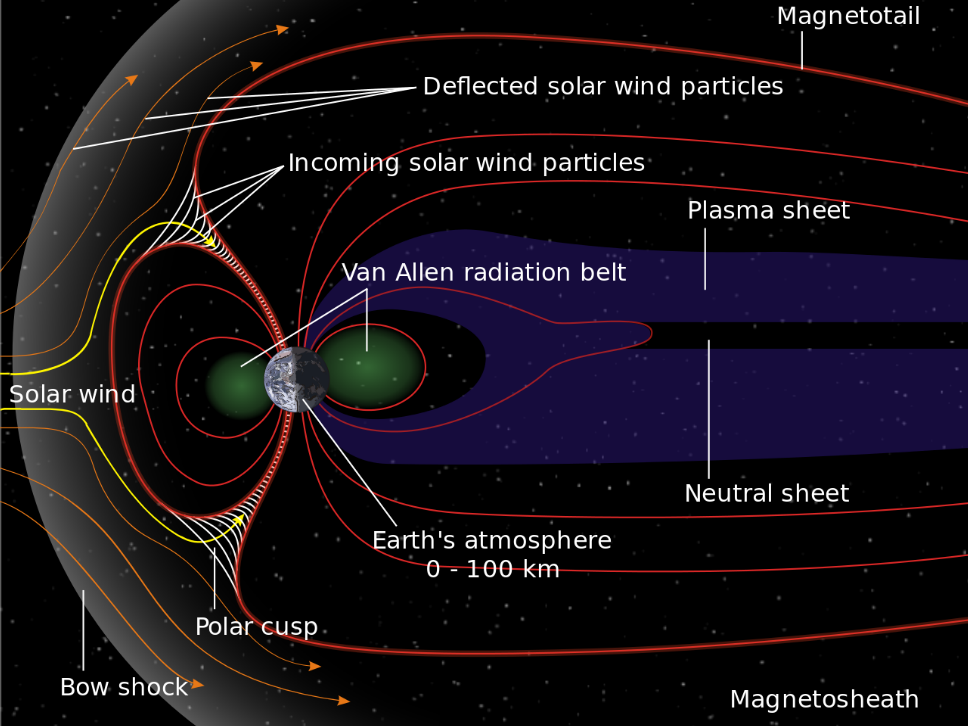
There are two classes of SEP events, implying that there are two different sources



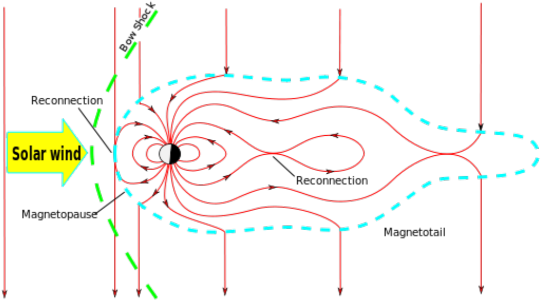
- Impulsive events
  - Accelerated near flare site
  - Association with magnetic reconnection
- Gradual events
  - Diffusive shock acceleration by a CME shock wave
  - Produce highest SEP intensities near Earth

The Earth's magnetic field

- The Sun sends high velocity magnetized plasma, solar energetic particles, and/or EUV & X-ray radiation toward Earth. Then what?
- The particle and plasma components impact Earth's magnetosphere
- The EUV/X-ray radiation and particle component affect Earth's thermosphere and ionosphere


Magnetotail
Deflected solar wind particles
Incoming solar wind particles
Plasma sheet
Van Allen radiation belt
Solar wind
Neutral sheet
Earth's atmosphere
0 - 100 km
Polar cusp
Bow shock
Magnetosheath

Geomagnetic storms are disturbances of Earth's magnetic field caused by impact of an ICME or interplanetary shock



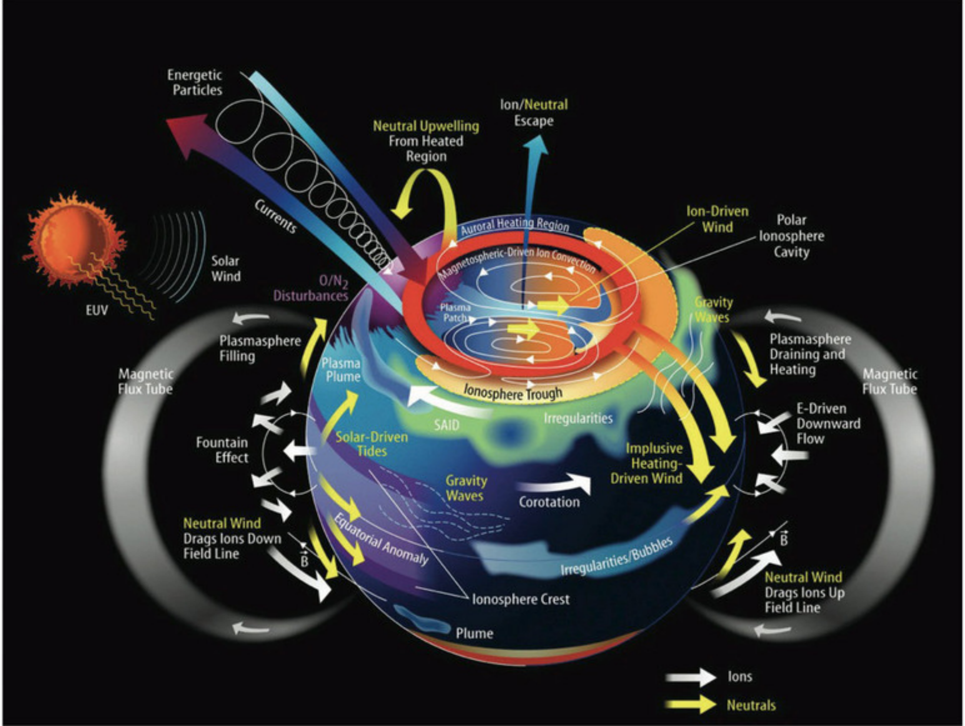
- Increased electric field and plasma flows in magnetosphere
- Geomagnetically induced currents
- Ionospheric disturbances
- Magnetic reconnection releases magnetic energy, initiates plasma flows, and accelerates particles
  - Dayside magnetopause
  - Nightside magnetotail

NOAA Space Weather Scales

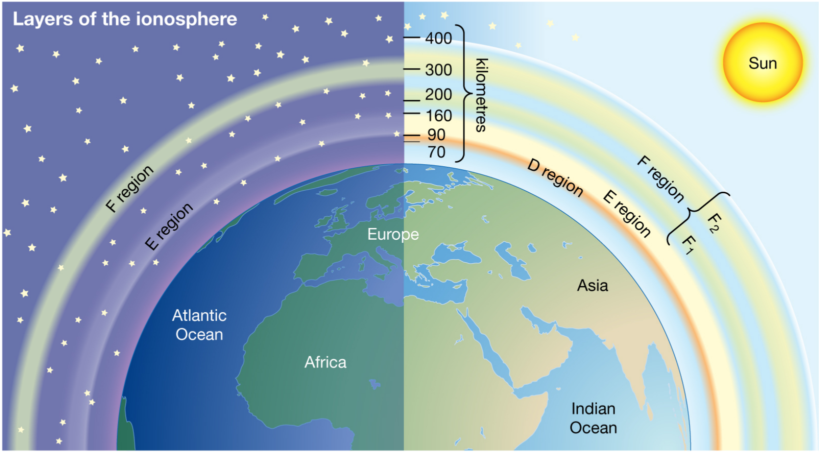
Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread 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)

* Based on this measure, but other physical measures are also considered.

** For specific locations around the globe, use geomagnetic latitude to determine likely sightings (see www.swpc.noaa.gov/Aurora)

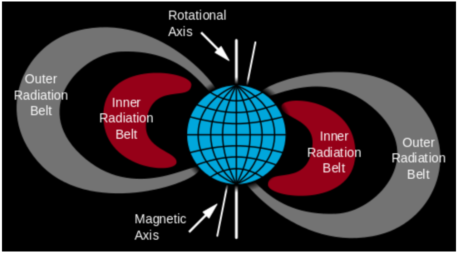

Energetic Particles
Ion/Neutral Escape
Neutral Upwelling From Heated Region
Currents
Solar Wind
EUV
O/N2 Disturbances
Auroral Heating Region
Magnetospheric-Driven Ion Convection
Ion-Driven Wind
Polar Ionosphere Cavity
Plasma Patch
Gravity Waves
Plasmasphere Filling
Plasmasphere Draining and Heating
Magnetic Flux Tube
Plasma Plume
Ionosphere Trough
Magnetic Flux Tube
SAID
Irregularities
E-Driven Downward Flow
Fountain Effect
Solar-Driven Tides
Implusive Heating-Driven Wind
Gravity Waves
Corotation
Neutral Wind Drags Ions Down Field Line
Equatorial Anomaly
Irregularities/Bubbles
B
B
Neutral Wind Drags Ions Up Field Line
Ionosphere Crest
Plume
Ions
Neutrals

The ionosphere is the layer of our atmosphere that is ionized by solar radiation



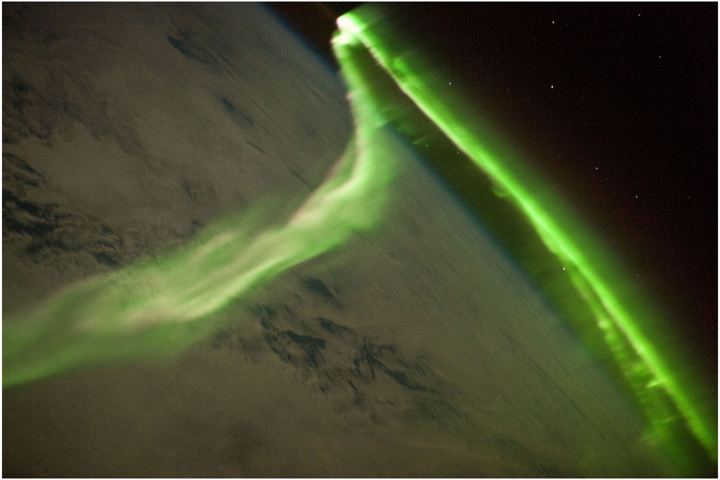
- Reflects radio waves
- Impacted by space weather events

The Van Allen belts are layers of trapped energetic particles in the inner magnetosphere



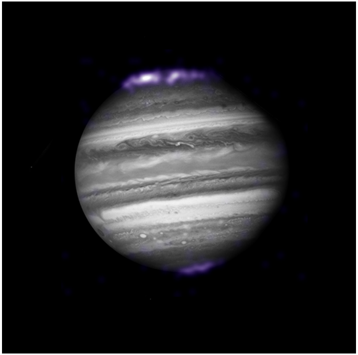
- Heights of $\sim$1000 to $\sim$60000 km
- Particles originated from solar wind or cosmic rays
- Currently under investigation by the Van Allen Probes
- Structure of belts varies with time and solar activity
  - Sometimes additional belts may transiently exist

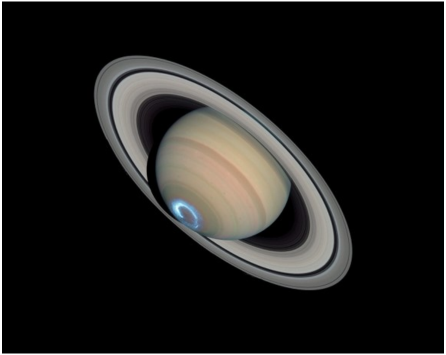
Aurora viewed from the International Space Station



- Energetic electrons propagate along field lines and precipitate into the upper atmosphere
- Collisional excitation of air particles leads to auroral emission
- Enhanced aurora during geomagnetic storms

Aurora around Saturn & Jupiter





- Left: X-ray aurora observed by Chandra around Jupiter
- Right: UV aurora observed around Saturn
- Aurora recently observed in radio around brown dwarf
- Can observations of aurora help characterize the magnetic field and space environment of exoplanets?

Open questions in heliophysics and space weather

- How do solar and planetary dynamos operate?
- How are the chromosphere, corona, and solar wind heated?
- What accelerates the slow and fast solar winds?
- How does reconnection release magnetic energy in solar and space plasmas?
- Can we predict major flares and CMEs?
- Can we predict if and when ejecta and energetic particles will impact Earth?
- How can we predict the direction of the interplanetary magnetic field (IMF) at Earth using remote observations?
- How frequent are superflares around the Sun and other stars?
- How can we apply results from space plasmas to astrophysical situations?

Summary

- The heliosphere hosts a rich variety of plasma processes
  - Nearly all of the processes we've covered!
- Space weather involves astrophysical processes with real impacts on our increasingly technological civilization
  - Power grids, satellites, astronaut safety, etc.
- Drivers of space weather include
  - Solar wind
  - Flares
  - Coronal mass ejections
  - Solar energetic particles
- Space weather influences Earth's magnetosphere, ionosphere, and thermosphere