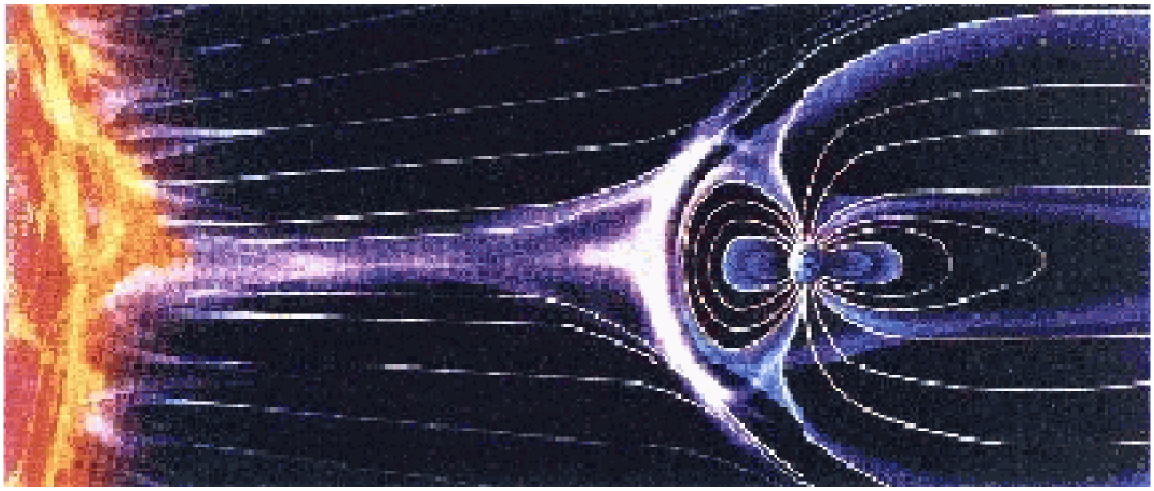
Space Weather
A Research Perspective



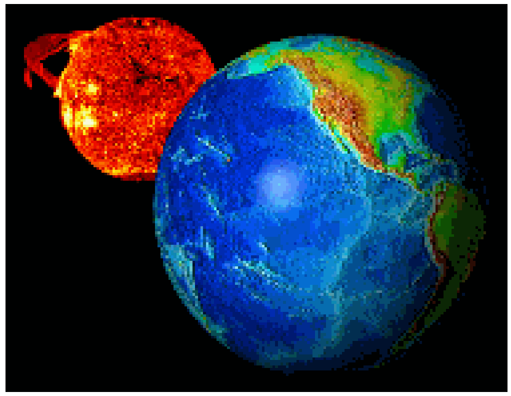
Committee on Solar and Space Physics
Committee on Solar-Terrestrial Research

Space Studies Board
Commission on Physical Sciences,
Mathematics, and Applications

Board on Atmospheric Sciences and Climate
Commission on Geosciences, Environment, and Resources

Space Weather: A Research Perspective

Preface



For decades, it has been known that solar-induced changes in the space environment can affect the performance and reliability of space-based and ground-based technological systems. However, "space weather" reports have not been widely disseminated in the past in part because of their potential military strategic applications and in part because society at large has only recently incorporated space technology into everyday living. The idea of a broadly based National Space Weather Service was conceived by a group representing the National Science Foundation (NSF), Department of Defense (DOD), National Aeronautics and Space Administration (NASA), Department of the Interior, Department of Energy (DOE), and the National Oceanic and Atmospheric Administration (NOAA) in early 1994. In part, this was a response to the current climate in the nation, where substantive, broad, and demonstrated relevance to economic and social causes has become a key goal of post-Cold War scientific research.

Prior to this era, space environment-related research and applications activities were sponsored to varying degrees by essentially all of the above agencies, with the NOAA Space Environment Center and the Air Force Forecast Center (55th Space Weather Squadron) providing most services to consumers of space weather information. However, the fruits of the diverse agency-supported efforts were never organized into a coherent program or product (although coordination occurred through the office of the Federal Coordinator for Meteorological Services). In particular, the efficient incorporation of new knowledge and observations into applications tools using the new information technologies did not always occur, and the testing of science-based models by their degree of success in "real-world" applications was not widely exploited.

The first opportunities for research support dedicated to space weather under the National Space Weather Program appeared in 1996. At the same time, scientists embarked on a period of unprecedented understanding of the Sun-Earth connections with the realization of the International Solar-Terrestrial Physics (ISTP) program. The ISTP combines a multinational network of Earth-orbiting spacecraft, including two

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implemented by NASA as principal, with supporting ground-based investigations and theoretical modeling. The ISTP has been anticipated since the 1980s, when the goal of understanding the coupled solar-terrestrial system was envisioned as achievable with current knowledge, instrumentation, and computational capabilities.

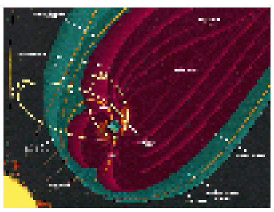
In response to this confluence of events, the jointly operating Committee on Solar and Space Physics (CSSP) and Committee on Solar-Terrestrial Research (CSTR) of the National Research Council have produced this brief perspective on the scientific roots of space weather. Many of the ongoing and planned experimental and theoretical modeling investigations in solar and space physics are in some way connected with the space weather issue. In particular, both the "solar connections" enterprise within NASA's Office of Space Science and NSF's Atmospheric Sciences and Astronomy divisions support investigations related to the nature of solar activity and its effects on the Earth. Space weather applications may require some "repackaging" of products based upon these studies to make them operational, for example, by using "real-time" measurements in space. Nonetheless, they should derive great benefit from exploitation of the research activities documented in individual agency reports and in the recently completed report A Science Strategy for Space Physics by CSSP and CSTR. The presentation is by no means comprehensive, but presents the subject a step removed from the applications emphasis. Its content is intended to illustrate the scientific directions and opportunities associated with the space weather enterprise.

Space Weather: A Research Perspective
What Is Space Weather?

"Space weather" describes the conditions in space that affect Earth and its technological systems. Our space weather is a consequence of the behavior of the sun, the nature of Earth's magnetic field and atmosphere, and our location in the solar system.

Space Is Not Empty

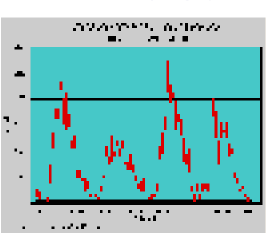
Earth is immersed in the escaping ionized outer atmosphere of the Sun. This "solar wind," flowing against Earth's magnetic field, shapes the near-Earth space environment. The magnetic bubble of the "magnetosphere," carved out by Earth's field, shields our upper atmosphere with its ionized region, the ionosphere, from the direct effects of the solar wind.



Cutaway illustration of Earth's magnetosphere, where the surfaces illustrate the internal magnetic field configuration and the boundary between the magnetosphere and solar wind. Key regions are labeled. The orbits of several spacecraft of the ISTP armada are shown to scale (from: P. Reiff, Rice University).

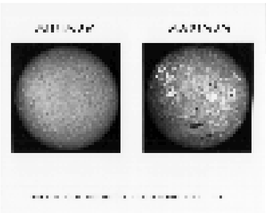
The magnetosphere is home to research, telecommunications, navigation, and weather satellites that are surrounded by the energetic particles of the Van Allen radiation belts and the thin gases of the upper atmosphere. The space shuttle and the future space station fly in the upper atmosphere, where influences from both above and below determine the local conditions. The Global Positioning System (GPS) satellites, used for navigation, surveying, and geophysical research, pass through the radiation belts, although they orbit Earth at altitudes above most of the atmosphere. Geosynchronous communication and weather satellites reside on the outer edges of the radiation belts, where disturbed space weather causes increases in the intensities of hazardous energetic particles. All spacecraft send and receive their signals through the ionosphere, which is sometimes dramatically altered by space weather events.

The Sun Is Not Steady



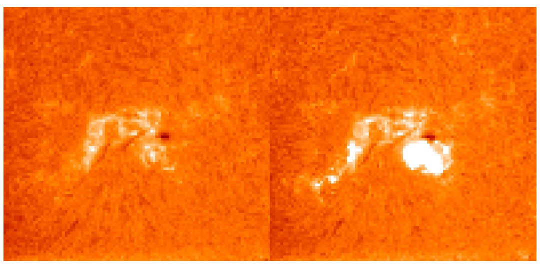
Monthly averaged sunspot numbers in the visible hemisphere of the Sun. The numbers of spots wax and wane with the 11-year solar activity cycle. Larger maxima usually mean more solar "storms" (from: The National Solar Observatory/Sacramento Peak).

The Sun and its atmosphere are always changing, in a sense having weather of their own. The Sun undergoes long-term (decade or more) "climate-like" variations such as the roughly 11-year solar cycle. This cycle first showed itself in the number of sunspots counted on the solar surface (above), but it is also seen in the appearance and disappearance of other less obvious features, like the filaments in the pictures below that can be seen with a special filter.



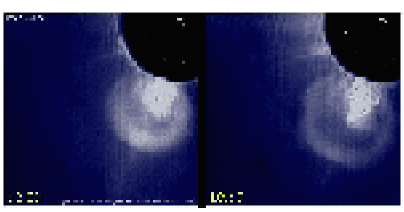
Images of the Sun obtained through filters that isolate the H-alpha emission line of hydrogen. Features on the photosphere stand out at this wavelength, in particular around solar maximum. The dark filaments are produced by cooler material that arches above the main surface, while bright "plages" are concentrated around active regions (from: The John W. Evans Solar Facility, National Solar Observatory/Sacramento Peak).

Space weather disturbances are generally caused by what are effectively solar "storms." One type of solar storm is called a solar flare because the brightening of a small area on the Sun heralds its occurrence.



A flare on the photosphere brightens the emissions of light from an active region (from: The Space Environment Center, National Oceanic and Atmospheric Administration).

The other type of common storm is called a "coronal mass ejection." These explosions of material from the Sun's upper atmosphere are hard to see by eye except during total solar eclipses. Because of this, they were recognized only in modern times.



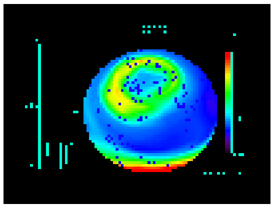
An eruption in the Sun's corona made visible by blocking the bright solar disk (from: The Solar Data Analysis Center, Goddard Space Flight Center).

The solar disturbances shown in the figures above are most frequent around "solar maximum," defined by the high points in the sunspot cycle. The "solar minimum" periods, however, are not without their own characteristic space weather.

The Response of Our Space Environment to the Constantly Changing Sun Is Known as "Space Weather"

"Storms" in our space weather generally follow severe solar disturbances. Dramatic changes in the particle populations and the electrical currents flowing within and through interplanetary space and near-Earth space are the result.

The details of what causes various types of space weather are subjects of active investigation. Sometimes cause-and-effect chains can be easily recognized; for example, the ionizing effects of flares' emissions in our atmosphere. At other times, the connections are more complicated and subtle. For example, the aurora is a hallmark of disturbed space weather, but auroral displays do not always follow a specific solar event. Radiation experienced by satellites in orbit may depend as much or more on the location of the orbit as on the level of solar activity.



The radiation intensities from energetic charged particles in the magnetosphere can reach close to Earth, to ionospheric altitudes, as is often observed by low-altitude satellites. An example of such a low-altitude influence is shown here, over a day in the life of a satellite called SAMPEX as it circles the globe at about 600 kilometers altitude. In this view, the energetic particle fluxes are most intense in the region of the red and yellow ring around the north pole (from: D.N. Baker and S.G. Kanekal, Goddard Space Flight Center).

The aurora occurs when energetic particles, mostly electrons, "rain" down from the magnetosphere during episodes of disturbed space weather. The auroral light is emitted by atmospheric atoms and molecules that become excited by the close passage of the electrons. The auroral electrons can also ionize the atmospheric particles, thus contributing to the local ionosphere (from: The Straight Scoop).

Space Weather Affects How We Live and Work Today

Most of the time space weather is of little concern in our everyday lives. However, when the space environment is disturbed by the variable outputs of the Sun, technologies that we depend on both in orbit and on the ground can be affected.

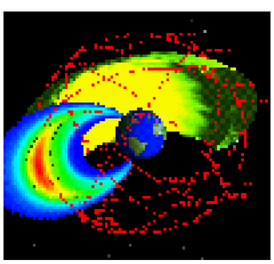


Illustration of the constellation of GPS satellites encountering the radiation belts (shown in cross section) as they orbit Earth (from: U.S. Air Force Phillips Laboratory home pages).

Forty years ago the first artificial satellite was launched. Today, we have a very large number of satellites in orbit and frequent manned presence in space. Increasingly, communication and navigation enterprises are replacing cables and repeater stations with "permanent" space-based networks.

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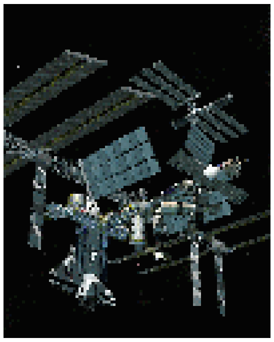
One configuration proposed for the International Space Station home page (from: The International Space Station home page)

Fifteen years from now there will be many hundreds of active satellites and a nearly continuous manned presence on the space station. Space weather will be something that we will hear more and more about, especially during periods when the Sun is active.

How does space weather figure into this vision of the present and future? Corrective or preventative measures can be taken to ensure that radiation doses and electrical charging of satellites in the Earth-space environment do not damage critical spacecraft components and functions, that disturbances of the ionosphere do not degrade the performance of navigation and communications systems, and that the ionospheric currents related to those disturbances which generate magnetic fields on the ground do not interfere with the operations of our large-scale power distribution grids. Precautions can also be taken to minimize exposure of astronauts and passengers in aircraft flying at high altitudes along polar routes to hazardous radiation levels *if* these conditions can be foreseen.

Can Space Weather Be Predicted?

Our understanding of space weather is at a primitive level, perhaps analogous to that of traditional meteorology in the early 1950s. Still, much progress has been made since the 1960s as a result of experiments carried out on spacecraft. Today, realistic space environment models and enhanced observational capabilities for detecting disturbed space weather conditions or their precursors have the potential to be applied to space weather prediction and management. This requires a framework whereby both expertise and facilities at a broad range of institutions are brought to bear on the task. Such an endeavor is the ultimate test of our knowledge of the Sun-Earth connections.

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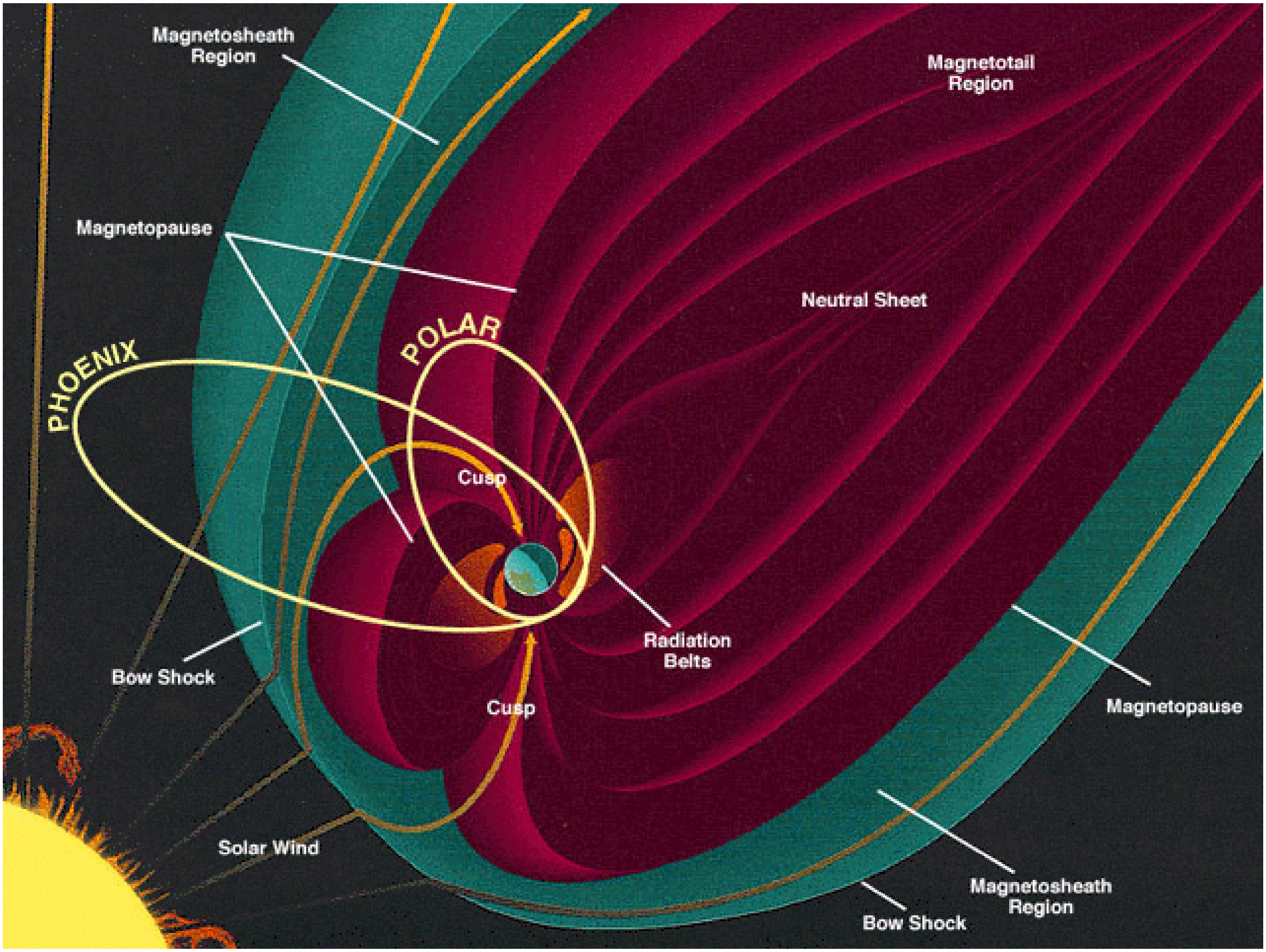

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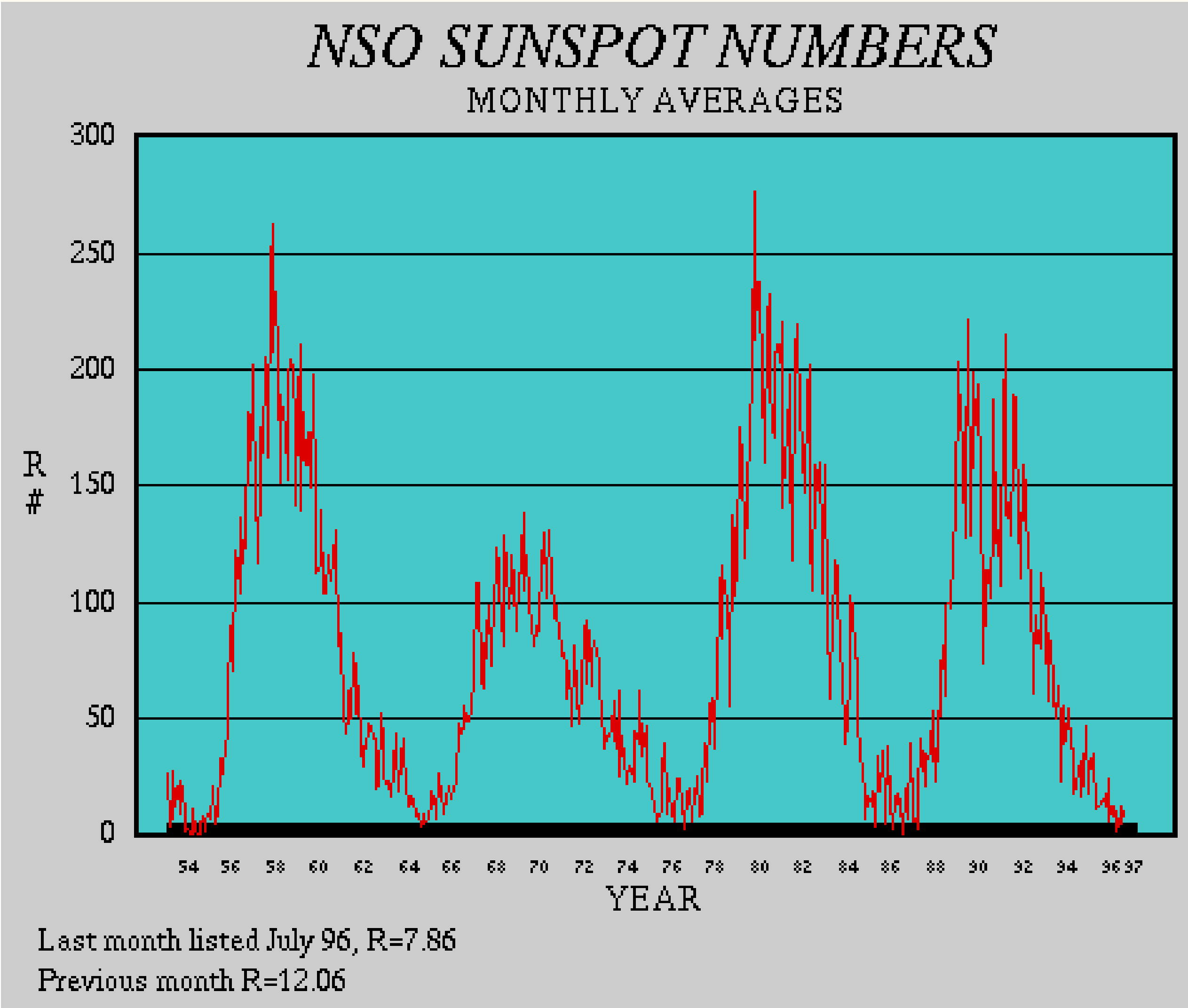

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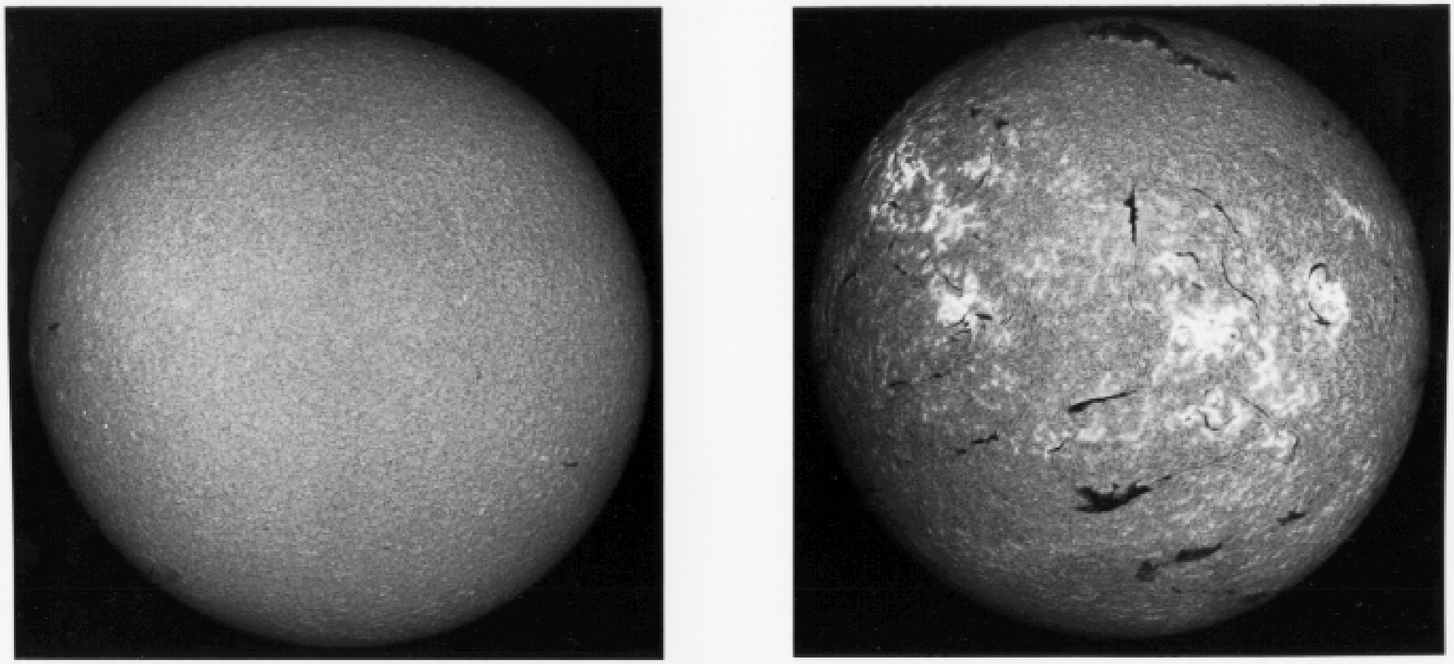

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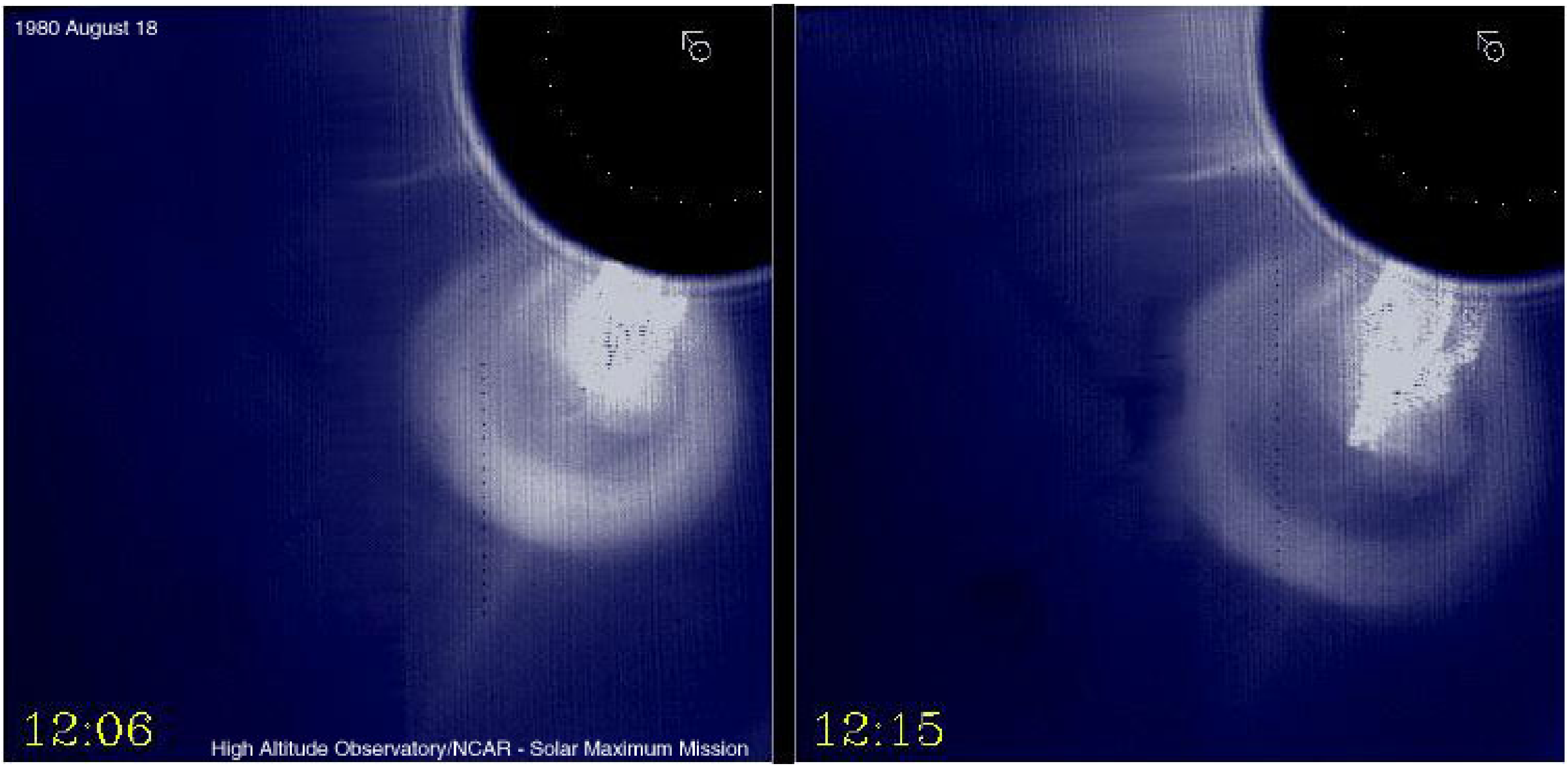

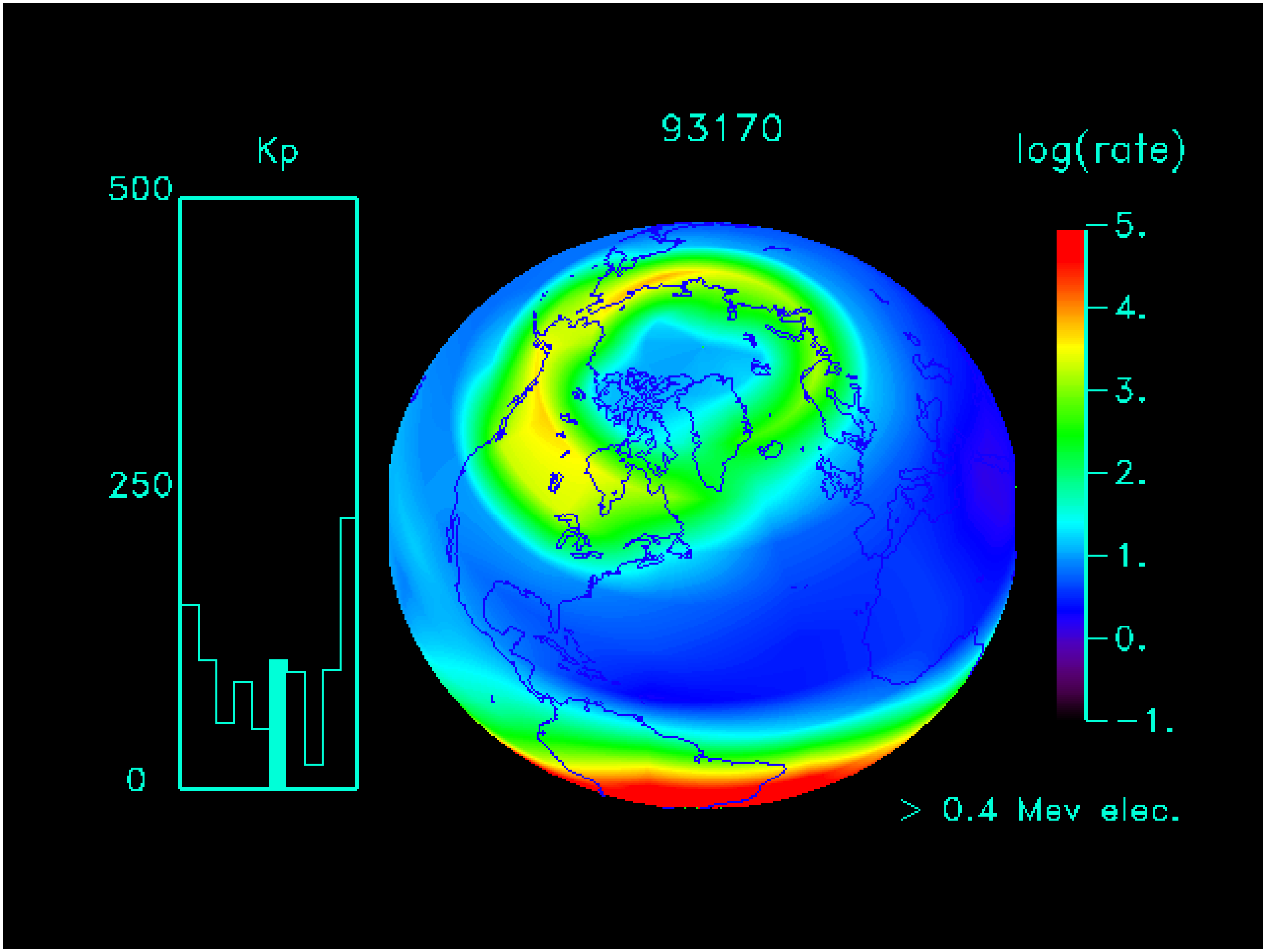
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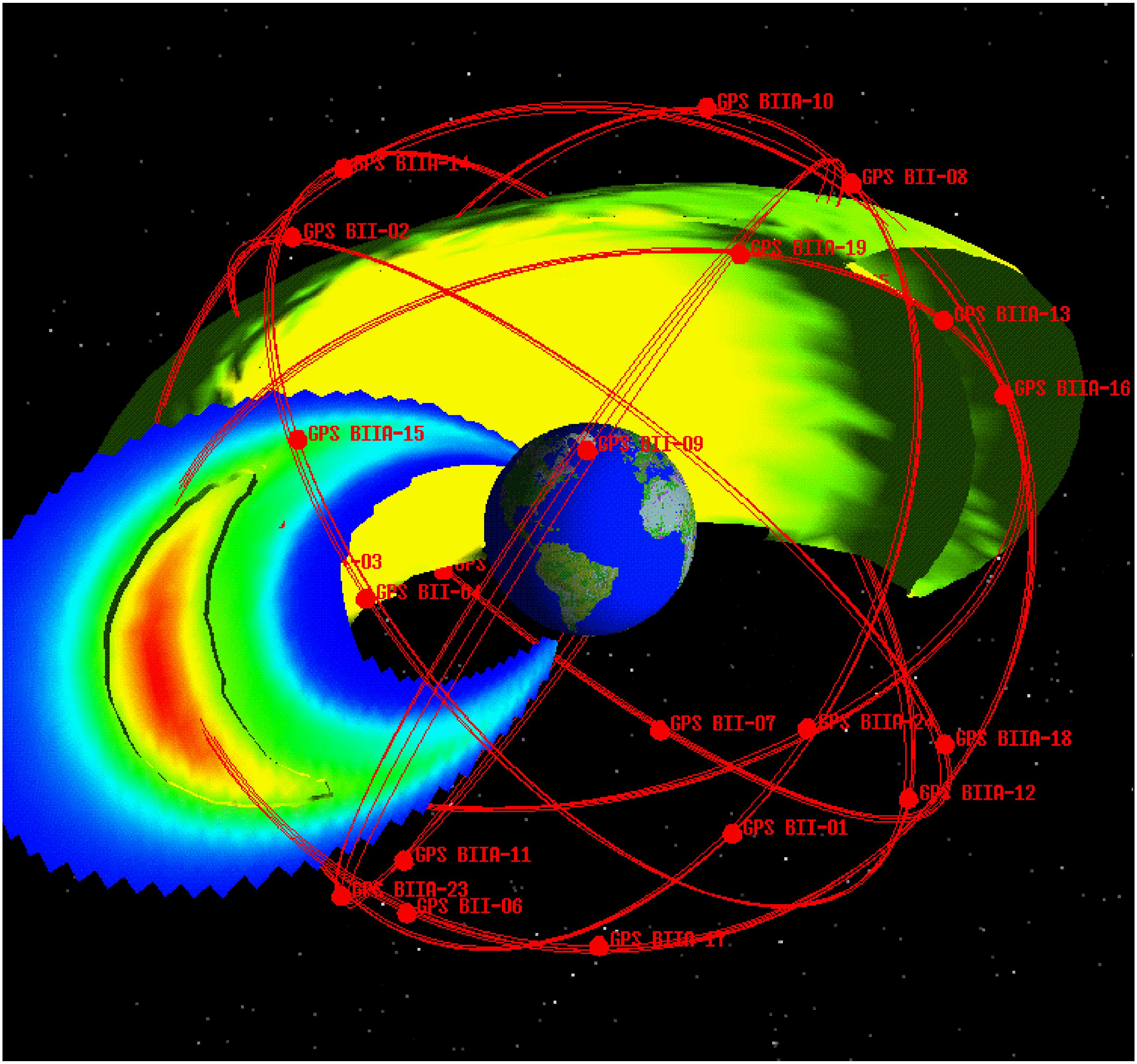


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Space Weather: A Research Perspective
The Elements of Near-Earth Space

The Sun

The Sun is a typical yellow star that, together with our solar system, formed from an interstellar cloud some 5 billion years ago.

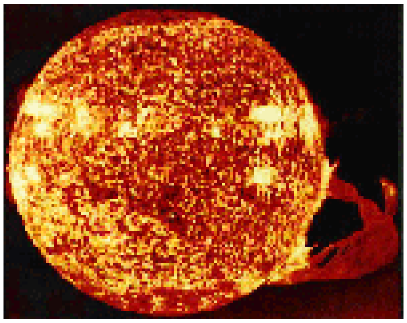
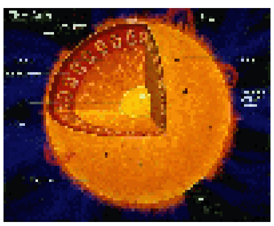


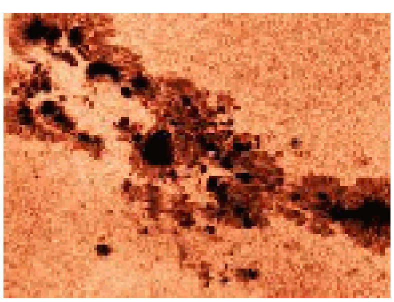
Image of the Sun in ultraviolet light showing a large prominence at the limb (from: The Space Physics Group at Oulu, Finland, Space Physics Textbook home page).

Solar energy is produced deep within the Sun by nuclear reactions. Most of this energy emerges as sunlight, at a remarkably constant rate, from the visible surface or photosphere. The Sun also gives off ultraviolet, x-ray, gamma-ray, and radio emissions that are much more variable than its visible emissions. The most extreme variability occurs in the localized explosive phenomenon known as a solar flare.



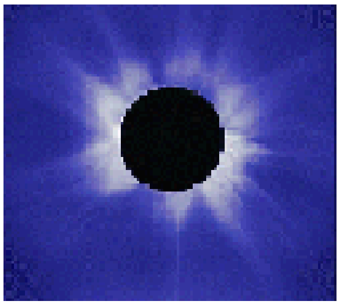
Cutaway diagram showing what is thought to be inside the Sun (from: The Space Science Institute home page).

The hot ionized gases in the interior of the Sun are constantly in motion as a result of the heat generated within, coupled with the Sun's rotation (one rotation every 27 days, approximately). Solar magnetic fields are generated below the photosphere by a still poorly understood process related to this circulation. These fields are sometimes concentrated in sunspots or complexes of sunspots forming active regions. Active regions are the usual sites of flares, which may occur when their complicated magnetic fields are suddenly rearranged.



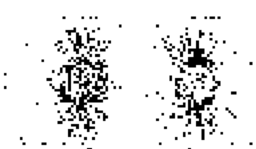
The surface magnetic field of the sun is concentrated in sunspots, which appear dark because the material in the sunspot is much cooler than the surrounding material. Sunspots often appear in groups called active regions (courtesy of C.J. Hamilton, Views of the Solar System home page)

Above the solar surface stretches the extended solar atmosphere, known as the solar corona. Propagating waves and/or processes associated with the constant rearrangement of the magnetic fields close to the Sun raise the temperature of the corona (to over 1,000,000 Kelvin), far above that of the solar surface (at about 6000 degrees Kelvin). Because of its temperature, the coronal gas is highly ionized and so its structure is affected by the coronal magnetic field. The picture of the corona below is in effect a picture of the coronal magnetic field structure.



A photograph taken during a solar eclipse on February 2, 1980. Concentrations of plasma, organized by solar magnetic fields, are clearly visible (from: the High Altitude Observatory public archives).

The solar magnetic field evolves over the solar cycle along with the sunspot number. Driven by the motions of the ionized gases beneath the visible surface, the North and South poles of the solar magnetic field reverse approximately every eleven years around sunspot number maximum. As a result, there is a roughly 22-year cycle in the Sun's magnetic "polarity," with the North or South magnetic pole in the northern hemisphere of the Sun during alternate sunspot maxima. The field is more complicated at solar maximum when the simple solar minimum structure, which resembles Earth's field or that of a bar magnet, is disrupted by the strong fields of many active regions.



Magnetic field structures in the corona at solar minimum (left) and solar maximum (right) inferred from ground-based observations. The structures are shown by "field lines" that track the direction of the field at the points they thread. The solar minimum coronal field resembles that of a bar magnet except at high latitudes, while the solar maximum field is much more complicated (derived from Wilcox Solar Observatory magnetograph data, courtesy T. Hoeksema).

Processes related to this evolution of the solar magnetic field are the ultimate causes of space weather. Effects of the 22-year magnetic cycle can be seen in some space weather records, but it is primarily the 11-year cycle of activity that is of concern in space weather.

The Solar Wind

The high temperature of the solar upper atmosphere generates an outward flow of the ionized coronal gas or plasma away from the Sun at typical speeds ranging from 400 to 800 kilometers per second. This outflow is known as the "solar wind." At the Earth (1 astronomical unit (AU) or 150 million kilometers away from the Sun), 1 cubic centimeter of solar wind contains about 8 protons and an equal number of electrons (so there is no net electrical charge in the gas). Helium and heavier ions are also present in the solar wind but in smaller numbers.

Since the Skylab mission in 1973, it has been realized that the solar wind does not flow uniformly from everywhere on the Sun. Measurements have shown that it comes mainly from low-density regions in the corona called "coronal holes." Coronal holes are so-named because they appear dark in x-ray images of the Sun (see the example below). They are usually located in the Sun's polar regions, but their irregular boundaries can dip into low solar latitudes where they affect conditions in interplanetary space. In general, the sizes, shapes, and distributions of coronal holes change over the solar cycle, with the largest coronal holes appearing around sunspot minimum when the coronal magnetic field has a simple configuration. The highest-speed solar wind streams observed at the Earth are often associated with these large coronal hole sources.

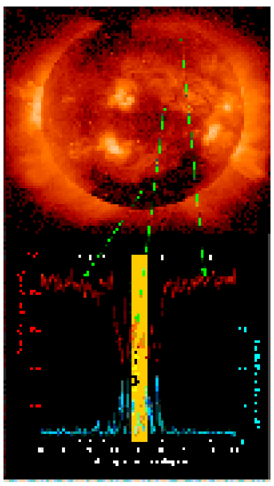


Illustration showing Ulysses spacecraft solar wind speed measurements referred to their source regions seen on an x-ray image from the Yohkoh satellite. The high-speed solar wind from the polar coronal holes (dark areas) was measured all of the time when Ulysses was at high solar latitudes (from: The Ulysses Mission home page).

Coronal magnetic fields are constantly being carried with the solar wind into interplanetary space. The solar rotation winds up the field into a spiral resembling the water streams from a rotating garden sprinkler because the source of the field keeps moving with the Sun.

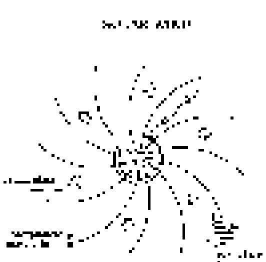
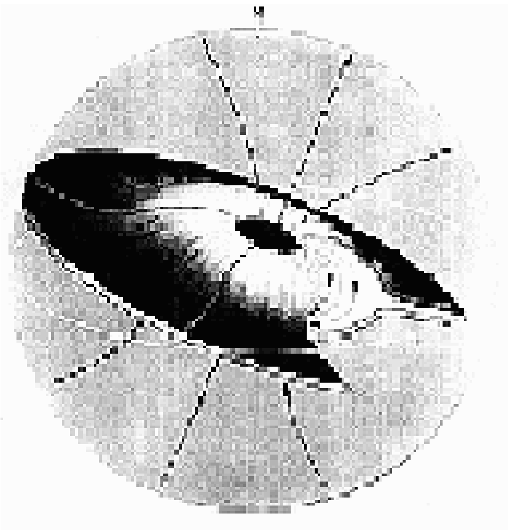


Illustration of the "winding up" of the magnetic field in the solar wind (courtesy of J. Luhmann, University of California at Berkeley).

At the Earth's distance from the Sun, the typical interplanetary magnetic field strength is about 5 nano teslas, or about 1/10,000 the strength of the Earth's magnetic field at the surface. The "polarity" of the interplanetary magnetic field depends on the direction of the coronal field at its roots. As illustrated below, the interplanetary field is typically organized into hemispheres of inward and outward field corresponding to the North and South magnetic poles of the solar field. The two hemispheres are separated by a sheet-like boundary carrying an electrical current. The interplanetary magnetic field directions reverse with the Sun's magnetic polarity near sunspot maxima.



Sketch showing the solar connections of the interplanetary current sheet. The directions of the magnetic fields (arrows) define their "polarity" (from: The Solar Data Analysis Center, NASA Goddard Space Flight Center).

Since the solar field is not a perfect configuration with simple North and South poles aligned along the Sun's rotation axis, the current sheet often has ripples like a ballerina's skirt.

The interplanetary current sheet shape appears like a twirling ballerina's skirt when the solar dipole magnetic field has an axis different from the solar rotation axis (from: Lund Space Weather and AI Center, Lund University, Sweden).

The passage of this current sheet is an important marker for space weather. During solar maximum, the structure of the current sheet can become quite complicated as the magnetic fields of active regions on the Sun disrupt this simple picture.

The Magnetosphere

Processes analogous to those in the Sun's interior work in the molten core of the Earth to generate our own magnetic field. The Earth's field is even more like that of a bar magnet than the solar field, with oppositely located North and South poles characterizing its very "dipolar" (two-pole) structure.

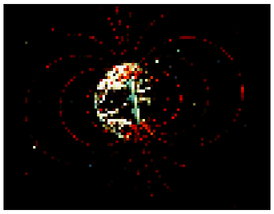
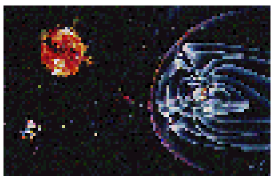


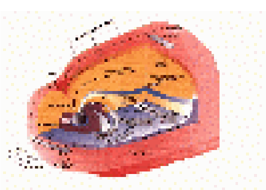
Illustration of the dipolar magnetic field structure generated in the Earth's interior (from NASA Goddard Space Flight Center Space Physics Education home page).

The highly conducting solar wind gas is not able to penetrate Earth's magnetic field at most locations, instead flowing around it. Before it is diverted, however, it slows down at a (shock) wave called the "bow shock" that stands upstream of Earth in the solar wind.



A bow shock stands upstream of the Earth in the solar wind plasma. It serves to slow the flowing ionized gas before it encounters the obstacle presented by the Earth's magnetic field, analogous to air flow around a supersonic aircraft (from: Rice University).

The diversion of the solar wind flow generally occurs at about 6 to 15 Earth radii above Earth's sunlit surface, where the variable solar wind plasma "ram" pressure is balanced by the pressure of the compressed dipolar field of Earth. The cavity that Earth's field makes in the solar wind stretches out into a long "magnetotail" on the nightside. This cavity and everything inside it make up the "magnetosphere." The size of the magnetosphere is smallest when the solar wind is strong, sometimes pushing the dayside boundary inside of the orbit of geosynchronous satellites.



The magnetosphere is the region of space above the atmosphere that is dominated by the Earth's magnetic field. This cutaway illustration shows the major structural features of this complex, dynamical system derived from spacecraft observations in many different orbits (from: Rice University).

Earth's magnetic field connects with the interplanetary magnetic field in the polar caps. This interconnection allows transfer of energy from the solar wind to the magnetosphere and ionosphere, as well as entry of charged particles from interplanetary space. The amount of interconnection is greatest when the interplanetary magnetic field has a southward direction.

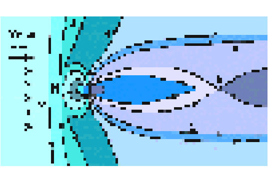
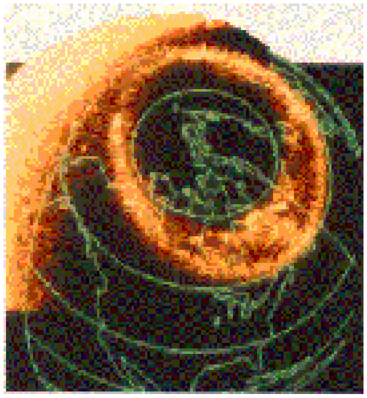


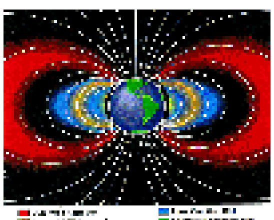
Illustration showing why southward-oriented interplanetary fields are more effective at transferring energy from the solar wind to the magnetosphere. The interconnection between the interplanetary and geomagnetic field is enabled at the "nose" of the magnetosphere because the fields are oppositely directed there. Once connected, the fields move roughly as indicated by the sequence of numbers (from: NASA Goddard Space Flight Center Space Physics Education home page).

The auroral ovals are located in the polar regions bordering the area threaded by the interconnected fields. Here, energetic charged particles from both the solar wind and the magnetosphere precipitate or "rain" into the atmosphere from above. This rain of typically kilovolt-energy particles is responsible for the aurora borealis (northern lights) and aurora australis (southern lights), produced when atmospheric atoms and molecules energized by collisions with the incoming particles emit light.



This image of the auroral oval shows the bright emissions that occur in the atmosphere at altitudes between 80 and 300 kilometers when atoms are excited by energetic electrons traveling along magnetic field lines. This image was obtained from the Dynamics Explorer spacecraft over the north polar region during winter, when the entire aurora borealis was over the night hemisphere of the Earth (from: Dynamics Explorer University of Iowa Imaging Experiment, L.A. Frank principal investigator).

Several concentrations of charged-particle populations with different origins, densities, and energies are found in the magnetosphere. The Van Allen radiation belts are one such population with sources as diverse as the decay products of cosmic-ray collisions with atmospheric atoms and ions that originated in the interstellar gas.



The electrons and ions in the Van Allen belts are effectively trapped in Earth's magnetic dipole field. Bouncing between hemispheres, they reverse their motion at their closest approach to Earth, while at the same time drifting around it. If their trajectories take them too deeply into the atmosphere where they collide with the ambient particles and lose their energy, they are lost from the radiation belts. In this figure, "trapped ACR" refers to ions that originate in the interstellar gas, while energetic secondary ions originate from collisions of cosmic rays with atmospheric gases (courtesy of J.B. Blake, The Aerospace Corporation).

Earth's upper atmosphere is another source of particles for the magnetosphere. Ionized atmospheric gases at high altitudes can be energized and transported around by a variety of processes that are still under study. The ions and electrons in the magnetosphere carry electrical currents that produce deviations in the magnetic field measured on the ground as well as in space.

The Upper Atmosphere and Ionosphere

At the base of the magnetosphere lie the upper reaches of Earth's atmosphere and ionosphere. The upper atmosphere is composed of atoms and molecules of gases such as oxygen and nitrogen, which become increasingly sparse with increasing altitude. At the 300- to 400-kilometer altitude of the shuttle orbit, the atmospheric density is on the order of 300 million (300,000,000) particles per cubic centimeter or about 1/10,000,000,000 times the density of all of the gases of the air at the ground. At typical weather satellite orbit altitudes (about 850 kilometers), the density is down to 1/100 to 1/1000 times the density at the shuttle orbit. However, these densities can increase by more than ten times when the upper atmosphere is heated by strong solar ultraviolet radiation at solar maximum or by processes occurring during disturbed space weather.

The ionosphere is the region of the atmosphere above 60-kilometer altitude that is slightly ionized by solar ultraviolet radiation. The UV radiation can eject negatively charged electrons from their "parent" atoms and molecules to make positively charged ions. These charged particles live for minutes to hours before recombining to again form neutral or uncharged gas particles in an ongoing cycle of ionization and recombination. On the average, the abundance of charged particles increases with altitude up to about 300 kilometers, decreasing gradually at higher altitudes (see the figure below). Ionization by energetic cosmic-ray particles contributes some of the lowest-altitude ionosphere.

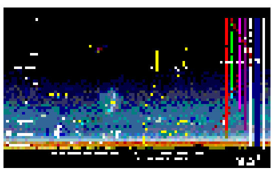


Illustration of the upper-atmosphere temperature variability and the regions of Earth's ionosphere, which are labeled by letters. The various ionospheric peaks are the result of the various sources of atmosphere ionization and the atmospheric chemistry at different altitudes (courtesy of J.H. Yee and associates, Applied Physics Laboratory, Johns Hopkins University).

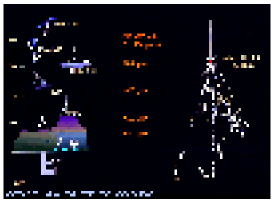
The aurora is produced at around 100-km altitude by the impact of energetic particles from above that cause the atmospheric gases to emit light in a process similar to that in a neon sign. At night, when the ionizing sunlight is absent, the particles that produce the aurora can also be the primary source of the local ionosphere.

The aurora borealis as seen from the ground. Different colors arise because different atmospheric gases are excited, and the excitation occurs at different altitudes as a result of the wide energy spread of the exciting electrons (from: Rice University educational home pages).

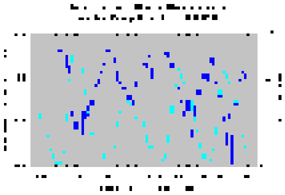
Even though there are many more neutral gas particles than ions and electrons in the ionosphere, the charged particles give it electrically conducting properties that make it an essential element of space weather.

Cosmic Rays

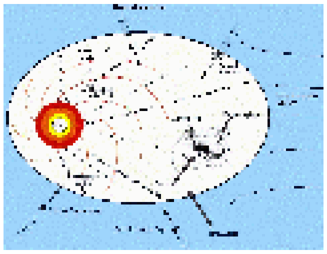
In addition to the space environment described above, Earth is immersed in an extremely tenuous bath of high-energy charged particles called cosmic rays. Most cosmic rays enter the solar system from the galaxy, but solar flares contribute on occasion and disturbances moving through the solar wind can energize particles in their path. Both solar wind particles as well as some originating from interstellar gas ionized in the vicinity of the Sun can be so energized. The cosmic rays produced within the solar system sometimes make up the dominant contribution near Earth. Although Earth's magnetic field acts like a shield, deflecting all but the fastest of these particles, even low-energy cosmic rays reach low altitudes in the polar regions where the planet's magnetic field interconnects with the interplanetary field. The most energetic cosmic rays can reach cloud levels (around 10-km altitude) where they affect cloud electrification, while a few may even reach the ground or create secondary particles in the atmosphere.


Cosmic rays can penetrate into the atmosphere, producing many "secondary particles" as products of their collisions with atmospheric nuclei (courtesy of M.A. Shea, Phillips Laboratory).

Particles that are produced when cosmic rays interact with the thin upper atmosphere can become part of the Van Allen belts. The local density of cosmic rays varies with the solar activity cycle because the disturbed solar wind during solar maximum sweeps these particles out of the solar system more effectively than does the quiet solar wind.

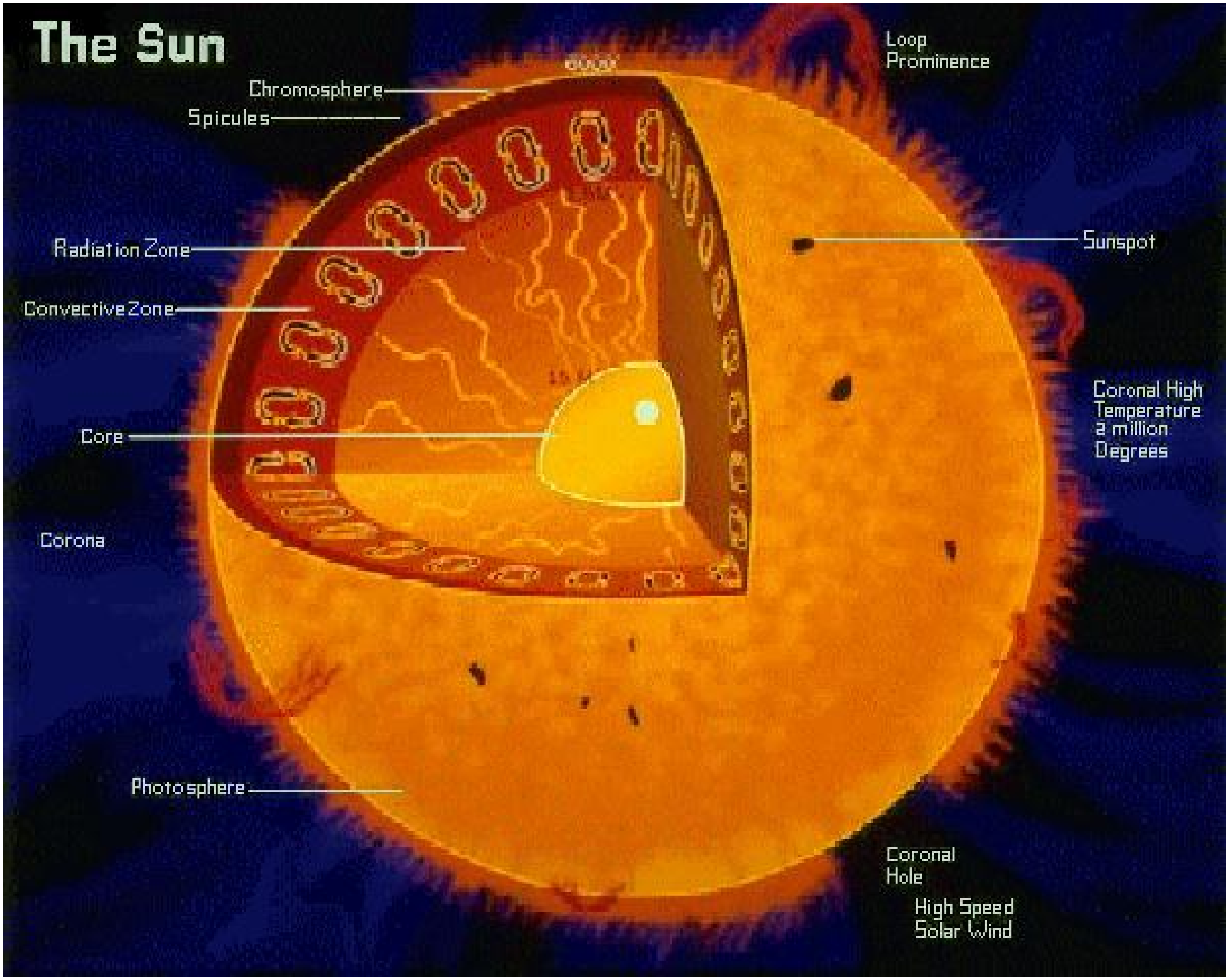

Data from the Climax, Colorado, neutron monitor operated by the University of Chicago. The cosmic rays counted exhibit an inverse relationship to the solar cycle because solar wind from the active Sun sweeps more away from the Earth than does solar wind from the quiet Sun (from: The NOAA National Geophysical Data Center, Boulder, CO).

The expanding solar wind forms a bubble in the interstellar material thought to extend at least 100 AU from the Sun. (For comparison, the outermost planet, Pluto, orbits the Sun at about 40 AU distance.) Space weather occurs everywhere within this bubble known as the "heliosphere." Every object in the solar system experiences the equivalent of Earth's space weather, although its detailed characteristics differ from place to place.

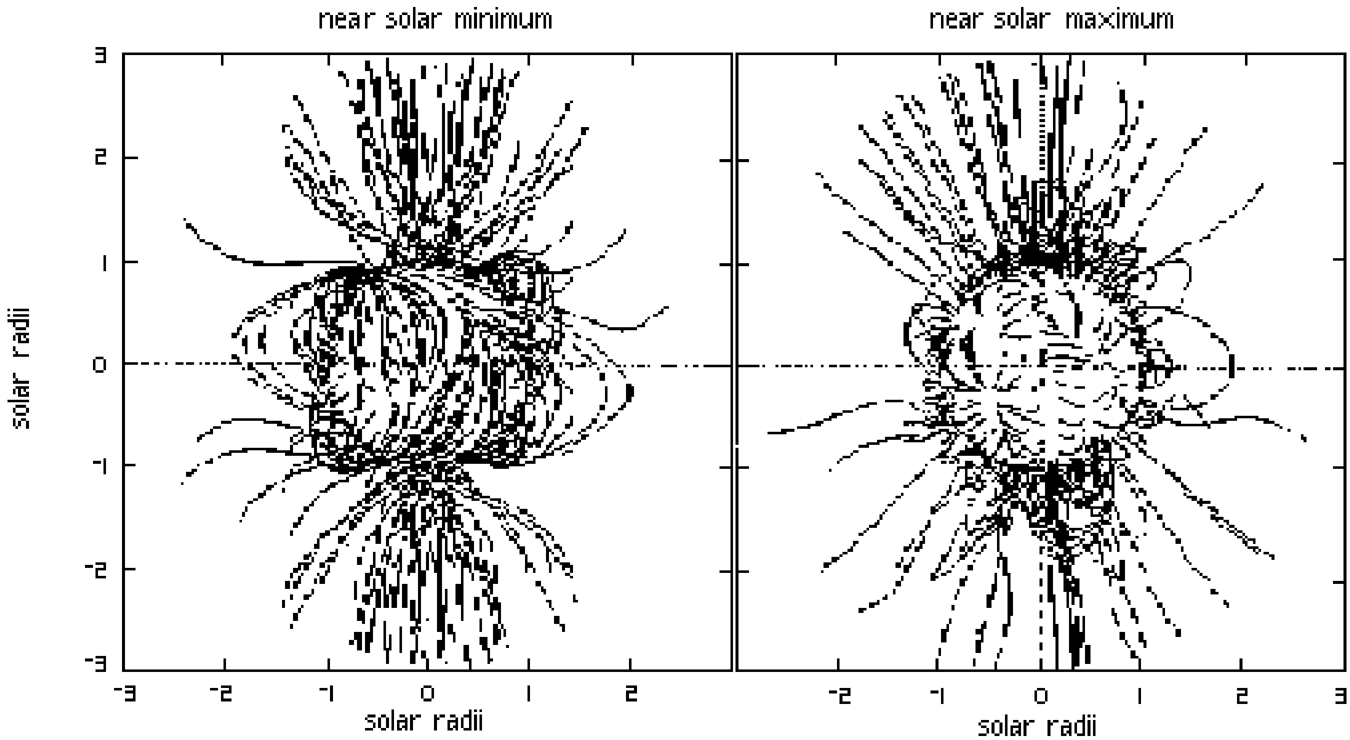


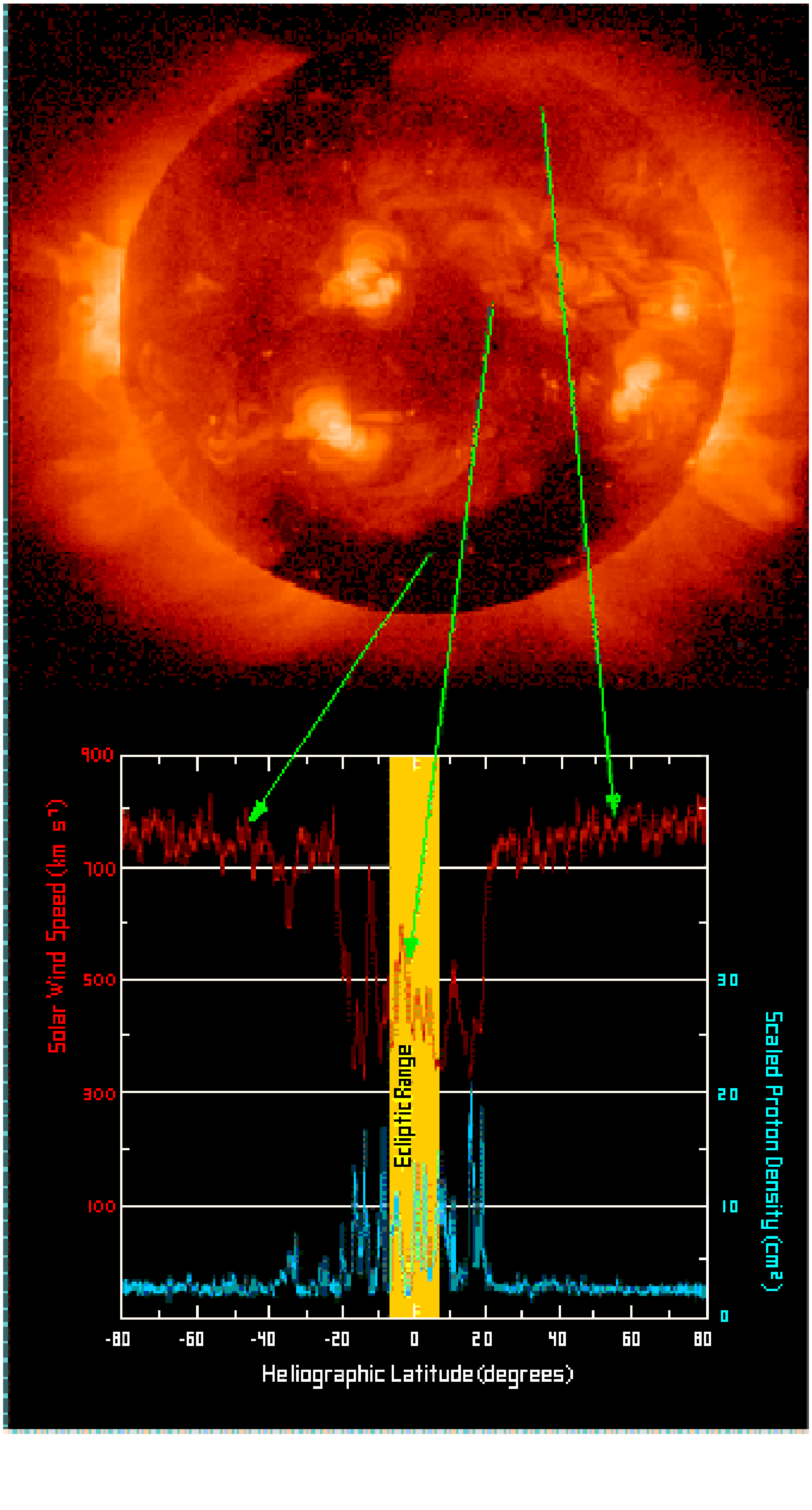
The heliosphere is a bubble, formed by the expanding solar wind, in the material between the stars (from: NASA's Solar Connections home page).

file:///S|/SSB/sunschem.jpg

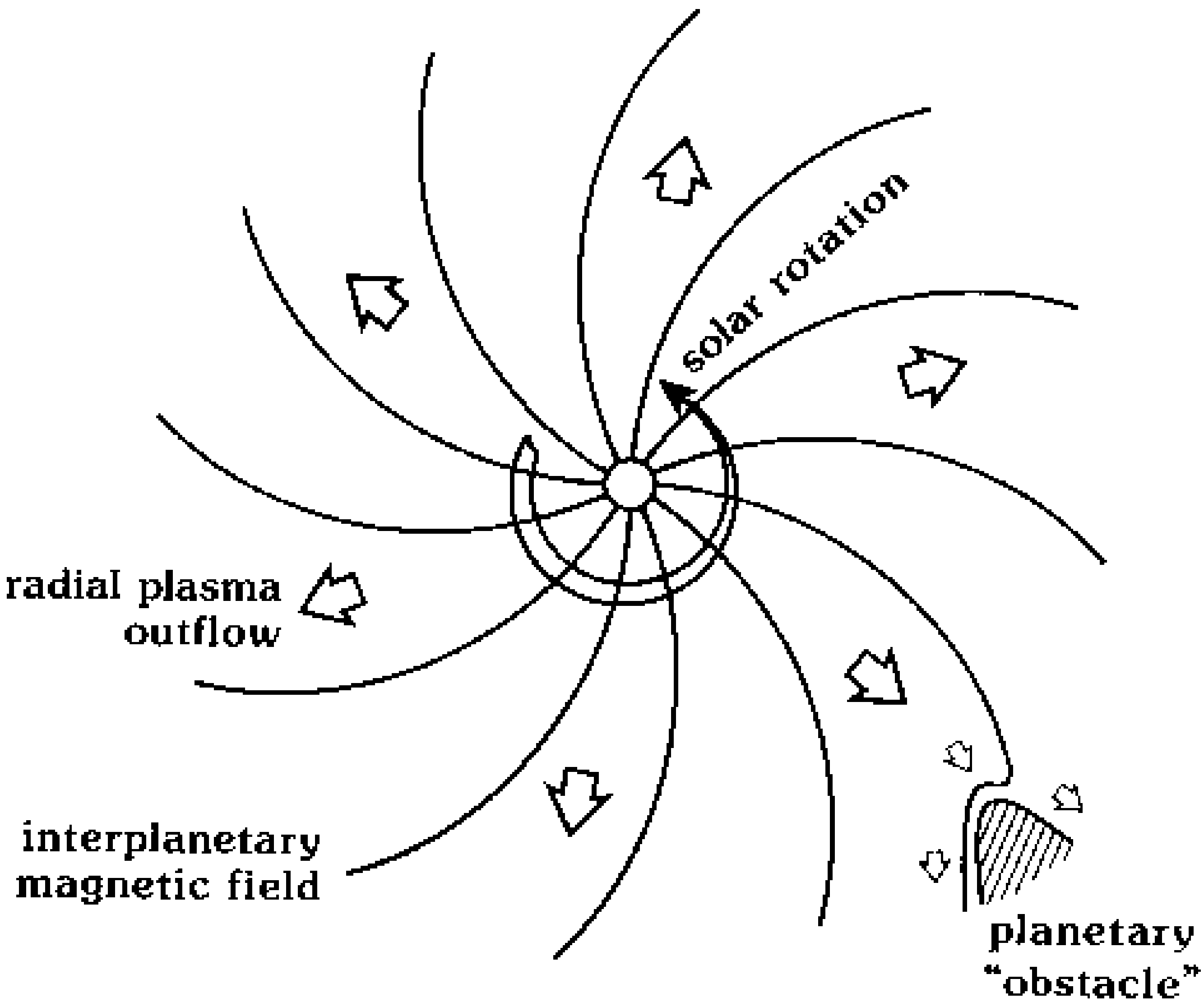


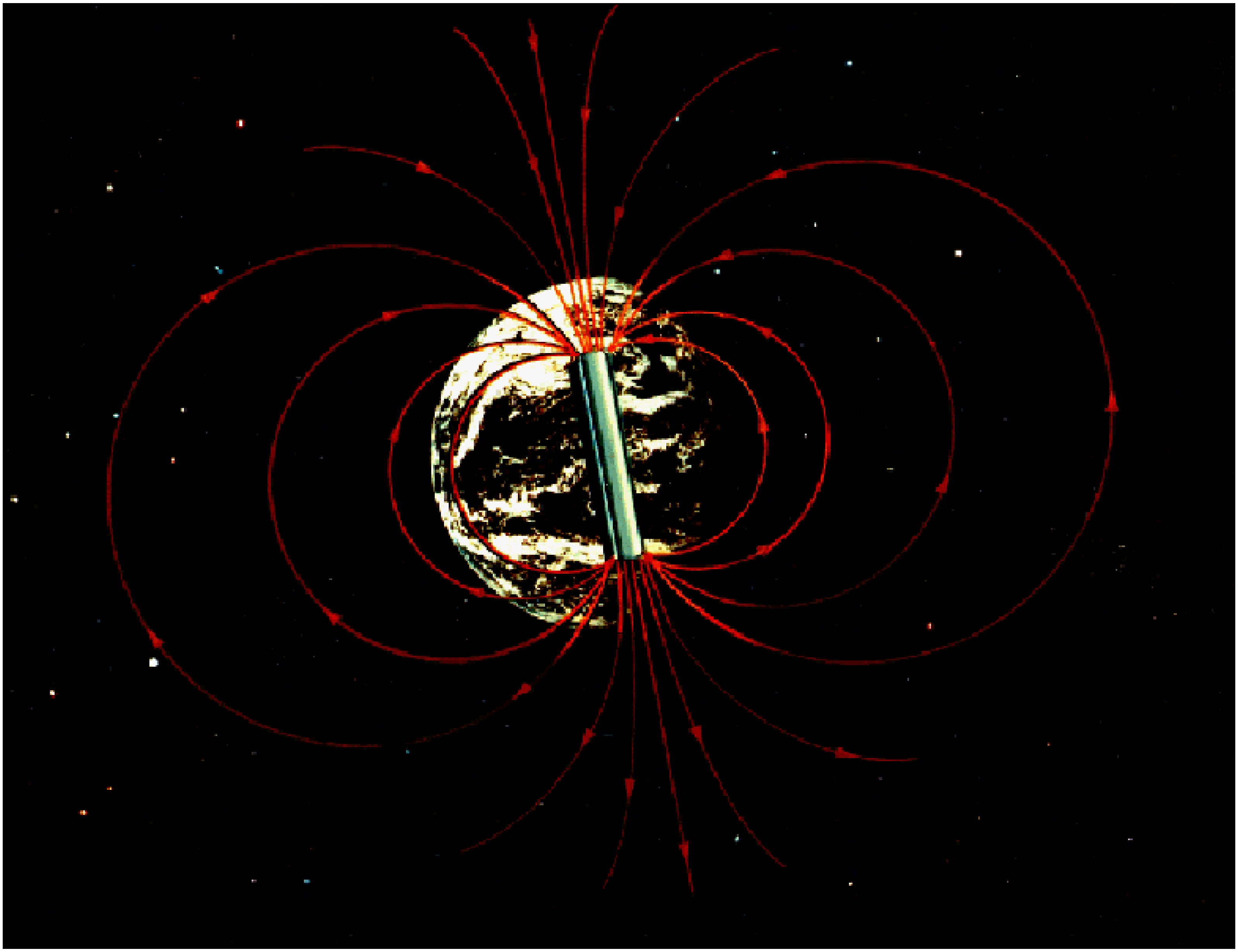
file:///S|/SSB/cabbage.gif

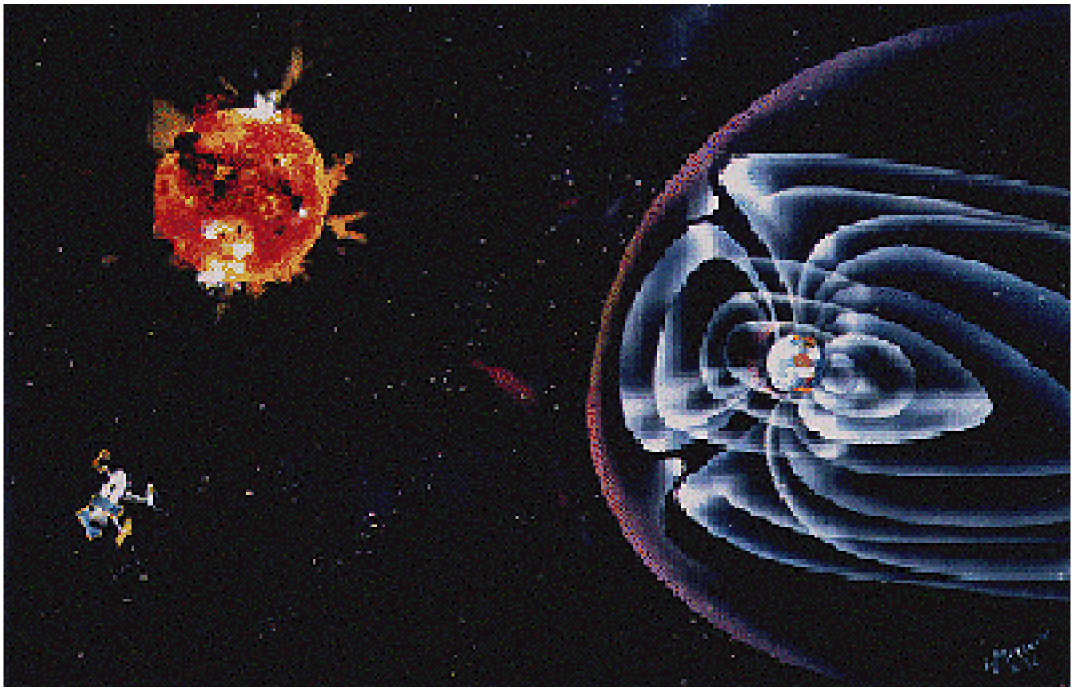


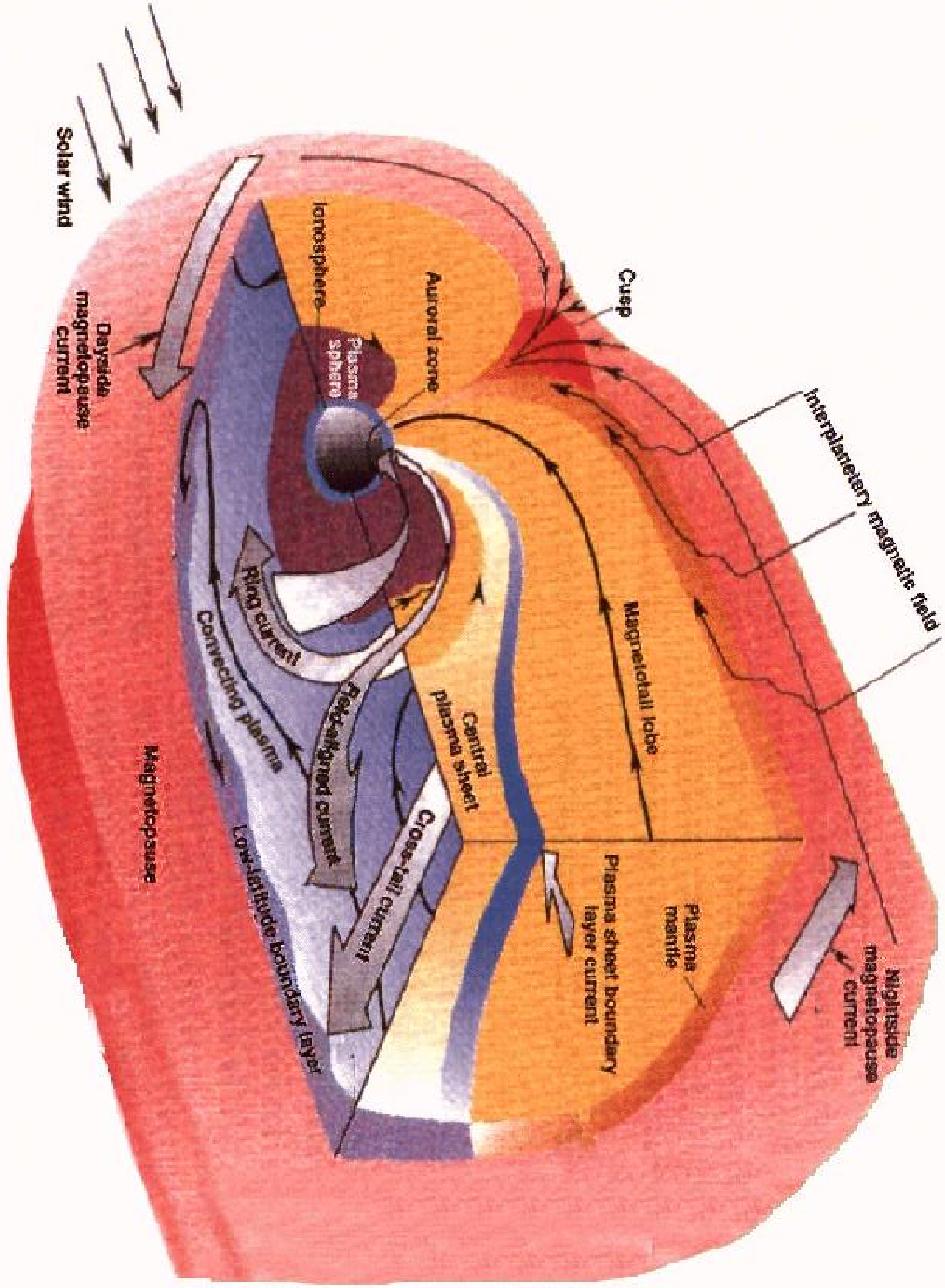

900
700
500
300
100
Solar Wind Speed (km s⁻¹)
30
20
10
0
Scaled Proton Density (cm⁻³)
Ecliptic Range
-80
-60
-40
-20
0
20
40
60
80
Heliographic Latitude (degrees)

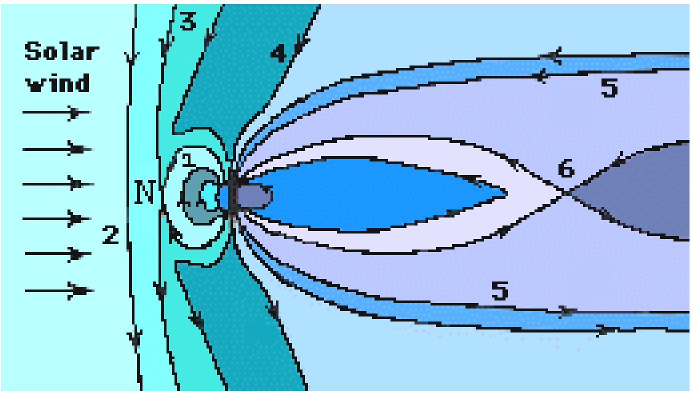
SOLAR WIND

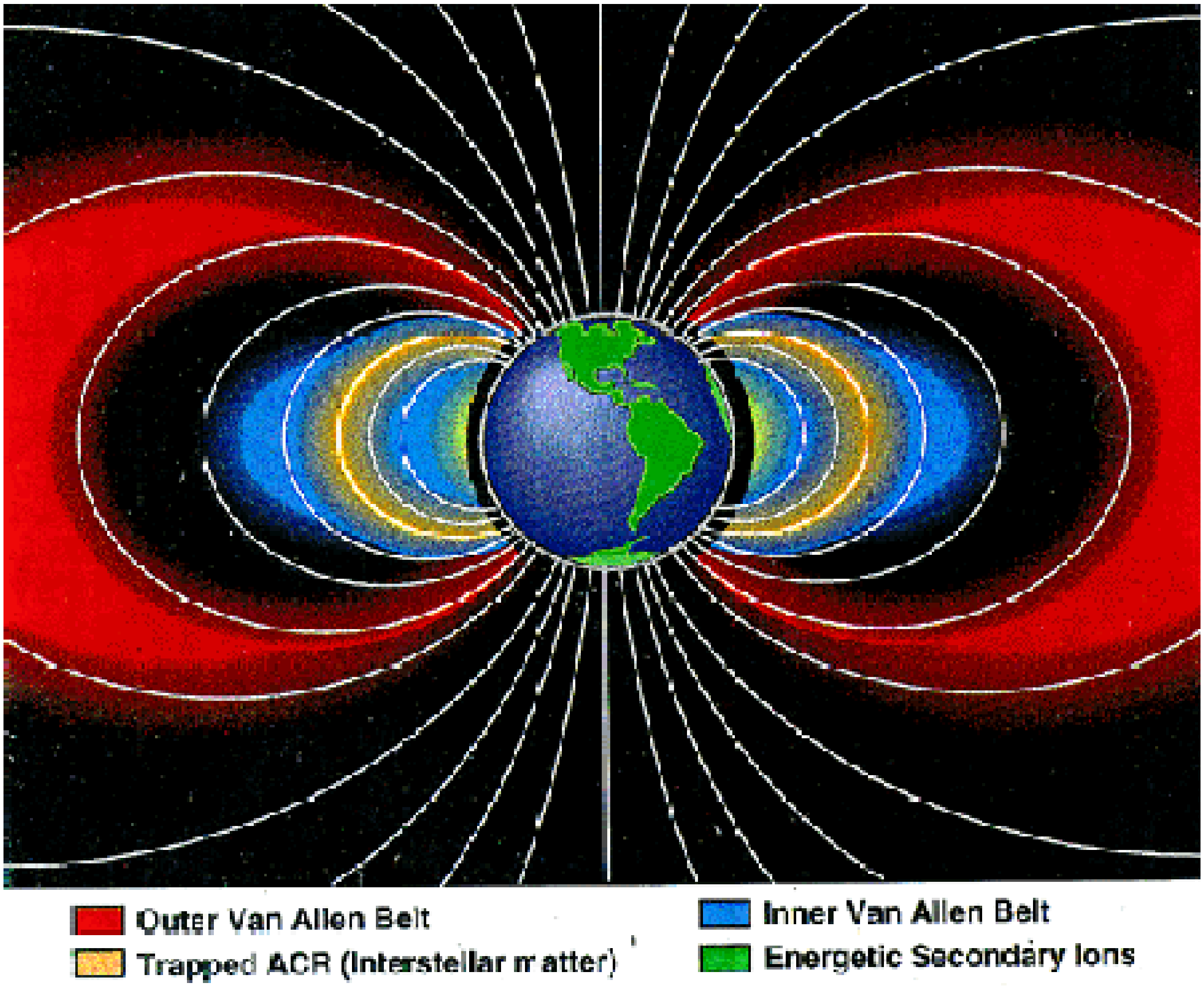

solar rotation
radial plasma
outflow
interplanetary
magnetic field
planetary
"obstacle"

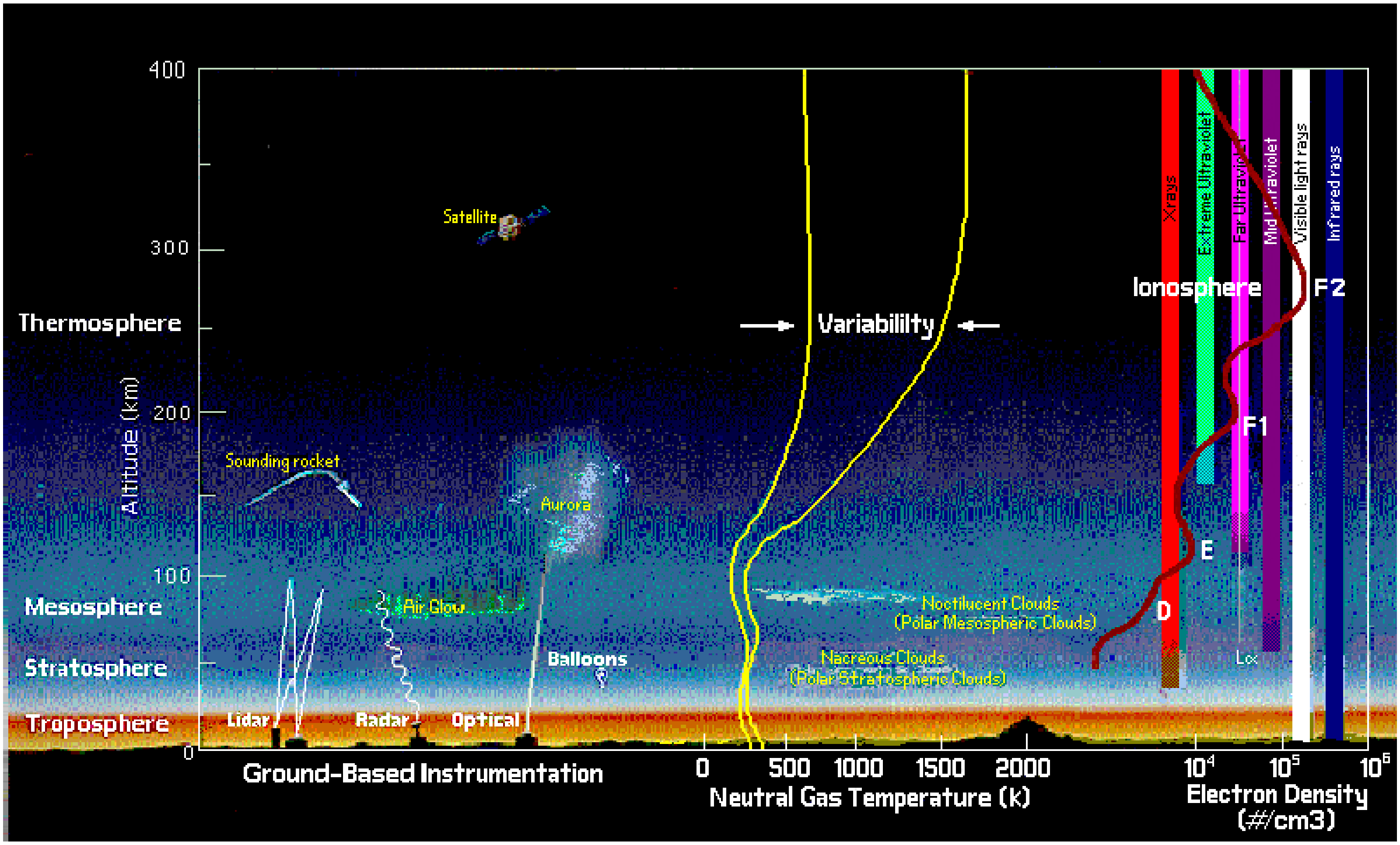


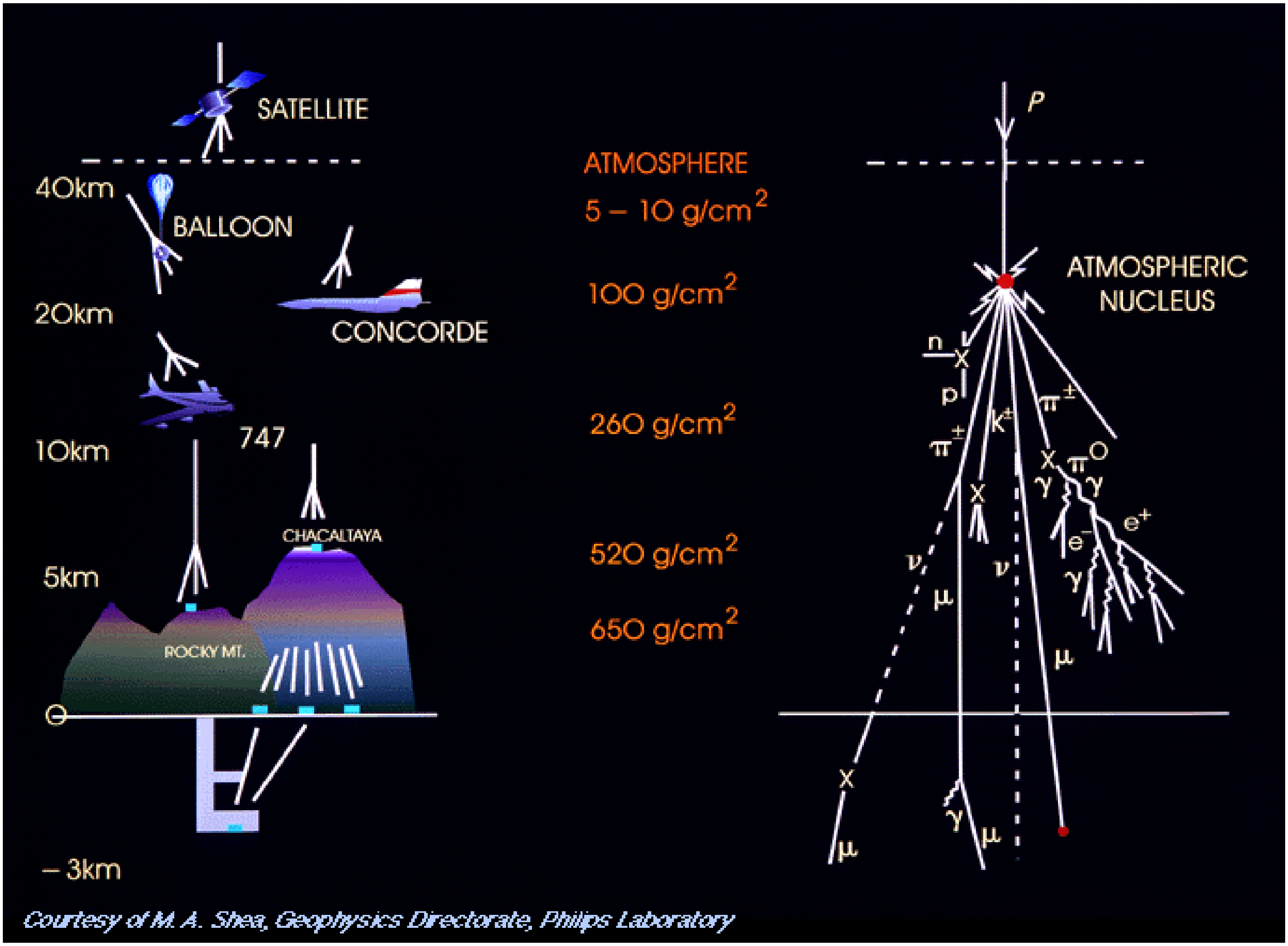


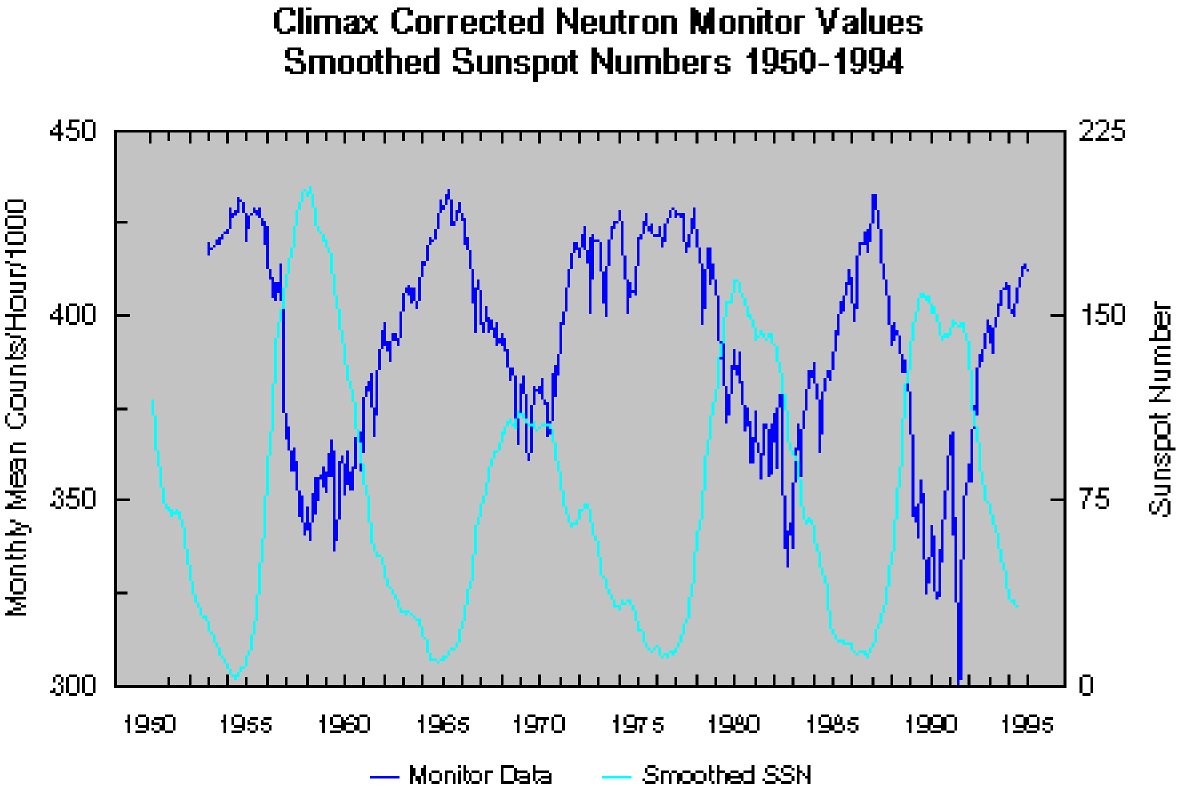

Solar wind
Interplanetary magnetic field
Cusp
Auroral zone
Ionosphere
Plasma sphere
Dayside magnetopause current
Magnetotail lobe
Central plasma sheet
Ring current
Field-aligned current
Convecting plasma
Magnetopause
Cross-tail current
Low-latitude boundary layer
Plasma sheet boundary layer current
Plasma mantle
Nightside magnetopause current

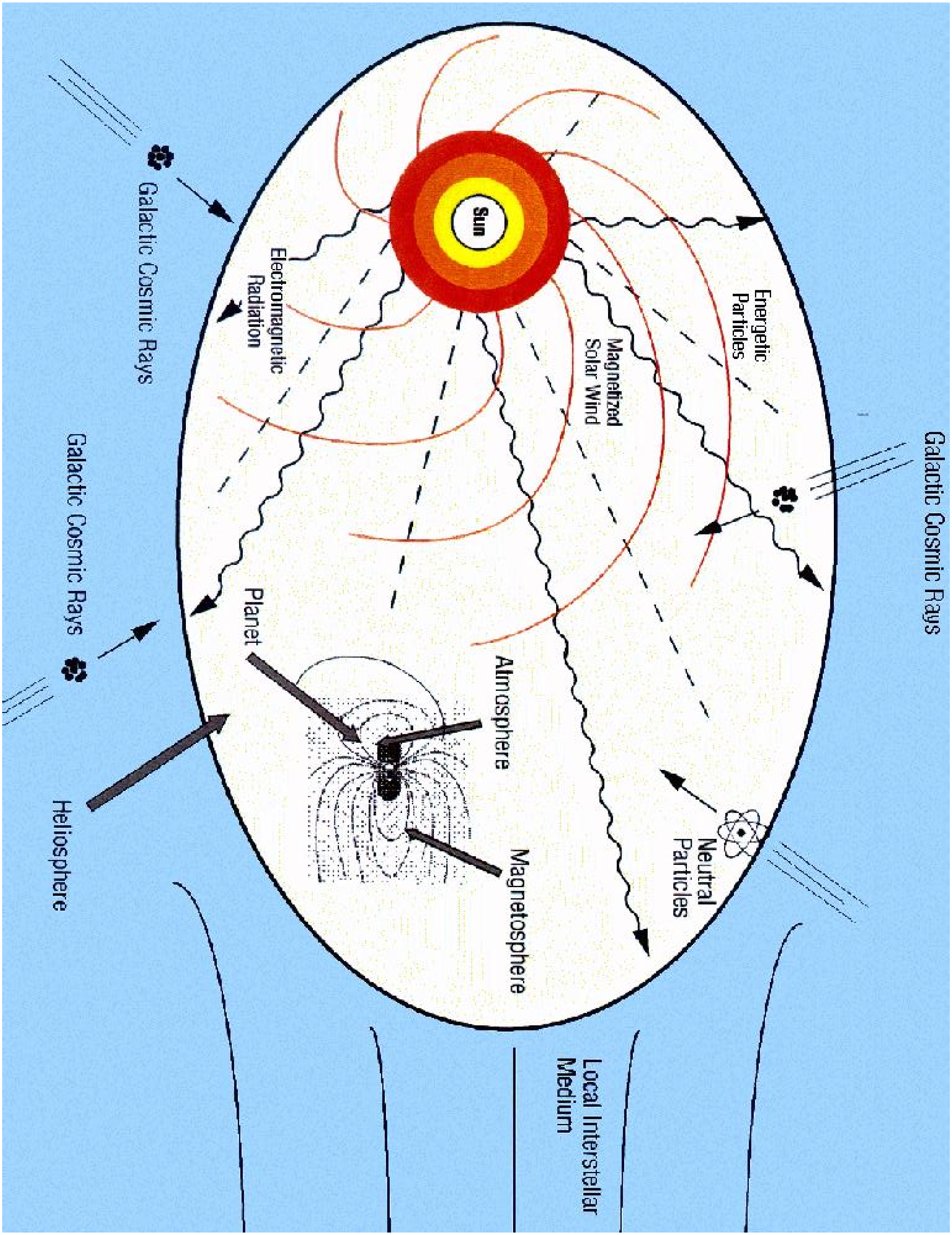

Solar
wind
N
1
2
3
4
5
6
5


Outer Van Allen Belt
Trapped ACR (Interstellar matter)
Inner Van Allen Belt
Energetic Secondary Ions


400
300
200
100
0
Altitude (km)
Thermosphere
Mesosphere
Stratosphere
Troposphere
Satellite
Sounding rocket
Aurora
Air Glow
Balloons
Lidar
Radar
Optical
Variabililty
Noctilucent Clouds
(Polar Mesospheric Clouds)
Nacreous Clouds
(Polar Stratospheric Clouds)
Xrays
Extreme Ultraviolet
Visible light rays
Infrared rays
Ionosphere
F2
F1
E
D
Lα
Ground-Based Instrumentation
0
500
1000
1500
2000
Neutral Gas Temperature (k)
10^4
10^5
10^6
Electron Density
(#/cm3)


SATELLITE
40km
BALLOON
20km
CONCORDE
10km
747
5km
CHACALTAYA
ROCKY MT.
– 3km
ATMOSPHERE
5 – 10 g/cm2
100 g/cm2
260 g/cm2
520 g/cm2
650 g/cm2
P
ATMOSPHERIC
NUCLEUS
n
p
π±
K±
π±
π0
γ
γ
e+
e−
γ
ν
ν
μ
μ
γ
μ
μ
Courtesy of M. A. Shea, Geophysics Directorate, Philips Laboratory


Climax Corrected Neutron Monitor Values
Smoothed Sunspot Numbers 1950-1994
Monthly Mean Counts/Hour/1000
450
400
350
300
Sunspot Number
225
150
75
0
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
Monitor Data
Smoothed SSN


Sun
Energetic Particles
Magnetized Solar Wind
Electromagnetic Radiation
Galactic Cosmic Rays
Galactic Cosmic Rays
Galactic Cosmic Rays
Planet
Atmosphere
Magnetosphere
Neutral Particles
Heliosphere
Local Interstellar Medium

Space Weather: A Research Perspective

Space Weather: A Research Perspective
Solar Origins of Space Weather

Solar Activity

Most of the effects we classify as space weather can ultimately be traced to changes occurring at the Sun. These include variations in both the solar electromagnetic radiation and the production of solar wind, plasma, and energetic particles. All of these are ultimately related to the evolution of the solar magnetic field. The figure below summarizes the different solar phenomena affecting our space weather, which are described here. Their relative importance in influencing space weather depends on where we are in the 11-year solar activity cycle.

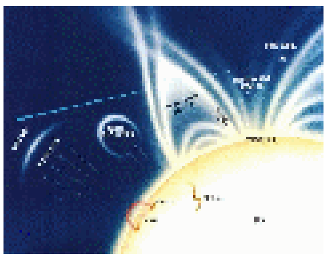
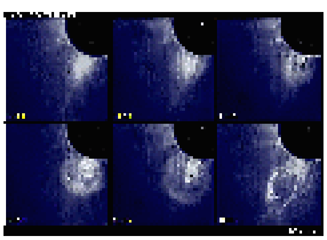


Illustration of the different solar and coronal structures that are the ultimate causes of space weather disturbances (courtesy of Solar-Terrestrial Environment Laboratory, Nagoya University).

Solar Wind Variability

Coronal Mass Ejections

Some of the most dramatic space weather effects occur in association with eruptions of material from the solar atmosphere into interplanetary space. These eruptions are known as coronal mass ejections, or CMEs. The sequence of coronal images below shows the release of a CME at the Sun.



Sequence of white light coronagraph images from the Solar Maximum Mission spacecraft showing the release of a coronal mass ejection, a huge bubble of coronal plasma and magnetic field, from the Sun (courtesy of High Altitude Observatory).

Near solar activity maximum, the sun produces about 3 CMEs every day, whereas near solar minimum it produces only about 1 CME every 5 days. The faster CMEs have outward speeds of up to 2000 kilometers per second, considerably greater than the normal solar wind speeds of about 400 kilometers per second. These produce large shock waves in the solar wind as they plow through it. Some of the solar wind ions are accelerated by the shock, which then becomes a source of intense and long-lasting energetic particle enhancements in interplanetary space.

Illustration of a coronal mass ejection plowing through the solar wind at high enough relative speed to produce a leading shock wave. The shock wave accelerates some of the underlying solar wind particles to cosmic-ray energies (adapted from Hundhausen, p. 395 in Solar Wind, eds. C.P. Sonett, P.J. Coleman Jr., and J.M. Wilcox, NASA SP-308, Washington D.C.).

Solar Wind Stream Structure

The nonuniform source of the solar wind is responsible for other interplanetary disturbances. Solar rotation causes the high-speed flows from the coronal hole regions to run into the slower flows as they propagate out from the Sun, producing compressive interaction regions. Because the solar source regions for the flows are relatively long lived, these stream interaction regions appear to rotate with the Sun in spiral configurations like that illustrated below. Enhanced interplanetary magnetic field strengths and solar wind densities are associated with these regions. These structures are most pronounced on the approach to, and during the minimum of, the 11-year solar activity cycle when the coronal holes are largest. At these times, 27-day patterns are clearly evident in the solar wind properties near Earth.

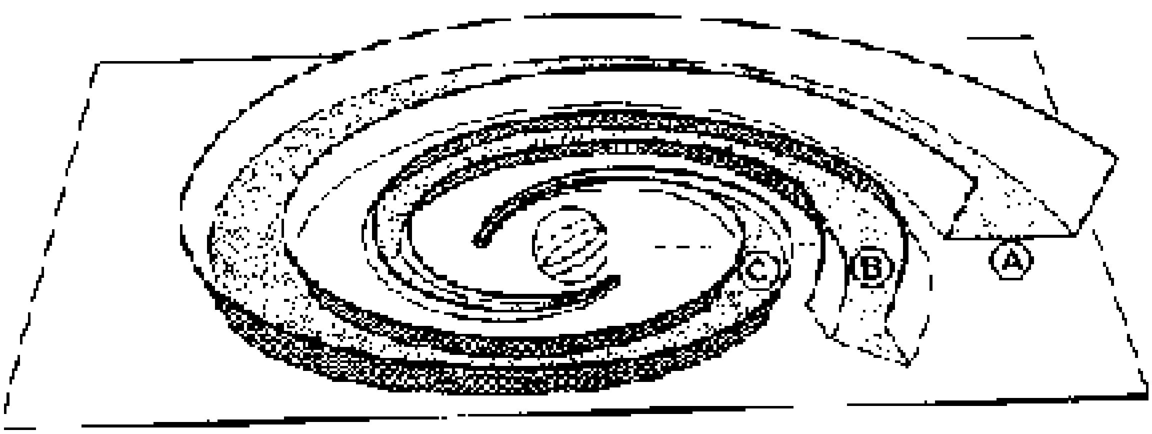
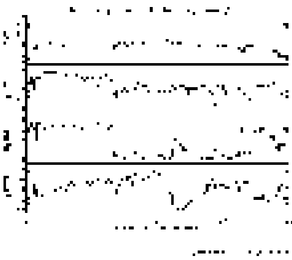


Illustration of the shapes of the compressive structures in the solar wind produced by interaction of the fast streams from the polar regions with slow solar wind from low latitudes. In this case the interactions occur because the magnetic dipole axis defining the coronal hole region is tilted with respect to the solar rotation axis (from V.J. Pizzo, 1994, J Geophys Res 99:4175).

Magnetic Field Variations

In addition to the striking solar-cycle-dependent changes, less dramatic variations in the solar wind are constantly occurring as processes in both the corona and interplanetary space produce waves and turbulence. To a large extent, it is these variations, superimposed on the underlying average conditions, that determine our typical space weather. The direction of the interplanetary magnetic field is particularly important in this respect since any southward inclination enables more efficient transfer of energy from the solar wind into the magnetosphere than a northward inclination. Because of this effect, even the orientation of Earth's magnetic axis relative to the solar direction, which changes throughout the year, modifies the magnetophere's response to a particular solar wind state.



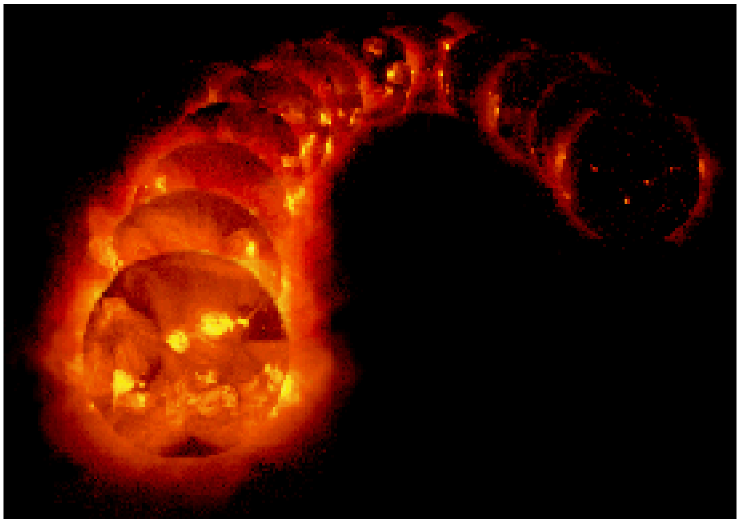
Sample of interplanetary magnetic field measurements from the WIND spacecraft when it was located more than 200 Earth radii upstream of Earth. The north-south magnetic field component is called "Bz." ("Bx" points toward the Sun and "By" lies roughly parallel to the equatorial plane, while "B total" is the field strength including all of these contributions.) Times of negative (southward) Bz are times of increased interconnection between the interplanetary and geomagnetic fields (courtesy of the WIND magnetometer team).

Solar Electromagnetic Variability

The Sun is not only the source of light and heat, it is also a powerful and highly variable source of radio waves, ultraviolet rays, and x-rays. The latter emissions are the primary reason for the existence of our ionosphere. Almost all of the variability of the Sun at these wavelengths is connected with solar activity.

Active Regions

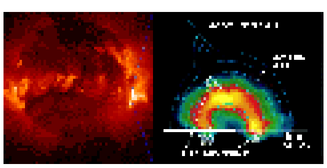
For well over a century, dark concentrations of intense magnetic fields called sunspots have been observed emerging from below the Sun's surface in an 11-year cycle. Recent space observations have revealed that the complexes of sunspots called active regions are the main source of long-lived solar ultraviolet and x-ray emissions. Solar gas, confined by the strong active-region magnetic fields into loop-like structures, is heated to temperatures of millions of degrees. During times of maximum solar activity, the average level of solar ultraviolet emission can increase to several times the quiet Sun level, while the x-ray intensity shows even greater enhancements. Since active regions usually last longer than the 27-day solar rotation period, the radiations they emit also vary periodically on this time scale. The changing appearance of the sun in low-energy x-rays from times of high to low solar activity is evident in the sequence of images below.



Collage of x-ray images of the Sun obtained on the Yohkoh satellite between 1991 and 1995 at 120-day intervals, showing the evolution in the appearance of the Sun in these emissions from active to quiet times. The dark regions are locations of low coronal density, which are the sources of the faster solar wind streams. The brightest regions are coronal loops heated above active regions (courtesy of Lockheed-Martin Solar and Astrophysics Laboratory).

Flares

Short periods of explosive energy release, known as solar flares, frequently occur in active regions during the period around solar maximum. An example of a flare observed on the limb of the sun is shown below. Flares have lifetimes ranging from hours for large gradual events down to tens of seconds for the most impulsive events. During a very strong flare, the solar ultraviolet and x-ray emissions can increase by as much as 100 times above even active-region levels. During solar maximum, approximately one such flare is observed every week. Flares heat the solar gas to tens of millions of degrees. The heated gas then radiates strongly across the whole electromagnetic spectrum from radio to gamma rays. The largest of these explosions are so bright that they can even be seen from Earth in visible light.



The Sun as seen in x-rays (left panel). The upper atmosphere or corona of the Sun emits x-rays because it is very hot, with temperatures of a few million degrees. The Sun's magnetic field traps the ionized gas (plasma) in loops. On the right limb of the Sun is a loop that has been illuminated by the extraordinary heating associated with a solar flare (enlargement in right panel). Flares are powerful explosions, lasting minutes to hours, that produce strong heating and acceleration of particles (courtesy of Solar Data Analysis Center, Goddard Space Flight Center).

Flares can accelerate protons and electrons that travel to Earth directly from the Sun along the interplanetary magnetic field (which "channels" the charged particles). These contribute to the high-energy particle environment in the vicinity of the magnetosphere if Earth's location is magnetically connected to the flaring region by the interplanetary magnetic field.

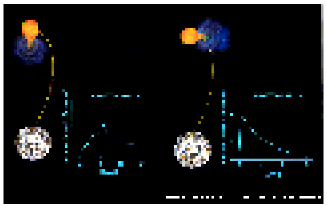
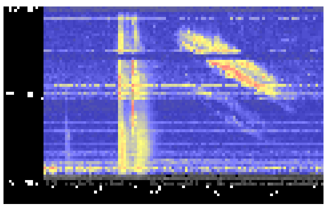


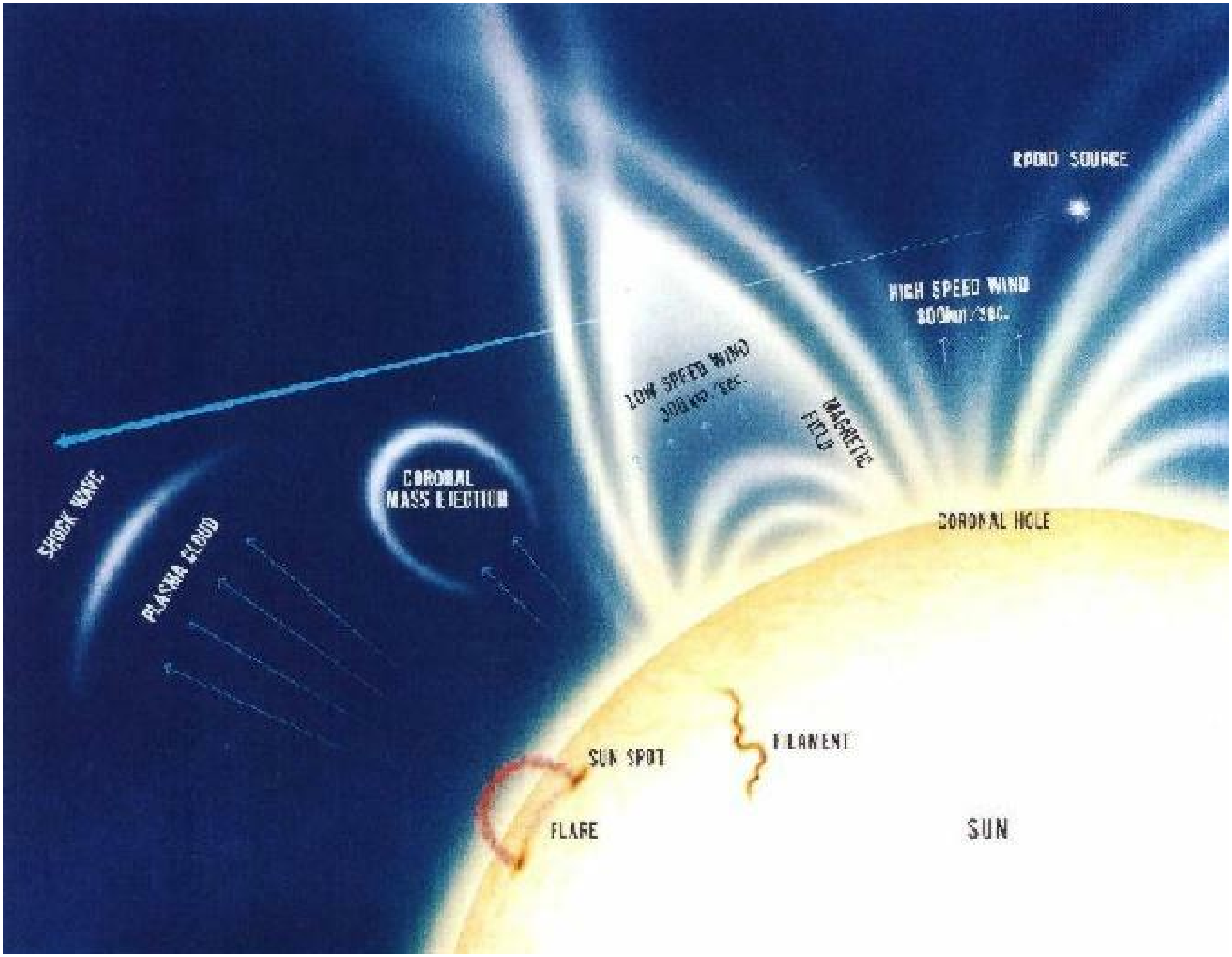
Illustration of the importance of magnetic connection to a flare site for determining the intensity of flare-accelerated energetic particle radiation at the Earth. Note that because of the spiral configuration of the interplanetary magnetic field, the best connections occur for flares on the right side of the Sun as viewed from Earth (courtesy of M.A. Shea, Phillips Laboratory).

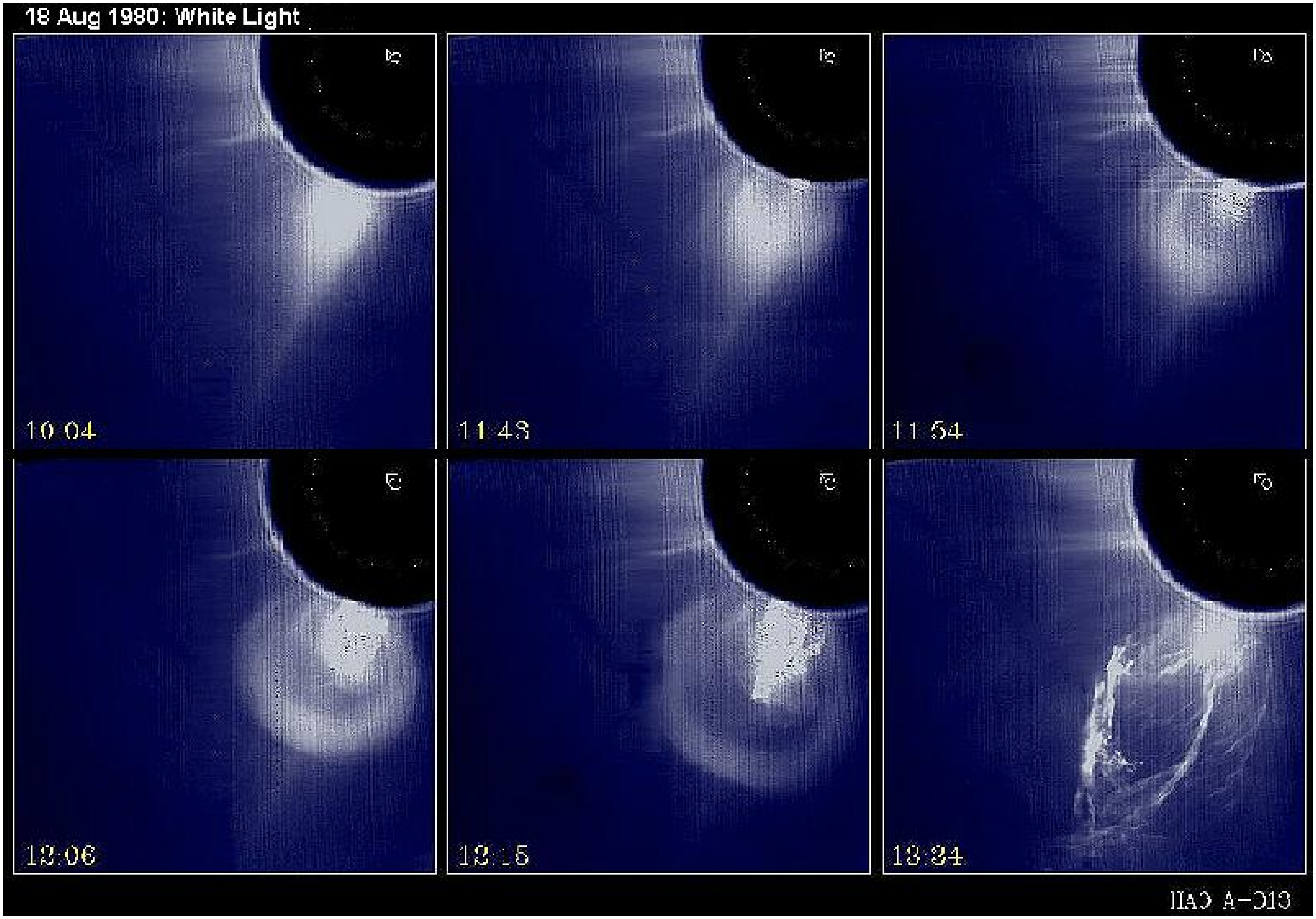
Radio Bursts

Unlike the case of solar ultraviolet and x-ray radiation for which we know the basic emission processes, the sources of solar radio bursts are poorly understood. Almost all manifestations of solar activity have some signature in radio waves, and the radio bursts themselves appear in many forms. The most notable radio emissions are intense bursts associated with flares or CMEs and long-lived noise storms associated with active regions. During such storms the emissions are strong for several days. The figure below shows an example of a strong radio burst detected over a range of frequencies.



Time history of the intensity of solar radio waves at various frequencies during a radio burst occurring in June 1992. The color reflects the intensity of the emissions (from: Culgoora Radio Observatory, Narrabri, New South Wales, Australia).


RADIO SOURCE
HIGH SPEED WIND
800km/sec.
LOW SPEED WIND
300km/sec.
MAGNETIC FIELD
CORONAL MASS EJECTION
SHOCK WAVE
PLASMA CLOUD
CORONAL HOLE
SUN SPOT
FILAMENT
FLARE
SUN


18 Aug 1980: White Light
10:04
11:48
11:54
12:06
12:15
12:34
HAO A-013

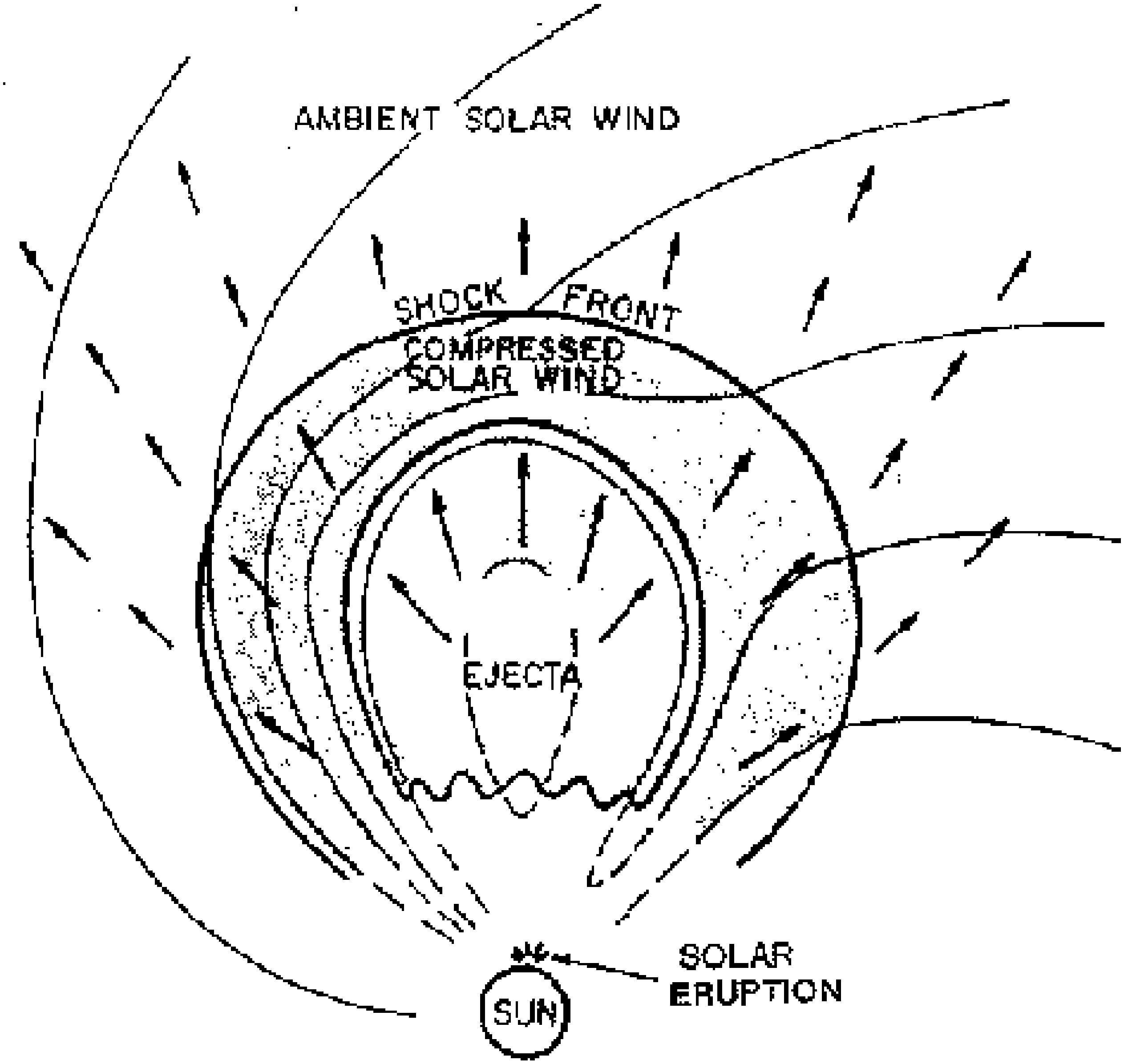


Figure adapted from Hundhausen, p. 395, in SOLAR WIND, eds. C.P. Sonett, P.J. Coleman Jr., and J.M. Wilcox, NASA SP-308, Washington DC

file:///S|/SSB/windimf.gif

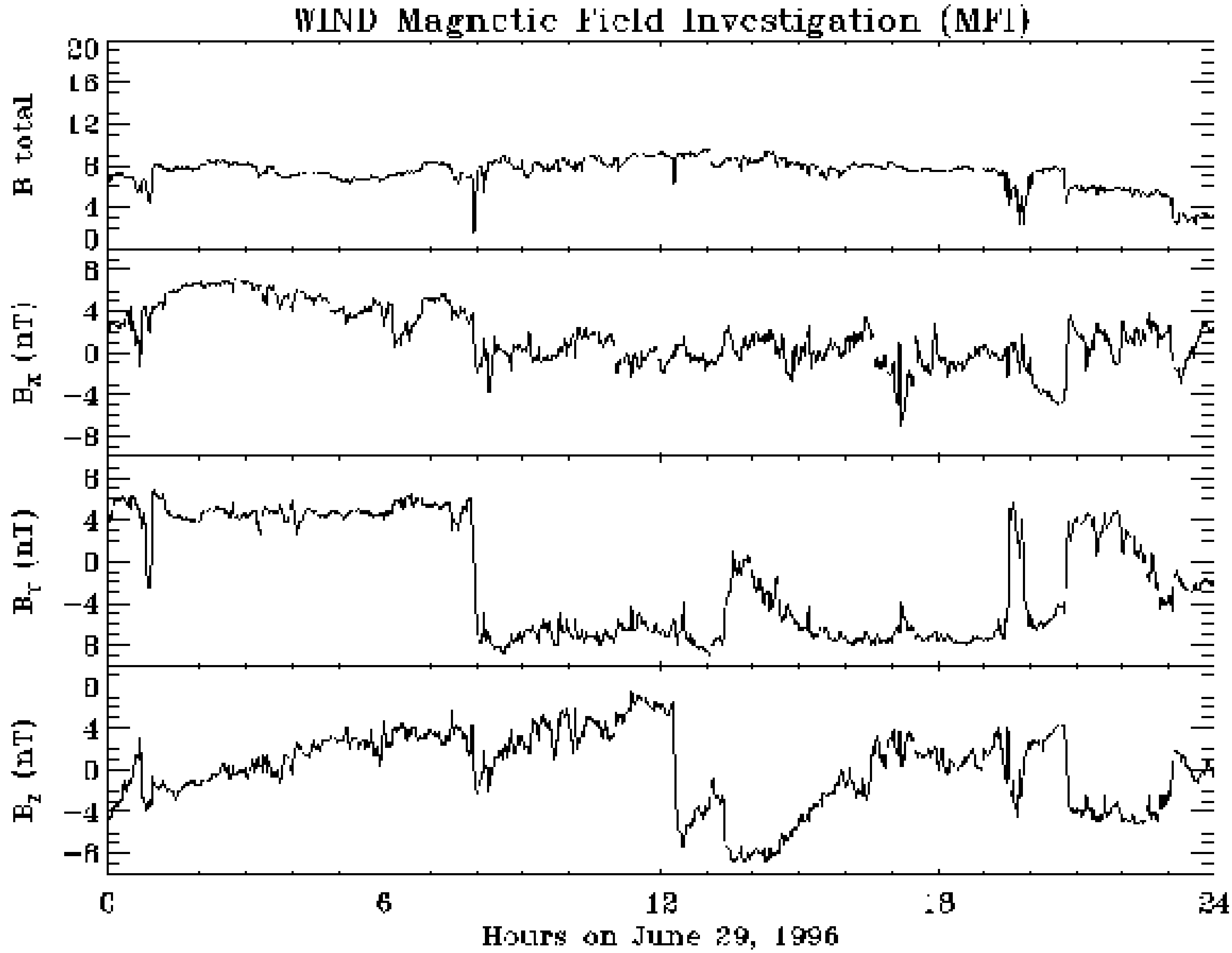
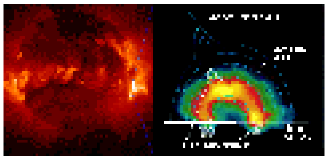
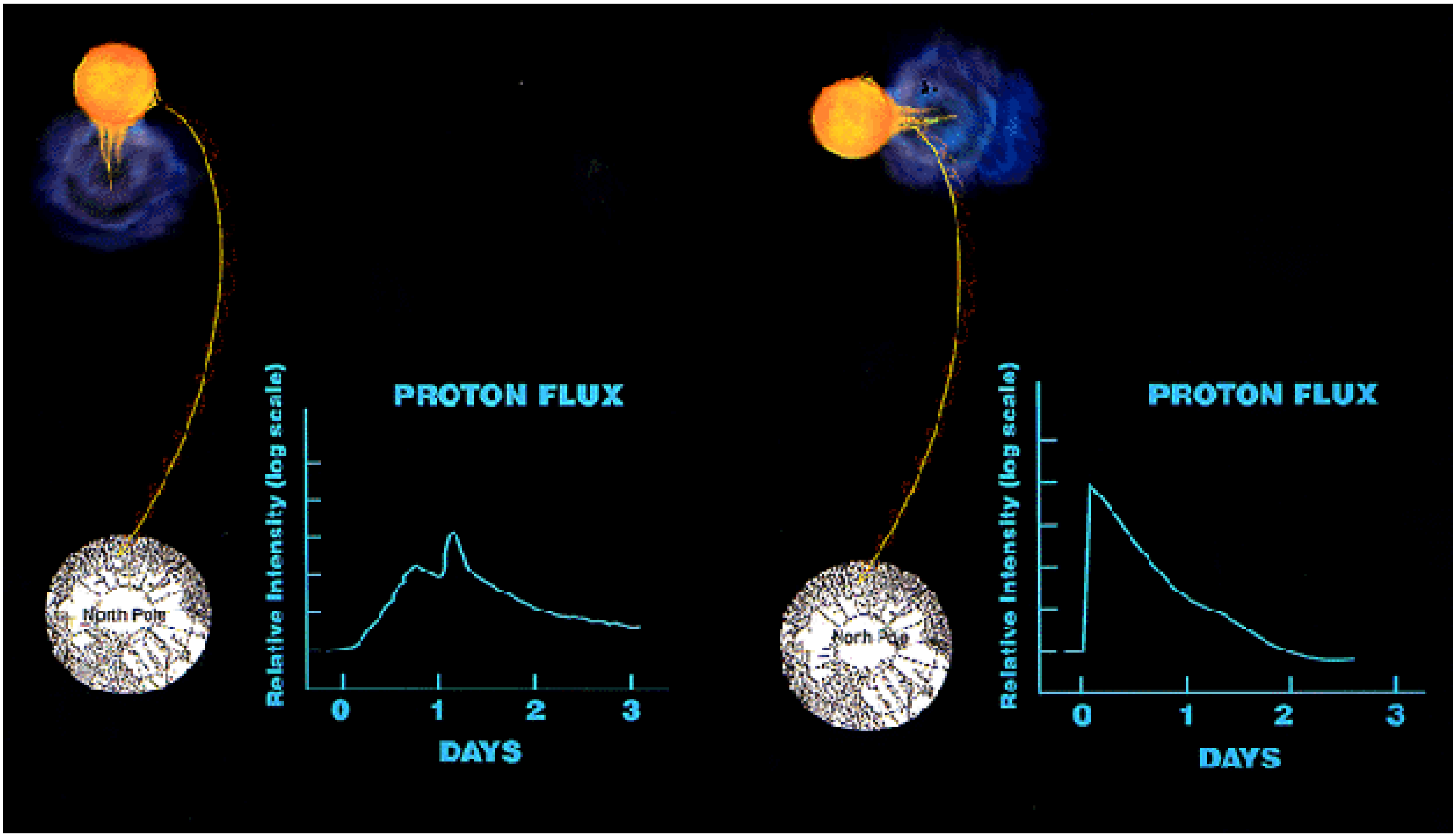
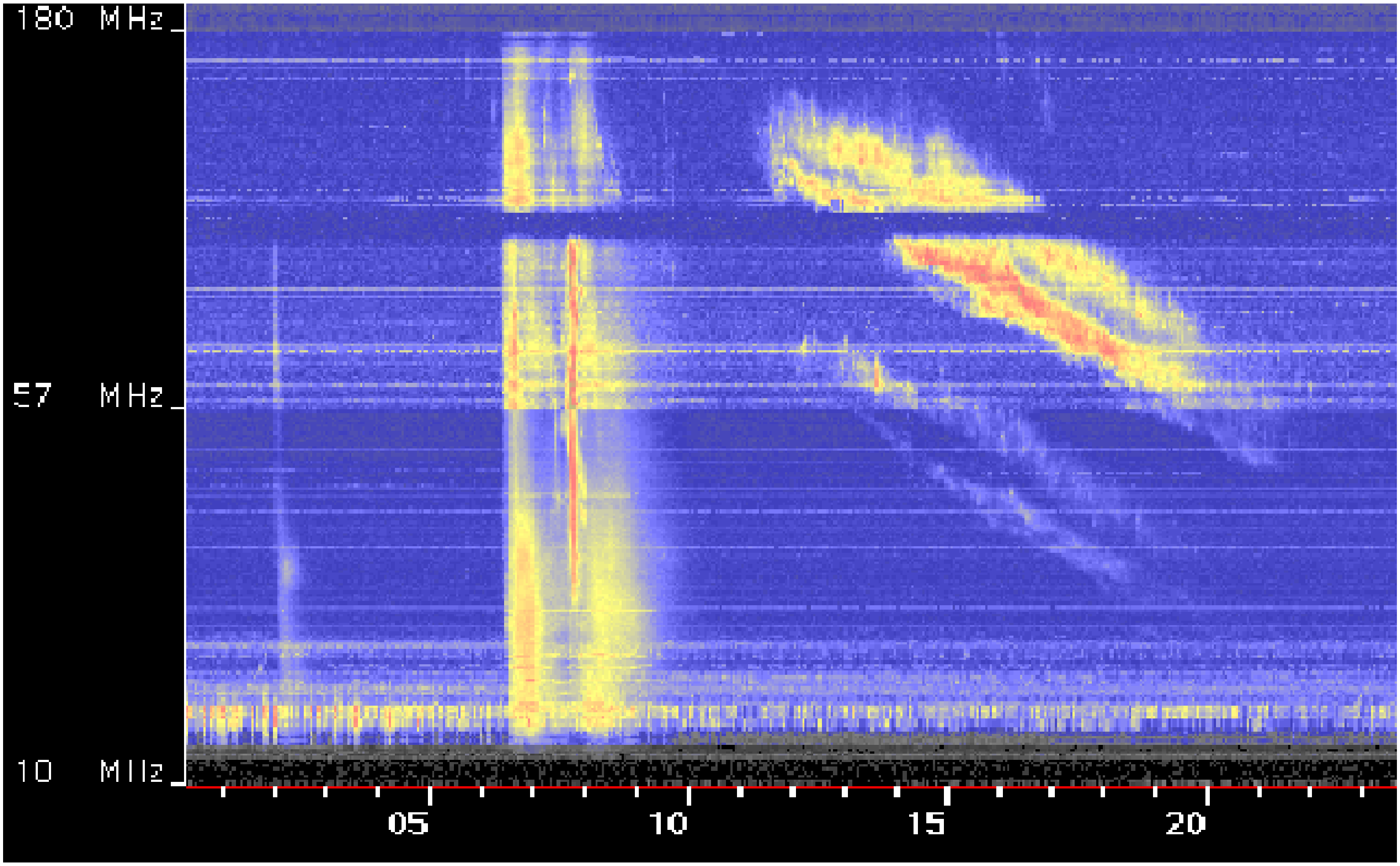


Figure courtesy of WIND Magnetometer team



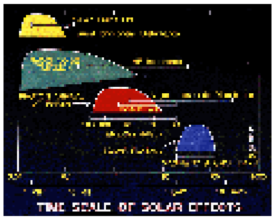

North Pole
Relative Intensity (log scale)
PROTON FLUX
0
1
2
3
DAYS
North Pole
Relative Intensity (log scale)
PROTON FLUX
0
1
2
3
DAYS


180 MHz
57 MHz
10 MHz
05
10
15
20

Space Weather: A Research Perspective
Earth-Space "Meteorology"

Disturbed Space Weather Conditions

The space surrounding Earth is a highly dynamic environment that responds sensitively to changes in the electromagnetic radiation, particles, and magnetic fields arriving from the Sun. Depending on the type of change, the near-Earth space environment responds with time delays of minutes to days. The sequence and approximate durations of various solar activity effects are illustrated below.



Time sequence of space weather events following a major solar disturbance. Not all elements of this sequence are detected every time (courtesy of M.A. Shea, Phillips Laboratory).

Sudden Ionospheric Disturbances

The energetic electromagnetic radiation bursts (ultraviolet and x-rays) accompanying flares on the Sun travel at the speed of light, and so arrive at Earth just eight minutes after leaving the flare site, well ahead of any particles or coronal material associated with the flare. Moreover, unlike the electrons and ions of the solar wind plasma and the solar energetic particle populations, the passage of electromagnetic waves is not affected by the presence of Earth's magnetic field. The direct response of the upper atmosphere to a burst of solar flare ultraviolet and x-ray emissions is a temporary increase in ionization in the sunlit hemisphere of minutes to hours duration called a "sudden ionospheric disturbance." The ionization increase below 100-km altitudes is especially significant on these occasions.

Solar Energetic Particle Events

Particles are accelerated to "cosmic-ray-like" energies by the interplanetary shocks preceding fast coronal mass ejections and in the vicinity of solar flare sites. The large extent of the shocks compared to the flares makes them a more common source of solar energetic particles near Earth. The most energetic particles arrive at Earth within tens of minutes of the event on the Sun, while the lower-energy population arrives over the course of a day. These particles temporarily enhance the radiation in interplanetary space around the magnetosphere. In the polar regions they then penetrate to low altitudes along the magnetic fields that map into the auroral oval. Sometimes they also find their way into the deeper magnetosphere by means of other transport processes. As shown by the figure below, although solar energetic protons are encountered most frequently around solar maximum, they can occur at any time in the solar cycle.

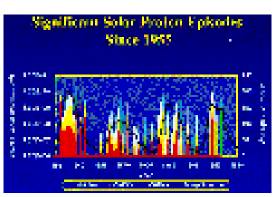
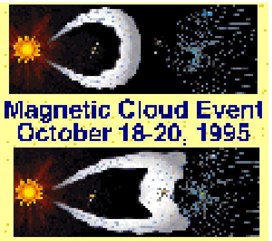


Diagram showing when major solar proton events occur during the solar cycle (courtesy of Ron Turner, ANSER home page).

Like the energetic solar electromagnetic emissions in the ultraviolet and x-ray wavelengths, the energetic solar particles enhance the ionospheric density below 100-km altitudes. In this case, however, the effect is limited to the polar regions where the particles can travel directly to the atmosphere. These deeply ionizing events can alter the local atmospheric chemistry in ways that affect the ozone concentrations in the upper levels of the ozone layer.

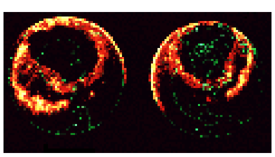
Space Weather Storms

In general, disturbances in the solar wind arrive at Earth 1-2 days after leaving the Sun. These disturbances, especially those caused by coronal mass ejections, trigger global changes in Earth's magnetic field and particle populations and are called magnetic storms. The fastest coronal mass ejections or CMEs, traveling at up to 2000 kilometers per second (compared to normal solar wind speeds of 400 to 800 kilometers per second) cause the most severe magnetic storms.

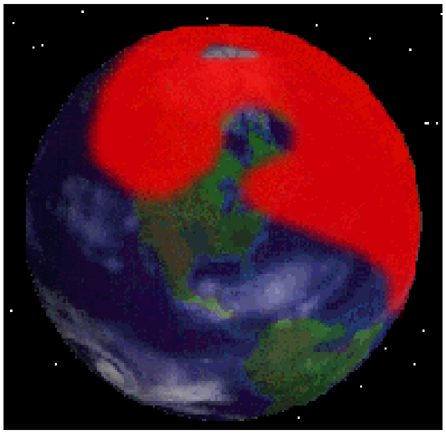


An artist's conception of the interaction of a coronal mass ejection with Earth's magnetosphere (courtesy of NASA).

The details of the Earth-space response are quite complex, and our understanding of it only partially complete. When a fast CME passes, its leading shock causes the sudden onset of a variety of magnetospheric activity. A large disturbance of the geomagnetic field reaching to latitudes near the equator signals the injection of a newly energized charged-particle population into the magnetosphere (forming what is called a "ring current"). New, temporary "radiation belts" may also appear. Intensifications of auroral light are caused by increases in the numbers of electrons and ions raining or "precipitating" from the magnetosphere into the upper atmosphere in the auroral oval. The magnetosphere as a whole is energized by a much stronger interaction than usual with the solar wind, resulting in enhanced ionospheric electric currents and an associated stronger coupling between the magnetosphere and ionosphere. The latter is particularly true if the disturbed magnetic field in the ejected coronal material or the piled-up interplanetary field preceding it has a long period (hours to days) of southward-directed magnetic field. Signs of this closer coupling include a substantial increase in the numbers of ionospheric ions appearing in the magnetosphere, as well as a greatly disturbed high-latitude ionosphere. Ionospheric currents, embedded in the region of intense auroral particle precipitation, intensify and spread equatorward with the expanding oval, an example of which is pictured in the image below.

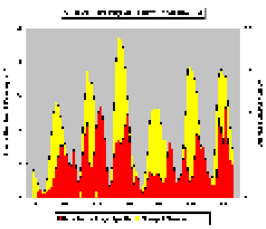

Ultraviolet images from the Dynamics Explorer satellite showing the expansion of the auroral oval during a magnetic storm (courtesy of Dynamics Explorer University of Iowa Imaging Experiment, L.A. Frank, principal investigator).

The upper atmosphere heats and then expands in response to the storm-generated increases in auroral currents and particle precipitation, which both deposit energy. During a large magnetic storm, the density of the upper atmosphere at satellite altitudes may reach 100 times its quiet time value. These episodic increases in the atmospheric density are superimposed upon longer-term trends in the overall heating and expansion of the atmosphere in response to the 11-year solar activity cycle.



The red areas in this image represent regions with 20% or more increases in the atmospheric density at the altitude of the space shuttle orbit (about 300 km) during a moderate magnetic storm period (courtesy of A. Burns, University of Michigan Space Physics Research Laboratory).

The occurrence rates of magnetic storms and all of their effects follow the frequency of CMEs and are highest during solar maximum periods (see below).



The annual number of geomagnetically disturbed days compared to the sunspot number. The solar activity cycle clearly controls the occurrence of disturbed space weather (courtesy of the NOAA National Geophysical Data Center, Boulder, CO).

Major space weather storms could in principle be predicted from observations of fast coronal mass ejections coming toward Earth. At the speeds of fast CMEs, this would allow about 1-2 days warning if the initiation was seen at the Sun. About 1 hour's warning is possible if the interplanetary disturbance is detected upstream of Earth at the location of most solar wind-monitoring spacecraft.

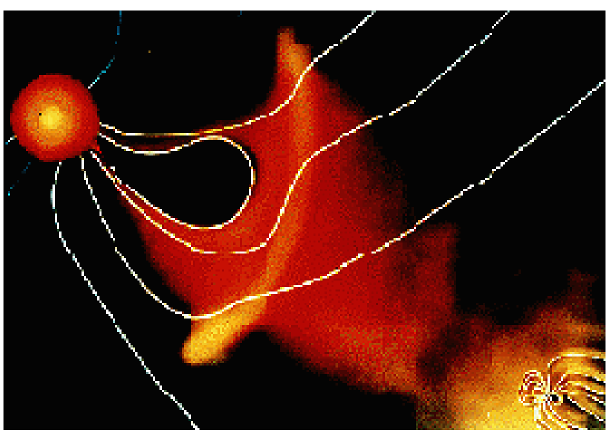


Illustration of the situation preceding (by the order of a day) a major magnetic storm (courtesy of the Space Physics and Aeronomy Section slide set, American Geophysical Union, Washington, D.C.).

Space Weather "Substorms"

"Substorms" are in some ways like small versions of the storms described above. However, substorms can occur without the passage of a major interplanetary disturbance. They are thought to build up during periods when the undisturbed interplanetary magnetic field has a southward component. Researchers believe there is a gradual transfer of solar wind energy into the magnetosphere under these circumstances because of the greater amount of interconnection between the interplanetary and Earth magnetic fields in the polar regions. Any small perturbation, like a solar wind pressure increase, or a change in the interplanetary field orientation, can release that stored energy in storm-like ways. The substorm may also occur spontaneously if the magnetosphere's ability to store the transferred energy reaches its limit. Substorms sometimes occur

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during the course of the major storms, modulating the longer term and more intense activity associated with them. The reconfiguration of magnetotail fields thought to accompany a substorm is shown below. This reconfiguration causes the dumping of some of the magnetosphere's particles into the auroral zone as the magnetosphere readjusts, producing auroras and ionospheric disturbances as do small magnetic storms.

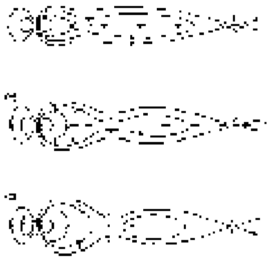
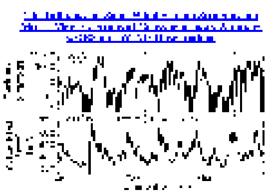


Illustration of the behavior of the stretched geomagnetic tail field during a substorm, as inferred from spacecraft measurements. In a sense the magnetotail is "shedding" some of the magnetic field that accumulates when a prevailing southward interplanetary field continues to interconnect with Earth's field (from: S.W.H. Cowley, December 19, 1995, EOS, v. 76).

Energetic Electron Increases

Earth's radiation belts are observed to undergo significant quiet time changes even in the absence of storms and substorms. In particular, it has been found that the population of relativistic electrons trapped in the magnetosphere increases and decreases with the prevailing solar wind velocity. The stream structure of the solar wind and solar rotation produce the 27-day modulation shown below in both solar wind speed measured on the WIND spacecraft upstream of Earth and energetic electrons measured by the GOES-8 spacecraft in the radiation belts. The reasons for the relationship between the solar wind speed and electron population are currently unresolved.



Comparison of solar wind speed measured on the WIND spacecraft upstream of Earth and the energetic electron flux in the radiation belts measured on GOES-8. The 27-day solar rotation influence is clearly seen here (courtesy of H. Singer and T. Onsager, NOAA Space Environment Center).

Ionospheric Irregularities

The ionosphere exhibits regular daily and seasonal variations, as well as disturbances directly caused by flares and by the auroral particles and currents during magnetic storms and substorms. In addition, the ionosphere exhibits irregular variations related to the dynamics of the underlying atmosphere. These depend upon the combination of traditional "weather" near the ground, which produces waves in the atmosphere like the waves in the deep ocean, and the winds between the ground and the upper-atmosphere levels that act like a filter to the passage of those waves. While this aspect of space weather may appear to have a non-solar origin, its effects are most pronounced when the upper-atmosphere winds or lower-ionosphere electron density is enhanced by the energy inputs from the active Sun or magnetosphere.

One striking example is equatorial "spread F," a disturbance of the nighttime low-latitude ionosphere. Spread F can be thought of as a huge convective storm in the ionosphere, thousands of kilometers across, as much as 1000 kilometers high, and dwarfing even the largest hurricanes. It derives its name from the effect of the associated ionospheric density irregularities on over-the-horizon radar and satellite-to-ground radio communications. The figure below shows regions in the ionosphere where 3 meter wavelength radar signals reflected from a spread F layer during a disturbance over Peru. Neither the origins nor solar controls of spread F conditions are well understood, although the interaction of the ionized and neutral gases in the affected layer seems to play an important role. As developing countries near the equator become more dependent on advanced systems for

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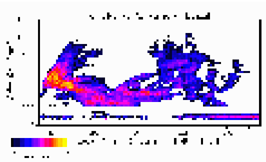
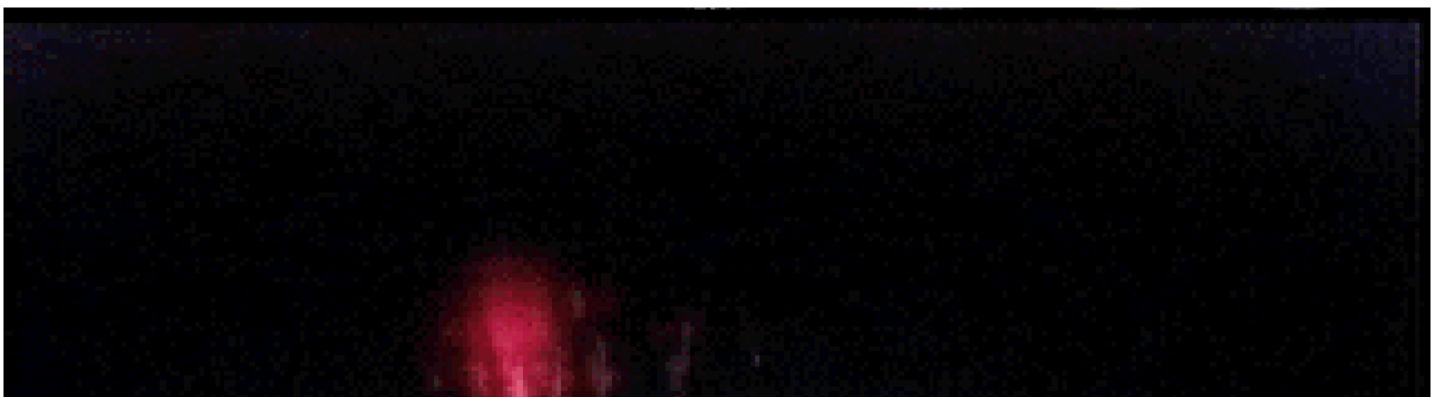
communication with the rest of the world, a better understanding of equatorial spread F will become essential.



A record showing where 3-meter wavelength radar signals reflected from the ionosphere over a site in Jicamarca, Peru, during an episode of "spread F" (courtesy of W. Swartz, Cornell University).

High-Altitude "Sprites" and "Jets"

Optical phenomena called red sprites and blue jets are observable by sensitive cameras at altitudes extending from the tops of strong thunderstorms (at around 15-kilometers altitude) to the lower ionosphere (about 95-km altitude). Possibly related to these optical signatures, short-duration gamma-ray bursts have been detected over thunderstorm regions on the Compton Gamma Ray Observatory, as were intense electromagnetic pulses (10,000 times stronger than lightning-related pulses) on the ALEXIS satellite. This collection of observations suggests that there may be a stronger connection between global thunderstorm activity and the ionosphere and upper atmosphere than previously suspected. In particular, they may signify the presence of powerful large-scale discharges in Earth's "global electrical circuit."



Picture of a red sprite and blue jet over a thunderstorm (courtesy of D. Sentman, Geophysical Institute, University of Alaska at Fairbanks).

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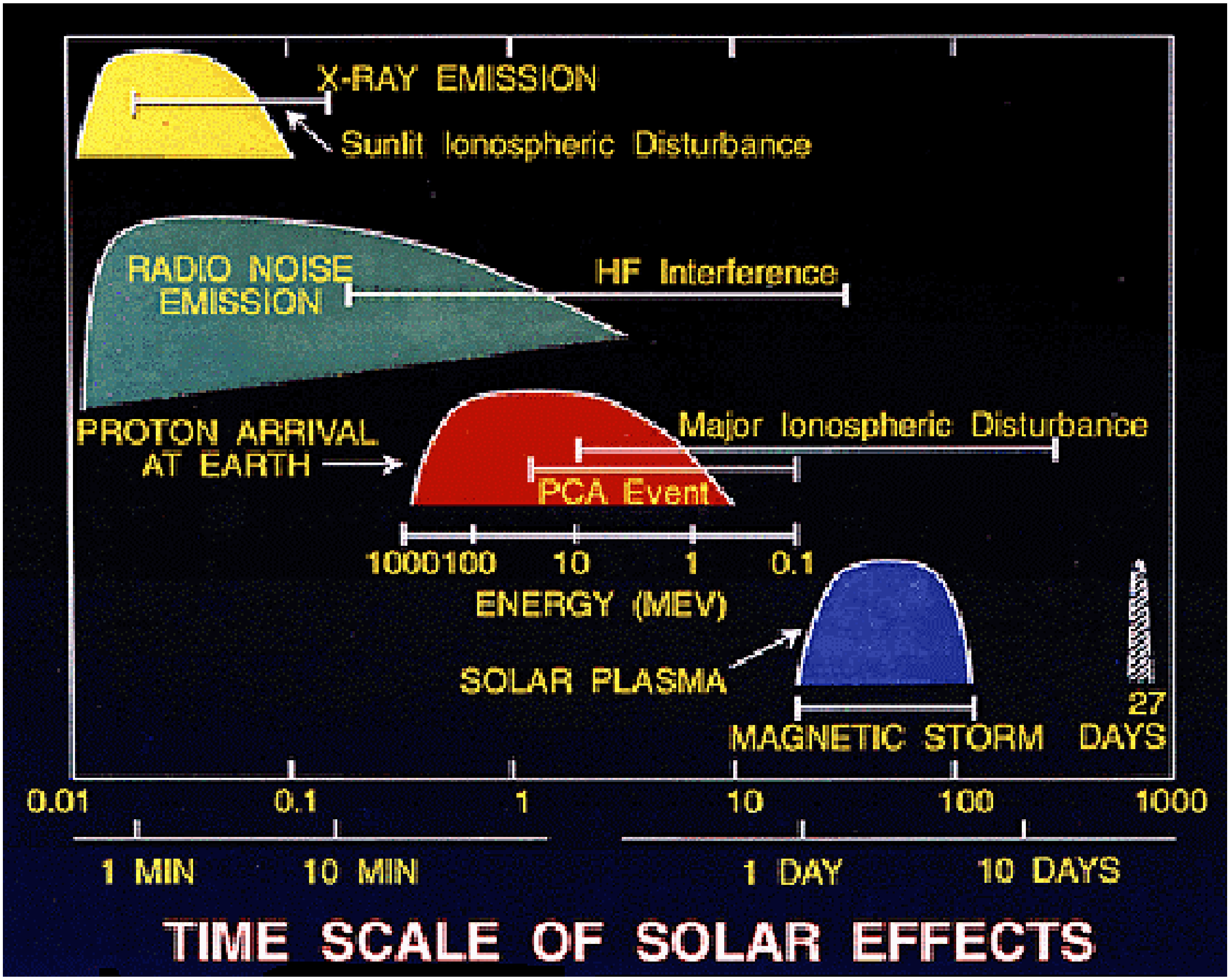
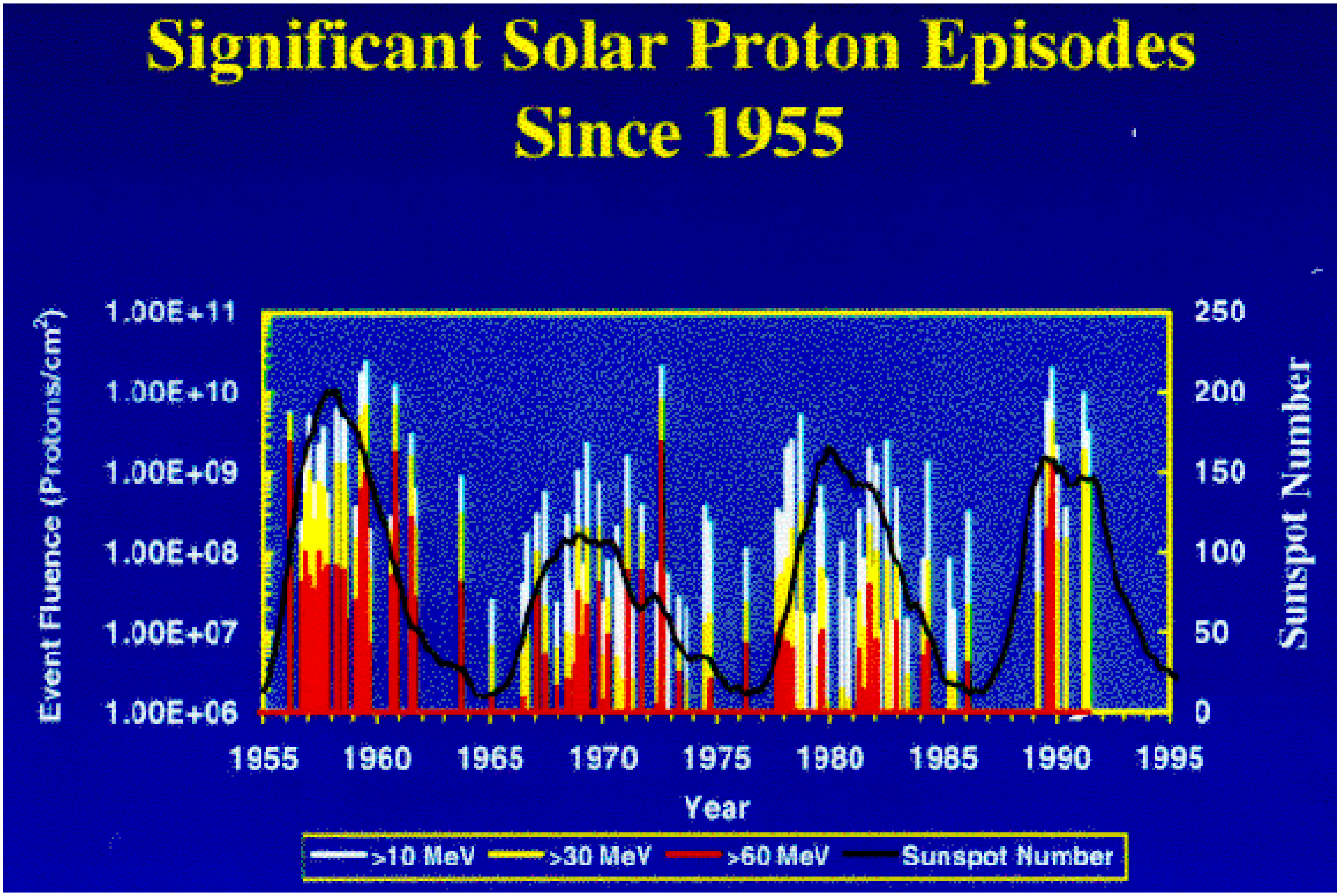
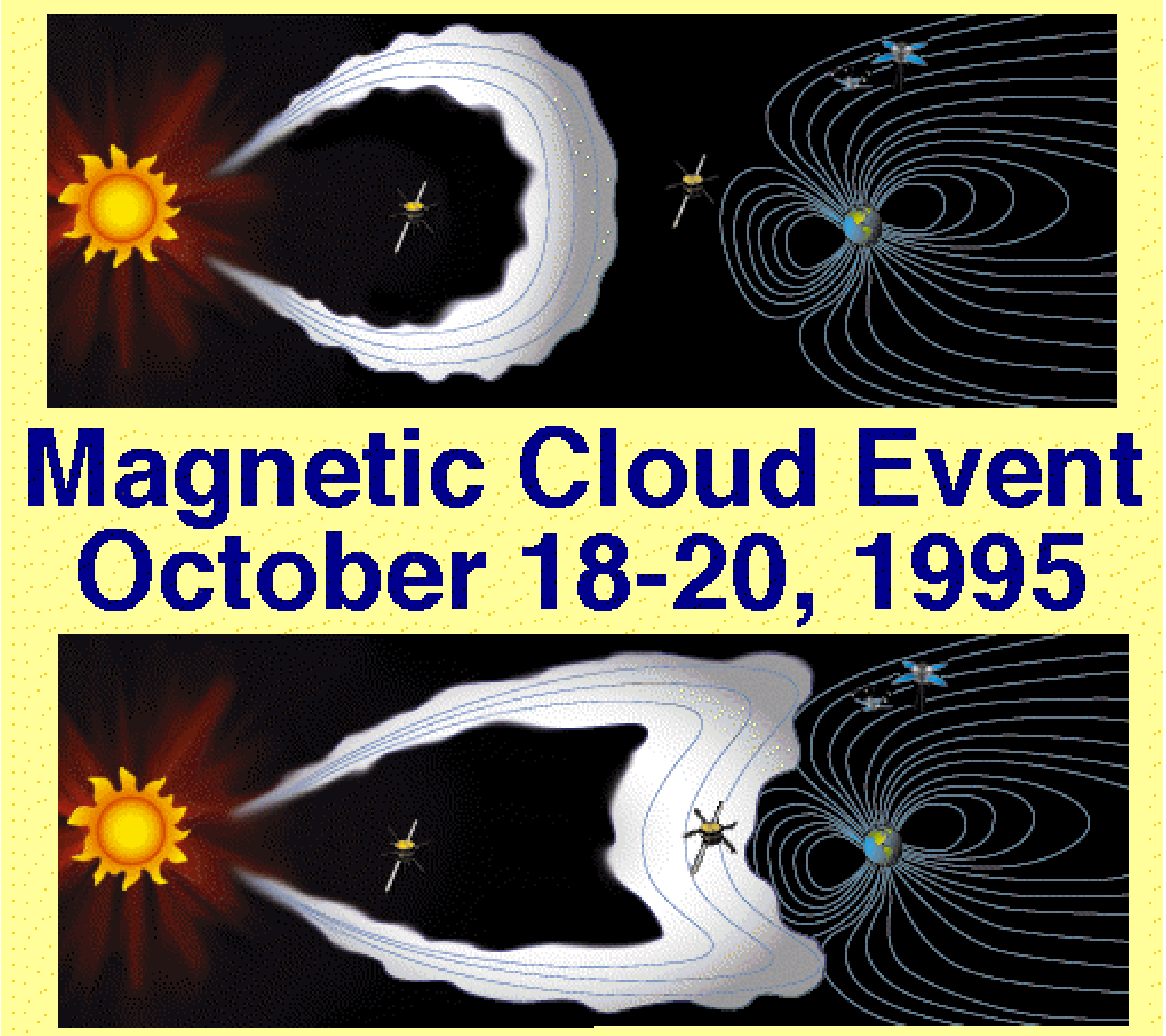



Significant Solar Proton Episodes
Since 1955
Event Fluence (Protons/cm2)
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
250
200
150
100
50
0
Sunspot Number
1955
1960
1965
1970
1975
1980
1985
1990
1995
Year
>10 MeV
>30 MeV
>60 MeV
Sunspot Number


Magnetic Cloud Event
October 18-20, 1995

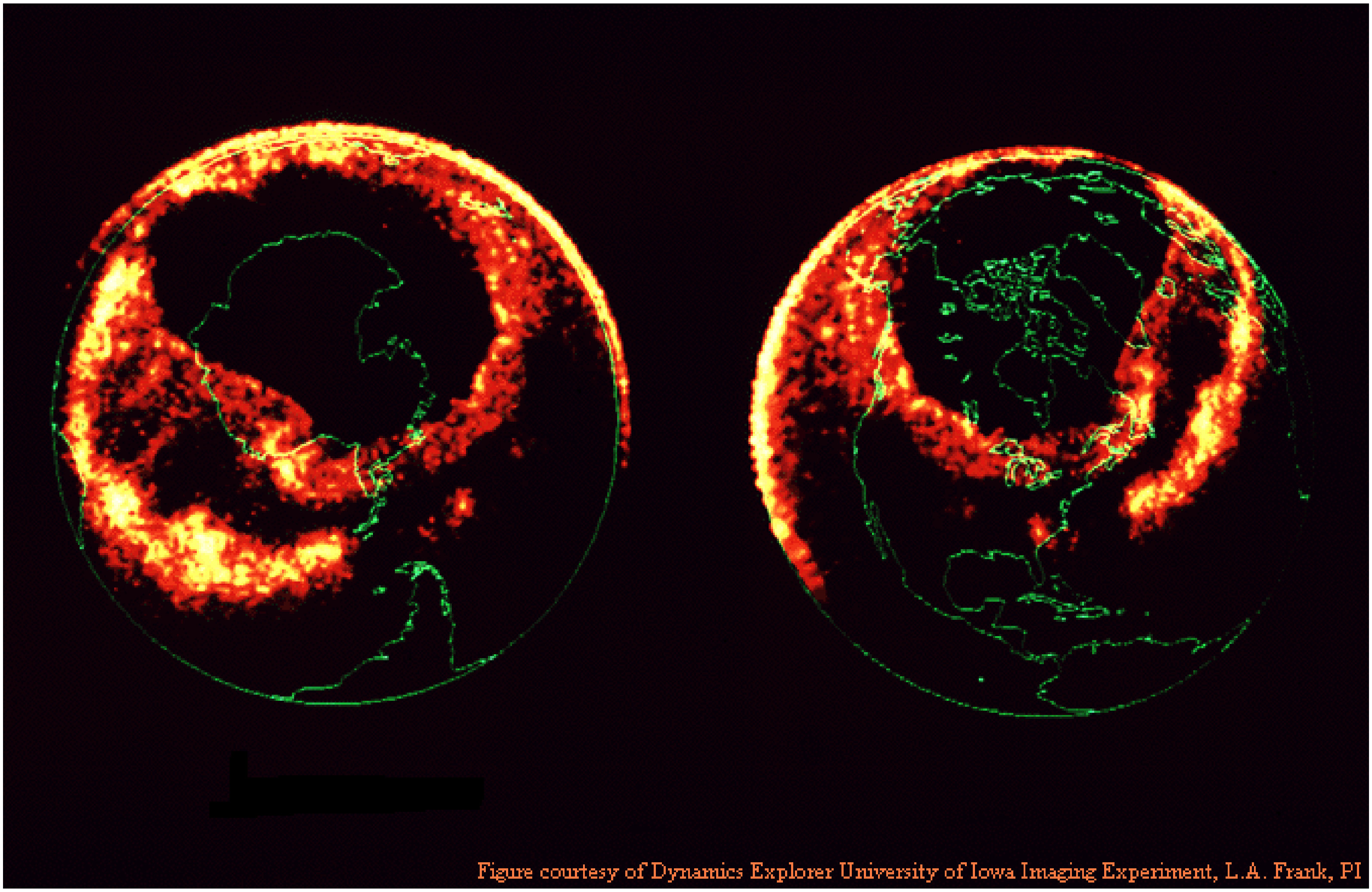


Figure courtesy of Dynamics Explorer University of Iowa Imaging Experiment, L.A. Frank, PI

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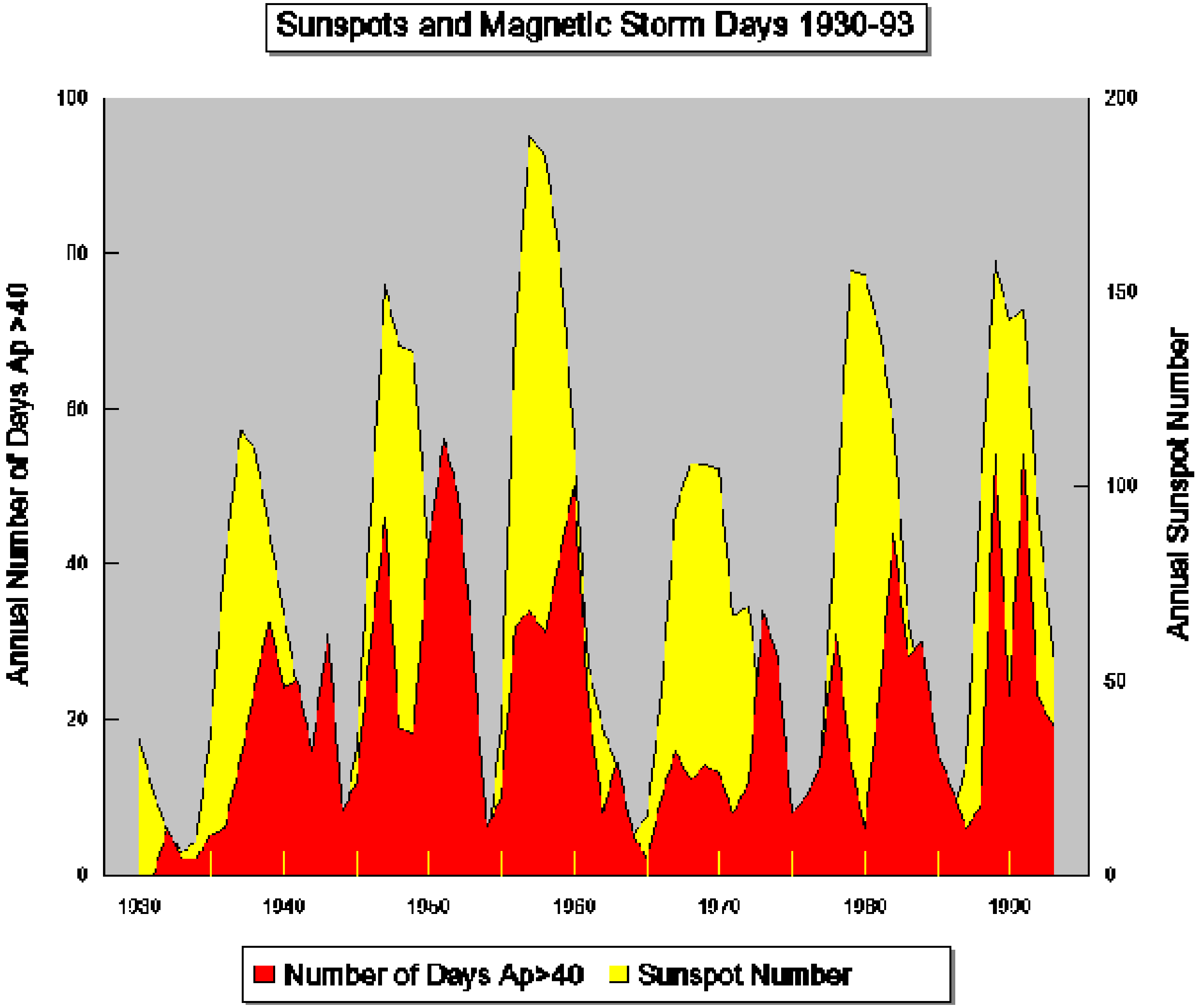

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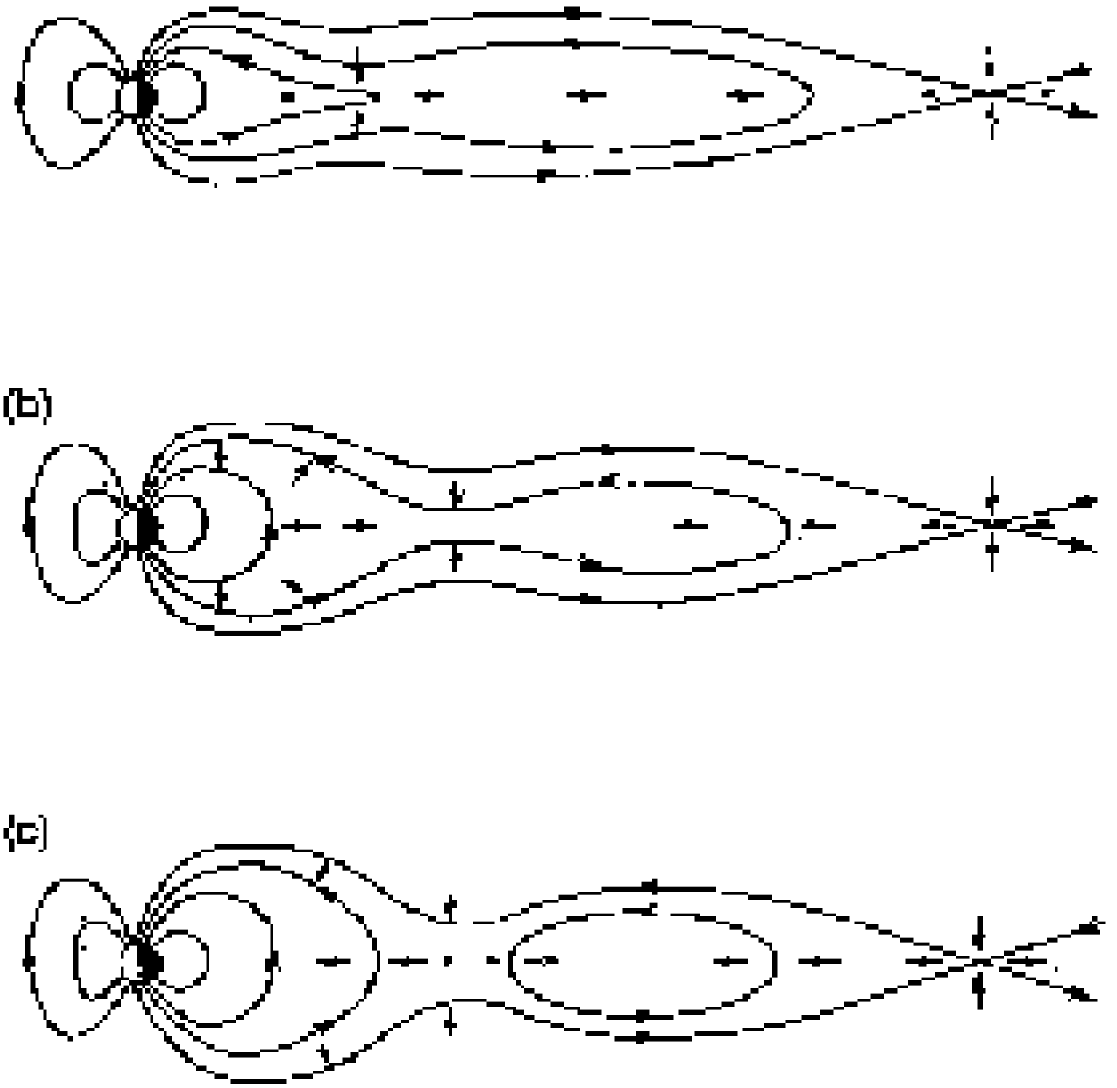
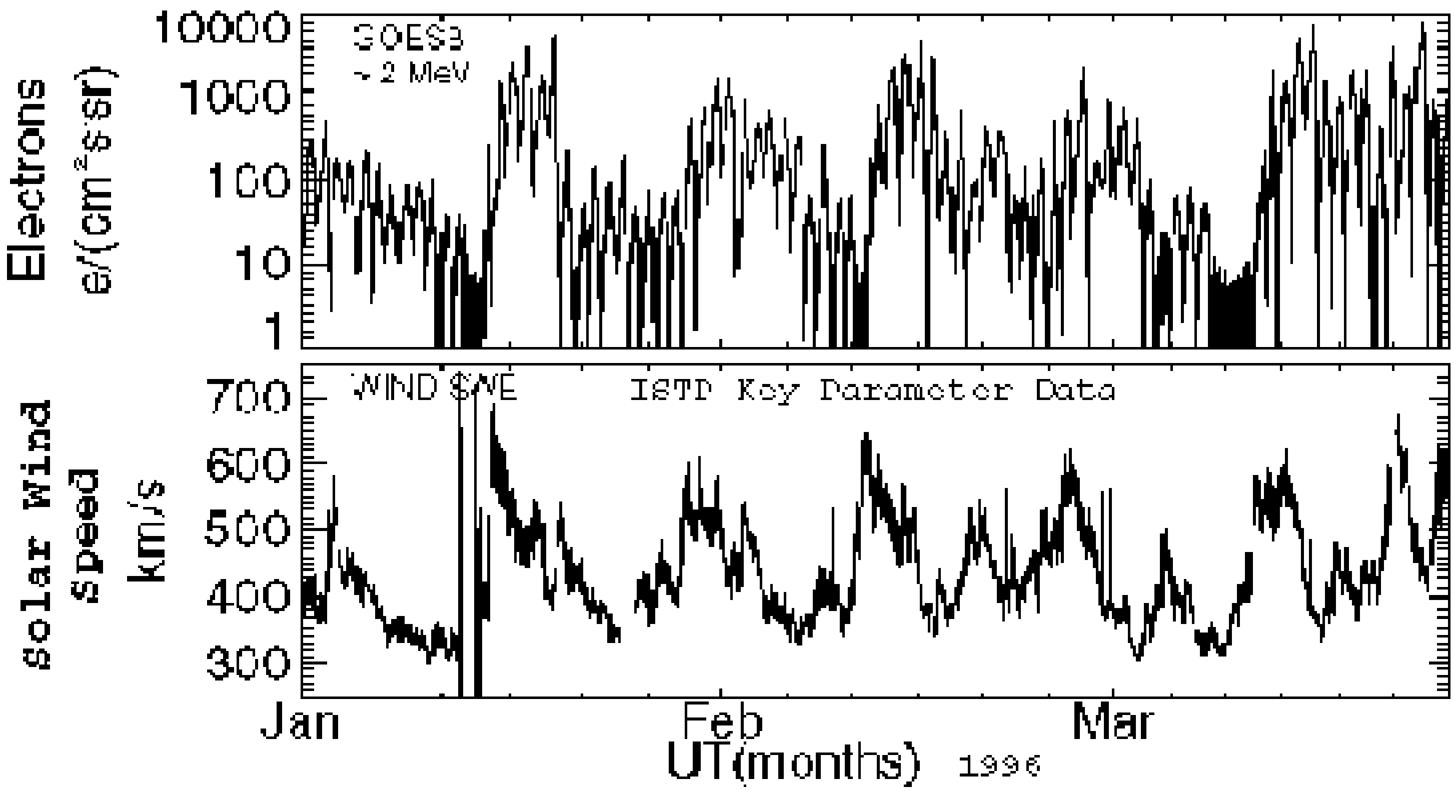
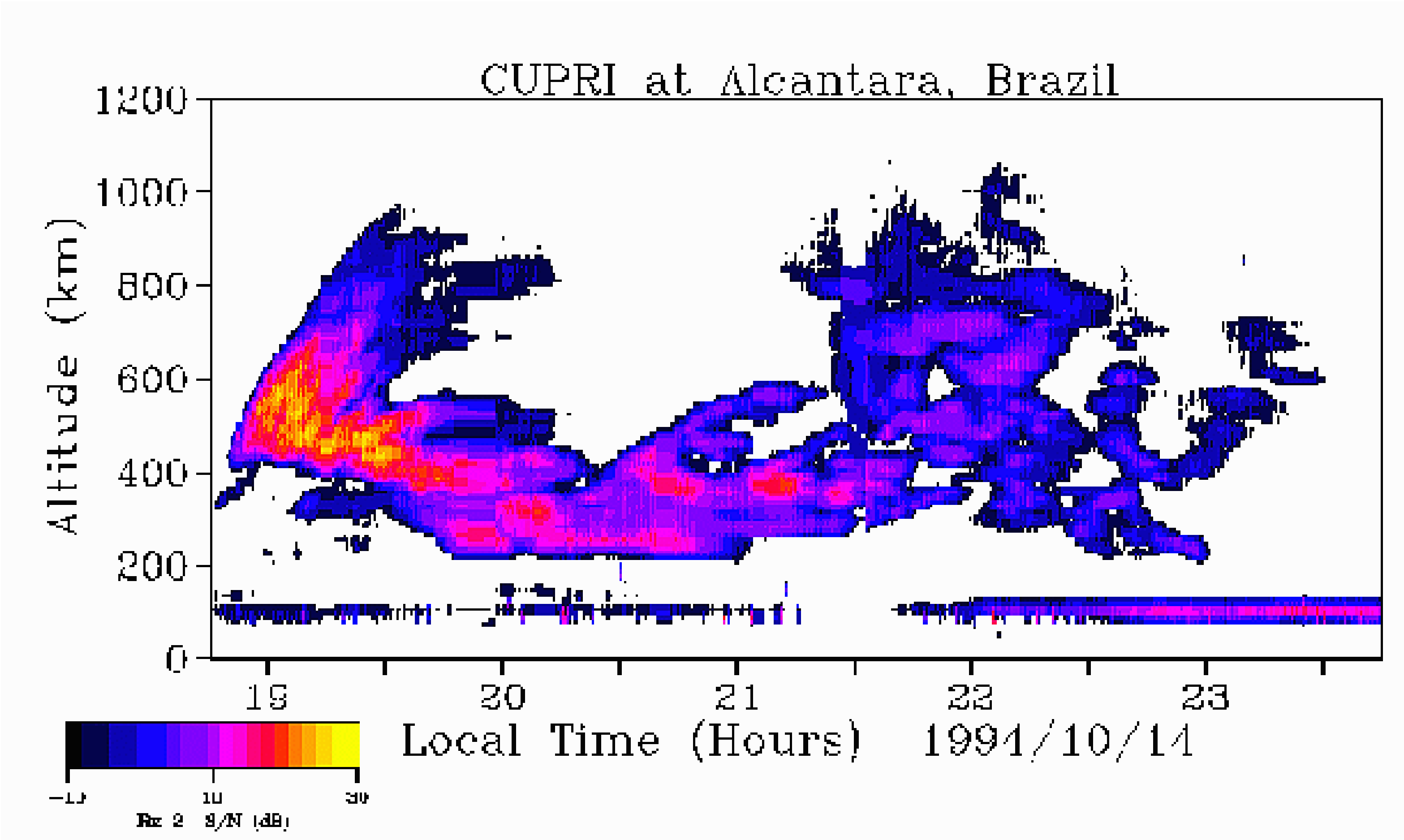


The Influence of Solar Wind Stream Structure on Multi-MeV Electrons at Geosynchronous Altitude: GOES and WIND Observations




CUPRI at Alcantara, Brazil
Altitude (km)
0
200
400
600
800
1000
1200
19
20
21
22
23
Local Time (Hours) 1994/10/14
10
30

Space Weather: A Research Perspective
Practical Consequences of Space Weather

Effects on Satellites

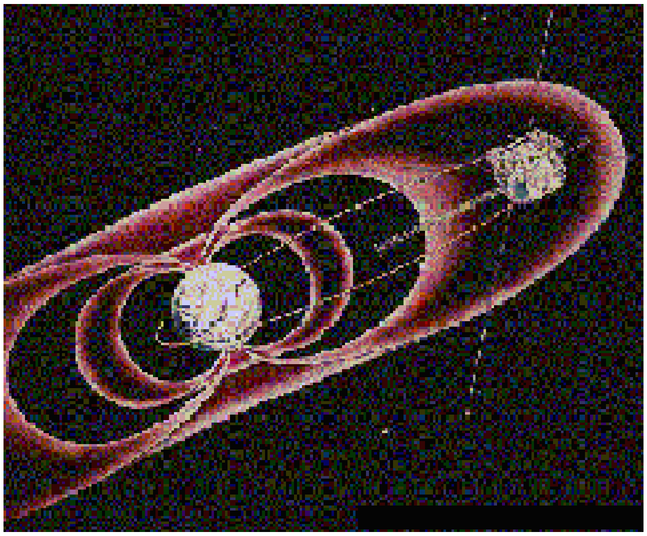


Illustration of a spacecraft in an orbit that traverses the radiation belts (courtesy of Lund Space Weather and AI Center, Lund University, Sweden).

Satellites often operate in the space environment for many years. As a result, they can sustain long-term exposure effects in addition to special "storm-time" problems. Depending upon their altitude, satellite electronic components, solar cells, and materials degrade from the accumulated radiation dose caused by repeated traversals of the Van Allen radiation belts. Similarly, the bombardment by atoms in the thin upper atmosphere can alter orbits and wear surfaces away. Some materials become brittle from long-term exposure to solar ultraviolet light above the protective absorbing atmosphere. Single penetrating cosmic rays can change the state in electronics components such as spacecraft memory chips.

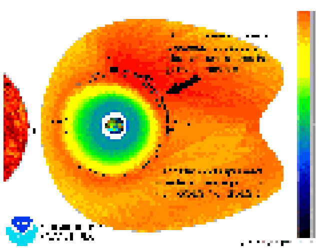
Newspaper headlines announce the failure of systems aboard the Canadian ANIK E-1 and E-2 communications satellites due to elevated intensity of activity of high-energy electrons in Earth's outer magnetosphere (courtesy of the Solar Data Analysis Center, Goddard Space Flight Center).

It is thought that the trapped energetic electron radiation whose intensity increases with solar wind velocity produces deep dielectric charging in the unshielded parts of a satellite. The figure below shows when the ANIK problems occurred compared to a record, from the SAMPEX satellite, of the energetic electrons near the geosynchronous satellite orbit (note that the 27-day rotation period of the Sun is also visible here).

History of energetic electron intensities in the radiation belts during the ANIK satellite failures (courtesy of D.N. Baker, University of Colorado)

Space weather "storms" add new problems while exacerbating the above cumulative effects. Some satellites charge up when they are suddenly immersed in enhanced radiation environments in the Van Allen belts, the auroral zone, or interplanetary space. Dielectric surfaces can charge to very high potential compared to the metallic surfaces of the satellite, leading to discharges between the two. Such discharges cause both material damage and electrical transients on the spacecraft.

Electrical transients from surface discharging, or from internal charging (caused by the above-mentioned energetic electrons producing charges deep inside electronics components), can masquerade as "phantom commands" appearing to spacecraft systems as directions from the ground. These events can cause loss of control of instruments and power or propulsion systems. Electrical transients often occur in the local time period between midnight and dawn following what appears to be an injection of electrons toward Earth from the magnetotail during geomagnetic disturbances.



Locations of spacecraft at times when they experienced anomalous discharges, presumably due to enhancements in the radiation environment accompanying magnetic storms and substorms (courtesy of the NOAA National Geophysical Data Center, Boulder, CO).

Another "danger zone" for spacecraft is in the region of the South Atlantic, where the energetic particle populations in the radiation belts are found at unusually low altitudes due to a local weakness in Earth's magnetic field.

Locations of spacecraft in low-Earth orbit when they experienced memory upsets. The concentration near South America arises because the Van Allen radiation belts are closest to Earth in this region (courtesy of M.A. Shea, Phillips Laboratory).

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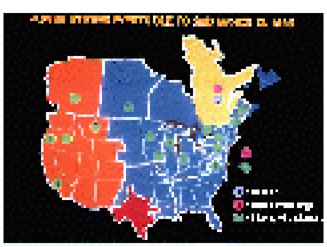
The upper atmosphere becomes inflated if it is heated by extra energy sources such as auroral particles and enhanced resistive ionospheric currents. The resulting increased atmospheric densities at 300-500-kilometers altitudes significantly increase the number of microscopic collisions between the satellite and the surrounding gas particles. This increased "satellite drag" can alter an orbit enough that the satellite is temporarily "lost" to communications links. It also causes the premature decay of the orbit (and necessitating shuttle "boosts" for some, like the Hubble Space Telescope).

The Hubble Space Telescope orbit is always decaying due to atmospheric drag. Increased atmospheric densities in low-Earth orbit from solar-cycle-enhanced solar ultraviolet emissions and geomagnetic disturbances hasten the decay for this and other satellites (courtesy of Students for the Exploration and Development of Space).

Effects on Power Systems

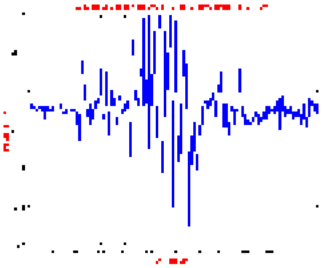
Electric power systems on the ground can be affected by the enhanced currents that flow in the magnetosphere-ionosphere system during geomagnetic disturbances. These currents cause magnetic field perturbations on the ground that in turn induce other currents in long transmission lines, especially those located at high latitudes. The slowly varying "DC" part of the currents can be large enough to cause overheating and damage to systems designed for AC. Disruption of power distribution systems can adversely affect many aspects of our daily lives, for example, should a blackout result.



Map showing the sites of power blackouts and other malfunctions of power grids during the large magnetic storm of March 13, 1989 (courtesy of Rice University).

Effects on Pipelines

Space weather-induced currents similarly flow in long conductors on the ground such as oil pipelines. These currents create galvanic effects that lead to rapid corrosion at the pipeline joints if they are not properly grounded. Such corrosion requires expensive repairs or can lead to permanent damage.



Voltage fluctuations observed on a long electrical cable caused by changes in the magnetic field on Earth during a magnetic storm. These changes are caused by a combination of magnetospheric, ionospheric, and induced ground currents (courtesy of Lund Space Weather and AI Center, Lund University, Sweden).

Effects on Communications Systems

Shortwave radio communication at HF frequencies (3-30 megahertz), which is still extensively used by the military and for overseas broadcasting in various countries, depends upon the reflection of signals from Earth's ionosphere. These electromagnetic waves are attenuated as they pass through the lower ionosphere (below 100 km), where collisions between the electrons and air molecules are frequent. Ionosphere attenuation affects the usable radio communication frequencies. If it becomes especially strong due to an increase in the local electron density, it can cause a total communications blackout. Solar flare ultraviolet and x-ray bursts, solar energetic particles, or intense aurora can all bring on this condition. Solar energetic particle events produce a particular type of disturbance called Polar Cap Absorption (PCA) that lasts up to days. The deep ionization produced by the solar protons also alters the path taken by the waves reflecting from the ionosphere.

Illustration of the communications effects of ionospheric changes caused by solar proton events, known as Polar Cap Absorption (PCA) events (courtesy of M.A. Shea, Phillips Laboratory).

The ionospheric changes that occur during disturbed times also increase the incidence of electron density irregularities, leading to sometimes severe variations or scintillations in the phase strength of signals sent from the ground to satellites at VHF and UHF frequencies (30 megahertz to 3 gigahertz).

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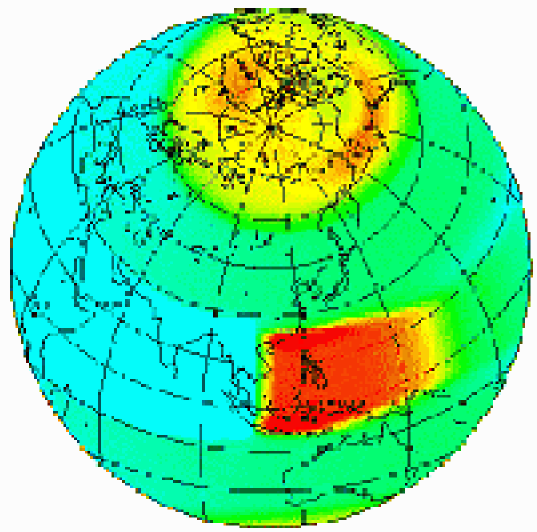


Prediction of the global pattern of ionospheric scintillation intensity from a model (courtesy of Northwest Research Associates).

Finally, solar radio bursts can directly interfere with communications in the frequency range between 245 MHz and 2.7 GHz, which is widely used. In summary, space weather-related disruptions to communication systems have wide-ranging effects—from social interactions to economic transactions on a global level to intelligence and surveillance activities.

Effects on Geomagnetic Surveys

An off-shore drilling platform (courtesy of Greenpeace International).

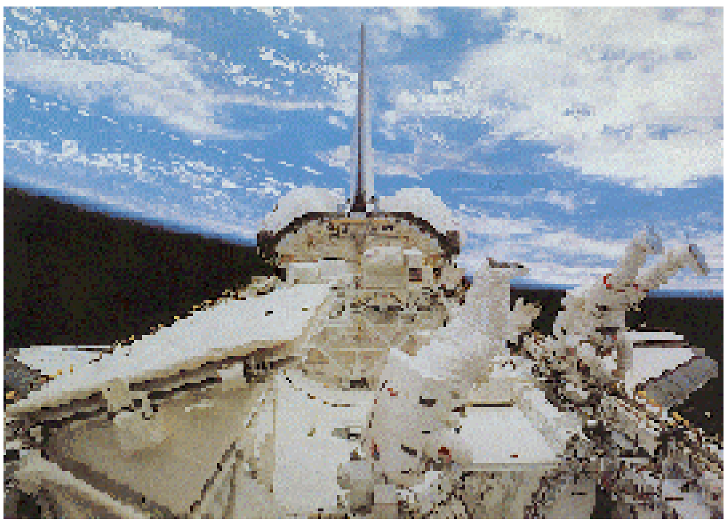
Geomagnetic surveys are important tools in the commercial exploration of natural resources. However, space weather-related perturbations can create signals in survey data that can be mistaken for signatures of subsurface resources. Survey schedules or operations must be modified, often suddenly and with significant cost impact, to avoid this contamination of the survey data.

Effects on Navigation Systems

Logo showing Coast Guard use of the GPS system (courtesy of U.S. Coast Guard).

The same disturbance-related changes in Earth's ionosphere that affect communications introduce changes in the time it takes signals to traverse the ionosphere. The abnormal time delays introduce position errors and decrease the accuracy and reliability of the Global Positioning System (GPS), which is used for many range-finding and navigational purposes. For example, phase scintillation in the ionosphere can defeat efforts on the part of surveyors who could otherwise use GPS to achieve distance measurements between separated receivers to centimeter accuracy.
The changes in ionospheric attenuation and reflection of electromagnetic waves described above also affect the use of "over-the-horizon" HF radars used to detect and monitor aircraft and sea conditions. Ionospheric irregularities also produce noise or "clutter" in the radar signals.

Hazards to Humans in Space

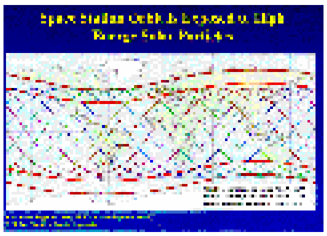


View of Earth across the space shuttle Bay. An astronaut undertakes some extravehicular activity. The space shuttle program has heightened our awareness of radiation dangers to humans in space (courtesy of Goddard Space Flight Center).

The principal space weather hazard to humans is radiation exposure to astronauts and passengers in high-altitude aircraft. Although the residual atmosphere above an aircraft provides a measure of protection from cosmic rays and solar energetic particles that enter the magnetosphere, there is still concern for flights on polar routes during major solar particle events. The primary means of reducing this hazard is to modify flight paths as necessary and to limit the flight time of personnel on high-altitude aircraft like the supersonic transport. It is clear that in this case early warnings of solar energetic particles are extremely desirable. While flares can be monitored at least on the visible disk of the Sun, solar indications of the shock-producing fast coronal mass ejections toward Earth are less apparent.

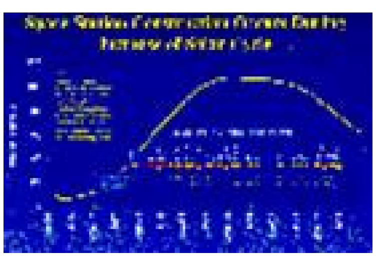
Potential hazards from the high-altitude electrical discharges called sprites and jets are unknown. Since they seem to occur between the cloud tops at around 15-km altitude and at the base of the ionosphere near 100-km altitude, interest in their effects will depend on the future use of this region of Earth-space.

Astronaut radiation exposure is a major concern of our manned space flight program. Most manned missions occur in orbits that are below the regions where the Van Allen belt radiation is most intense. Extravehicular activities (EVAs) in the region of anomalously high radiation over the South Atlantic are also avoided. However, the MIR space station and the currently planned International Space Station (ISS) have orbits sufficiently inclined from the equator to bring them into the expanded auroral zones that occur during geomagnetically disturbed times.



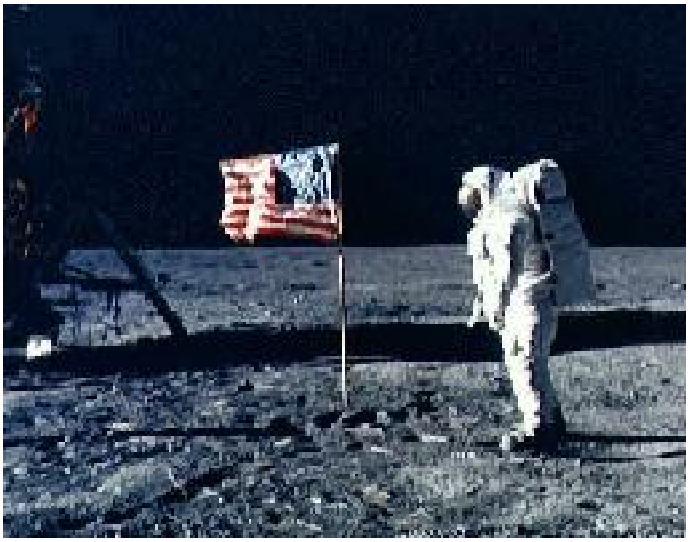
Ground track of the proposed International Space Station orbit. The South Atlantic anomaly region is circled (courtesy of Ron Turner, ANSER).

The potential impact of excursions into these high-latitude regions on both the station itself and the planned construction activities requiring EVAs is being explored. It is known, for example, that the intensity of galactic cosmic rays that reach the atmosphere is about ten times higher inside the auroral zone than near the equator and that solar particles have increased access to this same region. The likelihood of a frequently disturbed magnetosphere and presence of solar energetic particles is considerable given the phasing of the ISS construction with the next solar maximum.



One version of the International Space Station construction EVA schedule, compared to the expected phasing of the coming solar activity cycle (courtesy of Ron Turner, ANSER).

For missions that leave low-Earth orbit, like the Apollo missions to the moon, the ability to rapidly traverse the radiation belts and to predict the occurrence of solar energetic particle events is essential. While envisioned manned modules for future missions to Mars are generally equipped with shielded astronaut shelters, adequate warning is necessary for these to be useful.



An astronaut on the lunar surface would be in danger of a lethal dose of radiation from solar energetic particles were a major coronal mass ejection to occur unnoticed (Figure courtesy of NASA Apollo 11 image archives).

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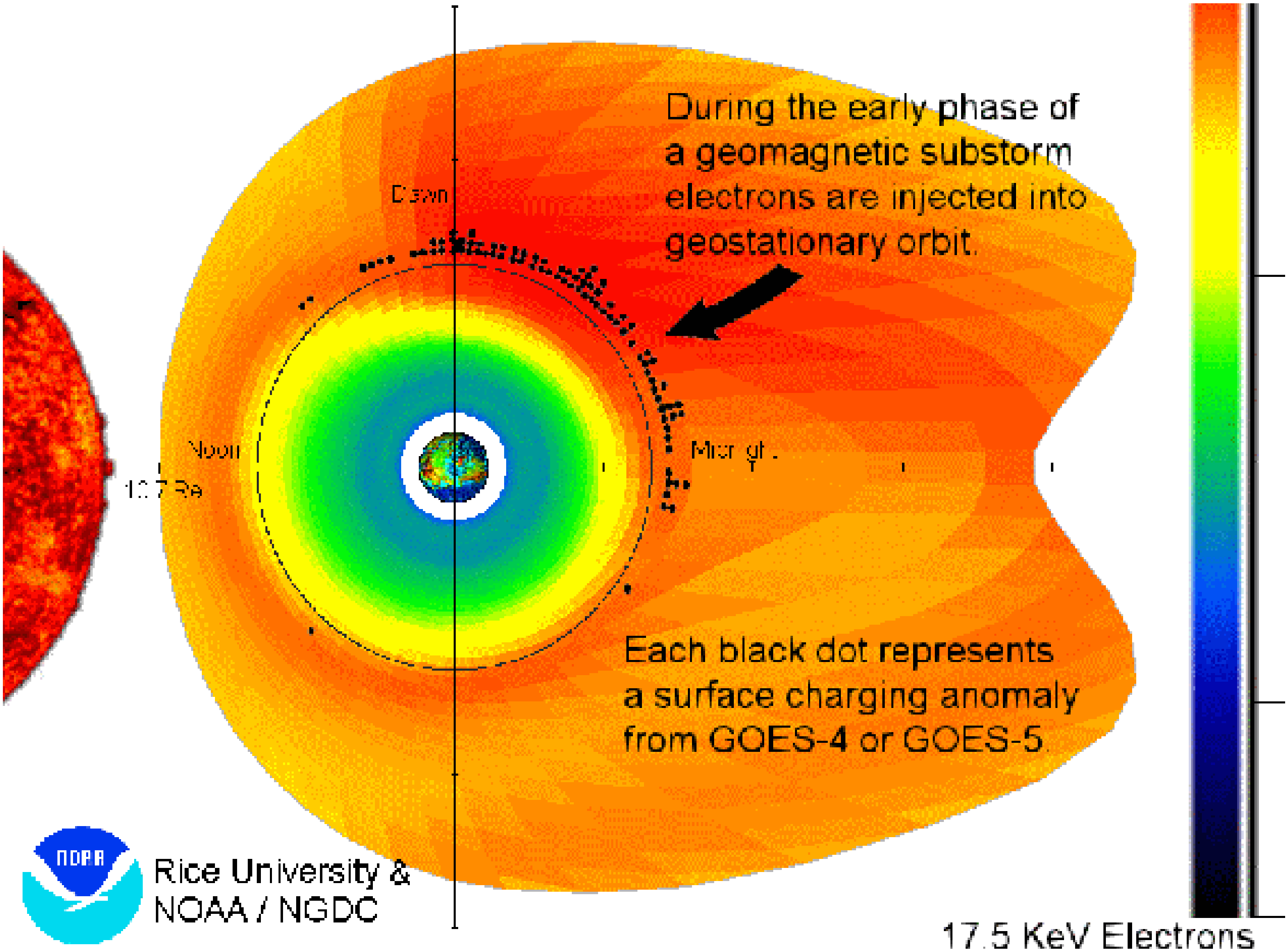
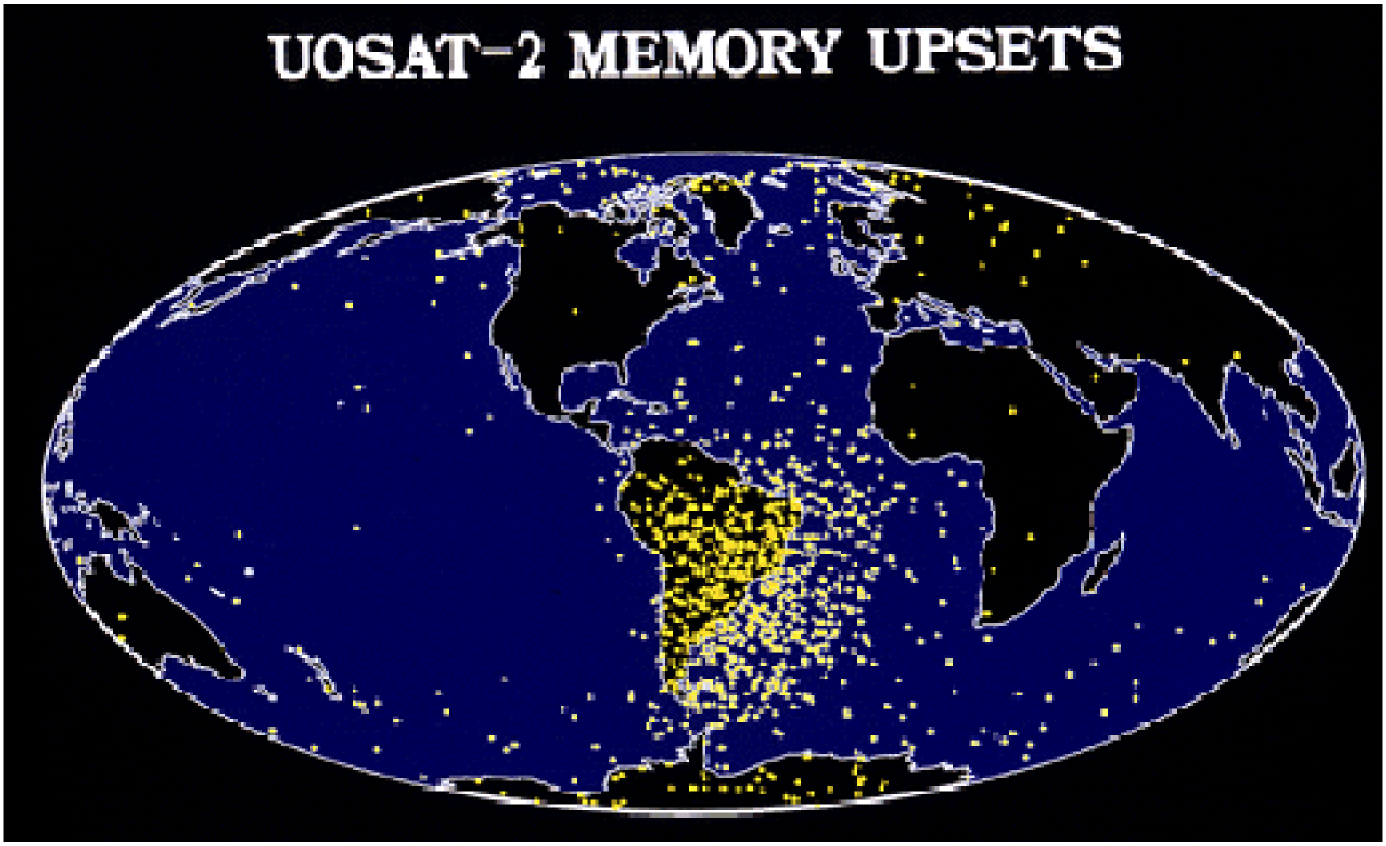
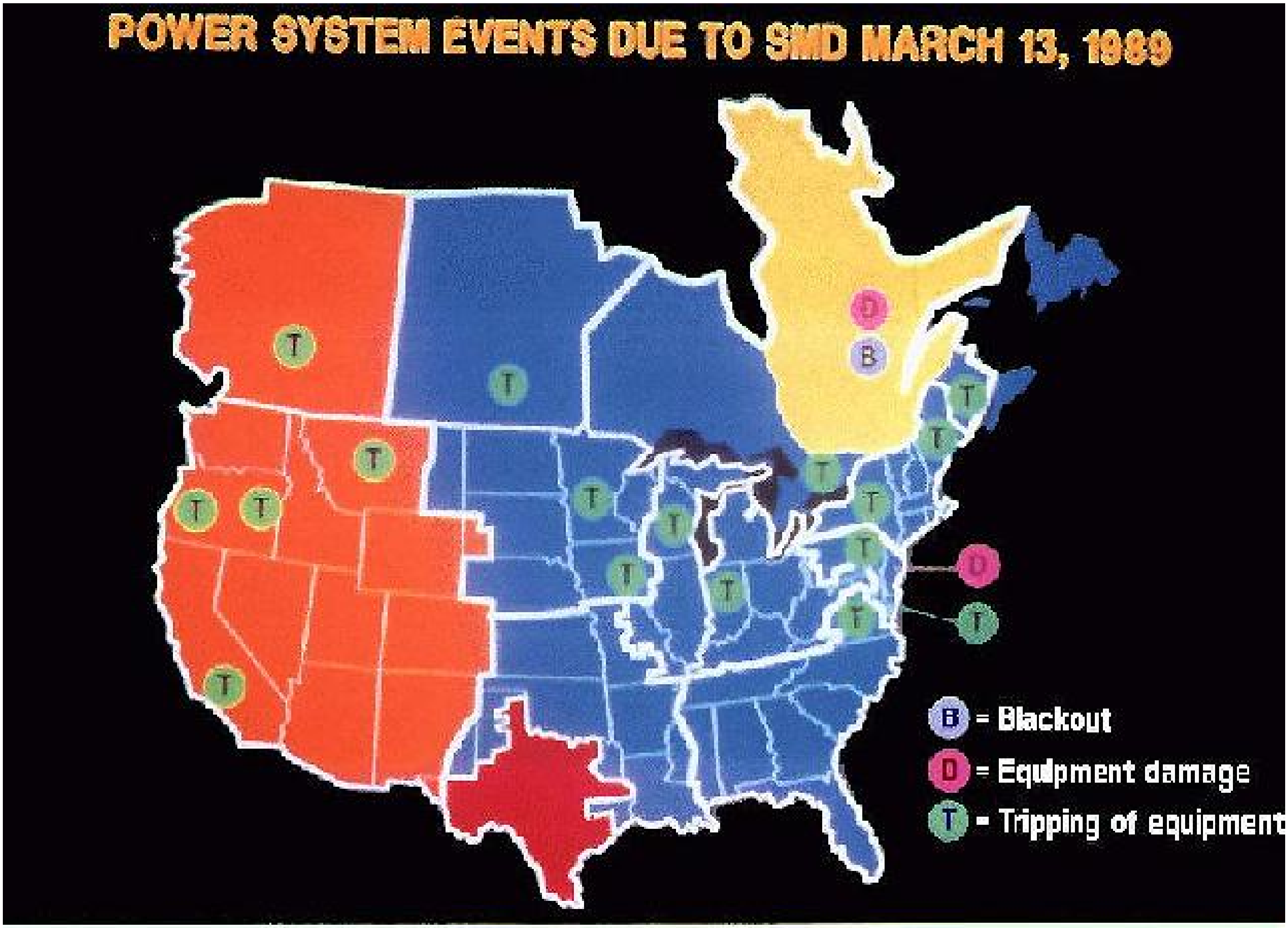



UOSAT-2 MEMORY UPSETS


POWER SYSTEM EVENTS DUE TO SMD MARCH 13, 1989
D
B
T
B = Blackout
D = Equipment damage
T = Tripping of equipment

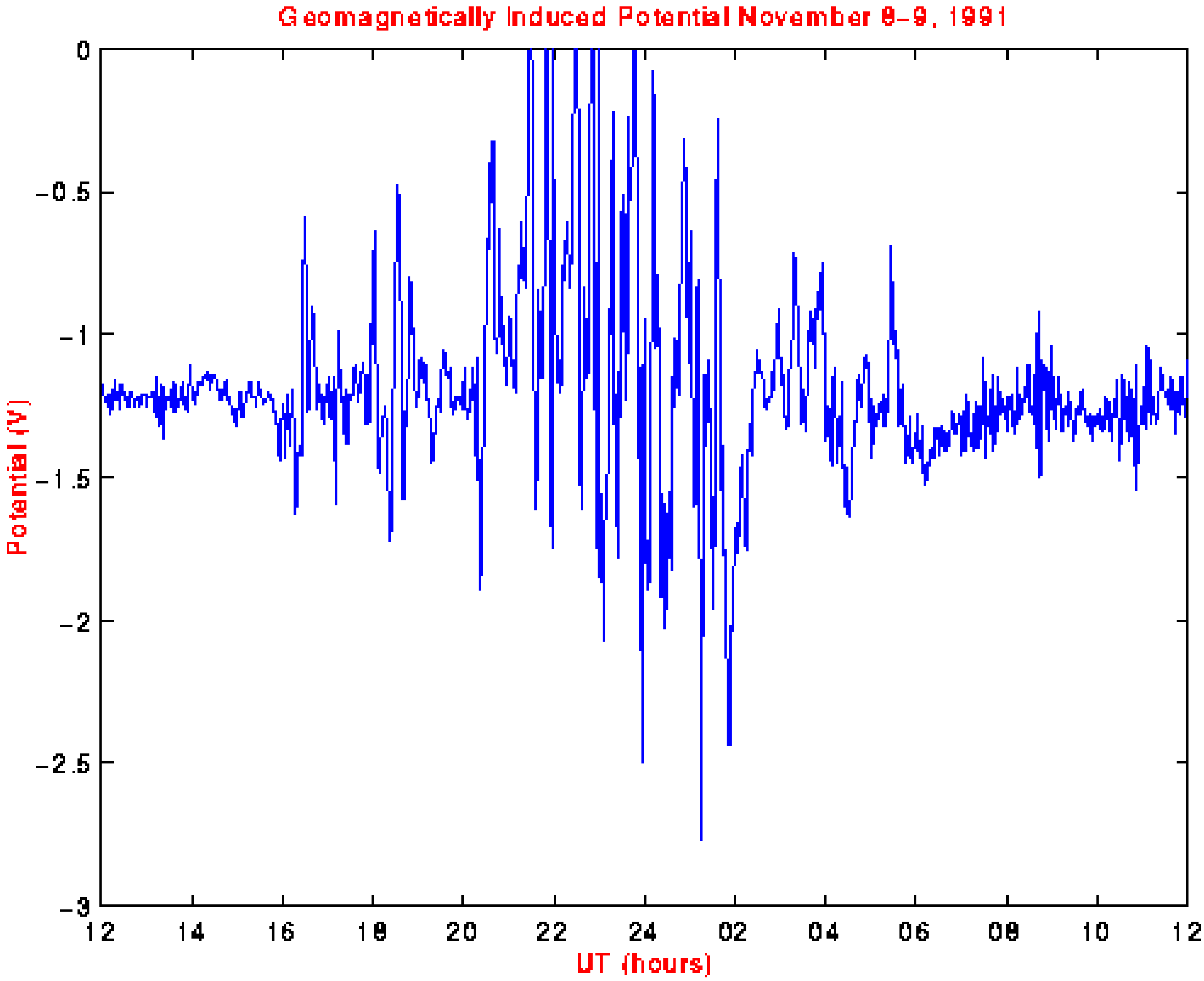
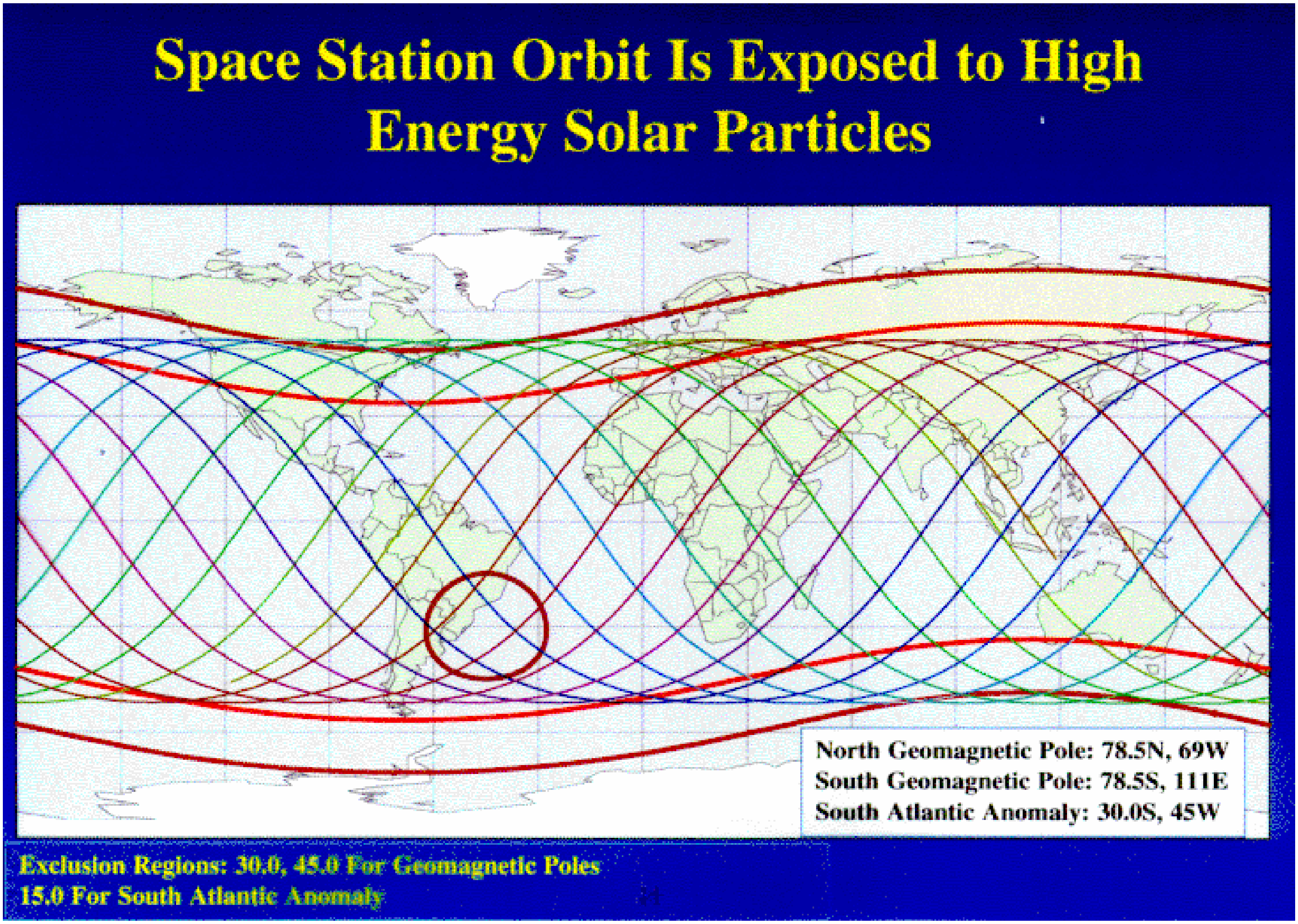
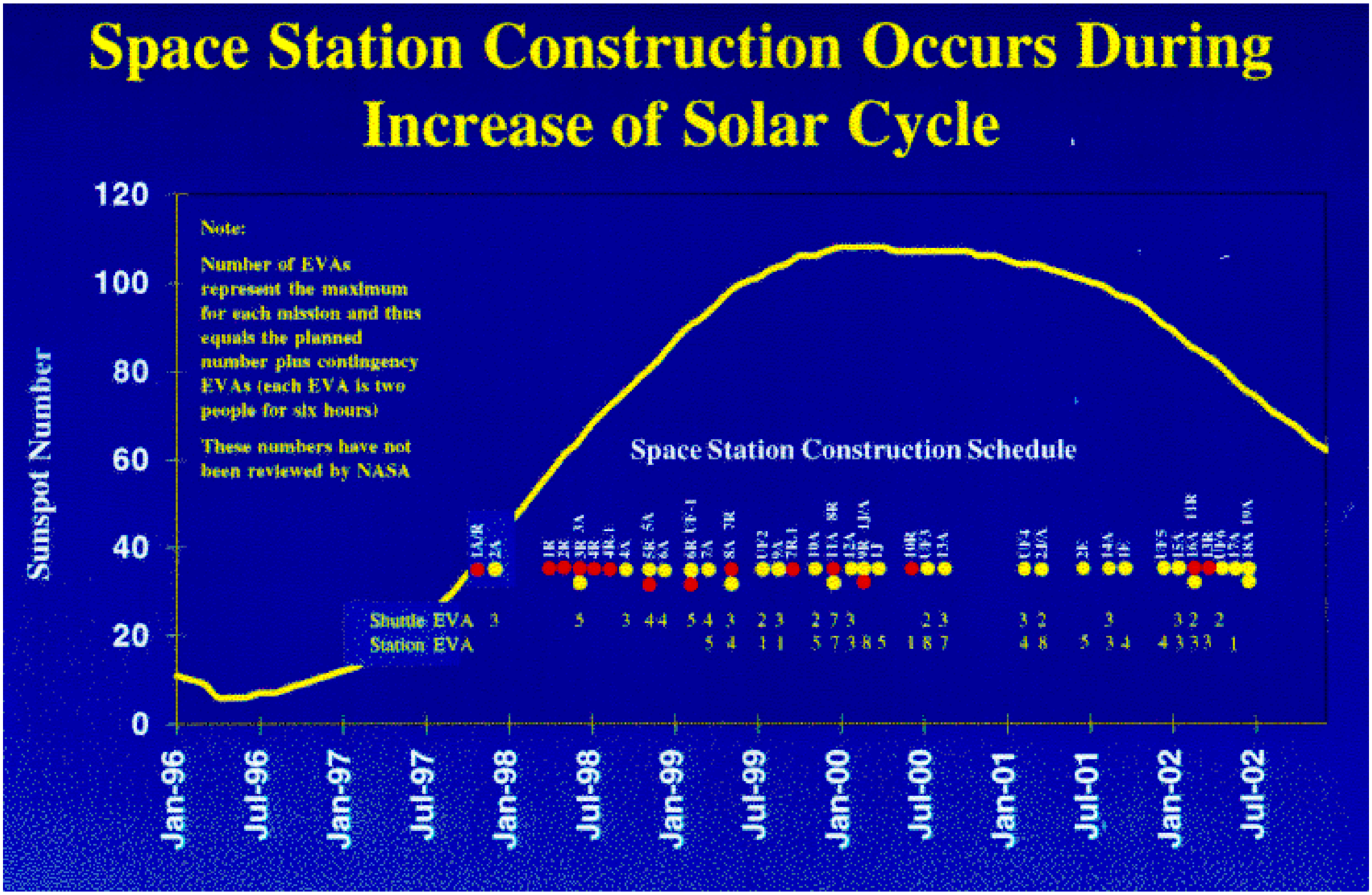

Geomagnetically Induced Potential November 8-9, 1991
Potential (V)
0
-0.5
-1
-1.5
-2
-2.5
-3
12
14
16
18
20
22
24
02
04
06
08
10
12
UT (hours)

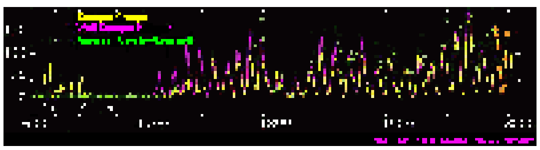
Figure courtesy of M.A. Shea, Geophysics Directorate, Phillips Laboratory


Space Station Orbit Is Exposed to High Energy Solar Particles
North Geomagnetic Pole: 78.5N, 69W
South Geomagnetic Pole: 78.5S, 111E
South Atlantic Anomaly: 30.0S, 45W
Exclusion Regions: 30.0, 45.0 For Geomagnetic Poles
15.0 For South Atlantic Anomaly


Space Station Construction Occurs During Increase of Solar Cycle
Sunspot Number
120
100
80
60
40
20
0
Note:
Number of EVAs represent the maximum for each mission and thus equals the planned number plus contingency EVAs (each EVA is two people for six hours)
These numbers have not been reviewed by NASA
Space Station Construction Schedule
Shuttle EVA
Station EVA
Jan-96
Jul-96
Jan-97
Jul-97
Jan-98
Jul-98
Jan-99
Jul-99
Jan-00
Jul-00
Jan-01
Jul-01
Jan-02
Jul-02

Space Weather: A Research Perspective
What the Future Holds

Many space weather events occur around the peak of the solar cycle, with stronger cycles (higher sunspot maxima) expected to produce a greater number of major disturbances. Yet sunspot numbers themselves have exhibited considerable variation in intensity from one solar cycle to the next, in addition to small changes in the cycle periods, throughout their recorded history. There also appear to have been intervals in the fairly recent past when sunspots disappeared altogether for several cycles. The most recent of these was the Maunder Minimum (1650-1715), seen in the extended sunspot number record below.



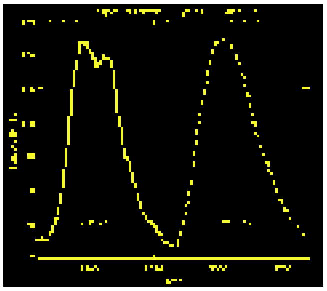
Historical sunspot number record. Early sunspot numbers have been scaled to recent numbers using information given on the method of counting (courtesy of the National Center for Atmospheric Research High Altitude Observatory).

It is notable that the Maunder Minimum was also a period of global cooling on Earth known as the Little Ice Age. Recent spacecraft measurements have shown that the solar activity cycle is accompanied by a small change (about 0.2%) in the amount of heat radiated by the Sun, with lower values corresponding to solar minimum. However, the existence of effects of the solar activity cycle on Earth's climate is still a matter of debate. The reason is that the physical mechanisms by which the related solar variations might cause such changes are not obvious. Subtle changes, such as the alteration of polar ozone chemistry and aerosols by the deeply penetrating ionization of the atmosphere accompanying some solar proton events, may have cumulative influences that are yet to be understood.

Space Weather: A Research Perspective

Painting by European artist Hendrik Avercamp (circa 1585-1663) of skaters on a frozen river during the Little Ice Age.

In contrast to the effect of the solar activity cycle on Earth's climate, there is clear evidence of the consequences of nonuniform solar cycles on space weather. Great magnetic storms occurred on February 4, 1872, and August 5, 1972. These were accompanied by exceptional auroral displays at middle and low latitudes. During the 1872 storm some telegraph communications were sent using the induced currents in the system, without power sources, while at other times they were totally disrupted. Space-based measurements available during the 1972 storm revealed potentially lethal doses of radiation had astronauts been outside the magnetosphere enroute to the moon. An extraordinarily active cycle when coronal material from numerous CMEs can overtake and reinforce each other's effects in interplanetary space, and flares occur frequently, should maintain a state of increased geomagnetic, atmospheric, and ionospheric disturbance. On the other hand, a period of reduced solar activity should be accompanied by increased access of galactic cosmic rays to Earth, and perhaps by intense electron radiation belts if the solar wind streams remain strong.



One prediction of the sunspot number for the coming cycle. Predictions such as this are based on analyses of the previous cycles and differ considerably from one another (courtesy of Interstellar Propulsion Society Radio and Space Services, Australia).

The figure above shows one of many projections for the approaching solar maximum of the sunspot number, which is related to the amount of solar activity. How will the solar cycle behave during future generations of cycles? Observations of Sun-like stars suggest that the solar cycle may continue in roughly its current state for a long time, but our understanding is insufficient to confidently predict the extent of its future variations.

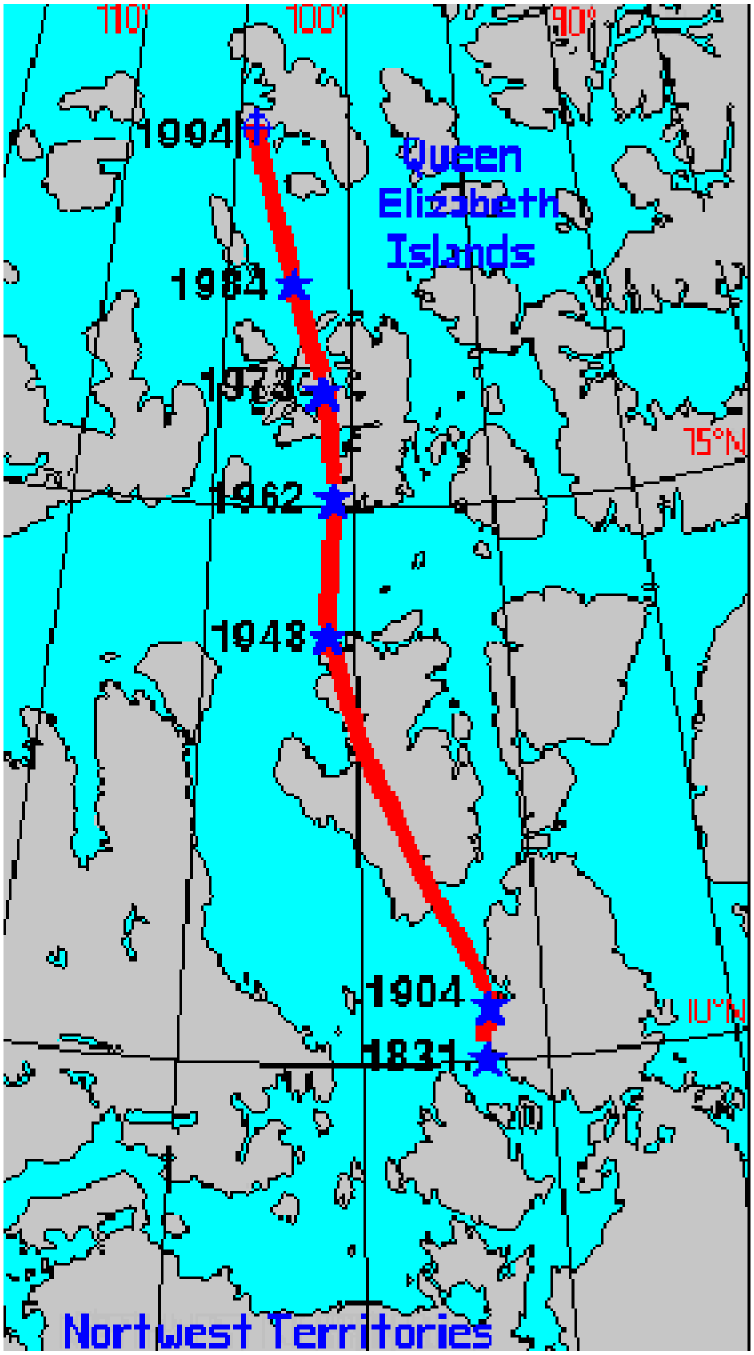
Solar activity, of course, is not the only part of the space weather equation. Earth's magnetic field is also constantly changing because, like the Sun's field, it originates in a complex dynamical system in the fluid-like interior. Convective motions in the molten core that are responsible for the field's existence respond to variations in internal chemical and radioactive heat sources and gravitational "stirring" by solidifying material settling toward Earth's center. Magnetization left in crustal rocks that solidified at different times in the past indicates that these motions have periodically undergone sudden adjustments (sudden on geological time scales of a billion years, at least). These adjustments affect Earth's field strength and even reverse the field polarity (exchanging the north and south magnetic poles). The dipole field strength appears to have varied on time scales measured in ten thousands of years, while the polarity reversals occurred less frequently with hundreds of thousands of years between them.

The last major change in the strength of Earth's dipole field 800,000 years ago seems to have been a 90% reduction accompanied by a polarity reversal. The records in the rock suggest that during this reversal the magnetic poles appeared to wander across the equator and the usually weaker, non-dipolar parts of the field became dominant. Such periods of reduced field intensity last on the order of 1000 to 10,000 years. We can only speculate about how our space environment and space weather would change in response to such an event. It seems clear that the radiation environments currently confined to the polar regions would expand equatorward, that the solar wind would more closely approach Earth, and that the aurora would become a more nearly global phenomenon.

Geomagnetic reversals are likely to continue to occur, albeit not within our lifetime.

Space Weather: A Research Perspective

As illustrated below, measurements show that the locations of the magnetic poles are drifting today. One estimation based on the current rate of decay of Earth's dipole field strength is that the next reversal could occur within the next 2000 years. While it is difficult to imagine what life on Earth will be like so many generations into the future, humankind present in the year 4000 may have quite different perspectives on their space environment than we have today.



The changing location of the north magnetic pole determined by measurements over the last decade and a half (courtesy of Canadian National Geomagnetism Program

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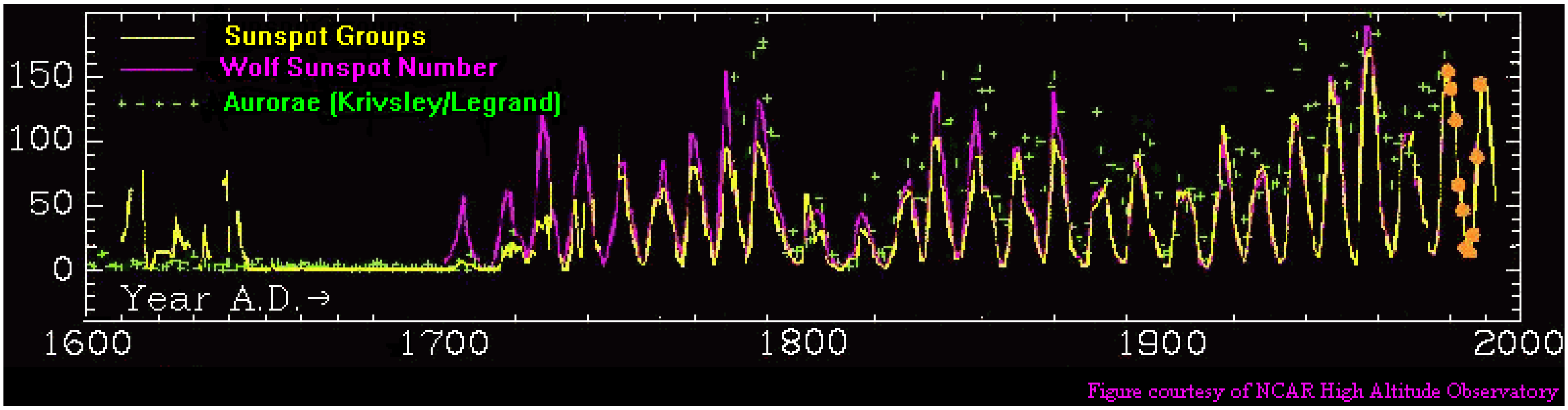

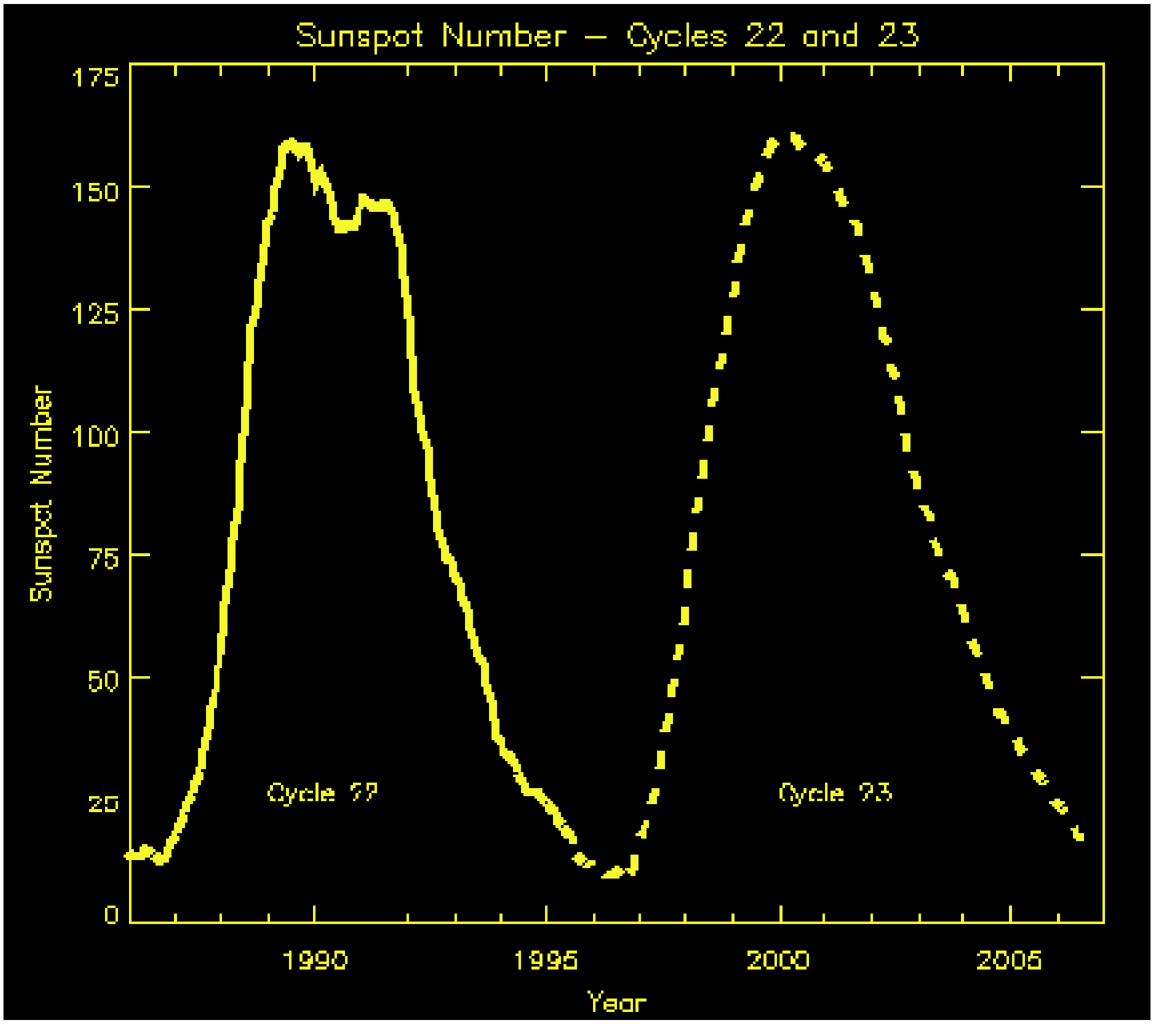
Sunspot Number — Cycles 22 and 23
Sunspot Number
175
150
125
100
75
50
25
0
Cycle 22
Cycle 23
1990
1995
2000
2005
Year

Space Weather: A Research Perspective

A Space Weather Plan for the Nation

Space weather is a part of our environment in the same sense as traditional weather. It is not limited to satellite problems or power system failures or astronaut radiation hazards any more than lower-atmospheric weather is limited to the damage from tornadoes, hurricanes, or floods. Just as weather is defined as the state of the atmosphere, so space weather is the state of Earth-space where our satellites, shuttles, and space stations orbit, and it is what deep-space probes experience en route to the planets. It is the result of the solar-terrestrial connection. It is an integral part of the space age that is also reflected in its consequences in the atmosphere and on the ground. Like traditional weather, it is most noticed when it causes problems.

Those who study space weather try to understand how the physical system of Earth-space works. It involves efforts to decipher how our most important star, the Sun, behaves, to understand how the space around our planet connects to interplanetary space, to understand the effects on Earth of the energy that is transferred in this interaction. The results of these studies can be used for practical purposes such as space weather forecasting and satellite or communications troubleshooting, but they also give us an eye-opening perspective on our place in space. Indeed they make us appreciate that we are all space travelers on a satellite of the Sun called Earth, that all planets around all stars have space weather in common, and that space weather has figured prominently in our origins and will certainly figure in our fate.

U.S. government agencies such as NSF, NASA, NOAA, and the DOD (especially the Air Force and Navy) support the study of space weather as a natural component of their research programs. In doing so, they have recognized that a space-age nation requires a broader view of Earth's environment than perhaps was necessary before. They have also recognized the intrinsic value to humans of understanding our local connections to the cosmos and the implications for understanding regions of space far from the solar system.

In the past, both the study and applications of space weather have not generally been coordinated across activities and agencies. A change has occurred within the last two years during which efforts have been initiated to bring together the various programs and to create a broader awareness of space weather. This collective effort has come to be known as the National Space Weather Program. With coordination at the management planning level, it has begun to provide support to investigations that lead coherently to a better understanding of space weather, drawing upon all available resources. A major goal is to establish a broadly based National Space Weather Service to provide information to both the professional and the interested layman about space weather.

The status of the National Space Weather Program is currently in flux, with a draft implementation plan created with the help of an advisory board of space scientists. The plan foresees coherent research activity that ultimately is transformed into an expert information system (e.g., for communications and power industries, spaceflight planners at government laboratories, satellite builders and operators, radio amateurs) and an educational resource. Information exchange systems such as the World Wide Web could easily provide access, while specialized applications could be designed for individual use off-line. The National Space Weather Program will provide an example of how science and technology can merge in the new millennium to bring the fruits of the nation's research efforts to everyone.

The development of the National Space Weather Program can be followed on the World Wide Web (at URL address http://www.geo.nsf.gov/atm/nswp/nswp.htm).

Space Weather: A Research Perspective

Glossary

AC: Alternating-current, referring (as an adjective) to electric phenomena that oscillate regularly in time.

active regions: Complex groups of sunspots that show signs of rapid evolution. Radio, ultraviolet, and x-radiation usually come from the vicinity of these regions.

ALEXIS: A small x-ray astronomy satellite built by the Los Alamos National Laboratory.

ANIK: A series of Canadian communications satellites.

AU: Astronomical unit, equal to the mean distance between the Sun and the Earth (150,000,000 km).

aurora: Light emitted from the polar upper atmosphere as energetic electrons bombard it from space. Aurora is another name for polar lights. The aurora borealis (northern lights) and aurora australis (southern lights) occur most frequently in the auroral oval.

auroral oval or auroral zone: The approximately circular band in the northern or southern hemisphere where aurora are most intense at any given time. The near-midnight portion of the oval, where some of the brightest emissions occur, is located at about 65 degrees latitude. The mean diameter of the oval is roughly 4000 km, but it expands toward the equator during magnetically disturbed periods, when the aurora also becomes brighter, and it contracts poleward during magnetically quiet periods.

charge neutrality: A condition that within a region of space the number of positive charges is equal to the number of electrons.

corona: The tenuous outer atmosphere of the Sun whose structure is controlled by solar magnetic fields. The corona has a temperature between 1 and 3 million degrees. It merges into the solar wind at its upper boundary about 1-2 solar radii above the visible surface or photosphere.

coronal holes: Regions of the Sun's corona where the density is lower than average, and the temperature and associated solar wind expansion velocity are higher than average. Their name reflects the fact that they appear dark in x-ray images of the corona due to their low density.

coronal mass ejection (CME): A disturbance of the Sun's corona involving eruptions from the lower part of the corona and ejection of large quantities of matter into the solar wind. These ejecta sometimes have higher speed, density, and magnetic field strength than is typical for the solar wind. If their speeds relative to the background solar wind are high, they can produce shocks in the plasma that precede them as they move outward.

coronal streamers: The dense and bright regions of the solar corona seen in eclipse photographs. These are shaped by the coronal magnetic field structure.

cosmic rays: Energetic particles with very high energies. These may come from the Sun, from shocks in the interplanetary medium or near the edge of the heliosphere, and from other parts of the galaxy.

DC: Direct-current, referring (as an adjective) to electric phenomena that do not oscillate in time.

deep dielectric charging: The addition of electric charge deep within a dielectric component of an electronic system by the impact of an energetic charged particle. This charging can disrupt the electronic signals of the system.

dielectric: A material that does not conduct electricity.

Space Weather Glossary

dipole magnetic field: A particular magnetic field structure having "north" and "south" poles from which fields of opposite sign appear to emerge.

Dynamics Explorer: A NASA spacecraft used to study Earth's upper atmosphere.

electrical transient: An impulsive current or voltage increase in an electrical system.

electromagnetic pulse: A strong pulse of electromagnetic radiation, generated by lightning or other effects, that can propagate like a radio wave throughout the atmosphere and space.

electromagnetic radiation: Radiation carried by combined electric and magnetic fields that propagate at about the speed of light. Radio waves, infrared radiation, light, ultraviolet radiation, x-rays, and gamma rays are all forms of electromagnetic radiation. The basic element of electromagnetic radiation is the photon.

electron: A negatively charged particle that when combined with a positively charged nucleus in numbers equal to its charge forms a neutral atom.

electron volt: A measurement unit for energy, equal to the energy an electron (or proton) would gain when accelerated by an electric voltage of 1 volt.

energetic particles: Electrons, ions, or atoms that have much higher energies than expected for the temperature of the gas from which they arise. In space physics, "energetic" usually means kilo- to giga-electron-volt energies.

filaments: Structures seen on the solar photosphere in the H-alpha emission line of hydrogen. Filaments are most likely to occur in active regions and so are most common near solar maximum.

gamma ray: Electromagnetic radiation with wavelengths less than 0.00001 micron.

geomagnetic disturbance: Any type of rapidly varying perturbation to Earth's magnetic field caused by electric current flowing in the magnetosphere and ionosphere.

geomagnetic tail: The long region extending from Earth, directed away from the Sun, filled by magnetic-field lines that connect to either the northern or southern polar region of the Earth. The geomagnetic tail is created by the action of the solar wind on Earth's magnetic field.

geosynchronous orbit: A circular satellite orbit at the distance from Earth at which the orbital period of a satellite is 1 day, i.e., equal to the rotational period of Earth. Because a satellite in this orbit remains above the same point on the ground, it is the location of many communications and weather satellites.

GGS: Global Geospace Science mission, includes the WIND solar wind spacecraft and the POLAR magnetospheric spacecraft that together allow studies of the solar wind-magnetosphere interaction. GGS is NASA's contribution to the ISTP.

global electrical circuit: The electrical circuit composed of phenomena that generate and dissipate electrical currents in Earth's atmosphere. The global electrical circuit includes regions of thunderclouds, which tend to drive current upward and charge the ionosphere positively, as well as fair-weather regions where the positive charge leaks back to the ground. Electrodynamic processes in the ionosphere and magnetosphere also influence the circuit.

Global Positioning System (GPS) satellites: A system of satellites orbiting Earth in a known configuration. By measuring the travel time for radio signals between the satellites and ground receivers, accurate information can be obtained on a user's location. The travel time between a GPS satellite and ground receiver is influenced by the ionosphere.

GOES: A series of geosynchronous orbiting weather satellites operated by NOAA.

GSFC: Goddard Space Flight Center, Greenbelt, Maryland.

H-alpha: Light at 656.3 nm emitted or absorbed preferentially by hydrogen atoms. When viewed through a filter at this wavelength, the details of surface features on the Sun such as filaments and plages become more visible.

heliosphere: The region of space dominated by matter from the Sun. It includes the Sun itself as well as the corona and solar wind, and extends beyond the orbit of Pluto to distances in excess of 50 AU.

heliospheric current sheet: A surface in the solar wind where there is a flow of electrical current that separates regions of oppositely directed interplanetary magnetic field. The origin of the current is the stretching out of the solar magnetic dipole field by the expanding solar wind.

HF: High-frequency, referring (as an adjective) to radio frequencies in the range of 3-30 megahertz.

IMF: Interplanetary magnetic field (see definition below).

IMP-8: One of the series of NASA's Interplanetary Monitoring Platforms.

infrared: Electromagnetic radiation with wavelengths in the range of 1 to 100 microns (micron = millionth of a meter).

injection: The sudden appearance in the near-Earth magnetosphere of greatly enhanced fluxes of energetic charged particles. Injections occur during magnetospheric substorms and appear to come from the magnetotail.

interplanetary magnetic field: The magnetic field carried out from the Sun by the solar wind, which permeates the entire heliosphere.

interplanetary space: A term referring to those portions of the

Space Weather Glossary

heliosphere in the vicinity of the solar ecliptic plane (the approximate plane of the planetary orbits), inside the orbit of the outermost planet of the solar system, but excluding the regions near the planets where the solar wind is influenced by the planet or its magnetosphere. Often, the term "interplanetary space" is loosely used as a synonym for "heliosphere."

ion: A positively charged particle produced when one or more electrons are stripped from an atom.

ionization: The process by which one or more electrons are stripped from an atom or molecule, leaving a positively charged ion and free electrons. Ionization can be caused by the absorption of electromagnetic radiation or by a "collision" with a sufficiently energetic particle.

ionosphere: The layer of Earth's upper atmosphere that is partially ionized by solar x-rays and ultraviolet radiation and energetic particles from space.

ionospheric currents: Electrical currents produced in the ionosphere by the relative motions of the ions and electrons.

ionospheric disturbances: Transient changes in ionospheric densities or currents, or the appearance of electron density irregularities, usually in association with the arrival of x-rays or ultraviolet bursts from solar flares or in association with aurora or geomagnetic activity.

ISTP: International Solar-Terrestrial Program. An international collaboration to study the solar-terrestrial connection. It includes an armada of Earth-orbiting spacecraft from the United States, Russia, Europe, and Japan, as well as ground-based observations and theory and modeling efforts.

jet, blue: A sporadic region of blue light that appears to move rapidly upward in the stratosphere above some thunderclouds.

JHUAPL: Johns Hopkins University Applied Physics Laboratory.

Space Weather Glossary

limb (solar): The edge of the Sun when viewed from a distance.

magnetic field: A force field whose direction can be visualized with a bar magnet and iron filings. A magnetic field can be created by a "permanent" magnet or by electric currents. Charged particles can move freely along magnetic fields, but may circulate around them rather than crossing them.

magnetic or geomagnetic storms: Periods when the magnetic field measured on Earth is highly disturbed, radiation environments intensify, auroras are produced, and electrical currents are enhanced in the ionosphere and induced in the ground. Magnetic storms are usually the magnetosphere's response to the passage of a coronal mass ejection. They generally last several hours to several days.

magnetosphere: The region surrounding Earth or another planet where the magnetic field of that planet tends to exclude the solar wind. Inside the magnetosphere the planetary magnetic field has a strong influence on charged particles.

magnetotail: The geomagnetic tail (see definition above).

MeV: Mega-electron-volt, or 1 million electron volts of energy.

molecule: A tightly bound combination of two or more atoms of any type.

MSFC: Marshall Space Flight Center, Huntsville, Alabama.

NASA: National Aeronautics and Space Administration.

neutron: An uncharged subatomic particle, similar in size and mass to a proton.

neutron monitor: Detectors operated on the ground to detect neutrons produced in collisions of energetic cosmic rays with the nuclei of atmospheric atoms. The neutron count rate is typically used as a measure of the intensity of galactic cosmic rays in Earth's neighborhood.

NOAA: National Oceanic and Atmospheric Administration.

NRL: Naval Research Laboratory.

NSF: National Science Foundation.

NSSDC: National Space Science Data Center.

nuclear reactions: Solar energy is generated in the central region of the Sun by nuclear transformation of hydrogen to helium, called fusion.

nucleus: The tightly bound protons and neutrons that form the core of an atom.

ozone: A gas whose molecules are composed of three oxygen atoms. Ozone strongly absorbs ultraviolet radiation.

ozone layer: The atmospheric region between about 10- and 50-km altitude where ozone molecules are most numerous, though their numbers are always much smaller than the numbers of other air molecules (mostly molecules of nitrogen and oxygen that have two atoms each). This layer approximately coincides with the stratosphere. It absorbs most of the solar ultraviolet radiation incident on the atmosphere, and thus protects plants and animals (including humans) from excessive ultraviolet radiation damage.

particle precipitation: The release of charged particles stored in Earth's magnetosphere into the atmosphere. The particles follow magnetic field lines, and when they strike the atoms of the upper atmosphere, they cause them to glow like a giant television screen, creating the aurora (northern and southern lights).

photon: A particle description of electromagnetic radiation, which can exhibit the behavior of either waves or particles.

photosphere: The thin layer of the Sun from which its visible light is emitted into space. When we look at the Sun we see the photosphere as its surface.

Space Weather Glossary

plages: Bright patches on the solar photosphere that are often associated with active regions and are primary emitters of solar ultraviolet radiation.

plasma: Ionized gas in which some electrons have been separated from their atoms or molecules. Plasma is electrically conducting and so is affected by magnetic fields. A plasma can behave in many ways like a fluid with any weak magnetic fields appearing to be "frozen in" or moving with the "fluid." The solar wind is an example of this type of plasma.

POLAR: A polar-orbiting spacecraft to observe the auroral zone particles, fields, and auroral emissions. One of NASA's contributions to the ISTP.

polar cap: The region inside the auroral oval where magnetic field lines from Earth extend into the distant magnetotail and sometimes into interplanetary space.

potential, electric: Another term for voltage.

proton: A positively charged subatomic particle. Together with neutrons, protons make up the nuclei of atoms. A single proton forms the nucleus of a hydrogen atom. The solar wind is made up primarily of protons and electrons.

radiation: A form of rapid energy transport, either by particles like fast-moving protons and electrons or by photons (electromagnetic radiation).

radiation belt: The Van Allen radiation belt of Earth or other similar trapped energetic particle regions at other planets having magnetic fields.

radiation dose: The amount of exposure to energetic electromagnetic or particle radiation. Radiation can cause microscopic damage by depositing energy deep in materials.

radio waves: Electromagnetic radiation with wavelengths above about 100 microns (micron = millionth of a meter).

Space Weather Glossary

range finding: The process of finding the distance (range) to some object, often using radio waves.

relativistic electrons: Electrons with velocities approaching the speed of light.

ring current: A current carried around Earth by charged particles trapped in Earth's magnetic field. The ring current intensifies when a magnetic storm or substorm occurs.

SAMPEX: Solar and Magnetospheric Particle Explorer spacecraft.

scintillation (radio): A fluctuation of the amplitude or phase of a radio signal caused by irregular structure of the medium through which it is propagating, like the ionosphere.

secondary particle: An energetic particle, like an electron or proton, that is produced when a cosmic ray or other highly energetic particle collides with an atom.

shock wave: A structure that stands in a medium (like the solar wind) ahead of an obstacle, when the obstacle speed is faster than the speed of waves in the medium. The "bow shock" stands in front of the magnetosphere, and interplanetary shocks precede fast coronal mass ejections as they travel from the Sun. At a shock, density and temperature increase, while velocity decreases to allow the medium to flow around the obstacle.

shortwave: An adjective referring technically to radio waves shorter than 80 meters, corresponding to a frequency of 3.75 megahertz or more. The term is often loosely used to refer to HF frequencies.

solar cycle: The regular increase and decrease in the level of solar activity, usually measured by the number of sunspots on the solar surface. The time between successive maxima or minima in the sunspot number is between 9.5 and 11 years. Periods of large sunspot number are called "solar maximum" periods, while periods of low sunspot number are called "solar minimum" periods.

solar energetic particle event: A burst of energetic ions (typically protons) or electrons accelerated at a solar flare site or at the shock preceding a fast coronal mass ejection in the solar wind.

solar flare: An abrupt release, from a localized region on the Sun, of large amounts of energy in ultraviolet light, x-radiation, and occasionally gamma radiation. Flares usually occur in or near complex sunspot regions and may be related to the rearrangement of the intense magnetic fields there.

solar physics: The study of conditions and processes throughout the Sun and its atmosphere.

solar radio burst: An impulsive intensification of radiation from the Sun at radio frequencies. Radio bursts are often used as indicators of solar disturbances such as flares and coronal mass ejections.

solar wind: The ionized atmosphere above the solar surface that has such a high temperature it can overcome the Sun's gravity and expand outward at supersonic speeds.

solar wind stream: High-speed solar wind originating in a coronal hole.

spacecraft charging: Electrical charge obtained by a spacecraft immersed in a plasma. Different materials will be charged to different levels, making discharges on the spacecraft possible. Charging levels tend to increase with the energies of the particles making up the plasma. Also deep dielectric charging.

space physics: The study of conditions and processes throughout space in the environment above the bulk of the atmosphere. Its domain includes the Sun, interplanetary medium, magnetosphere, upper atmosphere, and ionosphere.

sprite: A weak reddish flash of light at heights of 60 to 90 km associated with thunderstorm electrical activity.

stratosphere: The region of the atmosphere at altitudes of about 10 to 50 km, above the heights of usual meteorological phenomena.

stream interaction regions: Regions of compressed solar wind plasma and magnetic field that form when a faster solar wind stream runs into a slower flow ahead of it. At heliospheric distances beyond the Earth's orbit, these compressions steepen into huge interplanetary shock waves spiraling away from the Sun.

substorm: A sudden (tens of minutes) dynamic reconfiguration of the magnetosphere in which energy stored in the magnetic field is converted into charged-particle energy. The process involves enhanced auroral emissions, strong disturbances in the high-latitude magnetic field, and the sudden appearance of increased numbers of energetic particles in the magnetosphere.

sudden ionospheric disturbance: A rapid increase in the electron density of the lower ionosphere produced by solar-flare x-rays that can sometimes cause, among other things, severe shortwave radiowave absorption.

sunspot: A dark region on the solar surface where the magnetic field is so strong that the flow of energy from below is suppressed. Without this replenishing energy the sunspot cools below the average temperature and appears much darker than surrounding areas, although it would appear bright against a truly dark background.

sunspot number: The number of sunspots on the visible solar surface is counted by many solar observatories and is averaged into a single standardized quantity called the sunspot number. This number has been determined from observations dating back to 1620.

UHF: Ultrahigh frequency, referring here to radio frequencies in the range of 300 to 3000 megahertz.

ultraviolet (UV): Electromagnetic radiation with wavelengths in the range of 0.01 to 0.4 microns (micron = millionth of a meter).

upper atmosphere: A term used with different meanings in different contexts. It can denote those portions of the atmosphere bounded from below at either 10, 50, 80, or 100 km and from above at anywhere from about 500 km out to the magnetopause.

USAF: United States Air Force.

Van Allen radiation belts: A donut-shaped region in Earth's magnetosphere that contains a high density of energetic charged particles trapped in the dipole field of the planet.

VHF: Very high frequency, referring here to radio frequencies in the range of 30 to 300 megahertz.

WIND: A spacecraft that measures the properties of the solar wind incident on the magnetosphere. One of NASA's contributions to the ISTP.

x-ray: Electromagnetic radiation with wavelengths in the range of 0.00001 to 0.01 microns (micron = millionth of a meter).

Space Weather: A Research Perspective

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Support for this project was provided by Contract NASW 4627 between the National Academy of Sciences and the National Aeronautics and Space Administration.

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