National Aeronautics and Space Administration

Living With a Star: Science that Matters to People

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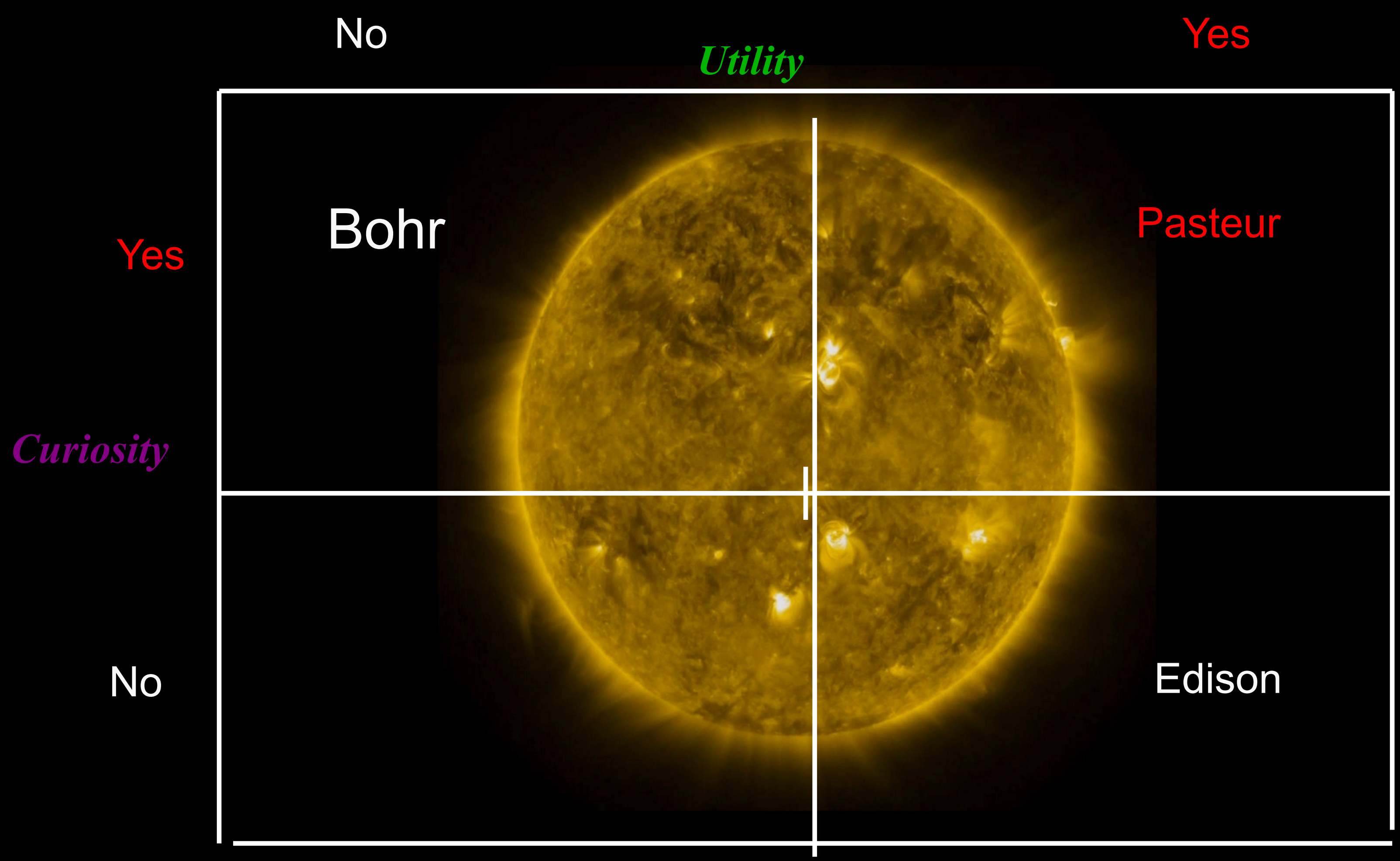
LWS Lead Program Scientist, Heliophysics
NASA Headquarters (On detail at NASA Ames)

Advanced Modeling & Simulation (AMS) Seminar Series
October 29th, 2015

Why Do Science?



Understanding the Sun and its interactions with the Earth and the Solar System.

Solve fundamental mysteries of Heliophysics
Understand the nature of our home in space
Build the knowledge to forecast space weather throughout the heliosphere

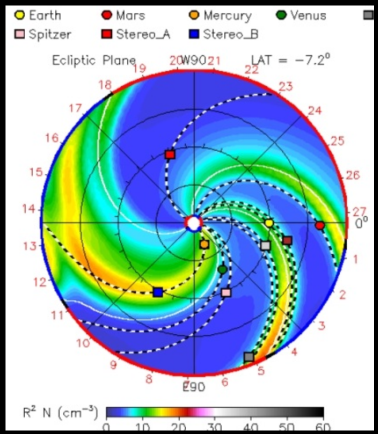
What is Heliophysics

Heliophysics is an environmental science:

a unique hybrid between meteorology and astrophysics

It has an applied branch

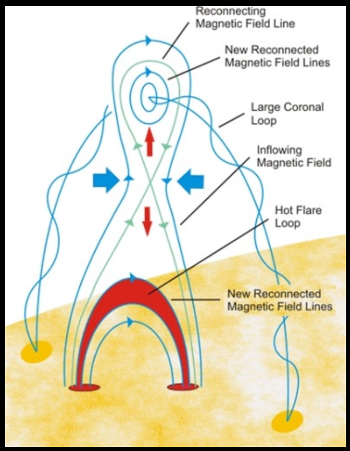
space weather



Propagation models of solar disturbances out to 2 AU

And a pure branch

fundamental physical process



Magnetic reconnection

In the US National Space Weather Program 1995

Living With a Star 2000, ILWS 2003

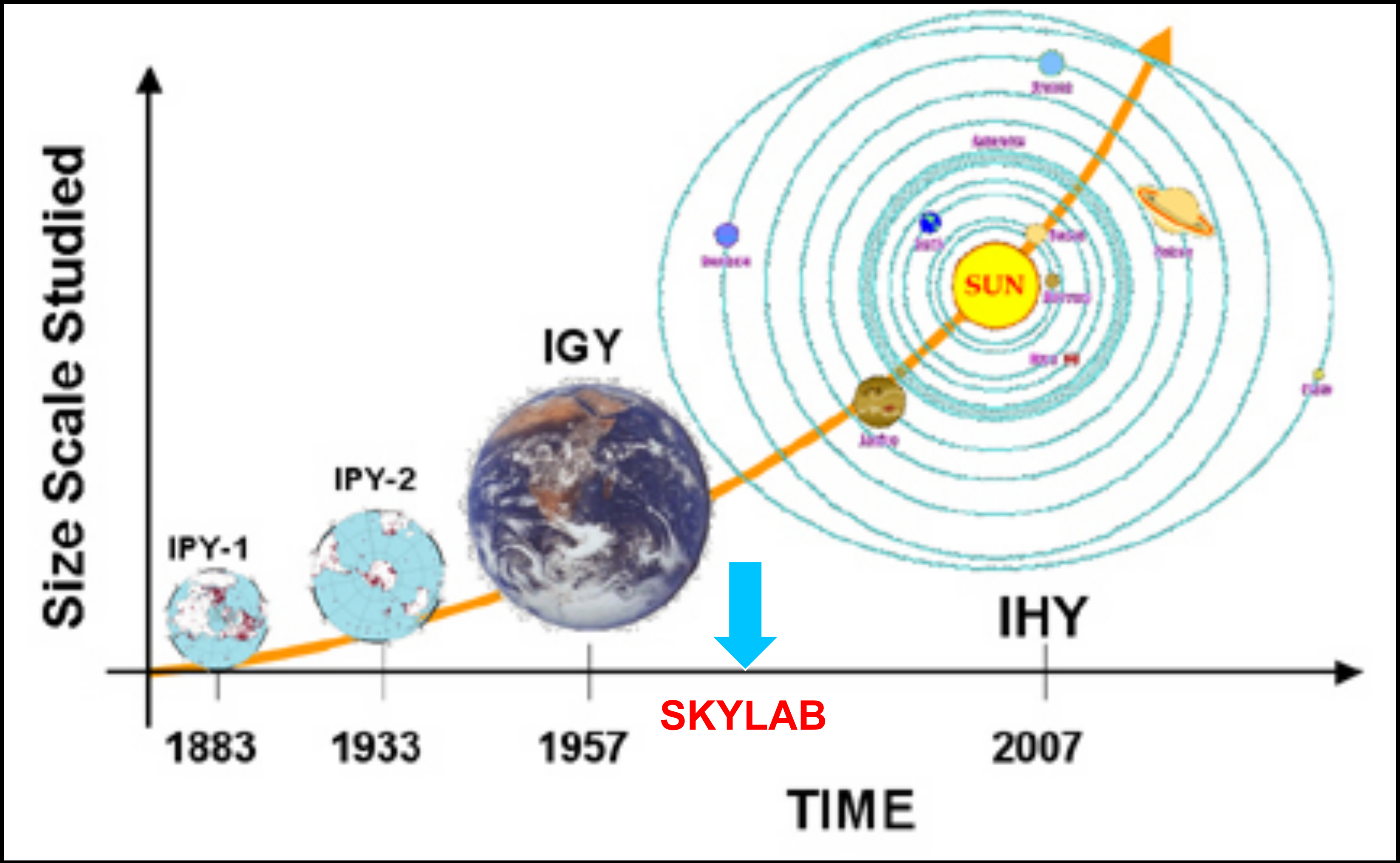
International Heliosphysical Year 2007

Applications directed science coordinated by NASA community

Add comparative heliospheric studies

Applications directed science coordinated by NASA & international community

Evolution of System Studies



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

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 and the world.

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

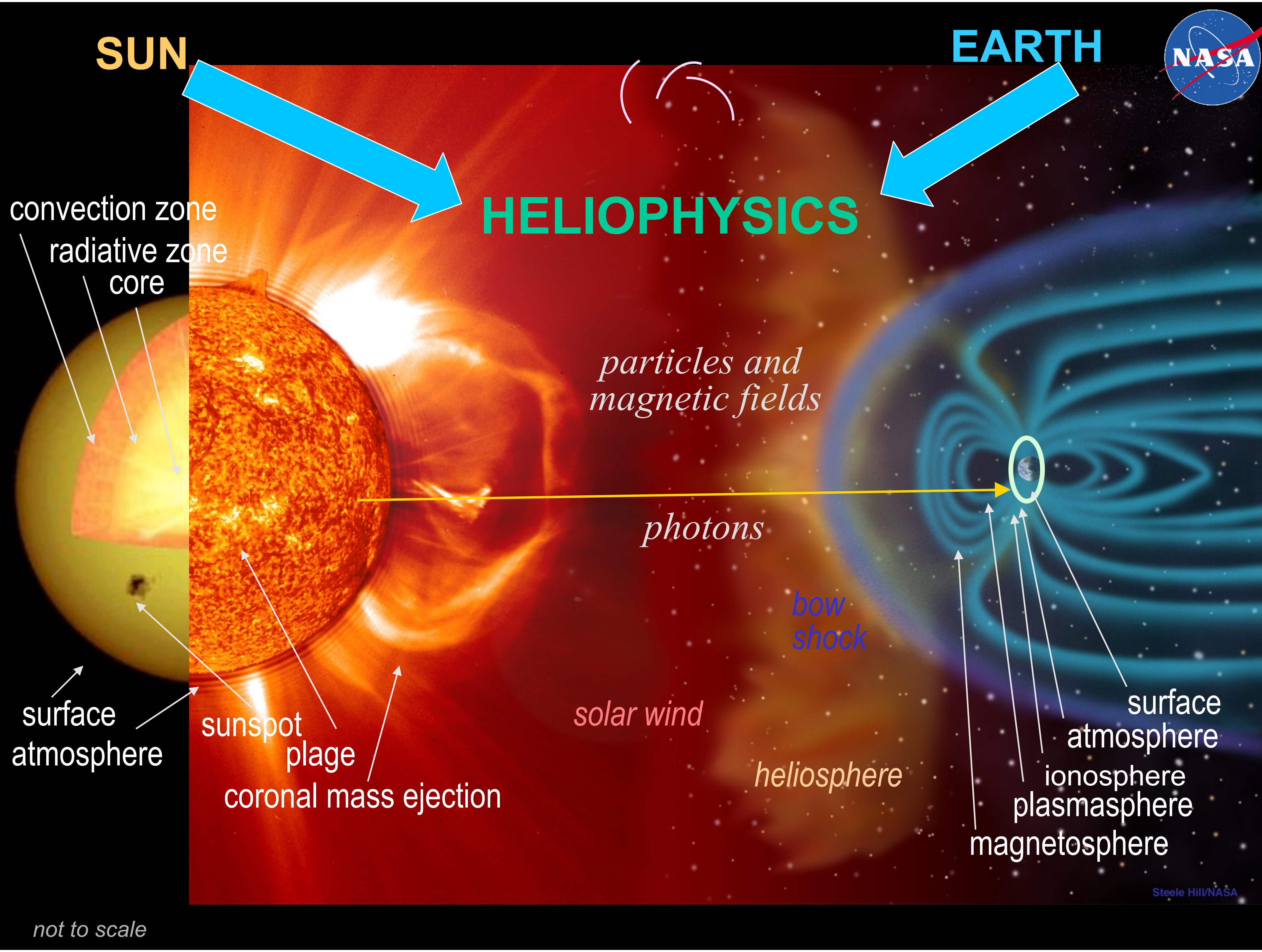
BIOLOGY
evolution, double helix

GEOLOGY
deep time, plate tectonics

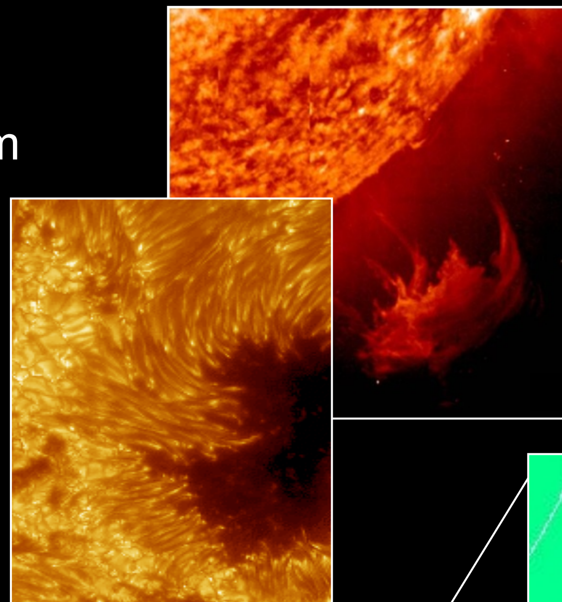
METEOROLOGY
Hadley cell, baroclinic instability

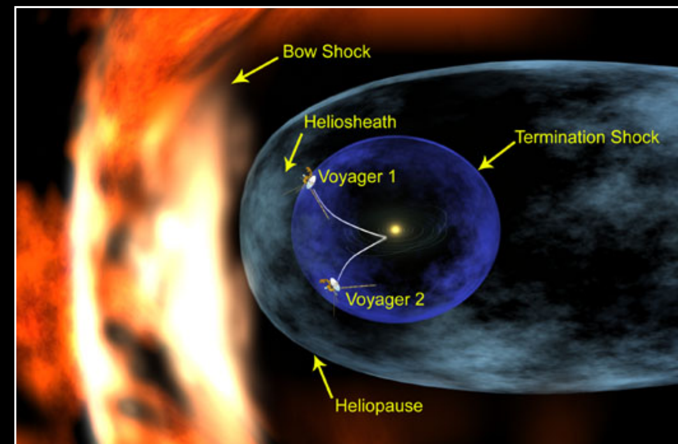
HELIOPHYSICS
solar (stellar) wind
magnetospheric convection
magnetic organization of matter
explosive energy conversion (CMEs & substorms)
magnetically (non-locally) coupled systems

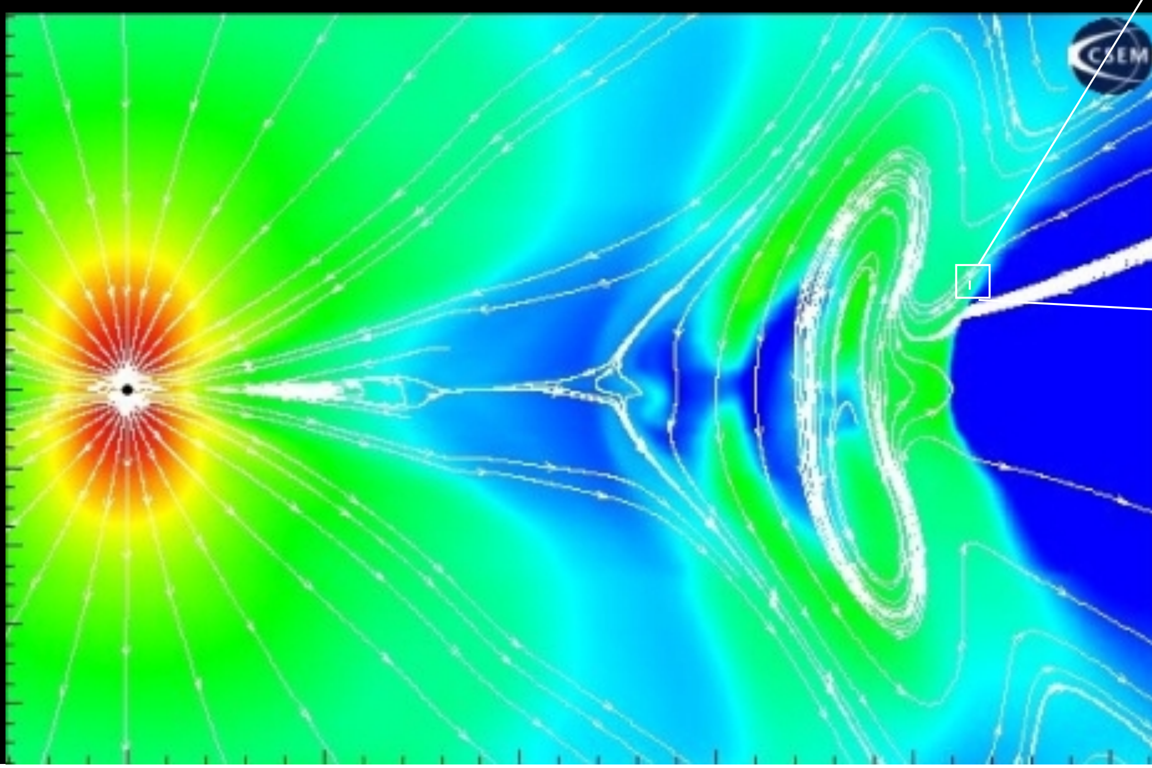
The project of uncovering universal processes of heliophysics corresponds to the 'Copenhagen' project of quantum mechanics

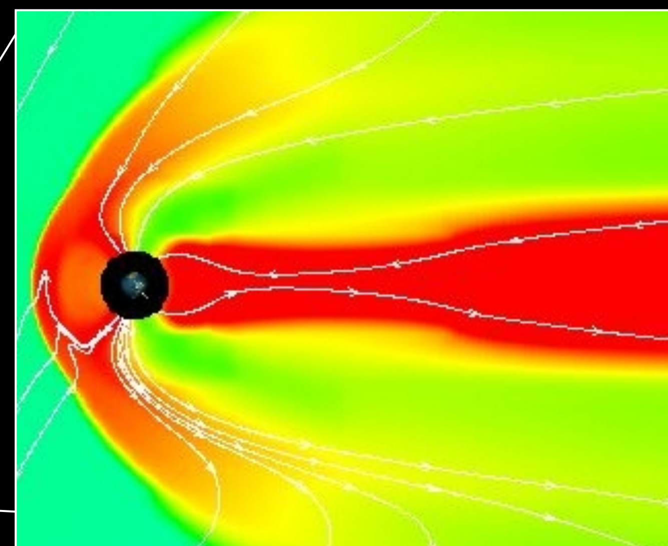

SUN
EARTH
NASA
HELIOPHYSICS
convection zone
radiative zone
core
particles and
magnetic fields
photons
bow
shock
surface
atmosphere
sunspot
plage
coronal mass ejection
solar wind
heliosphere
surface
atmosphere
ionosphere
plasmasphere
magnetosphere
Steele Hill/NASA
not to scale

- A quantitative, predictive understanding of a complex system
- Microphysical processes regulate global & interplanetary structures
- Multi-constituent plasmas and complex photochemistry
- Non-linear dynamic responses





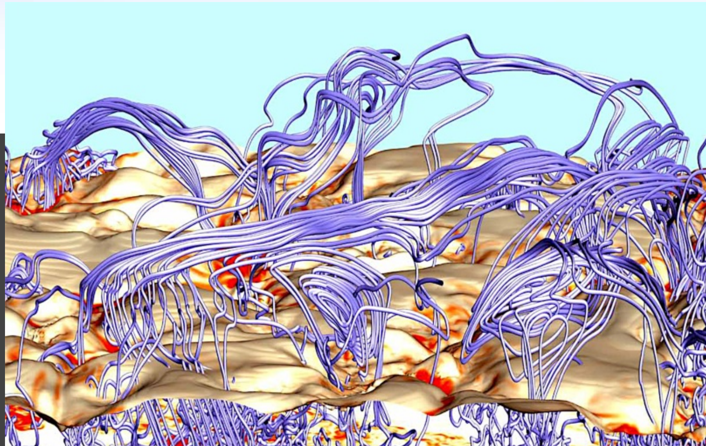




- Integration and synthesis of multi-point observations
- Data assimilative models & theory
- Interdisciplinary communities and tools

Ubiquitous Small-Scale Magnetic Fields on the Sun: Origin and Space Weather Effects

Irina Kitiashvili and Nagi Mansour (NASA/Ames)



“Magnetic carpet” on the Sun, simulated with the parallel 3D radiative magnetohydrodynamic code “StellarBox” using NASA’s Pleiades supercomputer. The “carpet” consists of small-scale magnetic fields generated by turbulent dynamo action just beneath the solar surface.

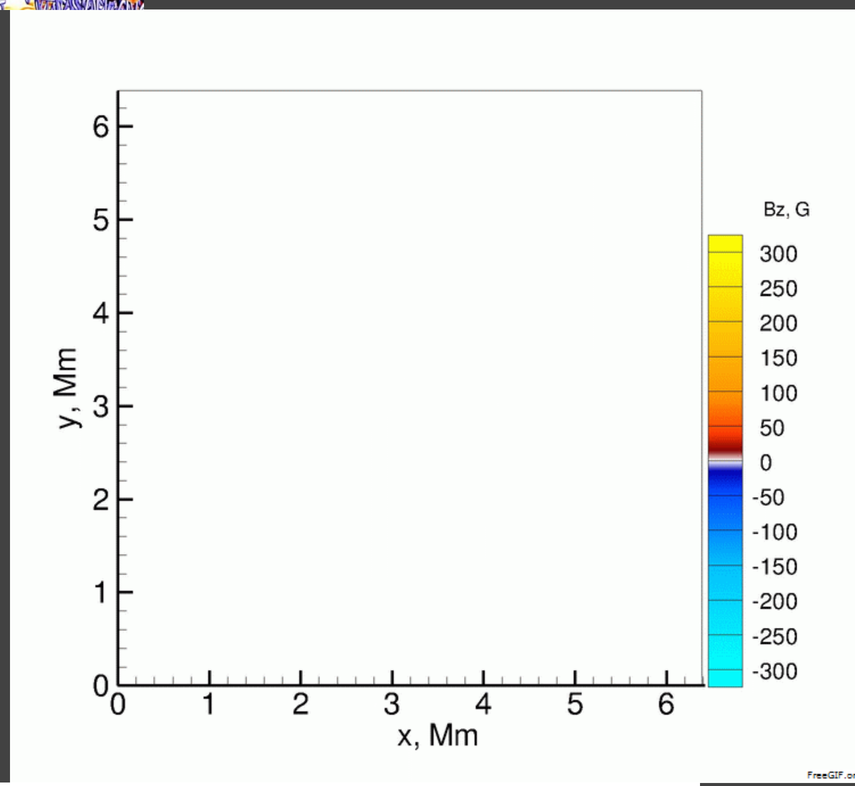


Image from a simulation of magnetic structures formed by a turbulent dynamo on the Sun, generated from an initial 10^{-6} Gauss randm seed field. The blue-red color scale corresponds to magnetic field strength from -300 to 300 Gauss. A typical size of the magnetic structures is 100 to 300 kilometers.

The simulations clearly demonstrate that:

- Small-scale dynamos are turbulent in nature.
- Local dynamos have their strongest efficiency in the subsurface layers of the convective zone.
- Different properties of seed magnetic fields have little effect on the properties of the generated magnetic fields.
- Small-scale dynamo action causes magnetic field amplification from extremely weak values (10^{-2} – 10^{-6} Gauss) to more than 1000 Gauss.

The results are used for interpretation of data from NASA’s Solar Dynamics Observatory, Hinode, and IRIS missions

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

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

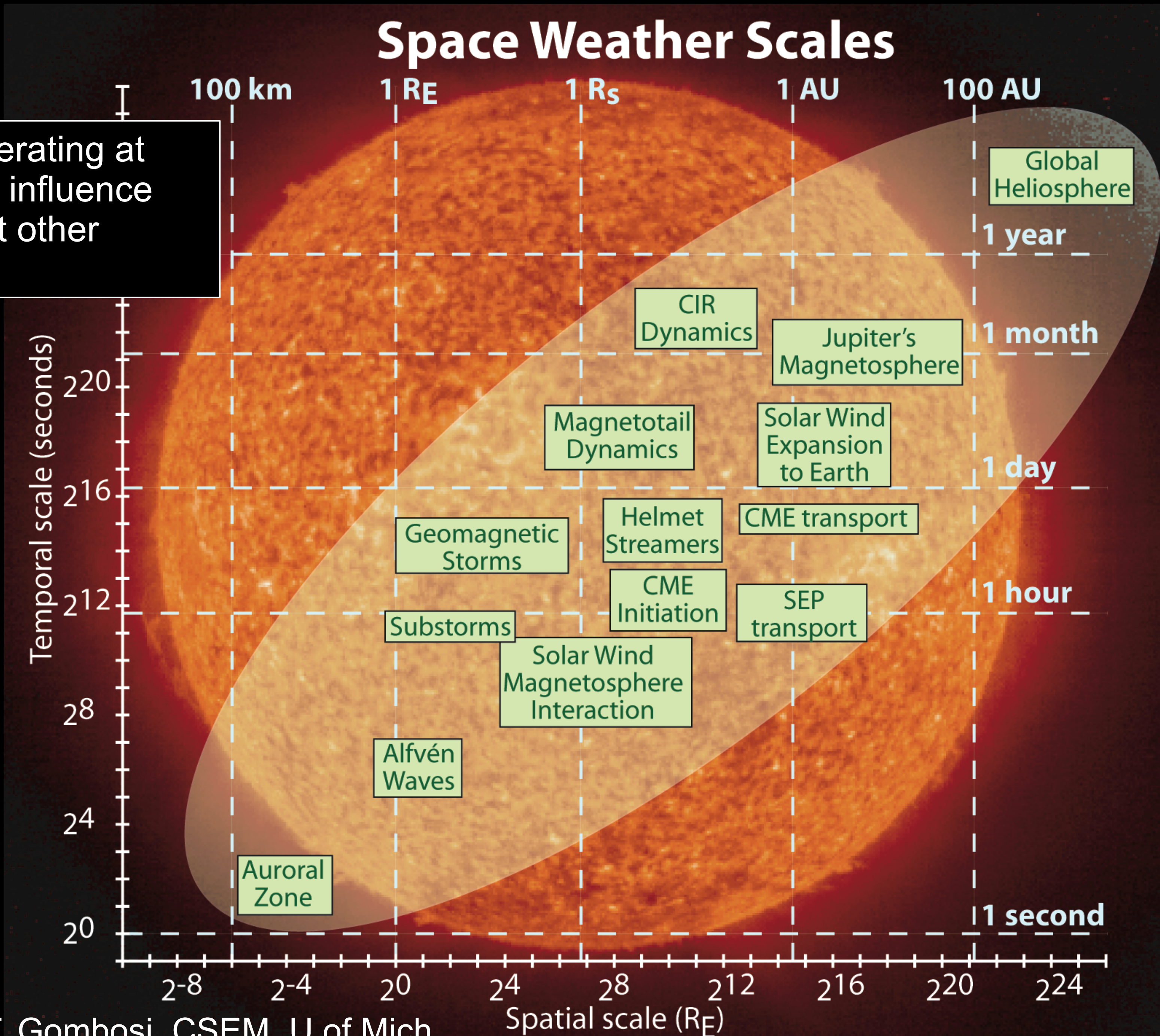
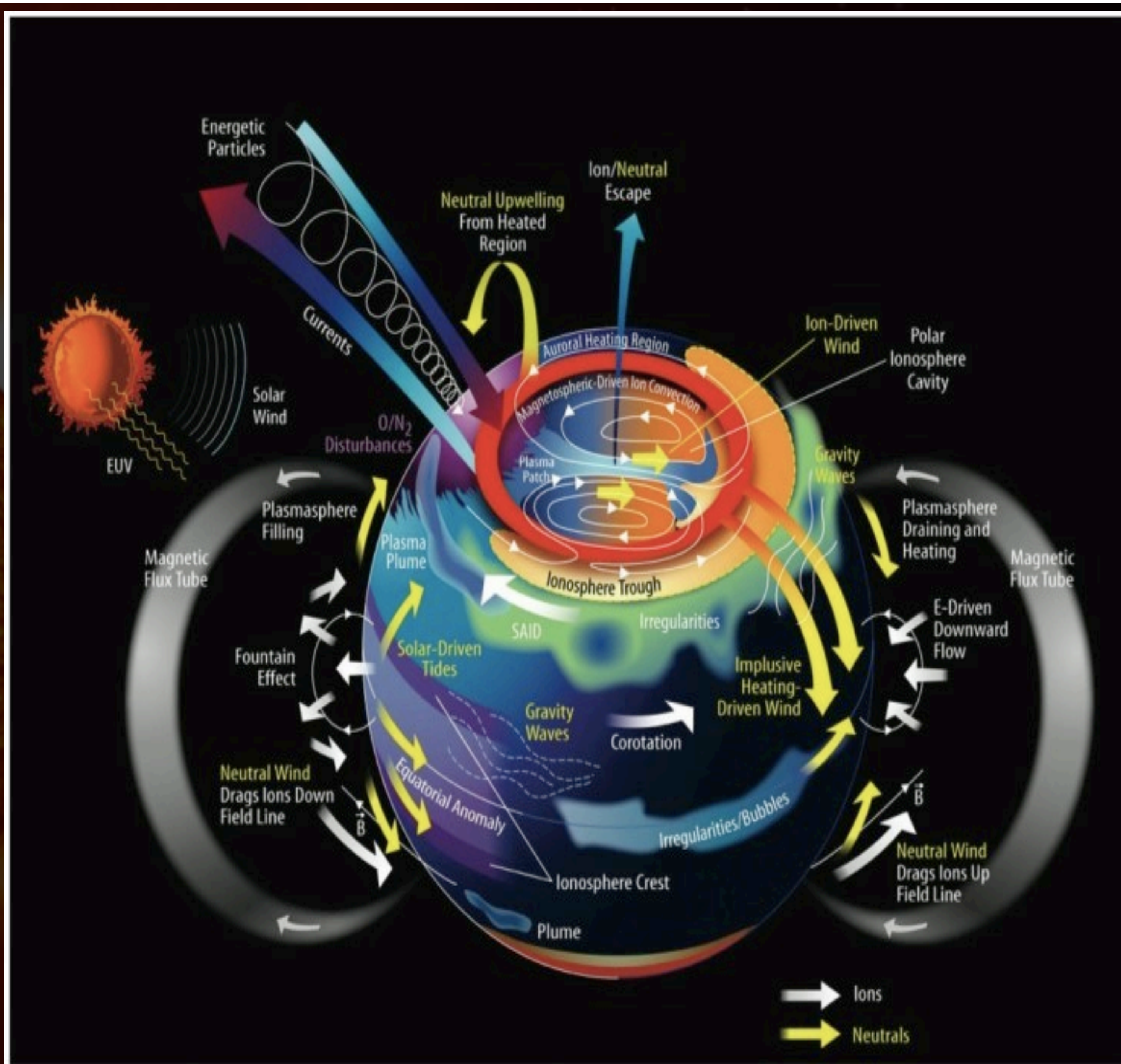
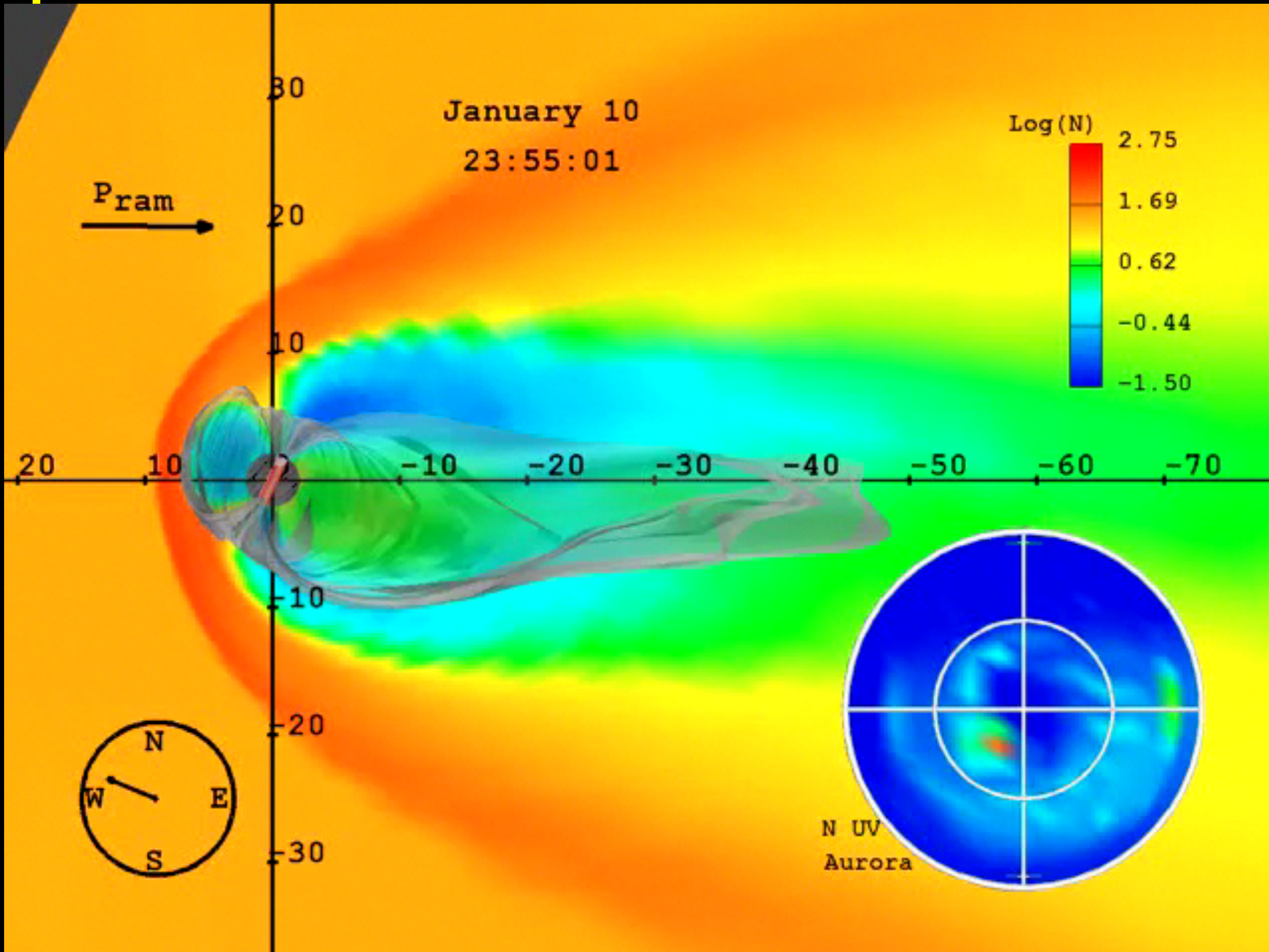


Image credit: T. Gombosi, CSEM, U of Mich



Space weather interacts with Earth's B-Field and can dramatically affect the Earth

Space Weather's Terrestrial Influence



A Coronal Mass Ejection Impacting Earth

A burst of fast material from the sun generates magnetic reconnection events in the Earth's magnetic field, eventually sending high-speed electrons and protons into the Earth's upper atmosphere to form aurora.

SkyLab Heliophysics GAME CHANGERS

The Corona is hot and controlled by magnetic fields

➔ X-Ray and EUV Variability at Earth **(NOAA R-Scale)**

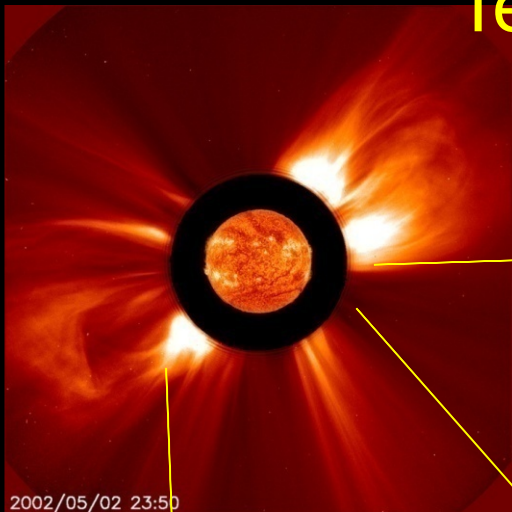
High-Speed Solar Wind originates from coronal holes

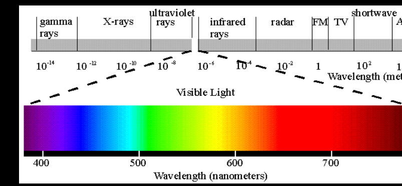
➔ Solar Particles Impact Earth **(NOAA S-Scale)**

Mass from the corona is ejected into interplanetary space

➔ Solar catastrophic events can impact Earth's magnetosphere **(NOAA G-Scale)**

Terrestrial Space Weather





Electro-magnetic Radiation

Ultra Violet and X-ray Radiation

8 minutes

R-Scale

Satellite drag; radio blackouts

Blame it on *B*
(magnetic field)

Matter

Charged Particle Radiations

10-30 minutes

S-Scale

NOAA Space Weather Scales

Matter

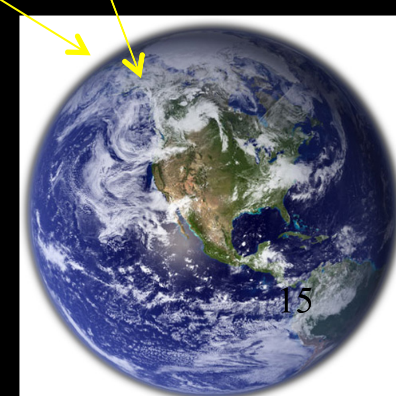
Magnetic Fields

Radiation:
astronaut health. aviation & satellite function

Magnetized Blobs of Solar Material

18-96 hours

G-Scale



Aurora;
geomagnetic storms & radio disturbances

It all started with Skylab…

HPD is Organized into Four Major Sections

Goal: Understand the Sun and its interactions with Earth and the solar system including space weather

Living With a Star

Goal Oriented Strategic Program that is Relevant to Life and Society (space weather)

Solar Terrestrial Probes

Curiosity Driven Strategic Mission Flight Programs (fundamental physics)

Solve the _*fundamental physics*_ *mysteries of heliophysics:* Explore and examine the physical processes in the space environment from the sun to the Earth and throughout the solar system.

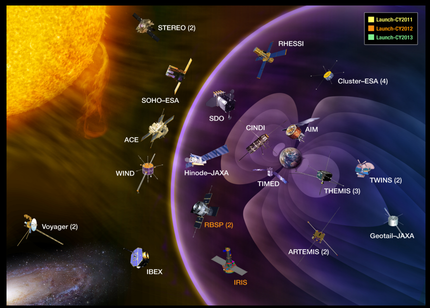
Build the knowledge to forecast space weather throughout the heliosphere: Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.

Understand the nature of our home in space: Advance our understanding of the connections that link the sun, the Earth, planetary space environments, and the outer reaches of our solar system

Explorers

Smaller flight programs, competed science topics, often PI-led

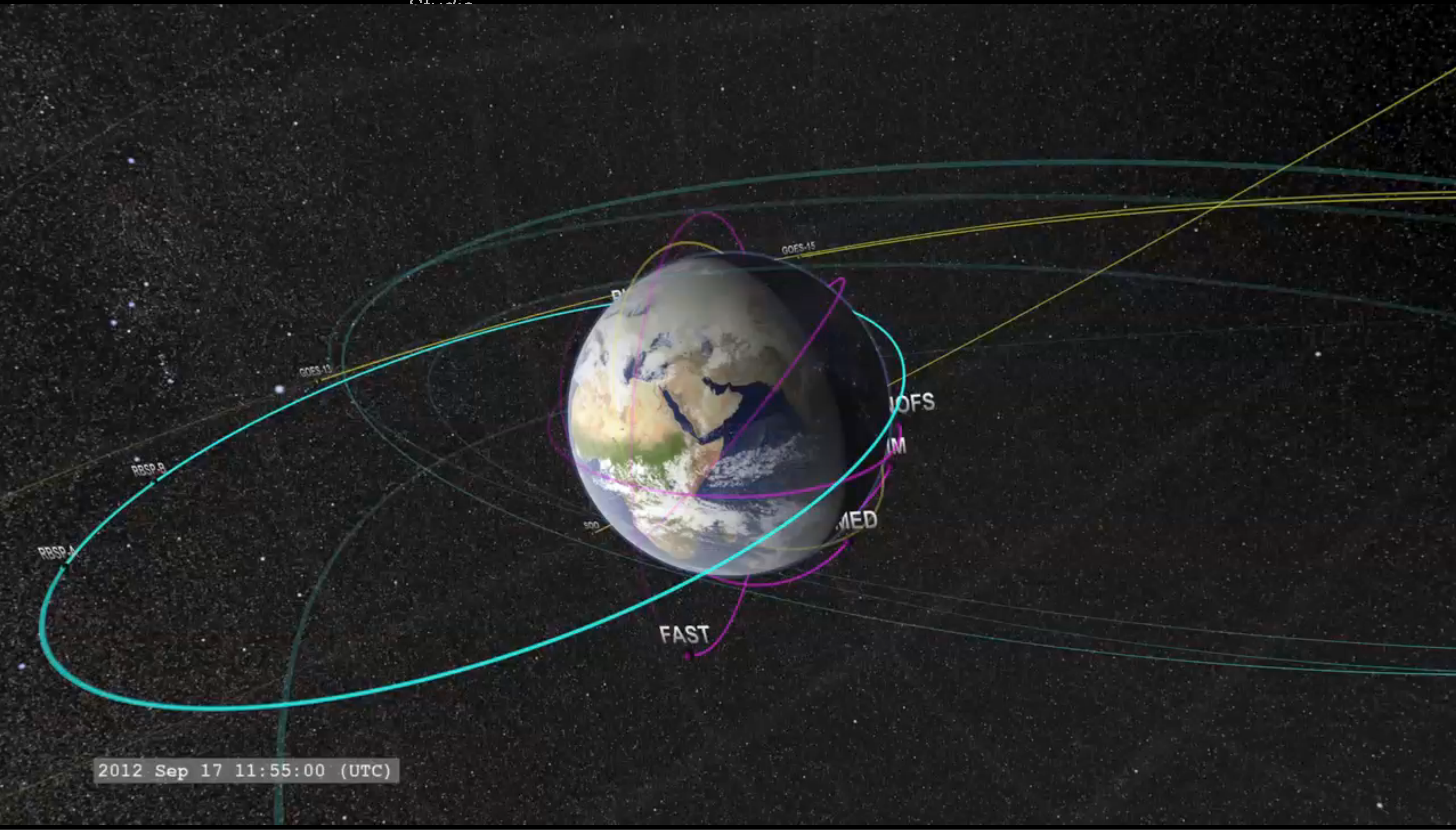
Research



Scientific research projects utilizing existing data plus theory and modeling

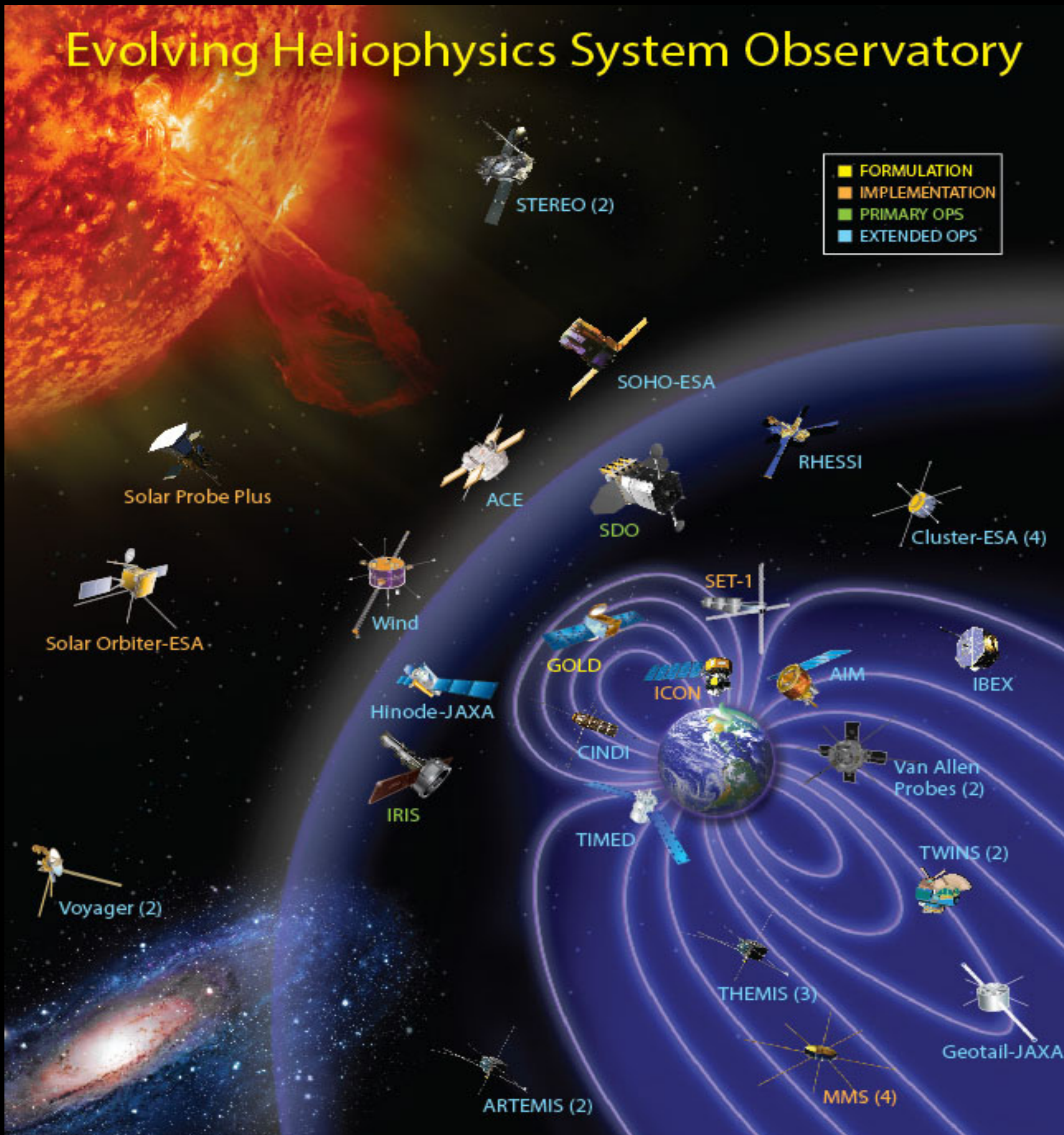
The Heliophysics Observatory Fleet

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 19 operating missions (on 33 spacecraft): Voyager, Geotail, Wind, SOHO ACE Cluster, TIMED, RHESSI, TWINS, Hinode, STEREO THEMIS/ARTEMIS, AIM, CINDI, IBEX, SDO Van Allen Probes IRIS, MMS

(Missions in red contribute to operational Space Weather.)

5missions are in various phases of development: SET, SOC, SPP, ICON, and GOLD

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

Looking Forward: New HSO Components

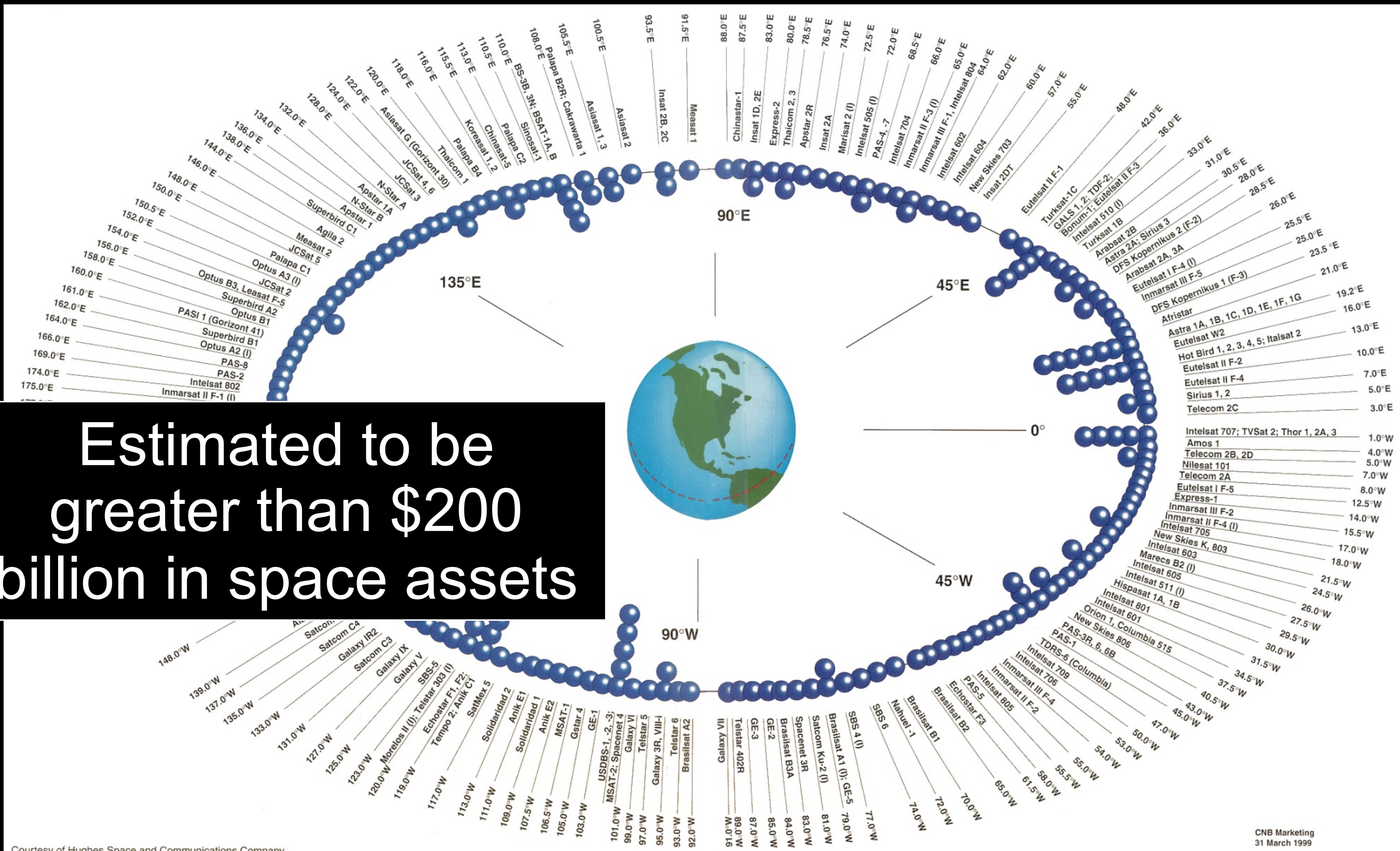
Addition of new HSO component where each component need not carry a comprehensive payload

- The network can grow serendipitously, with key measurements made on distributed platforms
- Single instrument MOOs
- Cubesats dedicated to one or two instruments
- Individual measurement sets add value by complementing the existing network

In addition, we need techniques to assess the value of additional components to the HSO as a whole

- Models of data assimilation effectiveness
- What is the minimum infrastructure?
- How can we assess and maintain system reliability

Civilian Spacecraft at Geostationary Orbit



Estimated to be greater than $200 billion in space assets

GPS

Global Positioning System used: In-vehicle navigation systems, railway control, highway traffic management, emergency response, commercial aviation, and much more…

NAVSTAR - USA
GLONASS - Russia
Galileo - Europe

GPS Global Production Value—expected growth:

2003 - $13 billion

2008 - $21.5 billion

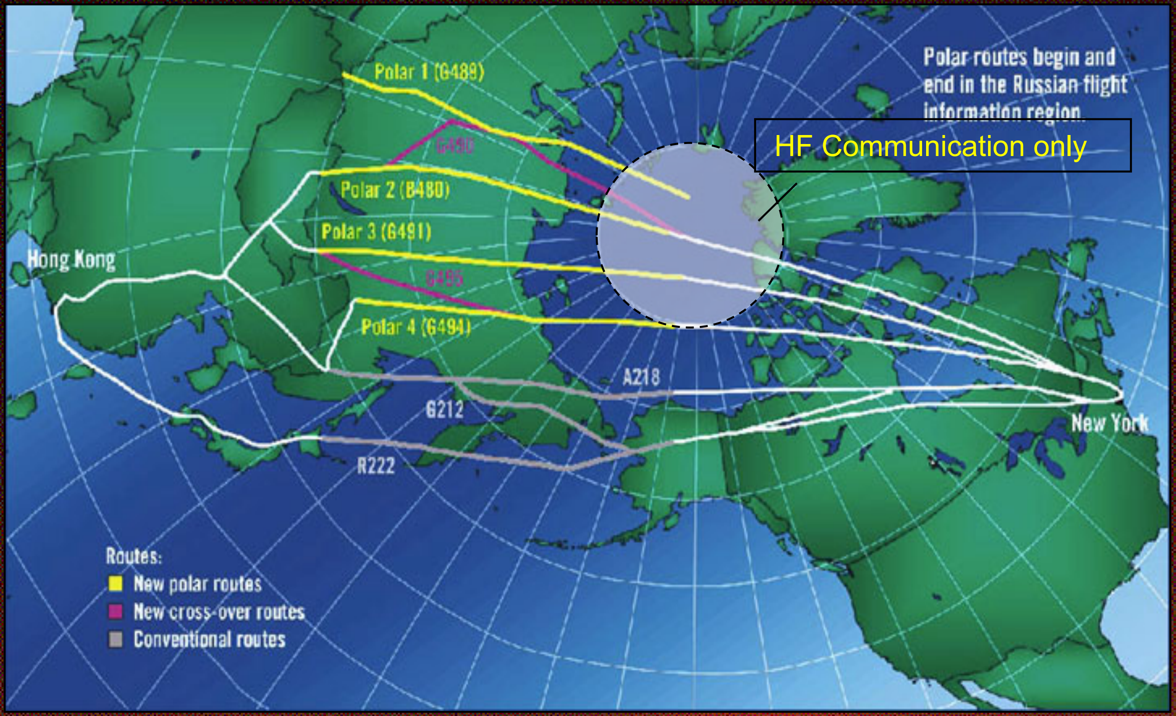
2017 - $757 billion

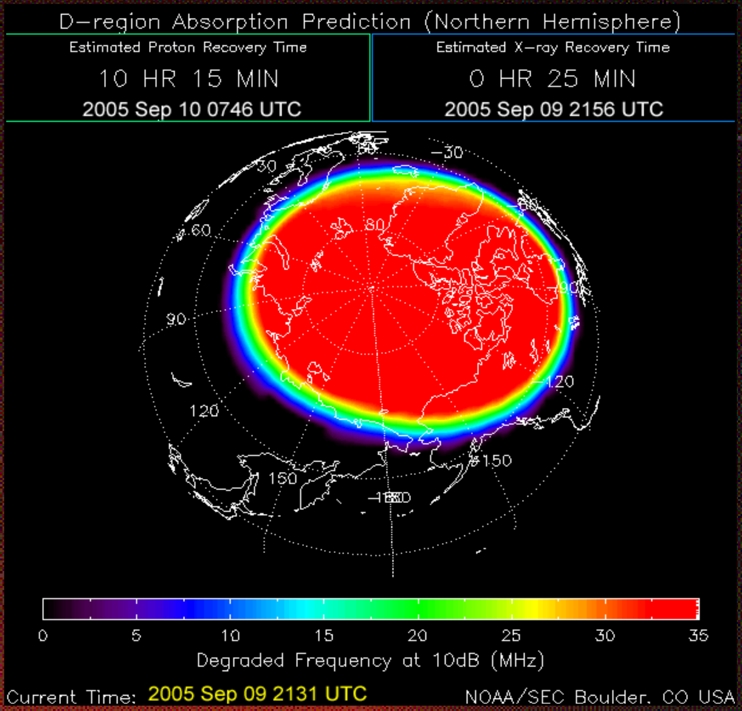
Industrial Technology Research Institute (ITRI) – Mar 2005

Space weather can create positioning errors larger than 50 meters

—A mid-latitude problem (where most users reside!)

Airlines and the Polar Routes



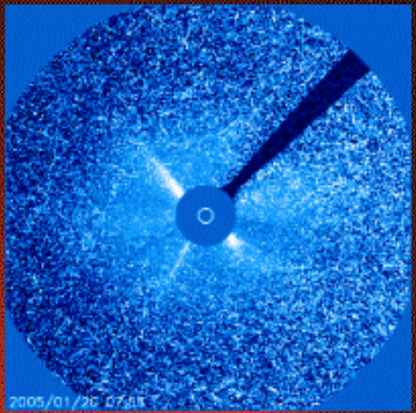


- Flights rely on HF (3 – 30 MHz) communication inside the 82 degree circle.
- Federal Aviation Regulation Sec. 121.99 – aircraft must have two-way radio communication over the entire route with dispatch office and air traffic control.
- Airlines will often re-route flights away from polar routes during radiation and geomagnetic storms at a cost that can exceed $100,000 per flight.

Satellite Industry

Needs Solar storm warnings and alerts:

- Instruments and/or spacecraft turned off or safed
- Maneuver planning
- Anomaly assessments
- Orbit determination accuracy
- Increased spacecraft and instrument monitoring for health and safety during solar storms



Electrical Power Grid…

The grid is becoming increasingly vulnerable to space weather events *Future Directions in Satellite-derived Weather and Climate Information for the Electric Energy Industry – Workshop Report Jun 2004*

"…blackouts could exceed even that of the very large blackout that occurred in August 14, 2003. And there is no part of the U.S. power grid that is immune to this… we could impact over 100 million population in the worst case scenario." John Kappenman - before U.S. House Subcommittee on Environment, Technology & Standards Subcommittee Hearing on *"What is Space Weather and Who Should Forecast It?"*

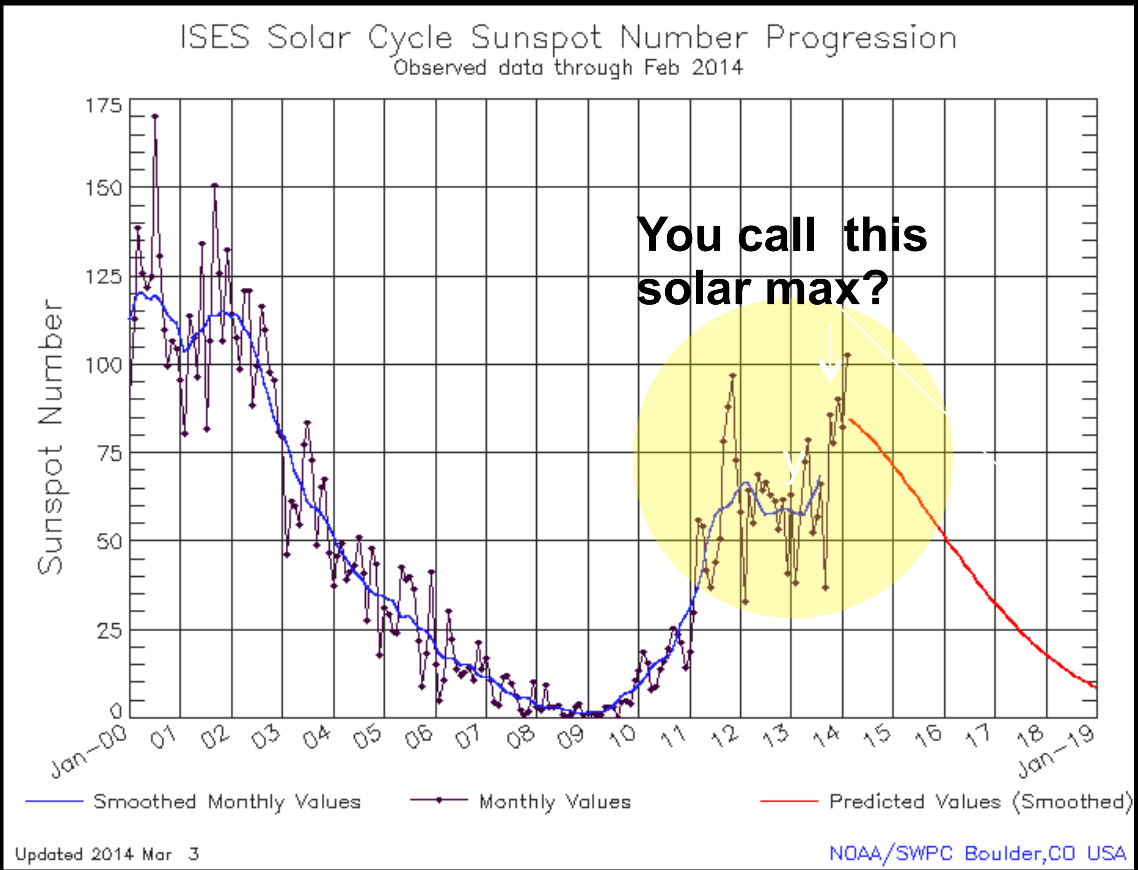
Transformer winding failure

Transformer exit lead overheating

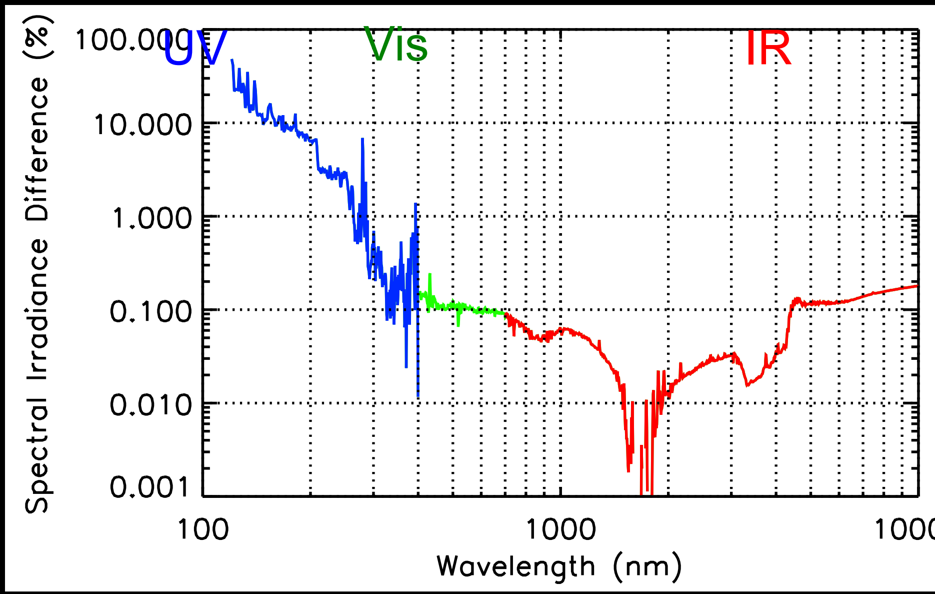
Look out! Solar activity is so low that Solar Max looks a lot like Solar Min.

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.



Spectral Solar Irradiance (SSI): SMax vs. SMin



Small variations in the visible (0.1%), but big changes in the UV. ***(UV, EUV and X-ray spectral irradiances are drivers of space weather)***

Space Weather Occurs at all Phases of the Solar Cycle...

Solar La Niña (low sunspot number)

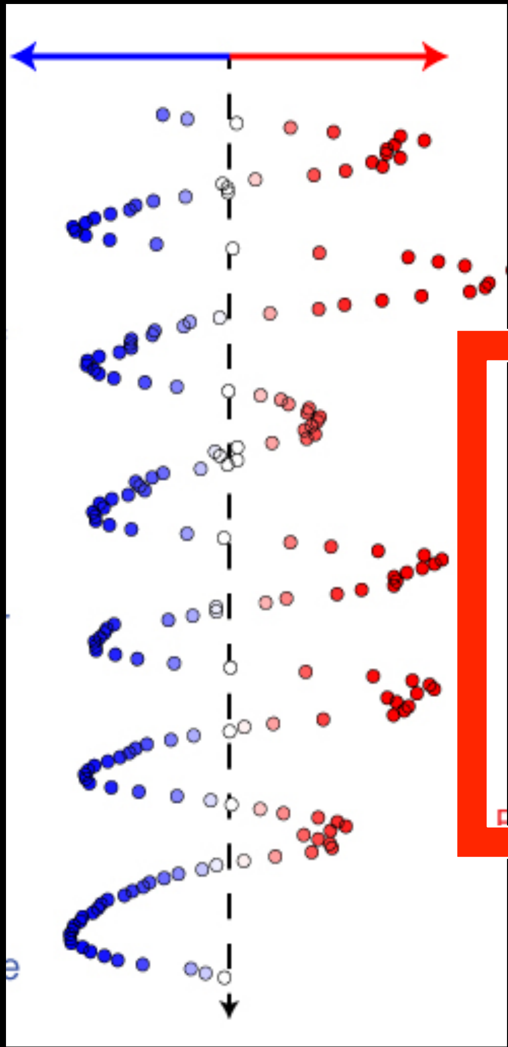
extreme galactic cosmic rays

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

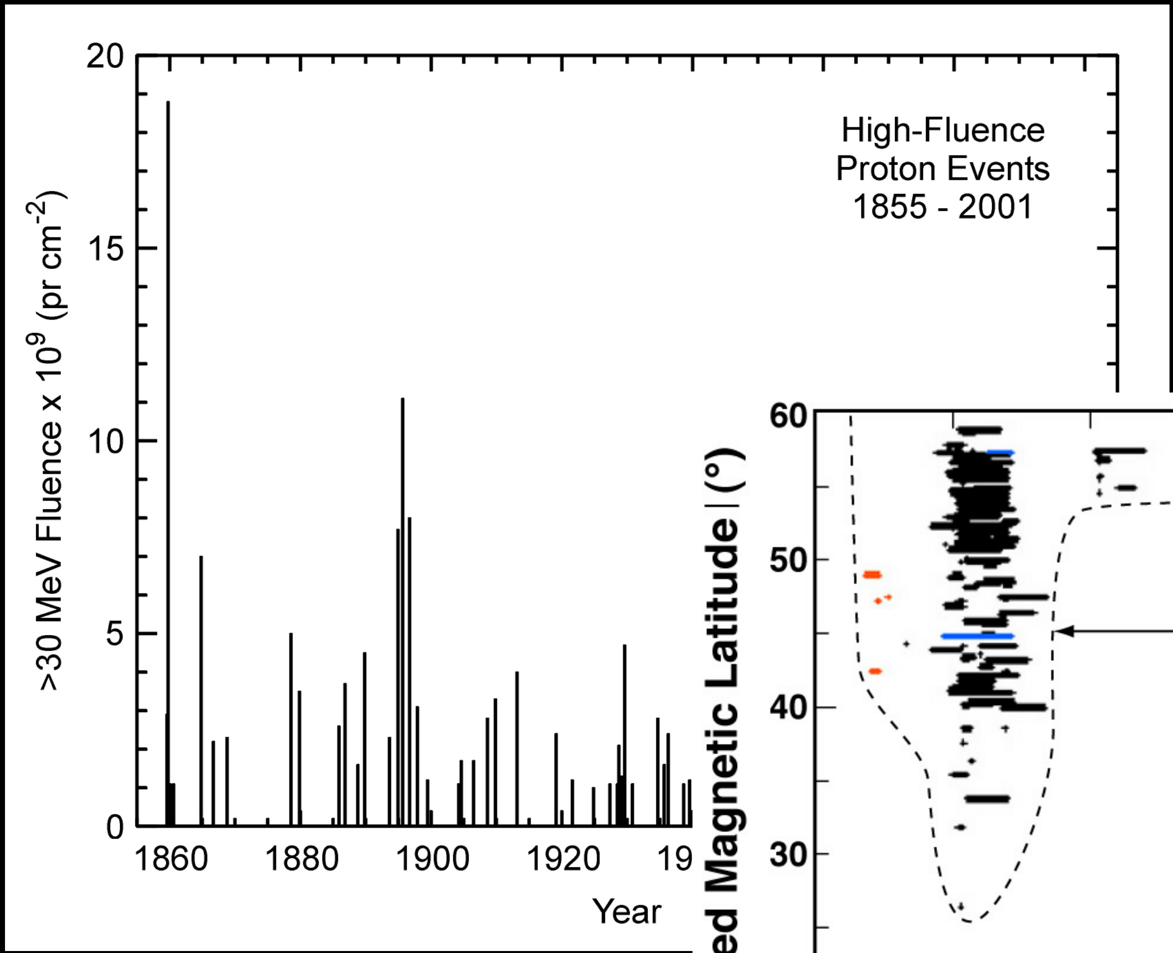
extreme geomagnetic storms

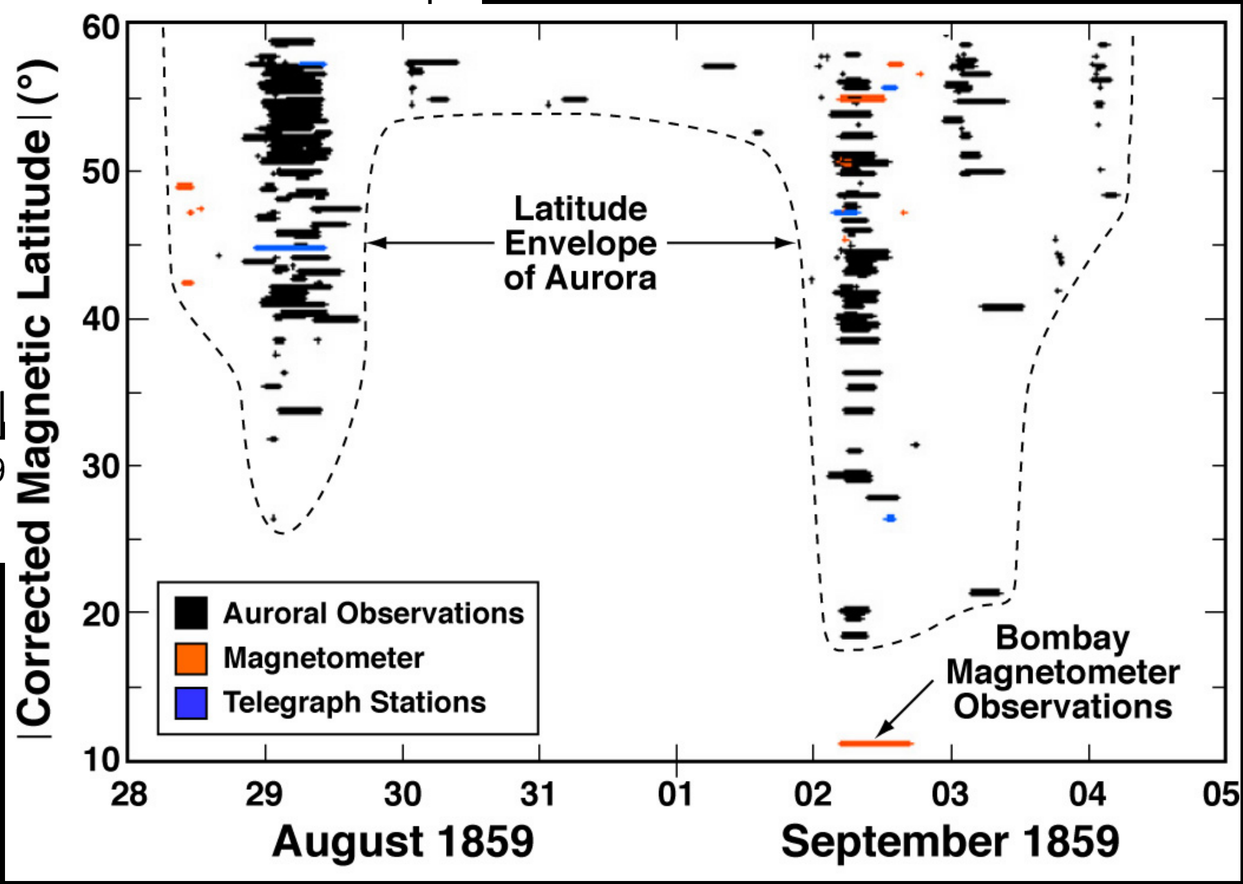
melted power grid transformers – power blackouts

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).

An Extreme Event: Carrington 1859

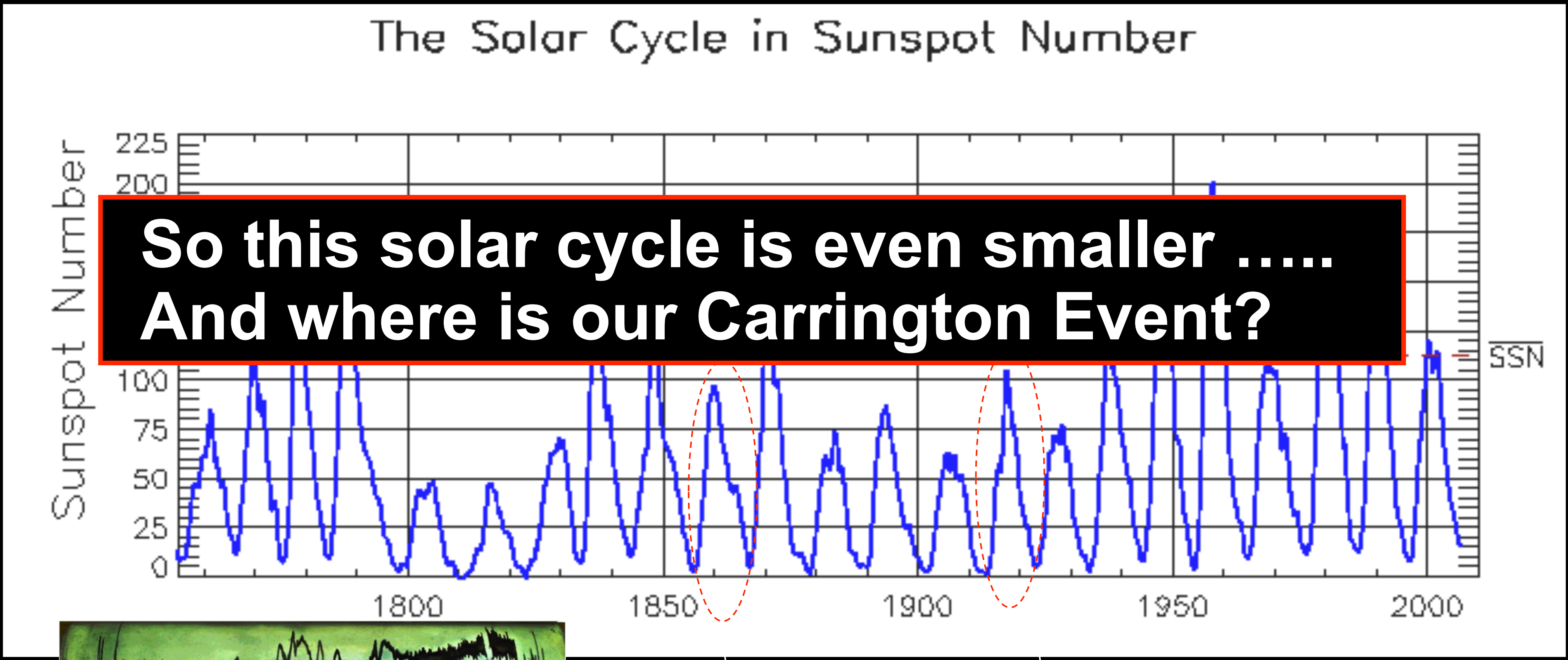


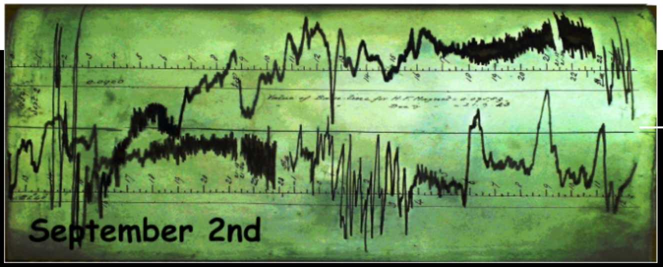


[Courtesy J. Green/NRC Study]

Large geomagnetic storms can occur with smaller cycles

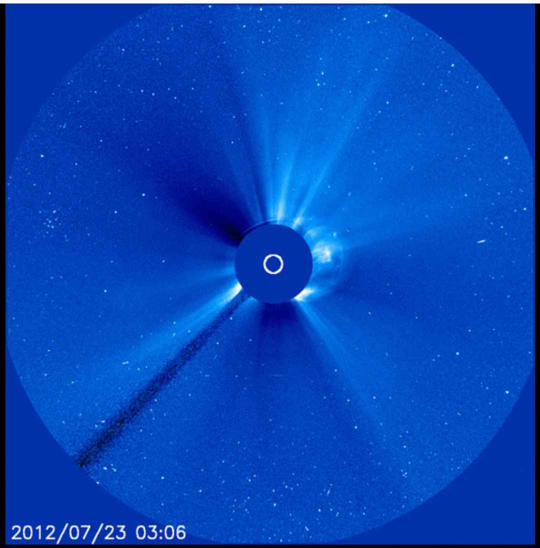
The largest geomagnetic storms on record occurred during lower than average cycles



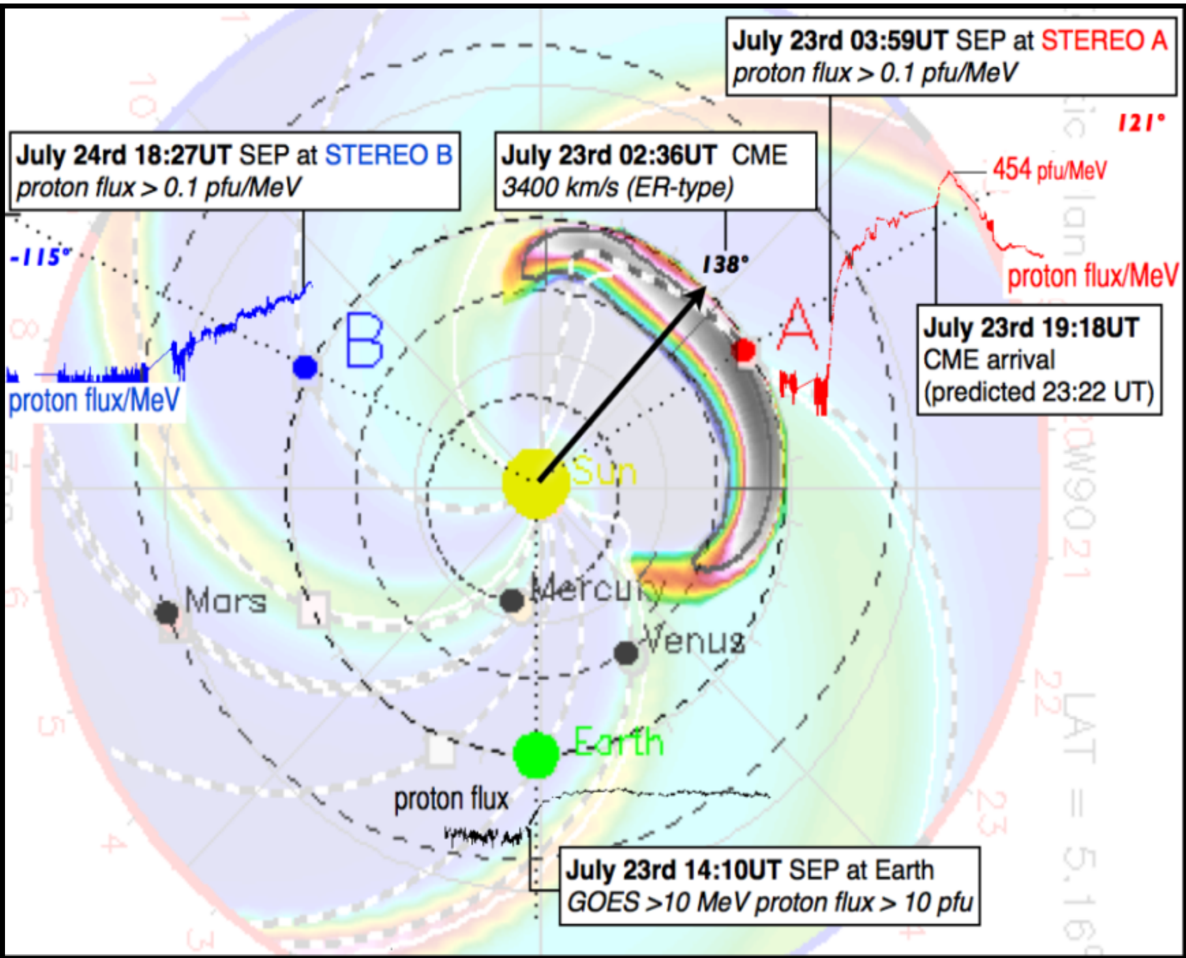


1859 Storm

1921 Storm

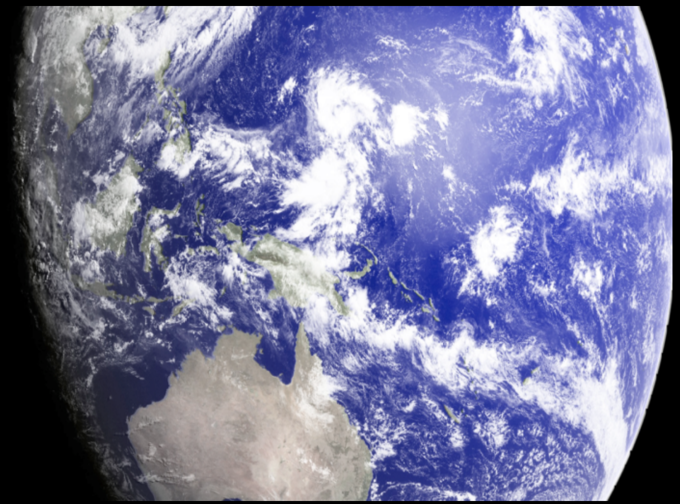


July 23, 2012, one of the fastest CMEs of the Space Age rocketed away from the western limb of the sun travelling at a speed greater than 3000 km/s.

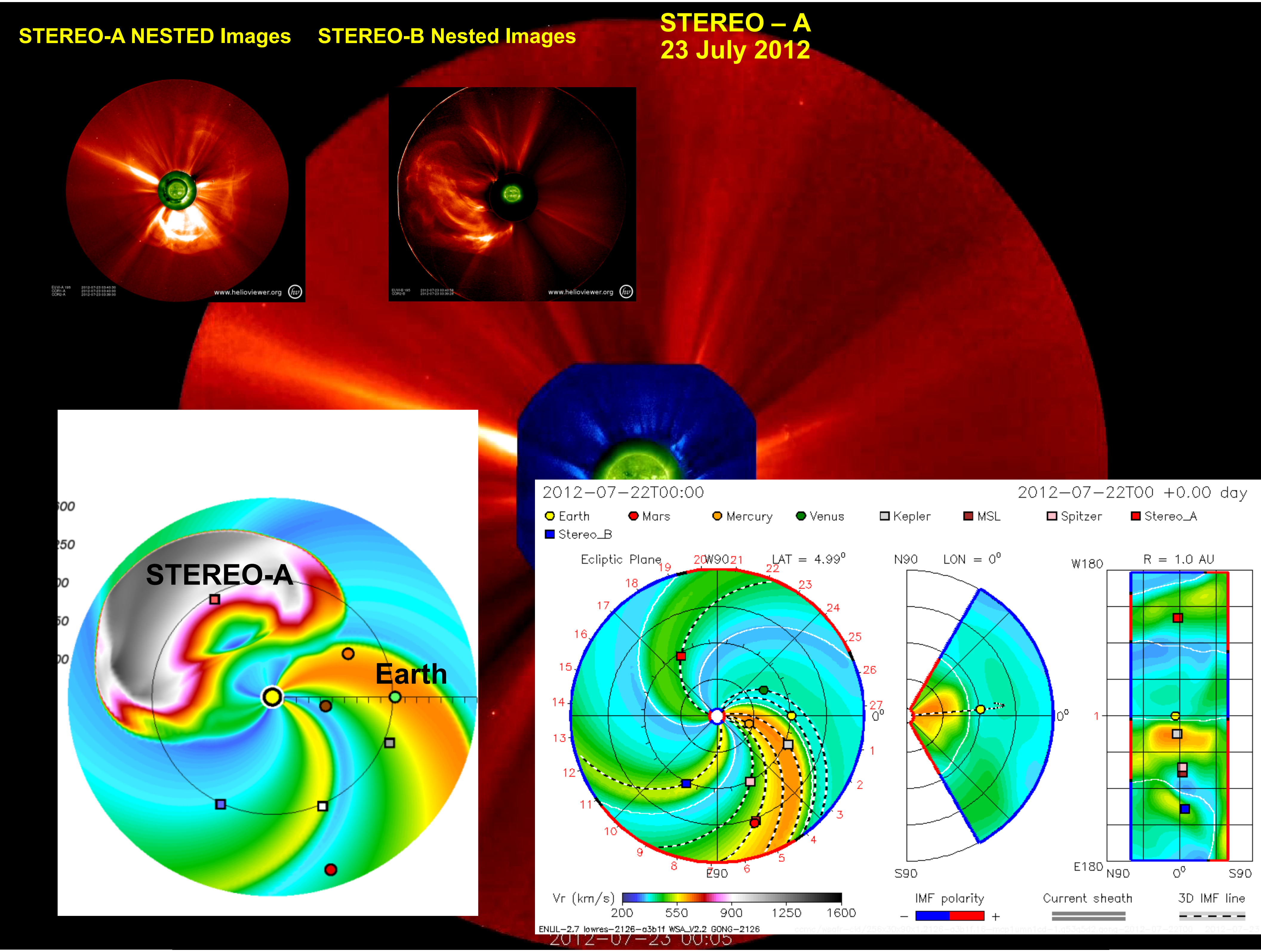


Surrounding the sun has allowed us to detect major storms that otherwise we might have missed.

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


STEREO-A NESTED Images
STEREO-B Nested Images
STEREO – A
23 July 2012
www.helioviewer.org
www.helioviewer.org
STEREO-A
Earth
2012–07–22T00:00
2012–07–22T00 +0.00 day
Earth
Mars
Mercury
Venus
Kepler
MSL
Spitzer
Stereo_A
Stereo_B
Ecliptic Plane
W90
LAT = 4.99°
N90
LON = 0°
W180
R = 1.0 AU
E90
S90
E180
N90
0°
S90
Vr (km/s)
200 550 900 1250 1600
IMF polarity
Current sheath
3D IMF line
ENLIL–2.7 lowres–2126–a3b1f WSA_V2.2 GONG–2126
2012–07–23 00:05

"If this storm had hit Earth, we would still be picking up the pieces."
--Dan Baker, 2014 Space Weather Workshop

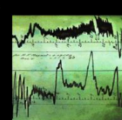
"Had it hit Earth, it probably would have been like the big one in 1859. The effect today [on] our modern technologies would have been tremendous.“
-- Janet Luhmann, 2014 UC Berkeley press release.

THE MAIN FOCUS OF MODERN SPACE WEATHER FORECASTING HAS BEEN EARTH

Frederek Edwin, 1865

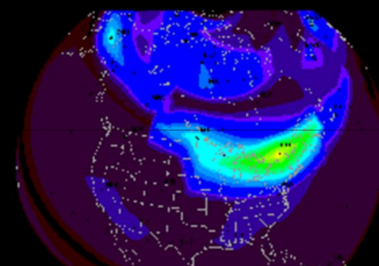
THE CARRINGTON EVENT

In September 1859, Earth experienced the strongest solar and geomagnetic storm in recorded history. Ground currents set telegraph offices on fire and Northern Lights were spotted in Cuba, Mexico, and across the islands of the South Pacific.



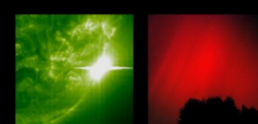
1859 Magnetogram

Clockwise from top: transformer damage, superstorm data, more industrial damage



QUEBEC BLACKOUT

In March 1989, a powerful geomagnetic storm caused the Hydro-Québec power grid to collapse. Transformers were also damaged in New Jersey and Great Britain.



Left: X28 flare
Right: rare red auroras

HALLOWEEN STORMS

In October-November 2003, 17 major eruptions, including a record-setting X28 flare, triggered intense geomagnetic storms on Earth. Blood-red auroras appeared as far south as Texas, Florida and Arizona.

Space Weather Swings Between Extreme Effects

Solar La Niña (low sunspot number)

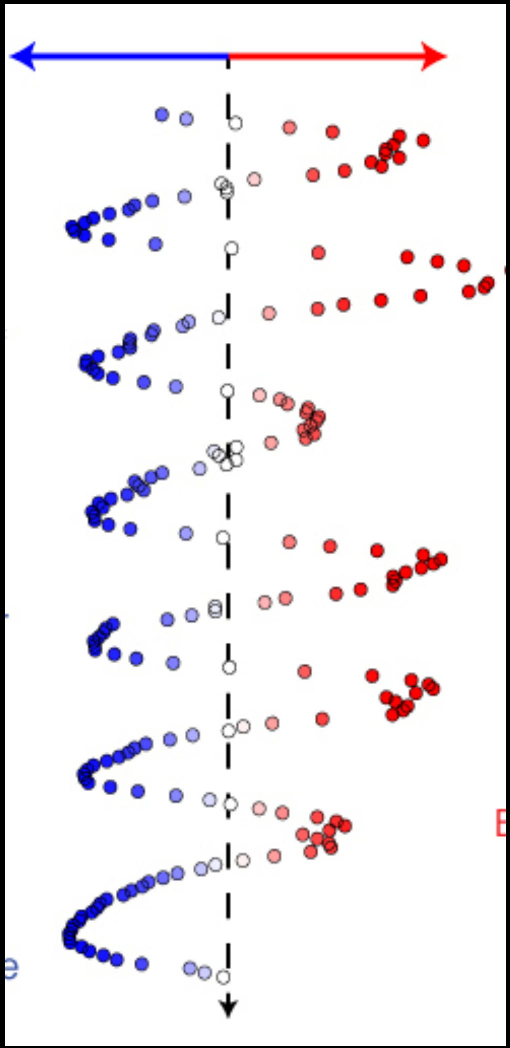
extreme galactic cosmic rays

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

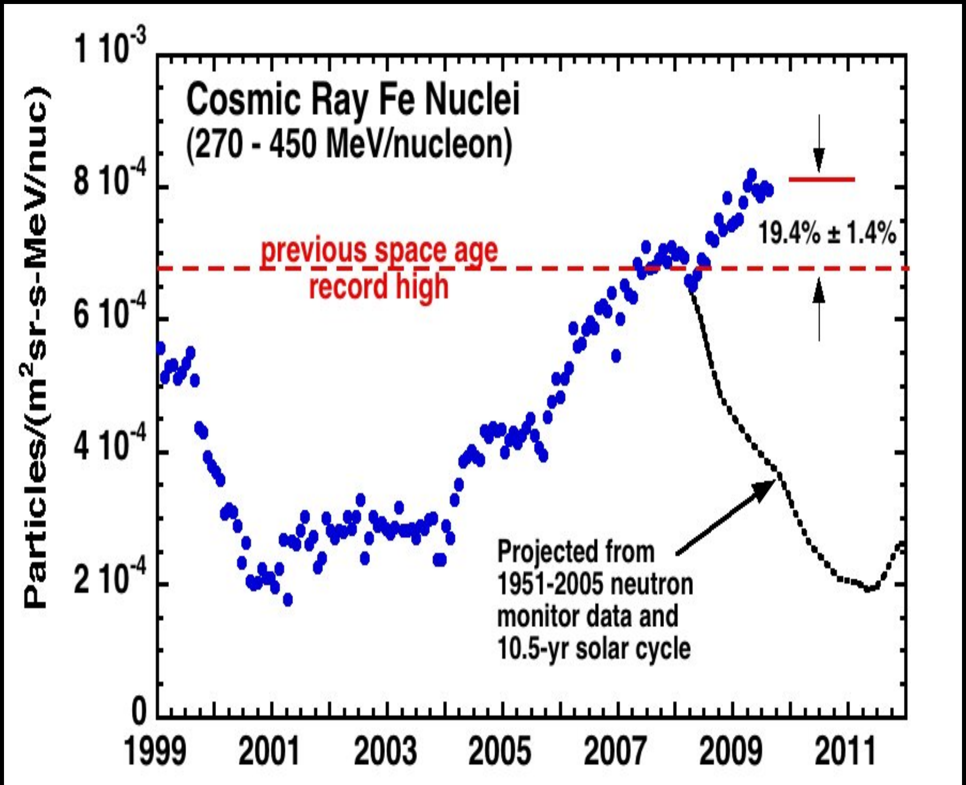
solar wind streams hit Earth

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).

Who's Afraid of a Solar Flare?

Cosmic rays are much scarier

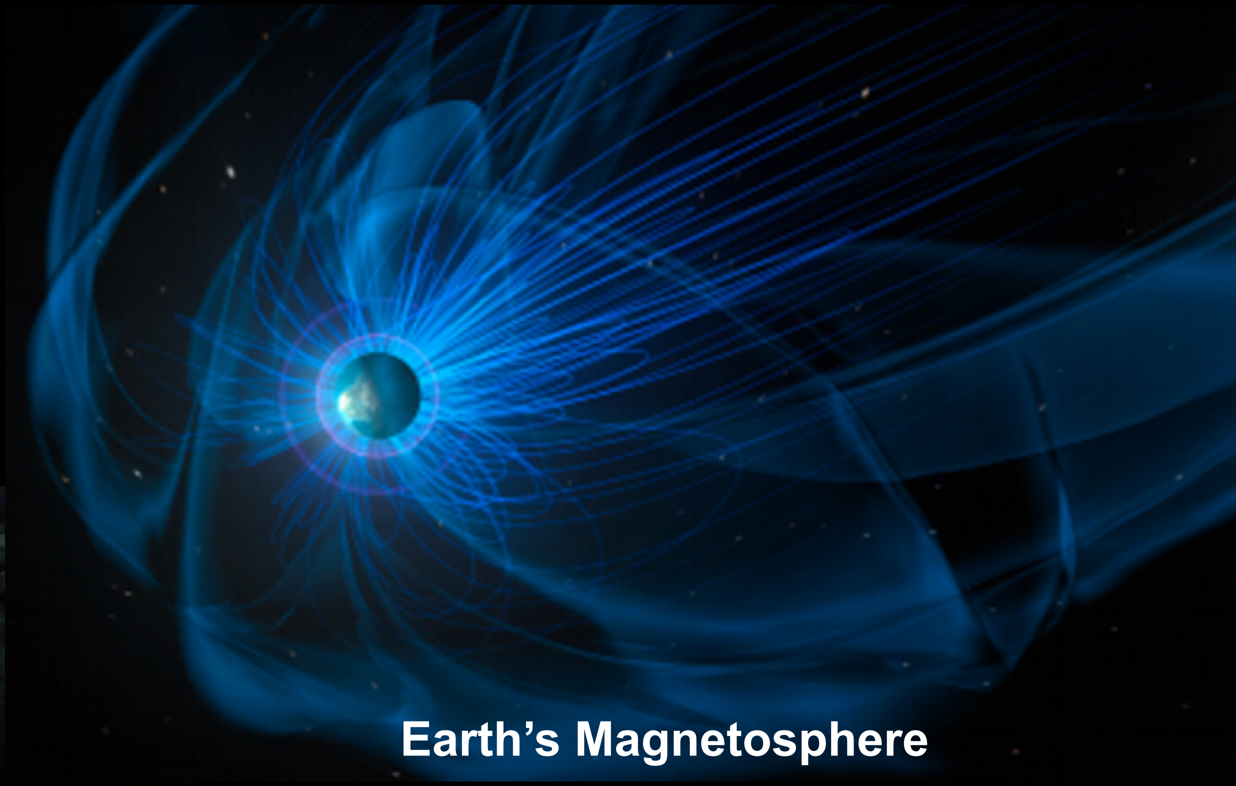
When solar activity is low, cosmic rays are able to invade the inner solar system. During the 2008-2009 solar minimum, cosmic rays surged to record-high levels.



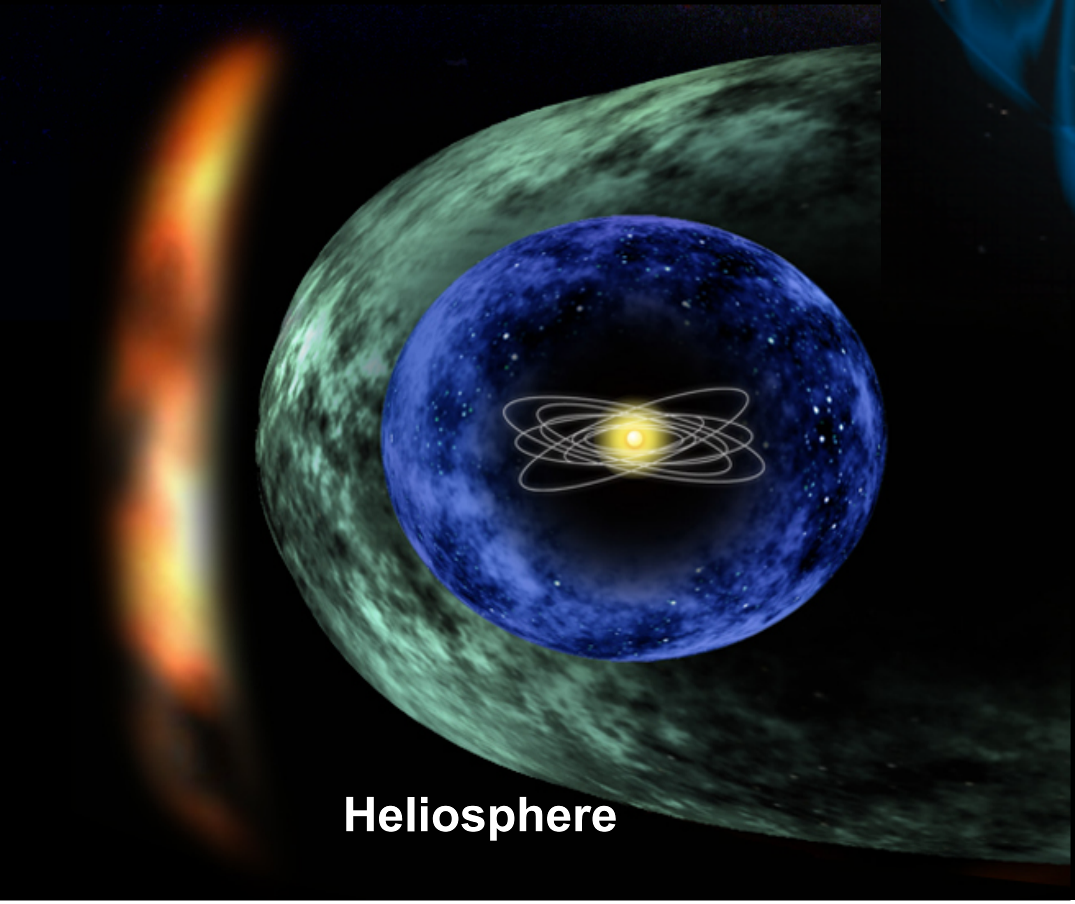
Cosmic rays from distant supernova explosions and black holes are far more energetic and penetrating than particles from relatively puny solar flares.

The Heliosphere

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

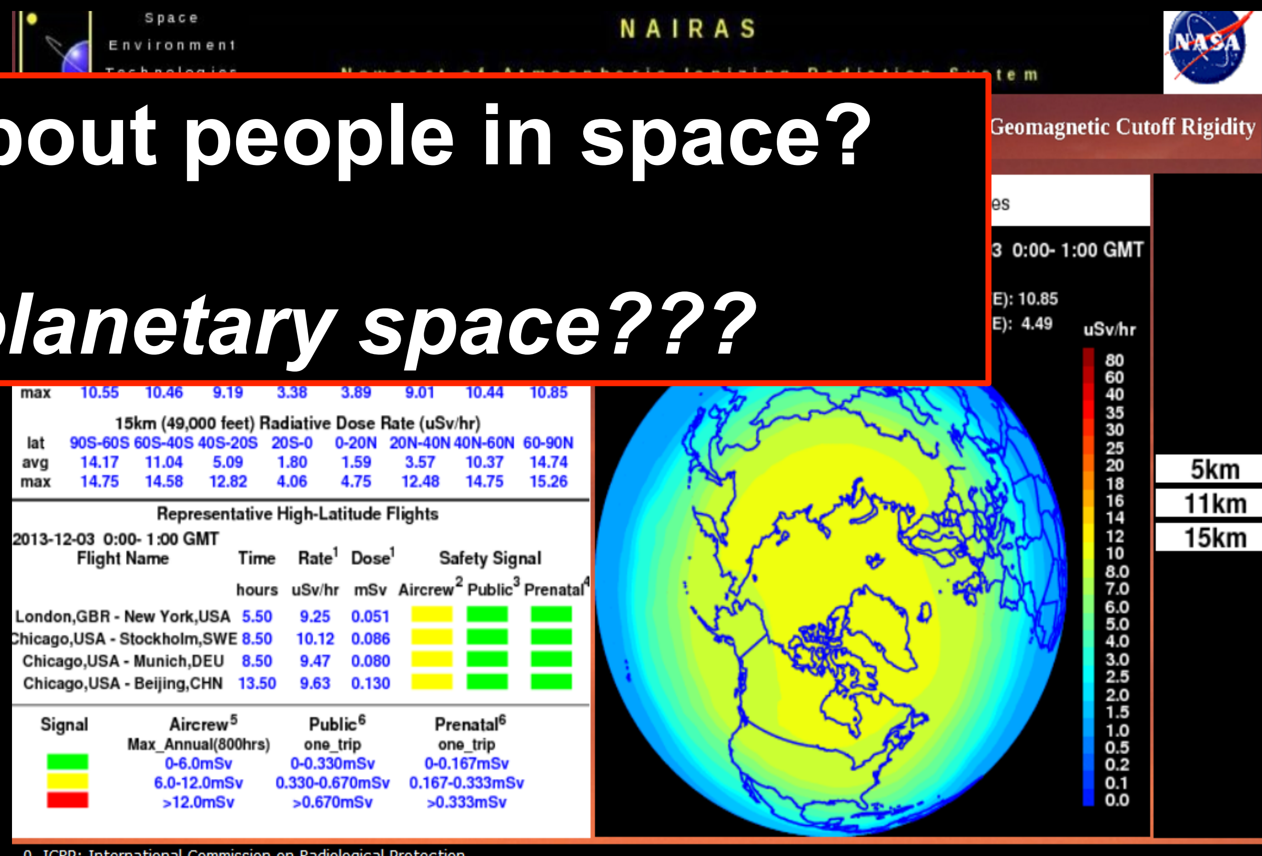


The solar system is protected from galactic cosmic rays by its heliosphere, the bubble surrounding the Earth and the planets that is created by the solar wind/magnetic field.



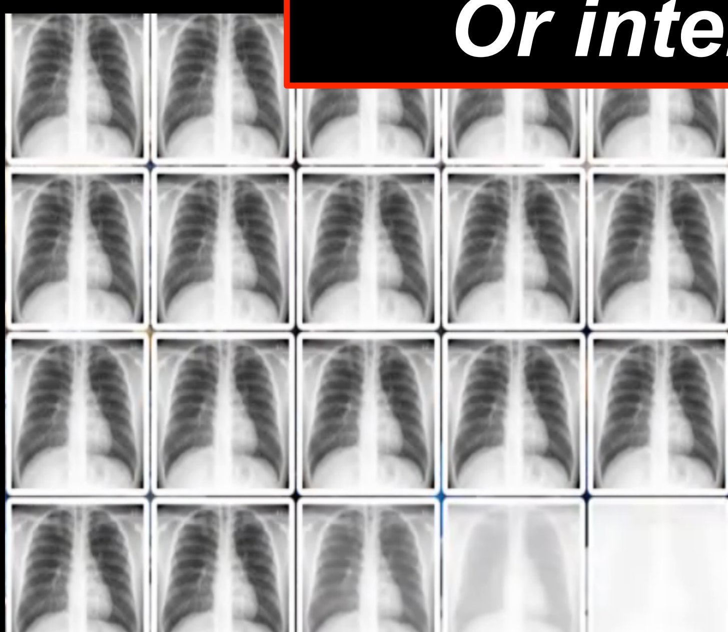
During periods of low solar activity, cosmic rays pose a threat not only to astronauts, but also to ordinary air travelers.

A 100,000 mile frequent flyer receives a dose equivalent to ~10 chest x-rays

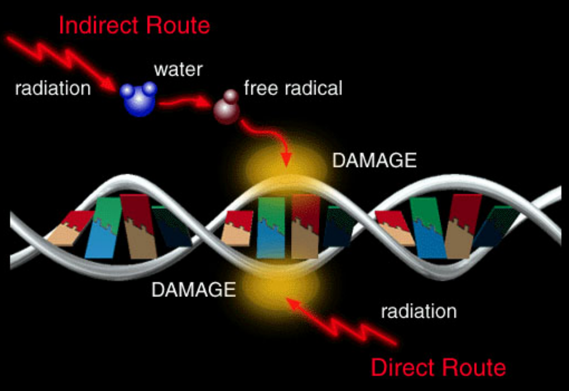


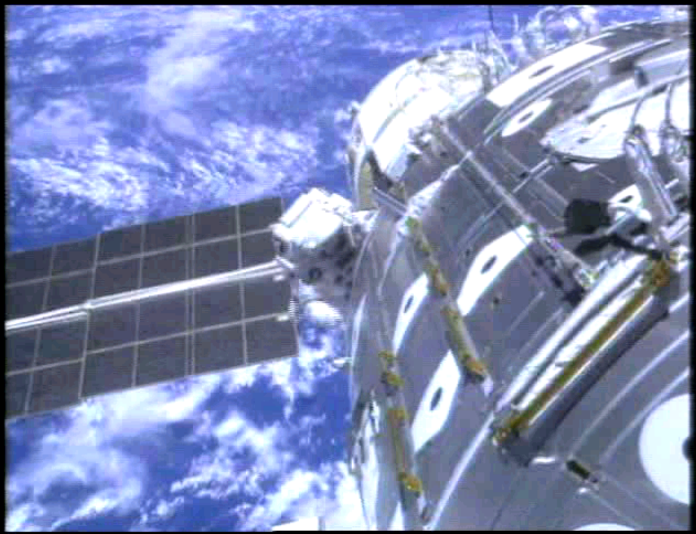
So what about people in space?

Or interplanetary space???



High Energy Particles Hazards to Humans



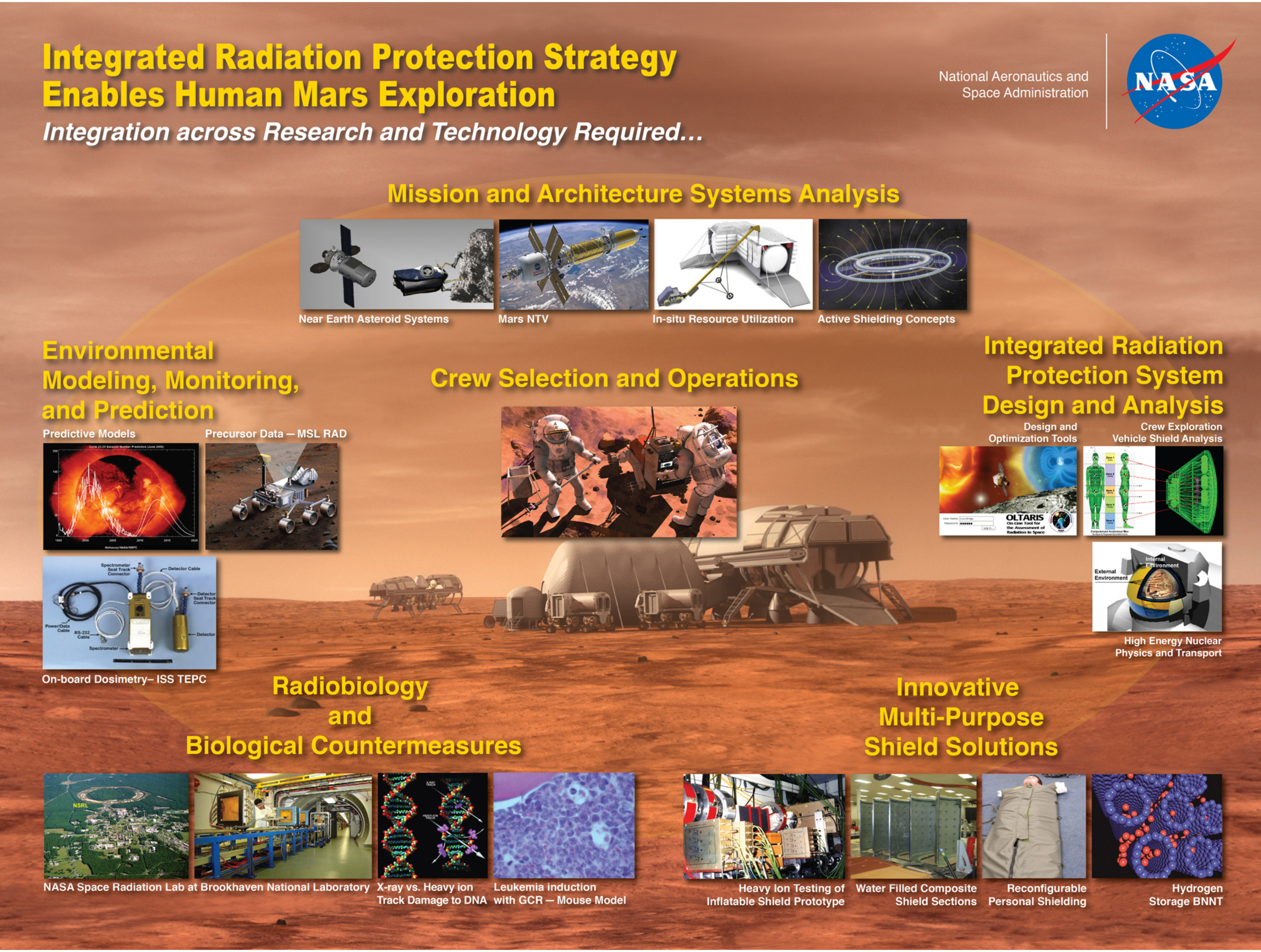


Humans in space

Space Shuttle, International Space Station, missions beyond low earth orbit to asteroid, moon, mars…

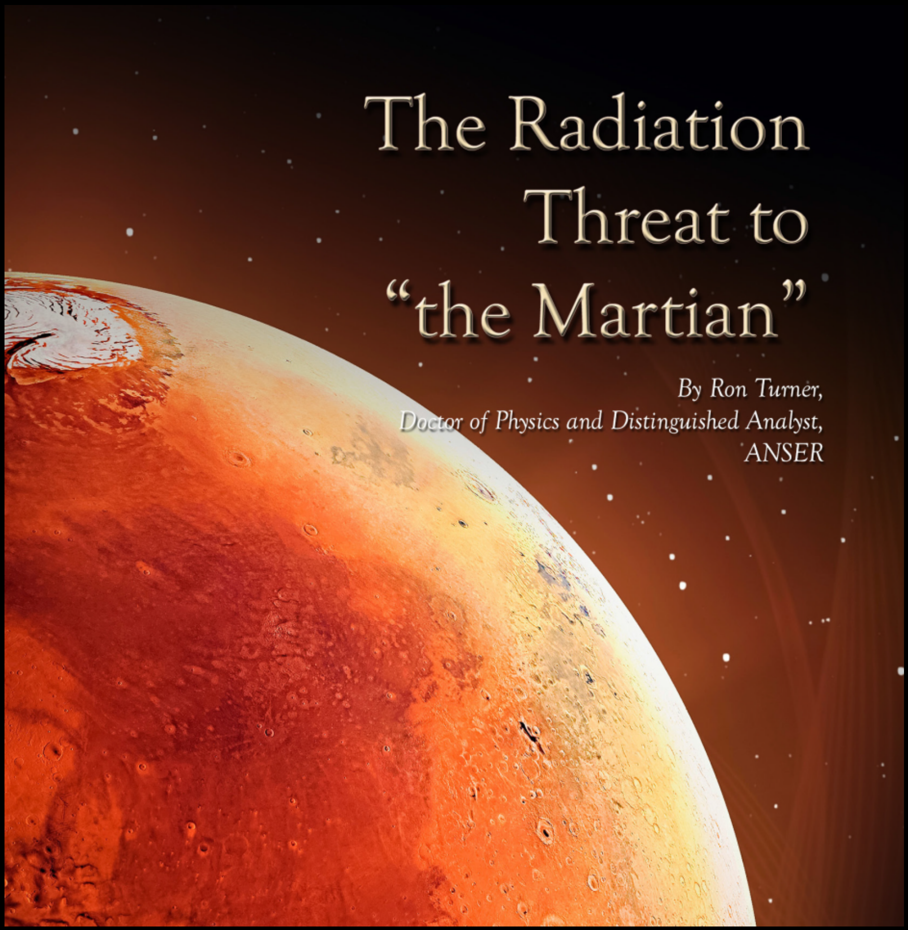
Crew/Passengers in high-flying jets and polar routes

Some airlines carry radiation detectors



Integrated Radiation Protection Strategy
Enables Human Mars Exploration
Integration across Research and Technology Required...
National Aeronautics and
Space Administration
NASA
Mission and Architecture Systems Analysis
Near Earth Asteroid Systems
Mars NTV
In-situ Resource Utilization
Active Shielding Concepts
Environmental
Modeling, Monitoring,
and Prediction
Predictive Models
Precursor Data — MSL RAD
On-board Dosimetry– ISS TEPC
Crew Selection and Operations
Integrated Radiation
Protection System
Design and Analysis
Design and
Optimization Tools
OLTARIS
Crew Exploration
Vehicle Shield Analysis
External
Environment
Internal
Environment
High Energy Nuclear
Physics and Transport
Radiobiology
and
Biological Countermeasures
NSRL
NASA Space Radiation Lab at Brookhaven National Laboratory
X-ray vs. Heavy ion
Track Damage to DNA
Leukemia induction
with GCR — Mouse Model
Innovative
Multi-Purpose
Shield Solutions
Heavy Ion Testing of
Inflatable Shield Prototype
Water Filled Composite
Shield Sections
Reconfigurable
Personal Shielding
Hydrogen
Storage BNNT

What About Mars?



The #1 movie in theatres right now is The Martian, a film adaptation of Andy Weir's eponymous book. It tells the heart-pounding story of fictional astronaut Mark Watney, who is stranded on Mars.

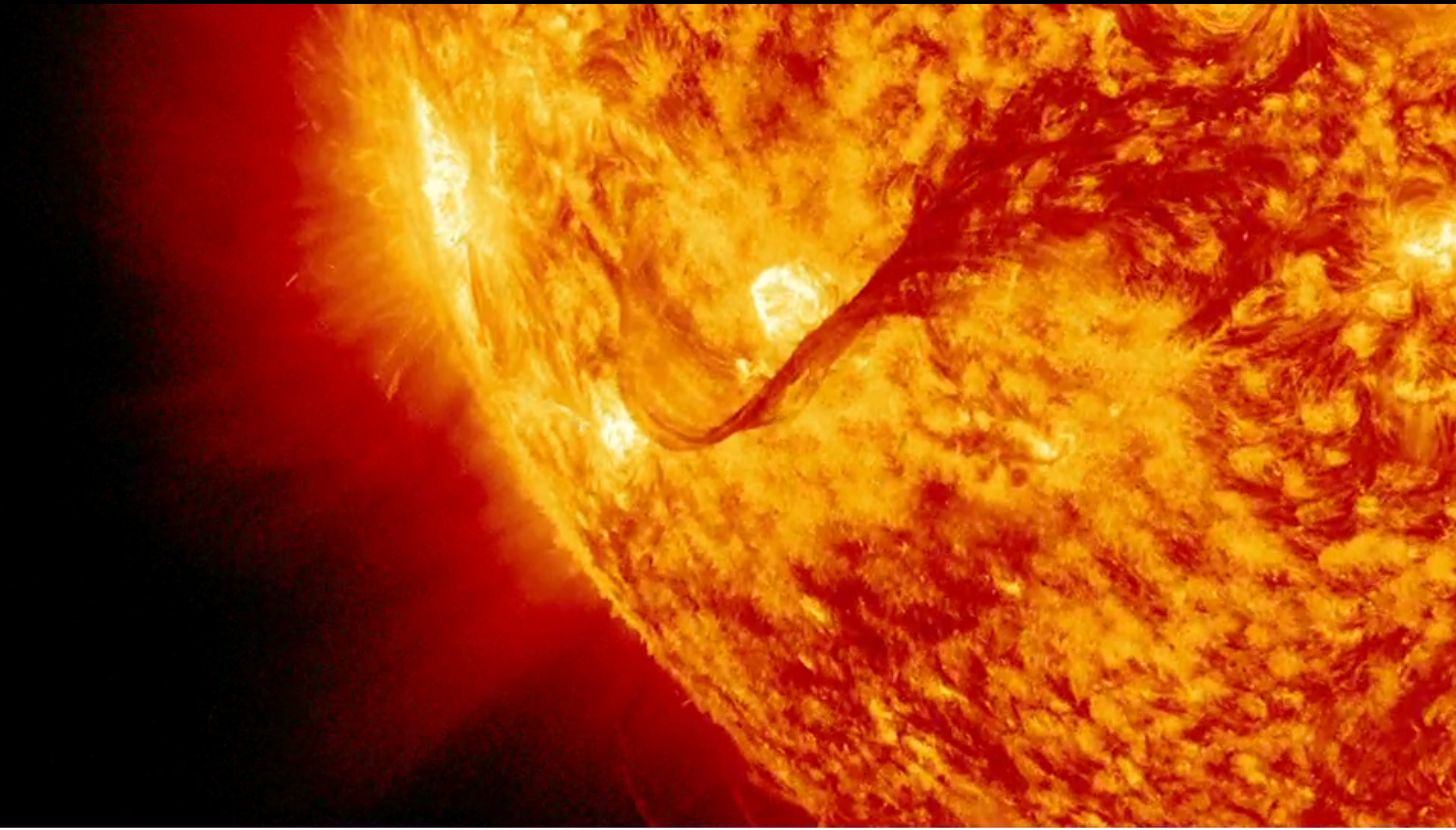
It's a thrilling adventure told with considerable accuracy—except, perhaps, for one thing.

Andy Weir does a good job of representing the risks faced by Mark Watney stranded on Mars, but he is silent on the threat of radiation, not just to Mark but particularly to the crew of the Hermes as they execute a daring rescue mission that more than doubles their time in deep space," according to Dr. Ron Turner.

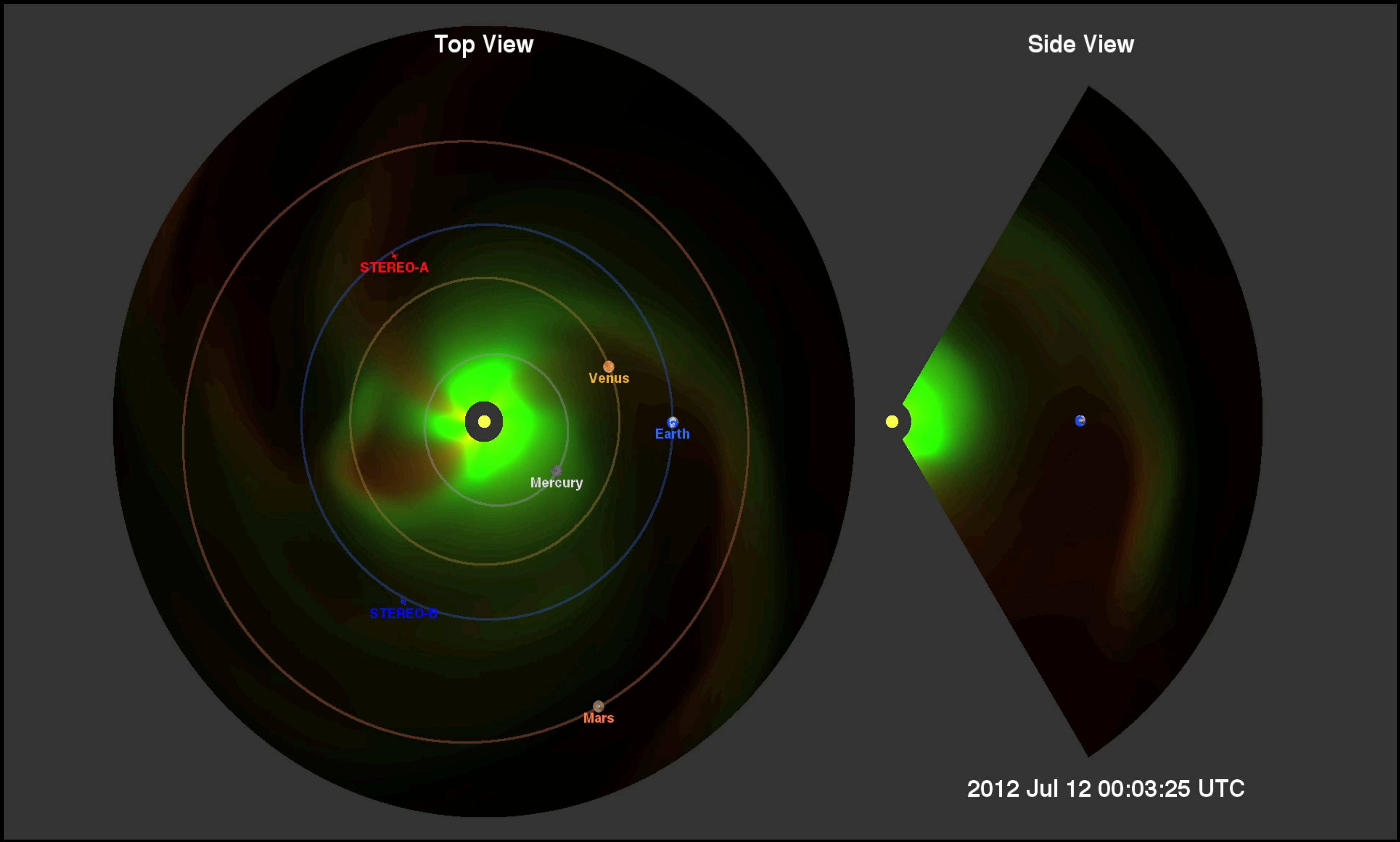
Watney is actually safer than the crew of the Hermes. Turner explains: "The radiation exposure is significantly less on the surface of Mars. For one thing, the planet itself reduces exposure by half. The atmosphere, while thin, further reduces the dose. The dose rate on Mars, while high, is only about 1/3rd of that on the Hermes."

We’re entering a new era of
Interplanetary Space Weather

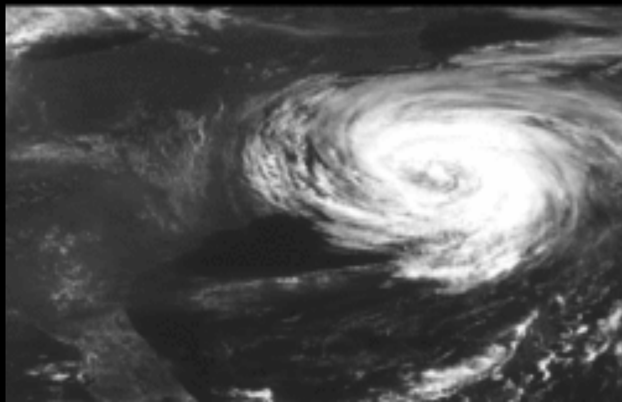
This is possible because
we’ve got the Sun surrounded.

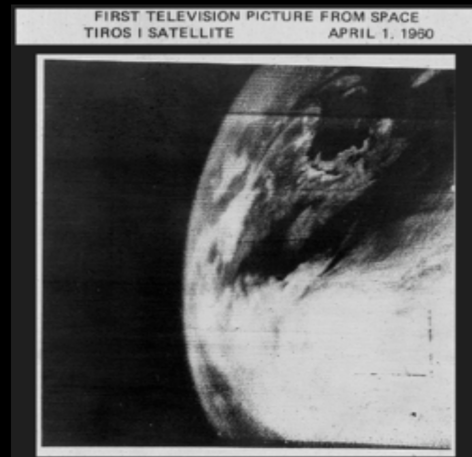


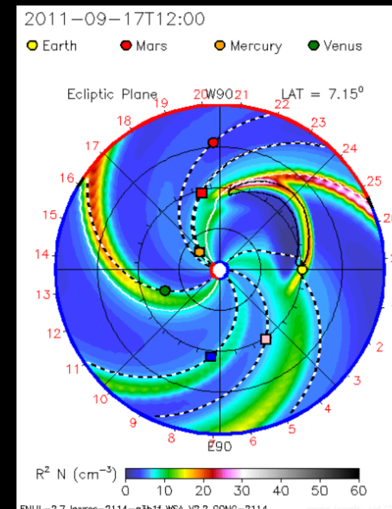
Interplanetary Space Weather: A New Paradigm



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

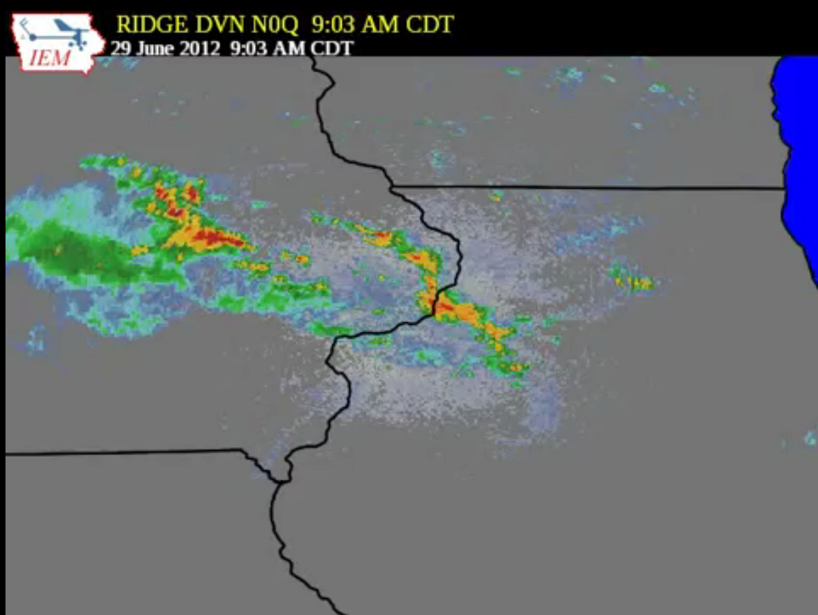






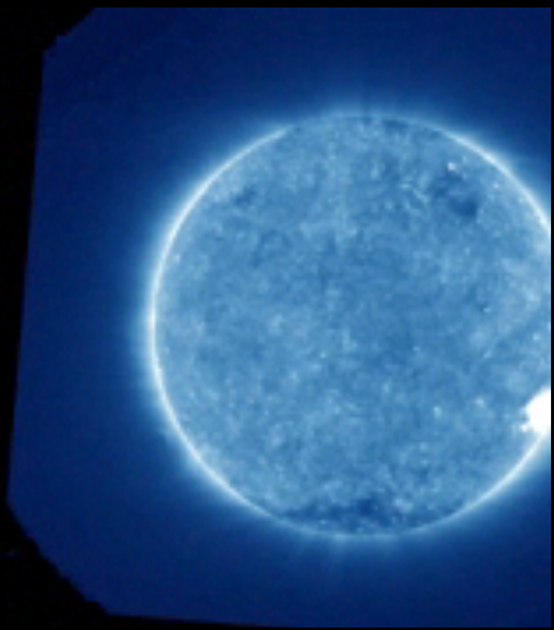
Tropospheric Weather: Storm Tracking is Essential for Mid-Term Forecasting

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



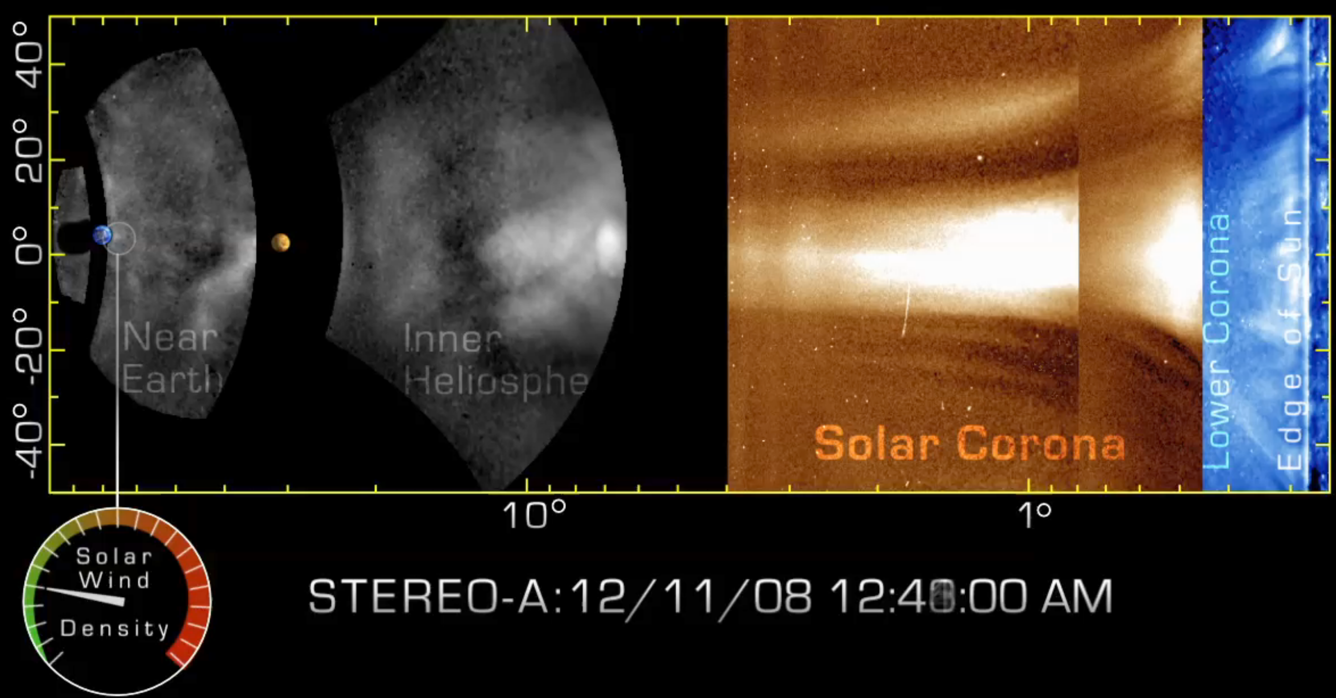
Weather in the mid-west today is Washington's weather tomorrow.

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 ultra hot corona to impact with the Earth’s magnetosphere

STEREO includes 5 telescopes that monitor the sky at large angles from the Sun



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.

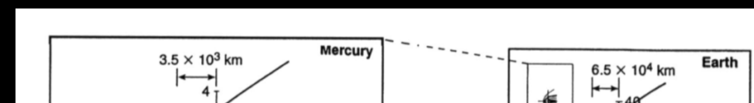
Spacecraft operations are also key. Energetic particles accelerated by solar storms can cause onboard computers to reboot, introduce confusing noise in cameras and other digital sensors, or simply accumulate on the surface of a spacecraft until a discharge causes serious problems.

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-Earth System Science:
Growth from a “consuming” science to a “producing” science for the benefit of humankind

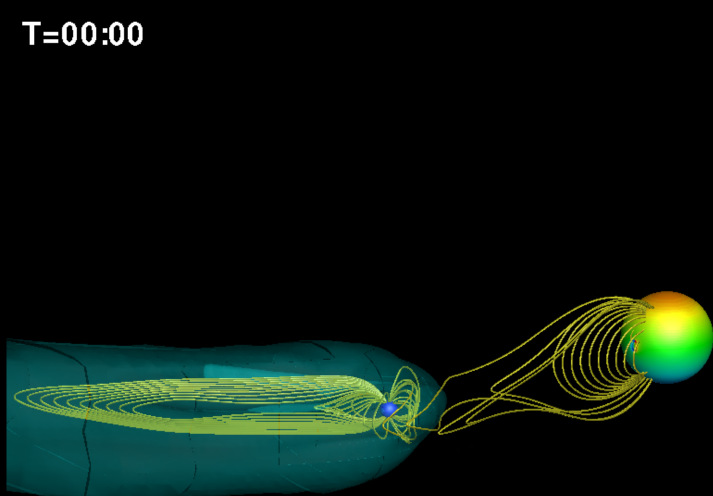
Space Weather is no longer the domain of Earth only!

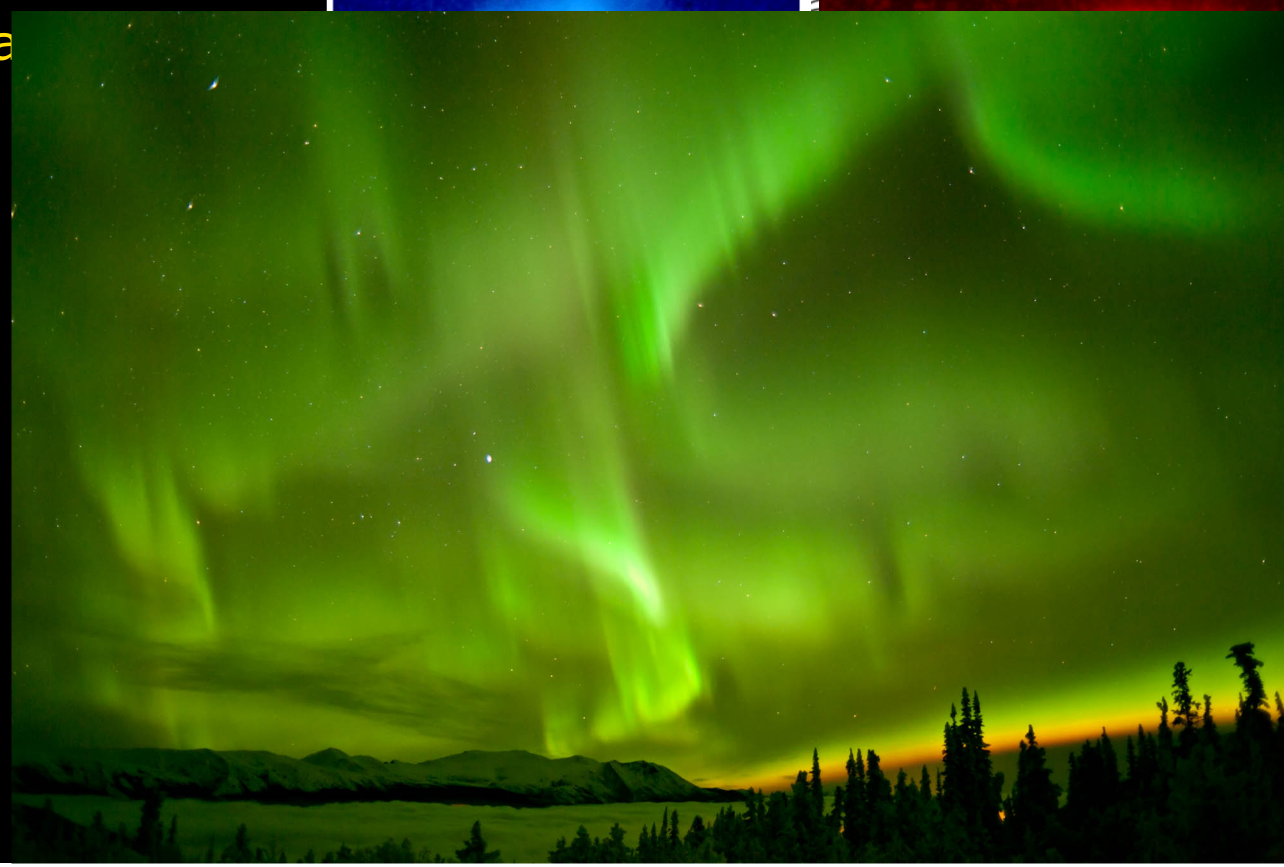
Space Weather is now also Interplanetary!!

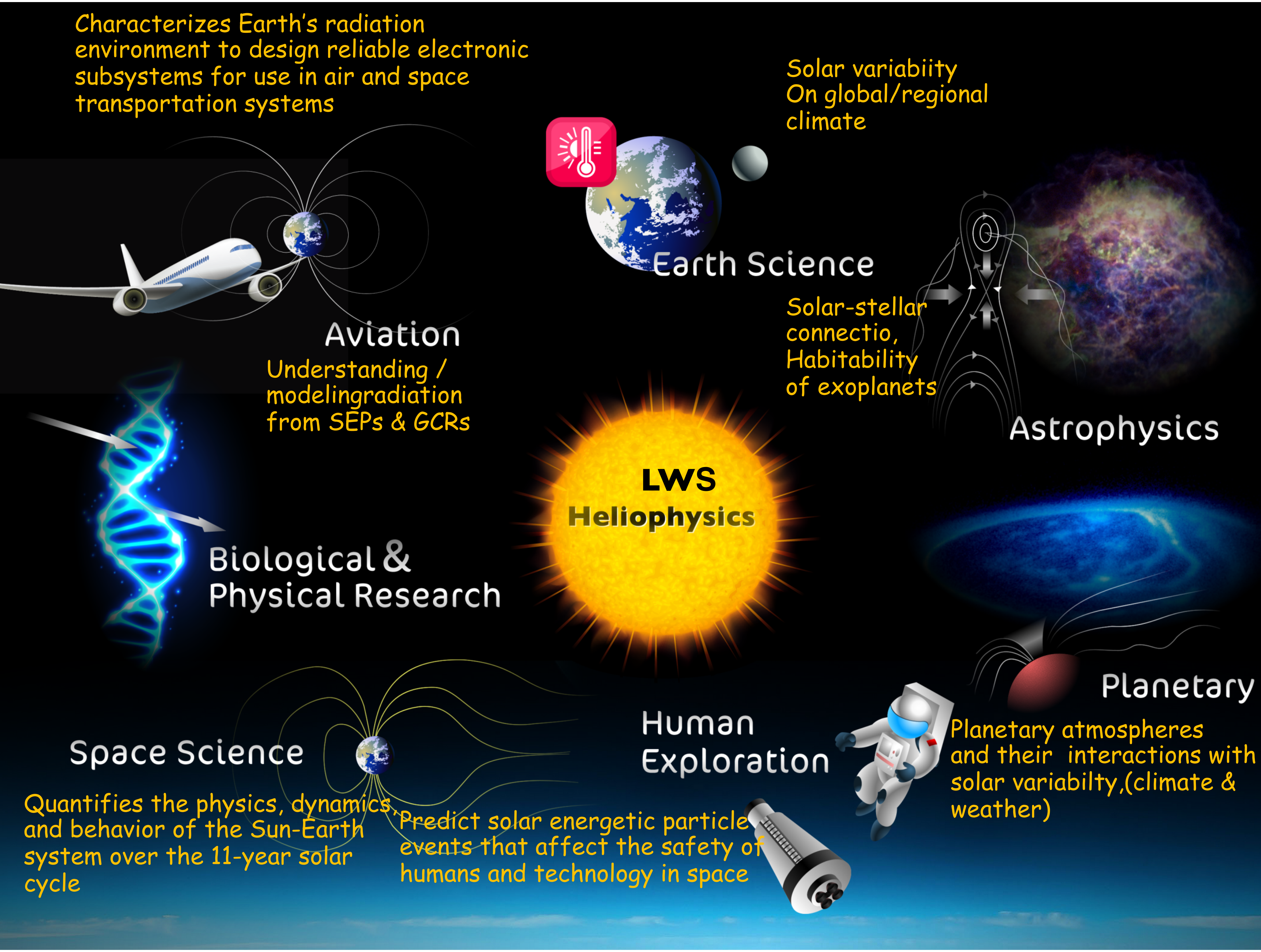


Space Weather just became Exopla

Extreme Space Wea






Characterizes Earth's radiation environment to design reliable electronic subsystems for use in air and space transportation systems
Solar variabiity On global/regional climate
Earth Science
Aviation
Understanding / modelingradiation from SEPs & GCRs
Solar-stellar connectio, Habitability of exoplanets
Astrophysics
LWS
Heliophysics
Biological & Physical Research
Planetary
Human Exploration
Space Science
Planetary atmospheres and their interactions with solar variabilty,(climate & weather)
Quantifies the physics, dynamics, and behavior of the Sun-Earth system over the 11-year solar cycle
Predict solar energetic particle events that affect the safety of humans and technology in space

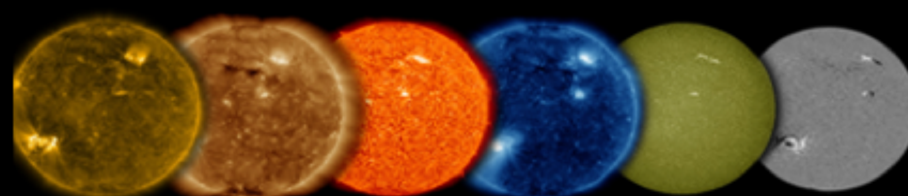
LWS Accomplishments
A New Discipline is Born

Since 2007-2015, we have had:

Total Students ~300
International Students ~130
PhD Level ~250
Masters Level ~50

Developed series of heliophysics textbooks – a fourth is in work

Heliophysics Institutes: Interdisciplinary topics chosen annually by steering committee of international experts.



LWS missions: Solar Dynamics Observatory, launched in 2010 and Van Allen Probes, launched in 2012

Jack Eddy Postdoctoral Fellowship 2010-2015, 21 appointments

To train the next generation of researchers needed in the emerging field of heliophysics, in honor of the pioneering

National Air and Space Museum Debuts Must-See Sun Video Wall

- Unveiled on March 18th, the 7 by 6 ft. Video Wall streams data from NASA's Solar Dynamics Observatory, or SDO.

- SDO takes ten images of the differing layers of the Sun's atmosphere every 12 seconds with an image size of 4096 x 4096 pixels. By comparison, a high-definition TV can only display 1920 x 1080 pixels.

- Tremendous computing power is required to visualize the data from SDO. This data is improving our understanding of the Sun's ever-changing magnetism.

- The Video Wall is located at the base of the Skylab exhibit in the Space Race Gallery.

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