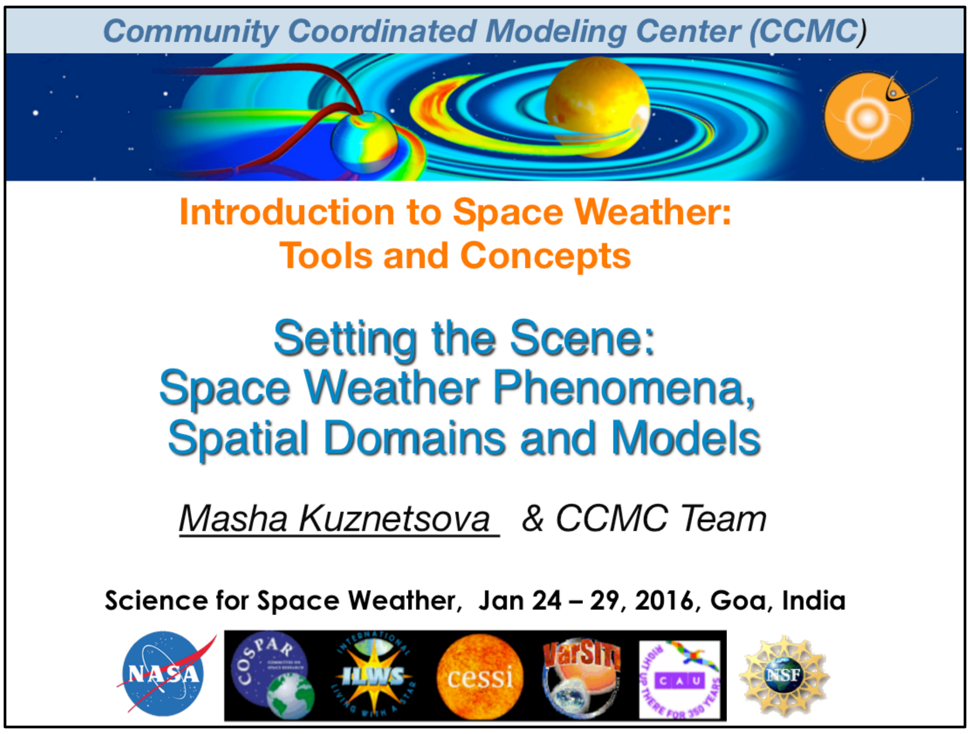


Welcome to the "**Introduction to Space Weather: Tools and Concepts**" School. My name is Masha Kuznetsova. I am leading the **Community Coordinated Modeling Center (CCMC)**. The CCMC (**http://ccmc.gsfc.nasa.gov**) is an asset of US multi-agency partnership including sponsoring agencies NASA and National Science Foundation. CCMC is also an asset of the entire space science and space weather community world-wide. Several members of the CCMC team came to this workshop to provide support for this school. You will learn more about CCMC, its tools and services during this school and workshop.

CCMC Staff: **http://ccmc.gsfc.nasa.gov/staff/index.php**
CCMC Staff attending the Workshop (at your service):

Masha Kuznetsova (magnetosphere scientist, CCMC director)

Marlo Maddox (lead developer of CCMC Integrated Space Weather Analysis System http://iswa.ccmc.gsfc.nasa.gov)

Yihua Zheng (magnetosphere and space weather scientist and analyst, lead of CCMC Space Weather Research, Education and Development Initiative (Space Weather REDI, http://ccmc.gsfc.nasa.gov/support/SWREDI/swredi.php)

Sandro Taktakishvili (solar and space weather scientist and analyst)

Ja Soon Shim (ionosphere scientist)

Satabjit Bakshi (CCMC IT Infrastucture engineer)

Alex Glocer (magnetosphere scientist, CCMC advisor)

What is Space Weather?

Space weather refers to the variable conditions on the Sun and in the space environment that can
- *influence the performance and reliability of technological systems in space and on the ground,*
- *endanger human life or health.*

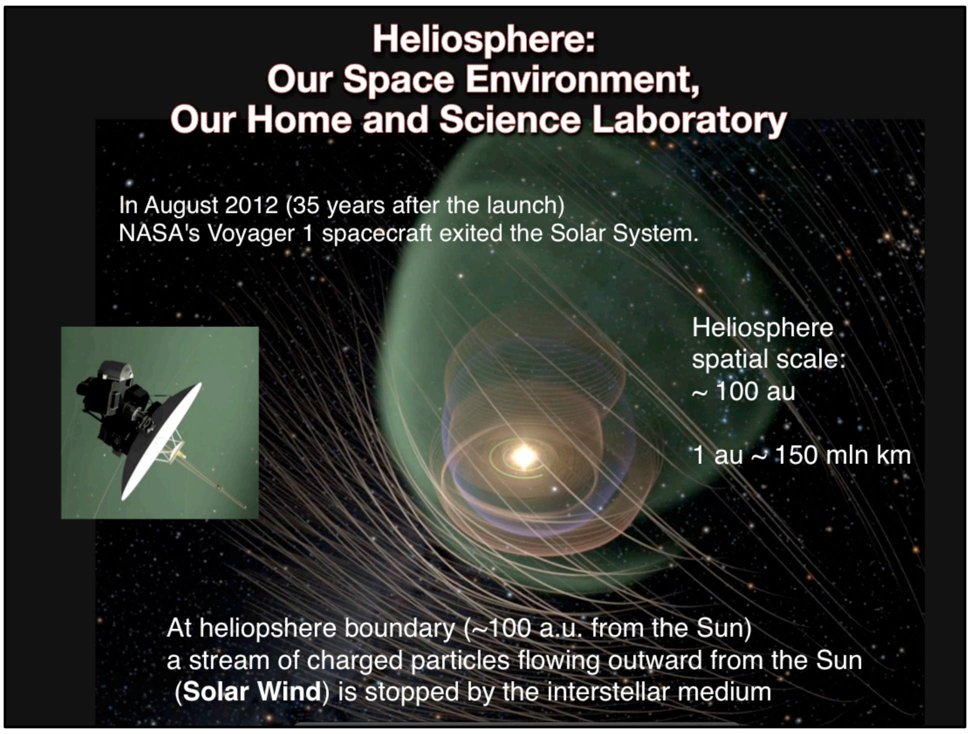
Space weather field is multidisciplinary as it encompasses
- space and plasma physics,
- computational science,
- engineering.

Space weather refers to the variable conditions on the Sun and in the space environment that can influence the performance and reliability of technological systems and critical infrastructure in space and on the ground, and can endanger human life or health.

Space weather is an emerging research area within space science that is rapidly gaining importance and public recognition because of its technological and societal impact.

Space scientist status is changing from "*satisfying curiosity*" to "*developing forecasting capabilities to help mitigate space environment impacts*".

Space weather is multidisciplinary field. Space weather encompasses
- space and plasma physics (coupled across a variety of spatial and temporal scales),
- computational science,
- engineering (as its ultimate goal is to protect technological and biological systems in space and on the ground).



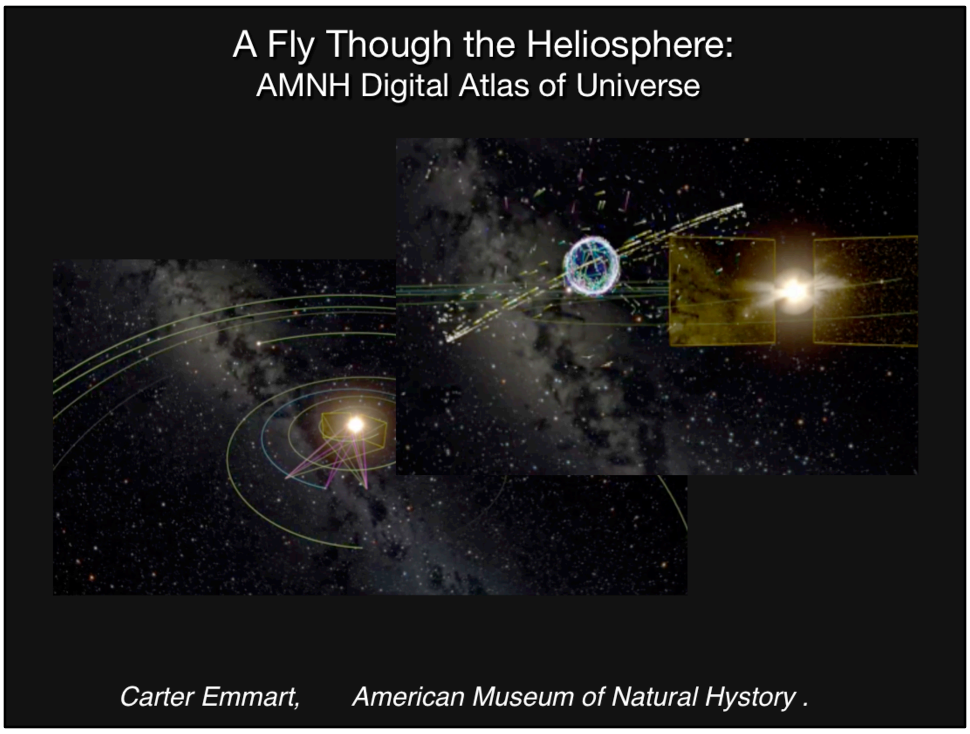
Our **terrestrial weather** atmosphere is about 30 km thick wrapped around the Earth (about 12,000 km in diameter). Typical clouds extend no further than only 10 km, about the height of Mt. Everest. While our **space weather** environment is heliosphere.

The image is a perspective visualization of the global simulations of the heliosphere boundary, where the stream of the charged particles flowing outward from the Sun is stopped by the interstellar medium.

Heliospere is extended atmosphere of our sun. The Earth and other planets are embedded into the solar atmosphere. Heliosphere bubble is our home and our science laboratory for studies of fundamental process in plasma physics.

In August 2012 (35 years after the launch) NASA's Voyager 1 spacecraft exited the solar system.

Voyger 1 is the first manmade object that reached that far to cross the heliosphere boundary, There are other missions throughout the heliosphere: e.g., New Horizons, STEREO, Cassini, Juno, Mars missions, ..).



To get a feel of the size of our home heliopshere and diversity of spatial scales let's fly from the heliopshere outer boundary towards our Sun using video based on Digital Atlas of Universe developed at the American Museum of Natural History

Space is NOT empty. Space is full of plasma

Planets are mostly located in one plane – called *ecliptic plane*.

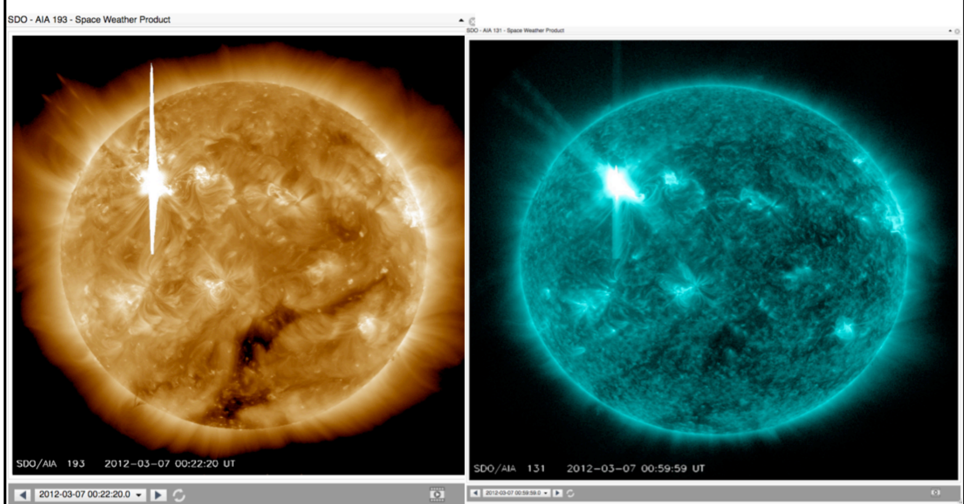
Several satellites orbiting the sun are taking images of the sun upper atmosphere, the Corona, Its outer layers are escaping in continue solar wind.

Trails and orbits around the Earth show paths of satellites. You can see satellites at geosynchtoneous orbit as well as Low orbiting satellites. So the environment relatively close to the Earth is becoming crowded.

The sun is more than a simple ball of gas but a dynamic magnetic beast.

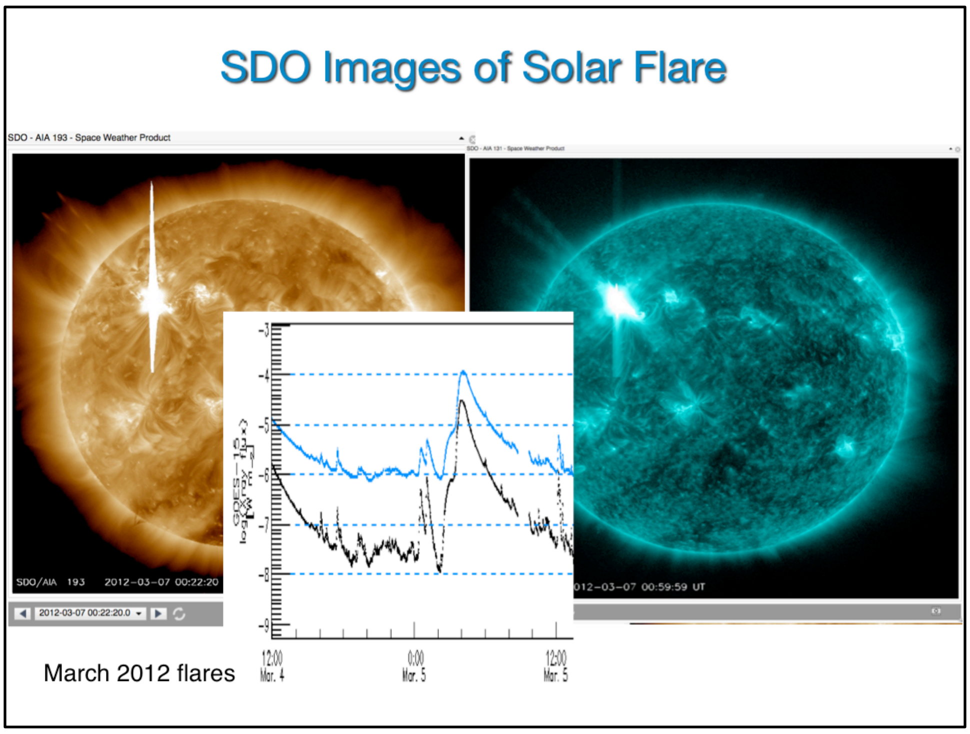
The stream of the charged particles flowing outward from the Sun in the so-called solar wind.

SDO Images of Solar Flare

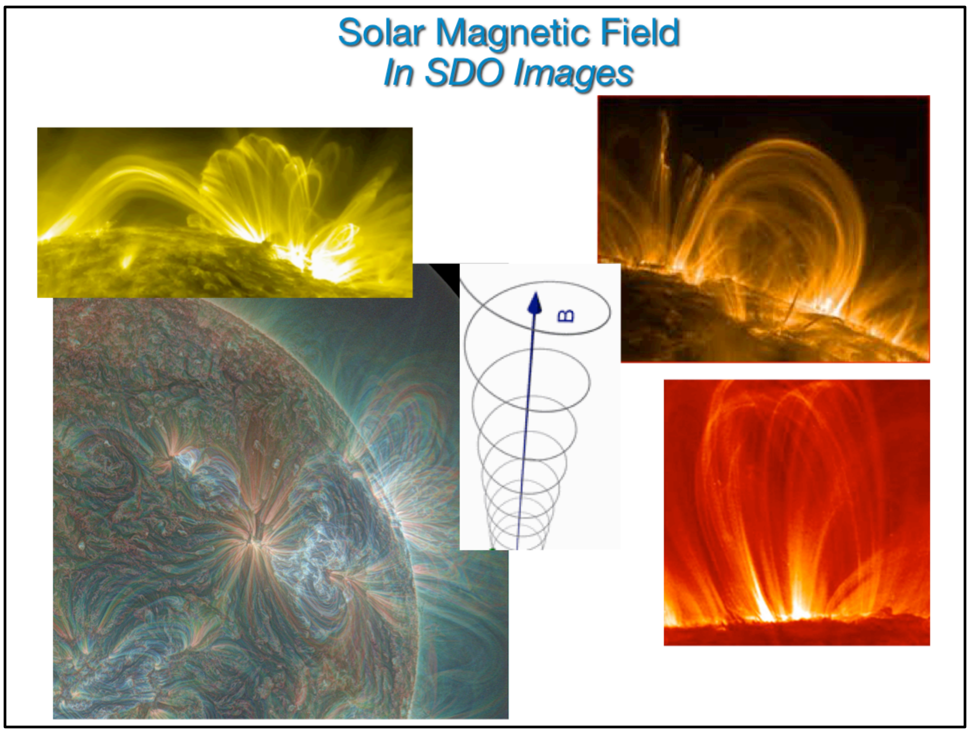


March 2012 flares

NASA satellite Solar Dynamic Observatory (SDO) brings us more amazing high resolution images revealing dynamics nature of the Sun.
You can see dark areas (so called coronal holes) and brightening or explosions, accompanied by sudden release of large amount of energy. These are the so-called solar flares. On this slide you can see images of solar flares observed by SDO (in different wave lengths).



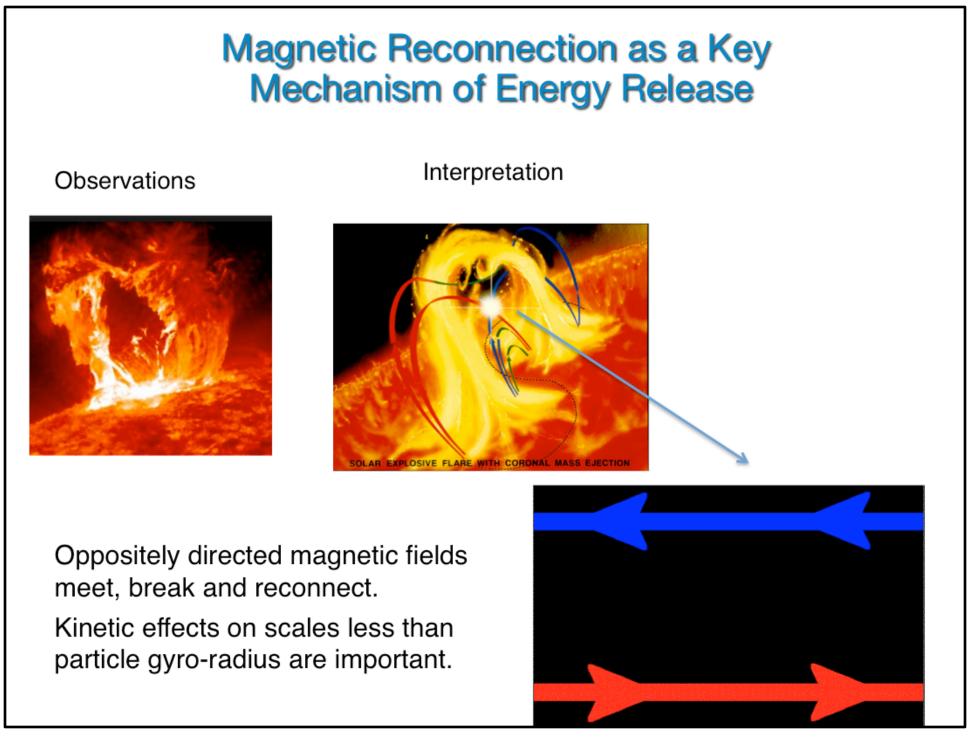
The solar flare are also detected by increases in X-ray fluxes by instruments at GOES satellite.



Let’s zoom even closer. These are SDO images that reveal the complicated loop-like structure of the magnetic field in the solar corona. Some people say that we are seeing magnetic field lines here. Actually you can not see magnetic field lines and those are just line of force.
The images are showing plasma particles that are moving along the magnetic field lines.

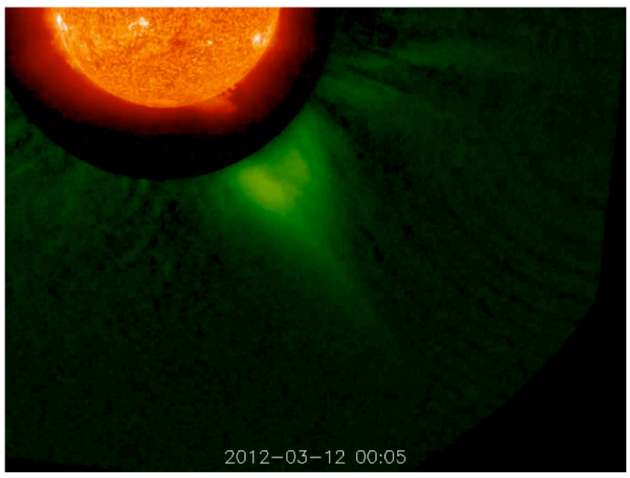
Gyro-radius depends on particle mass, energy, and the local strength of the magnetic field.

Spatial scales varies througout the Heliosphere:
e.g., 100 m – 1000 km



It is widely believed that energy during solar eruptions is associated wthe the so-called magnetic reconnection, which happen when oppositely directed magnetic field lines come close to each other causing magnetic energy to convert ot kinetic energy.

Solar Eruption accompanied by Coronal Mass Ejection (CME)

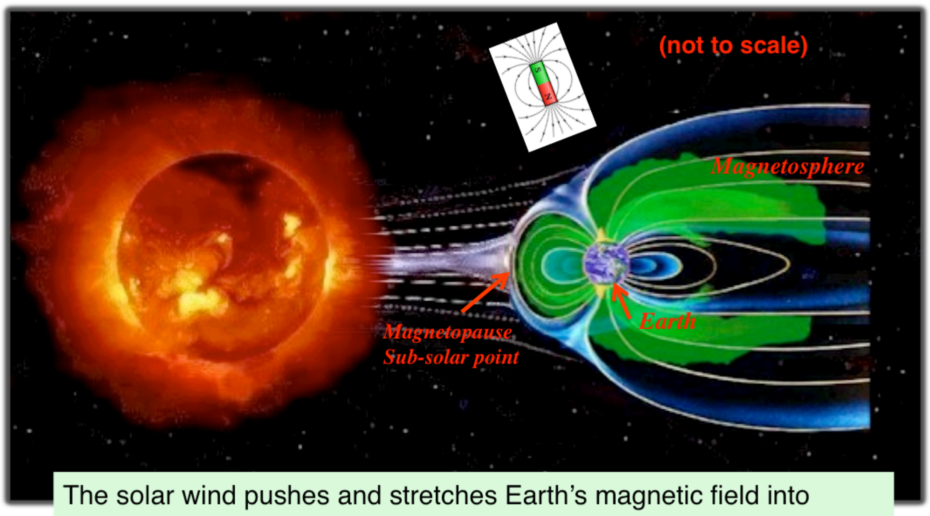


A view from STEREO A: 304A and coronagraph – line of sight perpendicular to Earth-Sun line

Solar flares are usually accompanied by Coronal Mass Ejections (CMEs). A movie shows solar eruption accompanied by CME.
The line of sight from STEREO A spacecraft (that is orbiting the Sun ahead of the Earth) is perpendicular to the Earth-Sun line. So the CME is propagating towards the Earth.

Coronal Mass Ejection propagates through the heliosphere and impact magnetized planets.

Earth Magnetic Field – Our Shield



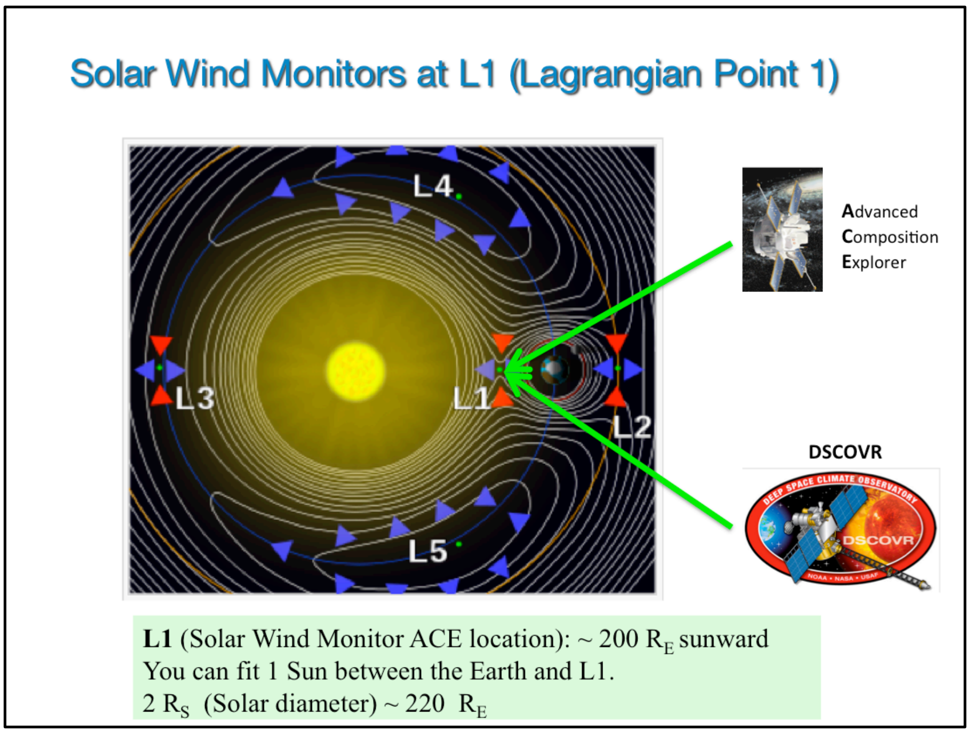
The solar wind pushes and stretches Earth's magnetic field into comet-shaped region called the magnetosphere. The magnetosphere and Earth's atmosphere protect us from the solar wind and other kinds of solar and cosmic radiation.

The stream of the charged particles flowing outward from the Sun, the so-called solar wind, interacts with Earth's magnetic field (and other magnetized planets). The Earth's magnetic field is similar to that of a bar magnet tilted 11 degrees from the spin axis of the Earth.
The magnitude of the magnetic field varies over the surface of the Earth in the range 0.3 to 0.6 Gauss. The solar wind pushes and stretches Earth's magnetic field into a vast, comet-shaped region called the magnetosphere. The magnetosphere and Earth's atmosphere protect us from the solar wind and other kinds of solar and cosmic radiation. Solar wind – Earth's magnetic field field interaction flatten the nose (dayside – towards the sun) and drag field lines to the tail (night-side – away from the sun).

The magnetopause separates Earth's magnetic domain from the solar wind and its embedded interplanetary field (IMF). The three-dimensional location of the magnetopause represents a balance of pressures: Pressures of solar-origin (predominantly solar wind flow ram pressure) balance pressures of Earth-origin (predominantly outward magnetic pressure) at the magnetopause.

The magnetic field is the shield that protects the Earth from the solar plasma particles because they have difficulty in moving across the magnetic field lines. If the Earth did not have the magnetic field, continuously blowing solar wind and CMEs would most likely wipe out all the life forms on the Earth. Scientists speculate that something like this could have happened on Mars, who lost its magnetic field over the time.

The Sun-Earth line cross the magnetopause at the Sub-solar point. Magnetopause stand-off distance is the distance to the magnetopause sub-solar point. Under quiet conditions the magnetopause sub-solar point is about 10 to 12 Earth's radii away from Earth. 1 R_E (Earth's radius) = 6370 km. In dense solar wind or in the presence of a strong and negative solar wind magnetic field component B_z, the magnetopause can move closer and even cross geosynchronous orbit (distance about 6.7 R_E).

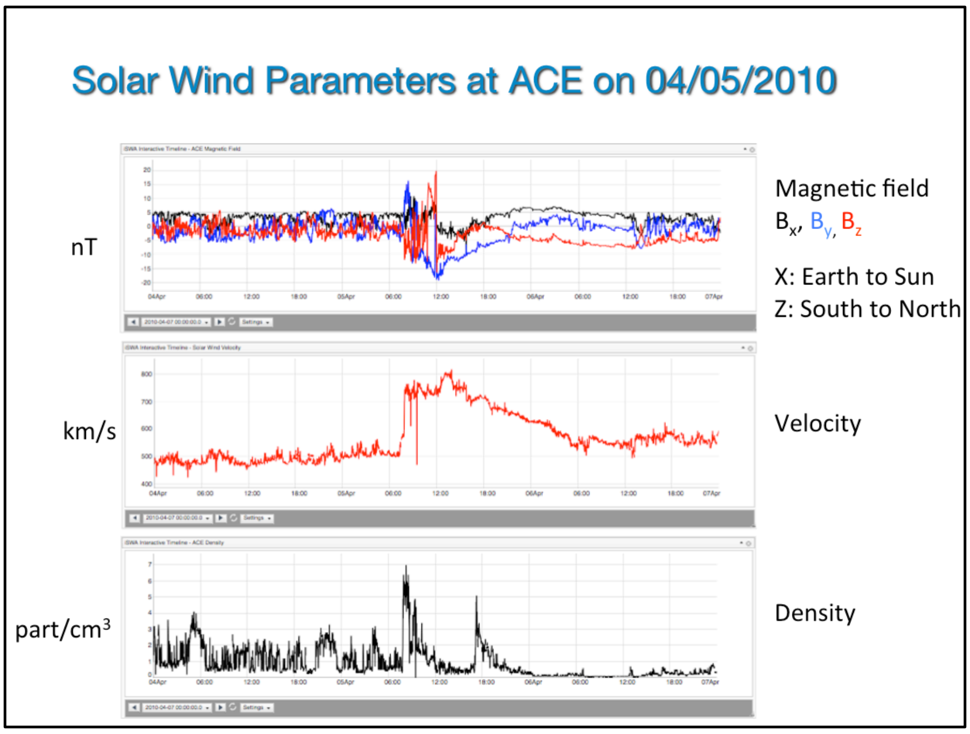


CME impact is detected my Solar Wind Monitors upstream of the Earths magnetopause at L1.

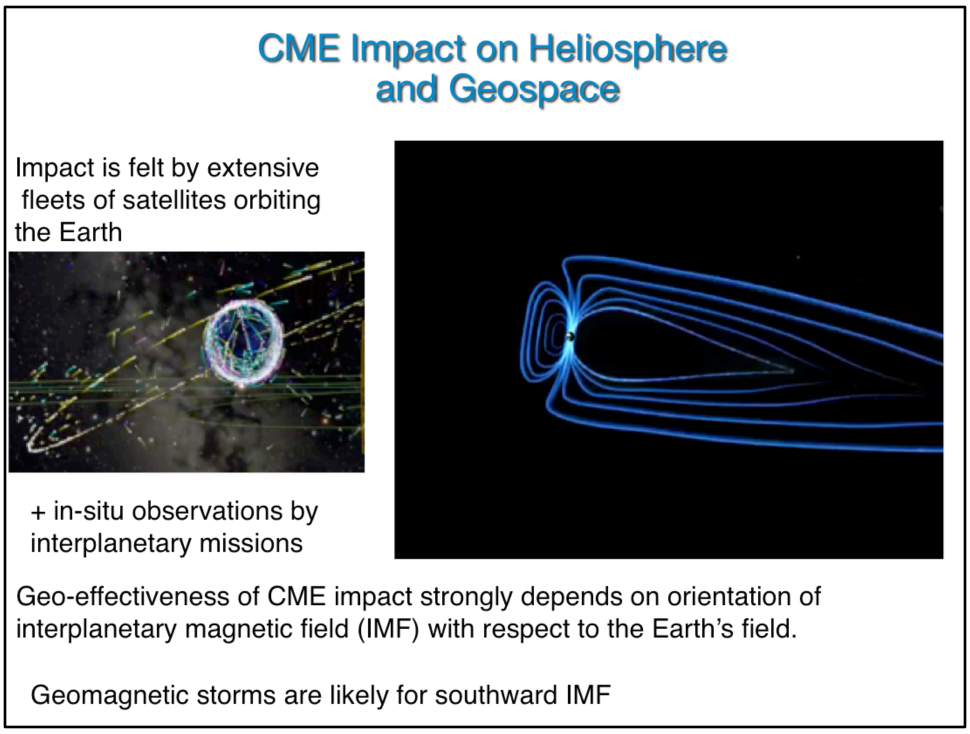
The **Lagrangian points** (/**L-points**) are the five positions in an orbital configuration where a spacecraft affected only by gravity can maintain its position relative to the two massive bodies (the Earth and the Sun).

Lagrangian points are perfect for continuous monitoring of Solar activity and solar wind.

You can almost fit 1 solar diameter (~ 200 R_E) between the Earth and L1.
Solar wind monitor ACE is positioned at L1 point. DISCOVR is coming soon.
It takes about 30 – 60 min (depending on the speed of the solar wind) for the disturbance observed at L1 to reach the Earth.
It would be nice to have monitor at other Lagrangian points (e.g. at L5).



1 nT = 10^{-5} Gauss



CME impact is also felt by extensive fleet of satellites orbitind the Earth
+ in-sity observations by intenplanetary missions
The video show artistic presentation of CME impact on the Earth.
Orientation of IMF with respect to the Earth’s magnetic field and magnetic reconnection control the geo-effectiveness of the CME impact.
The most geo-effective is southward IMF.

Geomagnetic storms are likely for southward IMF

NOAA Space Weather Scale: **Geomagnetic Storms**

Category	Effect	Physical Measure	Average Frequency (1 cycle= 11 years)
Scale/ Descriptor	Duration of Event Influences Severity of Effects	Kp values* determined every 3 hours	Events when Kp level met; (# of storm days)
G5 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 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 **9**	4 per cycle (4 days per cycle)
G4 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 **8**	100 per cycle (60 days per cycle)
G3 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 **7**	200 per cycle (130 days per cycle)
G2 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)
G1 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)

Kp - index

"*p*lanetarische *K*ennziffer" (= planetary index).

Geomagnetic activity index

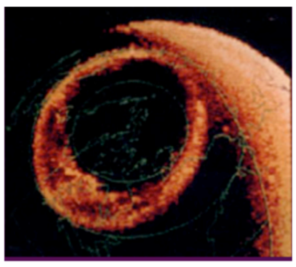
range from 0-9

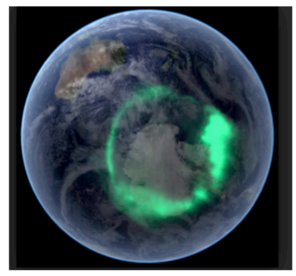
disturbance levels of magnetic field on the ground – currents

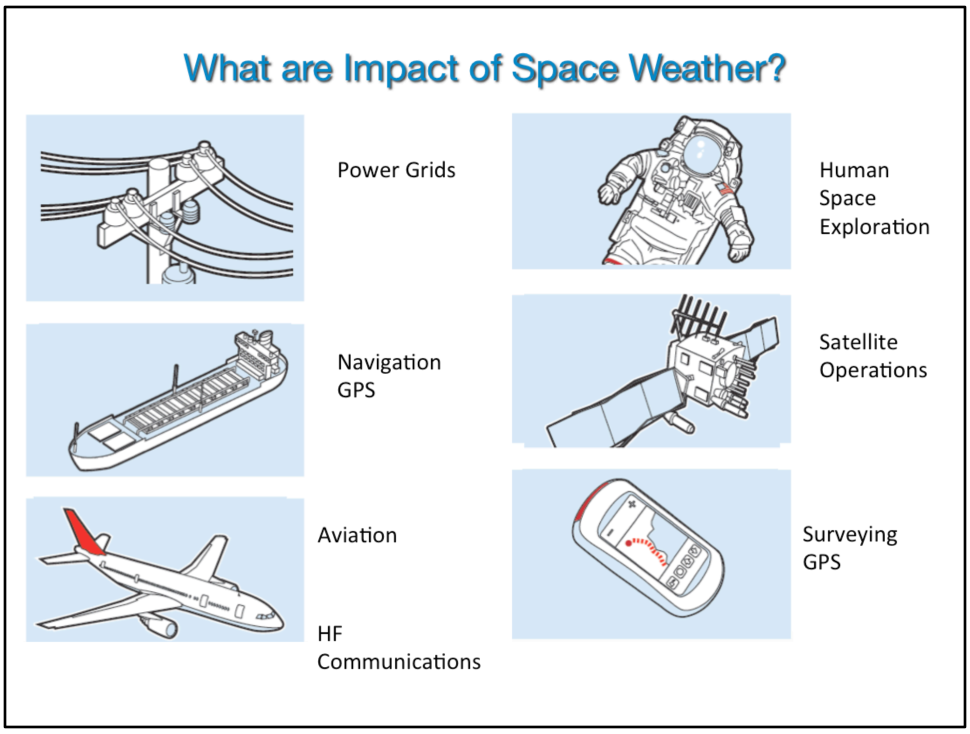
Kp > 4 : storm (see NOAA scale)

Kp < 5 quiet

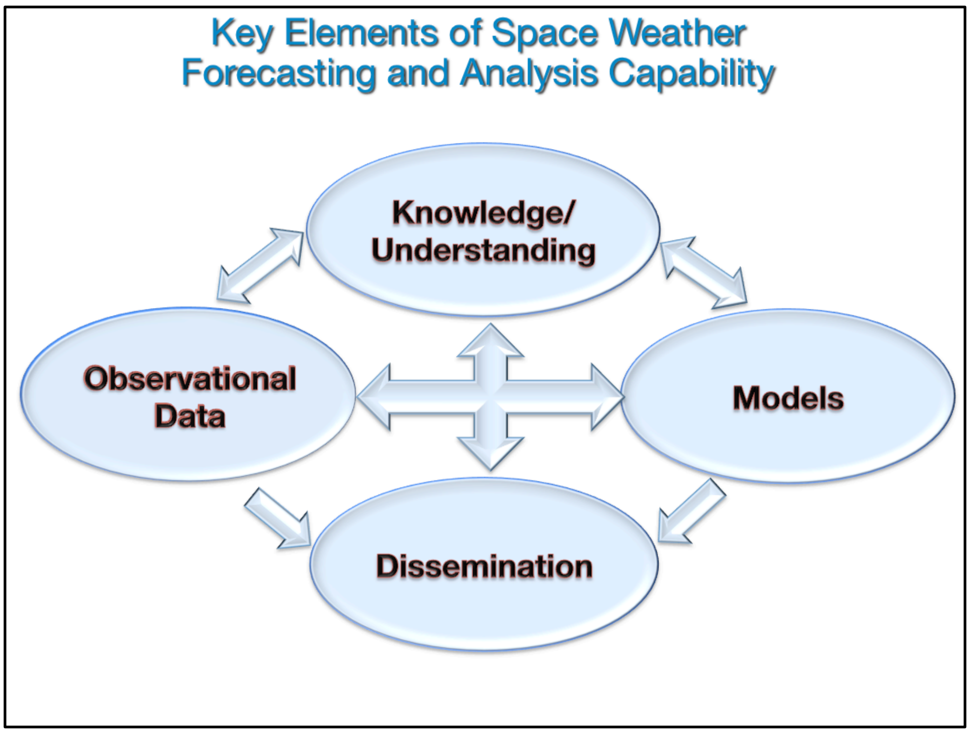
CME Impact on Geospace: Aurora



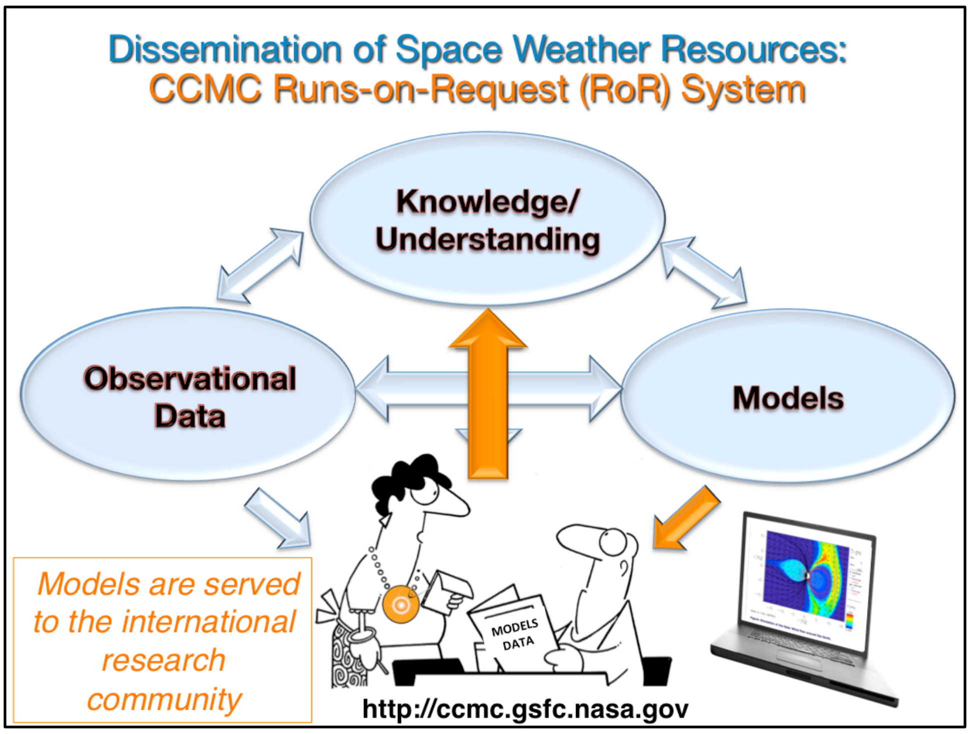




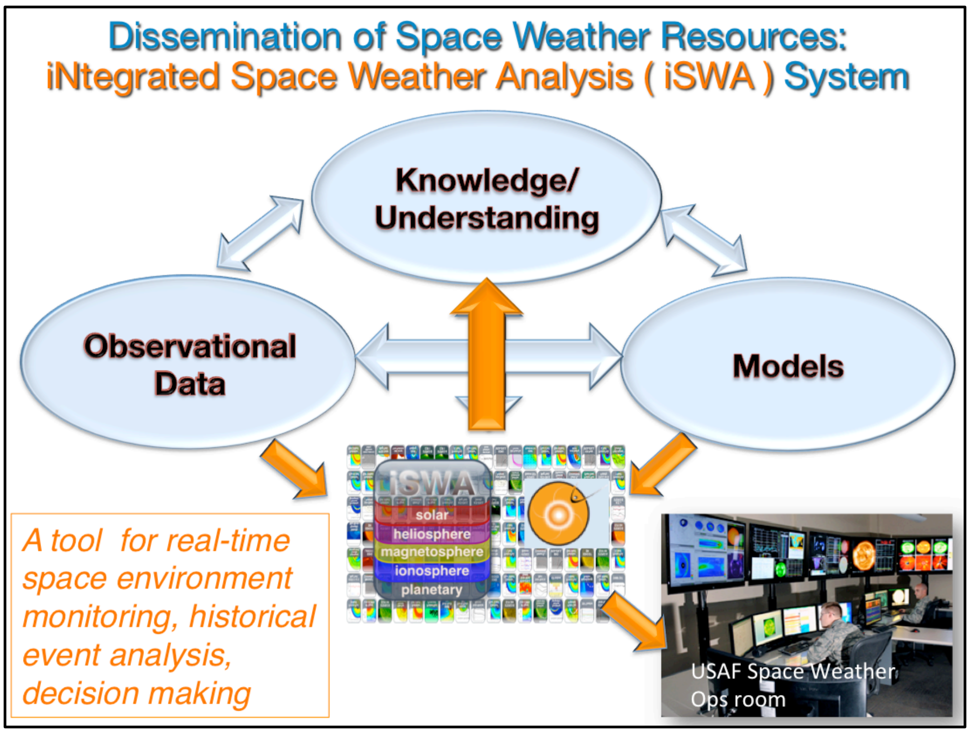
Check NOAA booklet and e-poster in your e-material



The scheme shows key elements of the space weather forecasting and analysis capability package. “Science for Space Weather” is in the top box.
To advance our understanding of space weather wen need information (observation data) and models. Easy access to models and data (disseminations) is important to maximize return on investment and to speedup the progress. All components are interconnected.



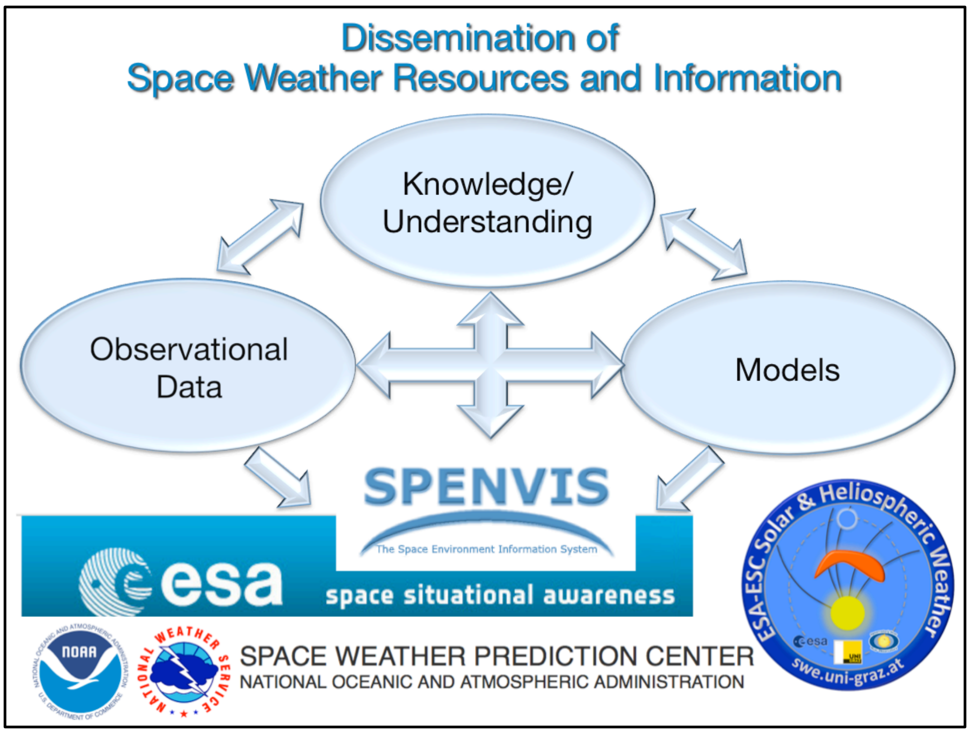
Dissemination of simulation results was an issue prior to CCMC (before 2000).
The CCMC brings you the power to access state of the art modeling capabilities through your laptop.
During one of the hands-on sessions you will learn how to use CCMC Runs-on-Request system.

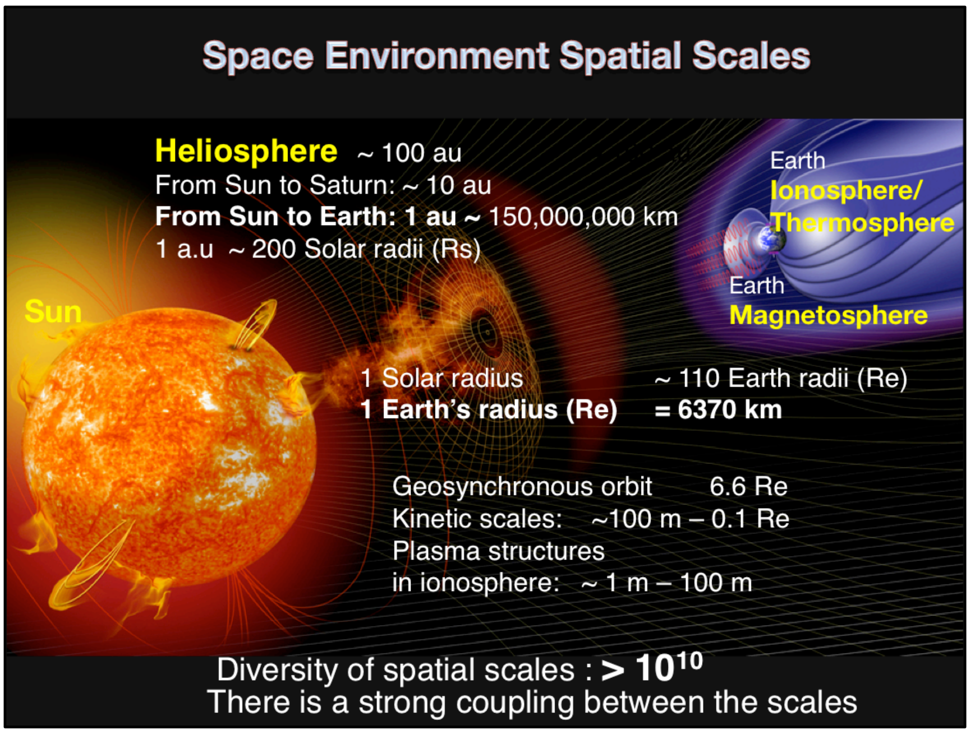


Model output data cubes with visualization software tailored for research in most cases are not that useful for space weather operators. There is a need for actionable products, easy-to-use forecaster tools (derived from models and observational data) tailored to specific applications and end-user needs.

During one of the hands-on sessions you will learn how to use **CCMC iNtegrated Space Weather Analysis (iSWA)** system – a tool for real-time space environment monitoring, historical event analysis, system science, informed decision making, forecaster training, and education.

The photo on the right shows iSWA system in US AF Space Weather Operations room.


Dissemination of
Space Weather Resources and Information
Knowledge/
Understanding
Observational
Data
Models
SPENVIS
The Space Environment Information System
esa
space situational awareness
ESA-ESC Solar & Heliospheric Weather
swe.uni-graz.at
NOAA
NATIONAL WEATHER SERVICE
SPACE WEATHER PREDICTION CENTER
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION



To summarize our ran through the space weather phenomena in heliopshere let's review spatial scale of the space weather system.

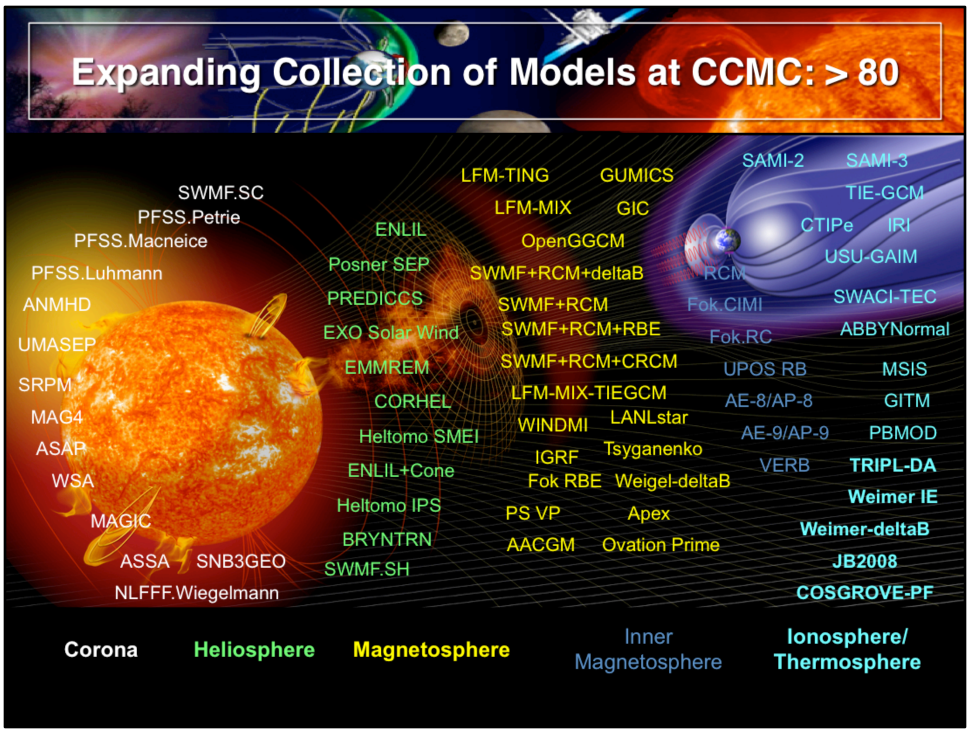
Heliosphere: ~ 100 au
From Sun to Saturn: ~ 10 au
From Sun to Jupiter: ~ 5 au
From Sun to Earth: 1 au ~ 150,000,000 km

1 a.u ~ 200 Solar radii (Rs)
1 Solar radius ~ 110 Earth radii (Re)
1 Earth's radius (Re) = 6370 km

Geosynchronous orbit 6.6 Re
Kinetic scales: ~100 m – 0.1 Re
(depending on particle mass, energy, local magnetic field strength)

Diversity of spatial scales (more that 10 orders of magnitude).

For comparison: terrestrial weather spatial domain is about 30 km thick (wrapped around the Earth).



Expanding collections of space environment models and model chains cover the entire domain from the solar corona to the Earth's upper atmosphere.
In the next slide I will present a few examples illustrating different sub-domain using simulation results of different models.

Type of Models

Empirical Models

Physics-based (first principle models with different approximations). Examples:
- Magnetohydrodynamics (MHD) – single species fluid
- Multi-fluid, Hall MHD
- Kinetic (particles)

Data assimilative

Modeling Sub-Domains

Solar Corona [Rs]: 1-2.5 Rs, 1-20 Rs
Heliosphere [au]: 1-2 au, 1-10 au +
Global Magnetosphere [Re]: 2-1000 Re
Inner Magnetosphere [Re]: 1-8 Re
- ring current (1- 8 Re)
- radiation belts

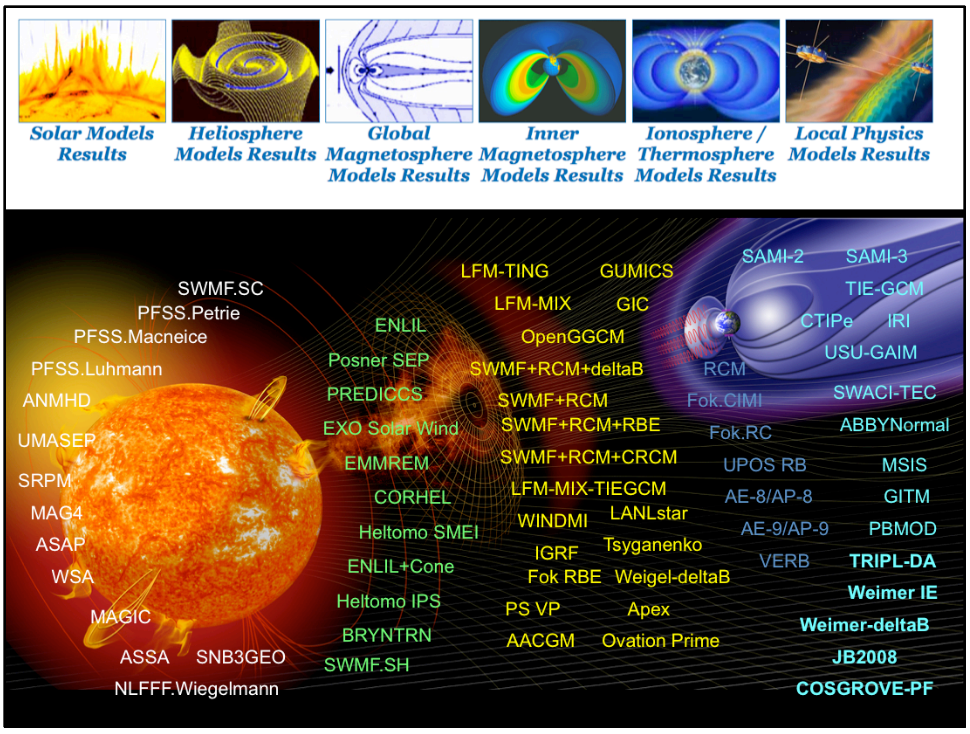
Ionosphere [km]: 80 – 1000 km

Multi-scale models, coupled model chains and adaptive simulation grids are required to model impacts from the Sun

Example: Space Weather Modeling Framework (SWMF), *Gombosi et al, U. Mich.*

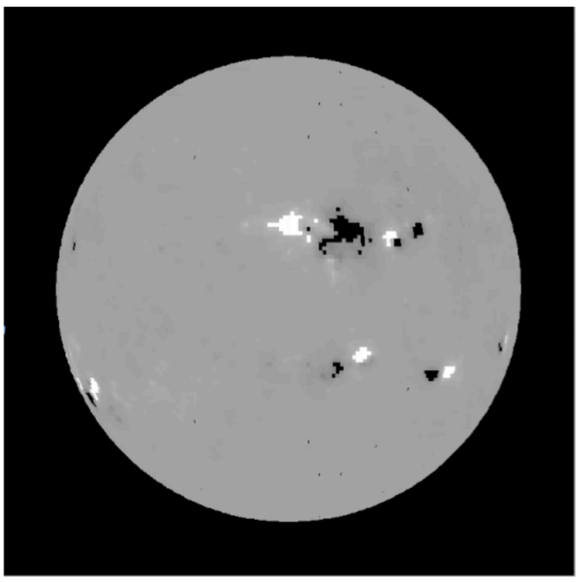
To address the issue of diversity of special scales the heliosphere is divided (for modeling purposes) into subdomains.
Different levels of approximations is required in different sub-domains depending on the underlying physical process.
There is a strong coupling between some subdomains

To trace CME propagation from the solar corona to the Earth's upper atmosphere – coupling model chain are required.
Community is building "Space Weather Modeling Frameworks".



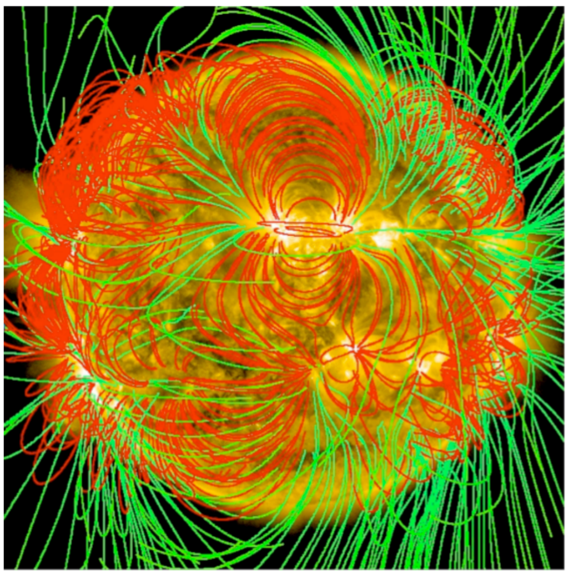
Models sorted by domain at the CCMC website:
http://ccmc.gsfc.nasa.gov

Solar Magnetograms: Input for Models of Solar Corona



Solar magnetograms are used as input for models of Solar Corona

Nonlinear Force-Free 3-D Coronal Magnetic Field Reconstruction

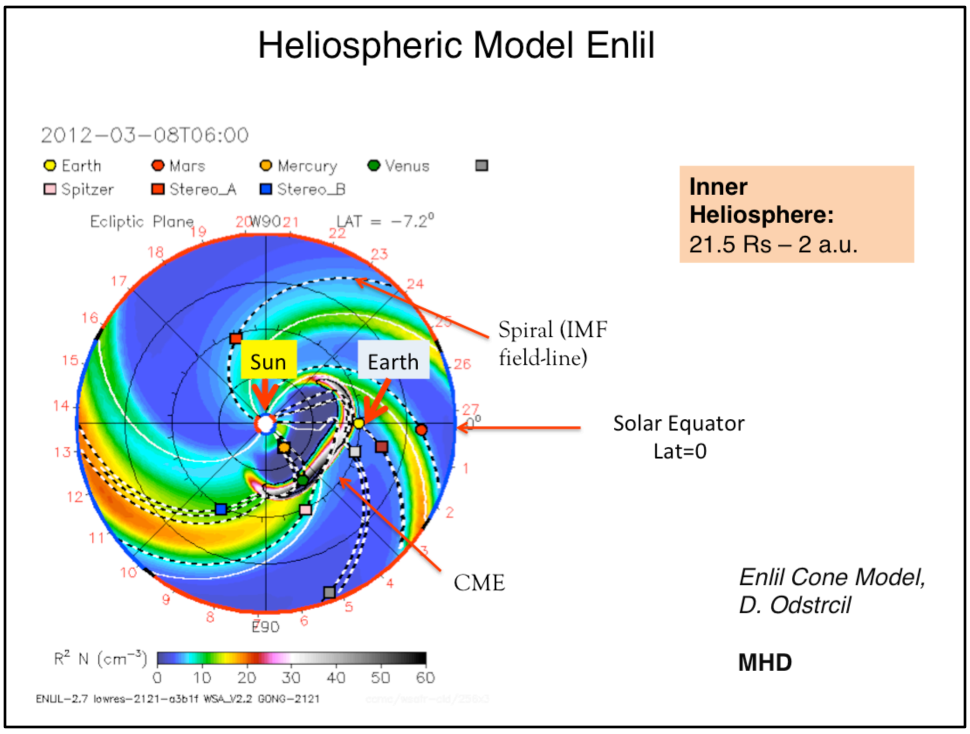


Solar Corona:
1-2.5 Rs,   1-20 Rs

NLFFF Wiegelmann Model

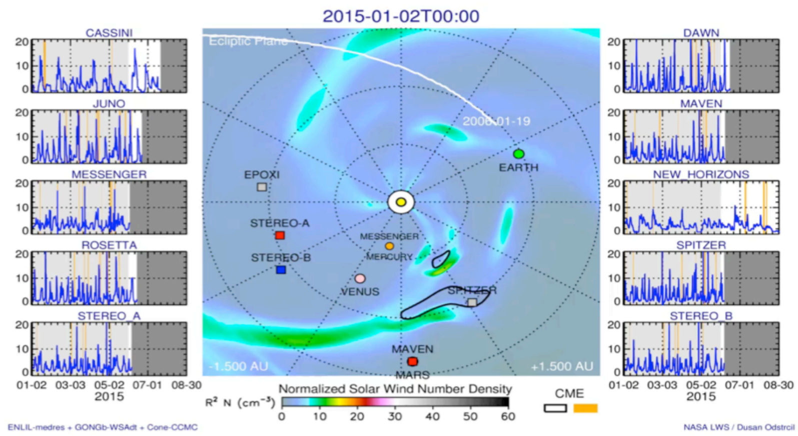
Solar Corona models

Solar Corona [Rs]: 1-2.5 Rs,   1-20 Rs



Enlil = Sumerian god of wind

Interplanetary Space Weather:
New Horizon Modeling Challenge



Simulations and visualization by Dusan Odstrcil
120 CMEs: kinematic parameters estimated by the Space Weather Research Center team at CCMC

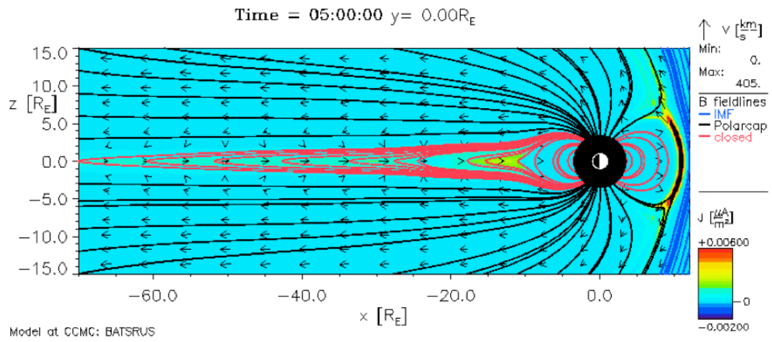
Heliosphere:
21.5 Rs – 40 a.u.

The animation illustrate the prediction of the solar wind parameters at the New Horizons spacecraft during its cruise phase to Pluto. Numerical simulations of more than 120 Coronal Mass Ejections (CMEs) during first six months on 2015 were performed using the heliospheric code ENLIL (Sumerian god of wind), developed by Dr. Dusan Odstrcil. ENLIL is implemented at the Community Coordinated Modeling Center (CCMC) located at NASA GSFC and utilized by NOAA Space Weather Prediction Center (SWPC) in operational space weather forecasting. Kinematic parameters of all CMEs are measured and stored in the web-accessible Database Of Notifications Knowledge Information (DONKI) by the CCMC's Space Weather Research Center (SWRC) team, while continuously monitoring space environment conditions in inner heliopshere in support of NASA's missions. Application to the outer helioshere is beyond the model's current capabilities and this simulation serves as an estimate. Solar wind would need around 4-5 months to propagate from the Sun to Pluto. All CMEs fitted by CCMC/SWRC in the last six months were used by ENLIL to estimate the disturbed solar wind parameters up to four months in the future.

Waiting for observational data from New Horizons.

Magnetosphere Model SWMF/BATSRUS (MHD)

Magnetosphere:
2 Re – 1000 Re

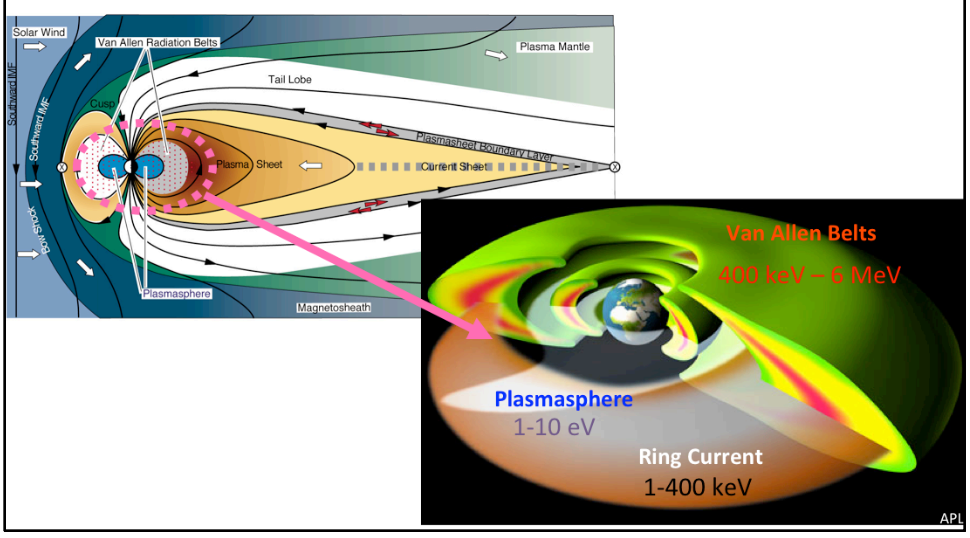


Sun

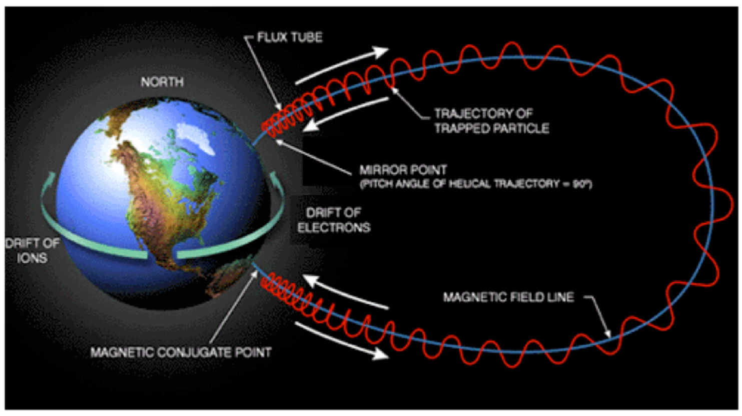
Space Weather Modeling Framework (SWMF), *Gombosi et al, U. Michigan*

Red lines (closed): Magnetic field (MF) lines with both ends connected to the Earth
Black lines (open): MF lines with only one end a the Earth
Blue lines (interplanetary): MF lines with both ends in the interplanetary space

Inner Magnetosphere
(up to ~ 10 RE)

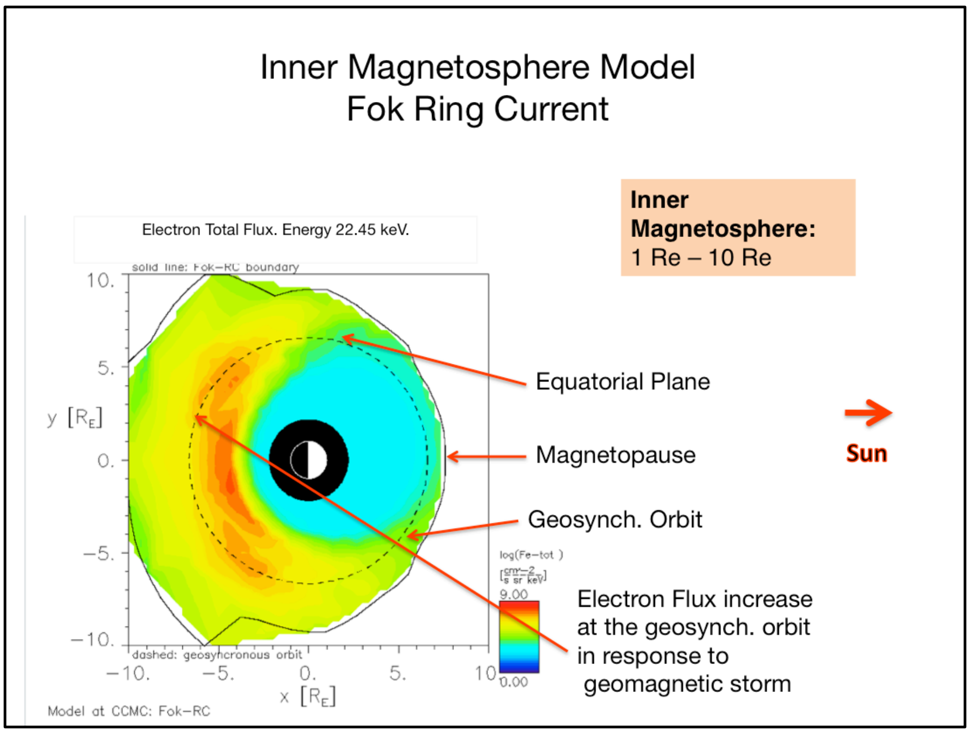


The charged particles that make up the **inner magnetosphere current system** are trapped in the Earth's magnetic field, *bouncing back and forth along the magnetic field lines between "mirror points" in the northern and southern hemispheres.*



~~**MHD**~~

Ring current circles the Earth in the equatorial plane and is generated by the **longitudinal drift** of energetic (10 to 200 keV) **charged particles** trapped on field lines.


Inner Magnetosphere Model
Fok Ring Current
Inner Magnetosphere: 1 Re – 10 Re
Electron Total Flux. Energy 22.45 keV.
solid line: Fok–RC boundary
dashed: geosynchronous orbit
y [R_E]
x [R_E]
10.
5.
0.
–5.
–10.
log(Fe–tot)
9.00
0.00
Model at CCMC: Fok–RC
Equatorial Plane
Magnetopause
Geosynch. Orbit
Electron Flux increase at the geosynch. orbit in response to geomagnetic storm
Sun