Living With a Star

The Sun-Earth Connection

Why Do Science?

For Understanding \ For Utility	No	Yes
Yes	Bohr	Pasteur
No		Edison

From Donald Stokes (Woodrow Wilson School for Public and International Affairs, Princeton University)

The Sun-Earth Connection -- Science in the Pasteur Mode

- How a star works
- How it affects humanity's home
- How to live with a star

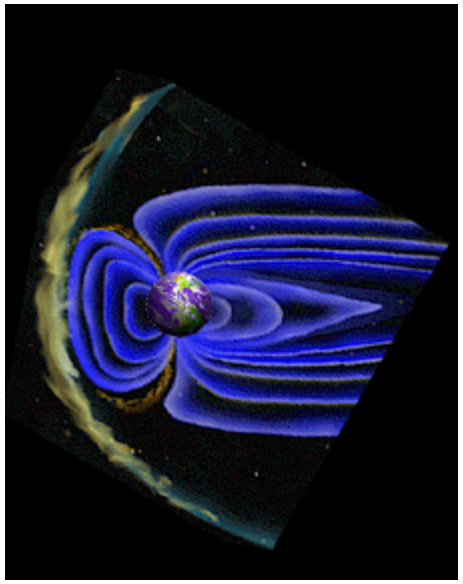
The Sun-Earth Connected System

Variable Star

Varying

- **Radiation**
- **Solar Wind**
- **Energetic Particles**

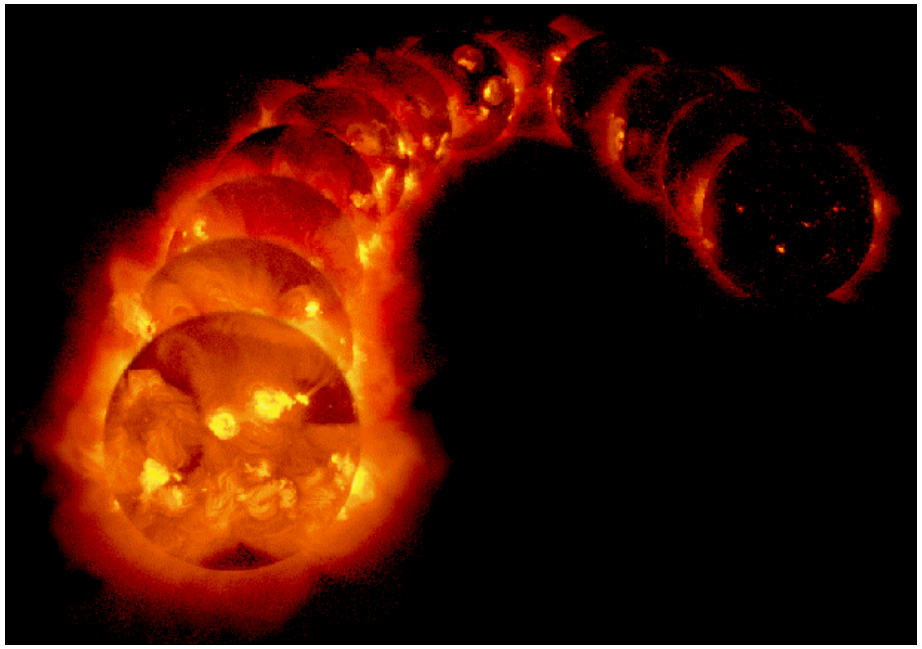
Planet



Questions:

- ***How and why does the Sun vary?***
- ***How does the Earth respond?***
- ***What are the impacts on humanity?***

Sun-Earth System -- Driven by 11 Year Solar Cycle

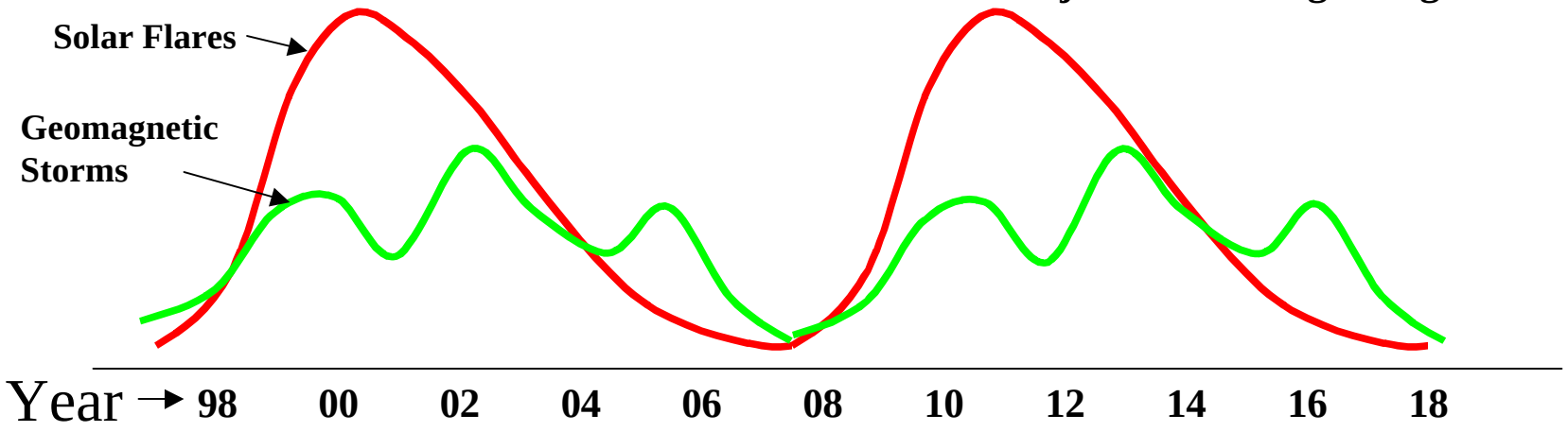


Solar Maximum:

- **Increased flares, solar mass ejections, radiation belt enhancements.**
- **100 Times Brighter X-ray Emissions 0.1% Brighter in Visible**
- **Increased heating of Earth's upper atmosphere; solar event induced ionospheric effects.**

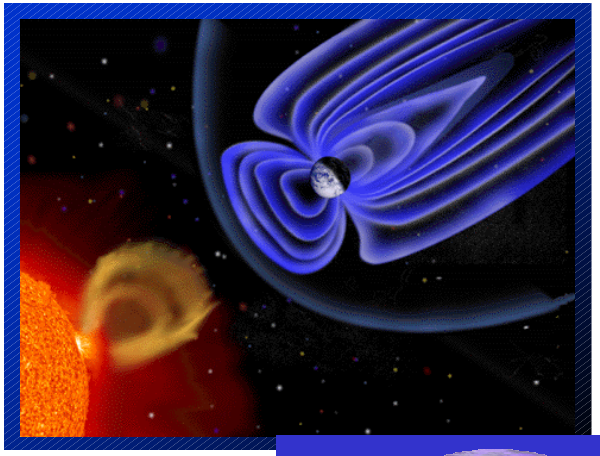
Declining Phase, Solar Mnimum:

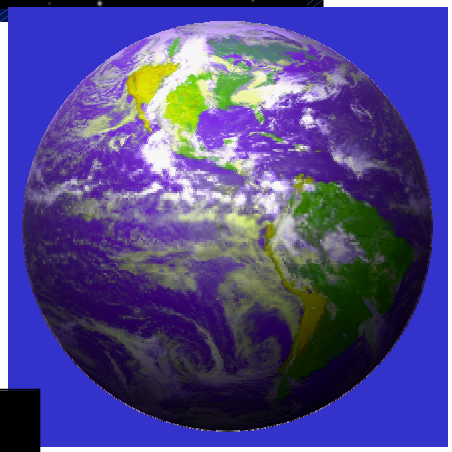
- **High speed solar wind streams, solar mass ejections cause geomagnetic storms.**



Why Do We Care?

- **Solar Variability Affects Human Technology, Humans in Space, and Terrestrial Climate.**
- **The Sphere of the Human Environment Continues to Expand Above and Beyond Our Planet.**
  - Increasing dependence on space-based systems
  - Permanent presence of humans in Earth orbit and beyond





Solar Variability Can Affect Space Systems

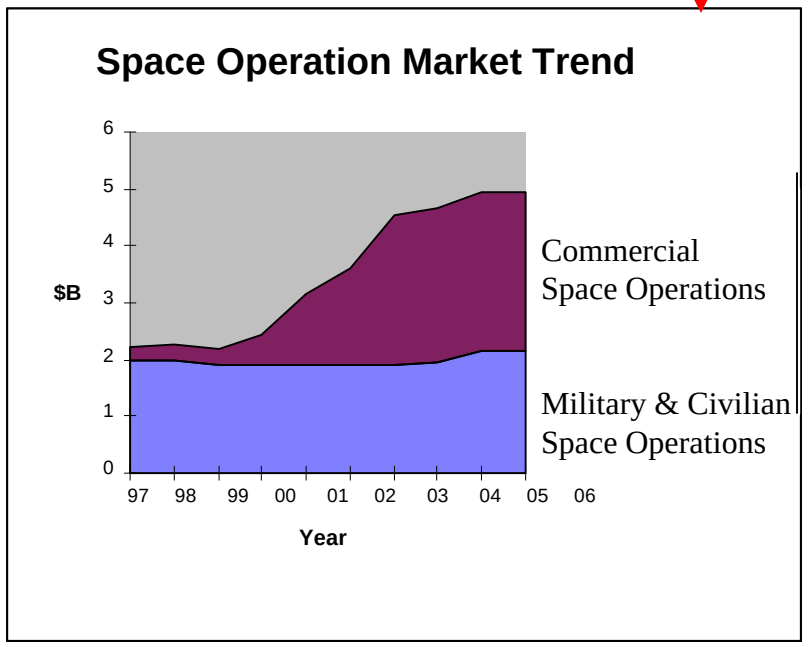
How?

- **Spacecraft charging.**
- **Solar cell damage.**
- **SEU's & damage to electronics.**
- **Atmospheric drag.**

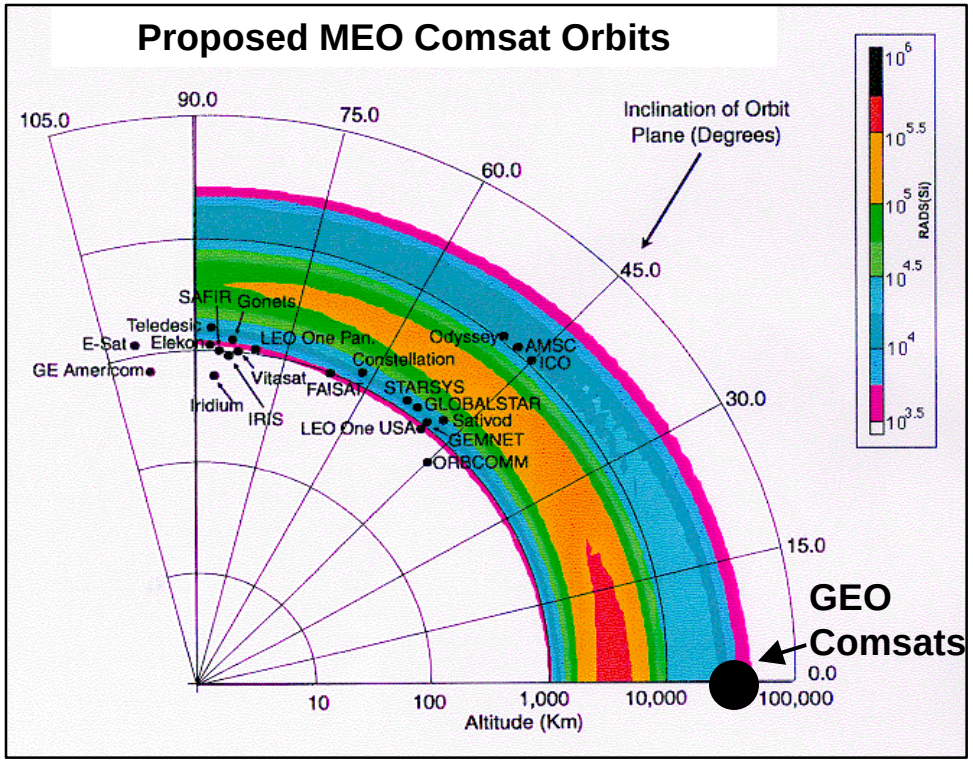
So What?

- **Space Industry yearly revenues will be $100B by year 2000.**
- **Society's dependence on space assets is increasing.**
- ***Prudence demands that we understand the space environment affecting space systems.***

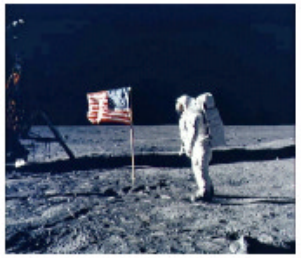
Why Now? **Expanding use of space.**



Source: KPMG Study

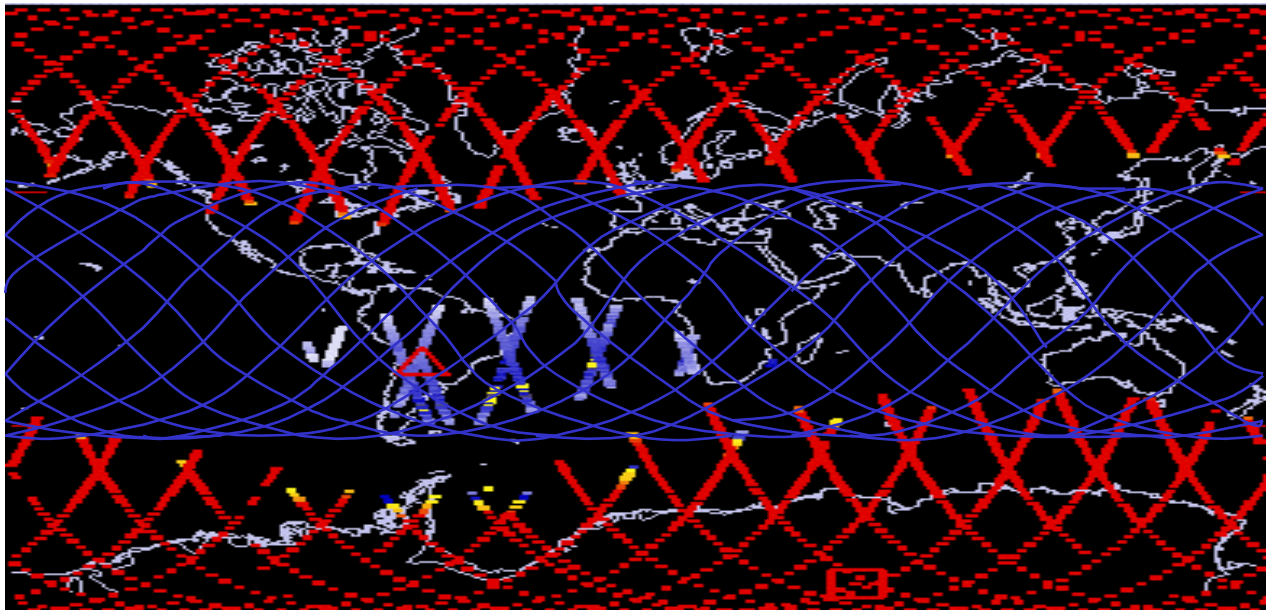


Solar Variability Can Affect Human Space Flight

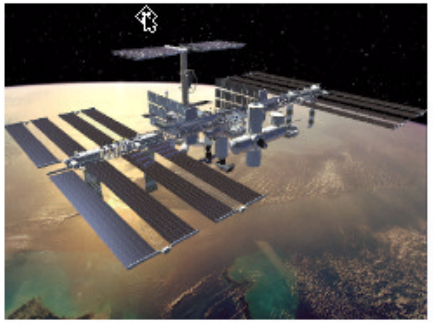


- **Radiation Protection operations for future human missions (both to the ISS and to Mars) should be provided with observations of CME's from several vantage points, such as would be provided by SOHO and STEREO.** 1997 Workshop: "Impact of Solar Energetic Particle Events for Design of Human Missions", Houston, TX.

- **Space Station Orbit is Exposed to High Energy Solar Particles**



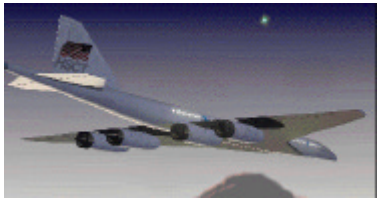
Oct 20, 1989
Solar Protons
NOAA-10

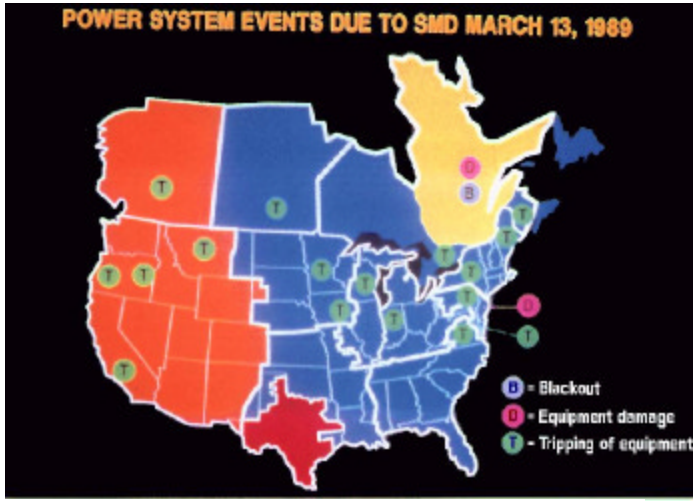


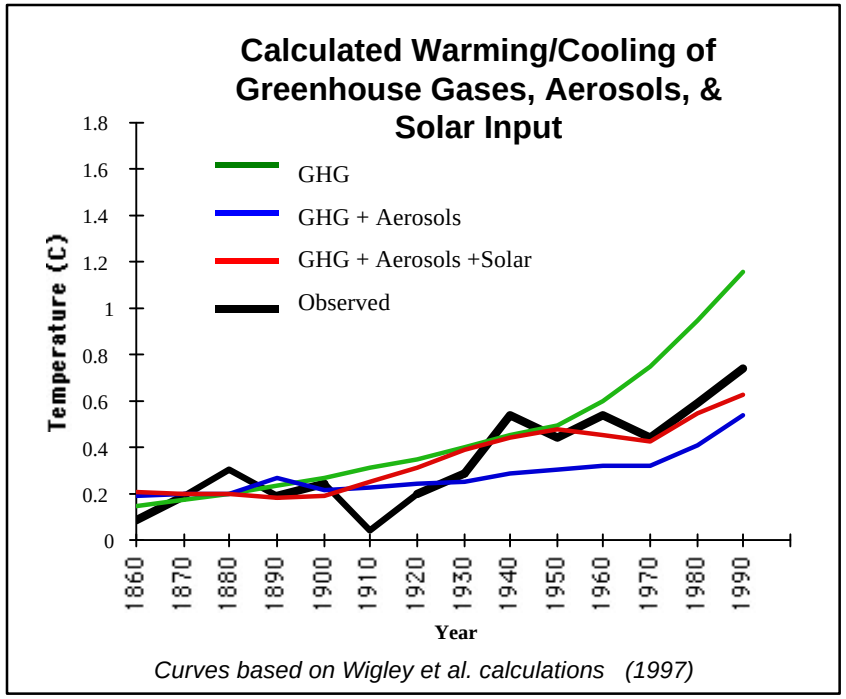
Issue: Requires focused research effort to improve knowledge about risk levels and possible risk mitigation techniques. Enabling research for human voyages beyond Earth.

Solar Variability Can Affect Where We Live

- **Electric grid disruption and power transformer damage.**
- **GPS signals, high frequency (HF and VHF) radio communications, and long range radar.**
- **Microelectronics and humans in high altitude aircraft.**
- **Telecommunication cables.**
- **High precision electronic chip fabrication.**
- **Terrestrial climate.** ***"The Sun's fingerprints are showing up all over the climate records. The 11- and 22-year sunspot cycles have turned up in other analyses of ocean temperatures and in ice cores...."*** *Science, March 8, 1996*

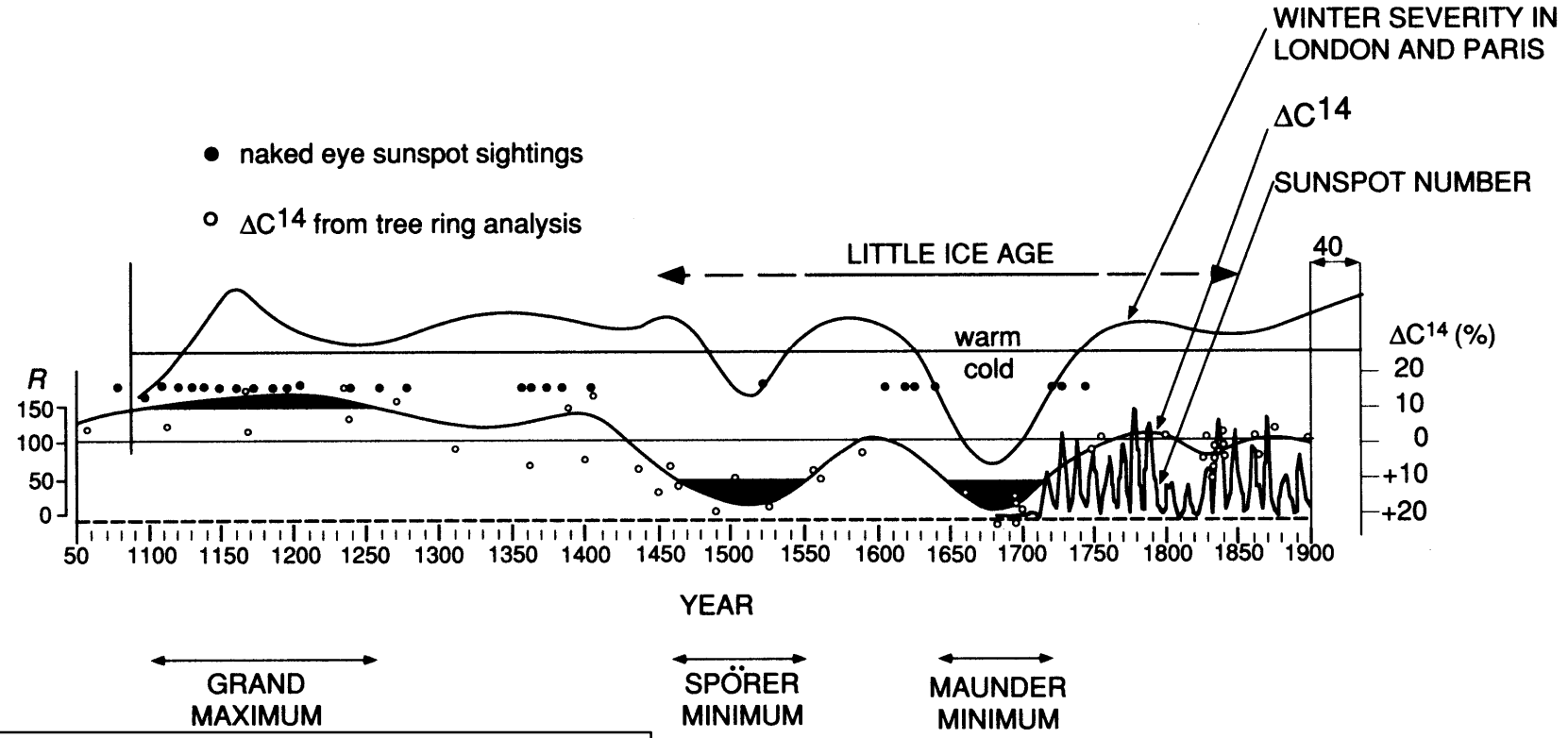






Curves based on Wigley et al. calculations (1997)

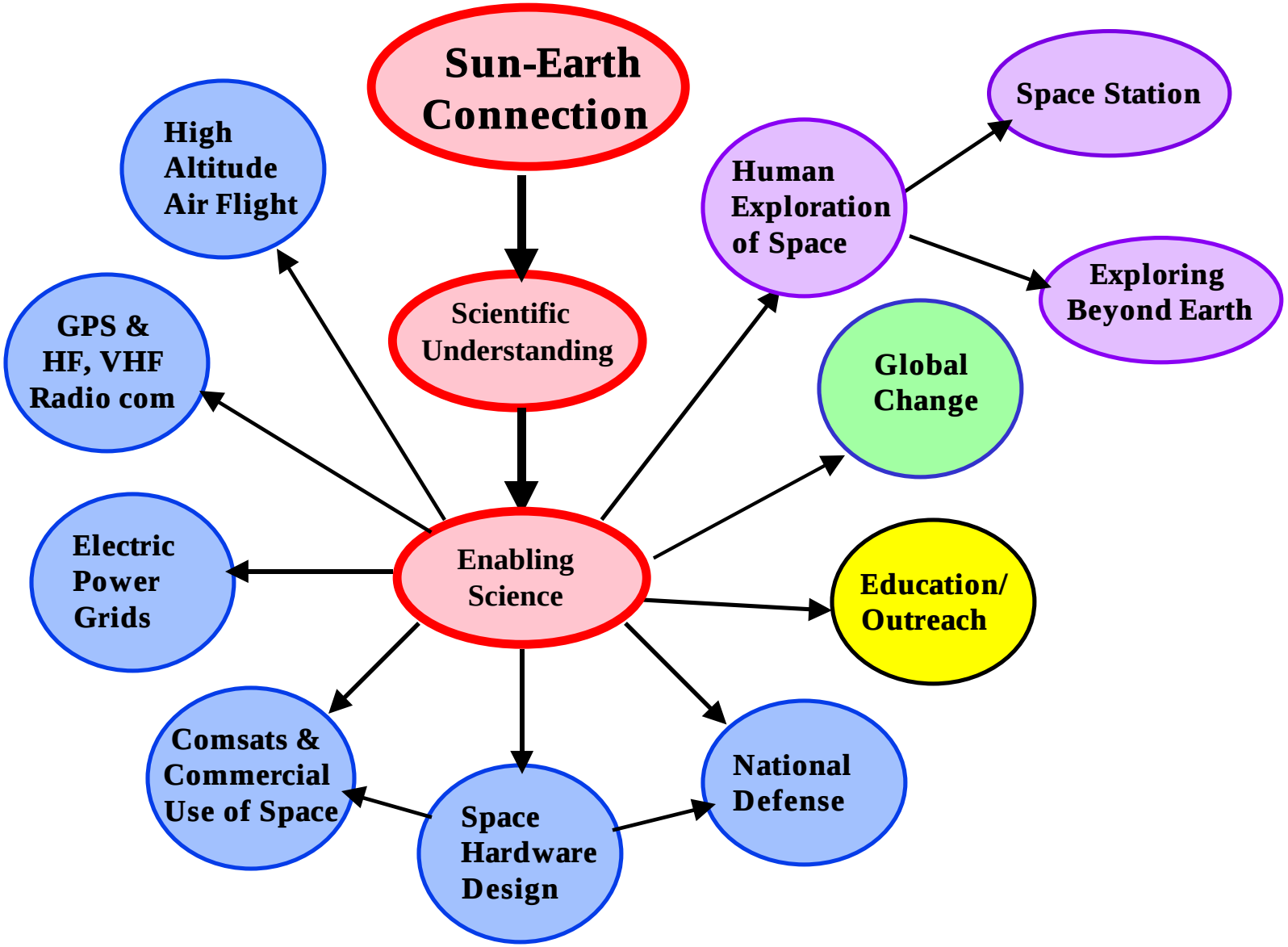
Solar Variability Can Affect Terrestrial Climate



During the Little Ice Age, London's Thames River froze in winter, something that no longer happens. This 19th century engraving depicts the annual Frost Fair held on the ice-bound river, this one during the winter of 1683-84.

Given the massive economic impact of small changes in climate, we should fully understand both natural and anthropogenic causes of global change.

Sun Earth Connections



What can we do about it?

Goals of the Sun-Earth Connection Initiative

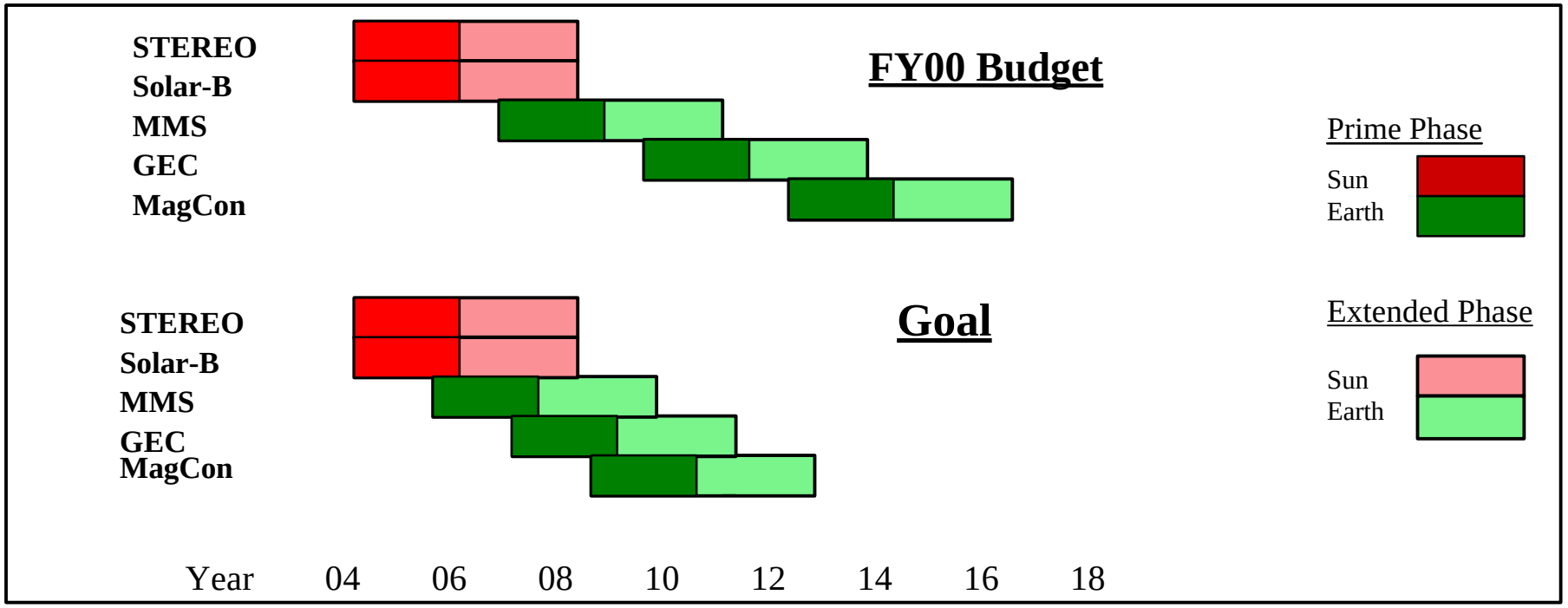
1. **Quantify physics, dynamics, and behavior of Sun-Earth connected system through the range of conditions occurring in the 11 year solar cycle.**
   - **Obtain improved measurements.**
   - **Better understand Sun-Earth disturbances.**
   - **Understand the solar cycle.** ***For long-range forecasting & assessing solar role in climate change.***
2. **Develop predictive models for the system that:**
   - **Demonstrate understanding of physics.**
   - **Have utility for prediction of space weather.**
3. **Minimize impact of space weather on technology and human space flight.**
   - **Determine space environmental conditions vs location, time in solar cycle.**
     Needed for design of systems to minimize sensitivity to space weather.
   - **Develop improved techniques for space weather conditions including SPE & their access to ISS and at locations of human explorers in deep space.**
   - **Fly low cost flight test beds for validation of rad-hard, rad-tolerant systems.**

Apply a systems approach.

I. Accelerate: Solar Terrestrial Probes

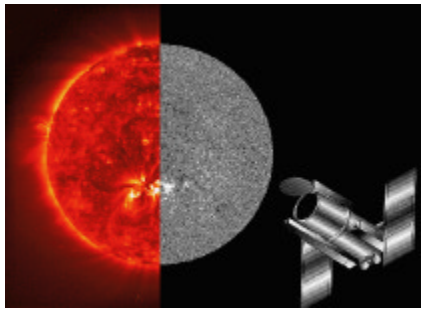
Why?

- **Studying Sun-Earth connected system requires simultaneous observation of interacting regions.**
- ***FY00 budget:*** **Missions have 2 yr design life and are launched at 2.5 yr intervals.**
  - **Limits synergism between missions studying different regions of Sun-Earth system.**
- ***Goal:*** **1.5 year interval between missions.**
  - **Enables simultaneous study of key linked regions in Sun-Earth system.**



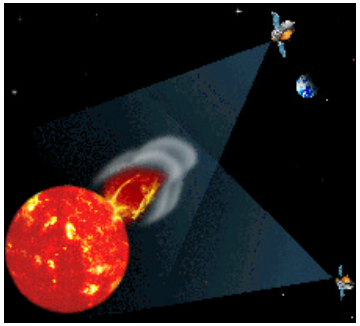
Solar Terrestrial Probes

Solar-B

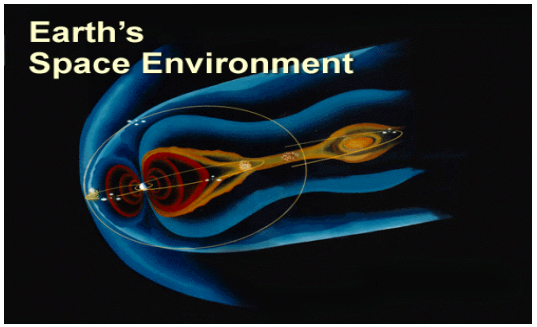


- Probing solar magnetic variability
- How is magnetic energy stored and explosively released to cause flares and coronal mass ejections?
- How are solar magnetic fields created and destroyed?

STEREO



- Stereo imaging of Sun; coronal mass ejections from birth to Earth impact.
- What determines the geo-effectiveness of solar mass ejections?
- What is their role in generating solar energetic particles?
- Research tool and prototype space weather & early warning system for solar energetic particles



Magnetospheric Multiscale

- Investigate magnetospheric response to coronal mass ejections.
- Investigate magnetic reconnection, plasma turbulence, and energetic particle acceleration with 5 formation-flying smallsats.

Geospace Electrodynamics

- Probe electromagnetic coupling between the Sun and terrestrial upper atmosphere with 5 formation-flying smallsats.

Magnetospheric Constellation

- Probe dynamics of geomagnetic tail with network of 20-100 nanosats.
- Test MHD storm theories.

What is Still Missing?

1. **Missing: Detailed information on dynamics of solar interior and the dynamo that generate and control solar variability *(including both short and long term variations).***

   Solution: A Solar Dynamics Observatory providing high time & spatial resolution data to probe:

   - **Solar interior & the subsurface structures underlying regions generating solar disturbances.**
   - **Dynamics of magnetic structures in solar atmosphere where these disturbances occur.**

2. **Missing: Continuous observations of solar regions generating solar disturbances ("solar weather patterns"); measurements of solar interior from other side of Sun.**

   Solution: Solar Sentinels:

   - **To observe the entire solar surface, *including far side from Earth.***
   - **To observe globally & in stereo solar wind disturbances from Sun into interplanetary space.**
   - **To obtain "missing" seismology data from solar far side.**

3. **Missing: Detailed information on the dynamics of the terrestrial space environment during geospace disturbances .**

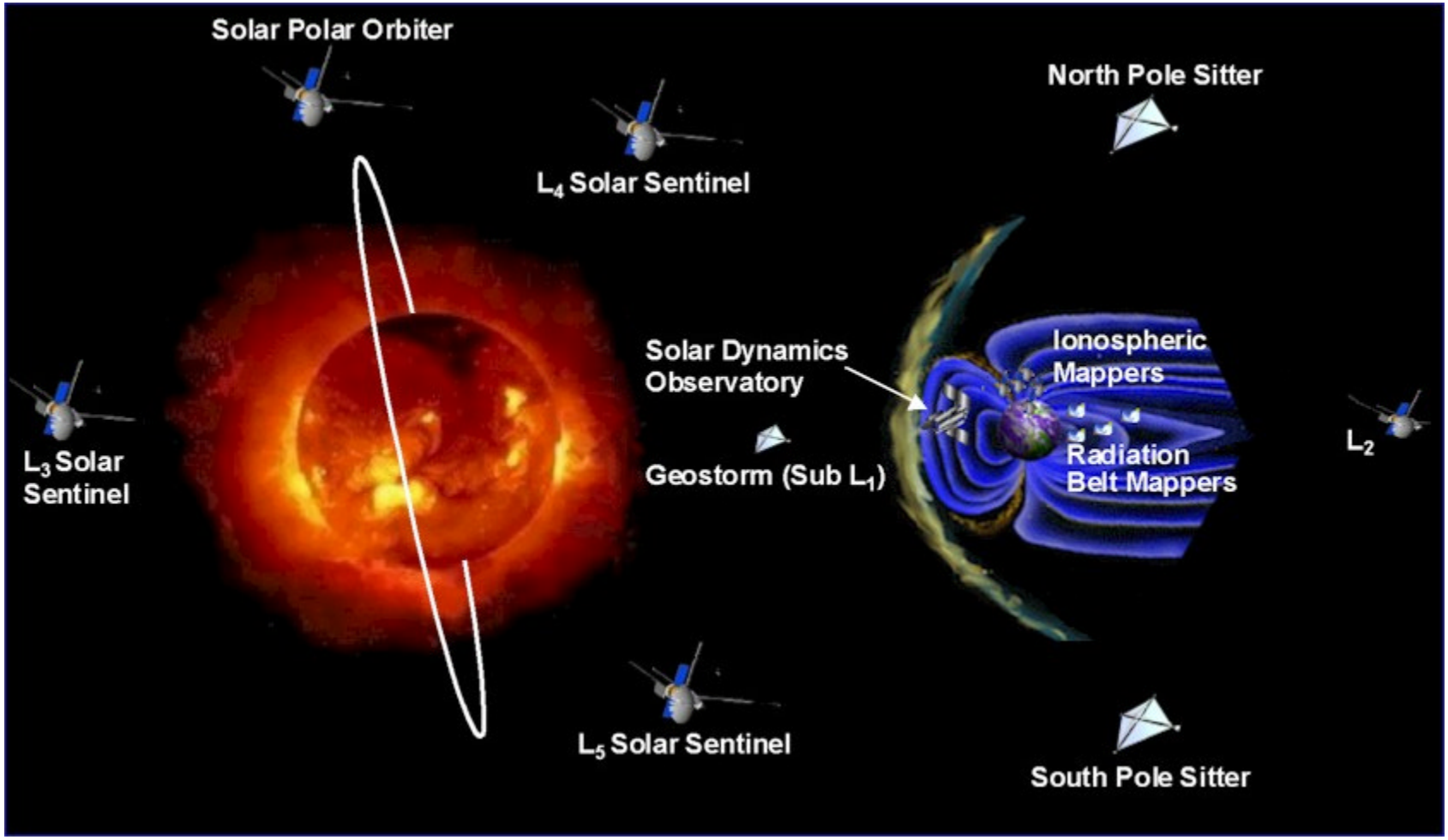
   Solution: Geospace Dynamics Network:

   - **Network of spacecraft to provide data with sufficient spatial and temporal coverage to specify the dynamics of disturbances affecting geospace and the neutral atmosphere.**

4. **Missing: Detailed information on long term effects/relation to global change of variable solar inputs on upper terrestrial atmosphere.**

   Solution: Geospace Dynamics Network:

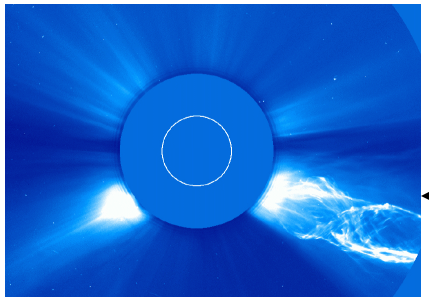
II. Establish Space Weather Network



Distributed network of spacecraft providing continuous observations of Sun-Earth system.

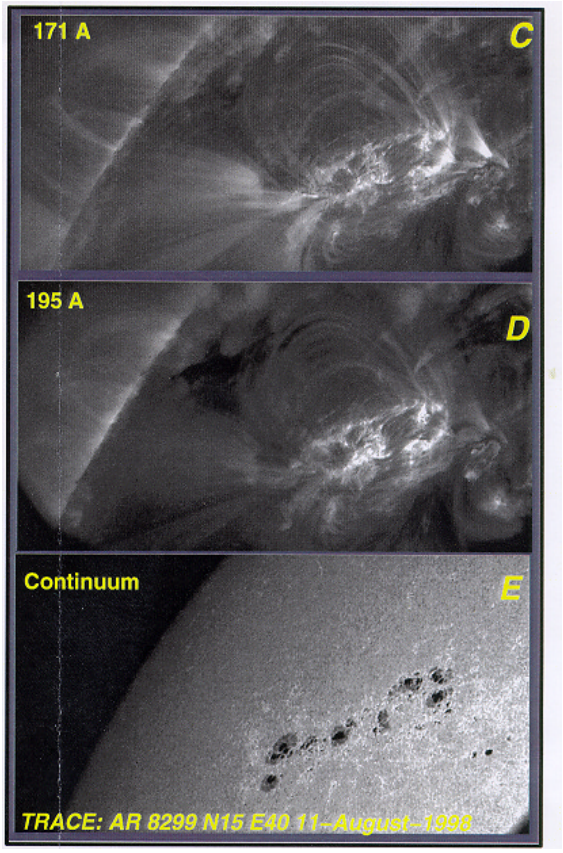
- ***Solar Dynamics Network*** **observing Sun & tracking disturbances from Sun to Earth.**
- ***Geospace Dynamics Network*** **with constellations of smallsats in key regions of geospace.**

Solar Dynamics Observatory - Next Generation SOHO

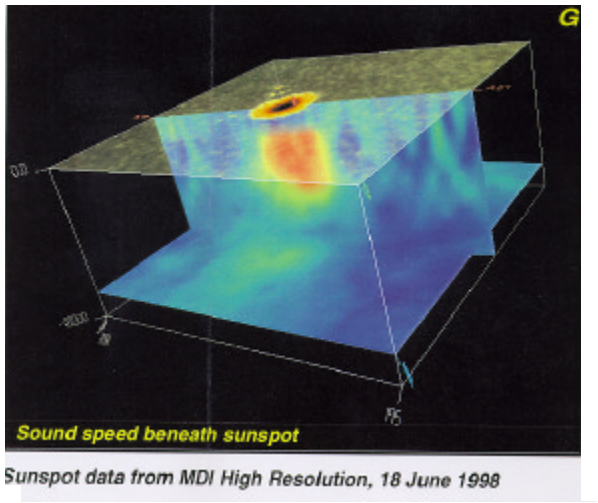


Imaging CME'S

- **Investigating solar dynamical processes and phenomena**
- **Observing development of magnetic and subsurface phenomena related to:**
  - **Flare &CME energy storage & triggering**
  - **The solar dynamo driving the solar cycle.**
- **High data rate from GEO orbit for studying dynamics (SOHO limited by low data rate from L1)**



Imaging Magnetic Structures
(rapid time sequences -- "movies")

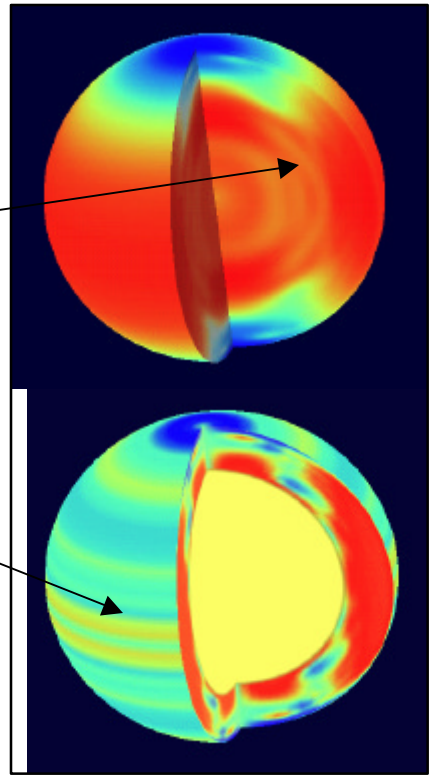


Imaging Subsurface Structures

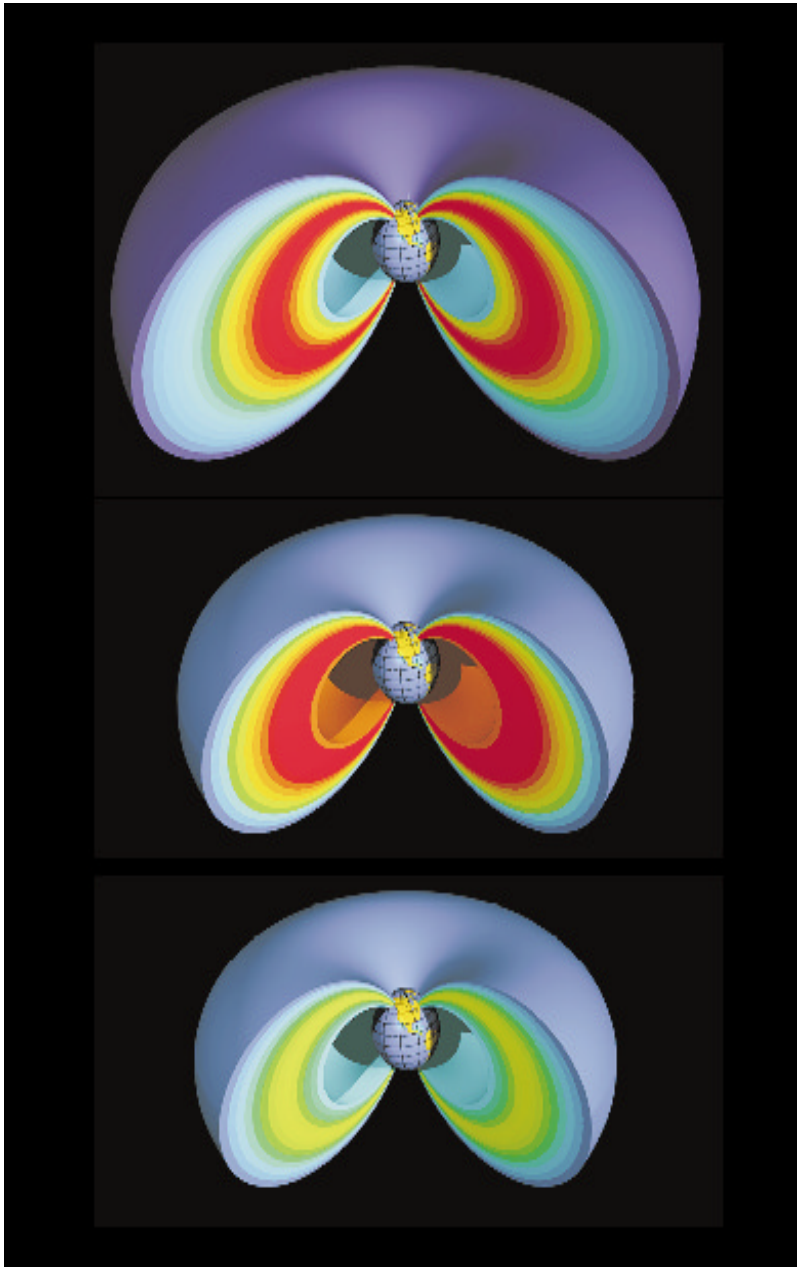
Red: Faster Rotation →
Blue: Slower Rotation

Solar Dynamo?

Link to solar cycle?

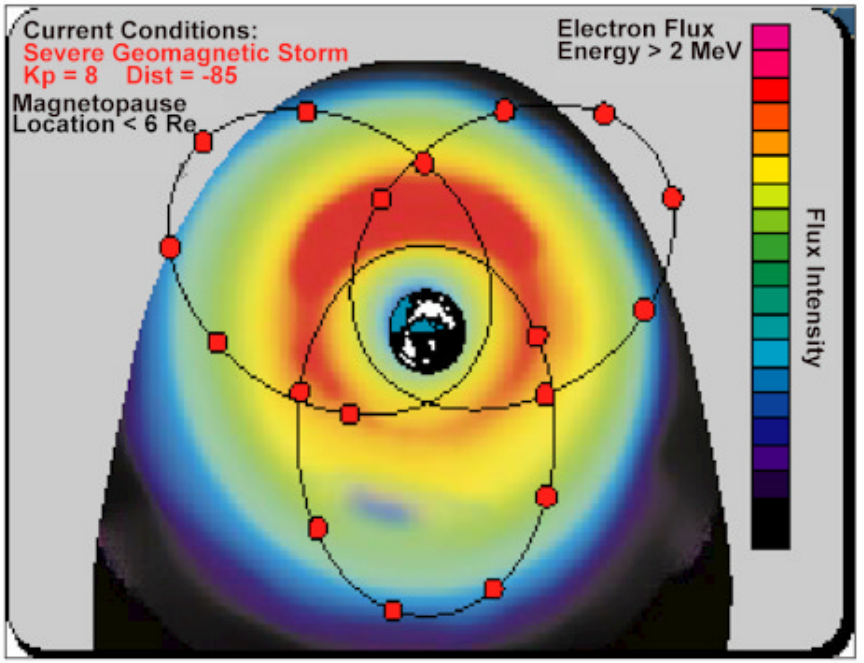


Imaging Solar Interior



Radiation Belt Mappers

- **Understand origin and dynamics of the radiation belts.**
- **Determine time & space-dependent evolution of penetrating radiation during magnetic storms.**
- **<u>First Element:</u> multiple spacecraft in 3 petal equatorial orbits; in-situ measurements.**
- **<u>Second Element:</u> Add higher latitude coverage.**



The Missions

Solar Terrestrial Probes

(Science)

Solar

Geospace

STEREO

Solar-B

MMS

GEC

MagCon

Future STP's

Space Weather Network

(Dual Use Science/Utility)

Solar Net

Geospace Net

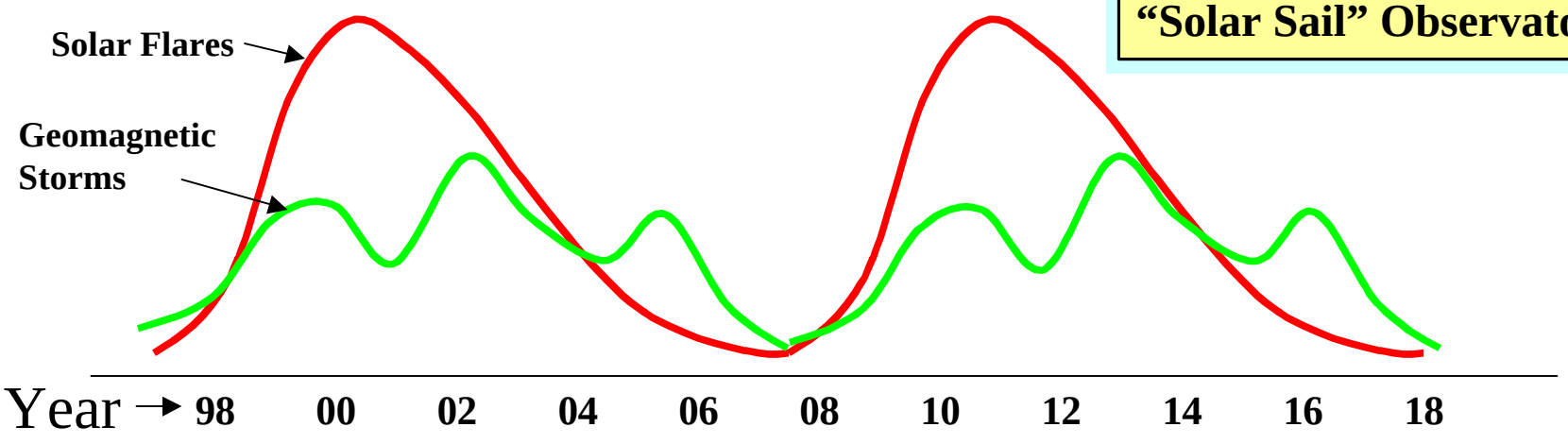
Solar Dynamics Observatory

Solar Sentinels

Radiation Belt Mappers

Ionospheric

"Solar Sail" Observatories

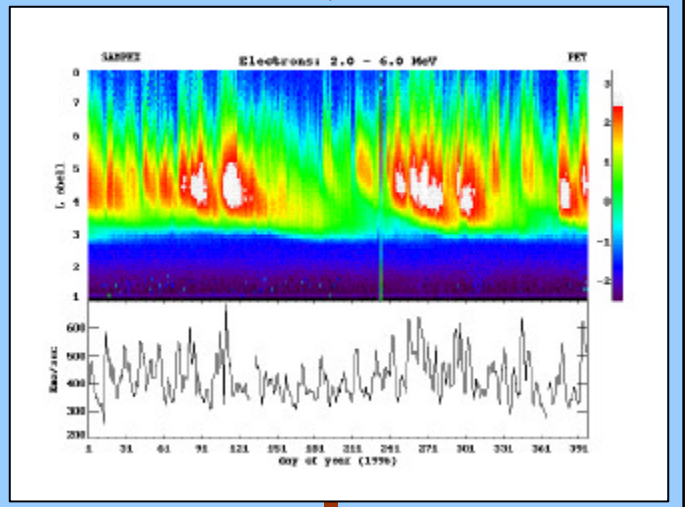


III. Establish Targeted Data Analysis & Modeling

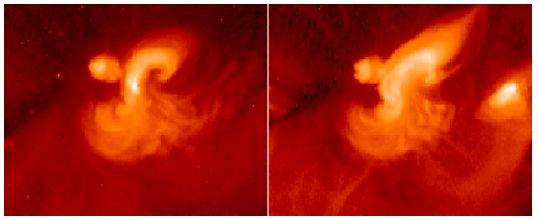
Exploit data from present and past missions:

- **To improve knowledge of space environmental conditions and variations over solar cycle.**
  - **To obtain reliable environmental specs for cost-effective design of spacecraft and subsystems to minimize space environmental effects & damage.**
  - **Important for commercial comsats and military space systems which must have "all weather" capability.**
- **Develop new techniques and models for predicting solar/geospace disturbances which affect human technology.**
  - **Recent example: "S Marks the Spot" discovery of an x-ray signature in regions with high probabilities for producing CME's.**
- **Develop cost-effective techniques for assimilating data from networks of spacecraft.**

Science - Data → Design Specs

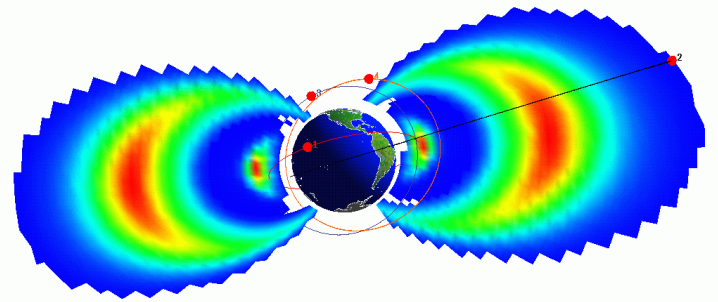


Bridges Gap Between Science Data Collection & Design/Ops Engineer

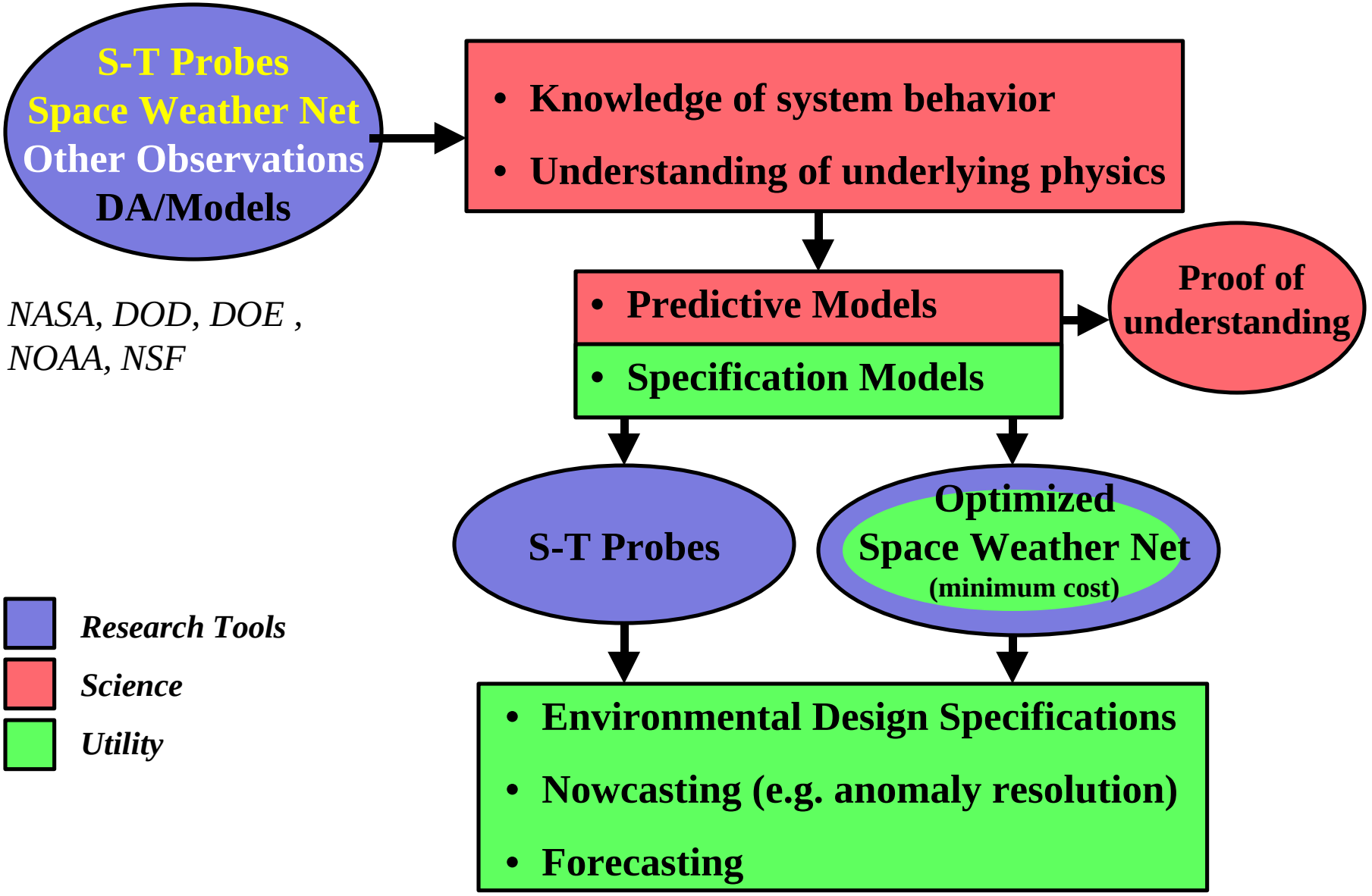


IV. Establish Orbital Technology Testbeds

- **Low cost validation of rad-hard, rad-tolerant systems in high radiation orbits.**
- **NASA, industry, DOD, other agency partnering.**



V. Establish and Expand Partnerships

- **Major contribution to National Space Weather Program (NSWP) involving DOD, DOE, DOI, FAA, NASA, NOAA, NSF.**
- **Establish/expand partnerships with DOD, DOE, NOAA, NSF.**
  - **Coordinated R&D on space environment and space weather.**
  - **Launch of LWS missions as secondary payloads on EELV's.**
  - **Use of LWS real time/near real time data for operational purposes.**
- **Establish partnerships for flight of NASA- provided and/or designed space environmental sensors on commercial and other government agency spacecraft.**

The Result: Scientific Understanding and Utility