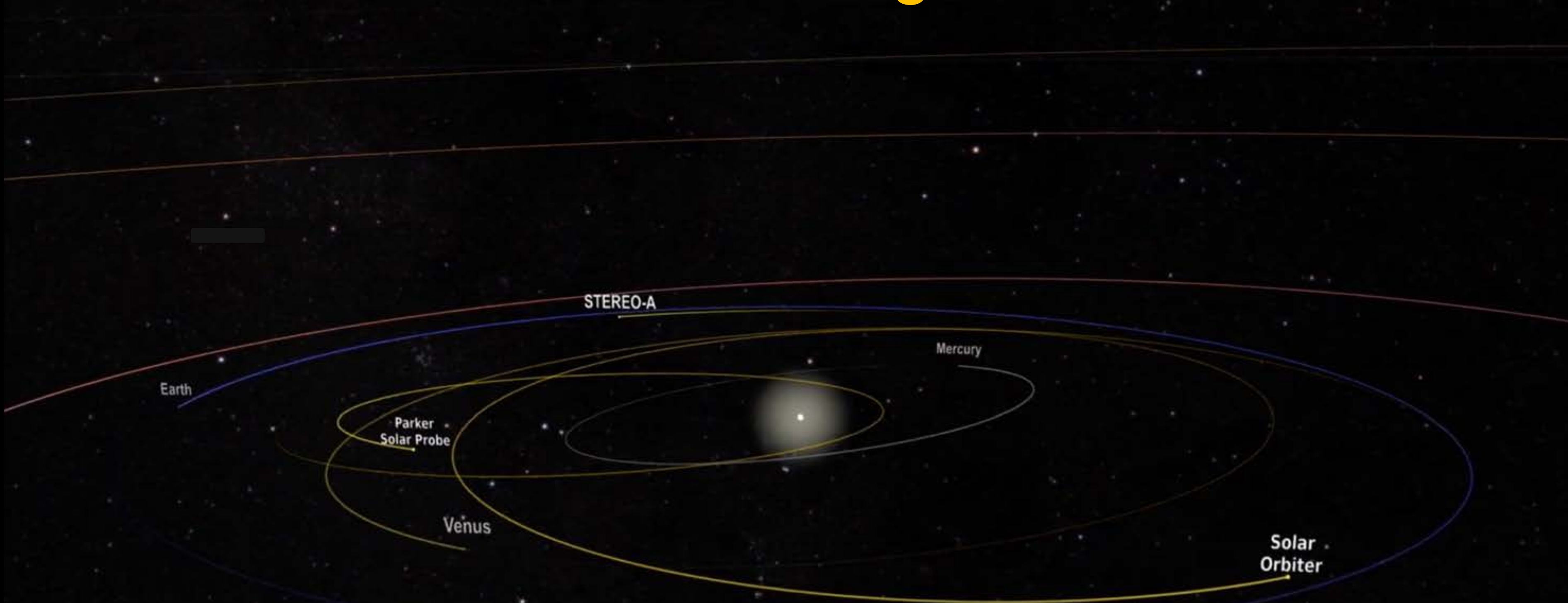
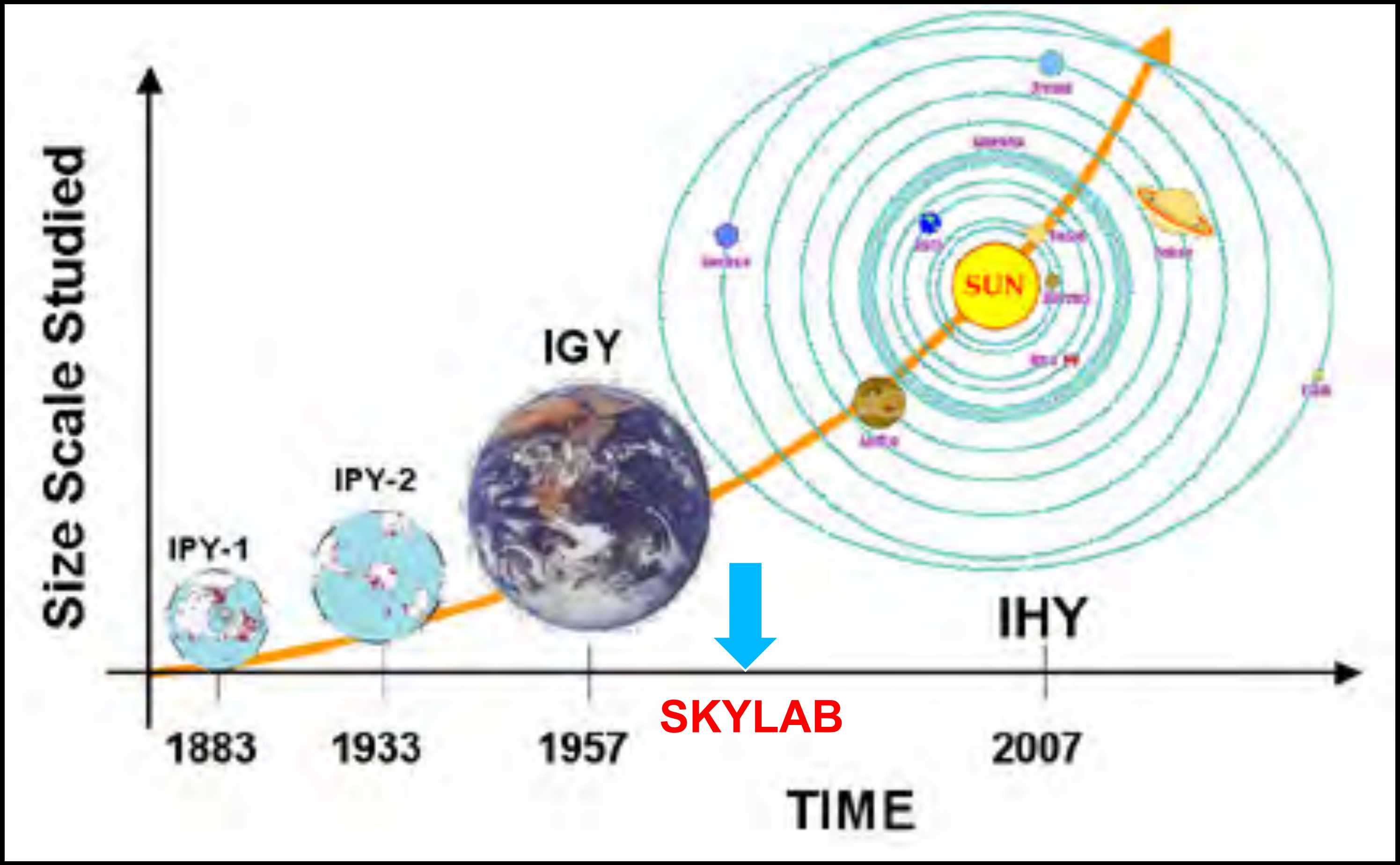
# Heliophysics System Science in the Era of Big Data




Lika Guhathakurta
Senior Advisor for New Initiatives, GSFC
Program Scientist, HPD
*HSS23 Virtual, 17th July 2023*

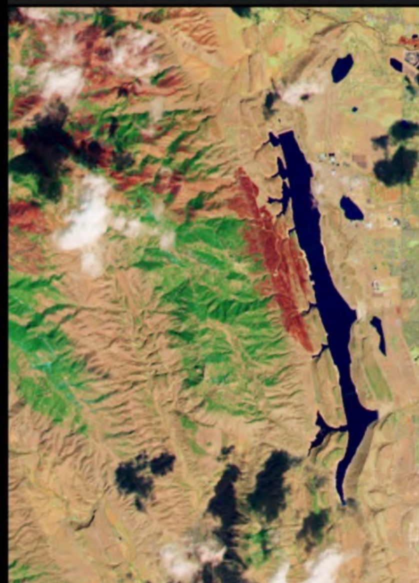
# Evolution of System Studies




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

# Science Mission Directorate

HELIOPHYSICS



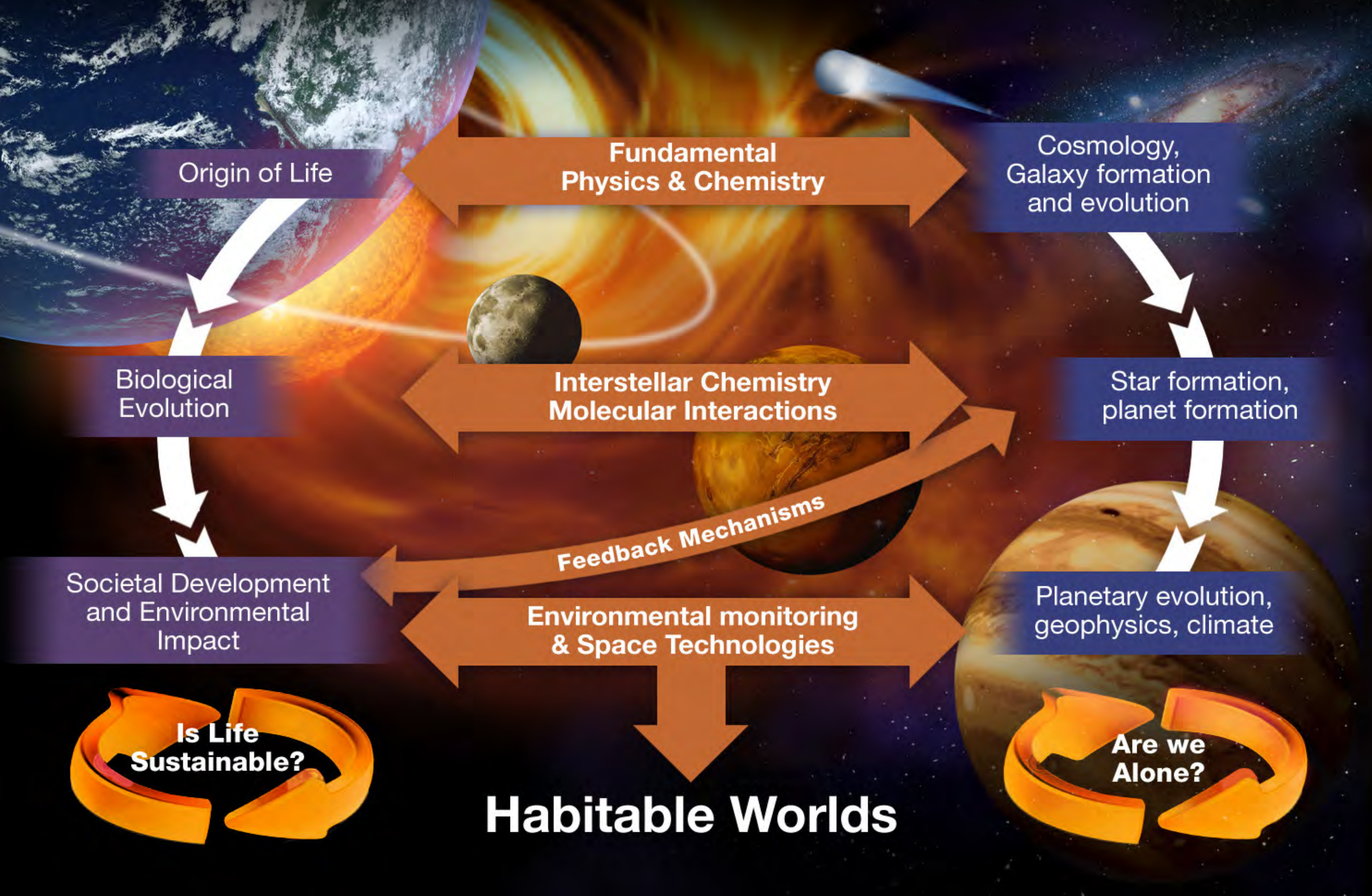
EARTH SCIENCE

PLANETARY SCIENCE

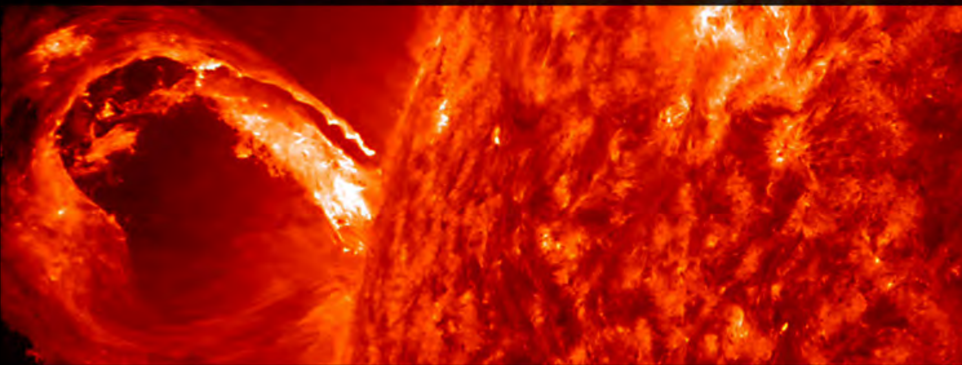
ASTROPHYSICS

An Integrated Program of Science

# NASA Science is Interconnected



## Heliophysics



Make possible accurate predictions of solar phenomena throughout the solar system and its impact on earth, planets and interplanetary medium

## Earth Science

Enable more accurate and useful environmental predictions, including weather, climate, natural and human induced events

## Planetary Science

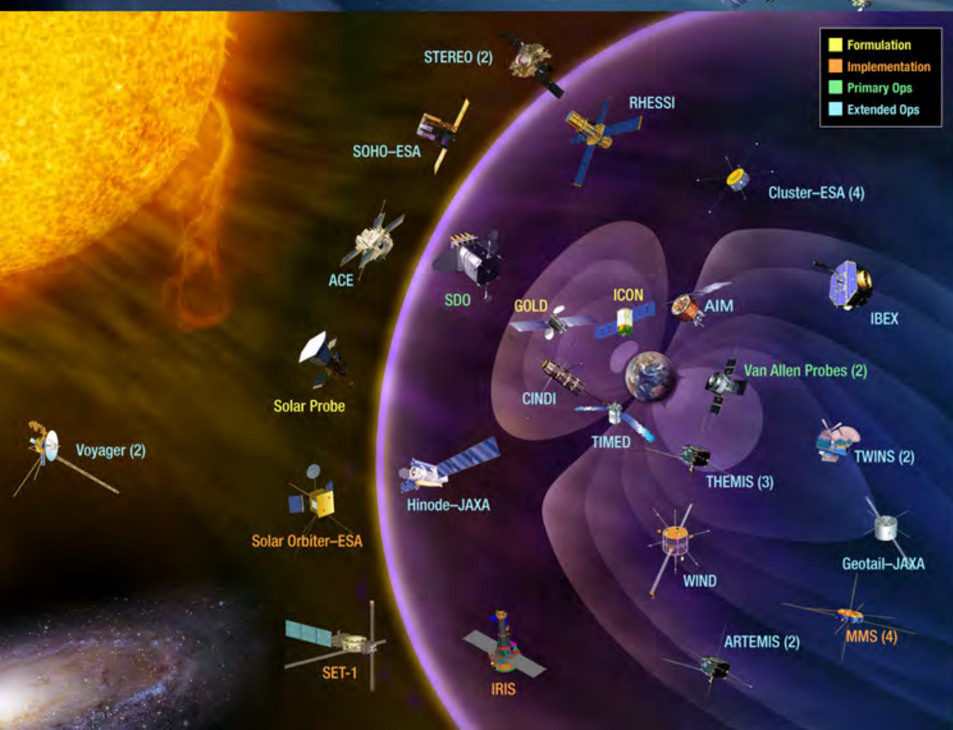
Explore habitable environments across the solar system with human and robotic explorers

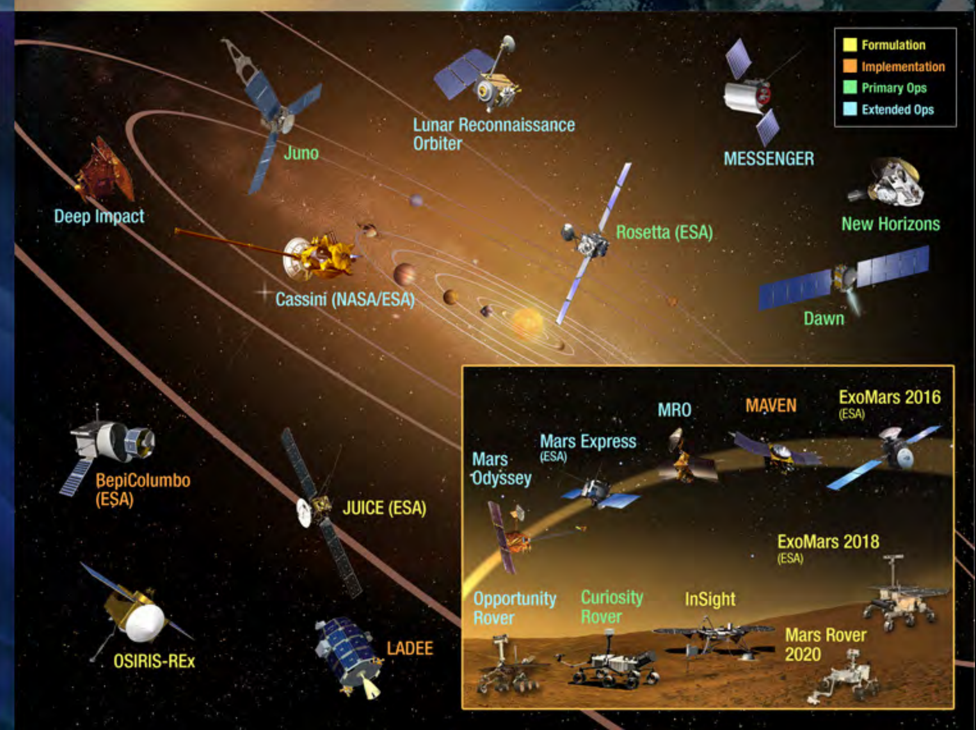
## Astrophysics

Answer the question:
“Are we alone?”


Formulation
Implementation
Primary Ops
Extended Ops
GPM
OCO-3
QuikSCAT*
OCO-2
GRACE-FO (2)
SMAP
SAGE III (on ISS)
CYGNSS
ICESat-2
SWOT
TRMM
EO-1
Landsat-7
(USGS)
ACRIMSAT
SORCE
Terra
Aqua
Aquarius
CloudSat
Suomi NPP
(NOAA)
CALIPSO
Aura
GRACE (2)
Jason
OSTM/Jason 2
(NOAA)
Landsat-8
(USGS)

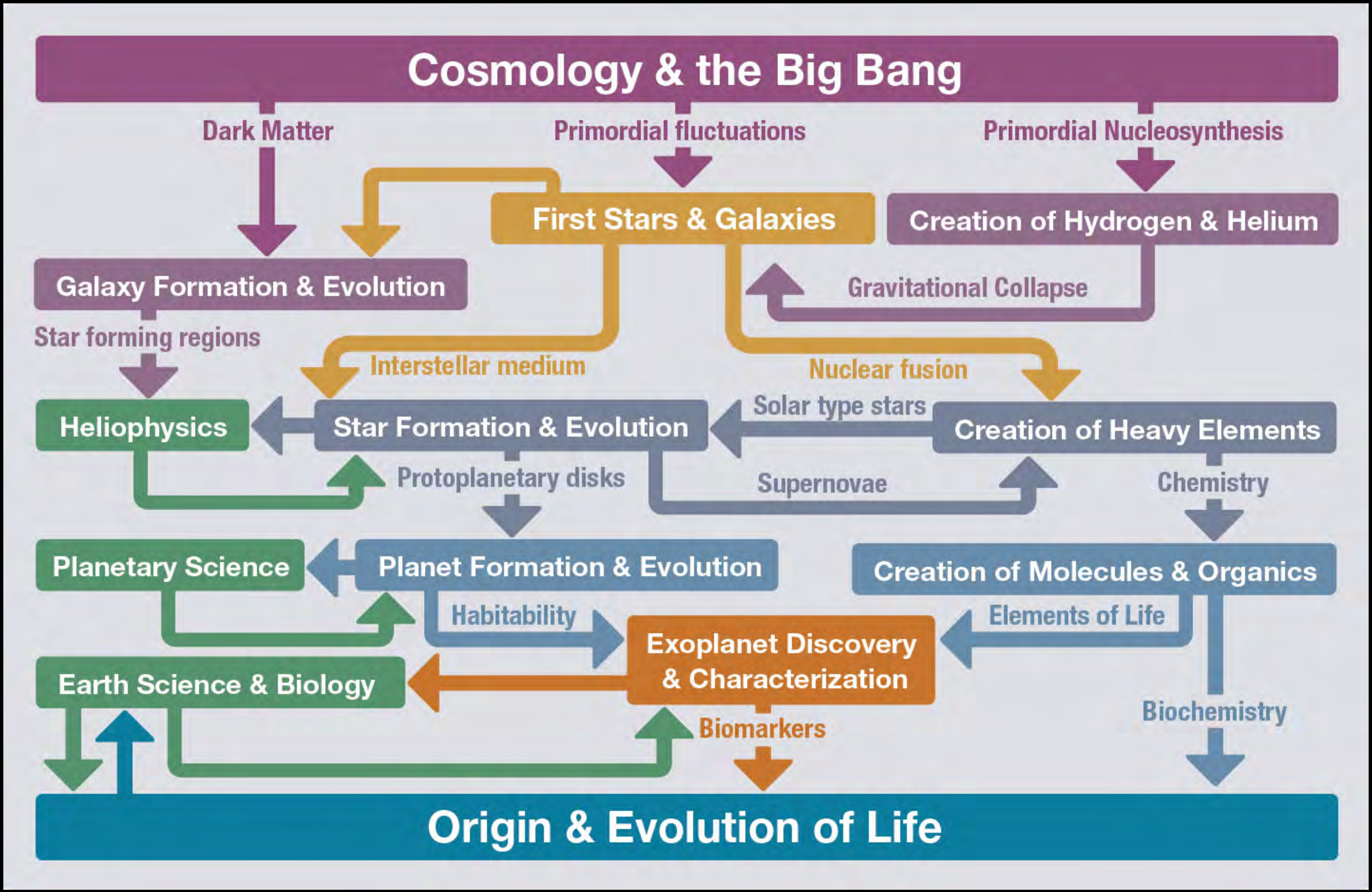

Formulation
Implementation
Primary Ops
Extended Ops
XMM-Newton (ESA)
12/10/1999
Swift
11/20/2004
Suzaku (JAXA)
7/10/2005
Fermi
6/11/2008
Euclid (ESA)
2020
Planck (ESA)
5/14/2009
Spitzer
8/25/2003
Hubble
4/24/1990
Kepler
3/6/2009
Astro-H (JAXA)
2015
Chandra
7/23/1999
JWST
2018
NICER (on ISS)
2016
NuSTAR
6/13/2012
TESS
2017
LISA Pathfinder (ESA)
2015
SOFIA
Full Ops 2014


Formulation
Implementation
Primary Ops
Extended Ops
STEREO (2)
RHESSI
SOHO–ESA
Cluster–ESA (4)
ACE
SDO
GOLD
ICON
AIM
IBEX
Van Allen Probes (2)
CINDI
Solar Probe
TIMED
TWINS (2)
Voyager (2)
THEMIS (3)
Hinode–JAXA
Solar Orbiter–ESA
Geotail–JAXA
WIND
ARTEMIS (2)
MMS (4)
SET-1
IRIS


Formulation
Implementation
Primary Ops
Extended Ops
Juno
Lunar Reconnaissance
Orbiter
MESSENGER
Deep Impact
New Horizons
Rosetta (ESA)
Cassini (NASA/ESA)
Dawn
MRO
MAVEN
ExoMars 2016
(ESA)
Mars Express
(ESA)
Mars
Odyssey
BepiColombo
(ESA)
JUICE (ESA)
ExoMars 2018
(ESA)
Opportunity
Rover
Curiosity
Rover
InSight
Mars Rover
2020
OSIRIS-REx
LADEE

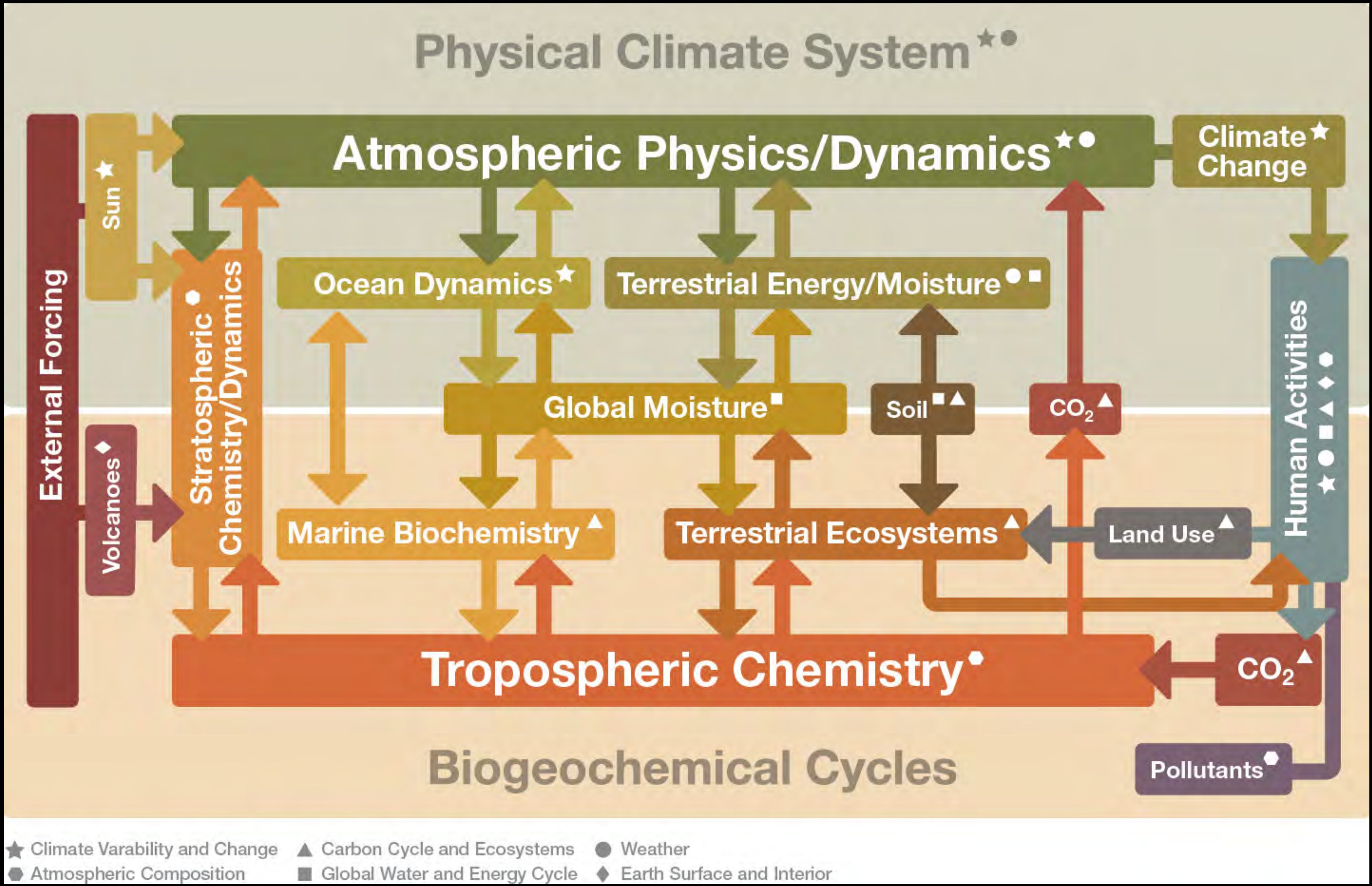
# Understanding the Universe

# Understanding The Astrophysics



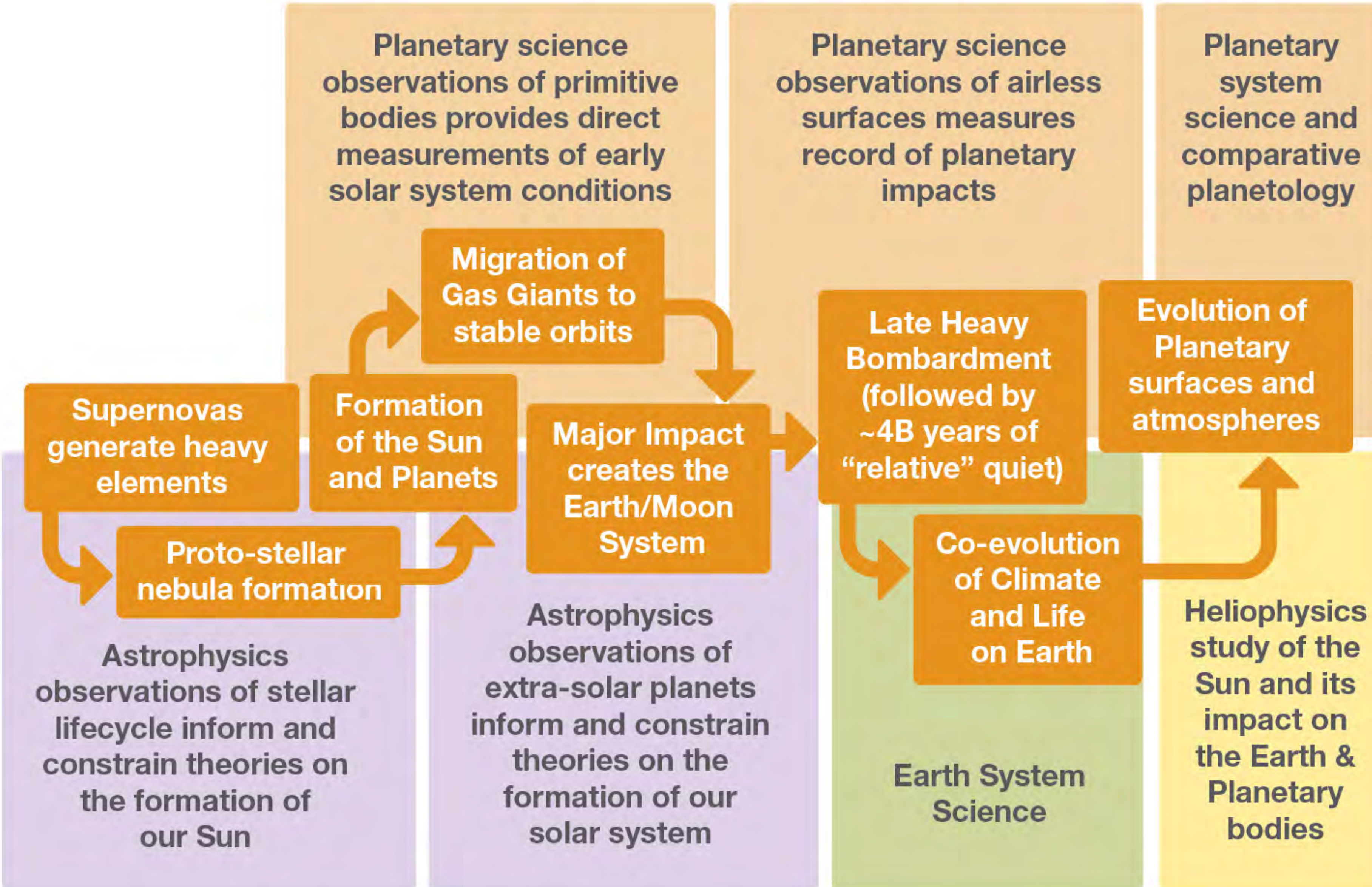
# Understanding the Earth as a System

# Understanding the Earth System

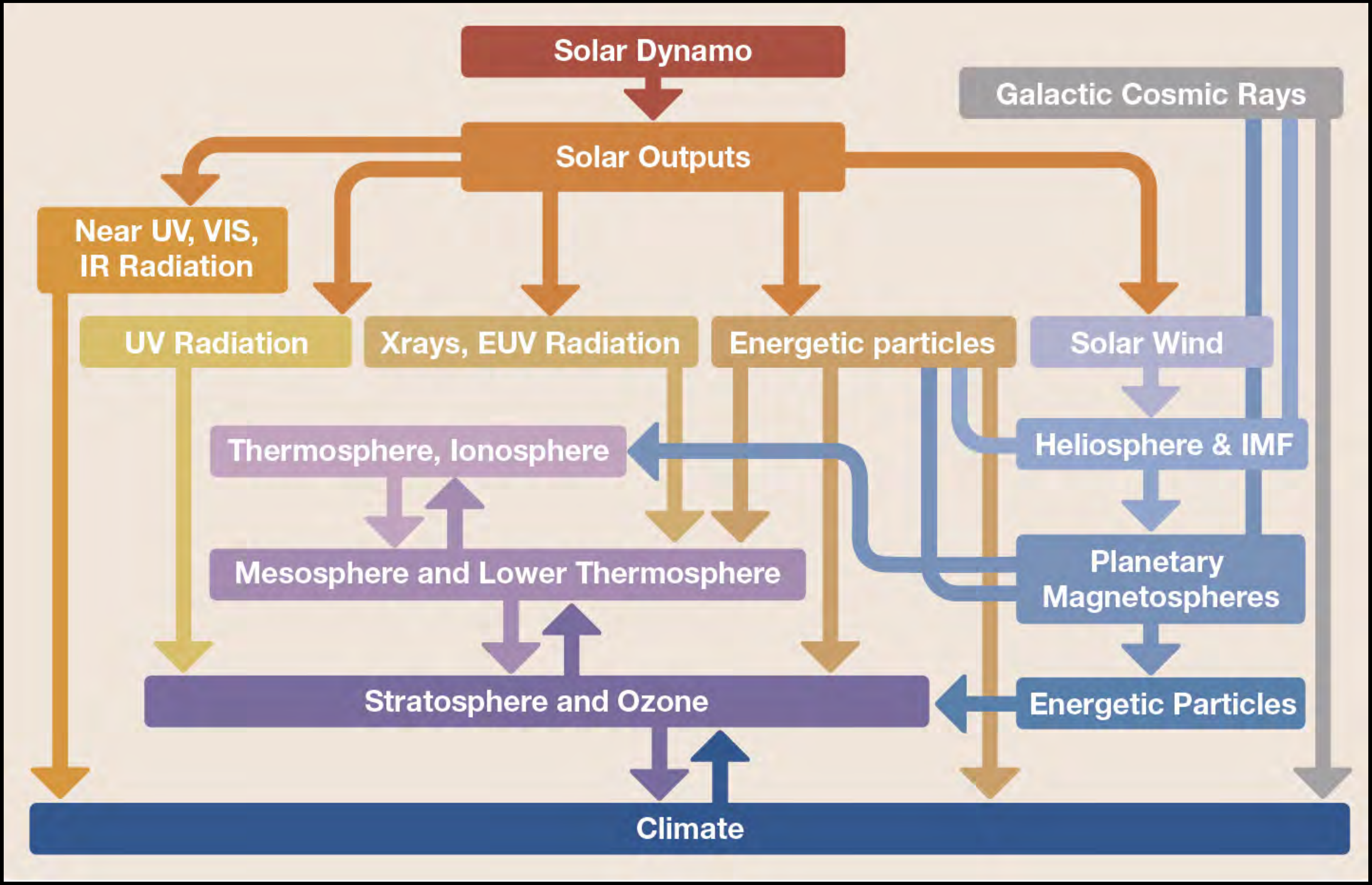


# Understanding our Solar System

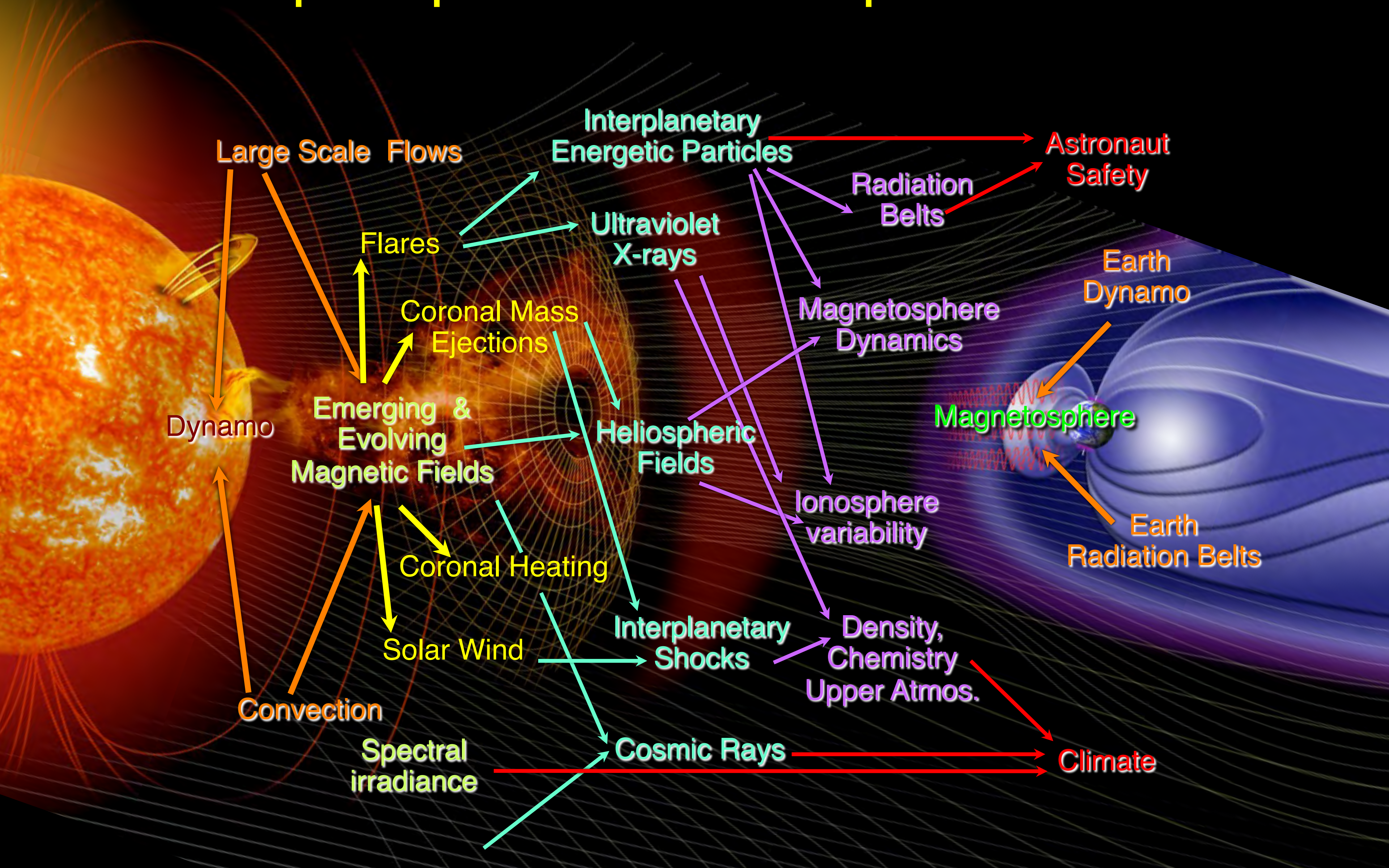
# Understanding the Planetary System



# Understanding the Sun’s System



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

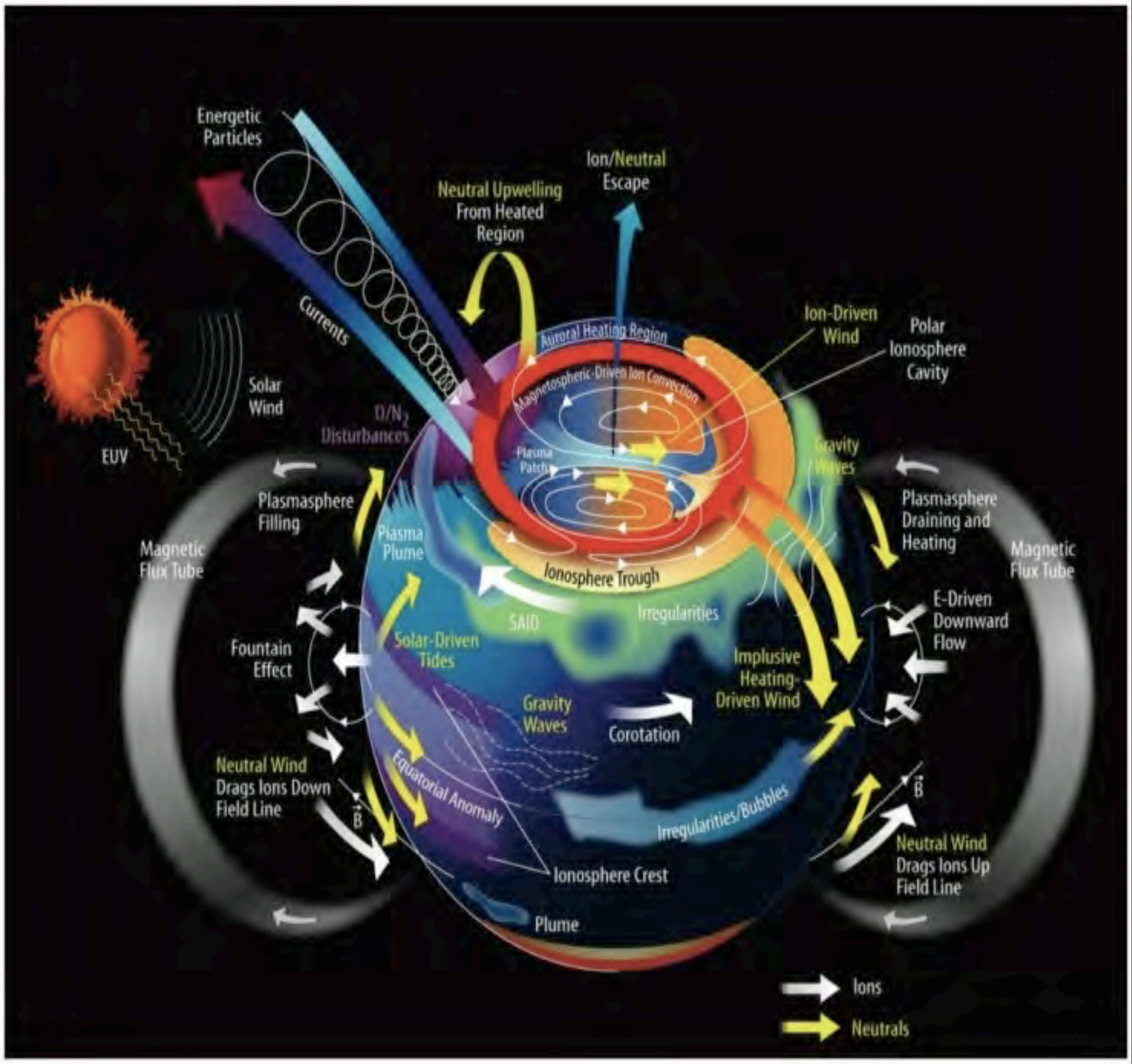



www.nasa.gov

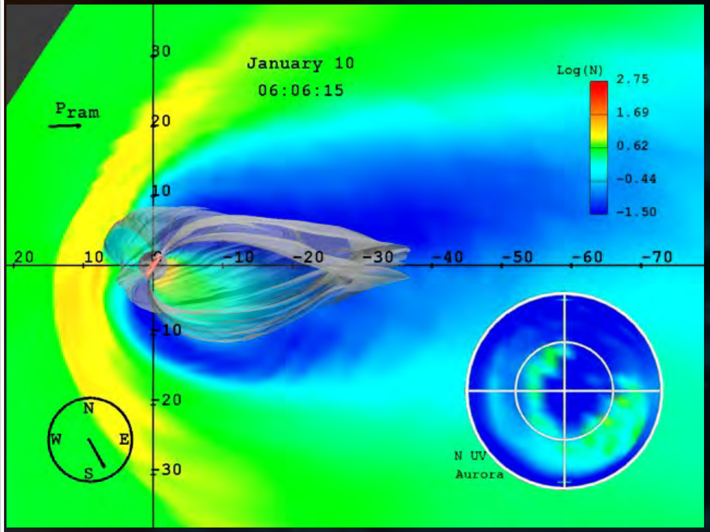
artist's impression

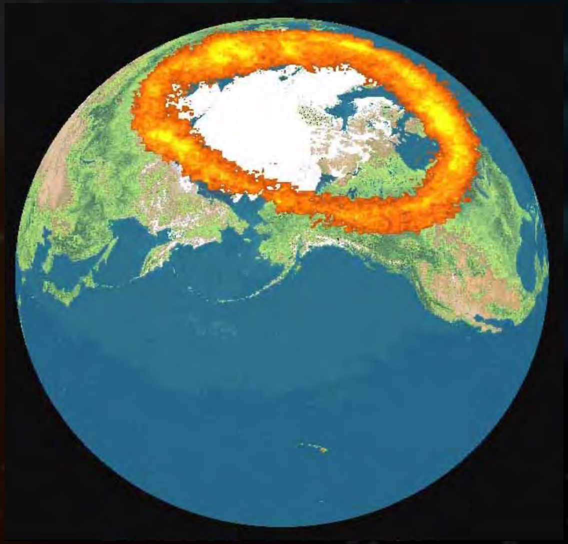
# Space Weather's Terrestrial Influence

(an example)




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



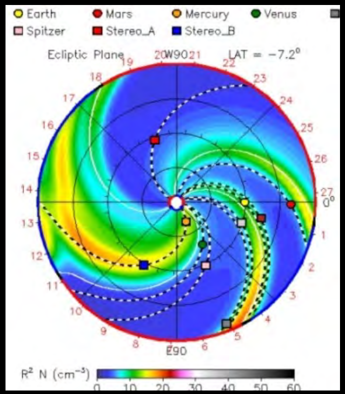
# What is Heliophysics

Heliophysics is an environmental science:

a unique hybrid between meteorology and astrophysics

It has an applied branch

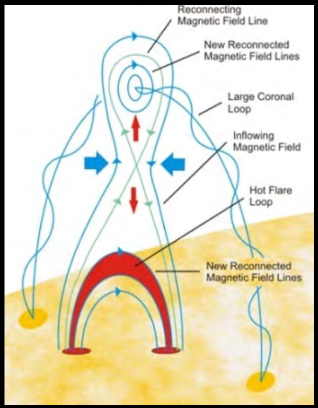
space weather




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

Applications directed science coordinated by NSF community

Living With a Star 2000, ILWS 2003

Applications directed science coordinated by NASA & international community

International Heliosphysical Year 2007

Add comparative heliospheric studies

# 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

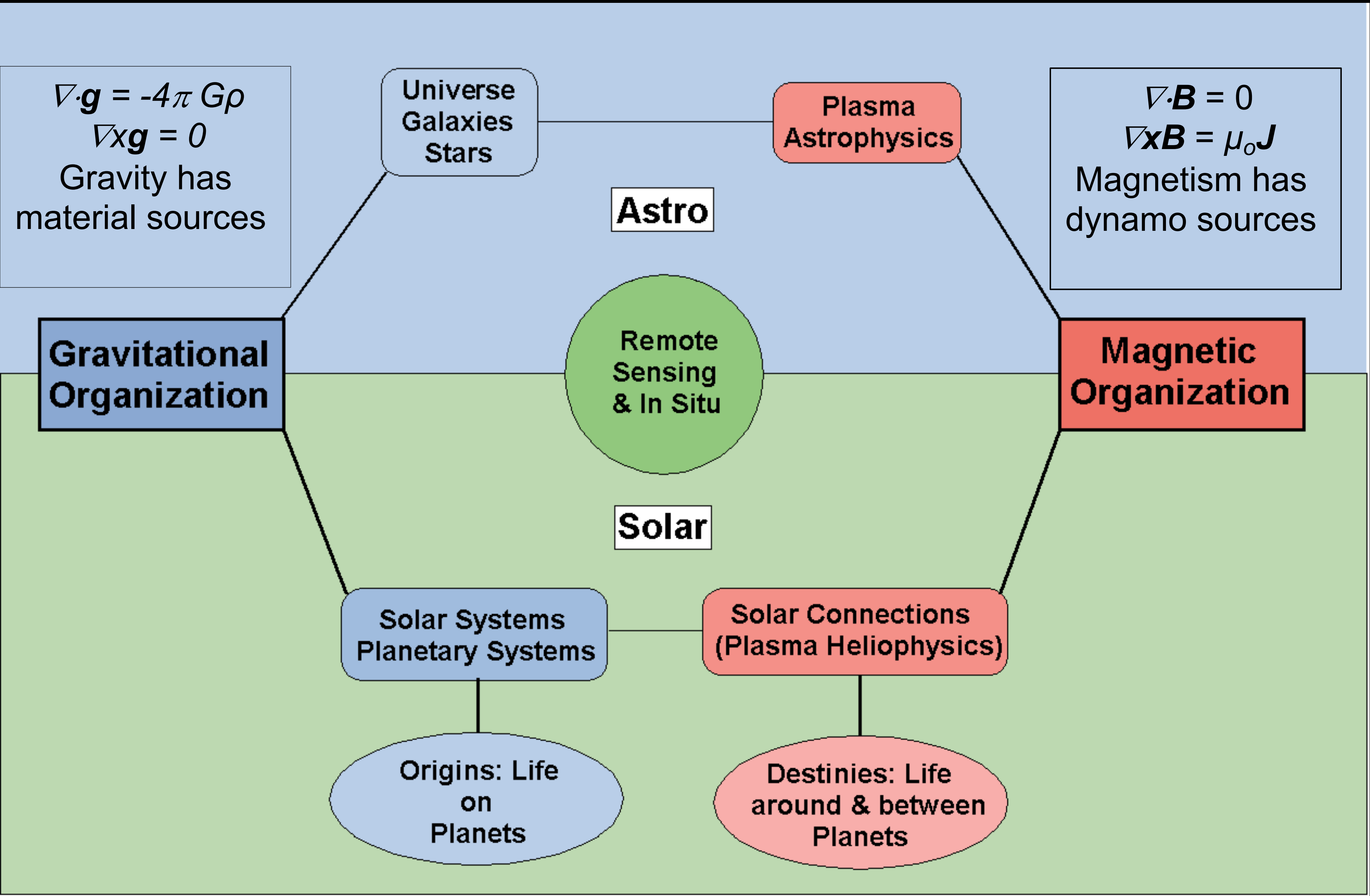
**BIOLOGY**
evolution, double helix

**GEOLOGY**
deep time, plate tectonics

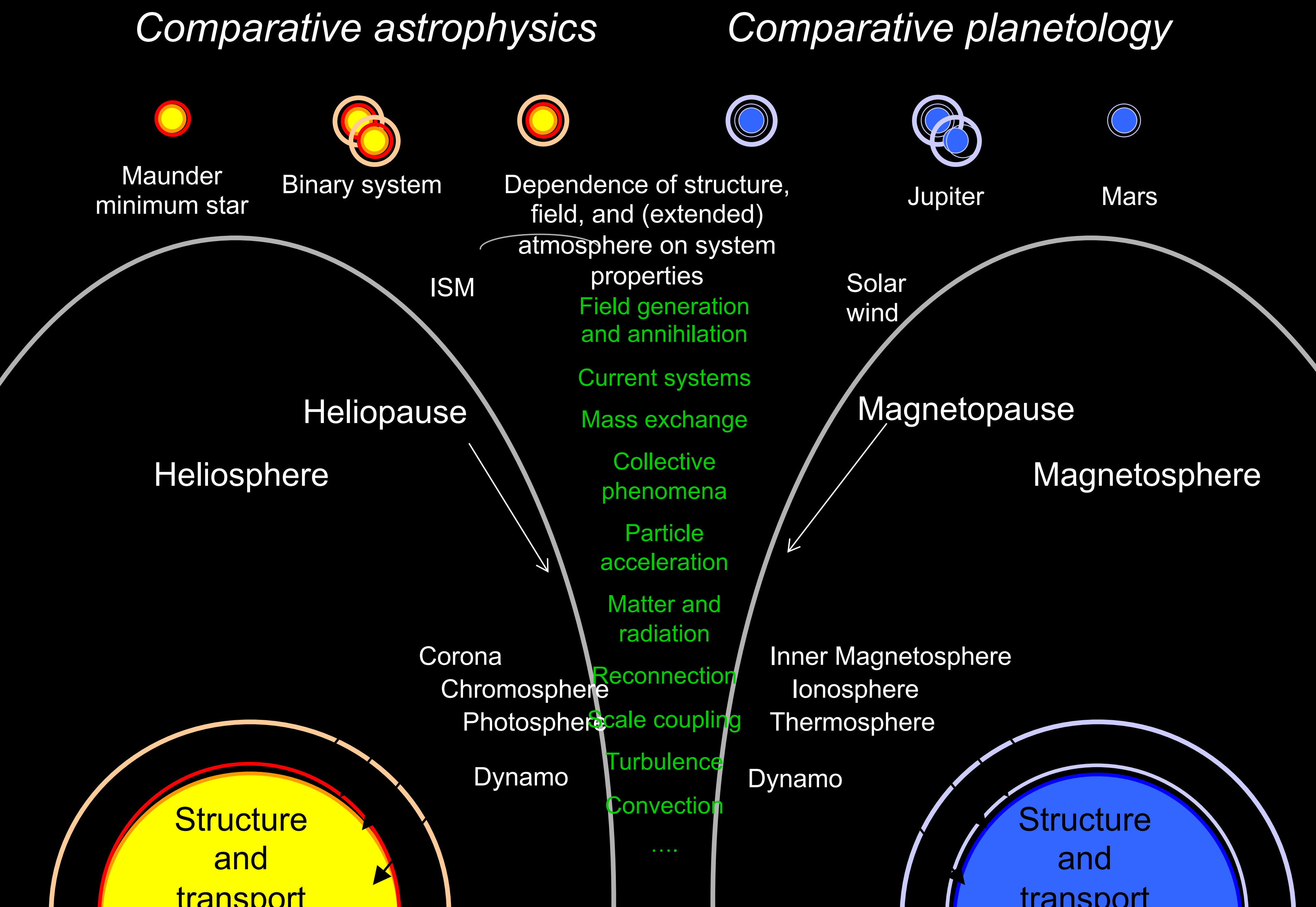
**METEOROLOGY**
Hadley cell, baroclinic instability

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

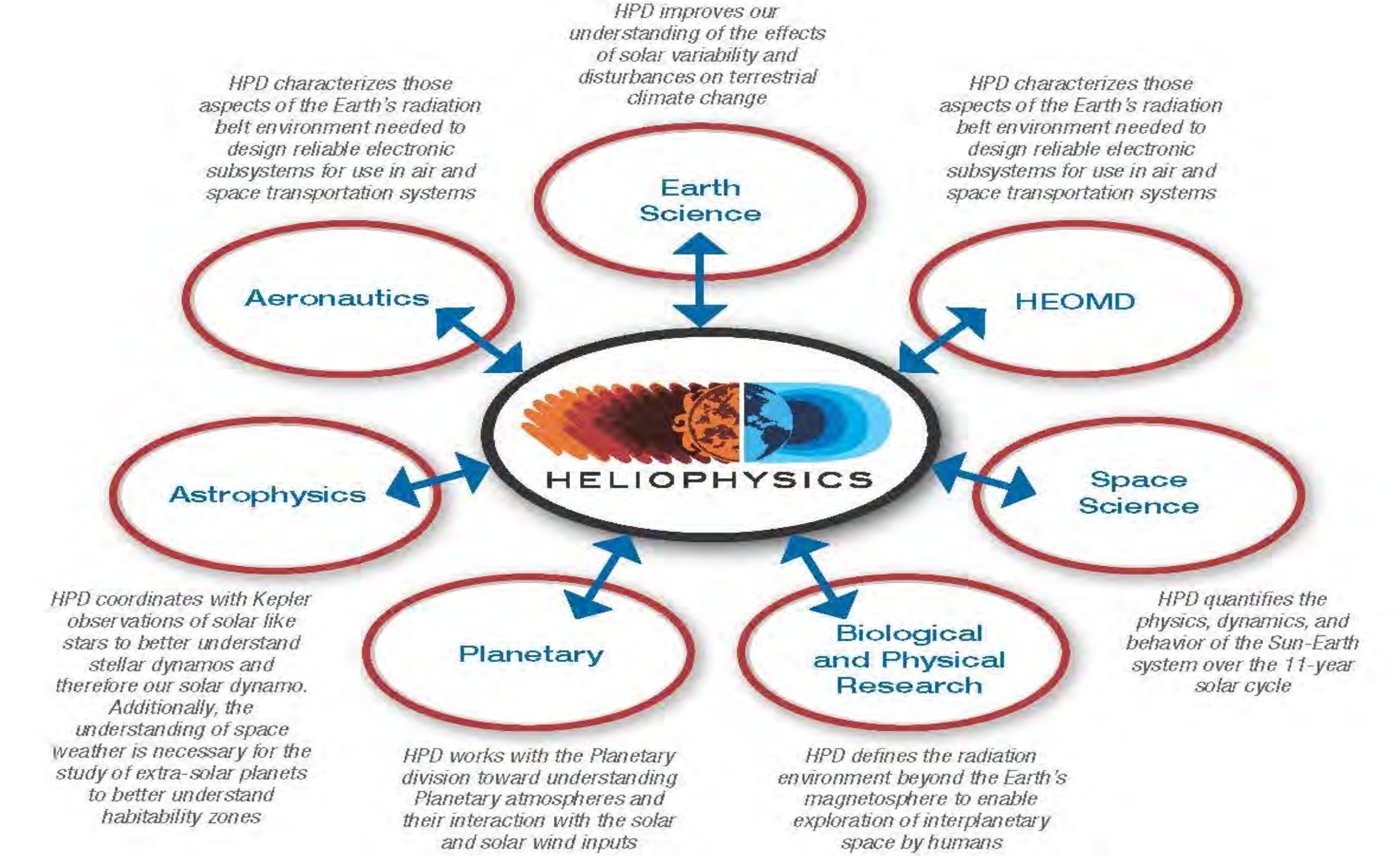
# Organization of the Universe By Long-Range Forces



# Exploiting natural parallels: Helio, Astro, Planetary & Earth



# Heliophysics Coordination with Exploration, Earth, Planetary, Astrophysics and Biological Sciences




*Examples of Heliophysics Coordinated Observations:*

- Astro to Helio – Kepler
- HEOMD to Helio – MSL/RAD
- Earth to Helio – SORCE, ACRIMSAT
- Helio to Earth – TIMED, AIM, SDO/EVE
- Helio to Planetary – ARTEMIS
- Planetary to Helio – Juno, MAVEN, Messenger, MSL, LADEE, LRO, Cassini

# SkyLab Heliophysics GAME CHANGERS

The Corona is hot and controlled by magnetic fields

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

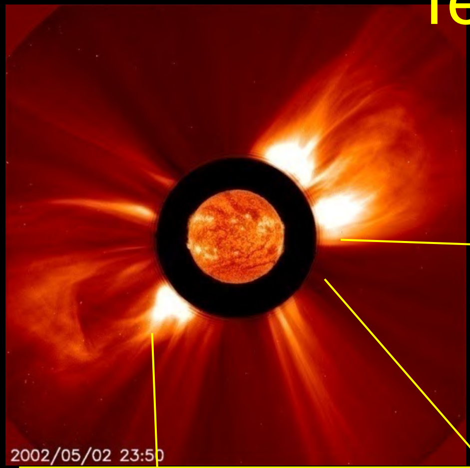
High-Speed Solar Wind originates from coronal holes

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

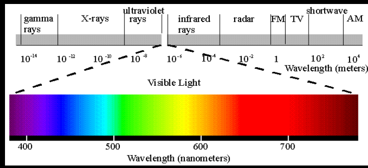
Mass from the corona is ejected into interplanetary space

➔ 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

Matter

Charged Particle Radiations 10-30 minutes

S-Scale

**Blame it on *B (magnetic field)***

Radiation: astronaut health. aviation & satellite function

**NOAA Space Weather Scales**

Matter

Magnetic Fields

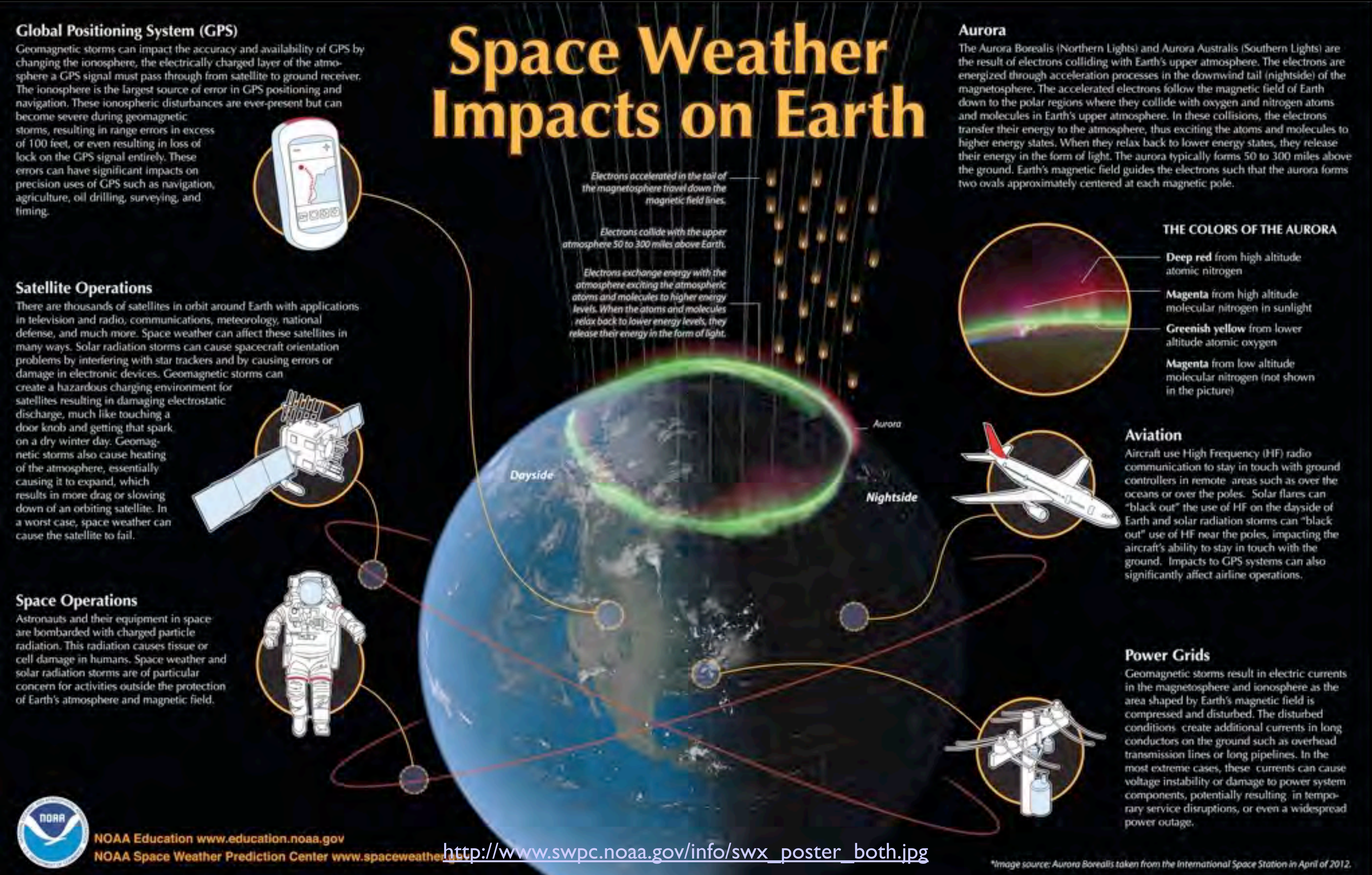
Magnetized Blobs of Solar Material 18-96 hours

G-Scale

Aurora; geomagnetic storms & radio disturbances

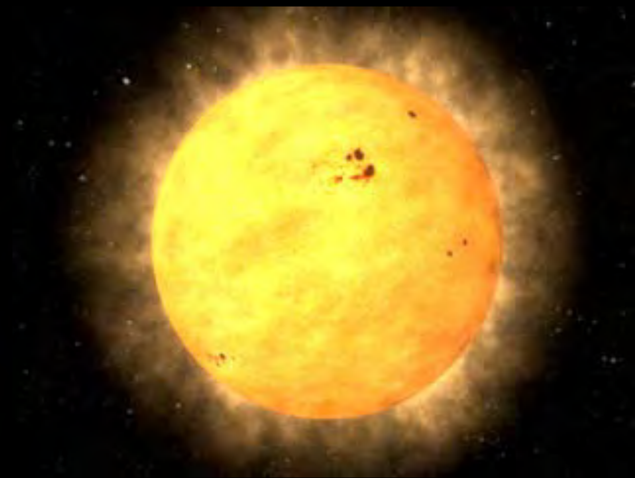
What the Sun sends our way
Light
Magnetized wind
Particle radiation
Highly variable X-rays/EUV
X-rays
ultraviolet rays
infrared rays
radar
FM
TV
shortwave
AM
10^-14
10^-12
10^-10
10^-8
10^-6
10^-4
10^-2
1
10^2
10^4
Wavelength (meters)
Almost constant brightness
400
500
600
Wavelength (nanometers)
Satellite drag; radio blackouts
Gusty wind; variable magnetism
Aurora; geomagnetic storm & radio disturbances
MARS
VENUS
RADIATION HAZARD
MERCURY
SUN
IONS
MAGNETIC FIELD LINES
ELECTRONS
MOON
EARTH
ELECTRON SIGNAL
Highly variable particle streams
Radiation: astronaut health & satellite function

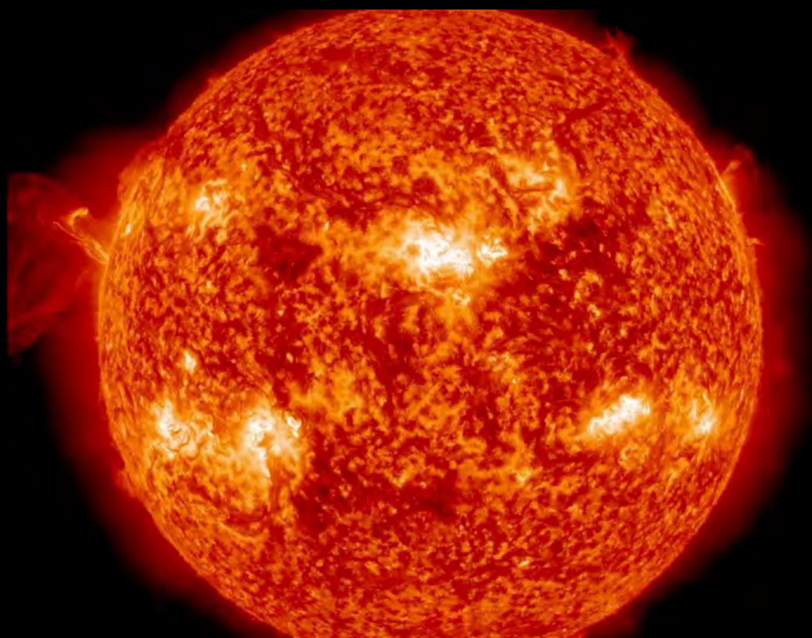
# Society is increasingly susceptible to its space environment




http://www.swpc.noaa.gov/info/swx_poster_both.jpg

SDO/AIA 4500 2011-12-07 12:00:08 UT





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

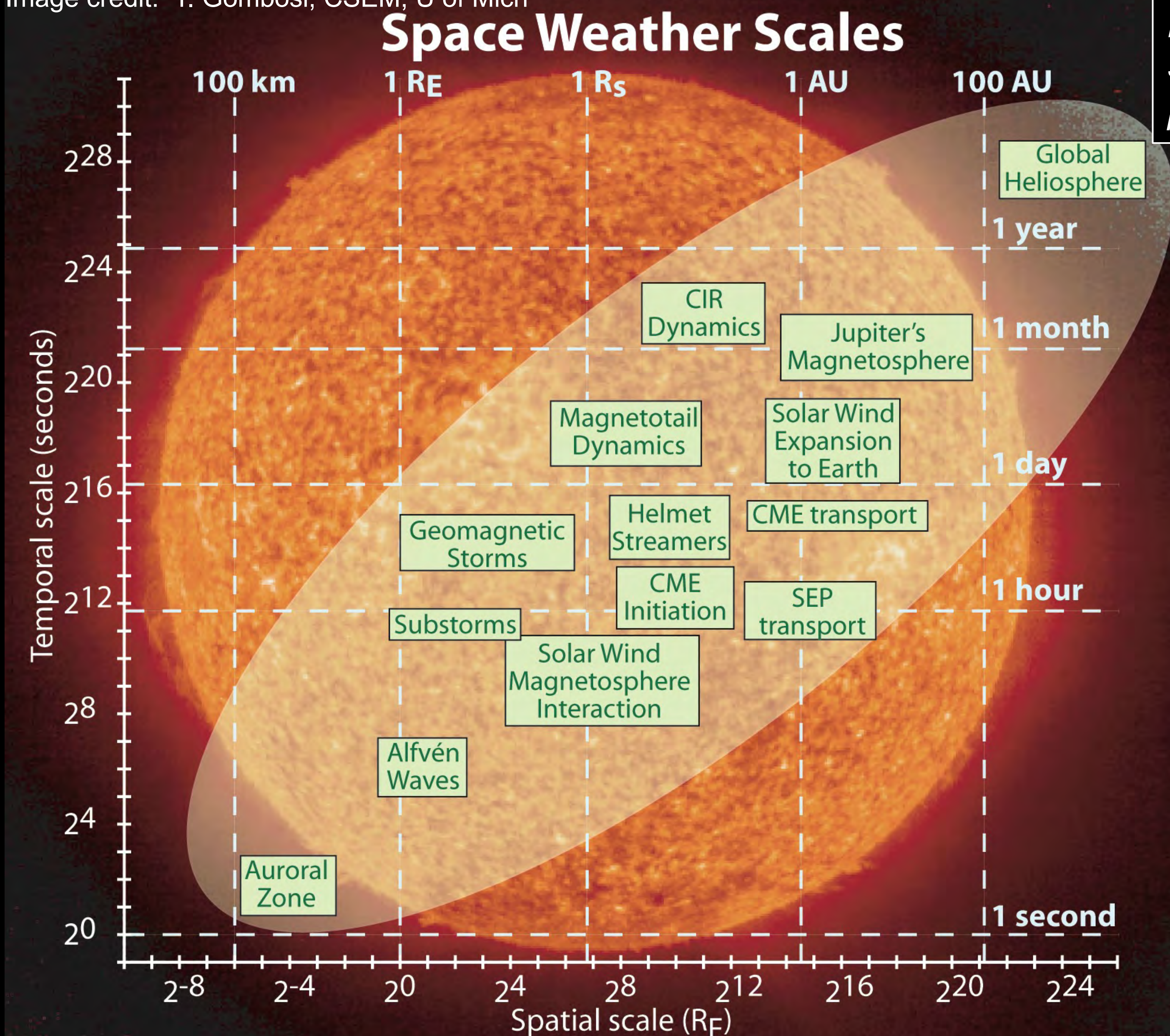
*Solve fundamental mysteries of Heliophysics*

*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

# 2 Gigabytes

## Every 15 seconds

# Heliophysics Missions

## Heliophysics Mission Fleet

Heliophysics missions are strategically placed throughout our solar system, working together to provide a holistic view of our Sun and space weather, along with their impacts on Earth, the other planets, and space in general. NASA's heliophysics mission fleet includes 19 operating missions using 26 spacecraft, 13 missions in development, 1 mission under study, a robust sounding rocket program and a variety of CubeSat missions.

- ESA = European Space Agency
- JAXA = Japan Aerospace Exploration Agency

*Numbers in parentheses indicate how many spacecraft each mission includes.

*Objects Not to Scale

**UNDER DEVELOPMENT**

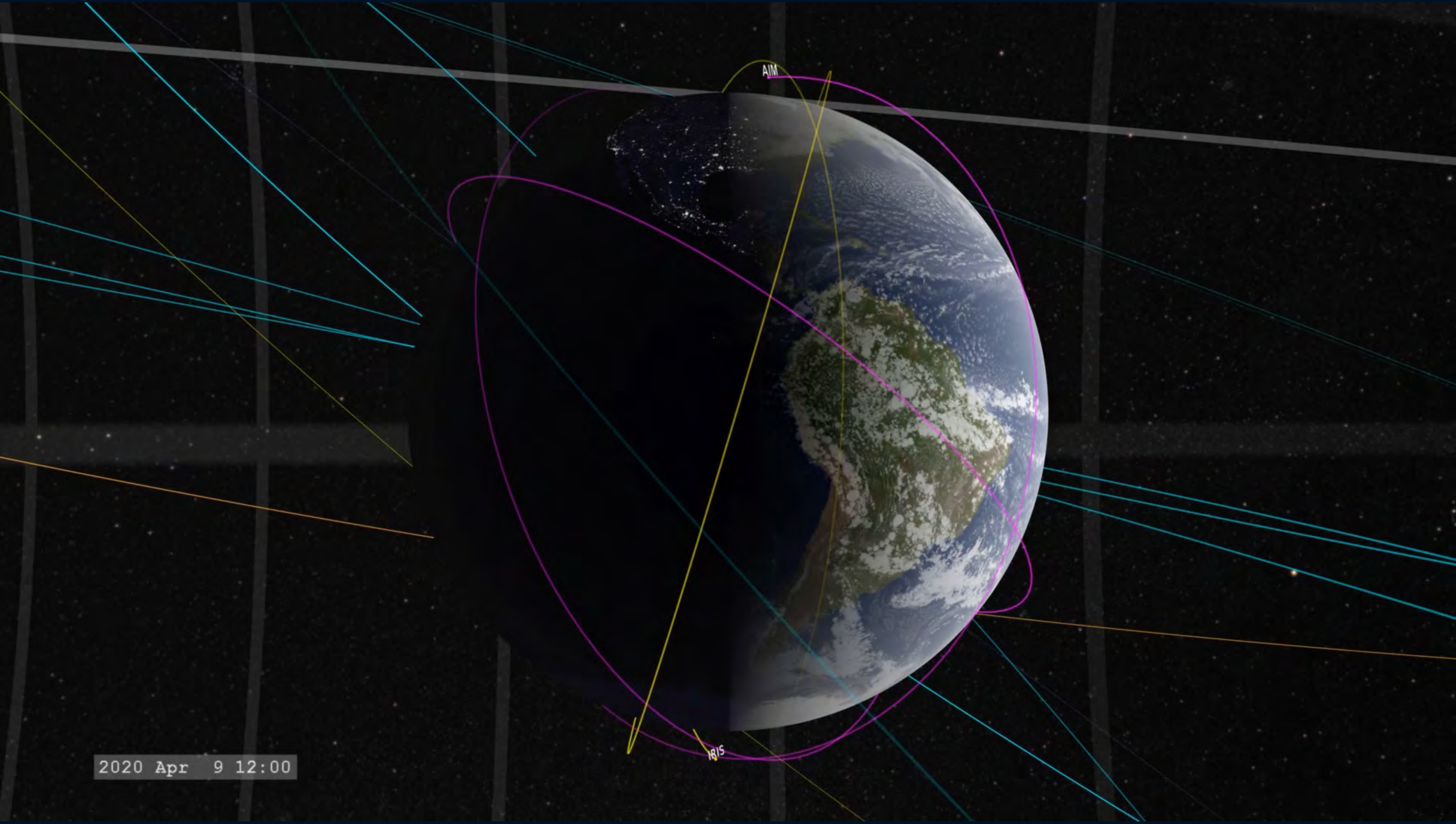
- AWE (ISS)
- Carruthers Geocorona Observatory
- ESCAPADE (2)
- EUVST (JAXA)
- EZIE (3)
- GDC (6)
- HelioSwarm (9)
- HERMES (Gateway)
- IMAP
- MUSE
- PUNCH (4)
- SunRISE (6)
- TRACERS (2)

**PRIMARY OPERATION**

- Parker Solar Probe
- Solar Orbiter (ESA)

**EXTENDED OPERATION**

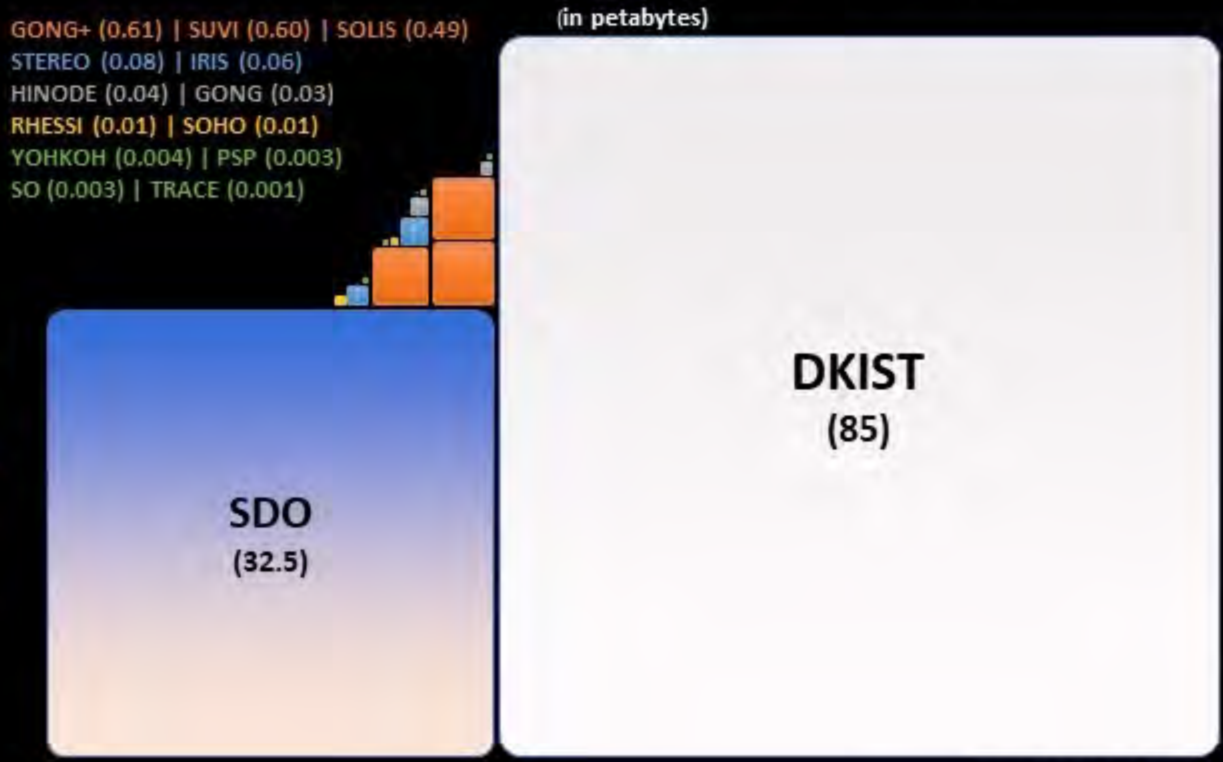
- ACE
- AIM
- GOLD (SES-14)
- Hinode (JAXA)
- IBEX
- ICON
- IRIS
- MMS (4)
- RAD (Curiosity)
- SDO
- SOHO (ESA)
- STEREO
- THEMIS-ARTEMIS (2)
- THEMIS (3)
- TIMED
- Wind
- Voyager (2)


AIM
IRIS
2020 Apr 9 12:00

# The Scale of Data

- There is currently over 8.7 PB of compressed AIA images and products.
- Uncompressed this would expand to over 20 PB.
- Optimized SSD reading at 7000MB/s would take over 14 days to read through all AIA files. *Real-world* read/write SSD speeds are closer to 500 MB/s or more than 200 days
- Size isn't the only issue, there are over 230 million AIA images.

Total Data Volume Over Projected Mission Lifetime*




* projected to year 2035

# Heliophysics Digital Resource Library (HDRL)

## Vision: *Where the Heliophysics System Observatory Comes Together*

**The HDRL enables the scientific analysis goals of the Heliophysics System Observatory:**

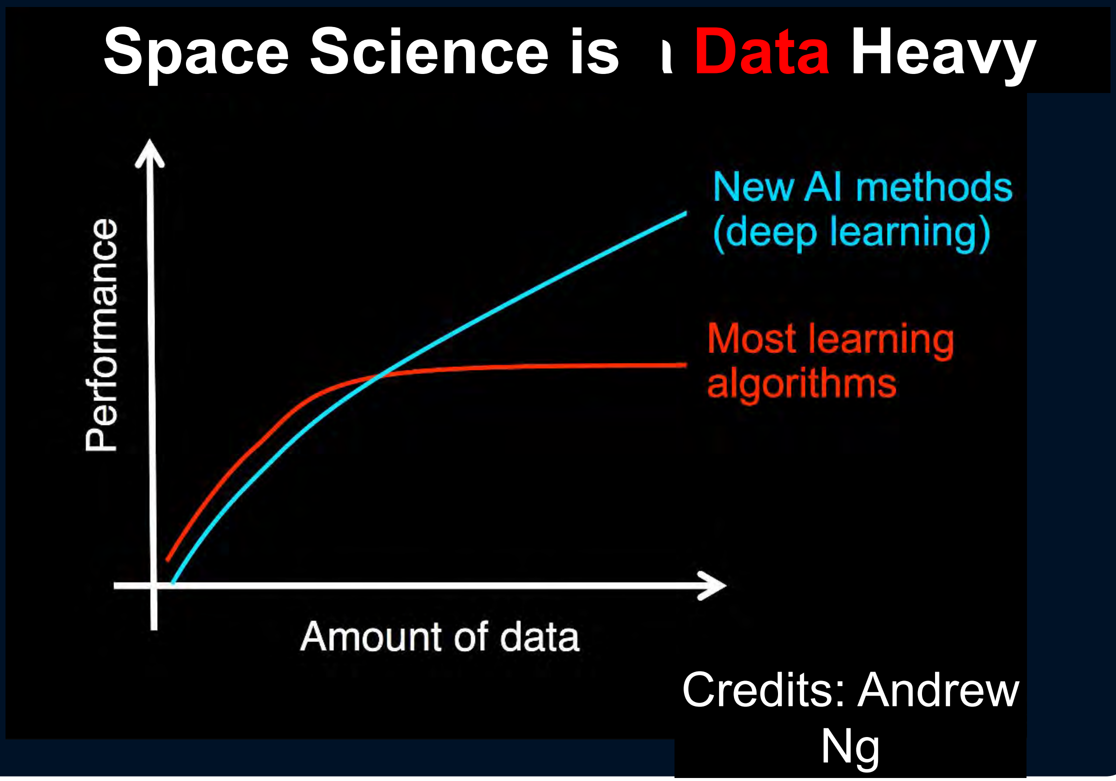
- ***provisioning and curation of scientific big data*** from many sources, PB volumes; (the Foundation: data, metadata, standards)
- ***support for data analysis and modeling*** in multiple computational environments;
- the design and implementation of a ***collaborative open science infrastructure***.

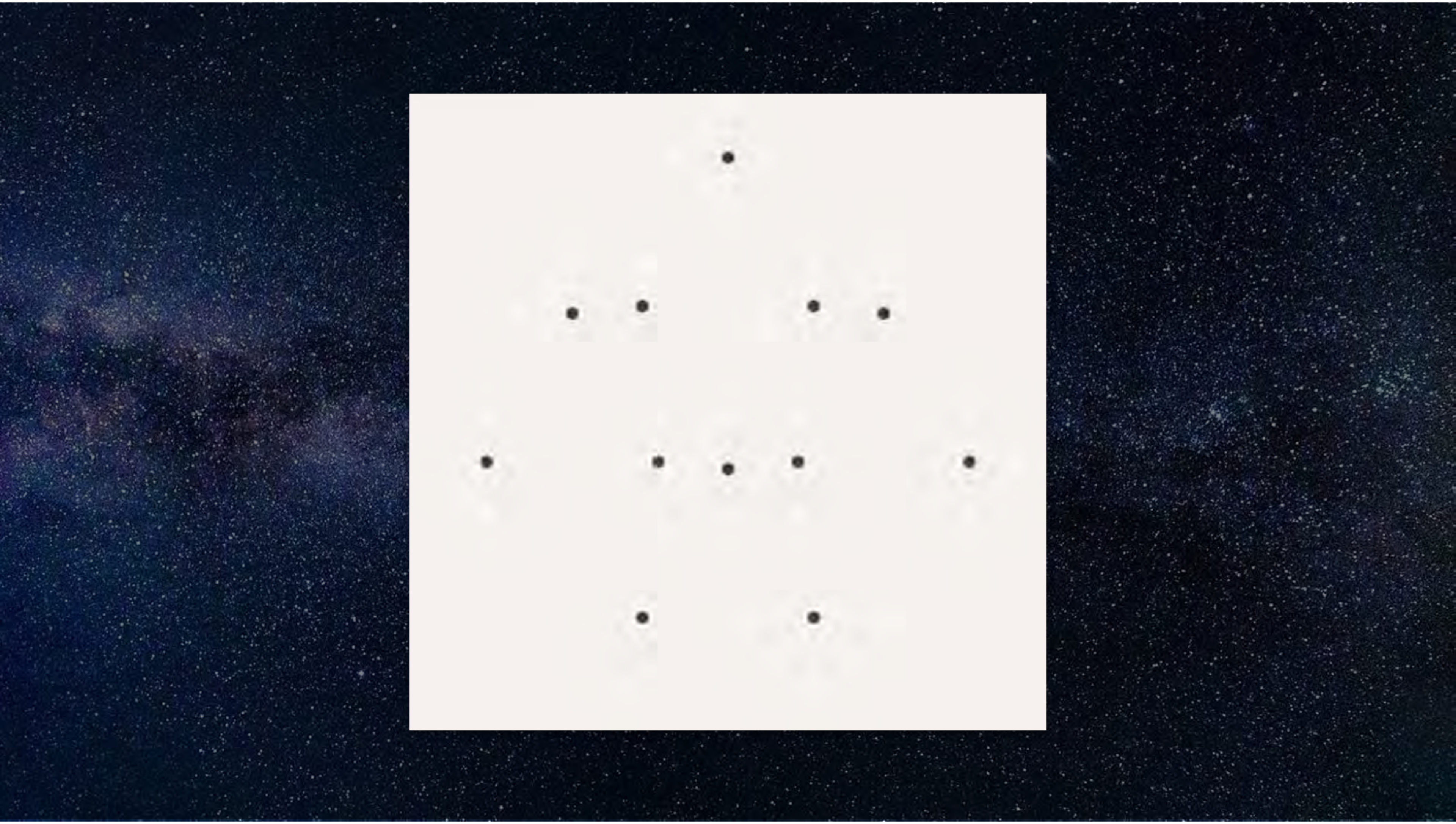
Individual missions can do great science

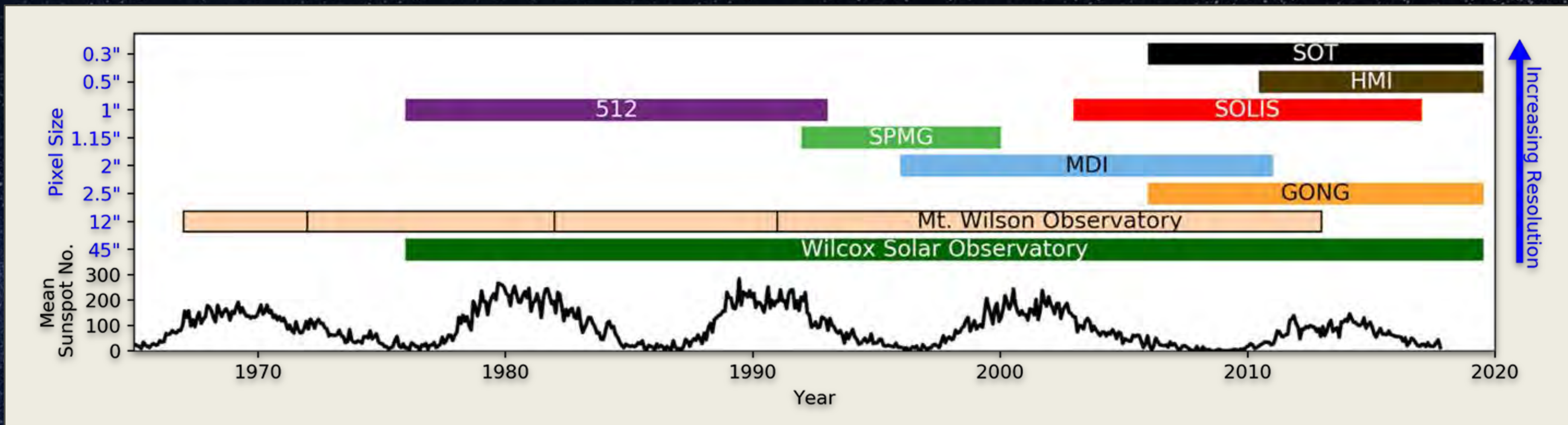
***Unlocking groundbreaking systems science requires the HDRL***

## Application of AIML to utilize HSO data and accelerate science discovery

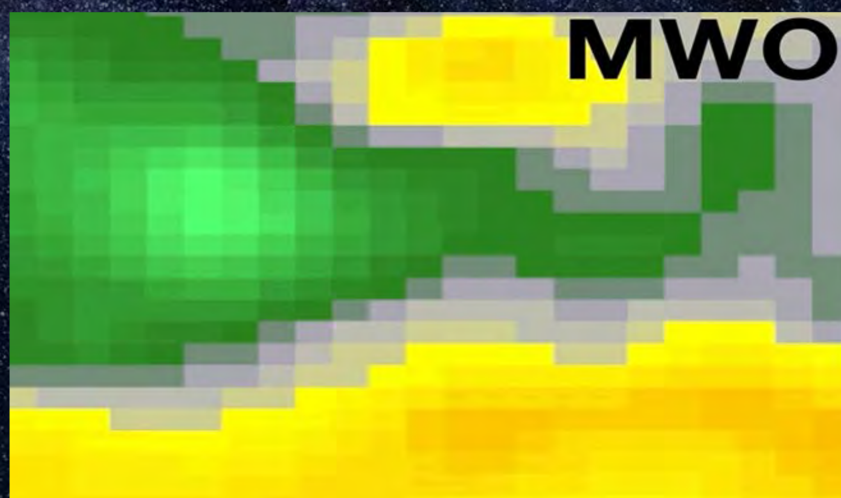
# Space Science and Deep Learning



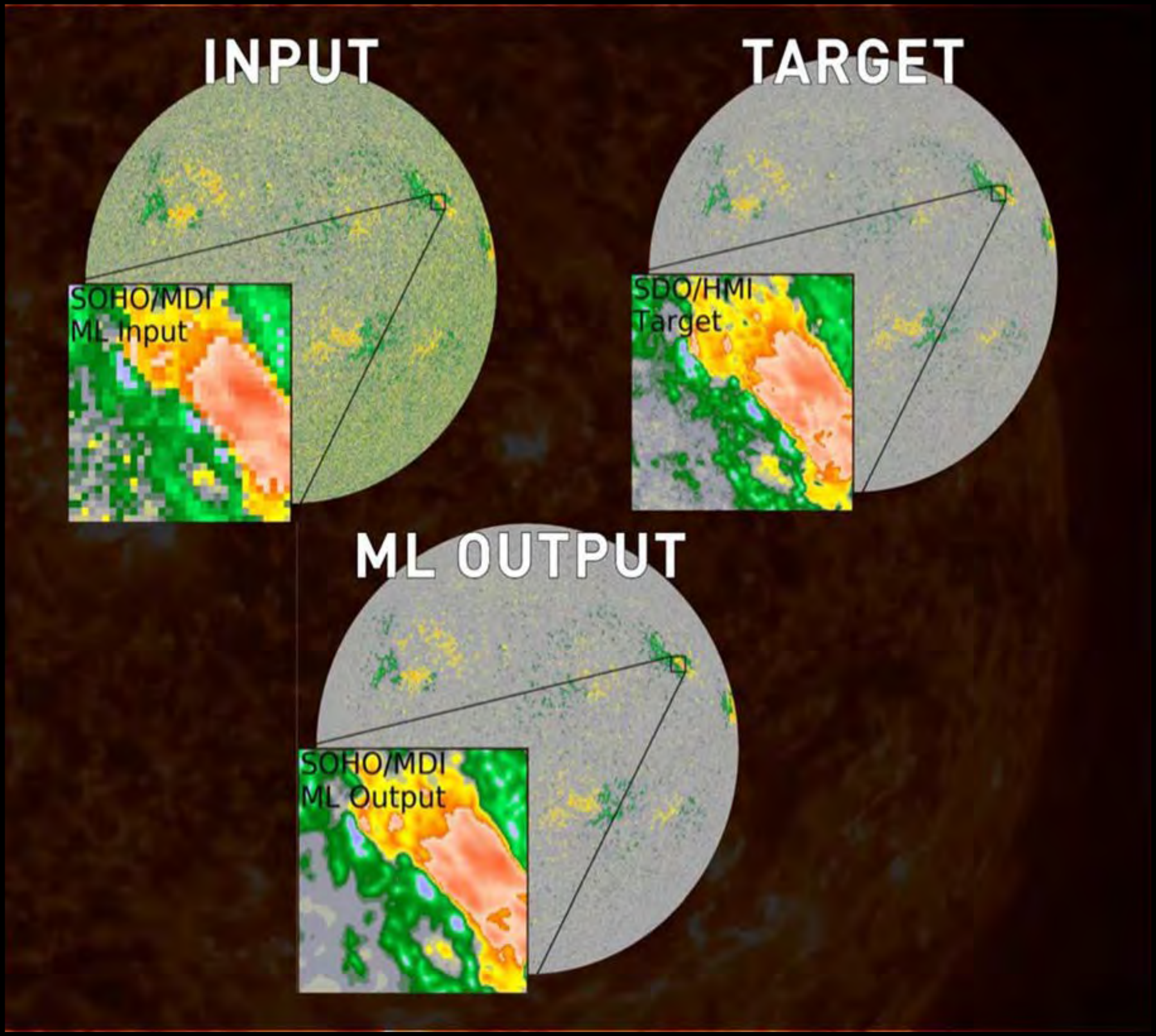





CREDIT: FDL




**BUT ALSO MAKE BETTER USE OF ARCHIVAL DATA...**




**"SOLAR MAG" UPSCALES HISTORICAL INSTRUMENTS TO THE SAME LEVEL AS HMI TO GIVE A HI-RES HOMOGENOUS DATA PRODUCT OF THE SOLAR MAGNETIC FIELD OVER MANY SOLAR CYCLES.**

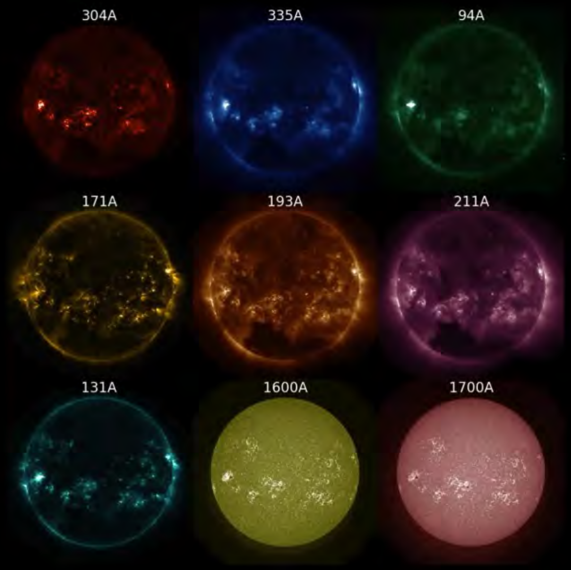

THE ASTROPHYSICAL JOURNAL
SUPPLEMENT SERIES

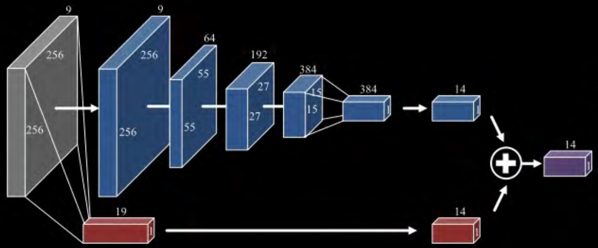
OPEN ACCESS

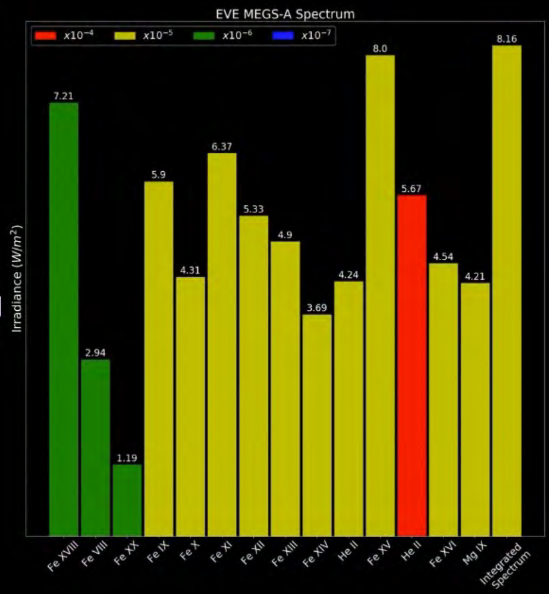
A Machine-learning Data Set Prepared from the NASA *Solar Dynamics Observatory* Mission

Richard Galvez[1], David F. Fouhey[2], Meng Jin[3,4], Alexandre Szenicer[5], Andrés Muñoz-Jaramillo[6], Mark C. M. Cheung[3,7], Paul J. Wright[8], Monica G. Bobra[7], Yang Liu[7], James Mason[9] + Show full author list

Published 2019 May 8 • © 2019. The American Astronomical Society.
The Astrophysical Journal Supplement Series, Volume 242, Number 1
Citation Richard Galvez et al 2019 ApJS 242 7

## Illustrative Outcomes in multiple domains

## "SDOML"

THE ASTROPHYSICAL JOURNAL
SUPPLEMENT SERIES

OPEN ACCESS

A Machine-learning Data Set Prepared from the NASA *Solar Dynamics Observatory* Mission

Richard Galvez[1], David F. Fouhey[2], Meng Jin[3,4], Alexandre Szenicer[5], Andrés Muñoz-Jaramillo[6], Mark C. M. Cheung[3,7], Paul J. Wright[8], Monica G. Bobra[7], Yang Liu[7], James Mason[9] + Show full author list

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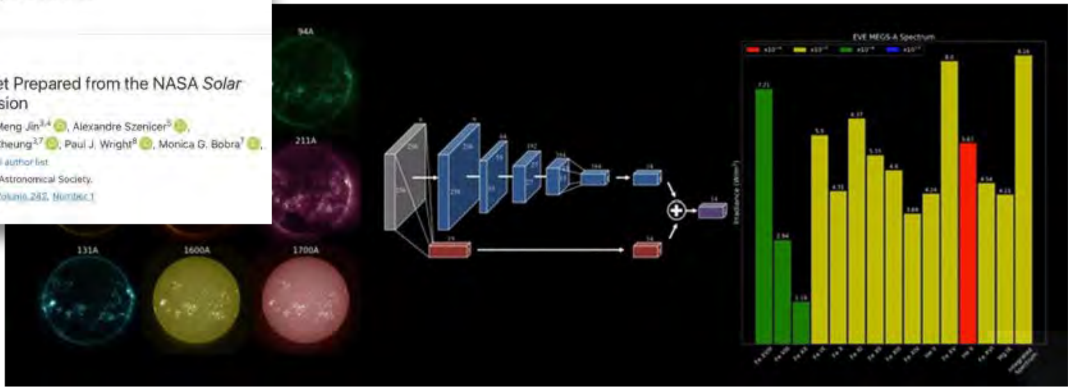
The Astrophysical Journal Supplement Series, Volume 242, Number 1

Citation Richard Galvez *et al* 2019 *ApJS* 242 7




DATASET

**SDOML**

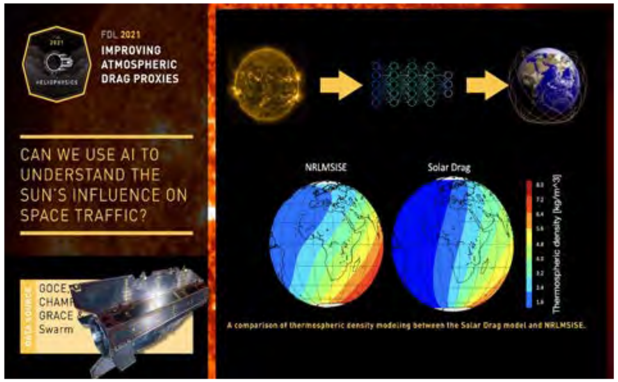
A Curated Data Set From The NASA Solar Dynamics Observatory (SDO) Mission In A Format Suitable For Machine-Learning Research

7TB

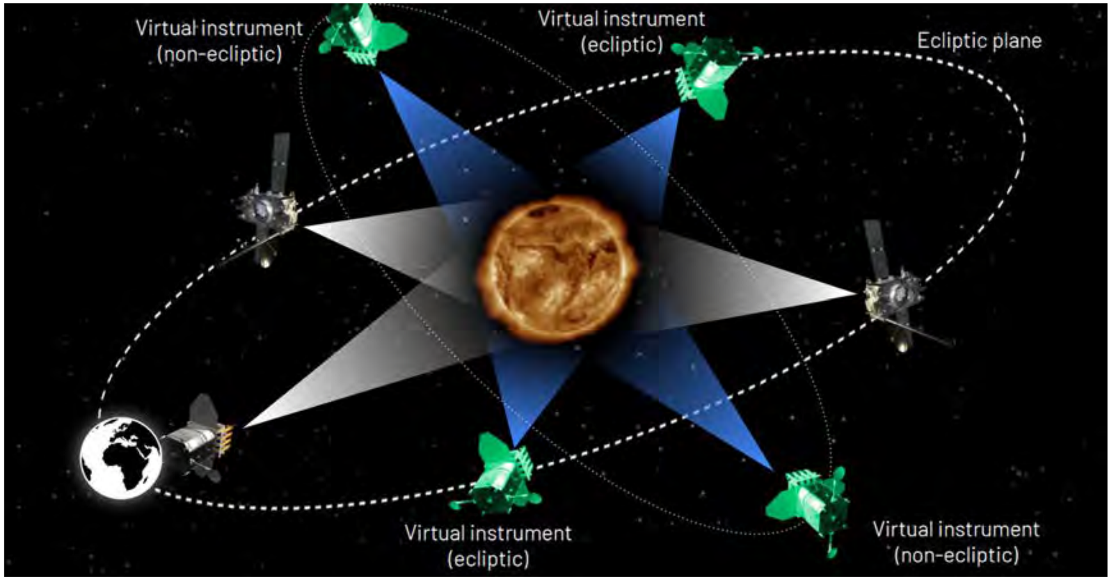

**Derivative outcomes**

**Auto calibration**

**Thermospheric density predictions**



## How can we observe the Sun & solar irradiance from any perspective?



FDL 2022 | HELIOPHYSICS

# 4π EUV IRRADIANCE: THE SUN AS A (FULLY-RESOLVED) STAR

## SPI3S: Spectral Irradiance of a 3D Sun

Margarita Bintsi, Robert Jarolim, Miraflor Santos, Benoit Tremblay, Anna Jungbluth, James Mason, Andrés Muñoz-Jaramillo, Sairam Sundaresan, Angelos Vourlidas

### CHALLENGE & OPPORTUNITY

**The Sun drives all life on Earth**, and as our closest stellar neighbor is the best example for studying the impact of a host star on its planets. The Sun's **extreme ultraviolet (EUV) radiation** is especially important to predict and forecast, since the absorption of EUV light in our atmosphere changes atmospheric density and degrades satellite orbits.

Fig. 1: Schematic of the ecliptic orbits of SDO/STEREO A and B.

We have access to 3 satellites that capture images of the Sun's EUV emission in different spectral bands, namely **SDO, STEREO A, and STEREO B**. While all three satellites are bound to Earth's ecliptic orbit, they are spaced apart to capture a 360° view of the Sun (Fig. 1). Nonetheless, combing the different satellite observations into a consistent dataset is challenging. In addition, only SDO is able to measure both images and irradiance spectra of EUV emission.

As a result, **the goal of this project is three-fold**:

1. **Combine SDO/STEREO A & STEREO B observations into a consistent 4π map of the Sun**
2. **Predict what the Sun's EUV emission images would look like from non-ecliptic viewpoints**
3. **Predict the corresponding EUV irradiance spectra from any, including non-ecliptic, viewpoints**

### TECHNICAL APPROACH

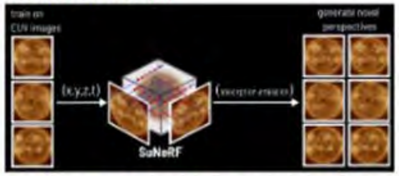


Fig. 2: Our solar Neural Radiance Field (SuNeRF) is trained on EUV images to create a 4π reconstruction of the Sun, and generate novel viewpoints.

We first homogenize SDO and STEREO observations using the approach presented by Jarolim et al.

We then **adapted Neural Radiance Field (NeRF)** networks to predict absorption and emission of the solar corona, and create a consistent **4π reconstruction of the Sun**. This solar NeRF (SuNeRF) is then used to **generate EUV images for arbitrary viewpoints** (Fig. 2).

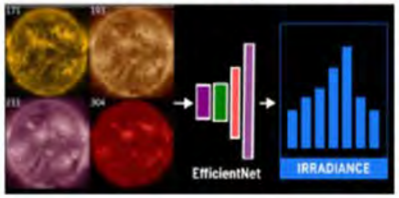


Fig 3: Irradiance spectra are predicted from EUV emission images.

Based on the work of Szenicer et al., who demonstrated the prediction of irradiance spectra from EUV images [2], **we train an EfficientNet model to predict irradiance spectra** using 4 of SDO's 9 channels. The trained model is then used to **predict EUV irradiance for the arbitrary viewpoints generated via our SuNeRF** (Fig. 3).

### OUTCOME

Using our SuNeRF approach, we create the first 3D reconstruction of the entire Sun (Fig. 4). While the original observations were limited to the ecliptic plane, we are now able to directly view the poles and observe solar eruptions from all angles.

Since our method creates unprecedented views of the Sun, we have no direct way of comparing our EUV images to real observations. Instead, we validate our approach by comparing the predicted irradiance at STEREO B's viewpoint to the actual irradiance measured by SDO 12 days later. Fig. 5 shows that our predictions match the actual measurements well. Finally, our work allows us to predict EUV irradiance from other planets (Fig. 6).

This is not only important for future human space exploration, but can also help us learn more about habitability of exoplanets around Sun-like stars.

Fig. 4: 3D reconstruction of the Sun using our SuNeRF.

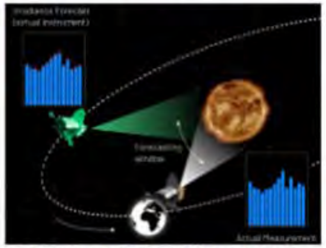


Fig. 5: Irradiance prediction to validate our approach.

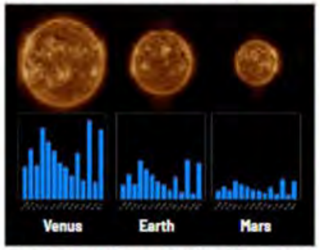



Fig. 6: The Sun and EUV irradiance from different planets.

### NEXT STEPS

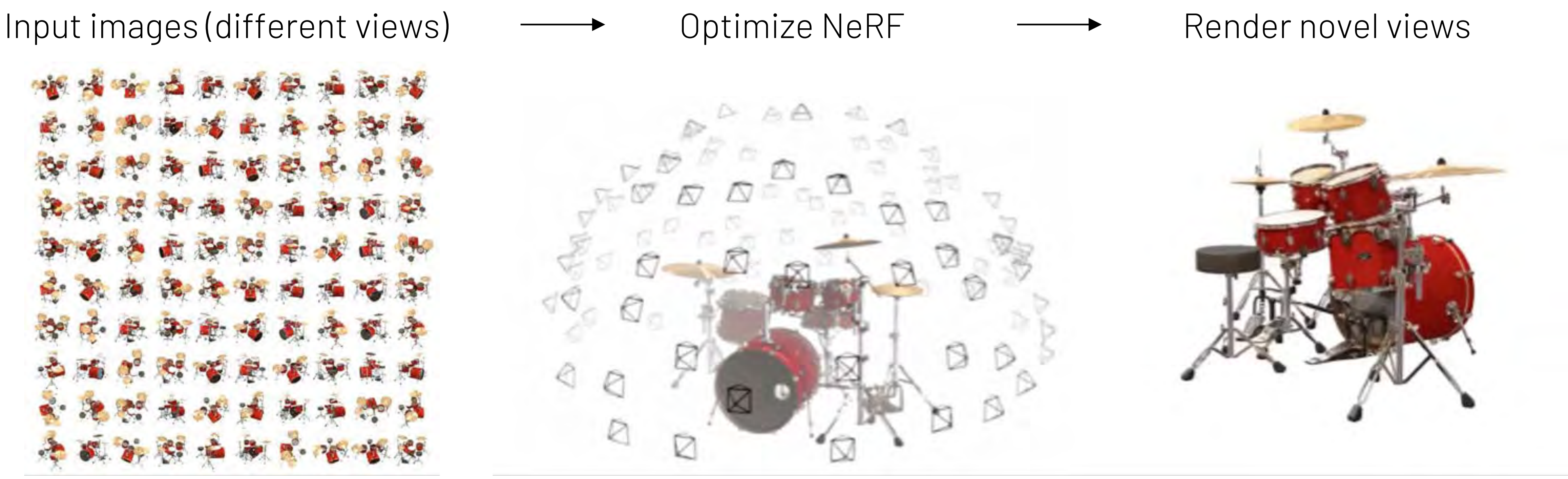
Next, we will further validate our results by testing how well downstream analysis tasks (such as the detection of coronal holes and active regions) perform on our 3D solar reconstruction. In addition, we will further investigate our irradiance forecasting ability and quantify how far in the future we can predict irradiance for.

### REFERENCES

[1] Jarolim, R., Veronig, A., Pötzi, W., & Podladchikova, T. (2022). Instrument-To-Instrument translation: Instrumental advances drive restoration of solar observation series via deep learning. DOI: 10.21203/rs.3.rs-1021940/v1

[2] Szenicer, A., Fouhey, F., Muñoz-Jaramillo, A., Wright, P. J., Thomas, R., Galvez, R., Jin, M., Cheung, M. C. M. (2019). A deep learning virtual instrument for monitoring extreme UV solar spectral irradiance, Science Advances. DOI: 10.1126/sciadv.aaw6548

# METHODS: NEURAL RADIANCE FIELDS (NERFS)

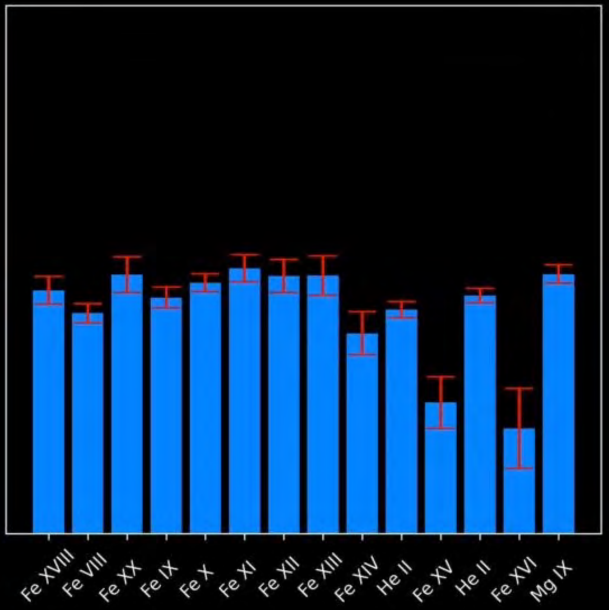



Credit: Mildenhall et al. (2020)

# THE SUN AS FULLY RESOLVED STAR

3D Sun

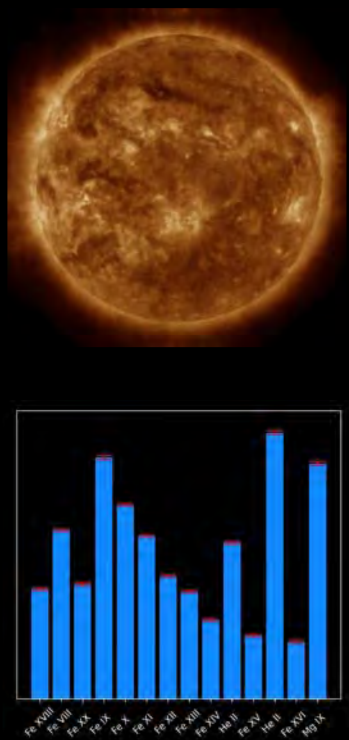
IRRADIANCE




4π Combines SDO/STEREO A & STEREO B observations into a consistent 4π map of the Sun

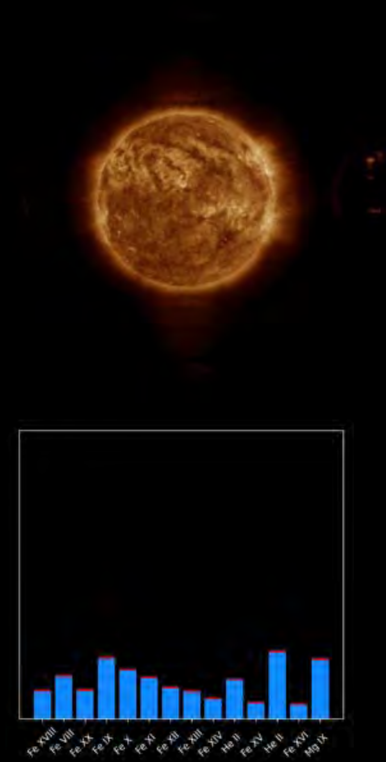
It predicts what the Sun's EUV emission images would look like from non-ecliptic viewpoints

**NeRFS (Neural Radiance Fields) AND ITI (Instrument to Instrument translation) ENABLE A 4PI VIEW OF OUR SUN IN EUV**

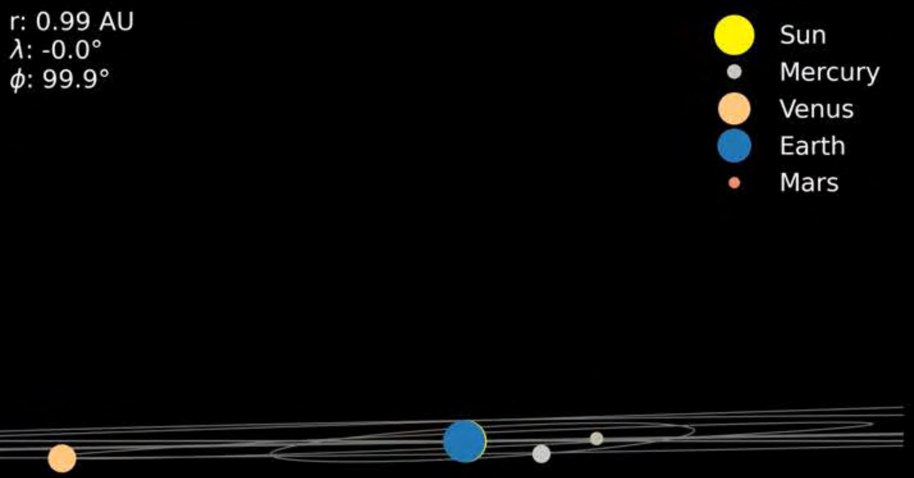



Venus


Earth




Mars


r: 0.99 AU
λ: -0.0°
ϕ: 99.9°
Sun
Mercury
Venus
Earth
Mars

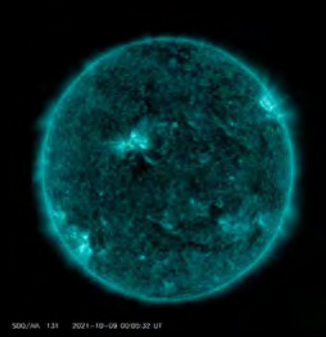

193Å

# The Sun Wakes Up: Solar Cycle 25 Is Here

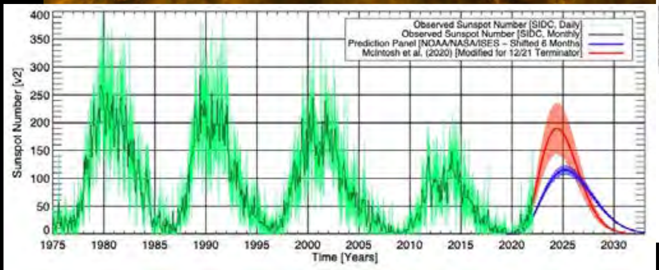
beginning of Solar Cycle 25, and the Sun's activity will once again ramp up until solar maximum, predicted for 2025.

This new solar cycle, and anticipated increase in space weather events, will impact our lives and technology on Earth, as well as astronauts in space.

This is the first solar cycle that many new commercial and government stakeholders will navigate.




Active October 2021 Sun Emits X-class Flare

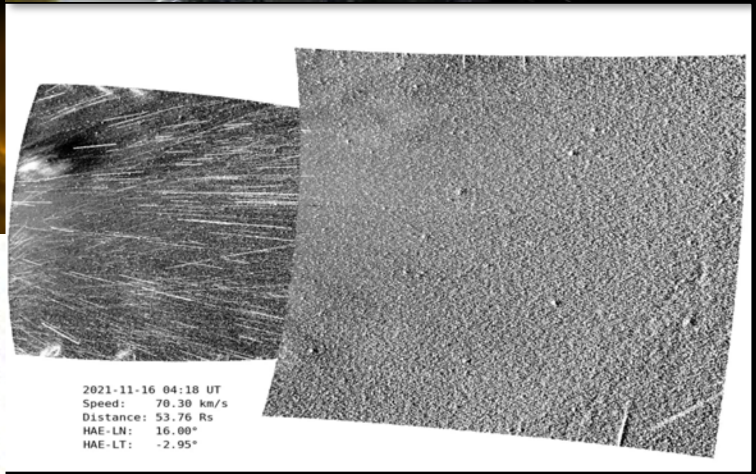




The New York Times

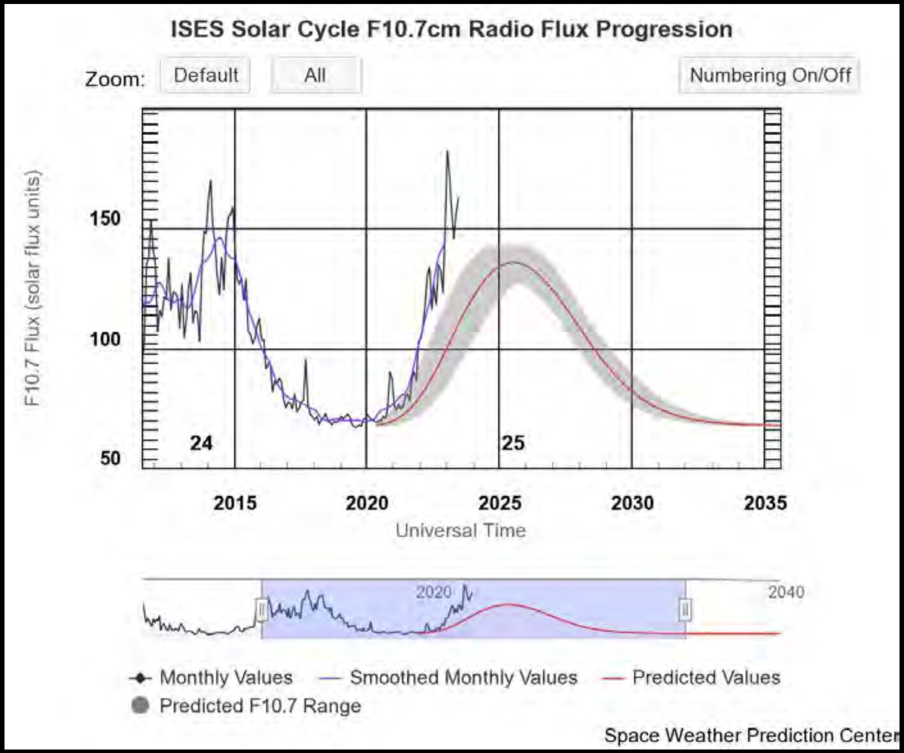
Feb 2022

*Solar Storm Destroys 40 New SpaceX Satellites in Orbit*

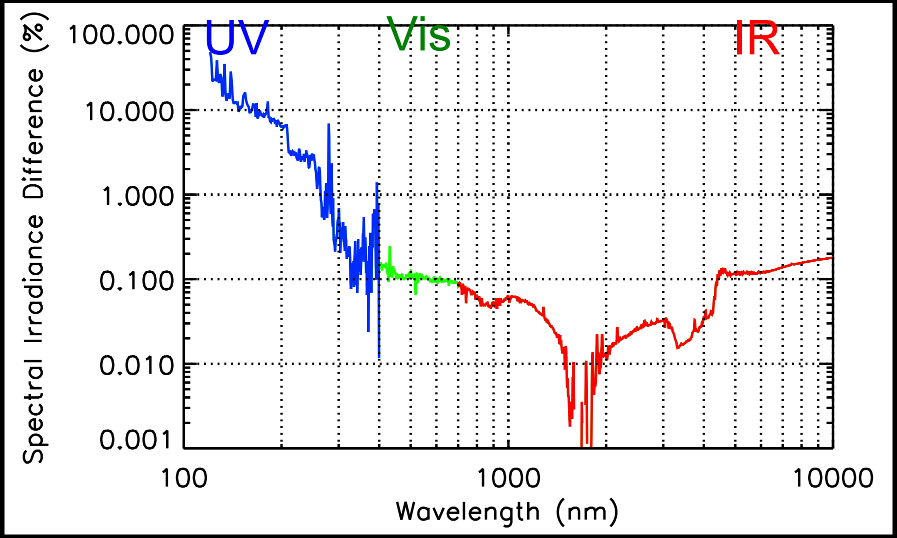


As the scope of space weather forecasting expands to other planets, it is also expanding in directions traditionally connected to climate research. Climate refers to changes in planetary atmospheres and surfaces that unfold much more slowly than individual storms. There is no question that solar activity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

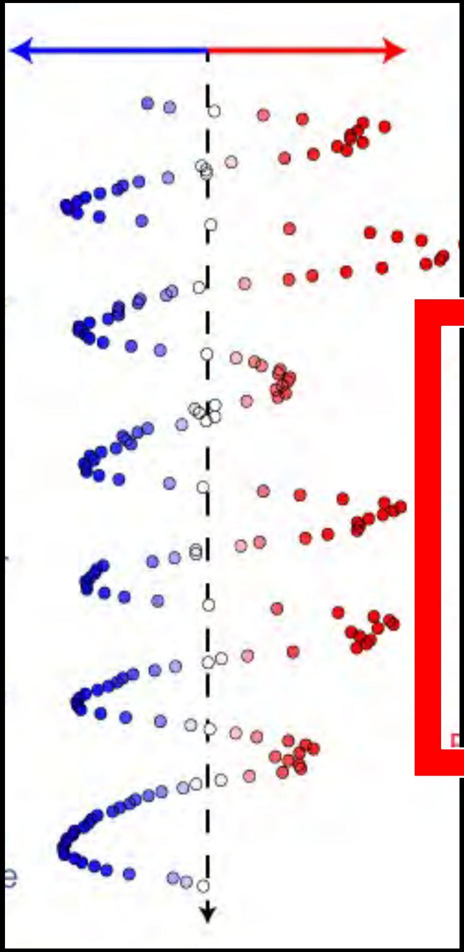
extreme galactic cosmic rays

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).

# Every Day Space Weather

To bring our focus back to Everyday Space Weather/Ordinary Space Weather, here is a new commentary in Journal of Space Weather & Space Climate https://www.swsc-journal.org/articles/swsc/full_html/2021/01/swsc210009/swsc210009.html

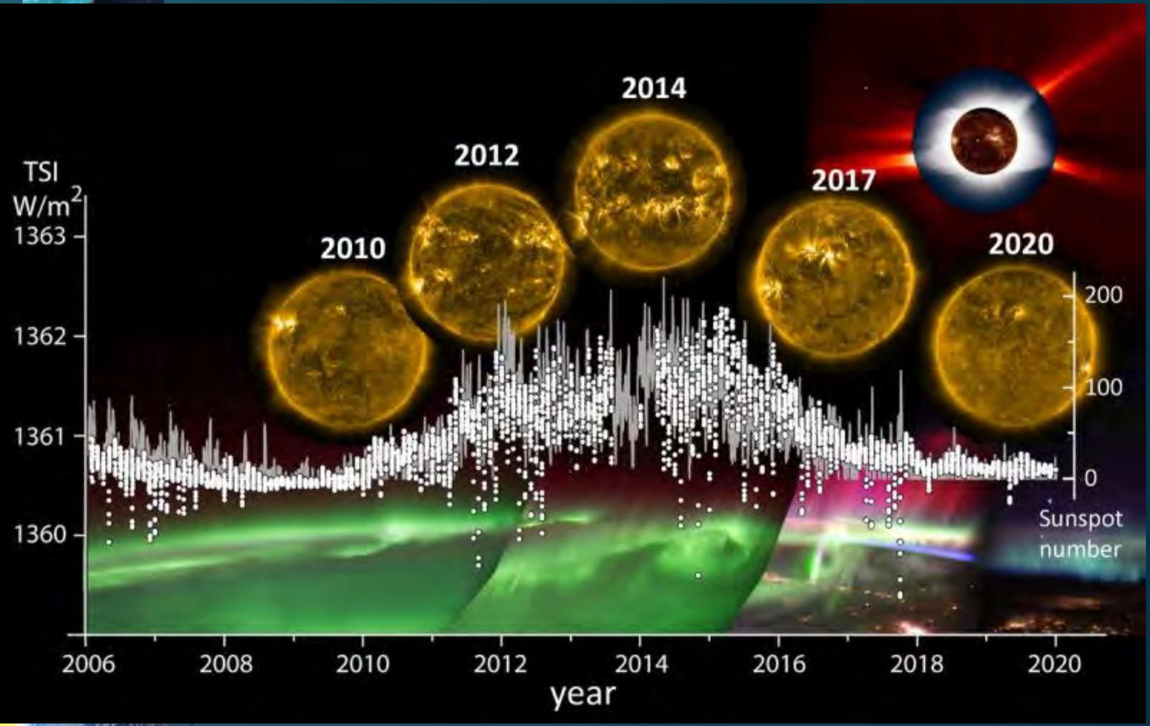
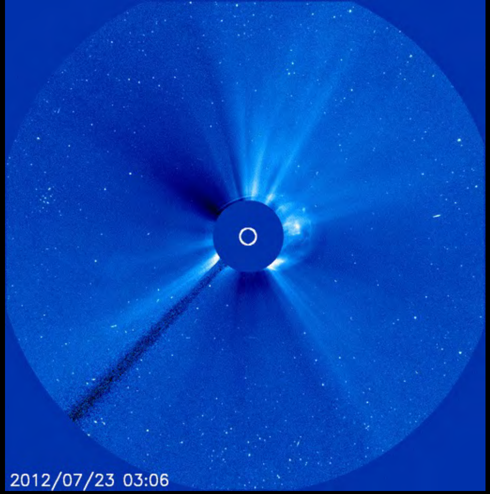
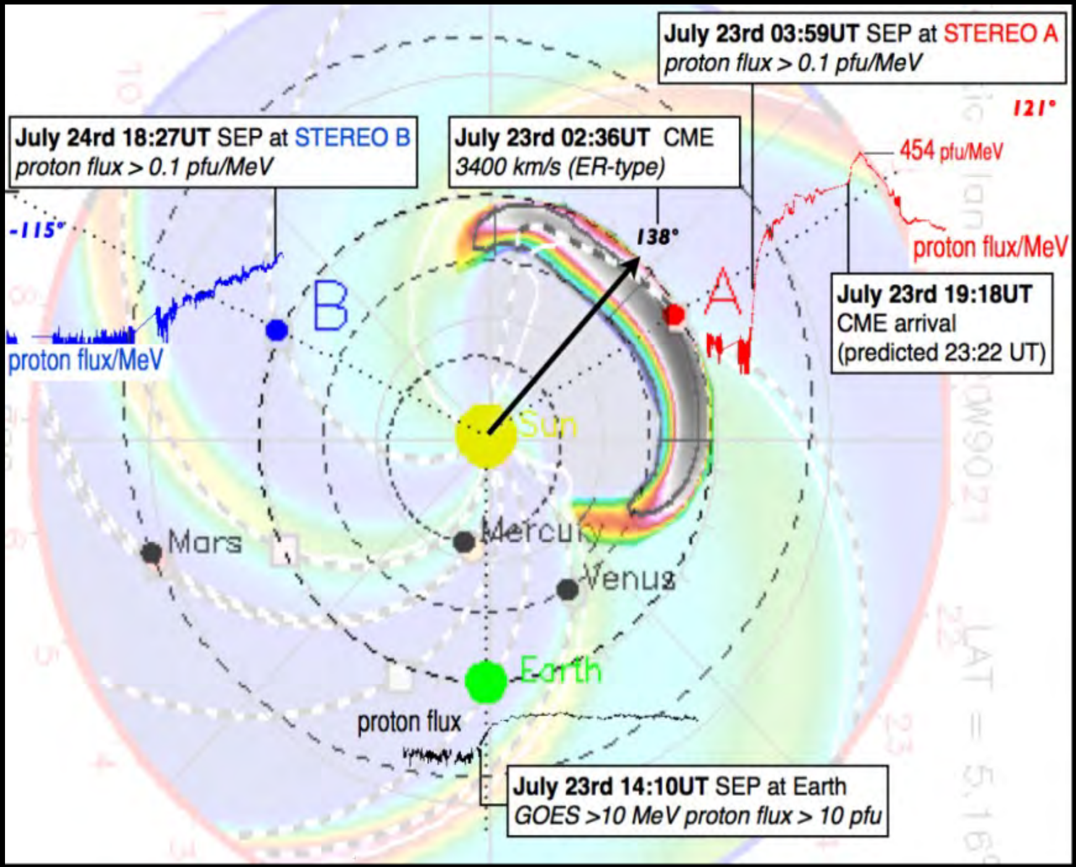



Illustration of solar activity impacts on the Earth's space environment during Solar Cycle 24. The solar activity increased the Total Solar Irradiance (TSI; white dots) during the solar maximum. Whole-disk observations of the solar corona in the extreme ultraviolet light from the Atmospheric Imaging Assembly (AIA) instrument onboard NASA's Solar Dynamics Observatory (SDO) show numerous brightenings caused by magnetic active regions emerging from the solar interior. Aurora images at the bottom are taken from the International Space Station at different solar cycle stages. The upper right corner shows a composite image of the Sun during the total solar eclipse of 2017, at the maximum of solar activity.




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.

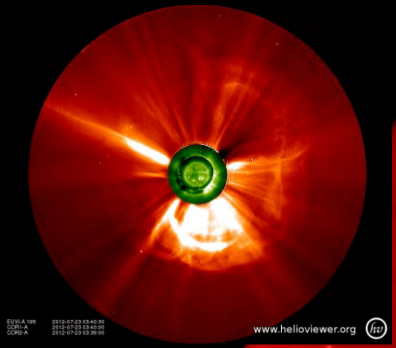
## A Solar Superstorm Narrowly Missed Earth in July 2012

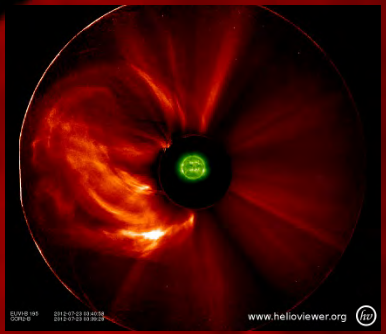
STEREO-A was in the line of fire, and the spacecraft was hit by a severe solar radiation storm. It was stronger than any proton event observed since 1976. Without STEREO-A, this major event would have passed unnoticed

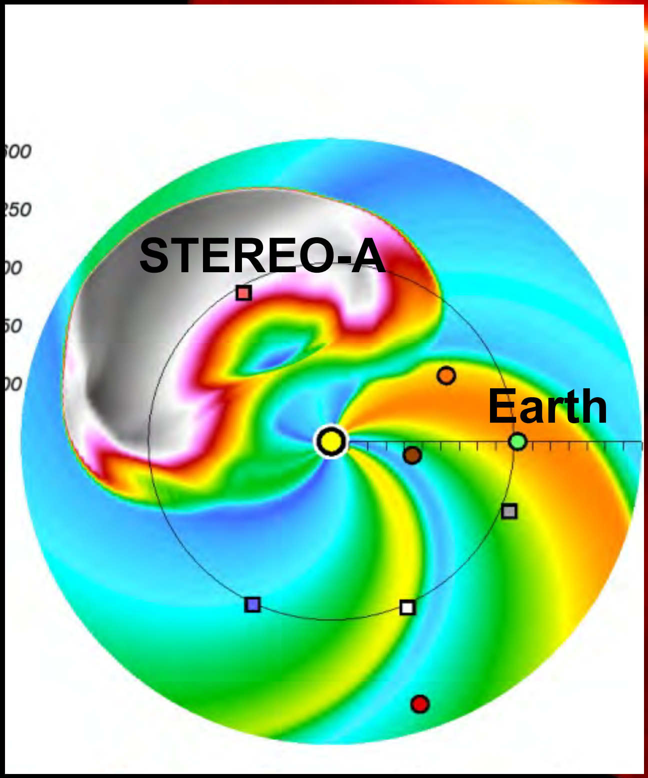
STEREO-A NESTED Images

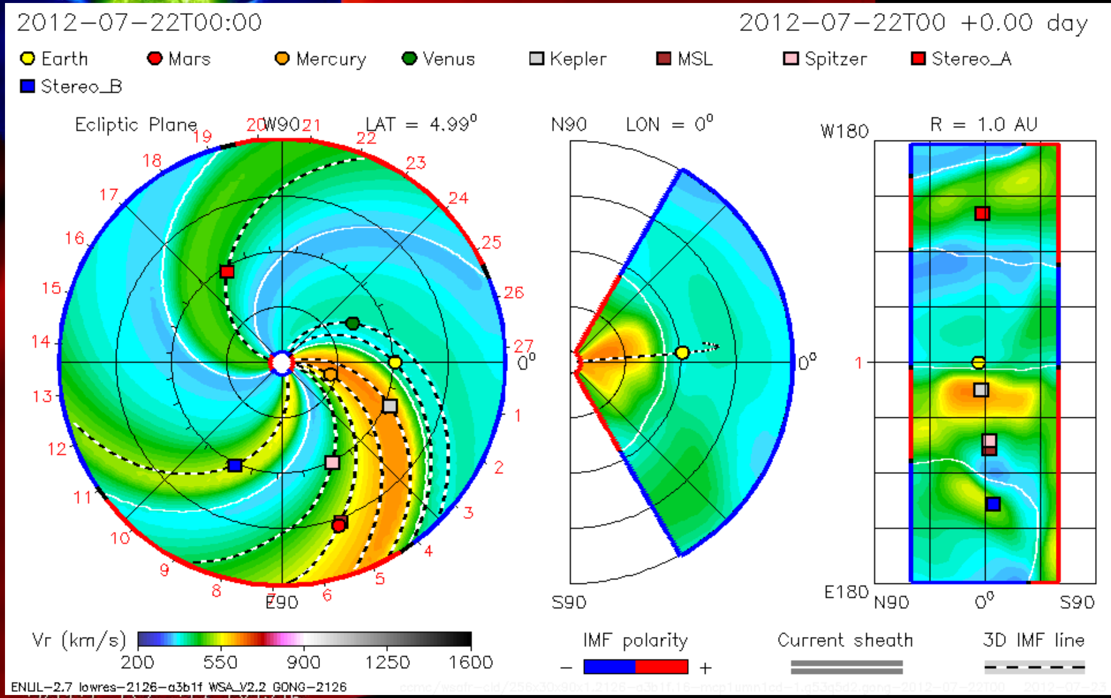
STEREO-B Nested Images

STEREO – A
23 July 2012



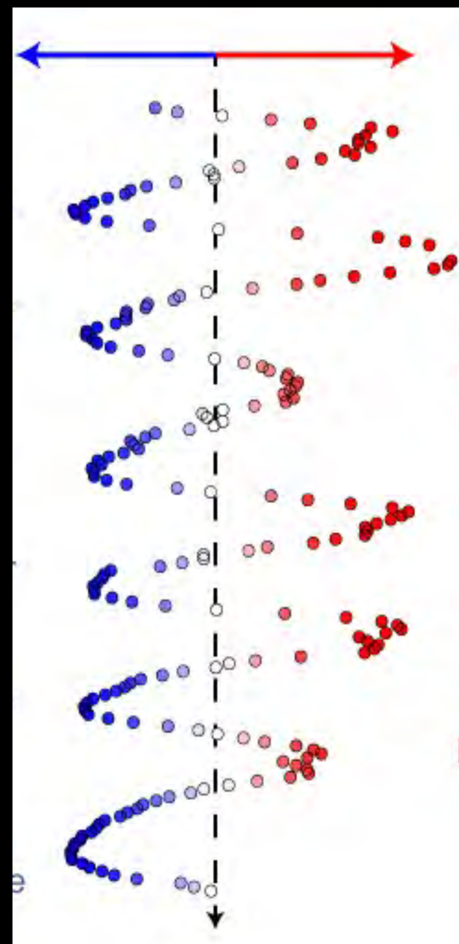



# Space Weather Swings Between Extreme Effects

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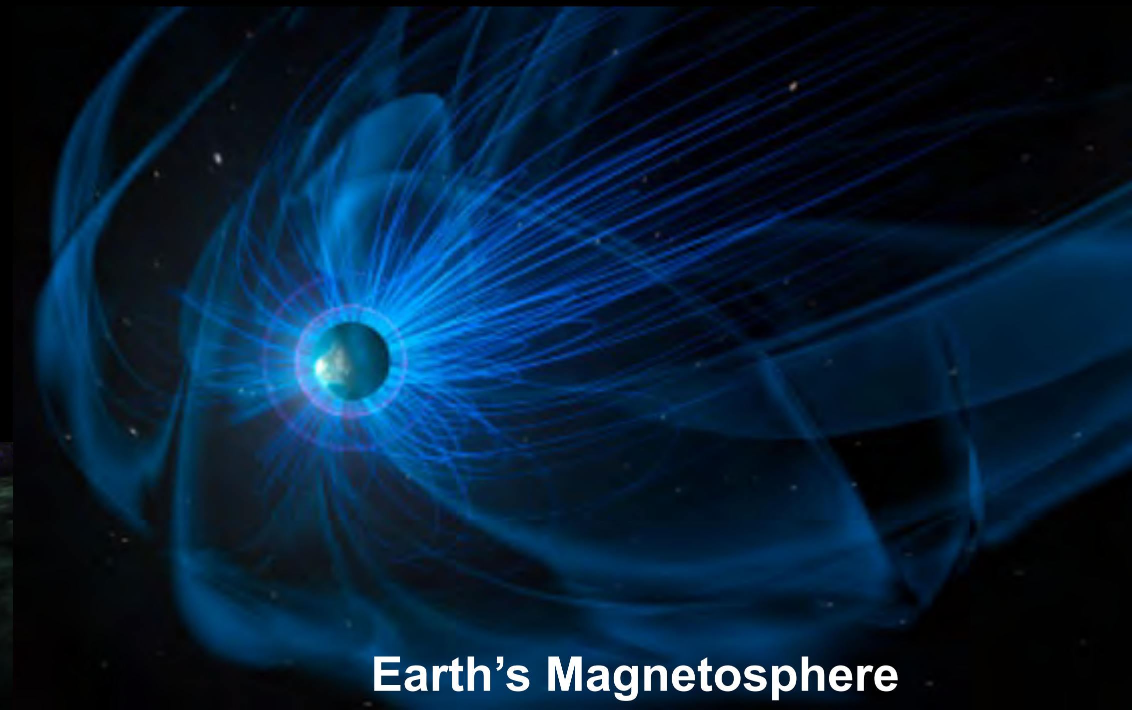
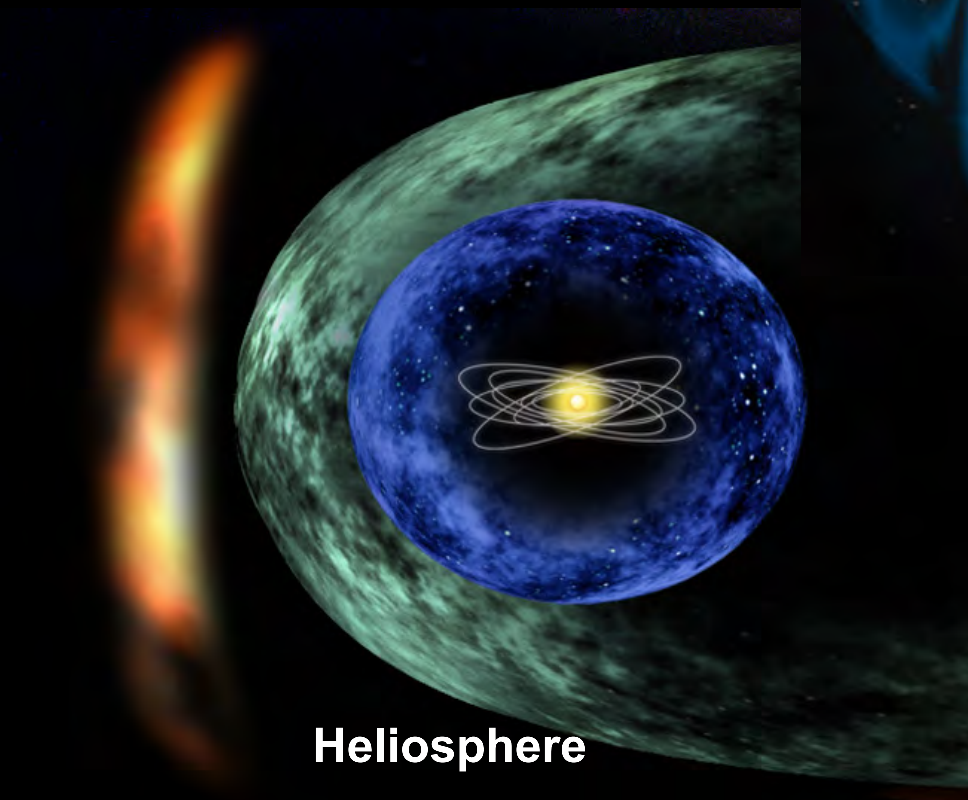
Illustration shows smoothed monthly sunspot counts from the past six solar cycles plotted horizontally instead of vertically. High sunspot numbers are in red and on the right, low sunspot numbers are in blue and on the left. Associated with each high and low sunspot numbers are different space weather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

# The Heliosphere

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



Earth's Magnetosphere



Heliosphere

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.

# The Space Radiation Environment

**Solar particle events** (SPE) (generally associated with Coronal Mass Ejections from the Sun):

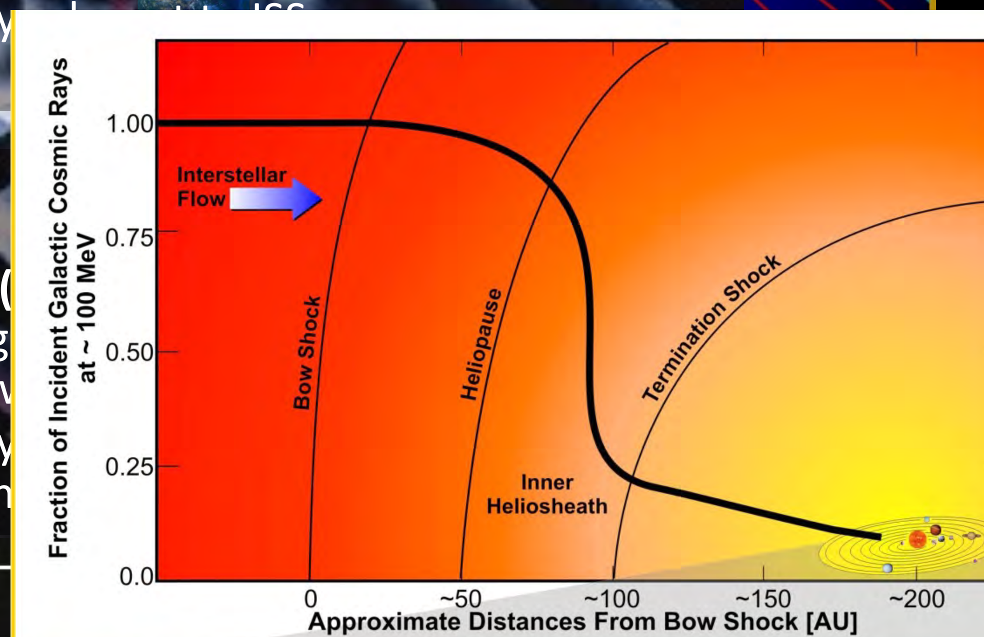
- medium to high energy protons
- largest doses occur during maximum solar activity
- not currently predictable
- MAIN PROBLEM: develop realistic forecasting and warning strategies

**Trapped Radiation**:

- medium energy protons and electrons
- effectively mitigated by shielding
- mainly
- MAIN

**Galactic Cosmic Rays** (GCR)

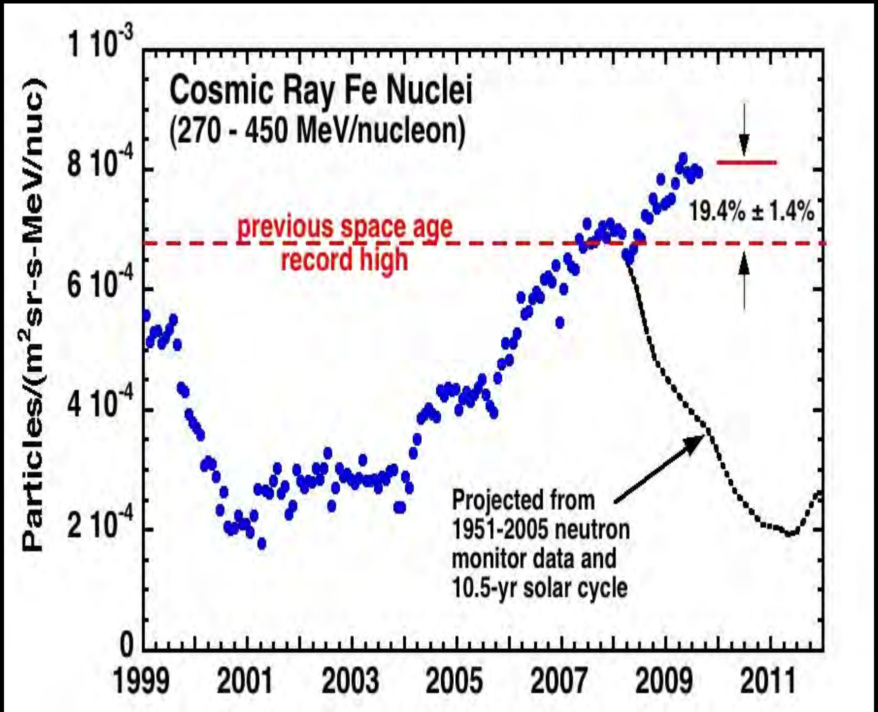
- high energy protons
- **highly charged, energetic atomic nuclei (**
- not effectively shielded (break up into lig
- abundances and energies quite well know
- MAIN PROBLEM: biological effects poorly
  significant long-term space radiation h

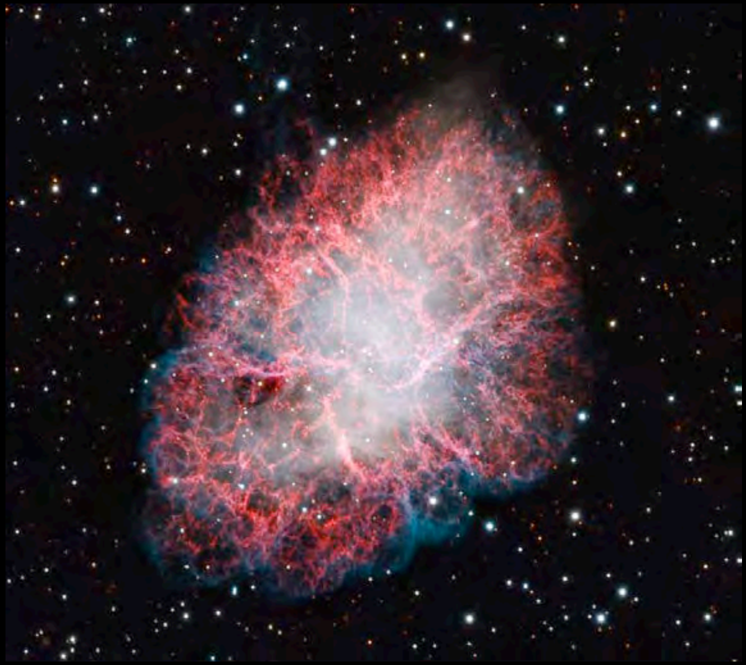


# Who's Afraid of a Solar Flare?

## 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.

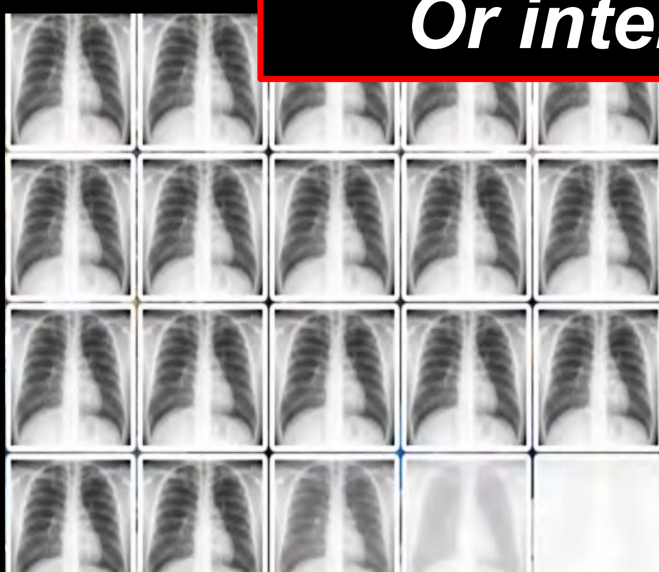


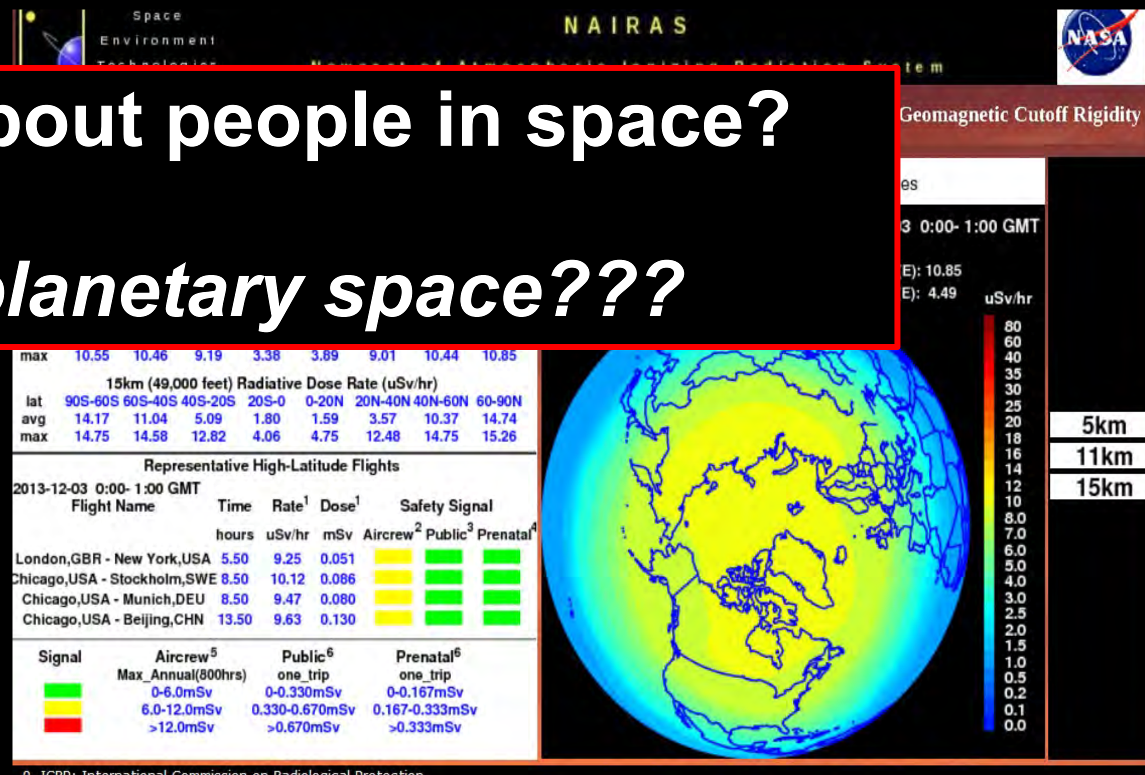



Cosmic rays from distant supernova explosions and black holes are far more energetic and penetrating than particles from relatively puny solar flares.

# 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

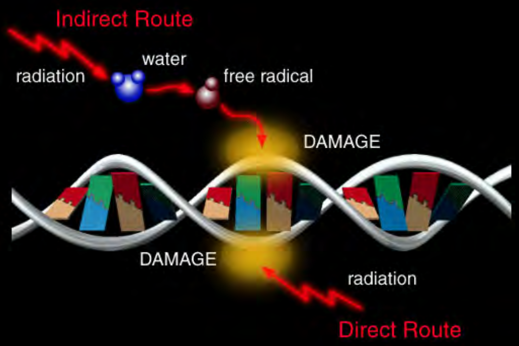





**So what about people in space?**

***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…*

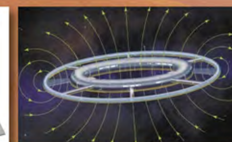
National Aeronautics and Space Administration

## Mission and Architecture Systems Analysis


Near Earth Asteroid Systems

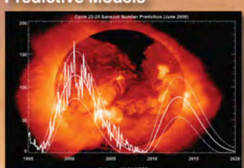

Mars NTV


In-situ Resource Utilization


Active Shielding Concepts

## Environmental Modeling, Monitoring, and Prediction

Predictive Models



Precursor Data — MSL RAD

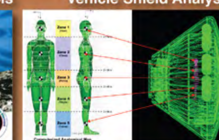
On-board Dosimetry– ISS TEPC

## Crew Selection and Operations

## Integrated Radiation Protection System Design and Analysis

Design and Optimization Tools


Crew Exploration Vehicle Shield Analysis

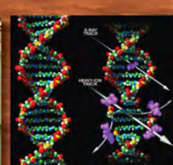


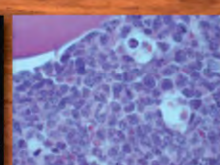
High Energy Nuclear Physics and Transport

## Radiobiology and Biological Countermeasures



NASA Space Radiation Lab at Brookhaven National Laboratory


X-ray vs. Heavy ion Track Damage to DNA

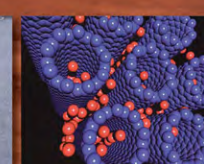

Leukemia induction with GCR — Mouse Model

## Innovative Multi-Purpose Shield Solutions

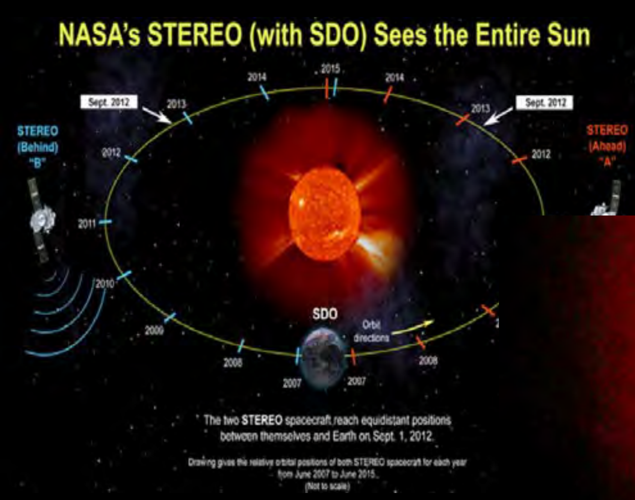

Heavy Ion Testing of Inflatable Shield Prototype


Water Filled Composite Shield Sections

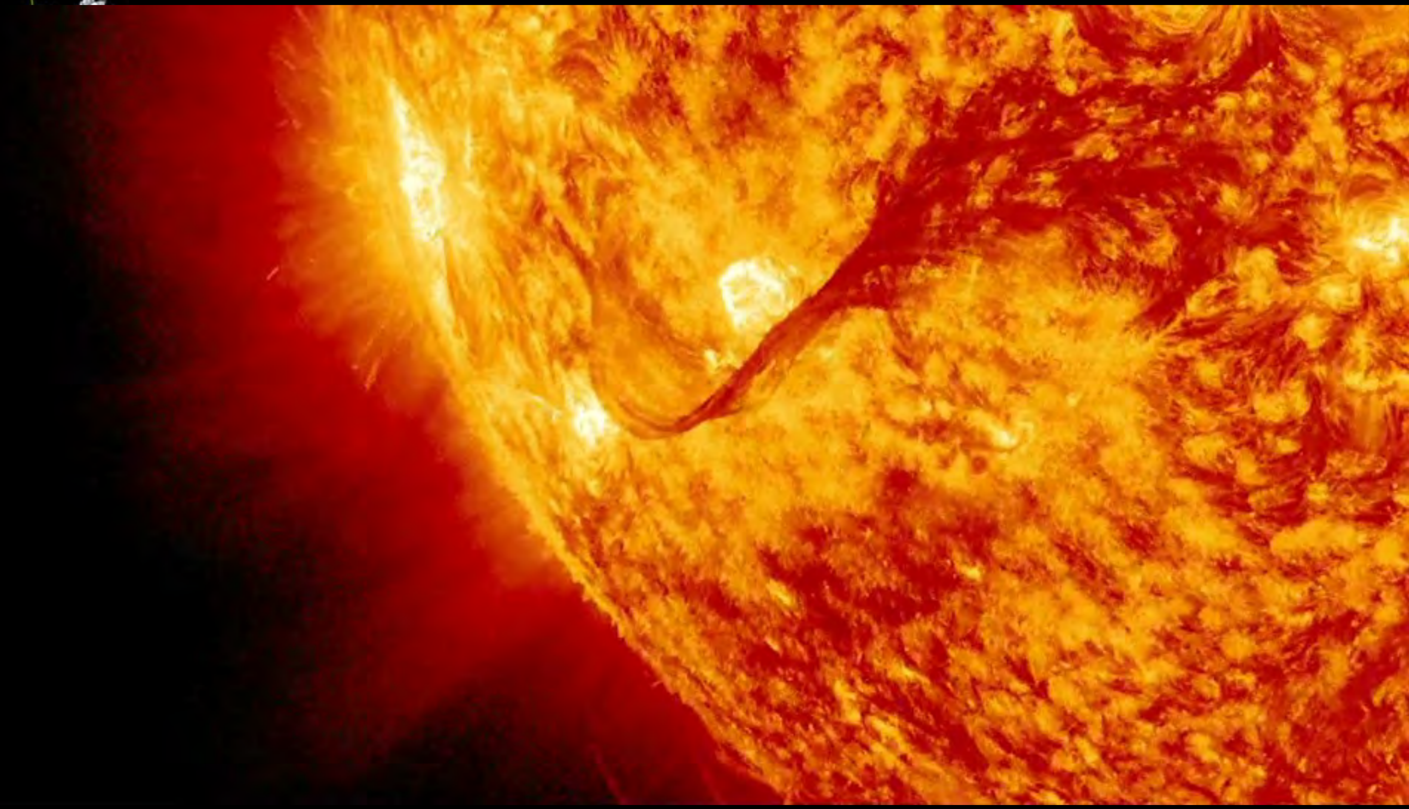

Reconfigurable Personal Shielding


Hydrogen Storage BNNT

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

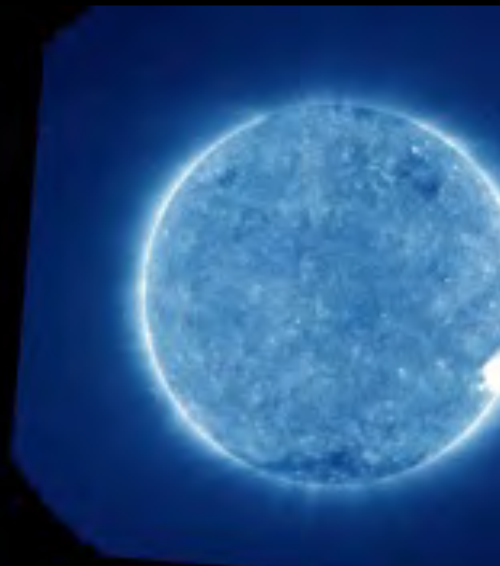



Thanks to SOHO, the twin STEREO probes and the Solar Dynamics Observatory, no significant eruption escapes detection, not even when it occurs on the far side of the sun



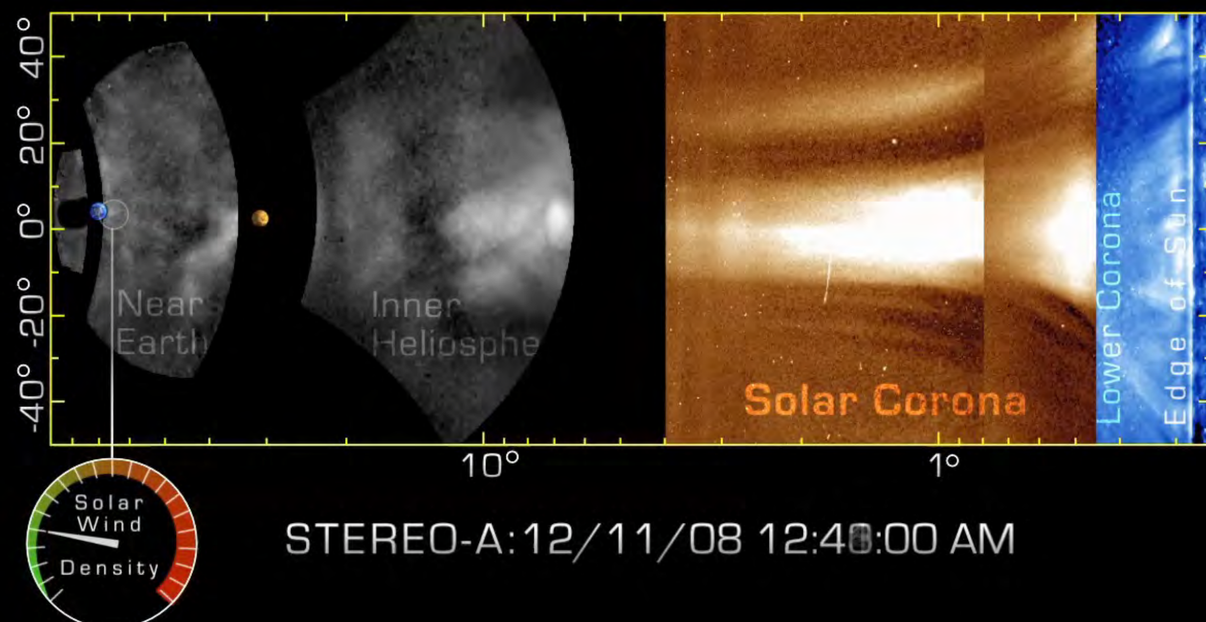
This is possible because **we've got the sun surrounded.**

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

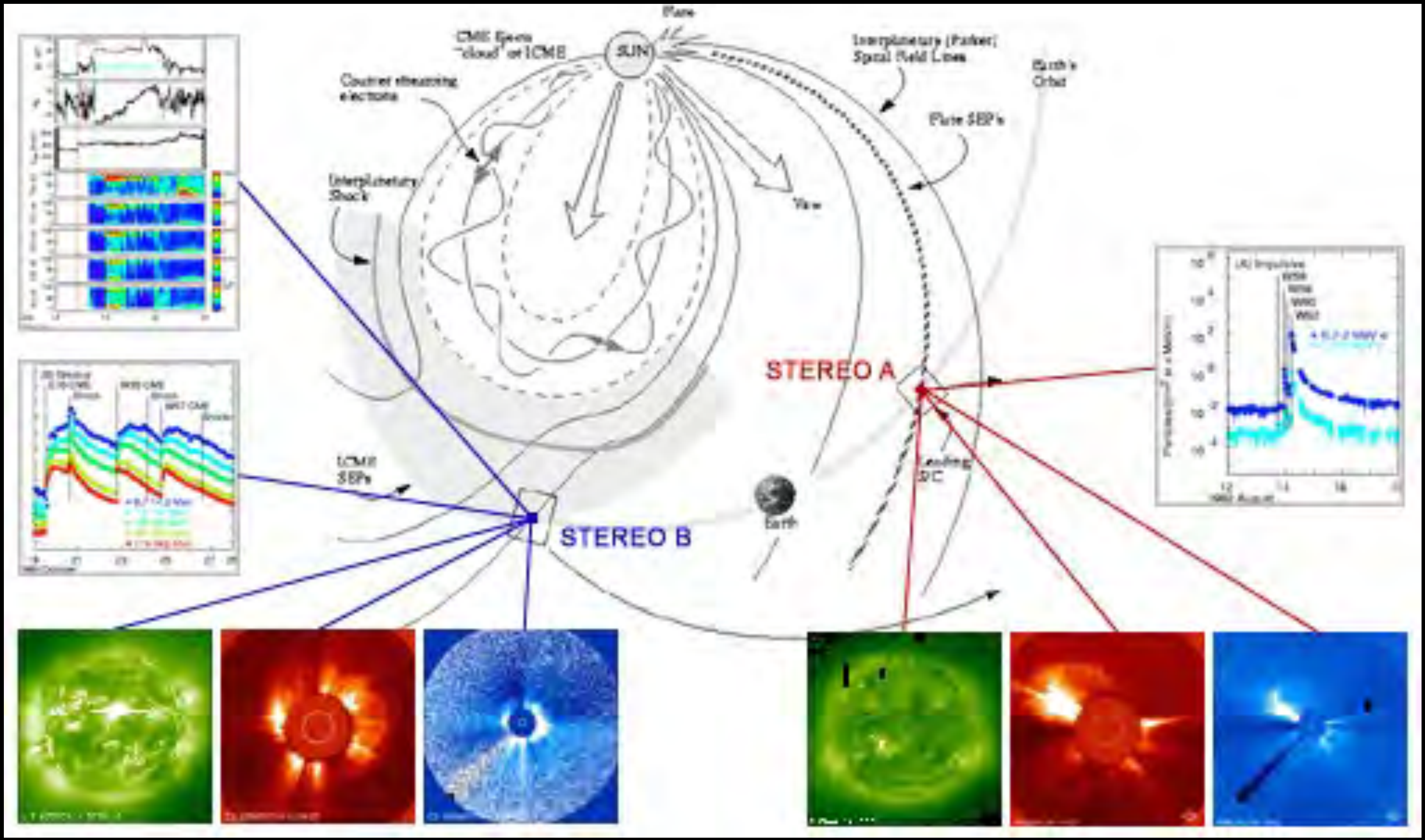


NASA's STEREO spacecraft and new data processing techniques have succeeded in tracking space weather events from their origin in the Sun's ultra hot corona to impact with the Earth's magnetosphere

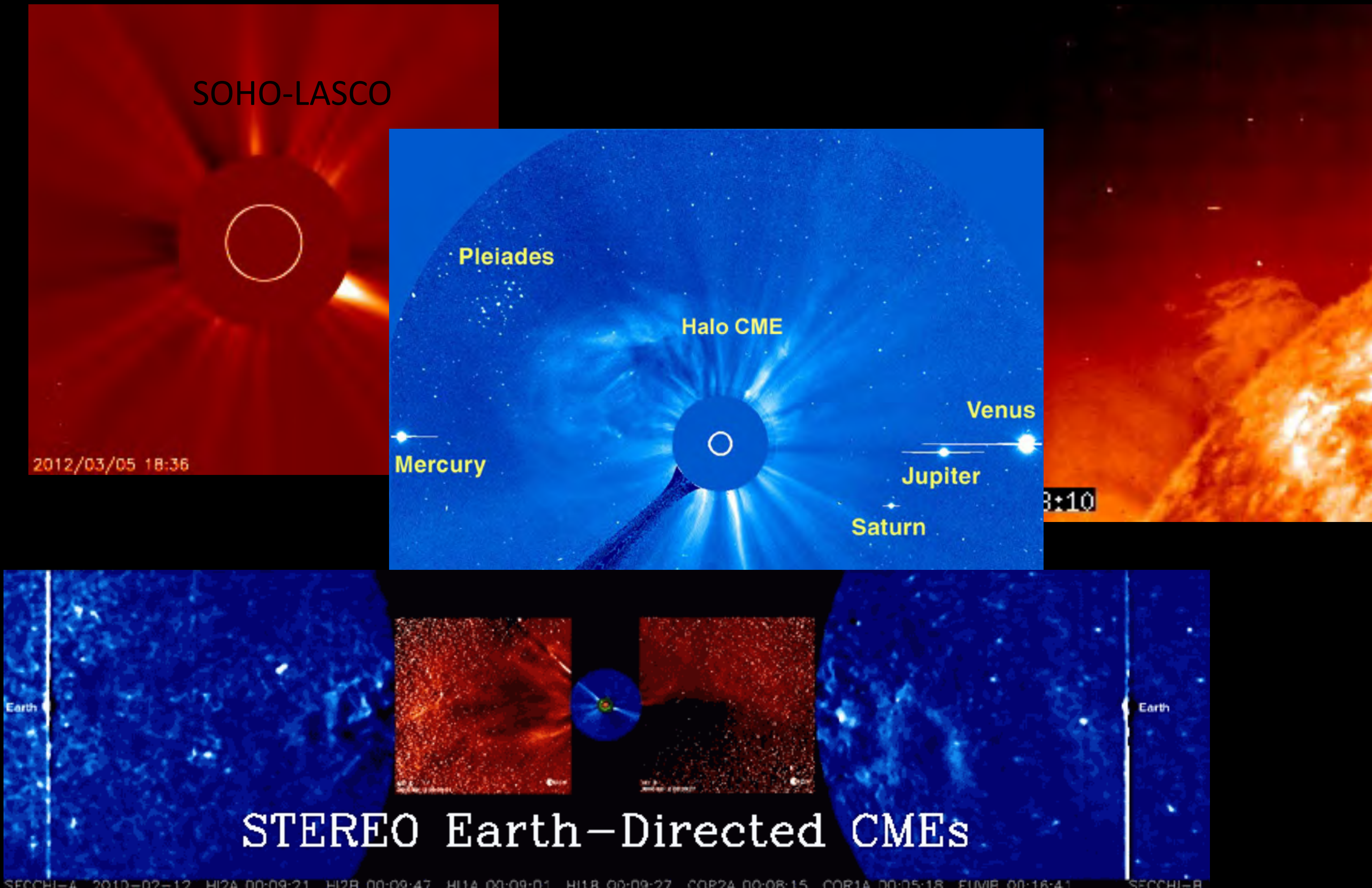
STEREO includes 5 telescopes that monitor the sky at large angles from the Sun



While we are imaging the Sun, in-situ detectors on STEREO and ACE measure the solar wind and energetic particle (SEP) signatures of space weather at their locations



# Not only Earth, but the entire solar system 'Lives with its Star'

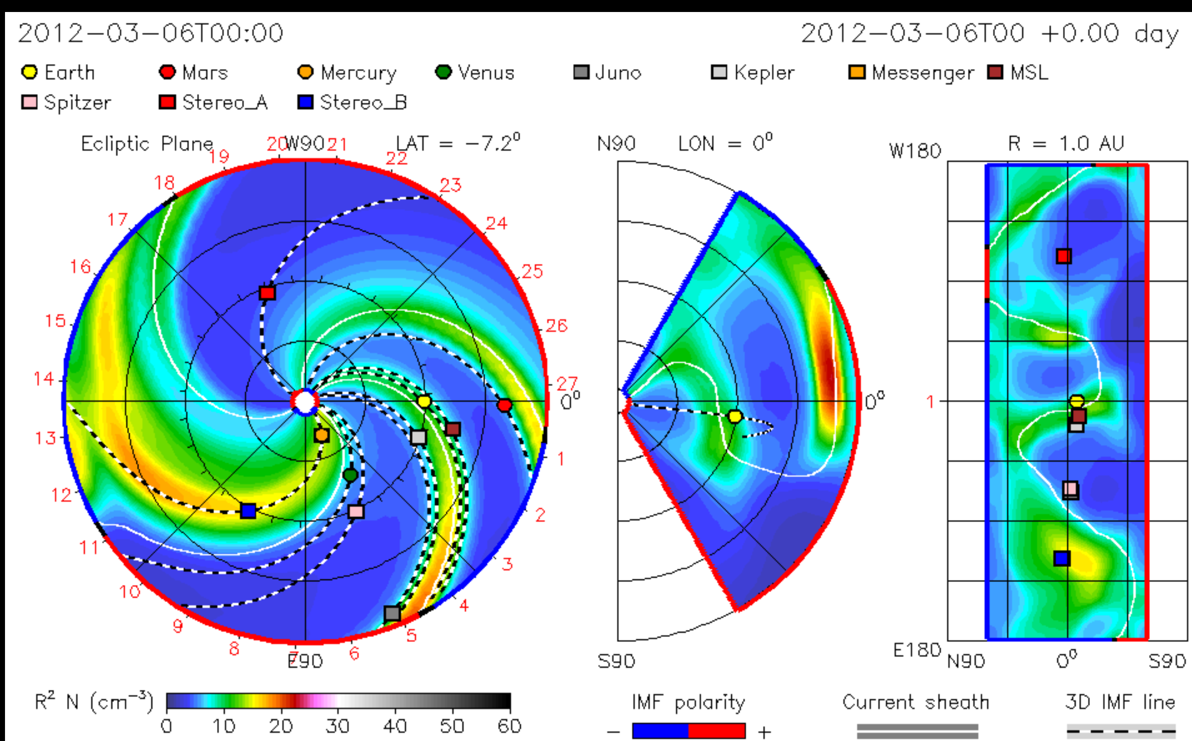


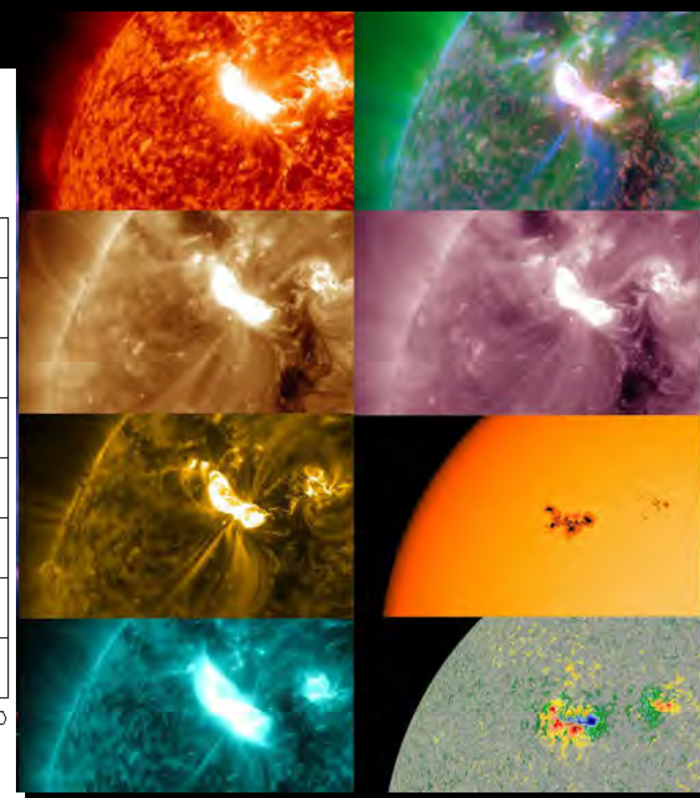

SOHO LASCO images and STEREO SECCHI images of coronal outflows and eruptions.
(from SOHO website and Ying Liu, SSL (STEREO panorama))

# 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.**



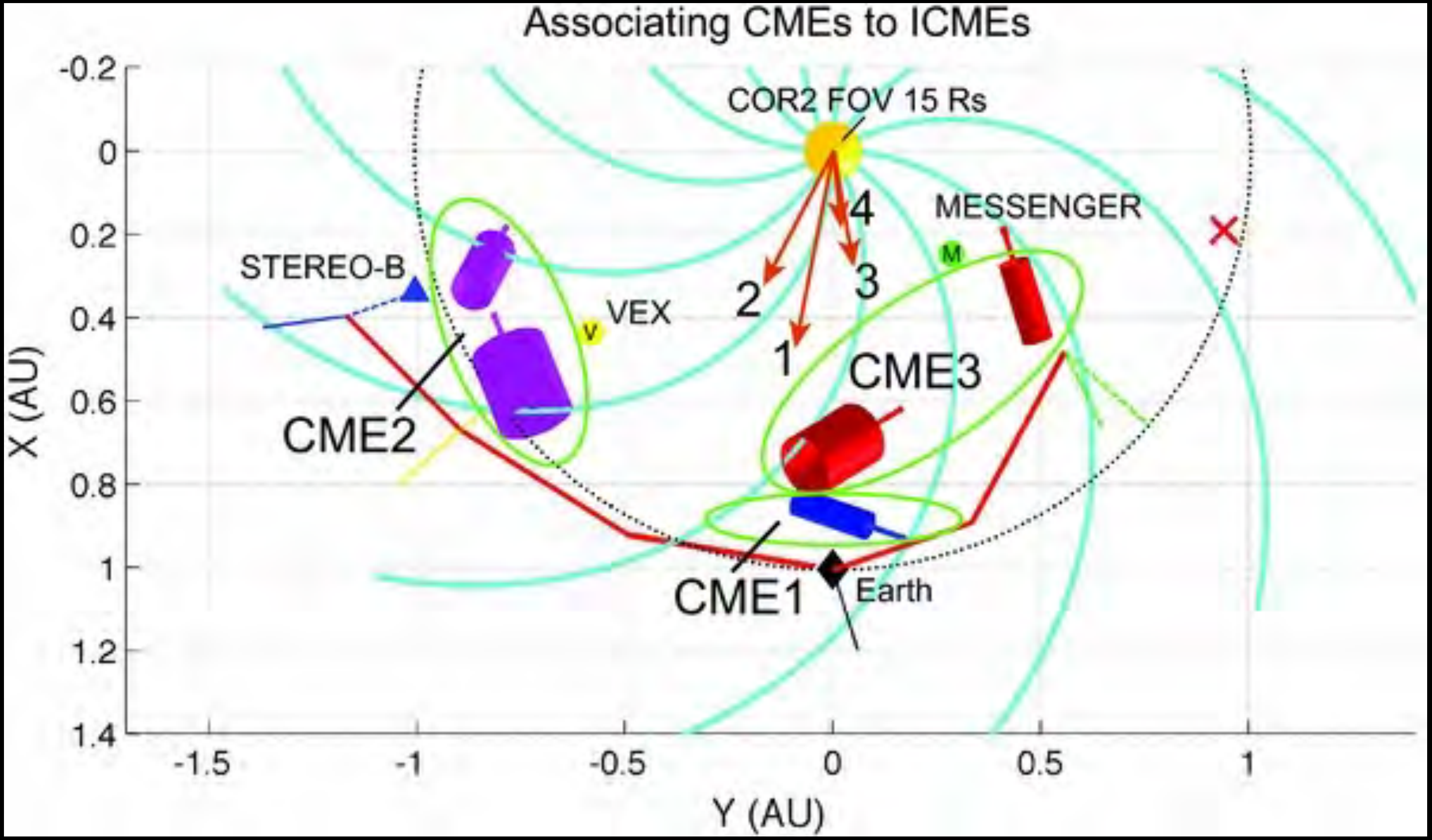
# Reasons for developing this predictive capability may be divided into three pressing areas:

**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.

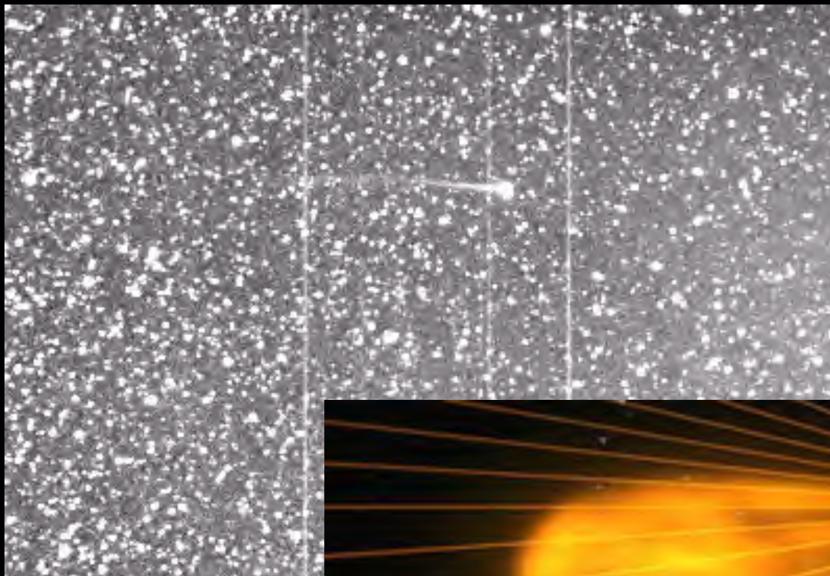
**Spacecraft operations** are also key. Energetic particles accelerated by solar storms can cause onboard computers to reboot, introduce confusing noise in cameras and other digital sensors, or simply accumulate on the surface of a spacecraft until a discharge causes serious problems.

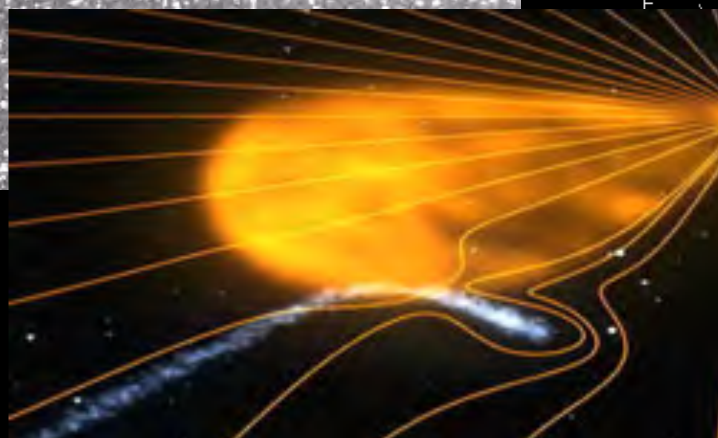
**Scientific research** could be the greatest beneficiary of interplanetary space weather forecasting. What happens to asteroids, comets, planetary rings and planets themselves when they are hit by solar storms? Finding out often requires looking at precisely the right moment.

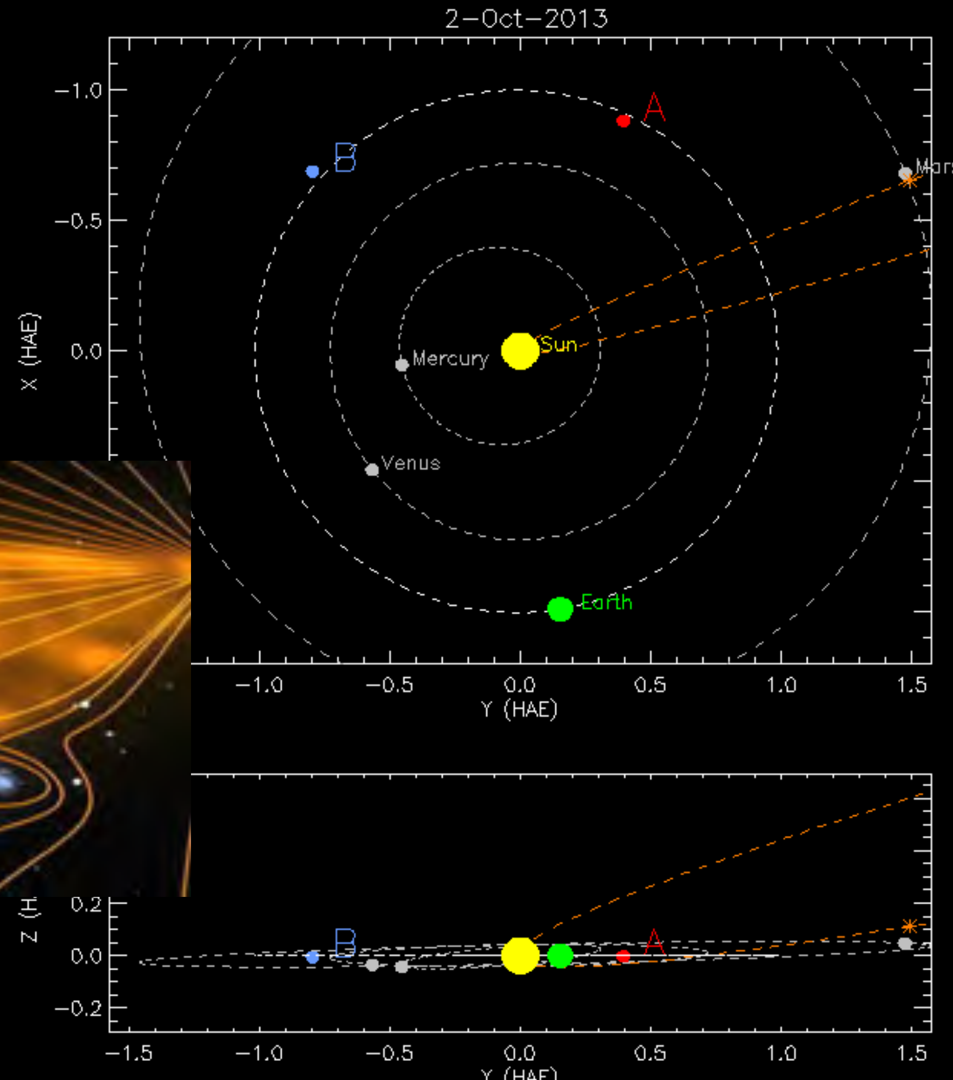
Combined with in-situ instruments on planetary missions, (MESSENGER, or ESA's Venus and Mars Express-VEX and MEX), 'reconstructions' of solar system-wide space weather conditions are now possible




Moestl et al., ApJ 2012








Images of a Cometary tail 'disconnection' following a CME encounter, and Artist's conception

*NASA website images from comet Enke passage*

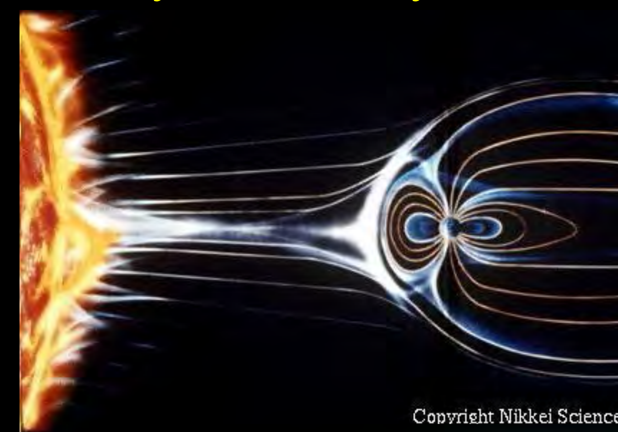
Support observations for other comets. Also, provided info to the Rosetta mission.

Both our terrestrial planet neighbors may have once had oceans and more temperate surface conditions

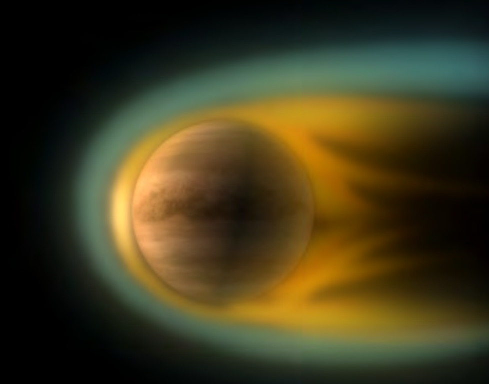
Do Magnetospheres shield planetary atmospheres from significant Solar Wind erosion?

Do solar activity and the related space environment determine their fates?

What are the possible implications for Earth and solar system history if so?




Both also have weak planetary magnetic fields



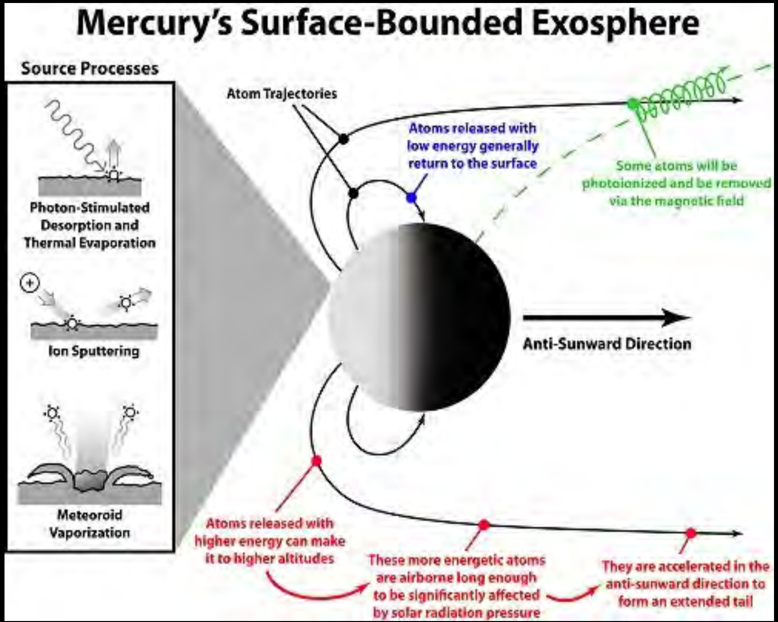
(image: ESA website)

# Space Weather on Mercury

The most ferocious space weather in the solar system is felt on Mercury, the closest planet to the Sun. MESSENGER has observed a highly dynamic magnetosphere with magnetic reconnection events taking place at a rate 10 times greater than what is observed at Earth during its most active intervals.

**A CME impact on Mercury**

Exactly what we would see is not known. Even garden- variety CMEs may be strong enough to overwhelm Mercury's magnetic field and strip atoms right off the planet's surface. Mercury's comet-like tail of sulfur is likely populated by this process. **If operators know when a CME is coming, special preparations can be made,**

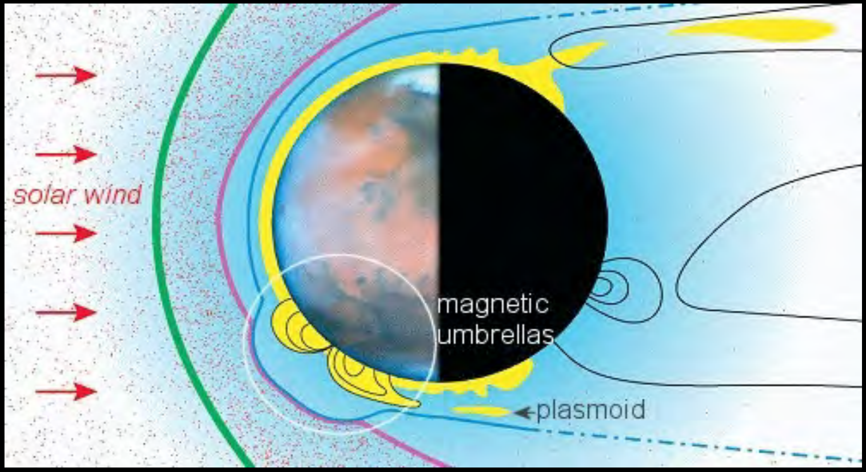



# Space Weather on Mars

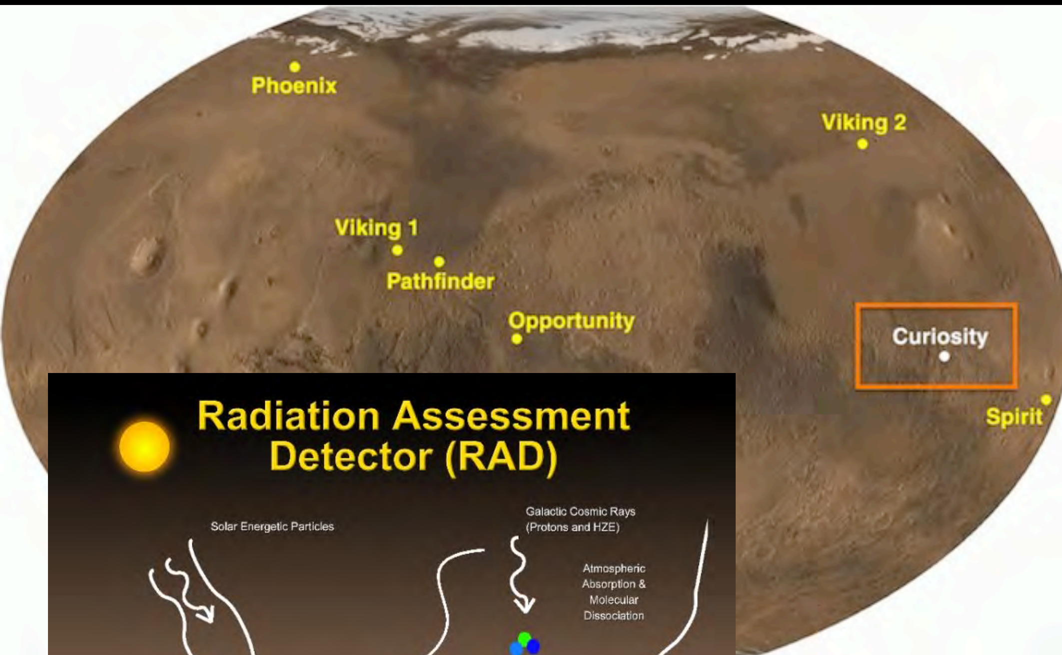
In 1998, MGS discovered that Mars has a very strange magnetic field. Instead of a global bubble, like Earth's, the Martian field is in the form of magnetic umbrellas that sprout out of the ground and reach beyond the top of Mars' atmosphere. These umbrellas number in the dozens and they cover about 40% of the planet's surfce, mainly in the southern hemisphere.

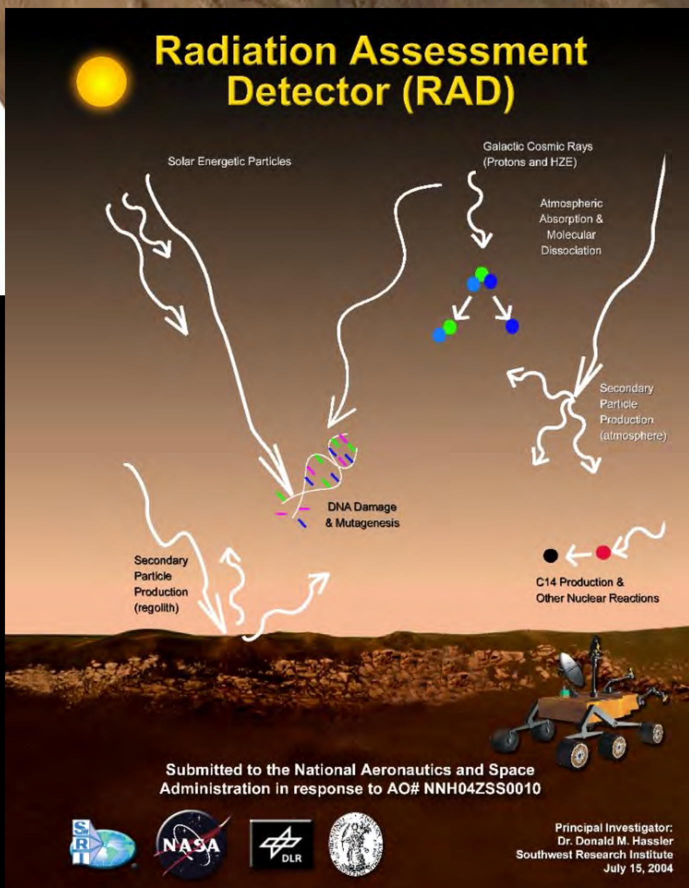
When Mars gets hit by a CME, the resulting magnetic storms take place not at the planet's poles but rather in the umbrellas.

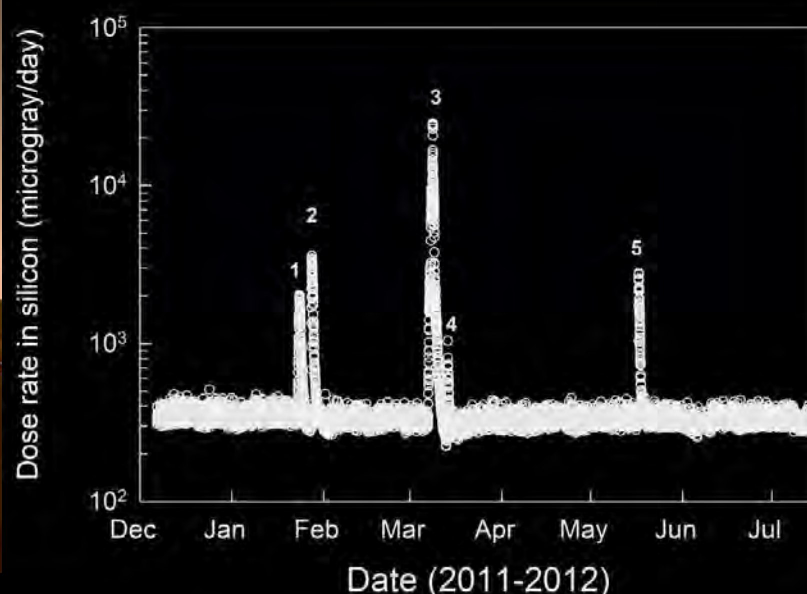
One important focus of MAVEN is to determine how CMEs and solar energetic particles alter the upper atmosphere and escape rates. Space weather alerts would certainly advance the goals of missions like this.



*Combinations of SDO, SOHO, STEREO and ACE contextual space weather information with MAVEN local orbital and MSL RAD measurements on the Martian surface are tieing into surface chemistry and biological implications*




Images from JPL and SWRI-RAD websites

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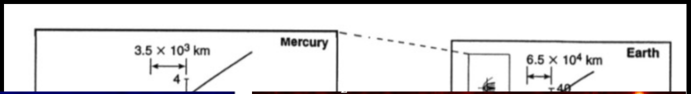
# Sun-Earth System Science:
# Growth from a “consuming” science to a “producing” science for the benefit of humankind

Space Weather is no longer the domain of Earth only!

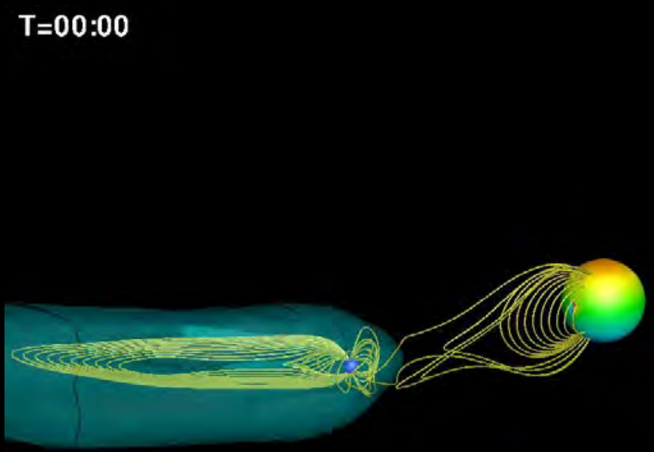
Space Weather is now also Interplanetary!!




Space Weather just became Exopla



Extreme Space Wea




# Heliophysics: A New Discipline


***Heliophysics I:***
“Plasma physics of the local cosmos”

***Heliophysics II:***
“Space storms and radiation: causes and effects”

***Heliophysics III:***
“Evolving solar activity and the climates of space and Earth”

***Heliophysics IV:*** *(In preparation for publishing January 2016)*
“Active stars, their astrospheres, and impacts on planetary environments”

***Heliophysics V:*** *(Online only )*
“Space weather and society”

**Since 2007-2015, we have had:**

**Total Students ~500,**

**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 scientist “Jack Eddy”**

# Star-planet connections: consequences of the connections between stellar and planetary dynamos on environmental conditions at planetary surfaces

Sun as  star. Technical breakthroughs in stellar astrophysics now permit us to place solar questions in a broad astrophysical context. Tools originally developed for the Sun are now becoming broadly applicable to stars.

Early Earth magnetosphere and atmosphere (also Mars, Venus as divergent path examples) subject to young-Sun activity (SSI, wind, and SEP)

Effects of stellar/solar wind evolution over the history of a planetary system on the exposure to (variable?) GCR input (including possible GRBs and Supernovae), tested against their possible  signatures in terrestrial natural records, lunar rocks, and other  objects with remaining signature radionuclide populations.

Paleo-climatic history of Earth over time as exposed to an evolving TSI/SSI and consequences on liquid water environments at the planetary surface.

Exoplanets of different atmospheric/magnetic properties subject to variable stellar magnetic activity and its output into asterospheres, including energetic particle exposure over time.

# Heliophysics from a whole solar system perspective

Heliophysics tells us more about how our Earth and its planetary neighbors got to be what they are. A rocky body about Earth size in the ‘habitable zone’ is not enough to make an Earth. Venus beinga key case-in-point. Comparative Planetary System research speaks to Earth’s history, uniqueness and stability. It complements the growing exoplanet activities within NASA by providing information relevant to remote detections and interpretations of stellar wind interactions with exoplanets. Our own Sun and solar system are the only ‘ground truth’ examples allowing detailed insights. And turning the tables, we can learn much from the exoplanets and their stars about our own star’s and solar system’s past (and future) .