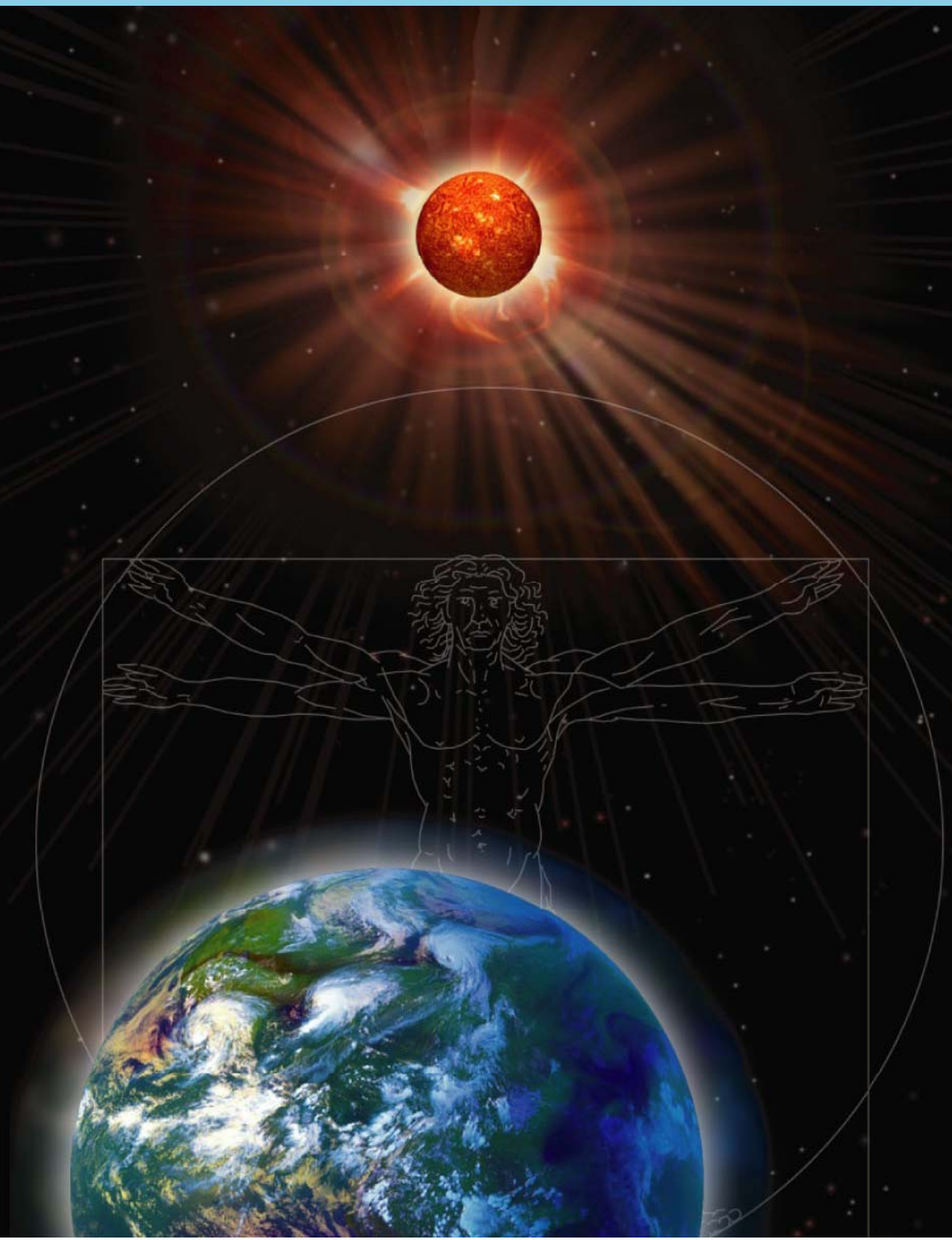
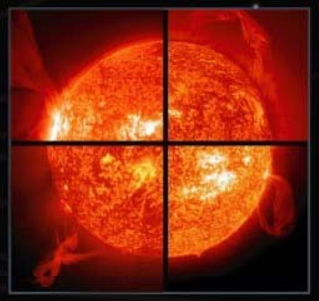
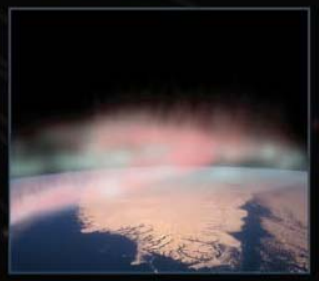
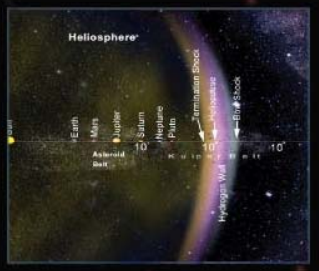
NASA Heliophysics Research Program: Past, Present & Future









Madhulika Guhathakurta
Lead Program Scientist, Living with a Star

NASAHeadquarters
Science Mission Directorate

Heliophysics Division

Space Weather Risks & Society
NASA Ames, Oct. 15-16, 2011

Overarching Principles

At the center of the solar system there is a magnetic variable star, the Sun, that drives the Earth and other Planets, and structures the interplanetary space itself .

All of NASA’s activities, all human endeavor, are subjected to forces in this neighborhood.

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.

Elements of HPD Strategy 2003-Present

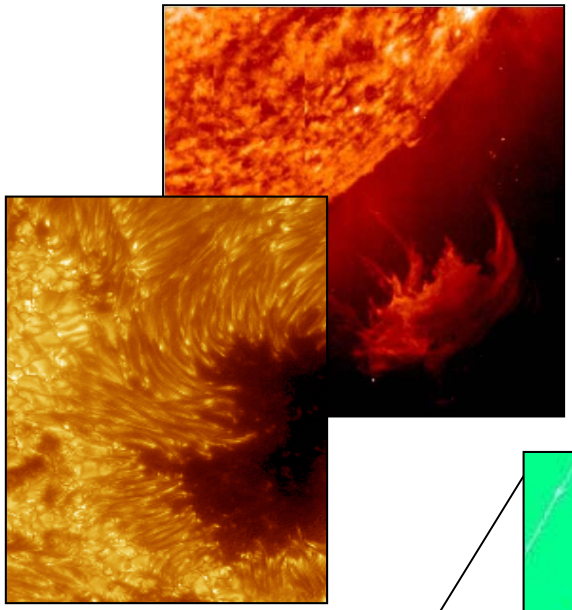
Vital Goal	HPD Roadmap (2009) NRC Decadal Study (2003) SMD Strategic Plan (2010)
Available Resource	STP Mission Line, LWS Program Mission Line, Explorer Program Competed R&A program
Political Will	Focus of the complex interconnected, interdependent, diverse adaptable system of systems -Scientific Community, Agency, Executive Branch, Congress, etc.

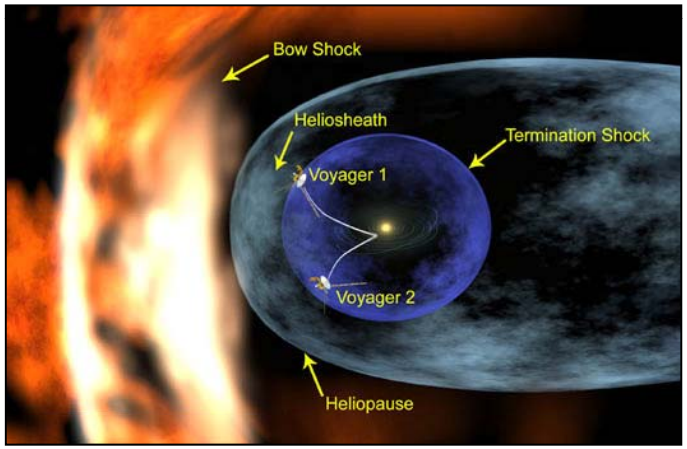
The HPD program utilizes the Keegan model of classical strategy – see: Keegan, J. (1988) *The Mask of Command*, Penguin Books, New York

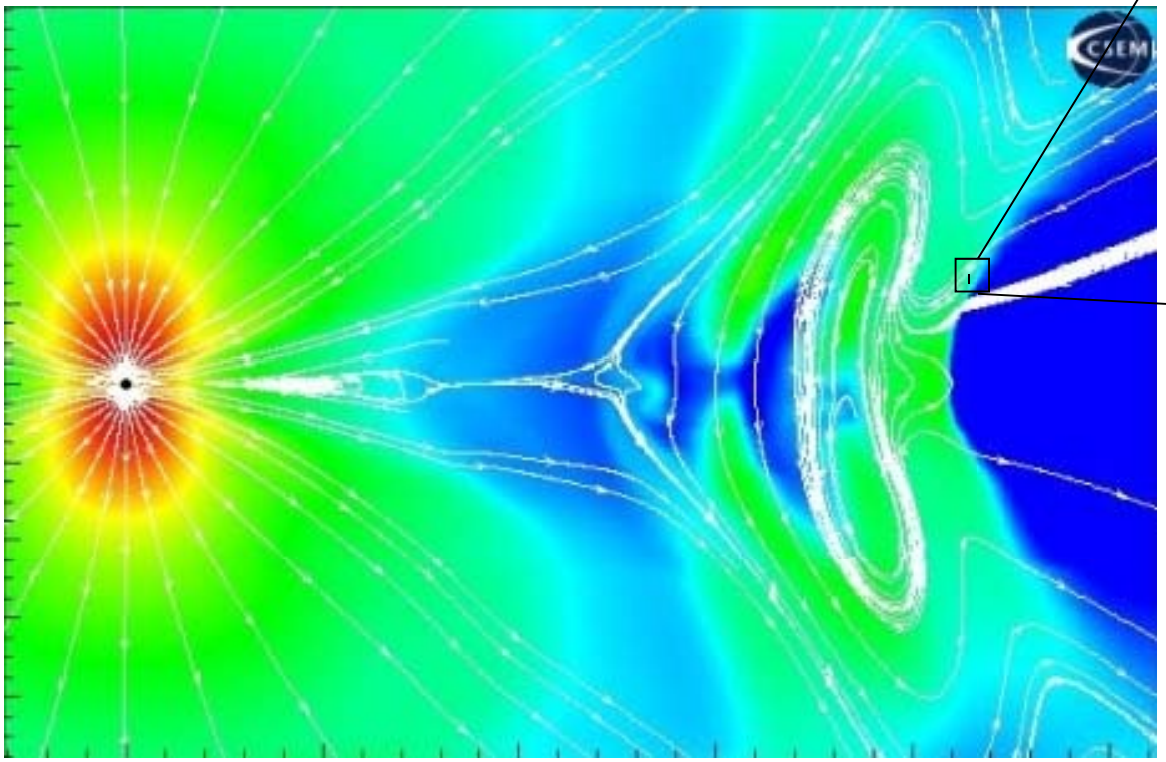
Nature of the Challenge

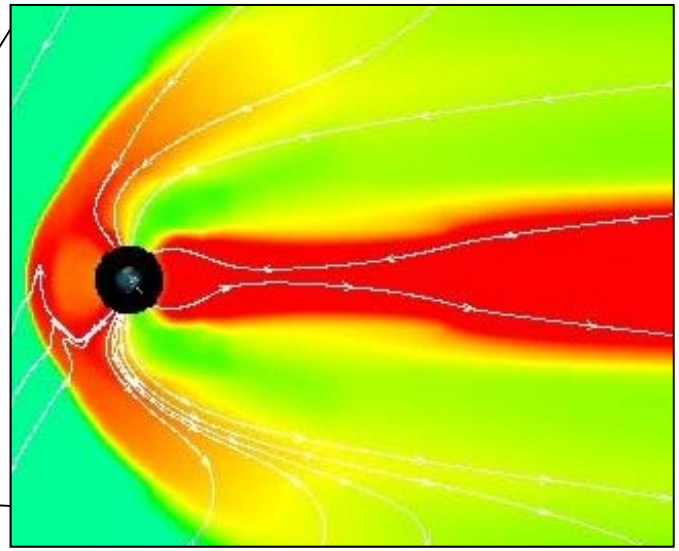
This is a complex system with many different temporal and spatial scales

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



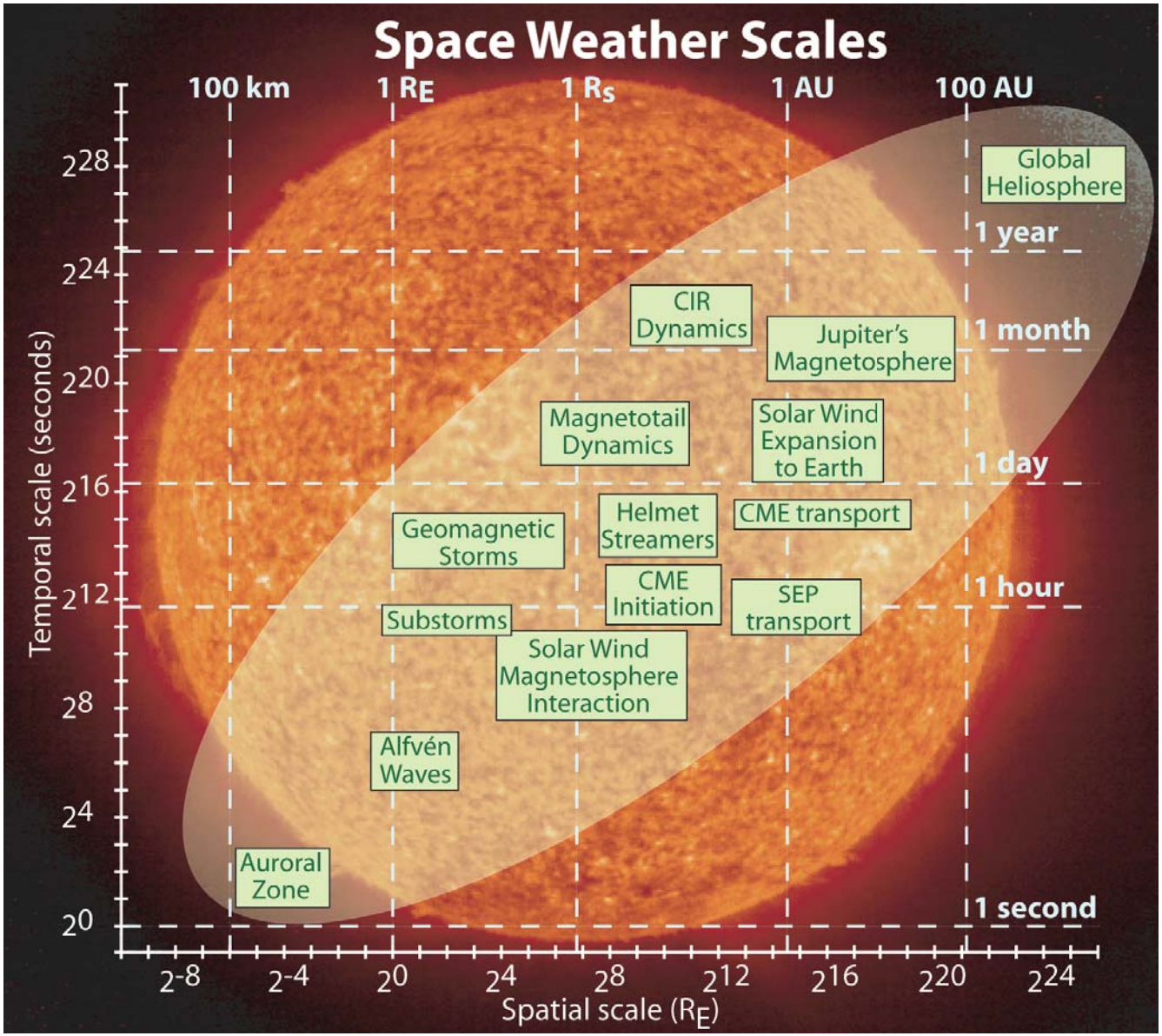






- Integration and synthesis of multi-point observations
- Data assimilative models & theory
- Interdisciplinary communities and tools

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

Complex System Properties

Prediction is difficult based on knowledge of components alone

Negative and Positive Feedbacks are Integral to System Behavior

Small changes in initial conditions can affect the final state

History Matters

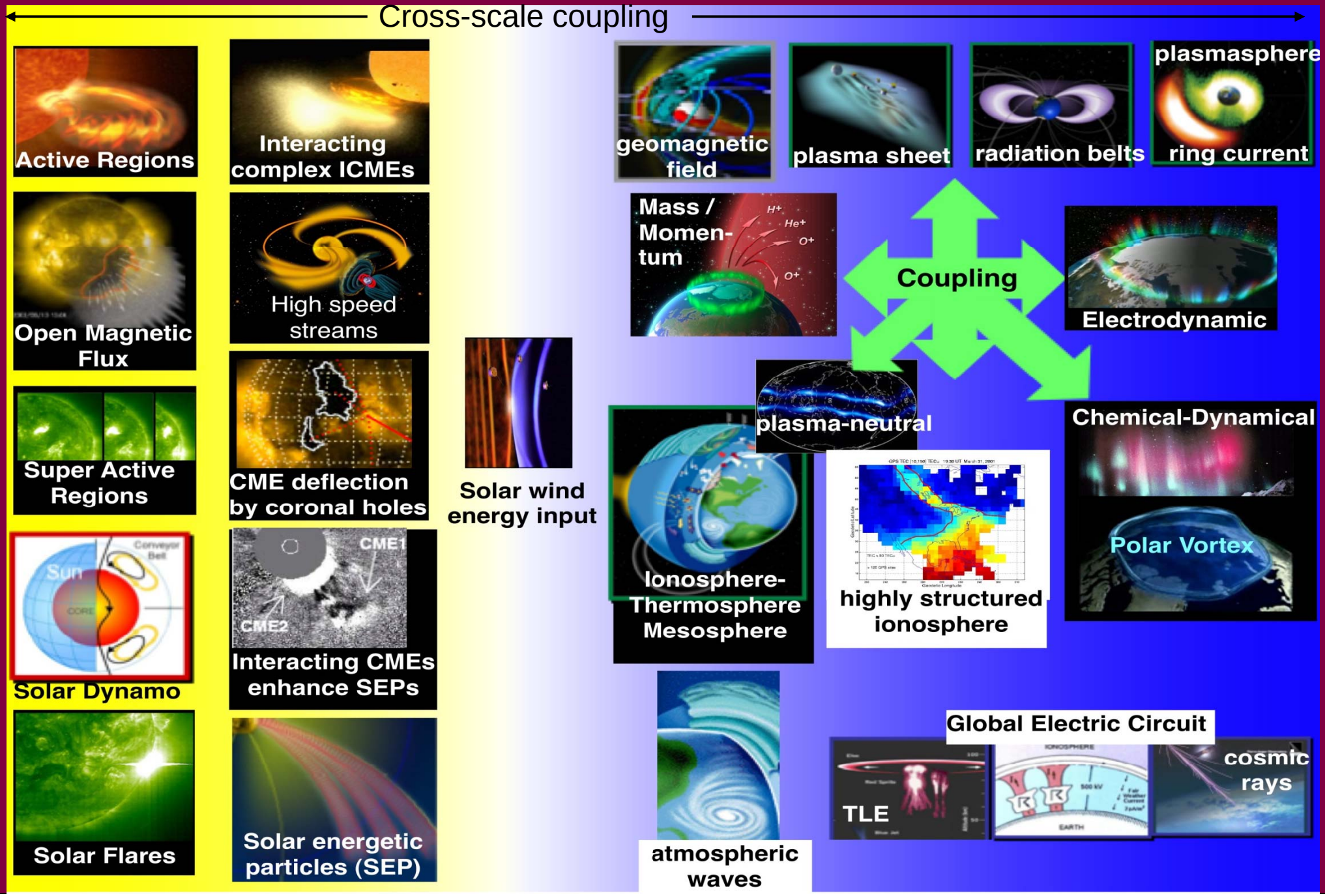
Emergent Features Appear

Consequences:

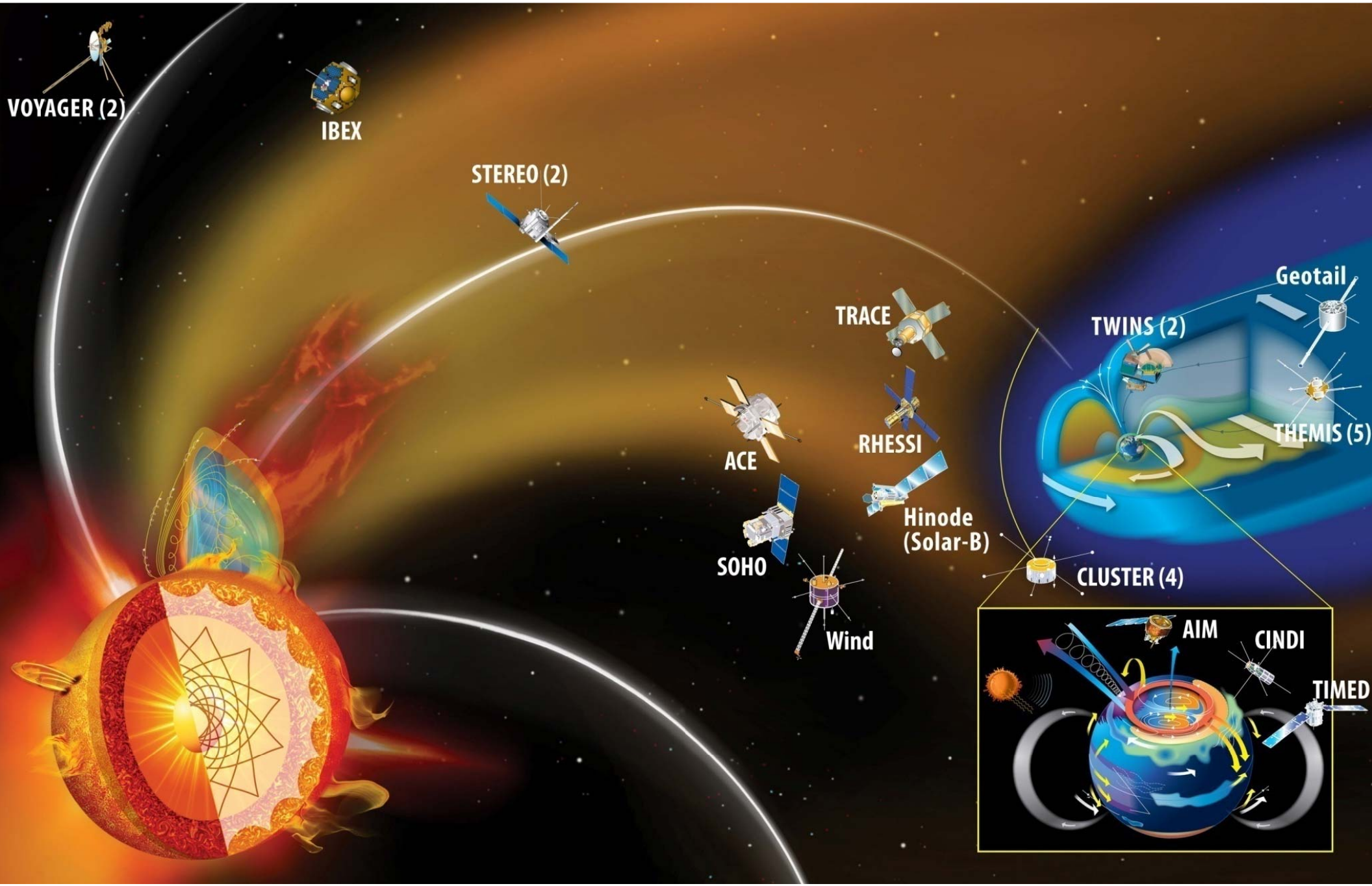
- Interactions between components often define the system response Not contained in the individual pieces
- Clear cause and effect appears only when these effects are disentangled.
- For these cases, cannot break system into smaller digestible pieces for study

Interacting components

Preconditioning, Initial Conditions, Memory, Feedbacks, Nonlinearity, Instability, Emergence

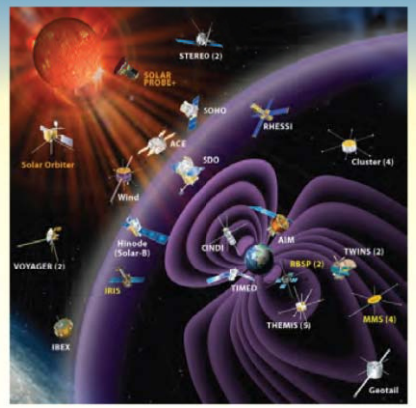


Heliophysics System Observatory - spacecraft working together on systems science



HELIOPHYSICS: An Integrated Program

DATA



- Heliophysics System Observatory (HSO)
- Virtual Observatories
- Low Cost Access to Space

MODELS

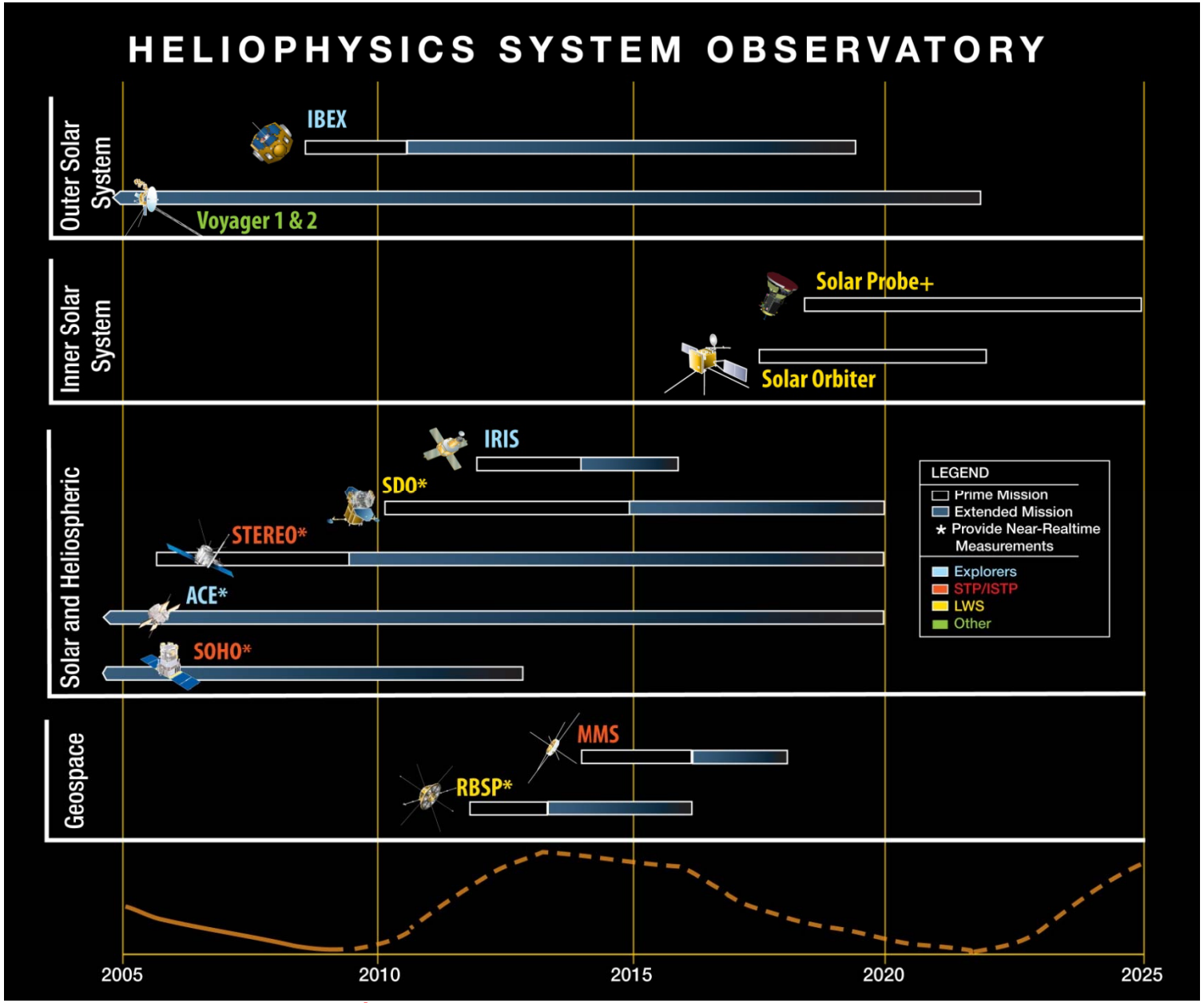
COMMUNITY COORDINATED MODELING CENTER

- Community Coordinated Modeling Center (CCMC)
- Guest Investigator Program
- integrated Space Weather Analysis System (iSWA)

THEORY

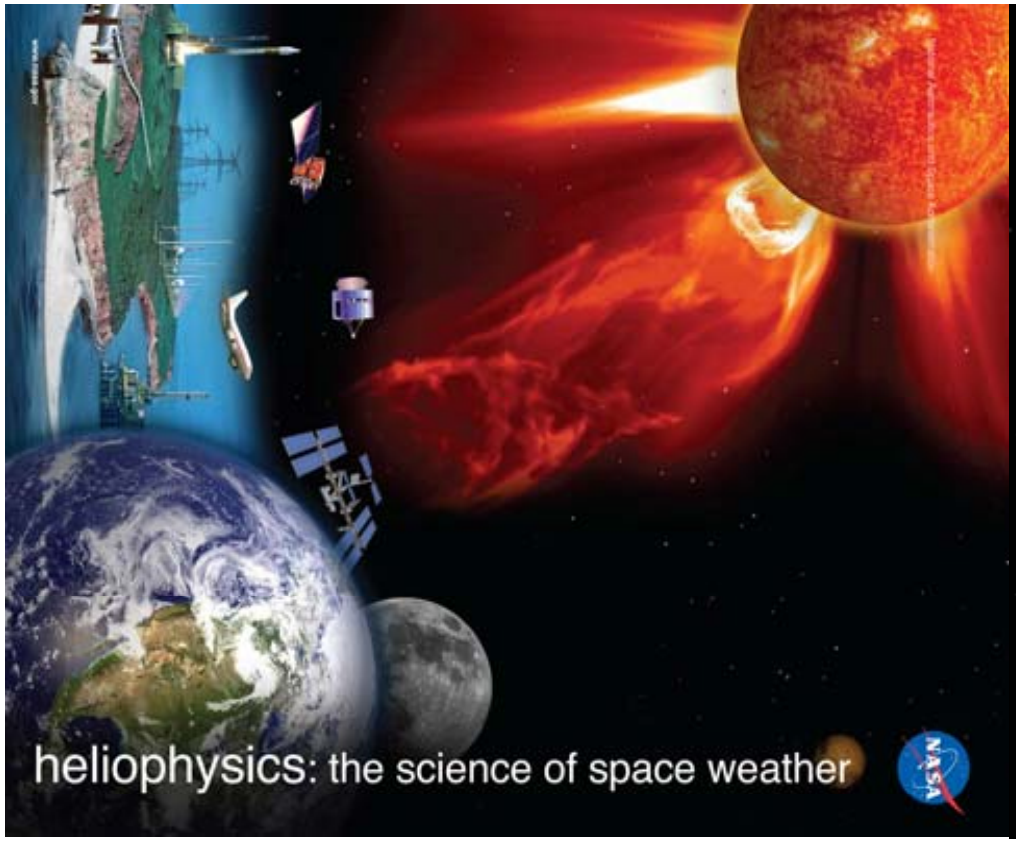
- Supporting Research and Technology (SR&T)
- Targeted Research and Technology (TR&T)
- Research and Analysis (R&A)
- Theory Program

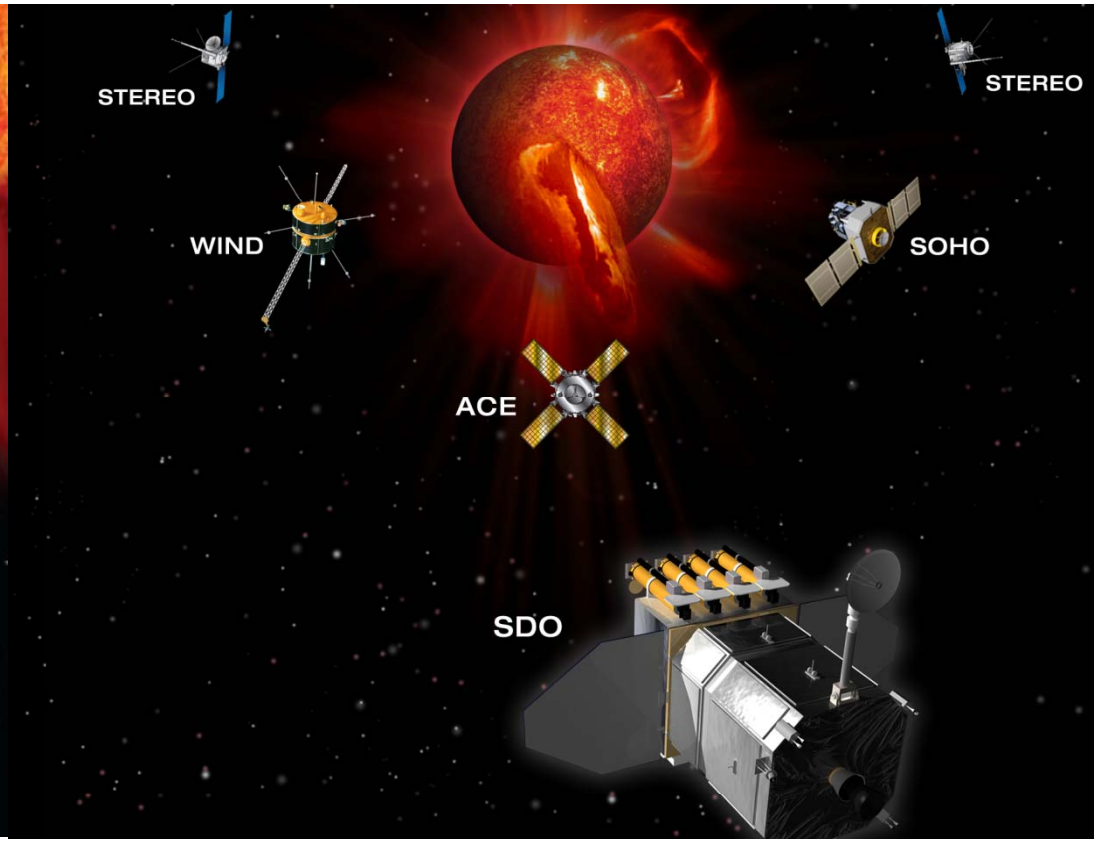
Heliophysics Strategic Flight Plan 2010-2020



12 Future Flt Program

Heliophysics and Space Weather (SWx)





Heliophysics research provides Theory, Data, and Modeling development at services to the national efforts in operational SWx.

The five research missions most often utilized are ACE, SOHO, STEREO (ahead and behind spacecraft) and SDO

Explore synergies between HEOMD and SMD

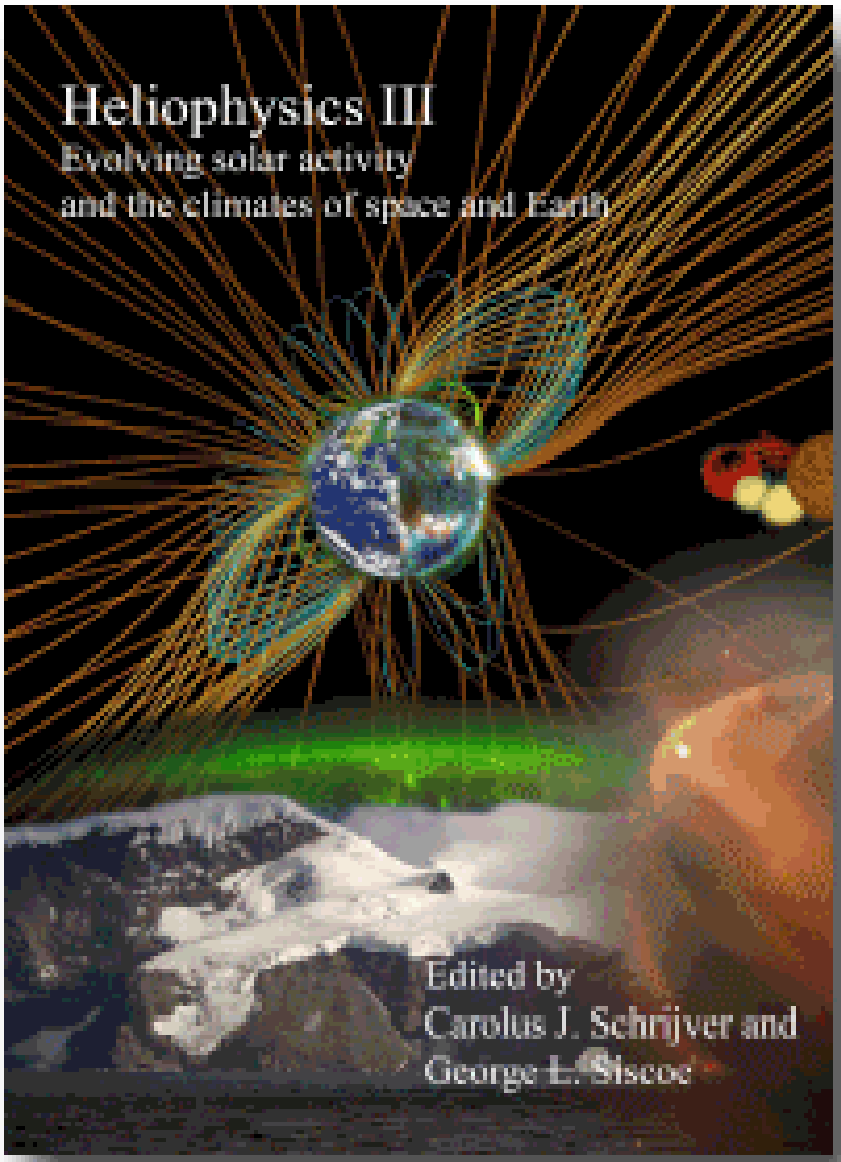
- **SWx instrumentation on SMD spacecraft**
  - *LRO CRaTER is a successful example*
  - *MSL RAD is nearing launch*
  - *Missed Opportunity: DAWN magnetometer was descoped*
  - *Opportunity: Solar Orbiter EPD/SIS and SPICE*
  - *Opportunity: OSIRIS-Rex has no environmental monitors*

- **Insure that "beacons" are included on SMD/Heliophysics missions, where relevant**
  - *Highly-compressed, continuous telemetry downlink (ACE, IMAGE, STEREO, SDO)*
  - *Beacon on RBSP (LRD:2012)*
  - *Presently beacons are only an informal SMD HPS policy*

- **Insure that environmental monitors are flown on planetary and interplanetary NASA spacecraft, where relevant**
  - *Significant aid in anomaly resolution*
  - *Useful for V&V to modeling community (TBC)*

- **Insure that SMD planetary missions gather cruise phase data, where relevant**

LWS Graduate Level Education



A three volume Series, an outgrowth of the LWS summer school series. The Heliophysics textbooks have been published by *Cambridge University Press*

Choice, the magazine of American Library Association has listed Heliophysics Vol I as an "Outstanding Academic Titles, 2010", Choice, v.48, no. 05, January 2011.

Vol 1 Plasma Physics of the Local Cosmos

Vol 2 Space Storms and Radiation

Vol 3 Evolving Solar Activity and the Climates of Earth and Space

Summer School Resources:

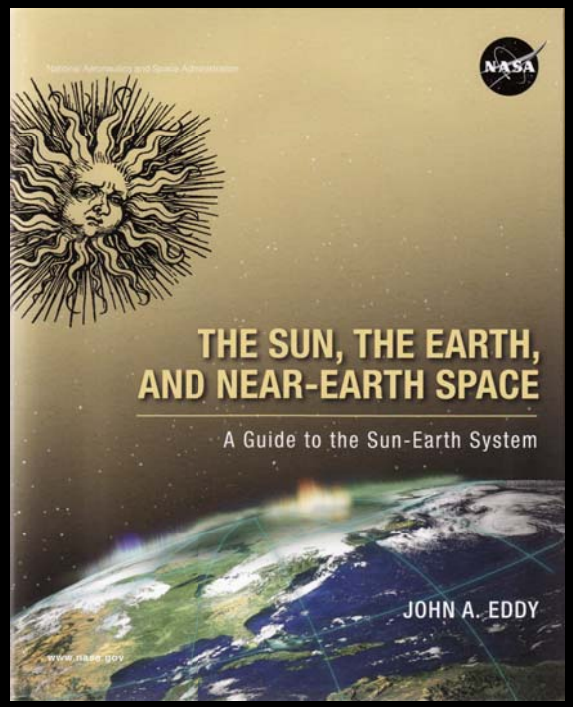
http/www.vsp.ucar.edu/HeliophysicsSummer School

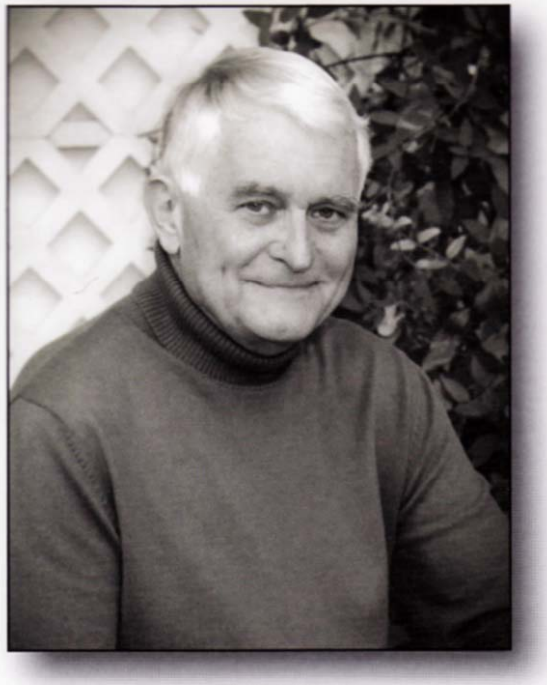
A Primer for Heliophyscs

The Heliophysics Postdoctoral Fellowship Program has been renamed to Eddy Fellowship Program

Eddy Cross-Disciplinary Symposium was held in Sun-Climate research was held in October, 2010 with a major goal to introduce the excitement and challenges of a challenging cross-disciplinary area of research to at least 20 undergraduate and graduate students.

A Japanese translation of this book will soon be available (http://www.maruzen.co.jp/corp/en/)





JOHN A. EDDY

Dr. John A. Eddy is a graduate of the U.S. Naval Academy and the University of Colorado who is best known for his work in recovering the history of the Sun and establishing the reality and nature of extended periods of anomalous solar behavior in the distant past, such as the Maunder Minimum of 1645 to 1715. He is known as well for his investigations of the astronomy of early Indians of the American plains; as a scientific editor and popular interpreter of science; and for many years, in promoting the interdisciplinary study of global environmental change. He is a fellow of the American Association for the Advancement of Science and a recipient of the Arctowski Prize of the National Academy of Sciences for pioneering work in solar-terrestrial physics.

So What Do We Mean by Extreme SWx?

From Cliver & Svaalgard (Solar Physics, 2004)

The biggest geomagnetic storm occurred in March 1989.

The biggest solar particle event occurred in Sept. 1859.

The lowest latitude auroras were observed in Feb. 1872.

The fastest CME on record crossed the sun-Earth divide in only 14 hours in August 1972.

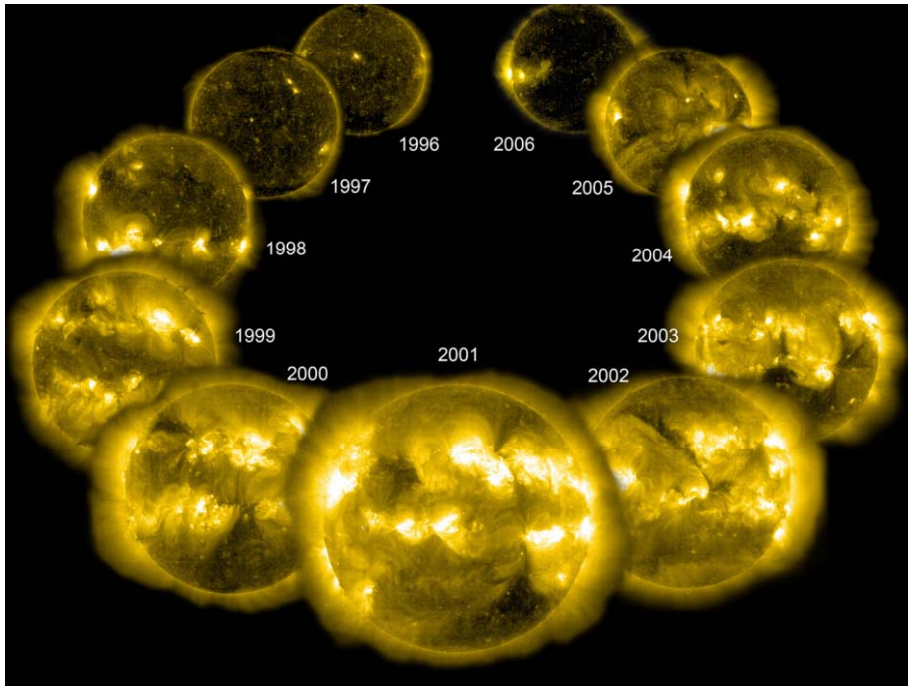
The most intense SID occurred during the Halloween storms of 2003.

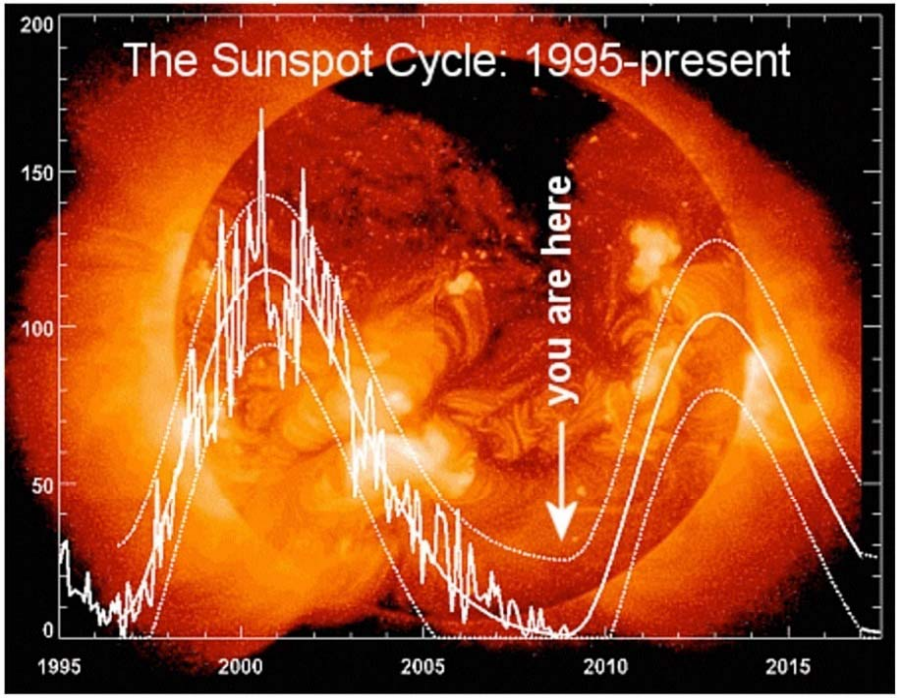
Busting the Scales

NOAA Space Weather Scales for solar radiation storms and radio blackouts make sense. S5- and R5-level events are truly seldom, and it is possible to make a short, finite list of all the extreme events of the Space Age.

NOAA's Space Weather Scale for geomagnetic activity is less useful. This is because of limitations in the K-index, which is easily saturated. In the historical record, dozens of storms with a wide range of consequences would all be described as G5 or "extreme."

Encountering an Extreme Solar Minimum





Since the dawn of the space age:

- Longest period with no sunspots
- Lowest solar X-ray flux
- Cosmic Rays Have Hit a Space Age High
- The Ionosphere Has Collapsed
- Space Junk Is Accumulating
- Radiation Belts are Charged with Killer Electrons
- A Drop in Solar Irradiance affects Earth Temperatures
- The Sun's Magnetic Field is in a Strange State

Heliophysics Future?
Interplanetary Space Weather & Climate Program

As human activity expands into the solar system, the need for accurate space weather and climate forecasting is expanding, too. Space probes are now orbiting or en route to flybys of Mercury, Venus, Earth and the Moon, Mars, Vesta, Ceres, Saturn, and Pluto.

As agencies around the world prepare for these missions to send robotic space craft, each of these missions (plus others on the drawing board) has a unique need to know when a solar storm will pass through its corner of space or how the subsequent solar cycles will behave.

Ultimately, astronauts will follow beyond Earth orbit, and their need for interplanetary space weather and climate forecasting will be even more compelling.

This is New Stuff (How new is it?)

Until recently, forecasters could barely predict space weather in the limited vicinity of Earth. Interplanetary forecasting was out of the question. This began to change in 2006 with the launch of the twin STEREO probes followed almost four years later by the Solar Dynamics Observatory. Together with SOHO, these spacecraft now surround the sun, observing active regions, flares, and coronal mass ejections around the full circumference of the star. No matter which way a solar storm travels, the STEREO-SDO-SOHO fleet can track it.

Areas of Interest

The need for interplanetary space weather forecasting may be divided into three main areas of interest:

(1) Human Safety

(2) Spacecraft Operations

(3) Science Targets of Opportunity

Space Weather is not always a problem, sometimes it is an opportunity

Human safety

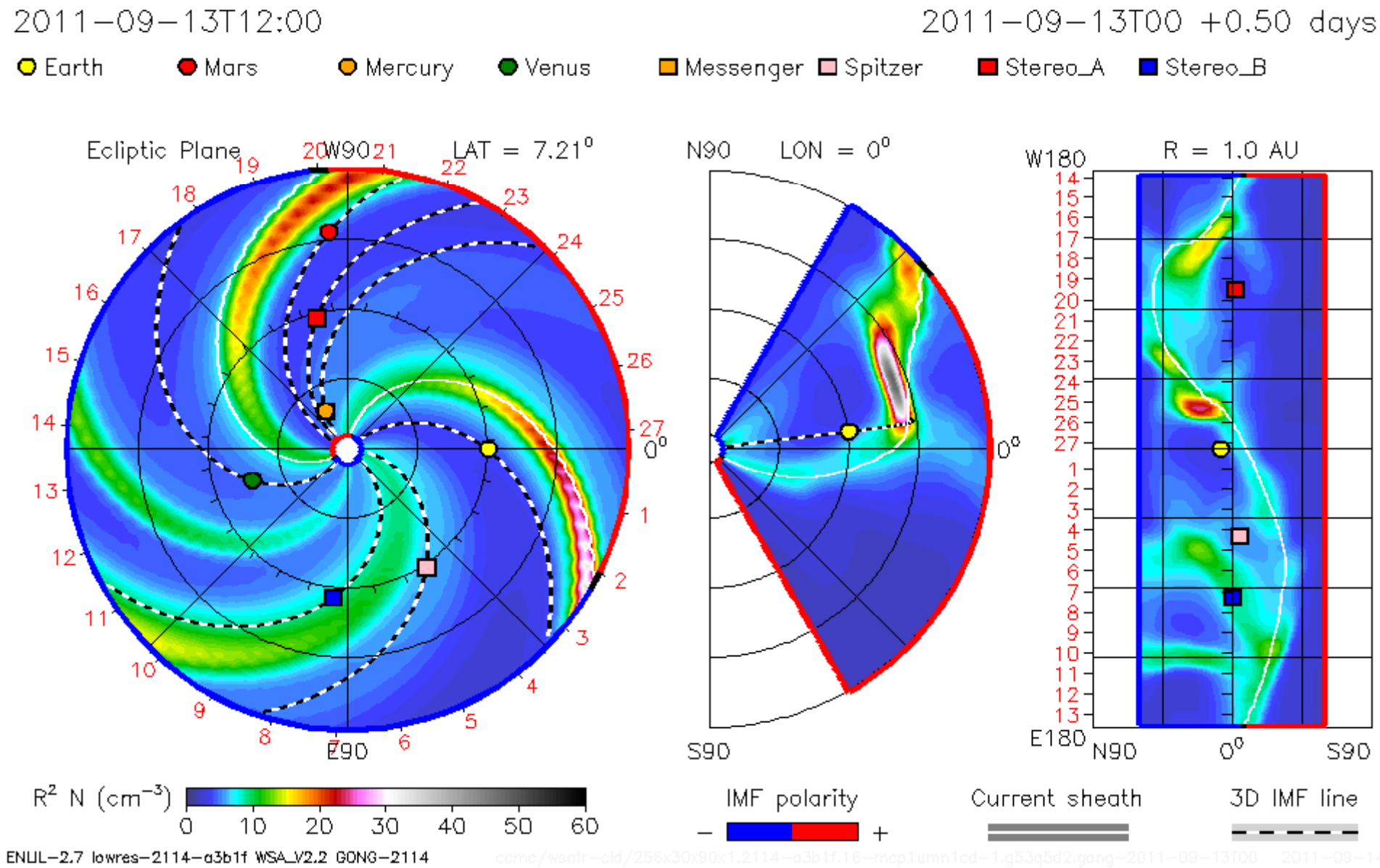
Human safety is of paramount concern. At the moment, humans are confined to low-Earth orbit where the planetary magnetic field and the body of Earth itself provide substantial protection against solar storms. Eventually, though, astronauts will travel to the Moon, Mars and beyond where natural shielding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

Spacecraft operations

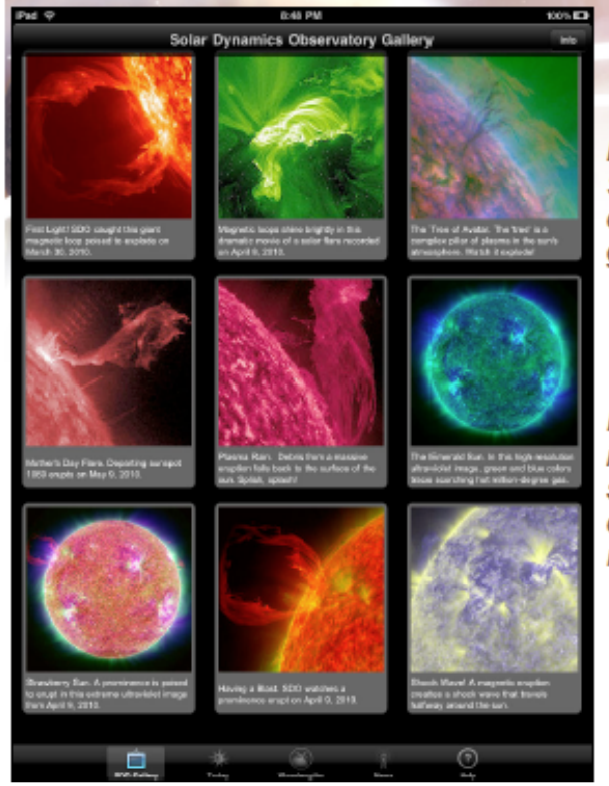
Spacecraft operations are also key. Energetic particles accelerated by solar storms can cause onboard computers to reboot, introduce confusing noise in cameras and other digital sensors, or simply accumulate on the surface of a spacecraft until a discharge causes serious problems.

Cosmic rays will provide another source!

Interplanetary Space Weather Alerts: Science Benefits



3D Sun App Allows Over A Million Users to Hold the Sun in the Palm of Their Hand



Left: Screenshot of SDO gallery

Right: iPad screenshot of recent news items

- With the release of the iPad version of 3D Sun App in June 2010, two notable thresholds have been crossed: **The app has now been downloaded by more than a hundred thousand people (109,000 as of June 28th) and it has been used more than a million times (1,000,858 as of June 28th) in 85 countries!**

- The original 3D Sun App containing STEREO data has been **updated to include images from NASA's Solar Dynamics Observatory**, launched in February 2010. Another new feature is a **section dedicated to Citizen Science** that allows amateur astronomers to highlight their observations and share them with the world.

- "3D Sun" lets you carry a virtual window onto today's Sun, right in your pocket. Open this app anytime to see what's happening today on the Sun's ever-changing surface. News alerts inform you of important solar events, great for aurora watchers who want to be notified of when they should look up!

- The app is **updated daily**, and has recently featured three special alerts about solar and geomagnetic activity: the June12th M-flare with radio sounds, the Father's Day Flares of June 20th, and "Auroras Underfoot" (ISS photos of aurora australis).

- **This free iPhone and iPad app can be downloaded from http://3dsun.org.**

Below: Examples of "Citizen Science" contributions

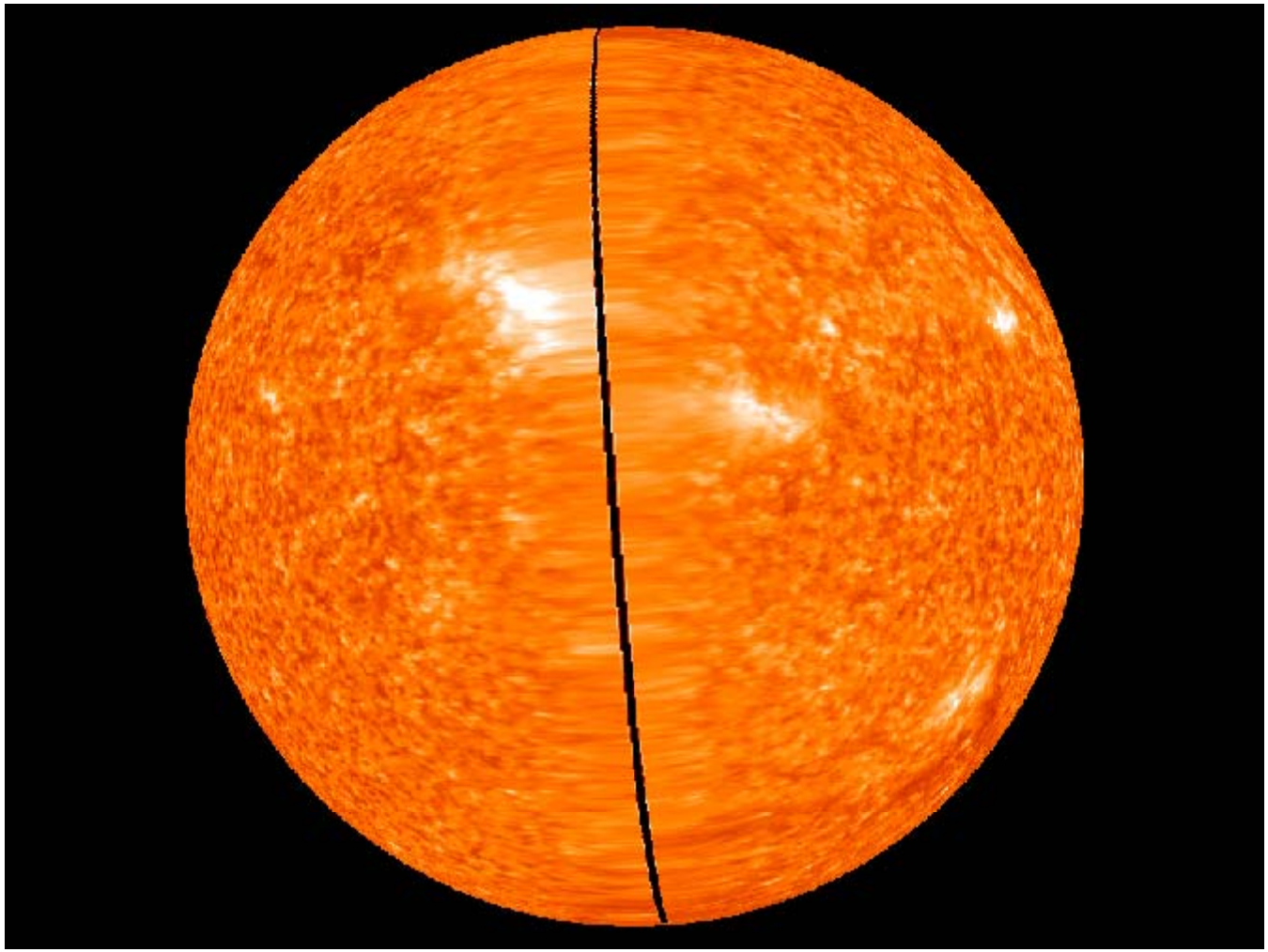
Geographic distribution of the App is holding steady at 85 countries. The top 10 are:

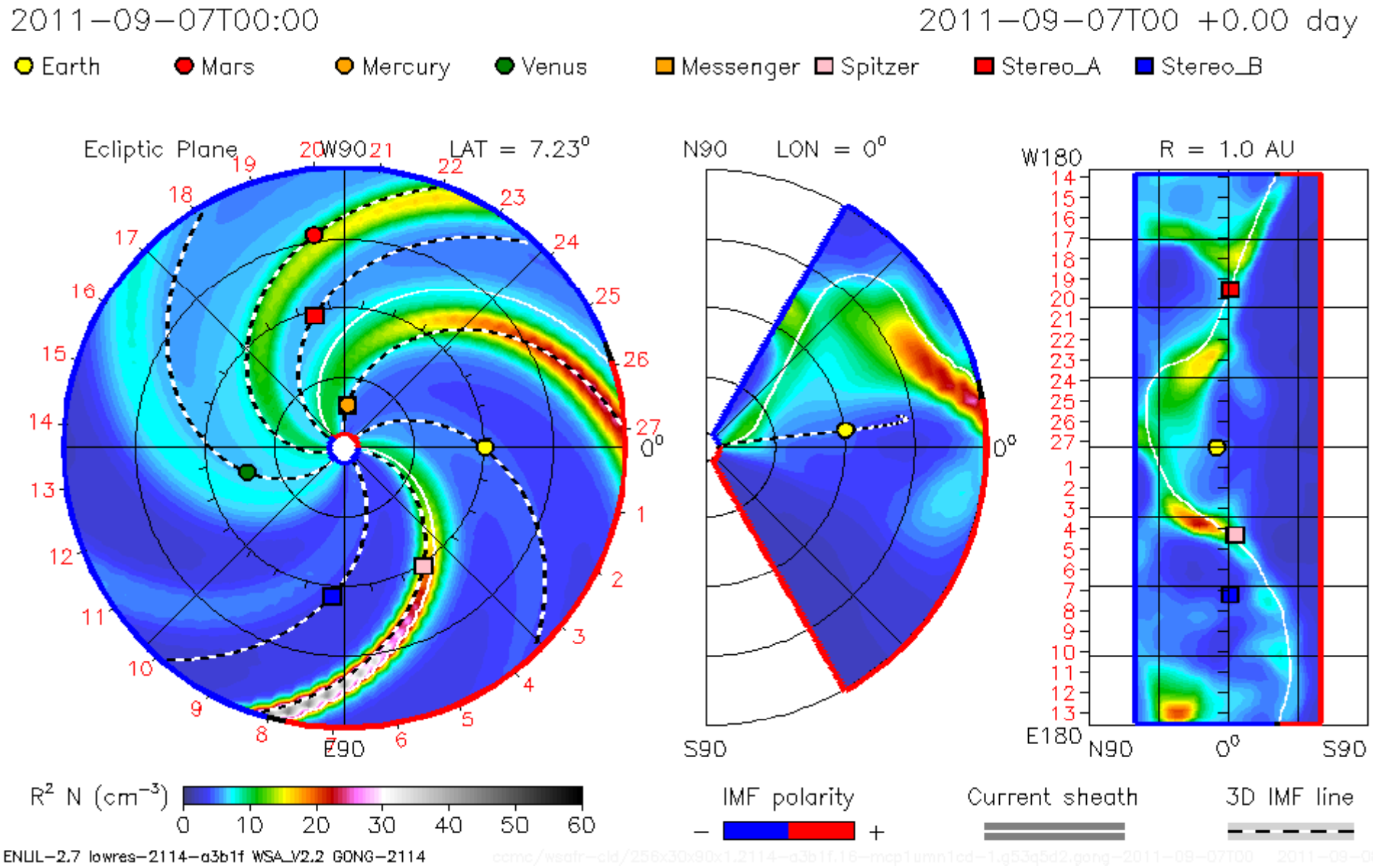
1. **United States 60483**
2. **Canada 6484**
3. **United Kingdom 6002**
4. **Italy 5363**
5. **Netherlands 3539**
6. **Japan 3394**
7. **Spain 3345**
8. **Germany 2589**
9. **Australia 2148**
10. **France 1224**

Happy Birthday, Interplanetary Space Weather Forecasting:

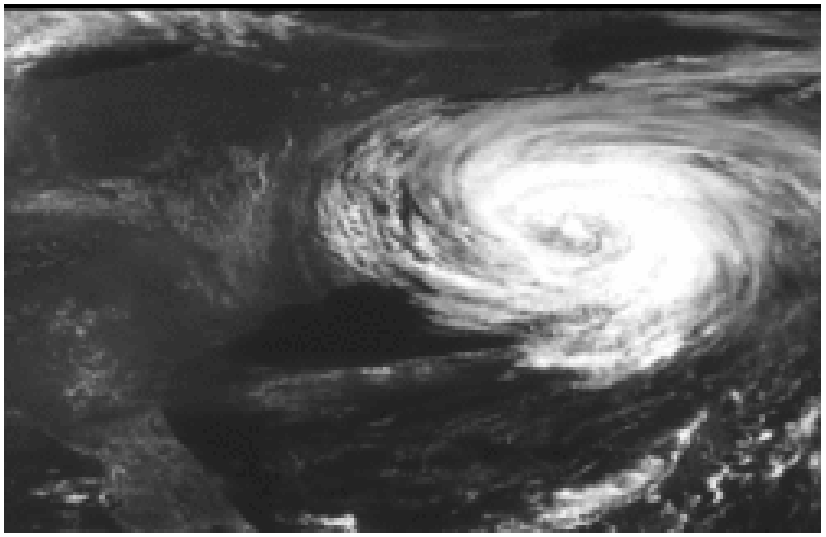
February 6, 2011

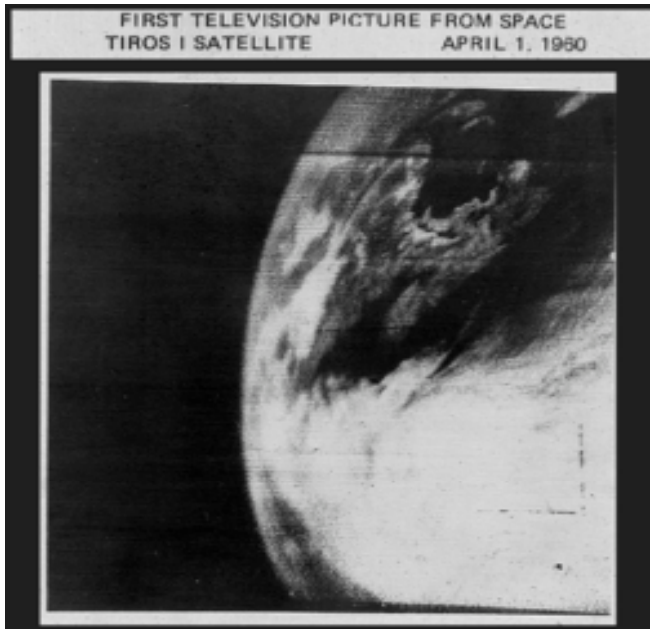
The STEREO spacecraft reached opposition, prompting NASA to release this almost-complete image of the sun:

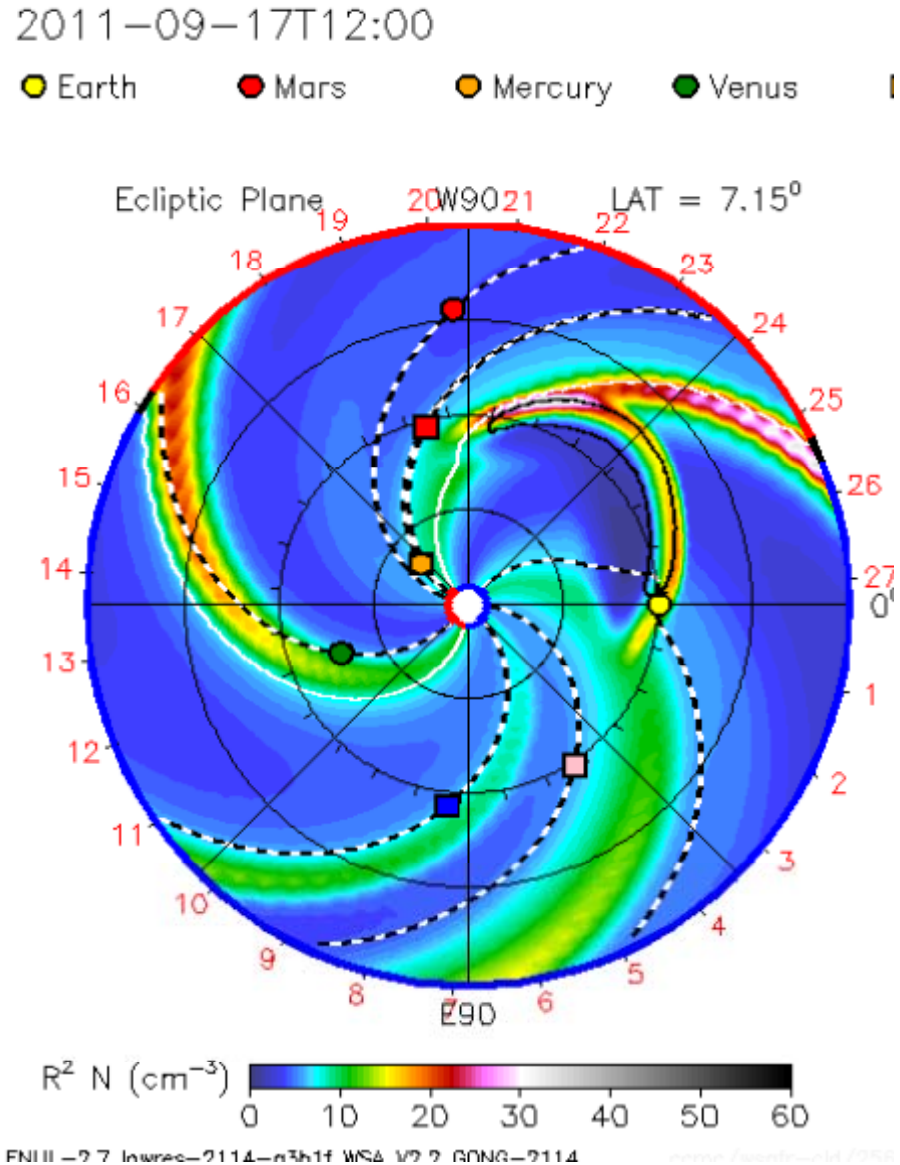



2011-09-07T00:00
2011-09-07T00 +0.00 day
Earth
Mars
Mercury
Venus
Messenger
Spitzer
Stereo_A
Stereo_B
Ecliptic Plane
LAT = 7.23°
W90
E90
N90
S90
LON = 0°
0°
R = 1.0 AU
W180
E180
R² N (cm⁻³)
0 10 20 30 40 50 60
IMF polarity
Current sheath
3D IMF line
ENUL-2.7 lowres-2114-a3b1f WSA_V2.2 GONG-2114

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







The Solar-Stellar Connection

Tools originally developed for the Sun are now becoming broadly applicable to stars

Technical breakthroughs in stellar astrophysics now permit us to place solar questions in a broad astrophysical context

- Seismology is now a powerful tool for both the Sun and stars
- Deep time-domain studies are placing the Sun in context
  - Magnetism impacts structure
  - Future prospects: butterfly diagrams, rotation-age diagnostics
- Differential rotation measurements indicate that the solar pattern is not universal
- New stellar capability: magnetic topology reconstruction

Comparative Climatology of Terrestrial Planets & Moons of Planets

Each of the rocky planets with atmospheres in our solar system has a climate. Initial conditions, climate forcing, and climate feedbacks are all different on these worlds, resulting in environments that are radically different from Earth's. While the physical and chemical principles that operate are the same, different climate processes dominate on each planet

TOPICS

1. Climate and atmosphere
2. Clouds, hazes, and precipitation
3. Interior-surface-atmosphere interactions
4. Solar-atmosphere interactions

1.What is the observational evidence for climate change on the terrestrial planets?
2. What is the sensitivity of each terrestrial planet climate changes in forcing due to geology,
impacts, and solar output?
3. How are energy balance and atmospheric dynamics coupled on Venus, Earth, Titan, and
Mars?
4. How do variations in solar output affect the climates of the terrestrial planets?

Future

Ultimately, expanding the reach of space weather & climate forecasts throughout the solar system will require advances in theory, observations, and computing power.

Recently published series of three volumes entitled the "Heliophysics Lecture Series that deal with this subject matter and the facility called the Community Coordinated Modeling Center (CCMC) are laying the groundwork for the accurate interplanetary forecasts using physics-based models.

The combination of two can really help in a big way to move this interdisciplinary field forward.

Heliophysics Vision?
Interplanetary Space Weather & Climate Program

Mission Line: Relevance with Science (reverse of LWS)

Relevance and Monitoring with Science Utility

Interplanetary SWx Institute

Virtual R2O interdisciplinary, e.g. Astrobiology Institute (an interdisciplinary consortium of experts scattered across many universities and agencies under a virtual NASA umbrella) e.g. If NASA sends a probe to Titan, say, other experts would come to the fore---e.g., a planetary scientist at Brown University who predicts tropospheric weather on Titan; a CME modeler at Goddard/CCMC who predicts the onset of geomagnetic storms at Saturn; an EUV expert at the University of Colorado who estimates the solar ultraviolet flux impinging on the giant satellite. An approaching Titan probe could get a genuine weather forecast for its target body. Whether the forecast is for Earth or Titan or some other body, the effort would take place under the overarching supervision and management of NASA. Moreover, NASA spacecraft would provide almost all key data underlying the forecasts, a situation which is already a reality even without this initiative.