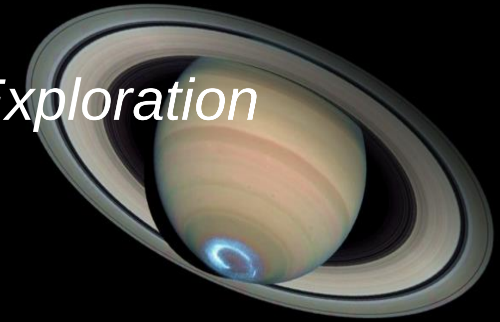
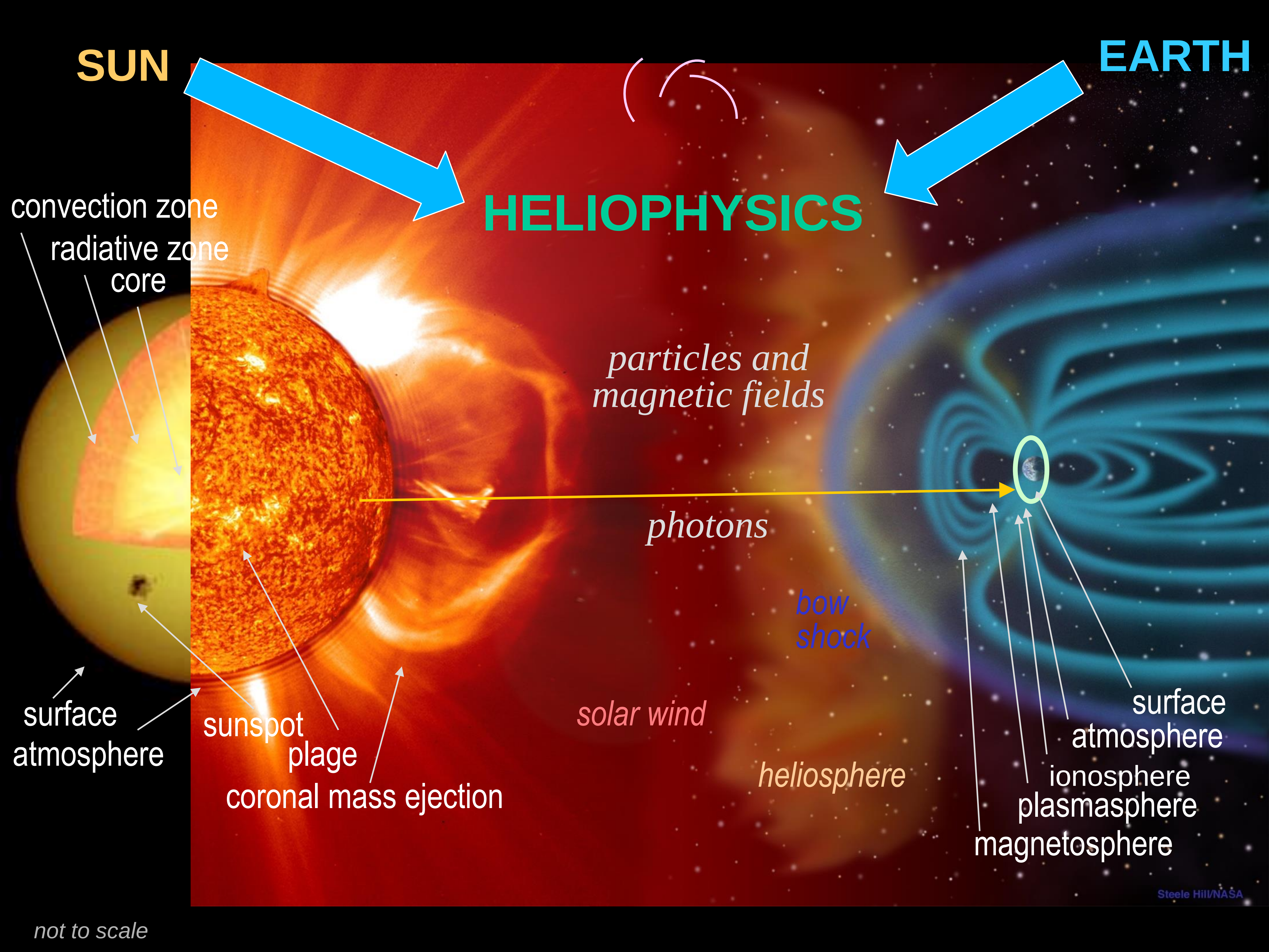
Challenges in Heliophysics and Space Weather And Solar Orbiter Contributions

Planetary Robotic and Human Spaceflight Exploration

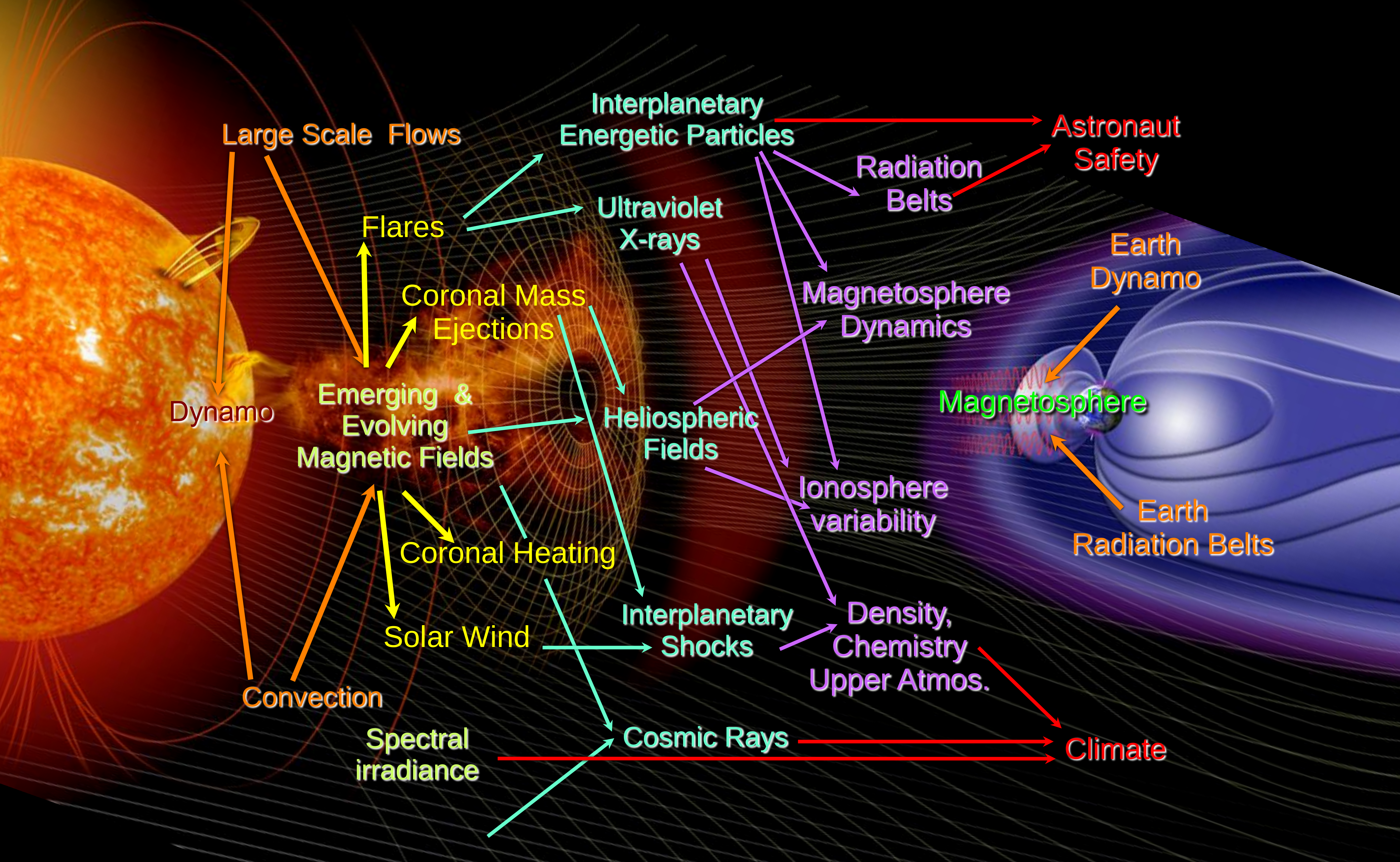


Madhulika Guhathakurta
NASA Headquarters
Science Mission Directorate/Heliophysics Division

09-22-2014


SUN
EARTH
HELIOPHYSICS
convection zone
radiative zone
core
particles and magnetic fields
photons
bow shock
surface atmosphere
sunspot
plage
coronal mass ejection
solar wind
heliosphere
surface atmosphere
ionosphere
plasmasphere
magnetosphere
Steele Hill/NASA
not to scale

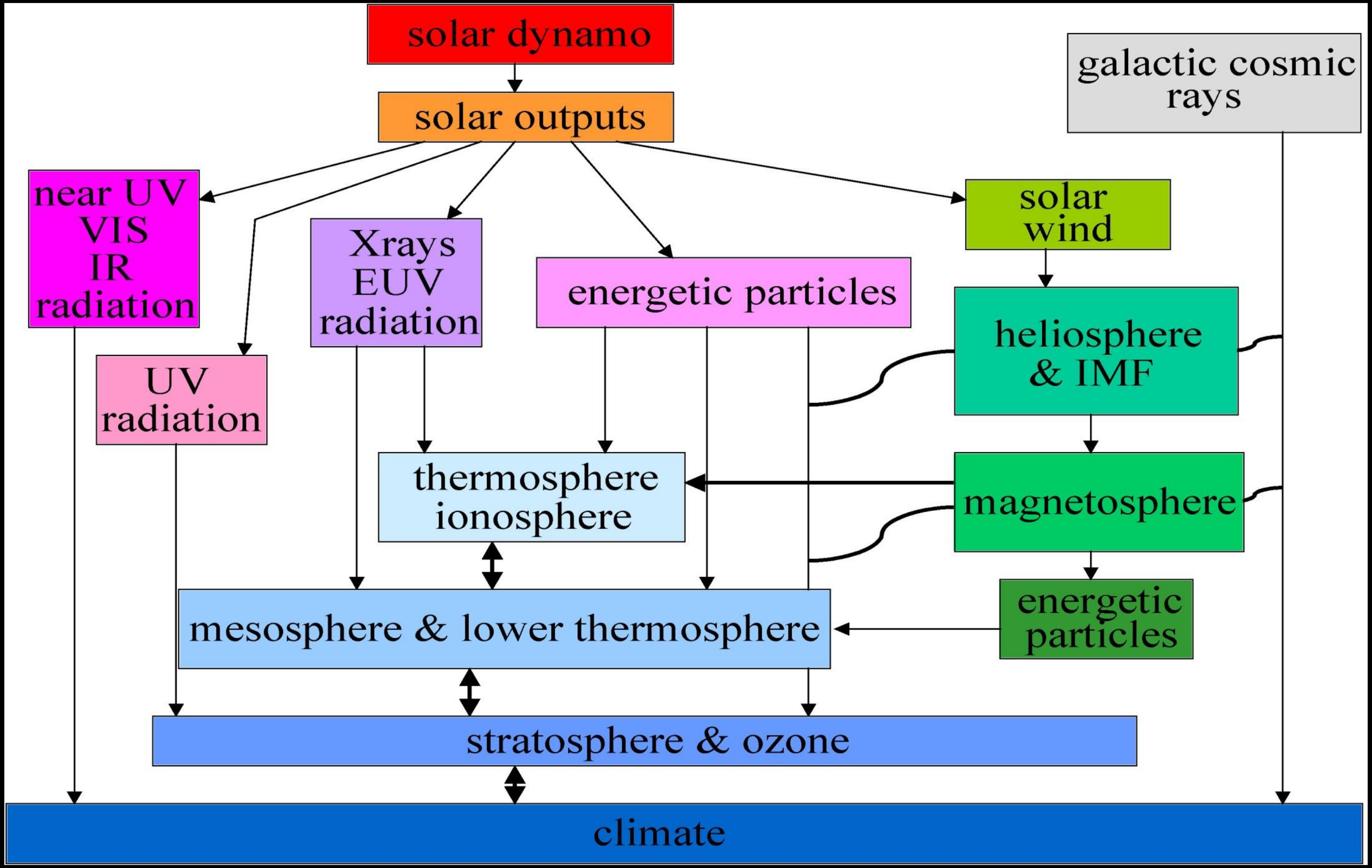
Sun-Earth connections: a complex system of coupled processes and phenomena



www.nasa.gov

A Systems Approach

Focus is not on any one region of space, but rather on our Sun Planet Region as one system.



A very important part is the study of the connection between the regions and how one drives a response in another.

Sun-Earth System Science: Growth from a “consuming” science to a “producing” science.

Program

1st International Polar Year 1882

2nd International Polar Year 1932

International Geophysical Year 1957

International Quiet Sun Year 1964

International M'spheric Study 1976

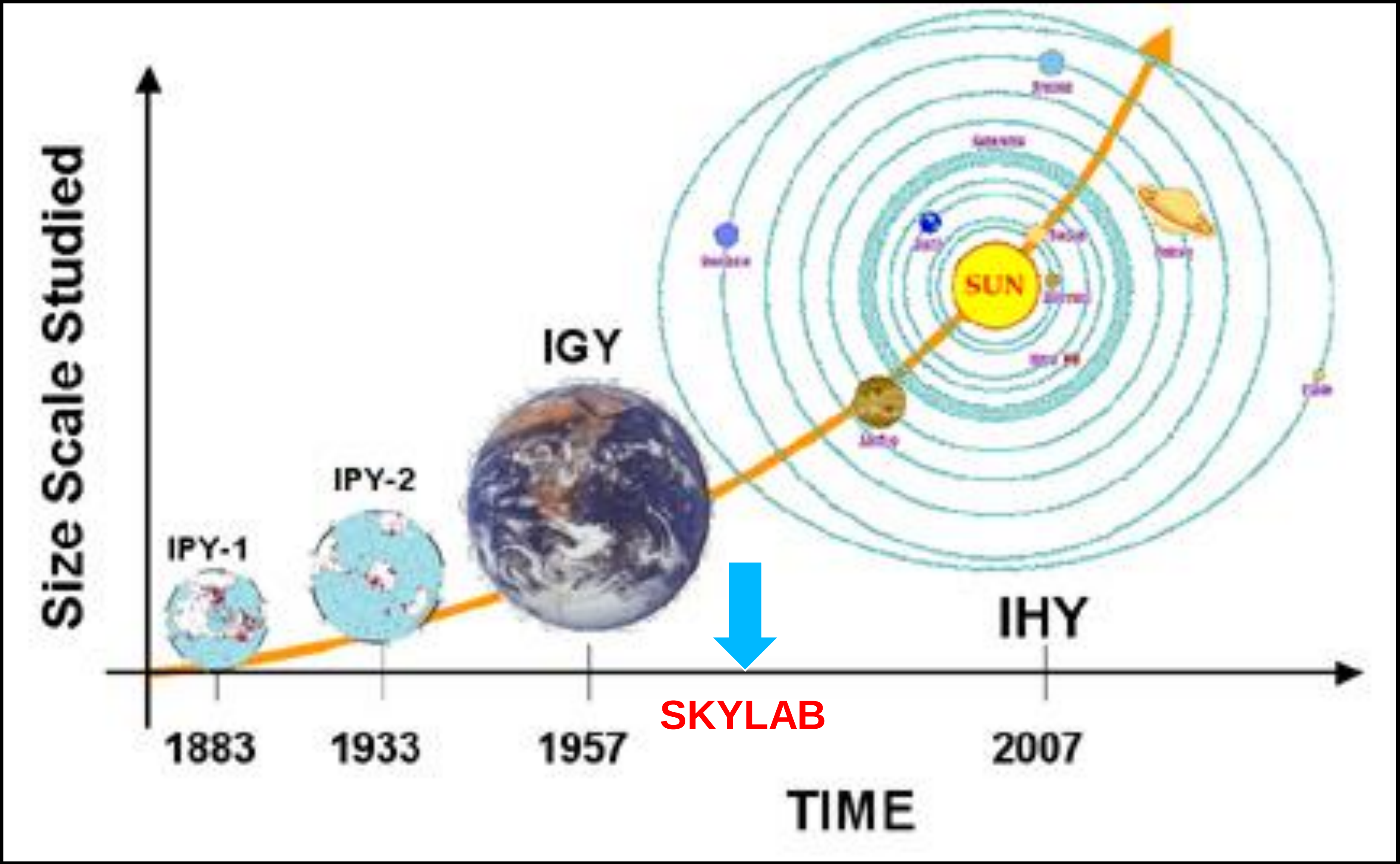
Solar-Terr. Energy Program 1990

National Space Weather Program 1995

Living With a Star 2000

International Heliosphysical Year 2007

Evolution of System Studies



Heliophysical: A broadening of the concept "geophysical," extending the connections from the Earth to the Sun & Interplanetary Space.

What is Heliophysics?

"Helio"-physics is the study of the physical domain defined by the Sun – the heliosphere, just like "astro"-physics is the study of the physical domain defined by stars.

This physical domain includes the Sun itself, the solar system, and stretches out to the start of interstellar matter.

In principle, Heliophysics studies everything inside the Sun's domain of influence.

Heliophysics is an environmental science:

a unique hybrid between meteorology and astrophysics

It has an applied branch:

Space weather started (NSWP) 1995
Living with a Star (NASA) 2000

And a pure branch:

Universal processes started (IHY) 2007

Heliophysics as a Scientific Discipline

NASA's Earliest scientific successes Explorer 1 in 1958 Radiation Belts) and Mariner 3 in 1963 (Solar Wind), and SkyLab (1973), discovered previously undetected processes and conditions, that directly modulate the Earth. These efforts set the stage for the discovery of the connected system of systems in the solar system that comprise the focus of heliophysics research (past).

The system of systems is driven by the interaction of three forces, pressure, gravity and magnetism; for which the universal physical processes governing order and disorder have not yet been fully uncovered.

The results of research to date have yielded not only new cultural and intellectual knowledge, but have provided benefits with utility, both, political and economic, to the nation.

Examples of Discipline-Specific General Laws or Principles

ASTRONOMY
Kepler's Laws, Hertzsprung-Russell diagram, expanding universe

CHEMISTRY
periodic table, valence, Le Chatelier's Principle

BIOLOGY
evolution, double helix

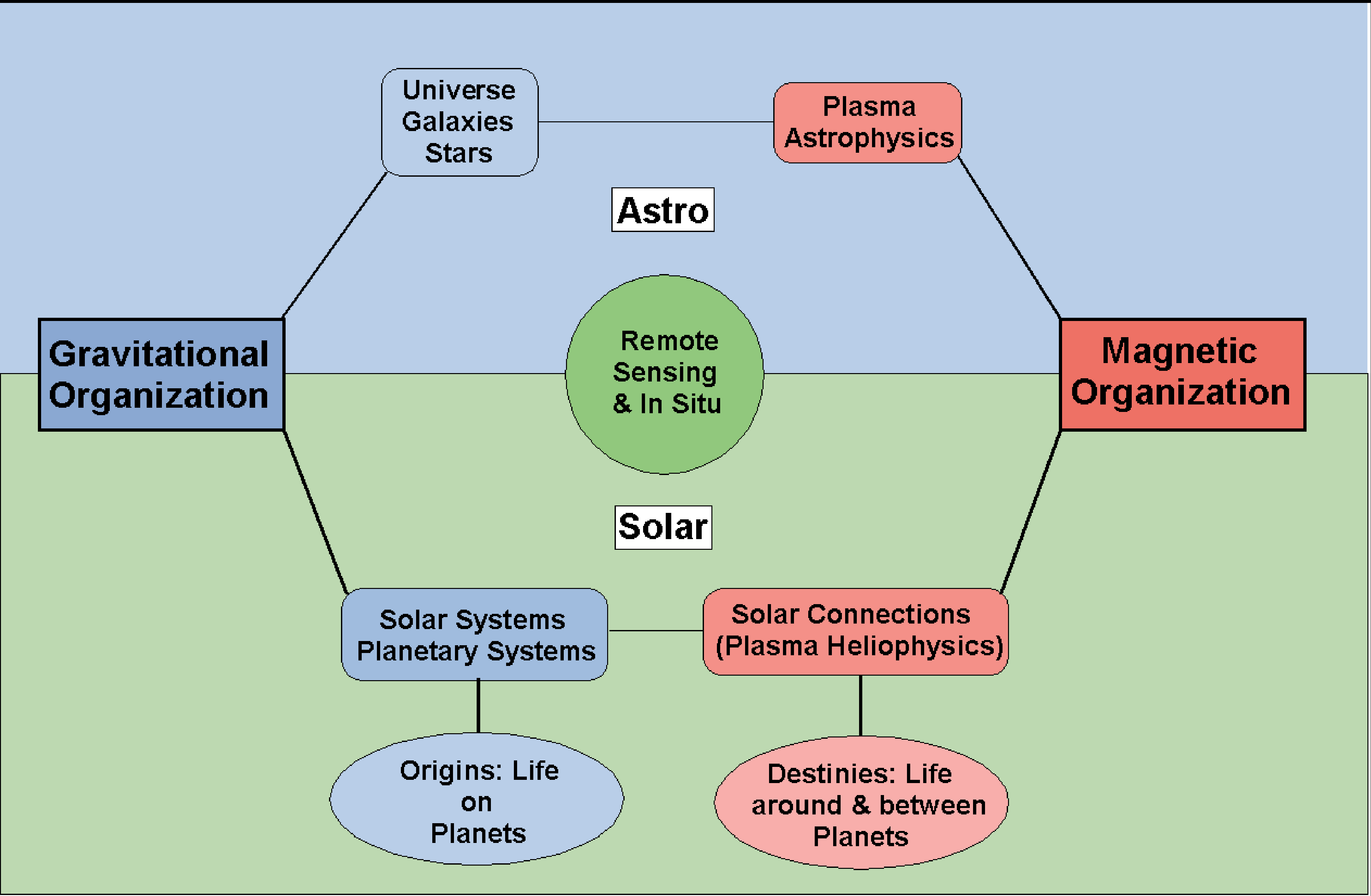
GEOLOGY
deep time, plate tectonics

METEOROLOGY
Hadley cell, baroclinic instability

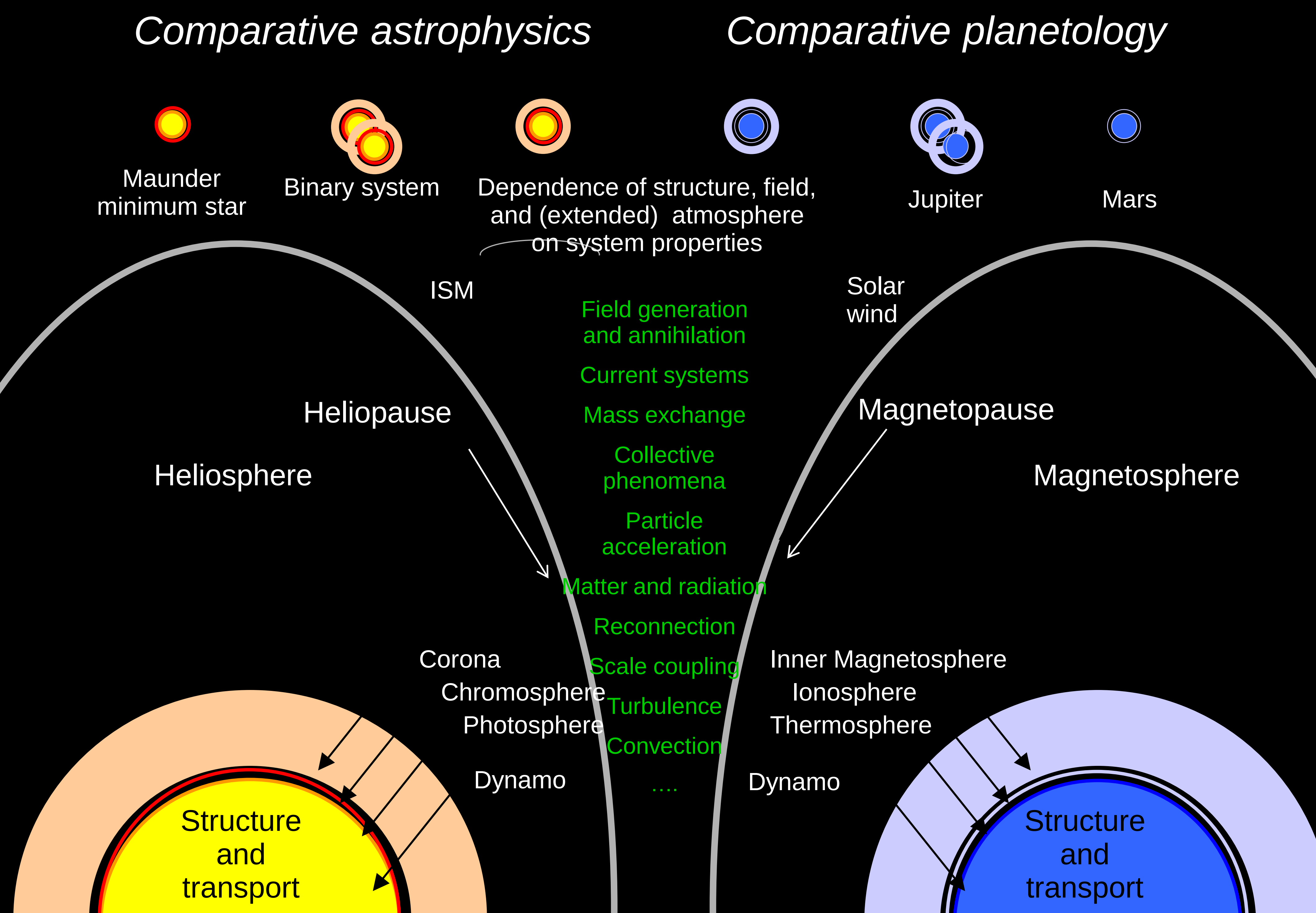
HELIOPHYSICS
solar (stellar) wind
magnetospheric convection
magnetic organization of matter
explosive energy conversion (CMEs & substorms)
magnetically (non-locally) coupled systems

The project of uncovering universal processes of heliophysics corresponds to the 'Copenhagen' project of quantum mechanics

Organization of the Universe



Exploiting natural parallels: Helio, Astro, Planetary & Earth



From SkyLab To Heliophysics/Space Weather

Skylab/Game Changers

The Corona is hot and controlled by magnetic Fields !!!

➔ X-Ray and EUV Variability at Earth

High-Speed Solar Wind originates from coronal Holes !!!

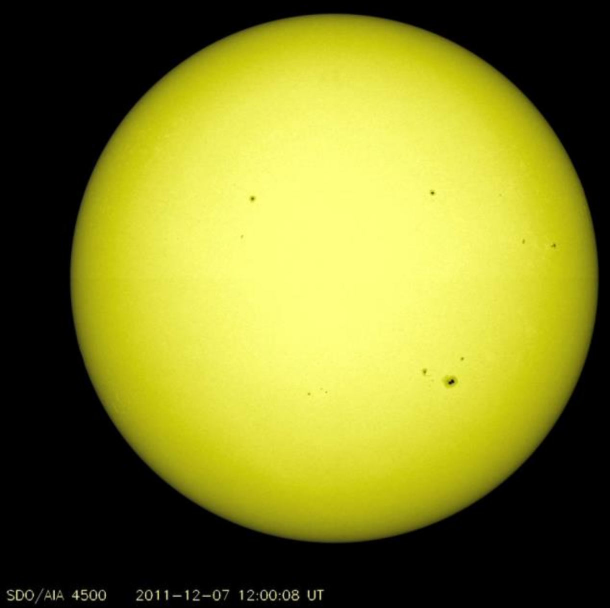
➔ Solar Particles Impact Earth

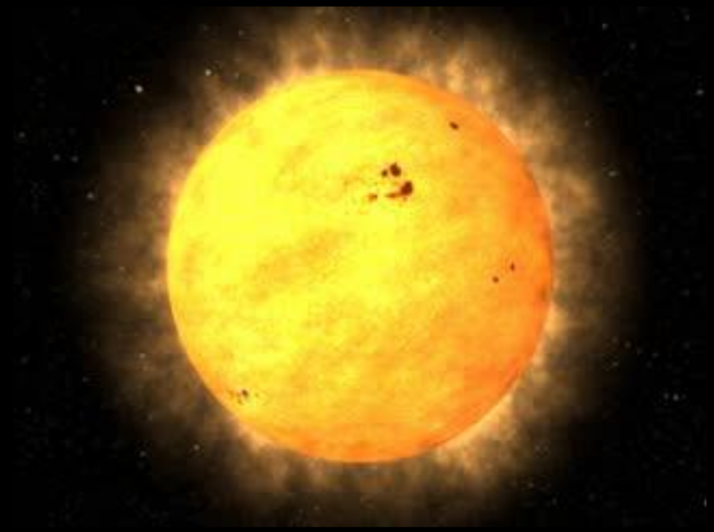
Mass from the corona is ejected into interplanetary space !!!

➔ Solar catastrophic events can impact Earth’s magnetosphere

Adapted from Dick Fisher’s talk at Smithsonian

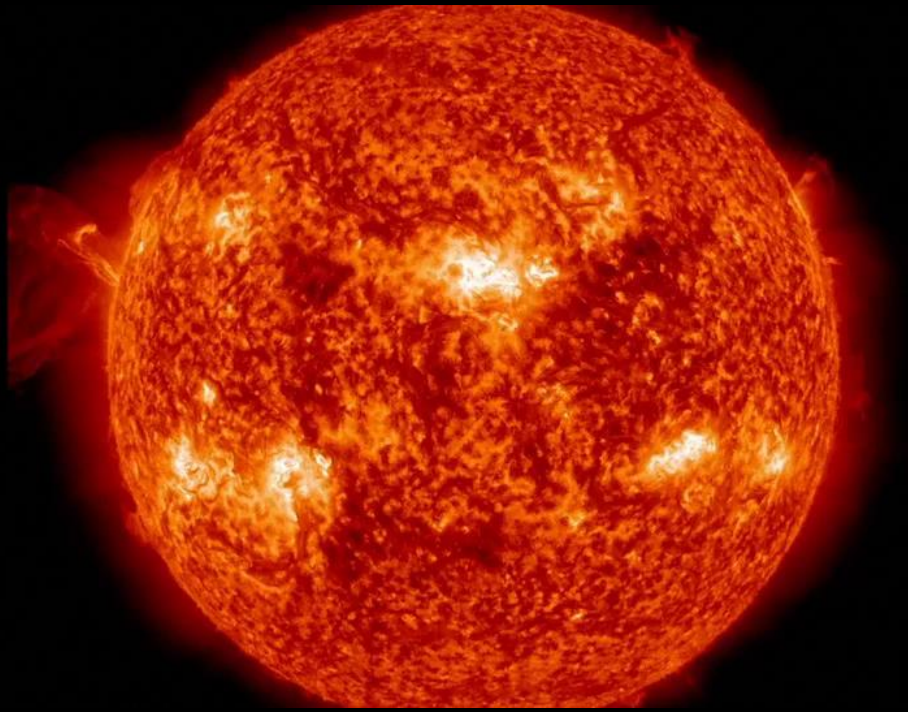
Understanding the Sun and its interactions with the Earth and the Solar System, including space weather





Solve fundamental mysteries of Heliophysics

Understand the nature of our home in space



Build the knowledge to forecast space weather throughout the heliosphere

This is a complex system with many different temporal and spatial scales. The system is multi-scale & couples between scales.

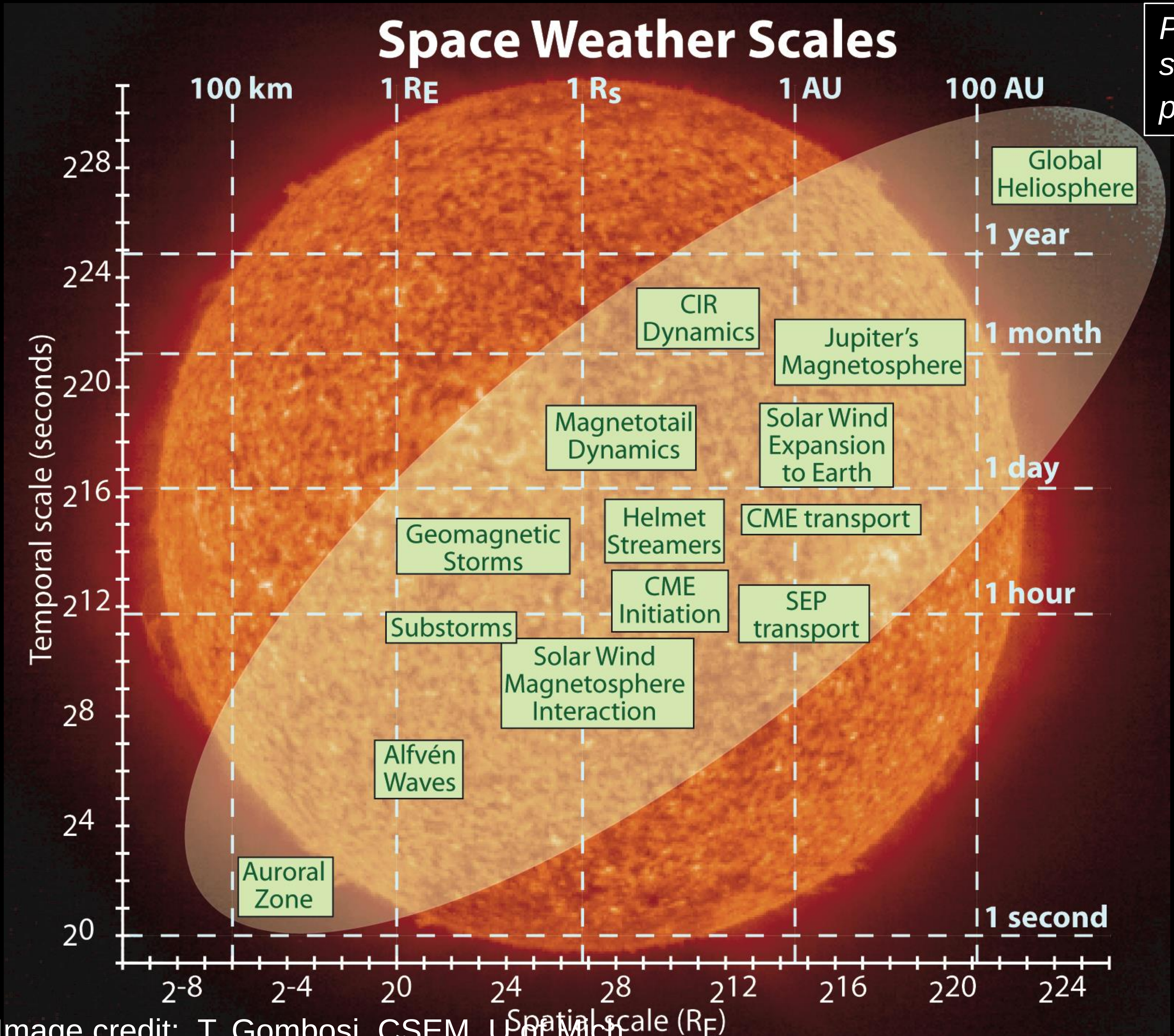


Image credit: T. Gombosi, CSEM, U of Mich

Processes operating at one scale can influence phenomena at other scales.

A quantitative, predictive understanding of a complex system

Microphysical processes regulate global & interplanetary structures

Multi-constituent plasmas and complex photochemistry

Non-linear dynamic responses

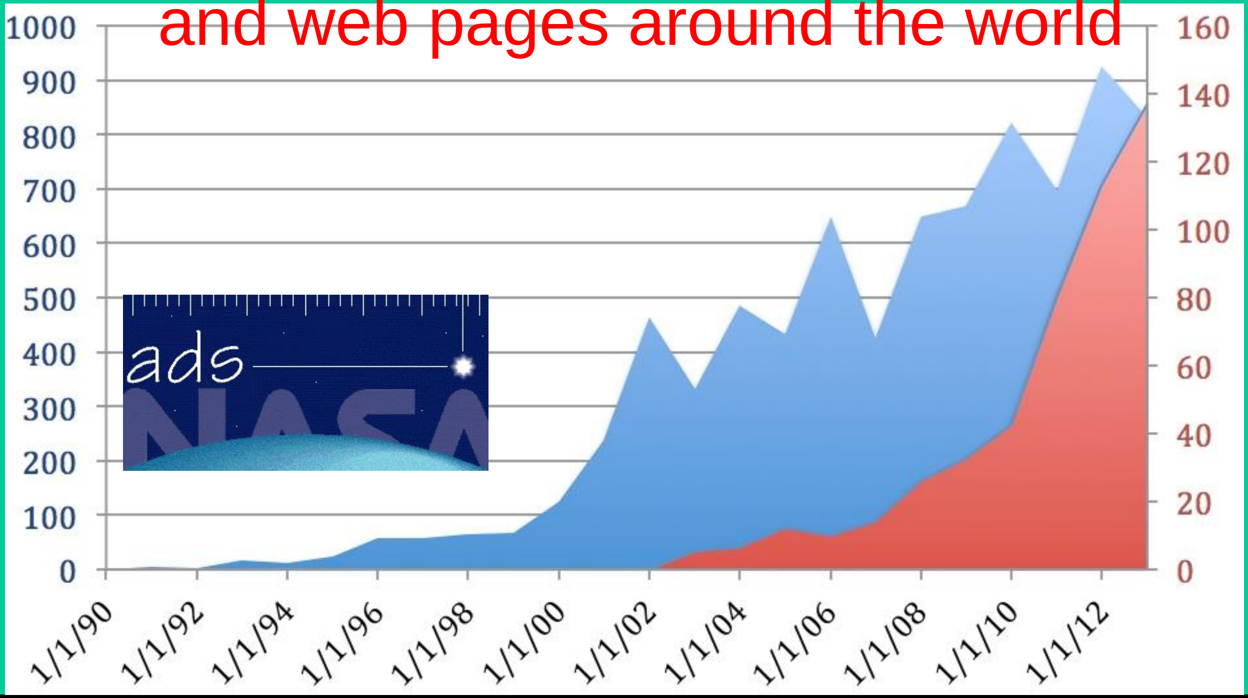
Integration and synthesis of multi-point observations.

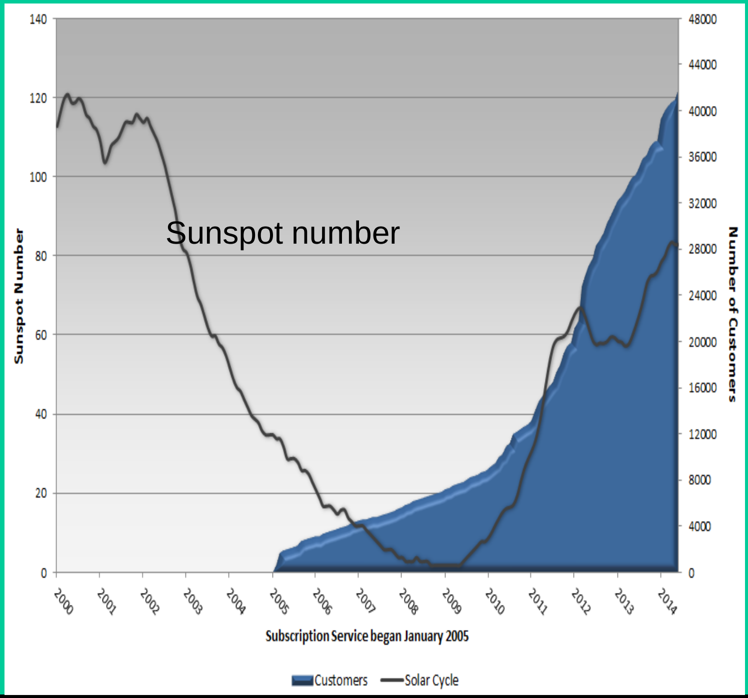
Data assimilative models & theory.

Interdisciplinary communities and tools

Increasing awareness of, and interest in, space weather

Space weather publications (in ADS), NOAA/SWPC subscriptions and web pages around the world





http://www.swpc.noaa.gov/forecast.html

http://www.tesis.lebedev.ru/en/forecast_activity.html

http://www.spaceweather.gc.ca/forecast-prevision/sf-eng.php

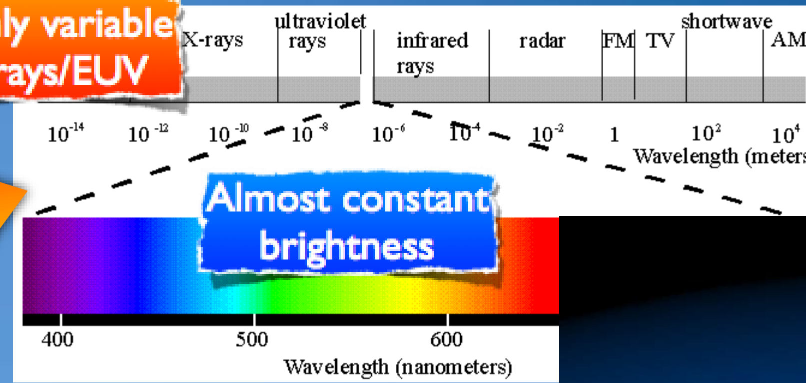
http://www.ips.gov.au/Space_Weather/1/1

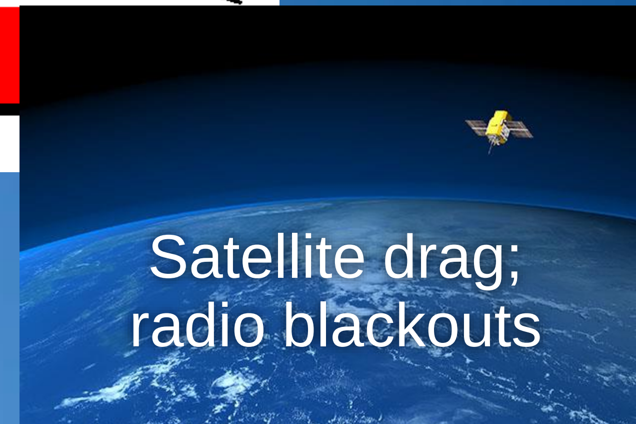
http://swc.nict.go.jp/forecast/index_e.php

http://www.esa-spaceweather.net

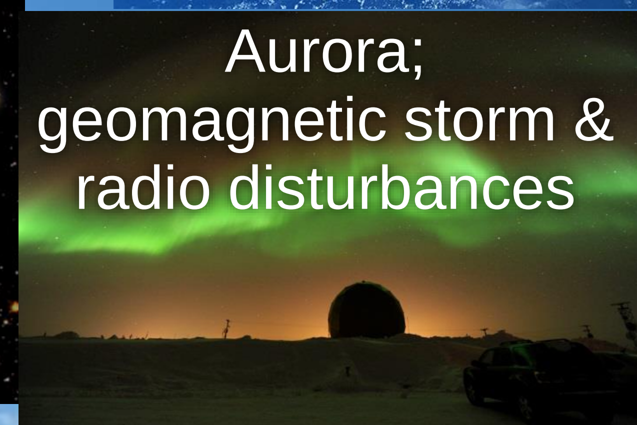
What the Sun sends our way

Light





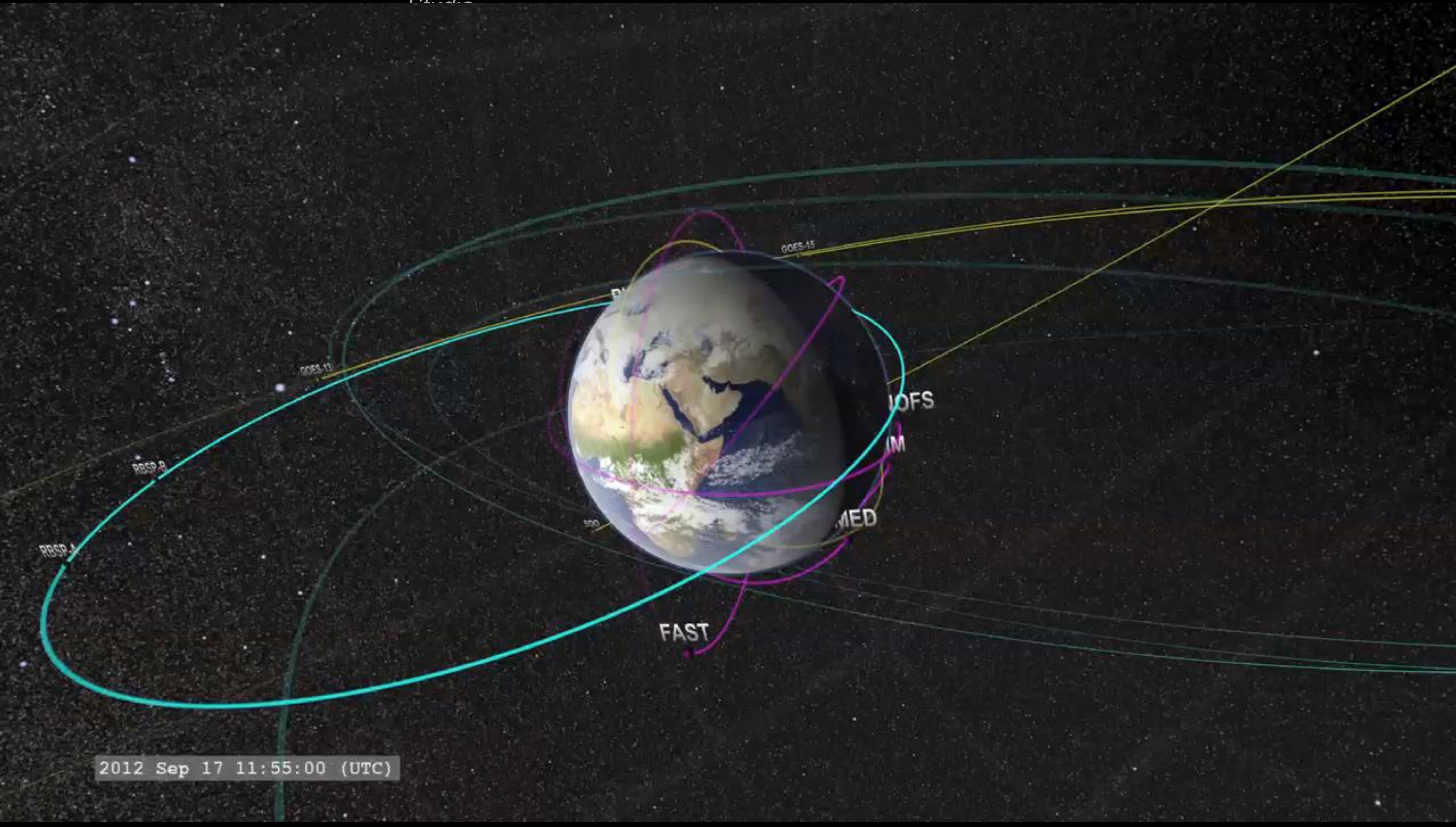
Magnetized wind



Particle radiation

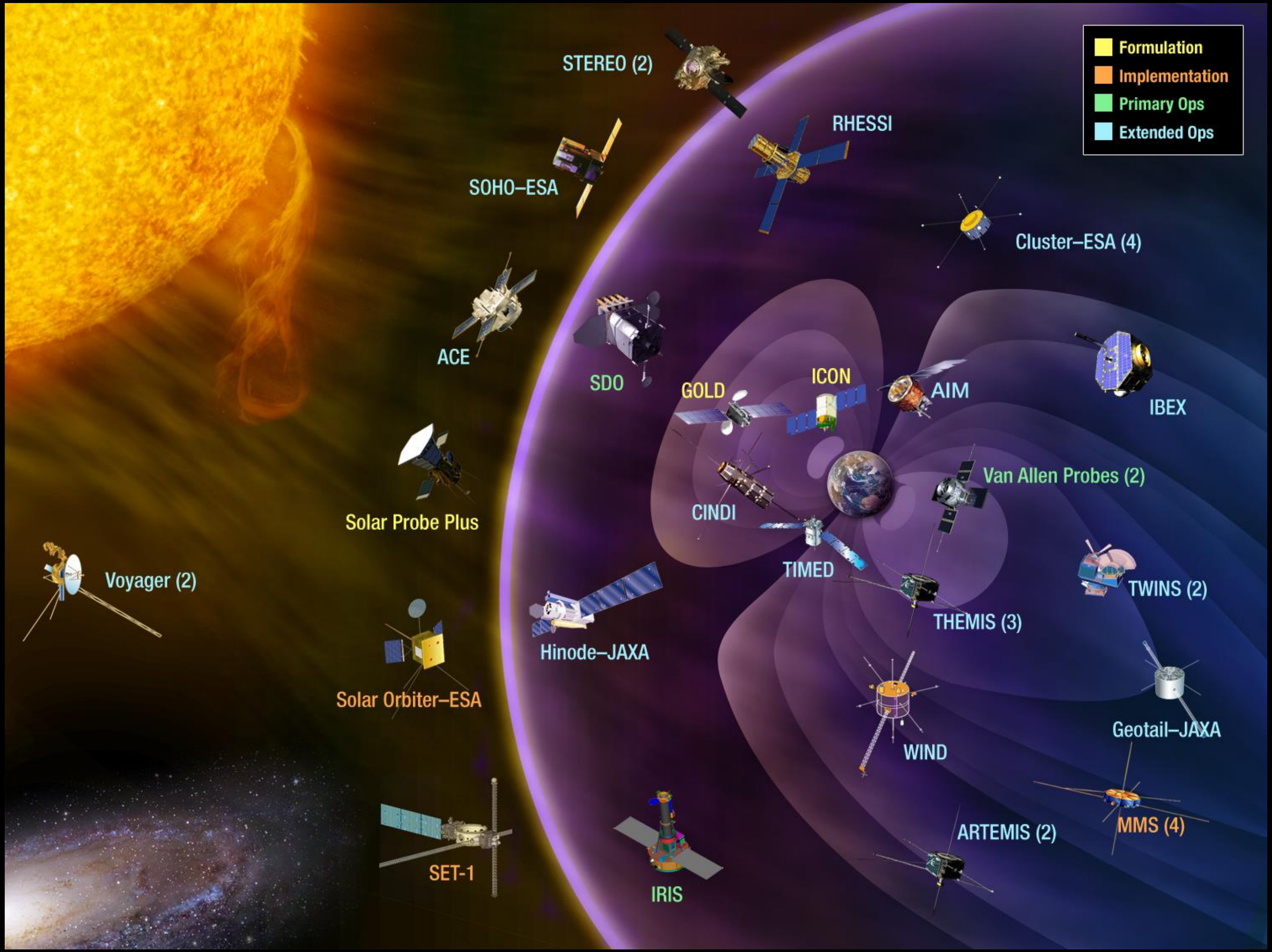
The Heliophysics System Observatory

NASA/Goddard Space Flight Center Scientific Visualization Studio



Heliophysics System Observatory

A coordinated and complementary fleet of spacecraft to understand the Sun and its interactions with Earth and the solar system

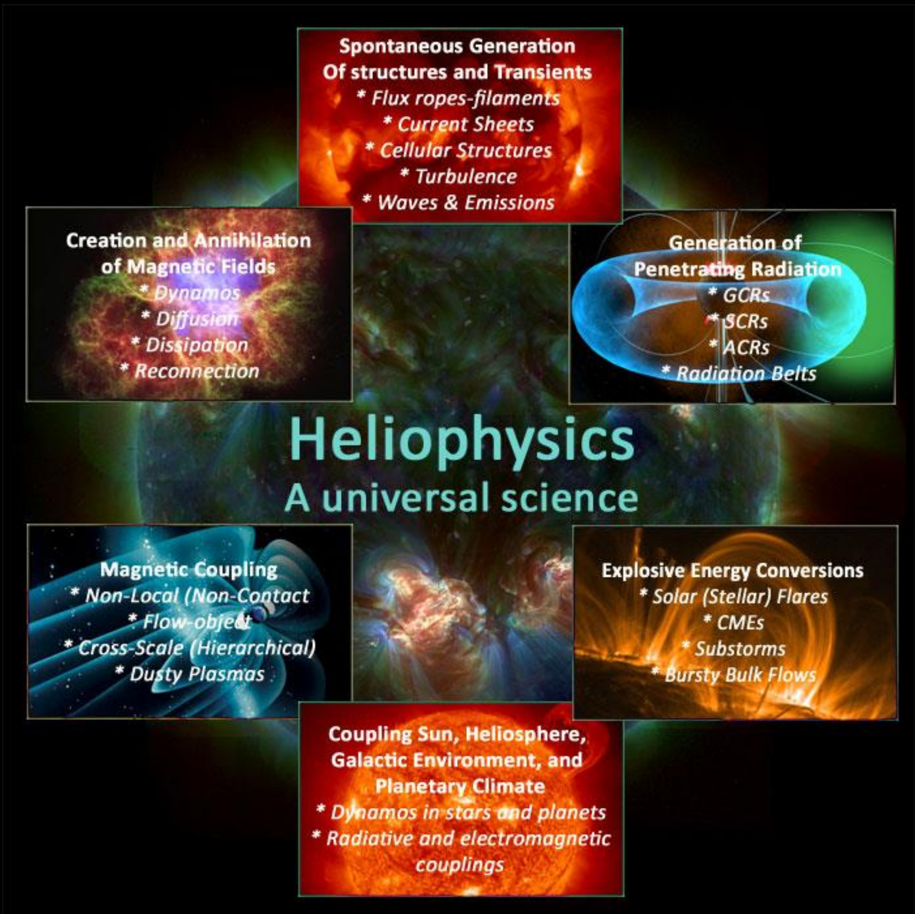


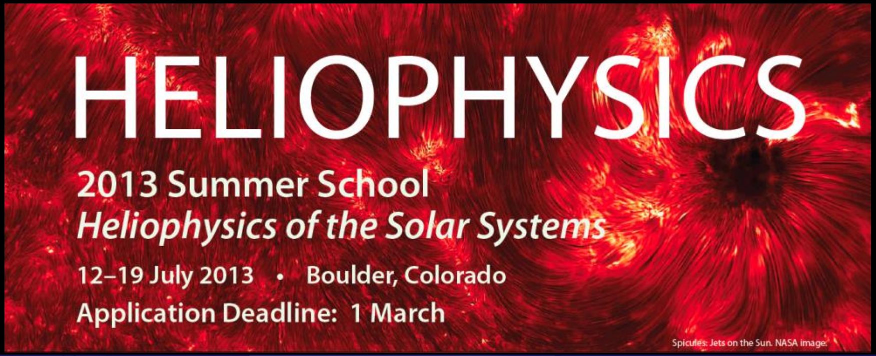
Heliophysics has 18 operating missions (on 29 spacecraft): Voyager, Geotail, Wind, SOHO ACE Cluster, TIMED, RHESSI, TWINS, Hinode, STEREO THEMIS/ARTEMIS, AIM, CINDI, IBEX, SDO Van Allen Probes IRIS

(Missions in red contribute to operational Space Weather.)

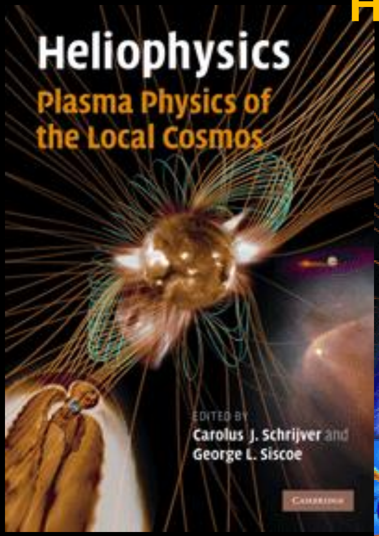
6 missions are in development: SET, MMS, SOC, SPP, ICON, and GOLD

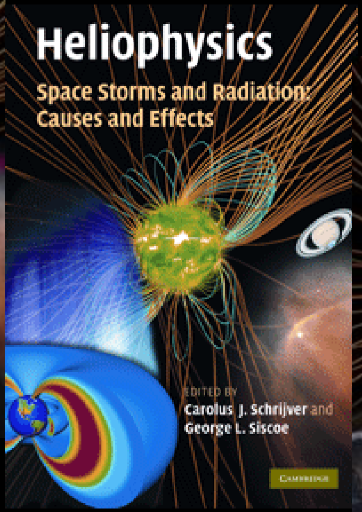
$5.5B total investment in Heliophysics space assets (excluding launch costs)
$68M annual operating budget (1.2% per year)

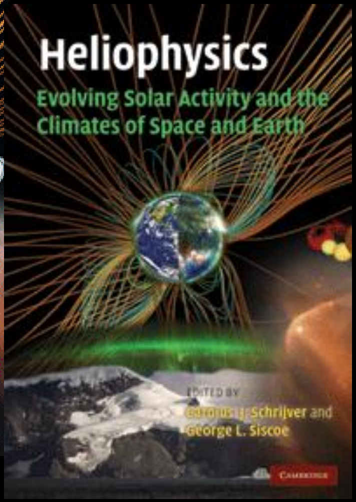




Heliophysics Text Books



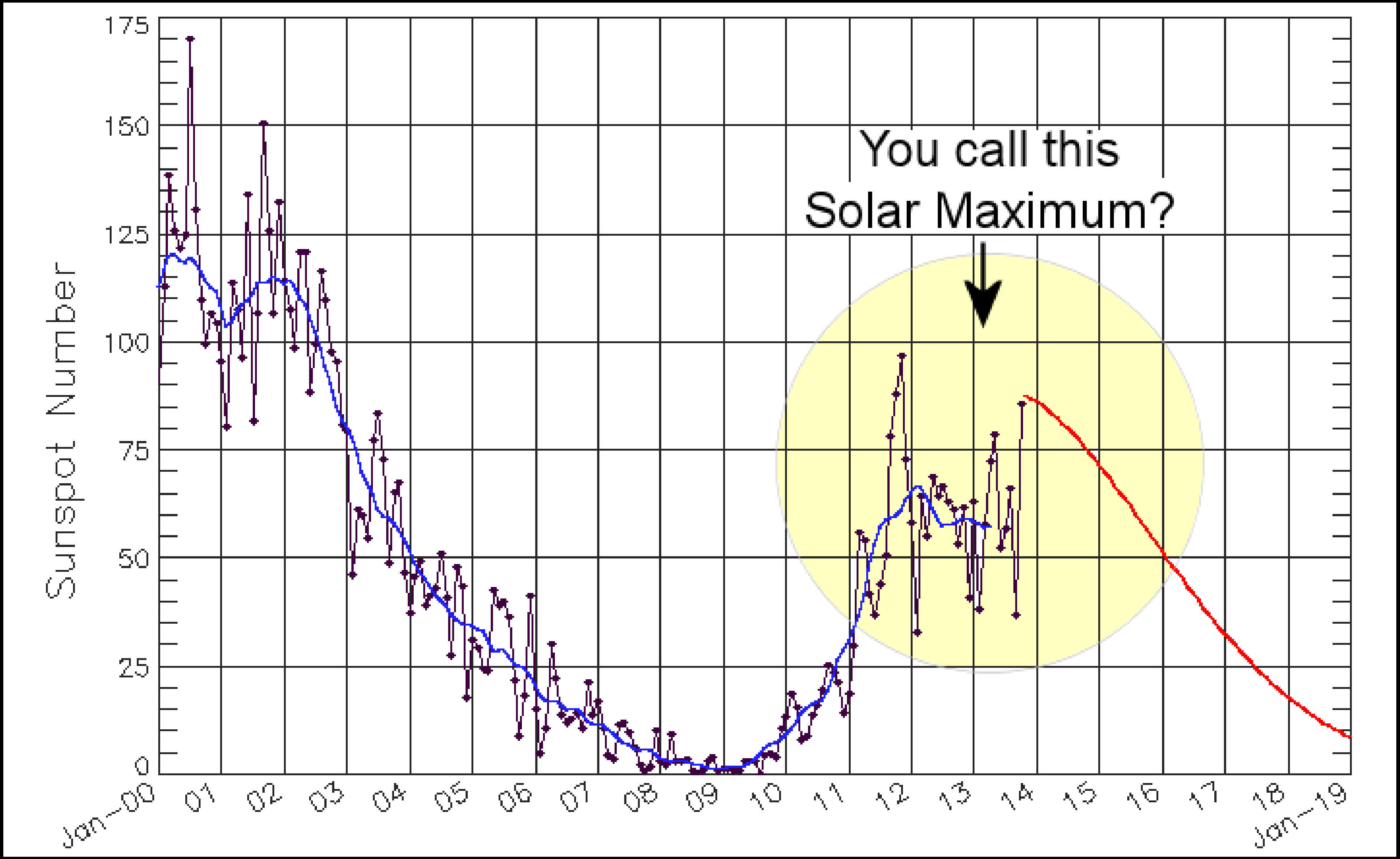




Approx. 250 national and international students (graduate & advanced graduate and post docs) have attended heliophysics summer school since 2007.

http://www.vsp.ucar.edu/Heliophysics/

Look out! Solar activity is so low that Solar Max looks a lot like Solar Min.



Courtesy of NOAA/SWPC Boulder CO

Space Weather Swings Between Extreme Effects

Solar La Niña
(low sunspot number)

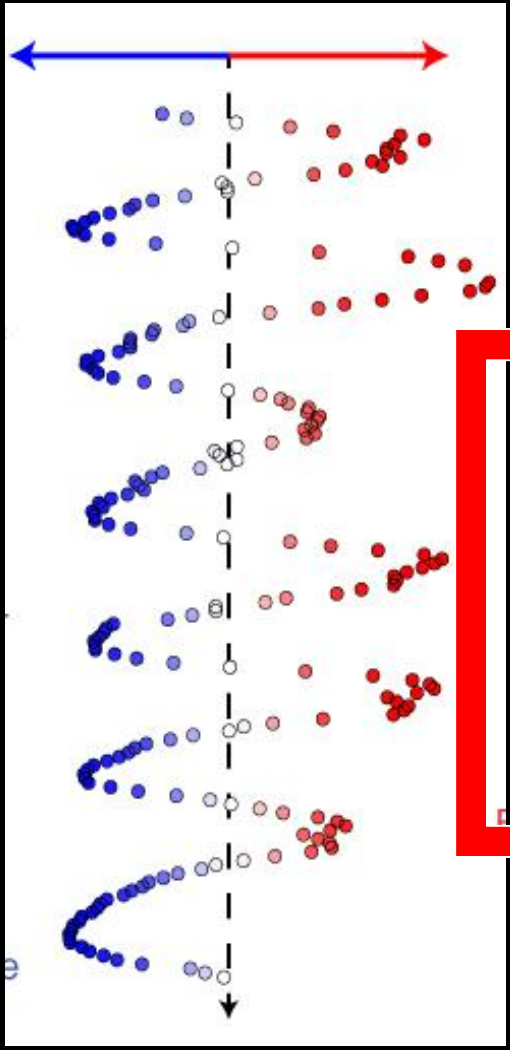
extreme galactic cosmic rays

rapid accumulation of space junk

sharp contraction of the heliosphere

collapse of the upper atmosphere

total solar irradiance changes



Solar El Niño
(high sunspot number)

super solar flares

extreme solar “cosmic rays” (energetic particles)

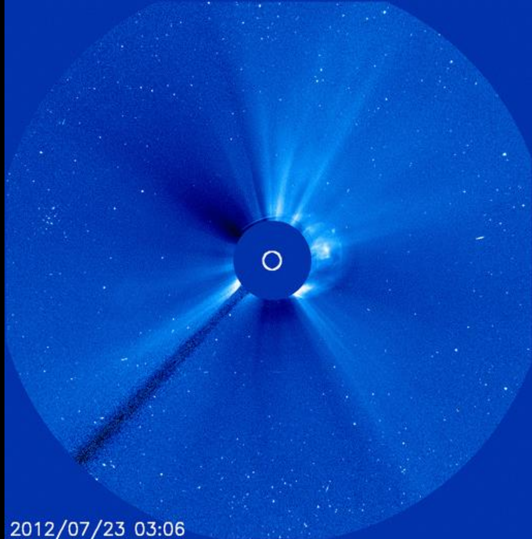
radio blackouts

extreme geomagnetic storms

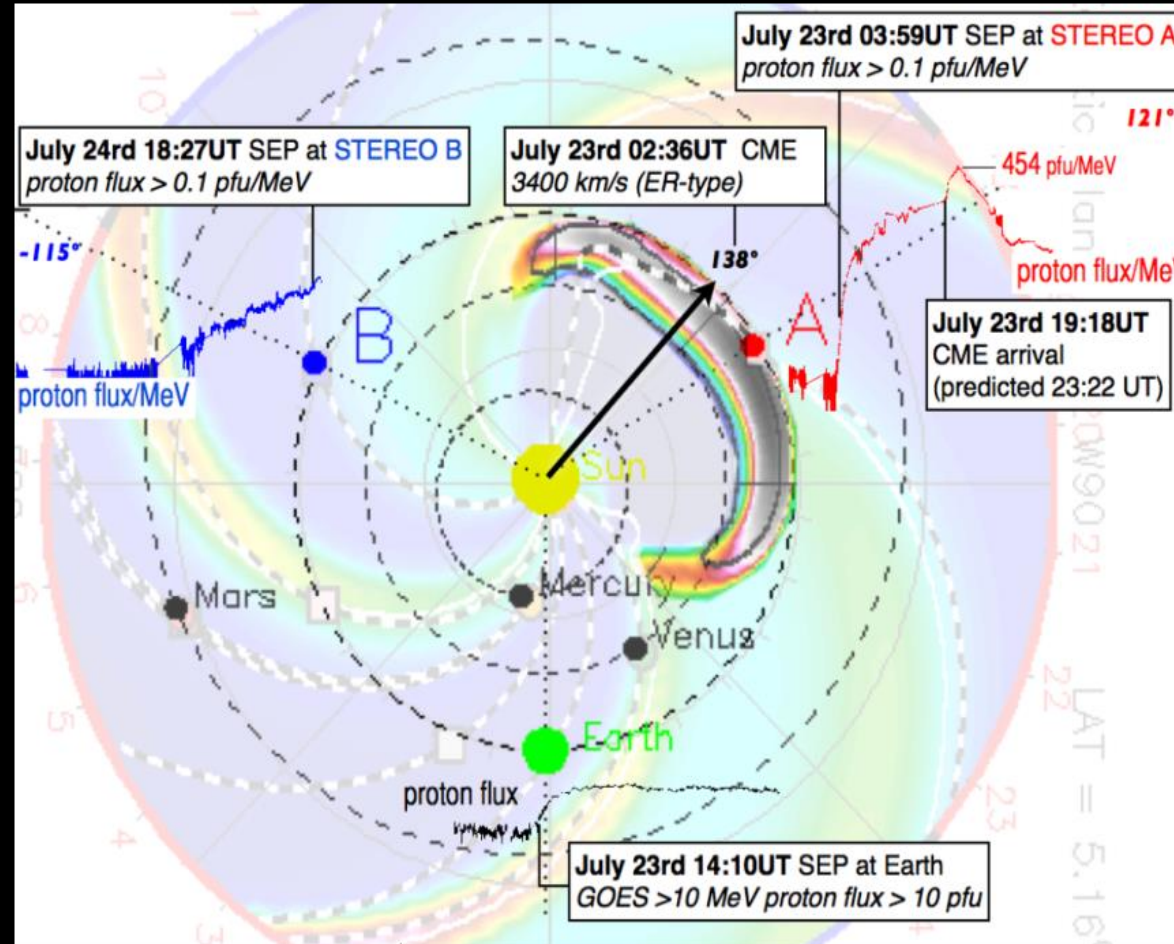
melted power grid transformers – power blackouts

solar wind streams hit Earth

Illustration shows smoothed monthly sunspot counts from the past six solar cycles plotted horizontally instead of vertically. High sunspot numbers are in red and on the right, low sunspot numbers are in blue and on the left. Associated with each high and low sunspot numbers are different space weather impacts experienced at Earth (doi: 10.1002/swe.20039).



July 23, 2012, one of the fastest CMEs of the Space Age rocketed away from the western limb of the sun travelling 3500 km/s.



Surrounding the sun has allowed us to detect major storms that otherwise we might have missed.

A Solar Superstorm Narrowly Missed Earth in July 2012

STEREO-A was in the line of fire, and the spacecraft was hit by a severe solar radiation storm. It was stronger than any proton event observed since 1976. Without STEREO-A, this major event would have passed unnoticed

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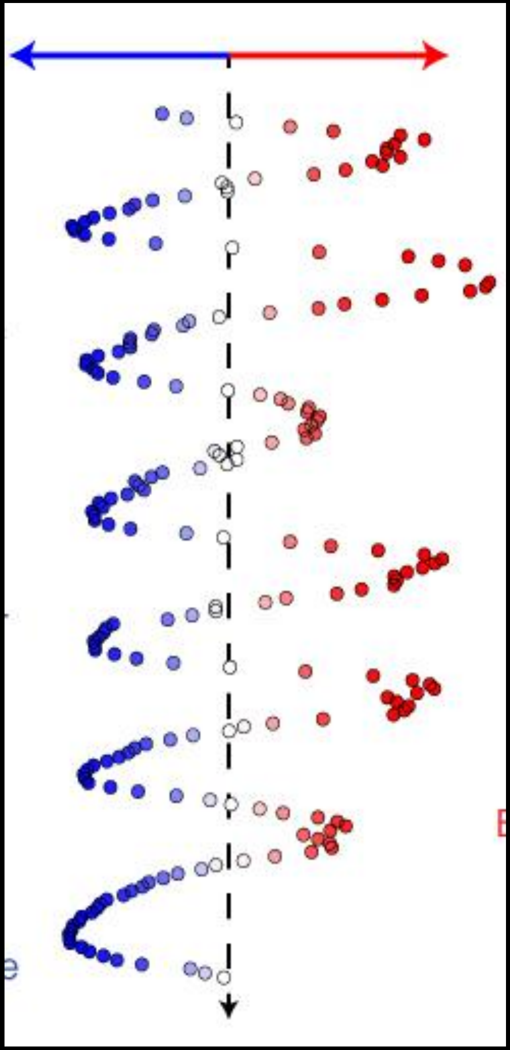

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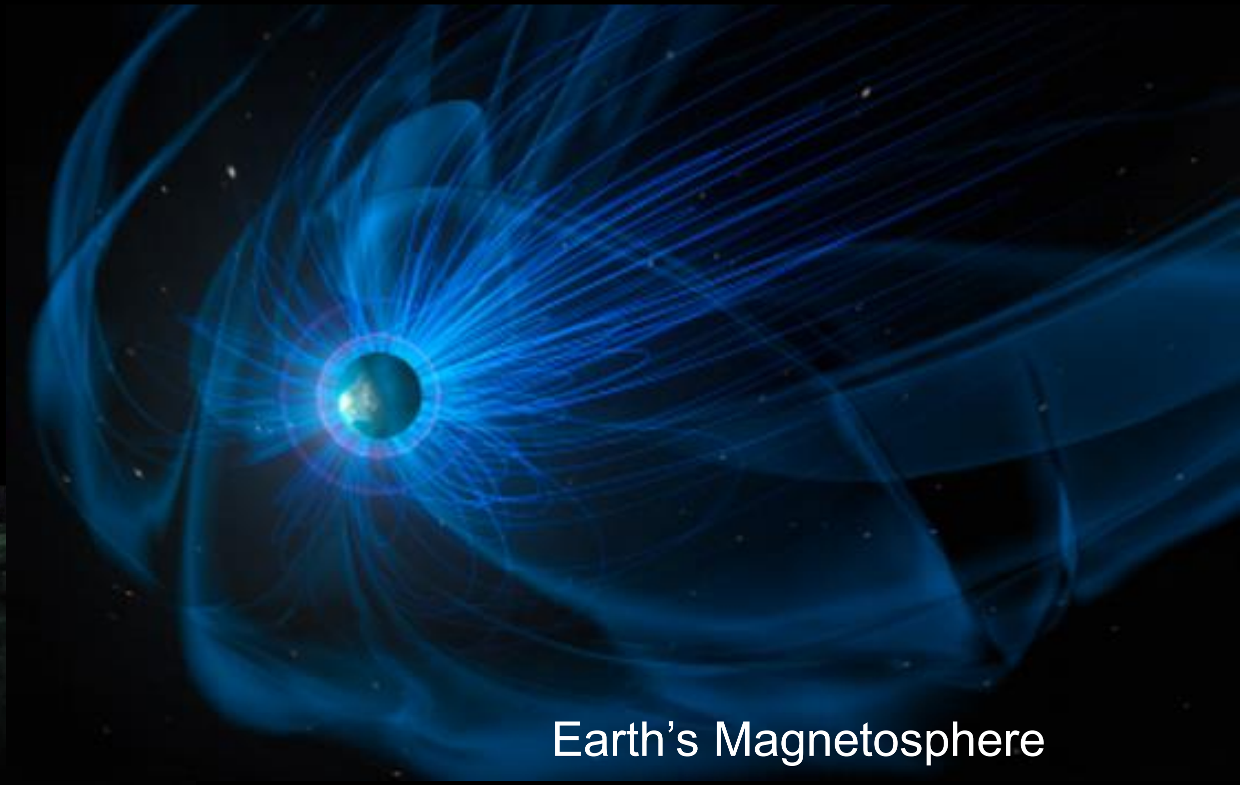
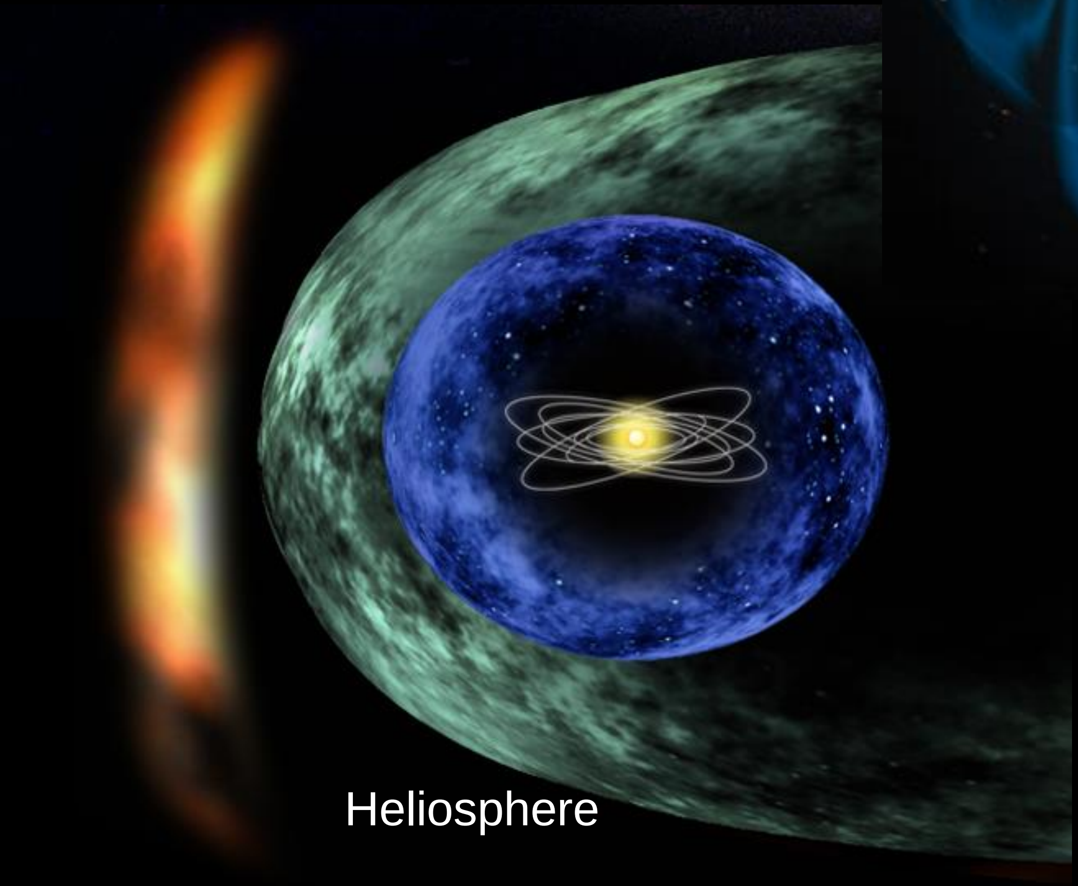
The Heliosphere

Just as Earth is protected from solar energetic particles by its magnetosphere…



Earth’s Magnetosphere

The solar system is protected from galactic cosmic rays by its heliosphere, the bubble surrounding the Earth and the planets that is created by the solar wind/magnetic field.

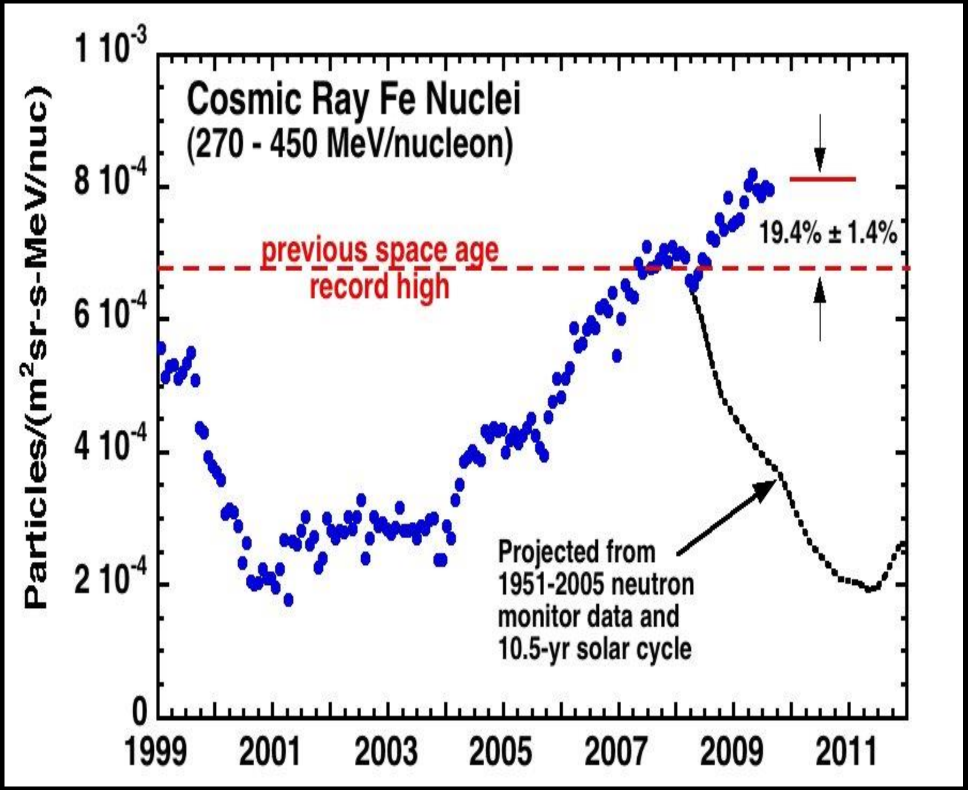


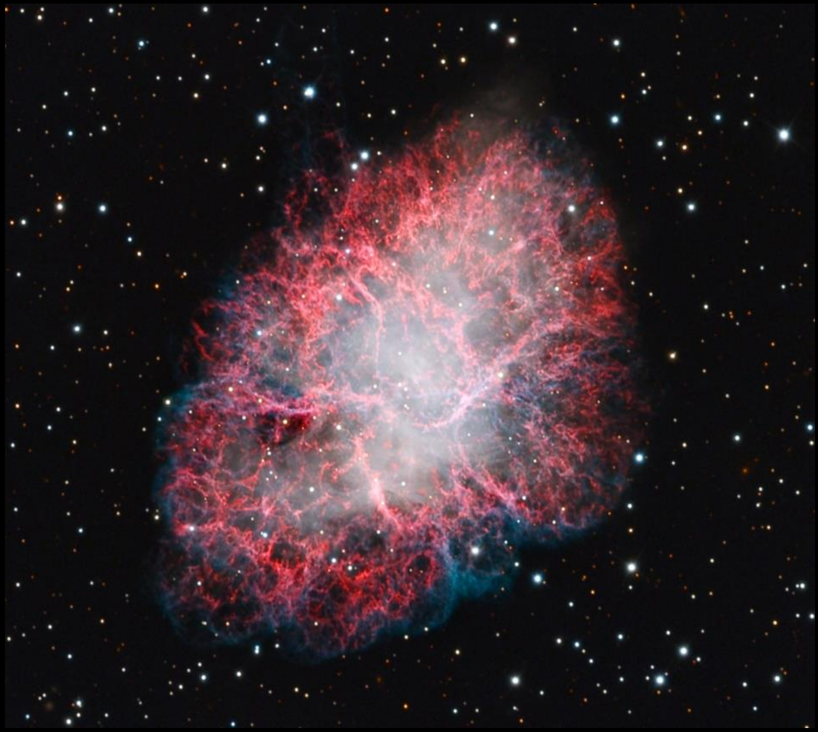
Heliosphere

Who's Afraid of a Solar Flare?

Cosmic rays are much scarier

When solar activity is low, cosmic rays are able to invade the inner solar system. During the 2008-2009 solar minimum, cosmic rays surged to record-high levels.





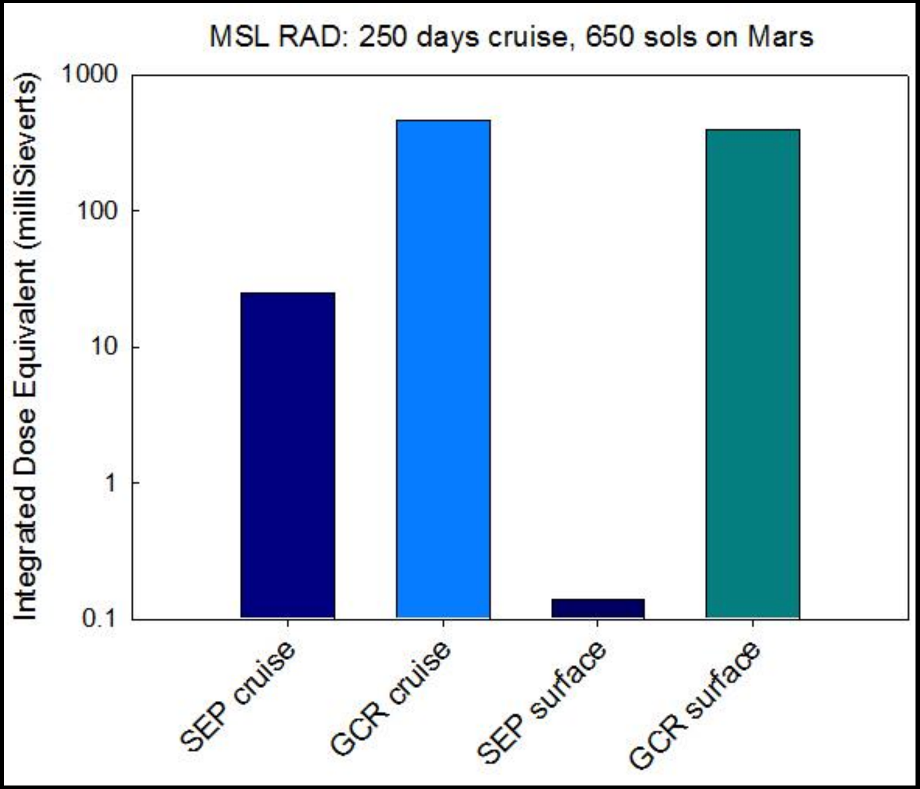
Cosmic rays from distant supernova explosions and black holes are far more energetic and penetrating than particles from relatively puny solar flares.

Radiation Exposure for Human Exploration

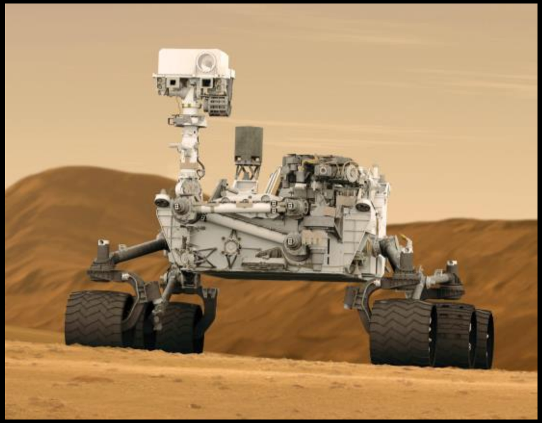
As demonstrated by MSL Radiation Assessment Detector measurements, the cancer risk to crewmembers in deep space is caused mostly by GCRs

During a trip to Mars, normal solar particle events would add approximately 10% additional exposure

Therefore, timing a mission near solar maximum reduces GCR health radiation risk and significantly increase the number of safe days for exploration crewmembers

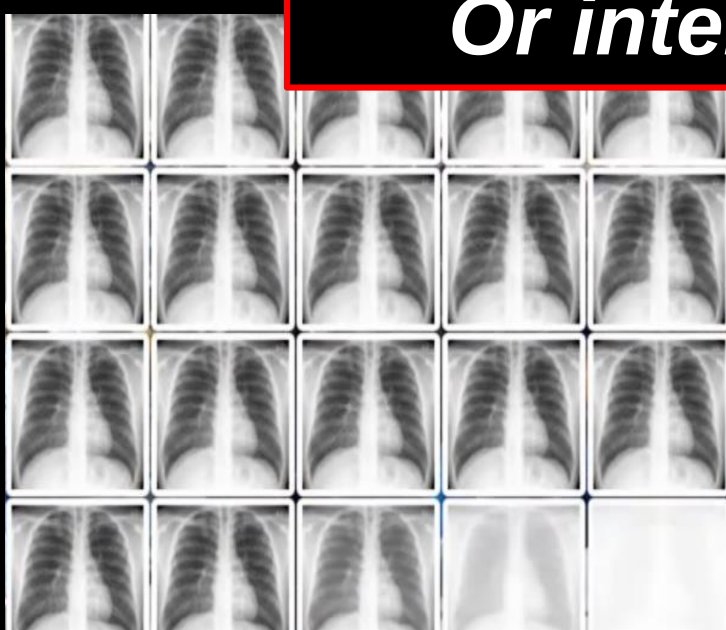


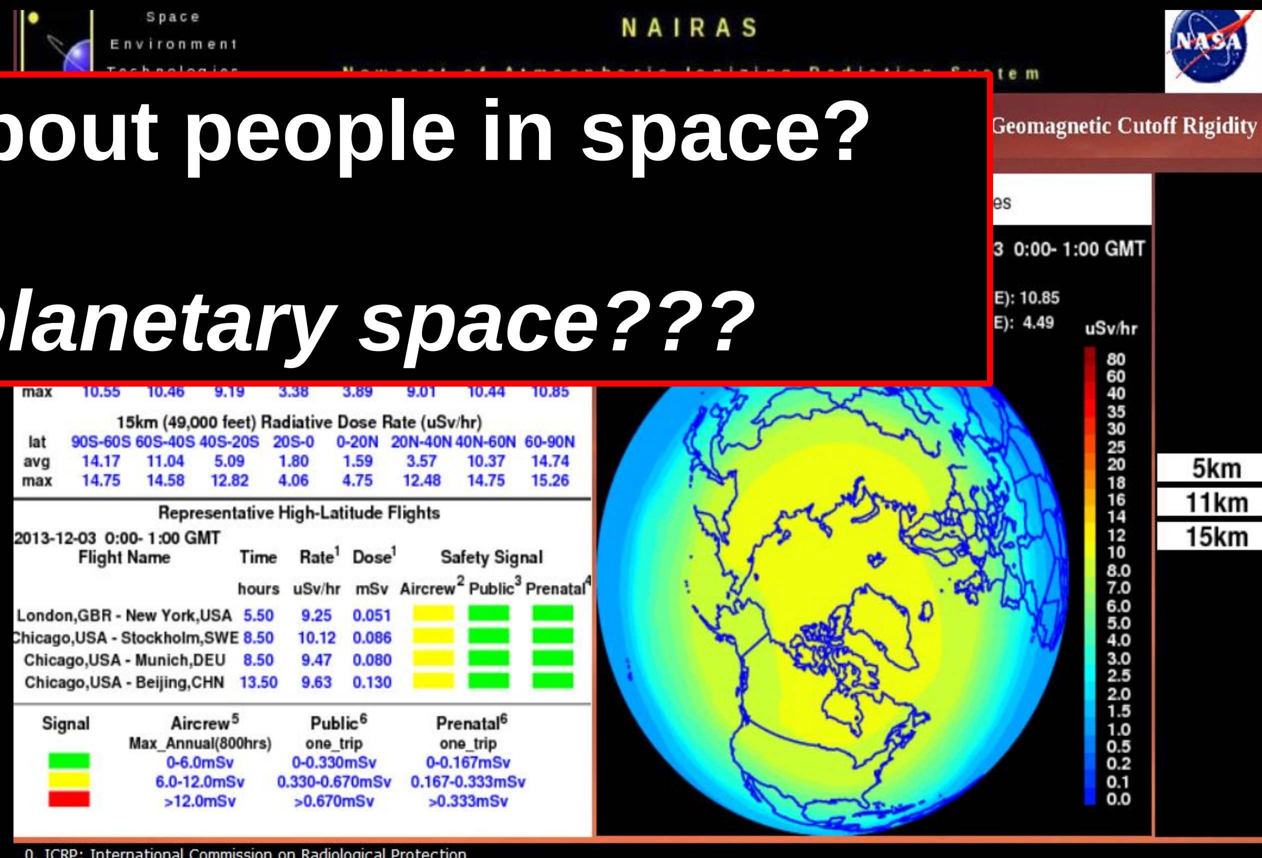
MSL Radiation Assessment Detector (RAD): RAD took measurements during its journey to Mars and continues on surface



During periods of low solar activity, cosmic rays pose a threat not only to astronauts, but also to ordinary air travelers.

A 100,000 mile frequent flyer receives a dose equivalent to 20 chest x-rays

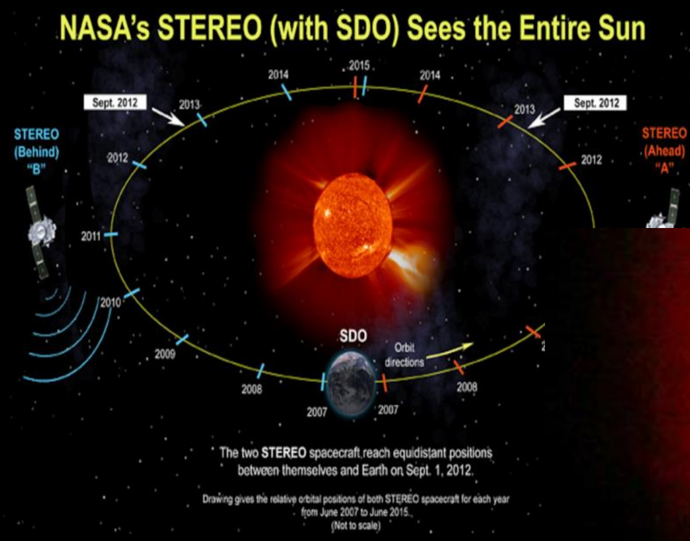




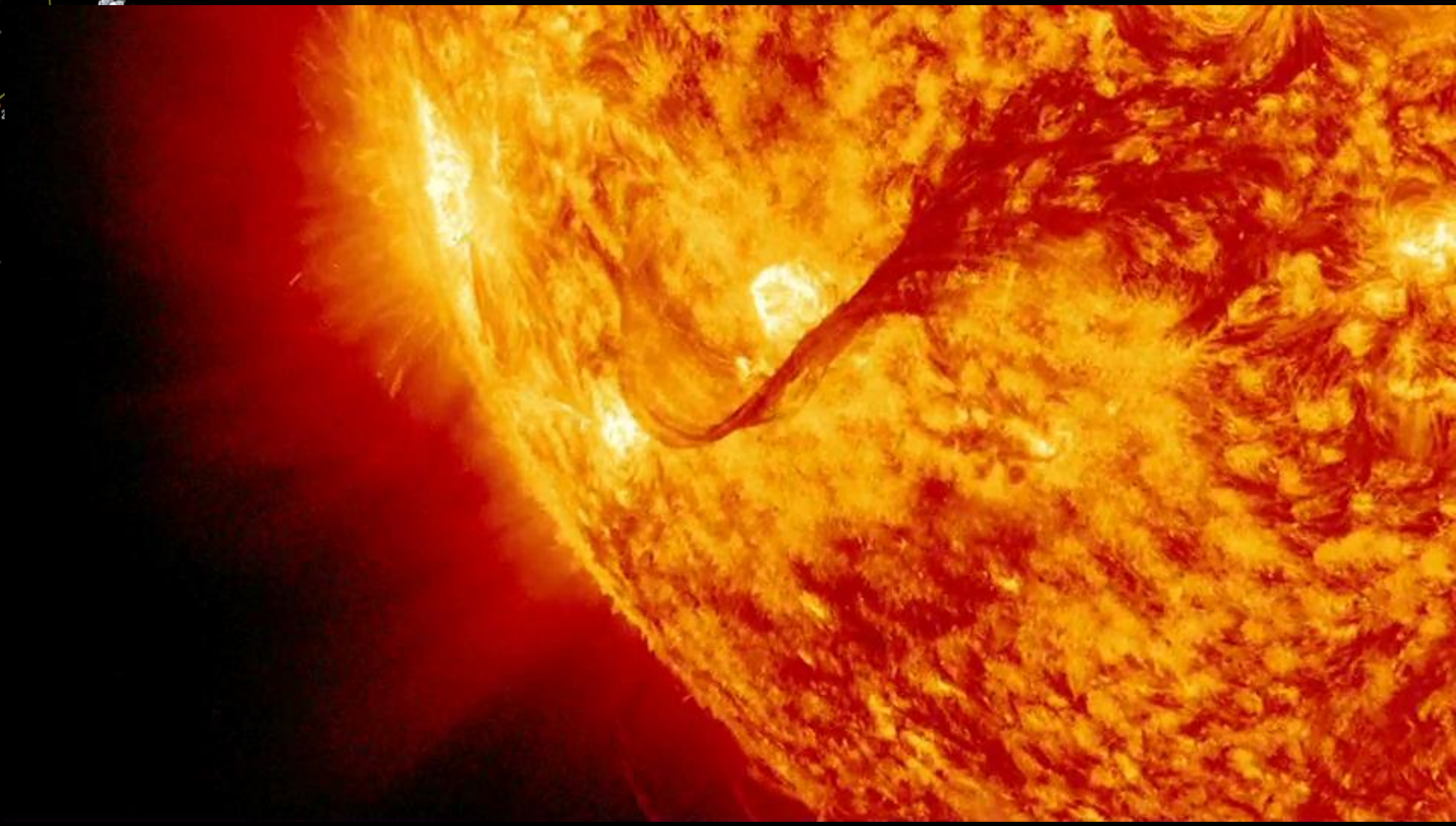
So what about people in space?

Or interplanetary space???

Birth of Interplanetary Space Weather(How new is it?) February 6, 2011



Thanks to SOHO, the twin STEREO probes and the Solar Dynamics Observatory, no significant eruption escapes detection, not even when it occurs on the far side of the sun

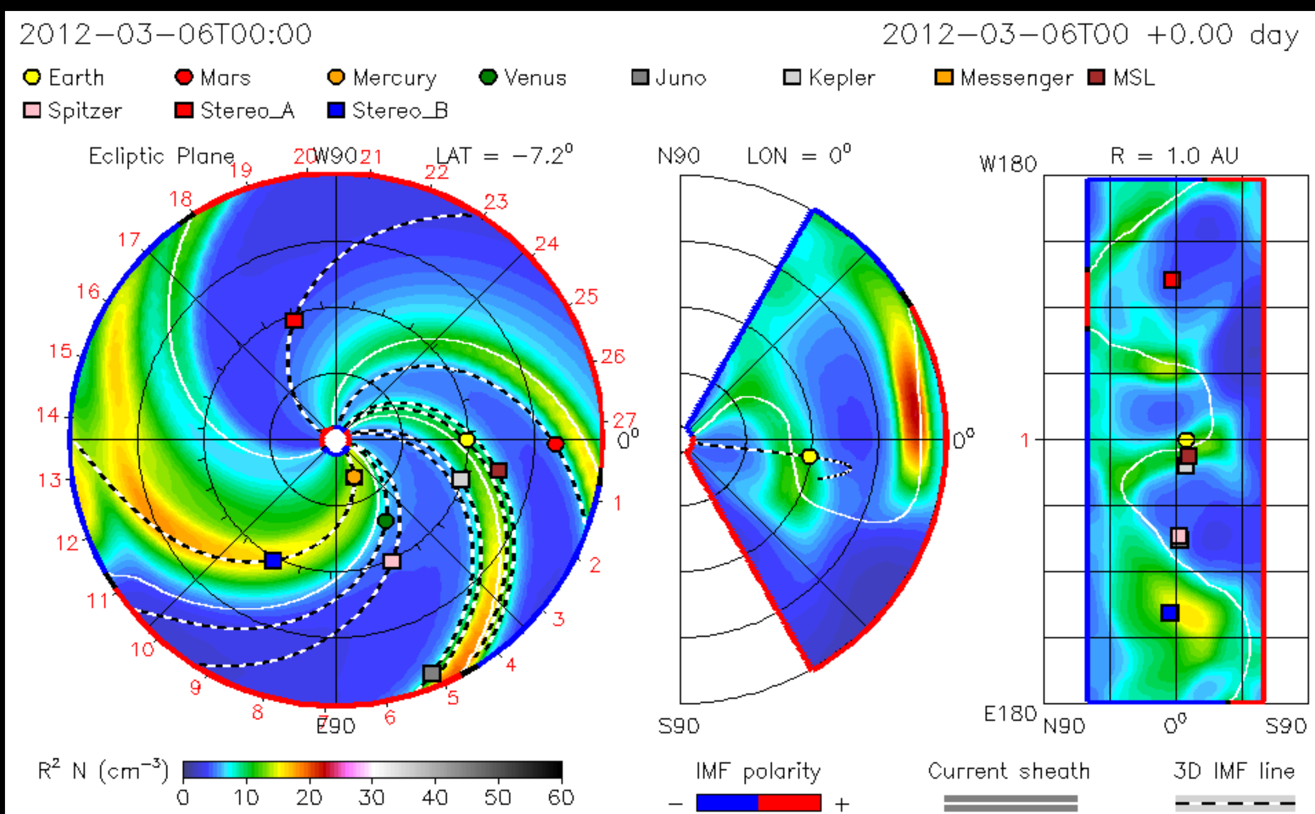


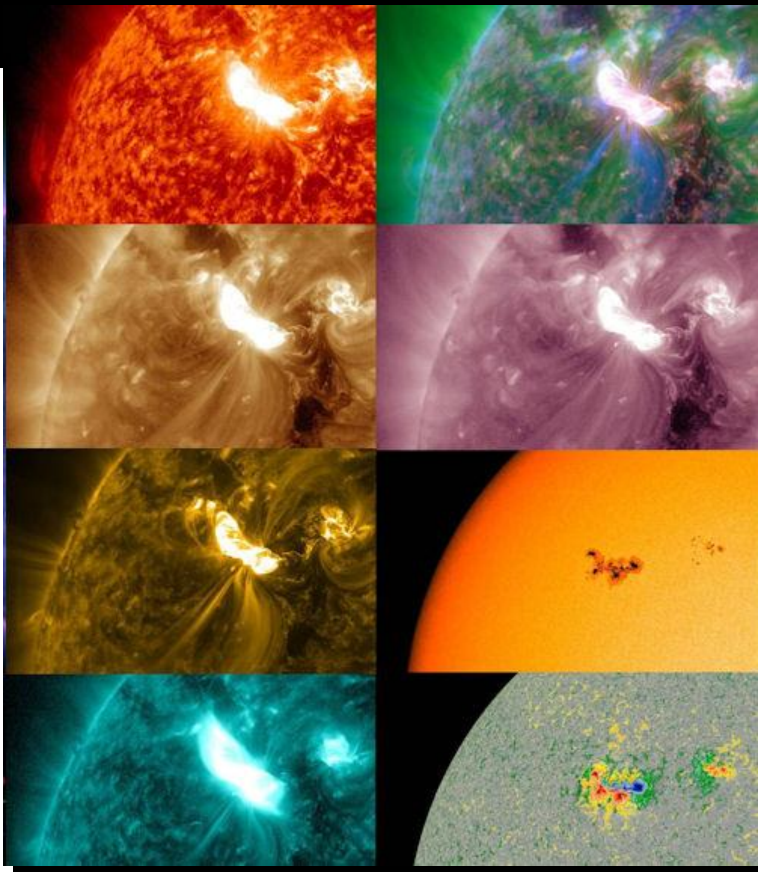
This is possible because **we've got the sun surrounded.**

Interplanetary Space Weather: A New Paradigm

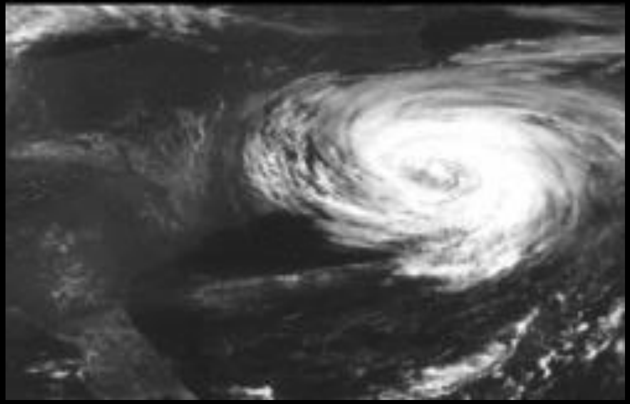
NASA and other space agencies have begun to expand their research into the solar system. **Probes are now orbiting or en route to Mercury, Venus, the Moon, Mars, Ceres, Saturn, and Pluto—and it is only a matter of time before astronauts are out there too**. Each mission has a unique need to know when a solar storm will pass through its corner of space.

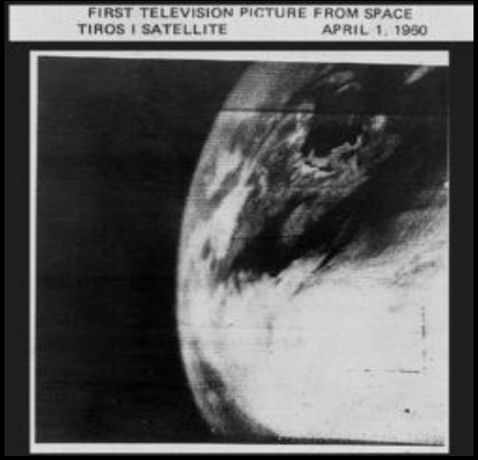
An intense episode of solar activity **in March 2012 drove this point home. It began on 2 March with the emergence of sunspot AR1429. For the next 2 weeks, this active region rotated across the solar disk and fired off more than 50 flares, 3 of which were X-class flares, the most powerful type of flare.** By the time the sunspot finally decayed in April 2012, it had done a 360-degree pirouette in heliographic longitude, hitting every spacecraft and planet in the solar system at least once with either a coronal mass ejection or a burst of radiation. **This extraordinary series of solar storms, referred to as the "St. Patrick's Day storms" caused reboots and data outages on as many as 15 NASA spacecraft.**

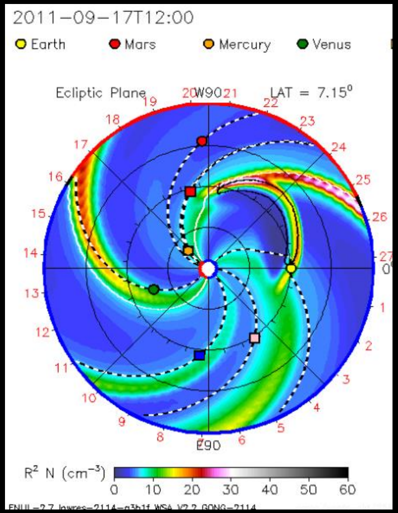




This development is akin to the first satellite images of hurricanes on Earth

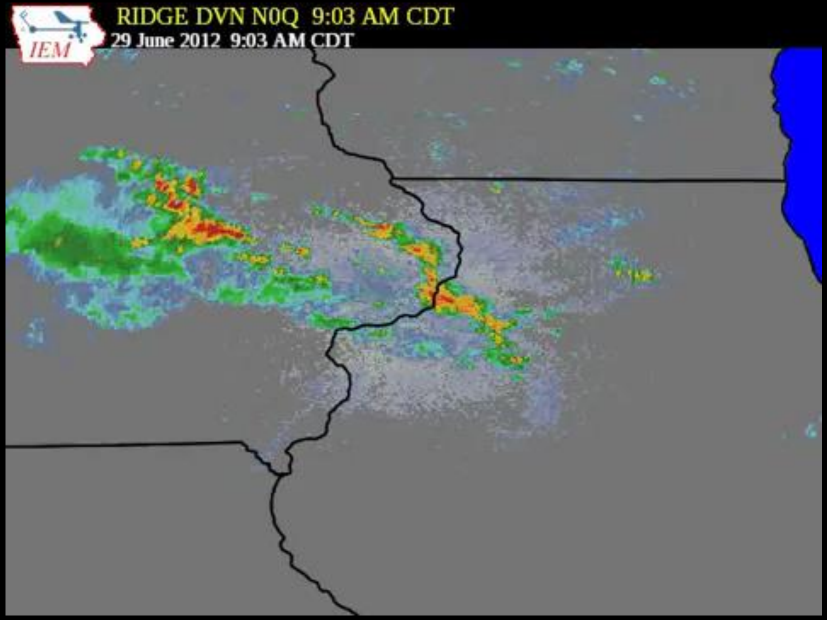




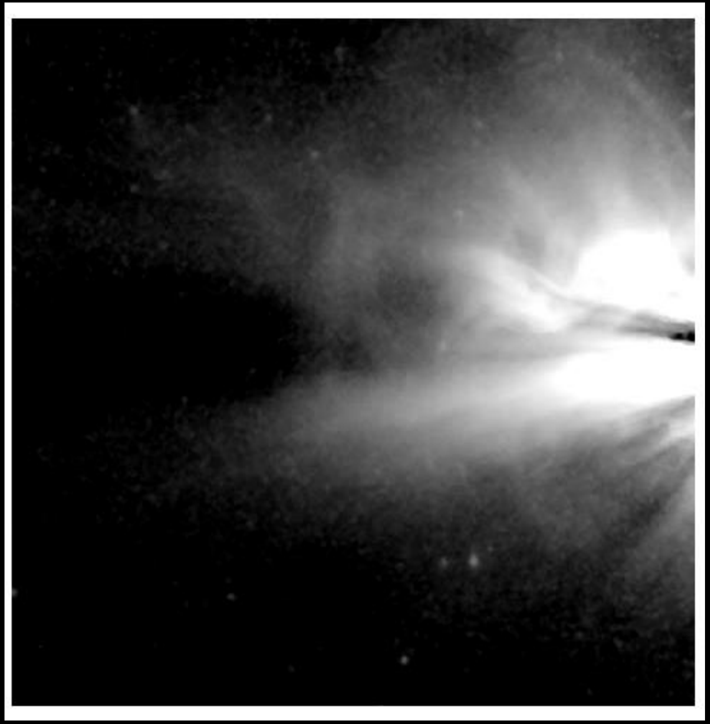


Tropospheric Weather: Storm Tracking is Essential for Mid-Term Forecasting

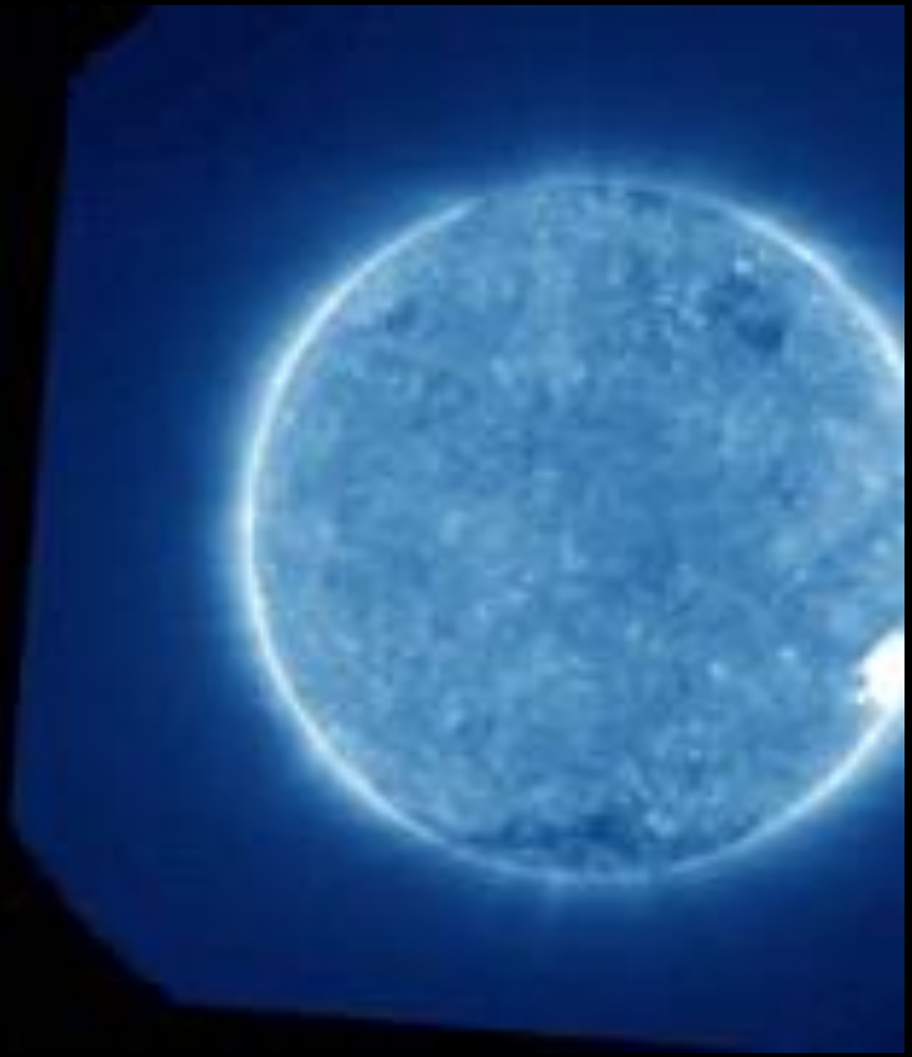
Space Weather Analogue:
Coronal Mass Ejection (CME) Tracking is Essential for Mid-Term Forecasting



Weather in the mid-west today is Washington's weather tomorrow.

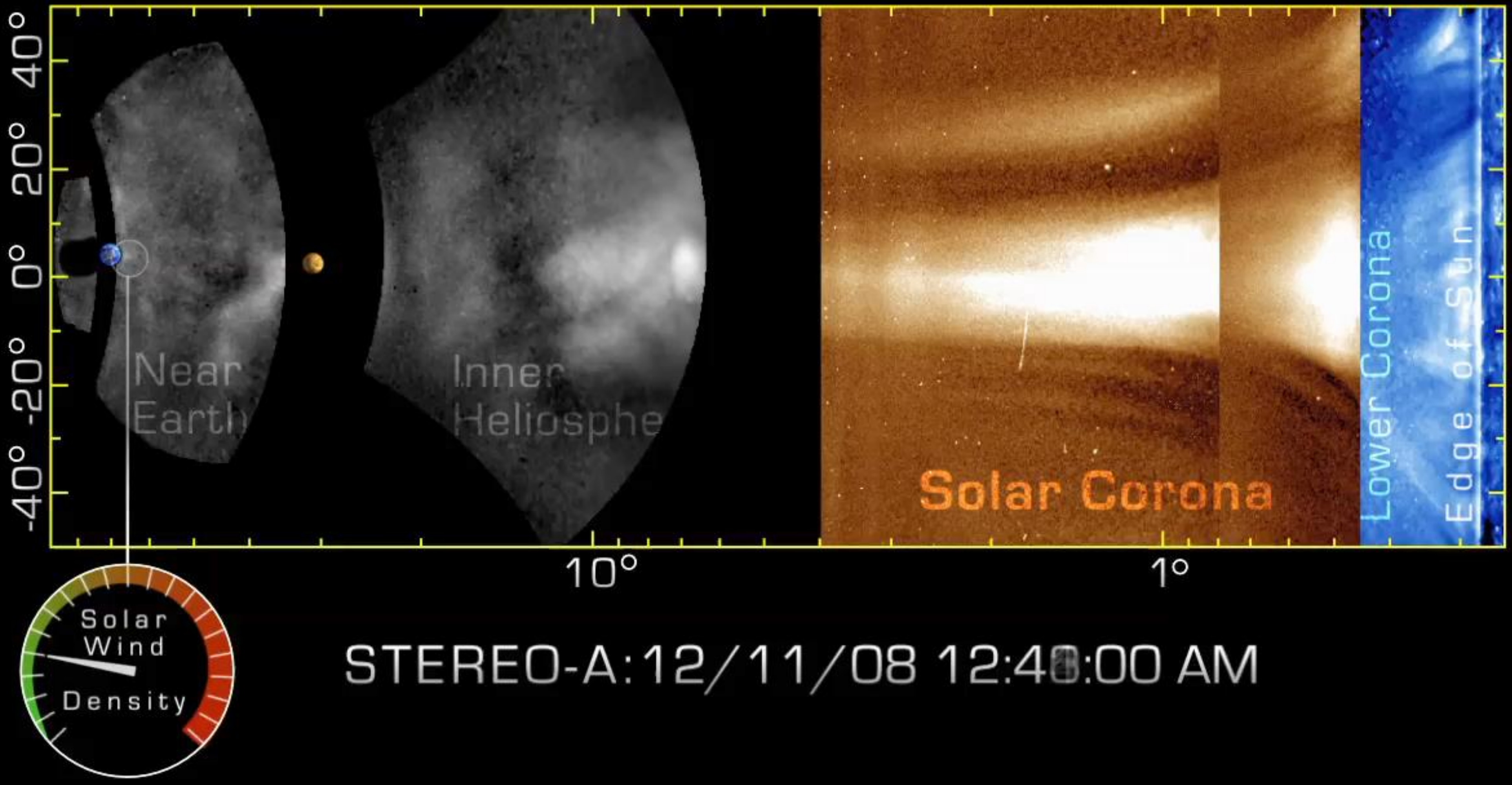


STEREO includes "heliospheric imager" cameras that monitor the sky at large angles from the Sun, but the starfield and galaxy are 1,000 times brighter than the faint rays of sunlight reflected by free-floating electron clouds inside CMEs and the solar wind; this has made direct imaging of these important structures difficult or impossible, and limited understanding of the connection between space storms and the coronal structures that cause them.



The next frontier in space weather forecasting involves the uninterrupted tracking of storm clouds from the sun to the planets.

NASA's STEREO spacecraft and new data processing techniques have succeeded in tracking space weather events from their origin in the Sun's ultrahot corona to impact with the Earth



Reasons for developing this predictive capability may be divided into three pressing areas:

Human safety is of paramount concern. At the moment, humans are confined to low-Earth orbit where the planetary magnetic field and the body of Earth itself provide substantial protection against solar storms. Eventually, though, astronauts will travel to the Moon, Mars and beyond where natural shielding is considerably less.

Spacecraft operations are also key. Energetic particles accelerated by solar storms can cause onboard computers to reboot, introduce confusing noise in cameras and other digital sensors, or simply accumulate on the surface of a spacecraft until a discharge causes serious problems.

Scientific research could be the greatest beneficiary of interplanetary space weather forecasting. What happens to asteroids, comets, planetary rings and planets themselves when they are hit by solar storms? Finding out often requires looking at precisely the right moment.

Sun Climate Connection

As the scope of space weather forecasting expands to other planets, it is also expanding in directions traditionally connected to climate research. Climate refers to changes in planetary atmospheres and surfaces that unfold much more slowly than individual storms. There is no question that solar activity is pertinent to climate time scales.

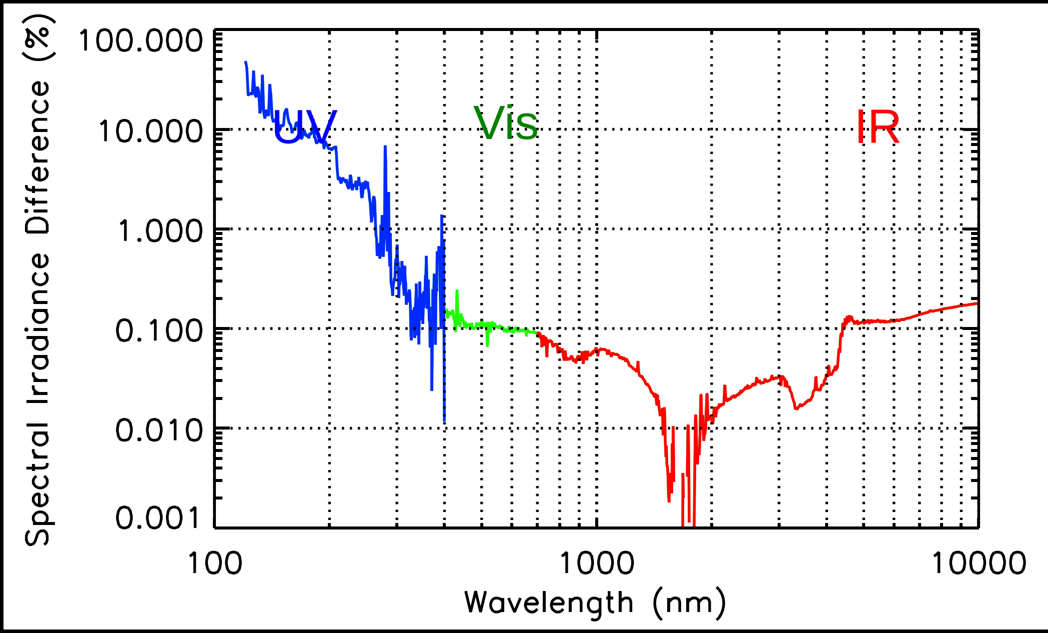
The radiative output of the Sun, the size and polarity of the Sun's magnetic field, the number of sunspots, and the shielding power of the Sun's magnetosphere against cosmic rays all change over decades, centuries, and millennia.

- The new paradigm of interplanetary space weather sets the stage for it to be cutting-edge research on other planets, too.

- How do magnetic storms affect the density of the Martian atmosphere?
- How do cosmic rays and solar energetic particles influence cloud cover on Titan?
-How do long-term changes in total solar irradiance alter surface temperatures of any rocky planet?

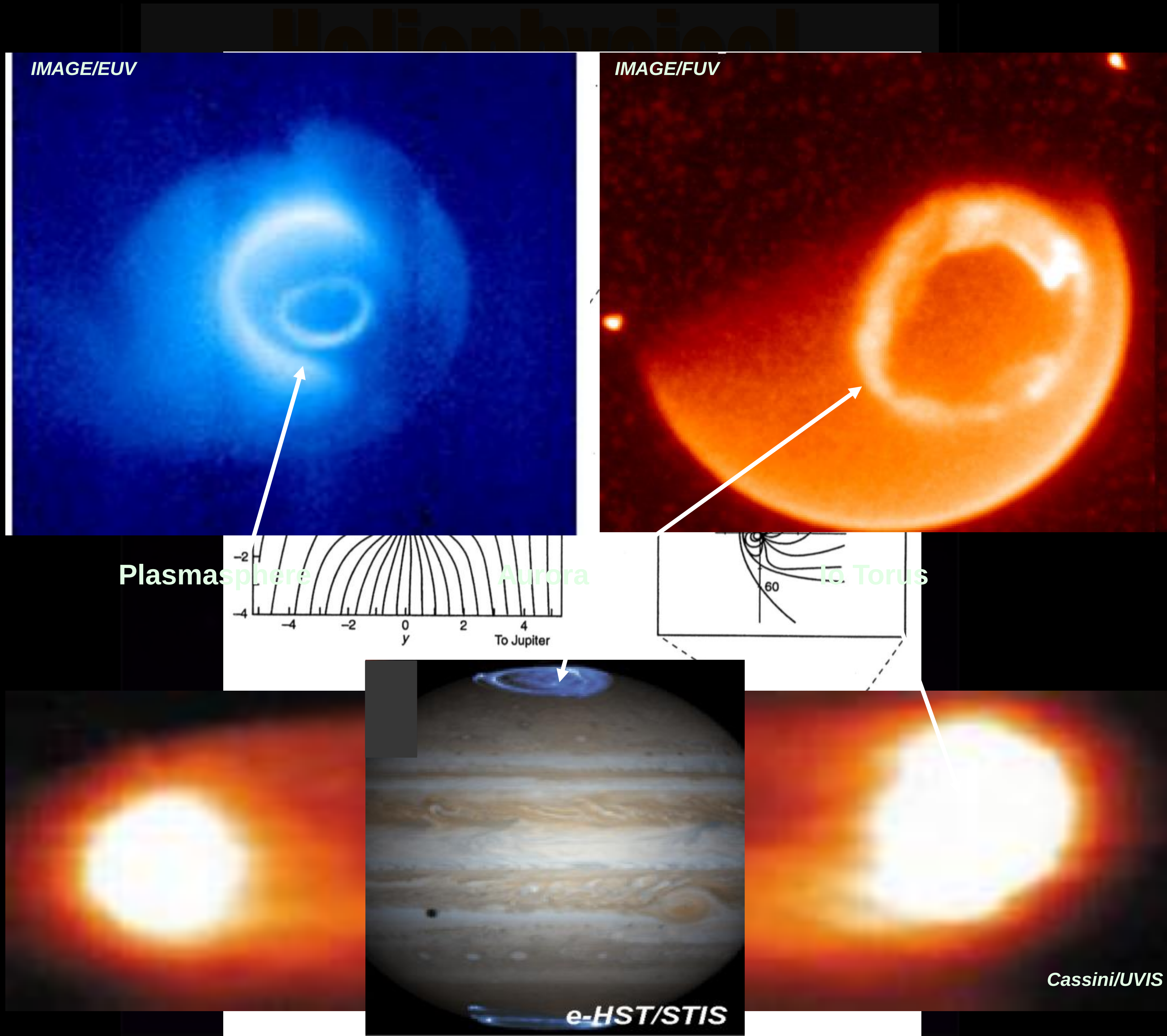
- These are questions that can be answered as we learn more about space weather conditions throughout the solar system. Moreover, comparative planetologists would tell us that we *must* answer these questions to get to the bottom of what's happening on Earth.

Spectral Solar Irradiance (SSI): SMax vs. SMin

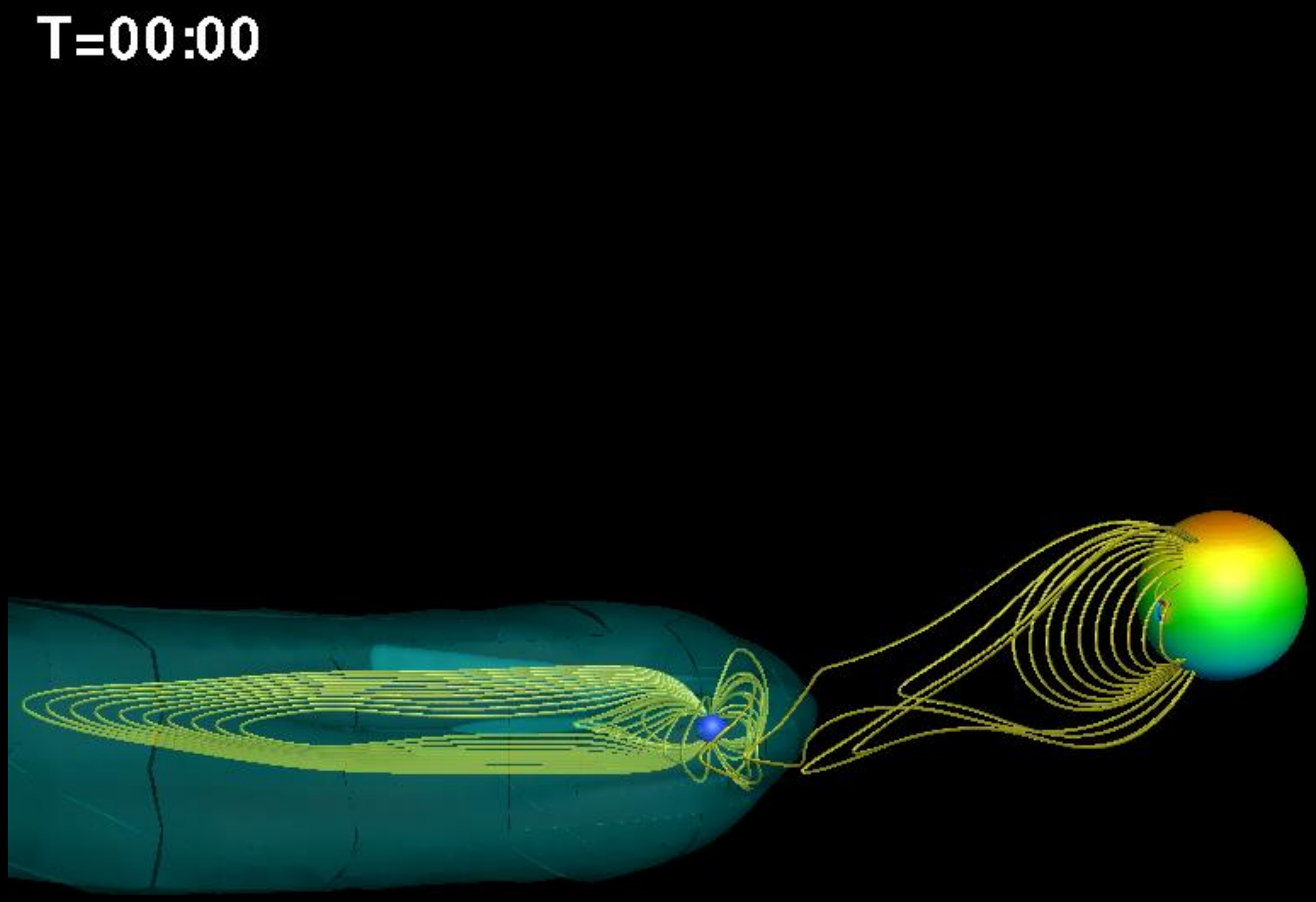


Small variations in the visible (0.1%), but big changes in the UV.

Comparative Magnetosphere/Ionospheres

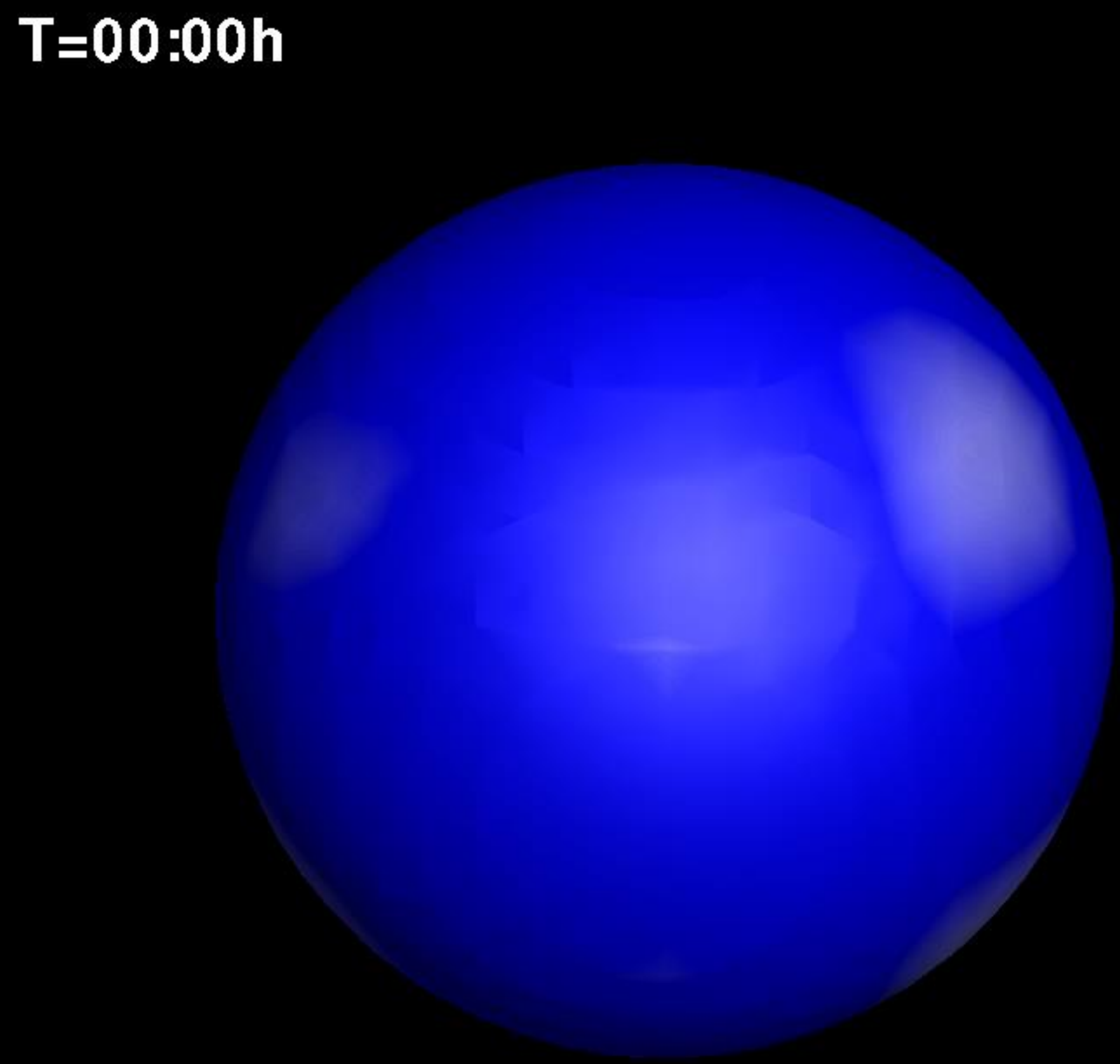


Extreme Space Weather on Close-in Exoplanets



Courtesy of Ofer Cohen (Smithsonian Astrophysical Observatory) & collaborators

“Exomagnetic” impact: Everywhere, not just the poles!



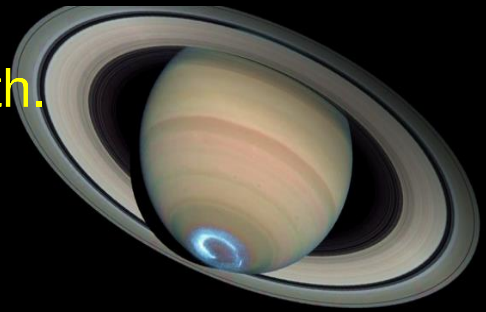
Courtesy of Ofer Cohen (Smithsonian Astrophysical Observatory) & collaborators

Solar Probe Plus: Humanity's First Mission to a Star

Ultimatey Solar Orbiter and Solar Probe Plus together with other missions will offer a truly unique epoch in heliospheric science. While each mission will achieve its own important science objectives, taken together these spacecraft will be capable of doing the multi-point measurements required to addres problems of CME initiation and propagation, including the large-scale topology and propagation dynamics. In particular, it may be possible to achieve many of the science objectives of previously envisioned multi-spacecraft heliospheric missions, such as NASA's 'Sentinels' concept.

"Space weather" refers to magnetic disturbances and high radiation levels that result from solar activity.

Auroras, power outages and radio blackouts are some of the manifestations we experience on Earth.



HUMANS & THEIR ROBOTS ARE MOVING INTO THE SOLAR SYSTEM. THE REALM OF SPACE WEATHER FORECASTING IS RAPIDLY EXPANDING.