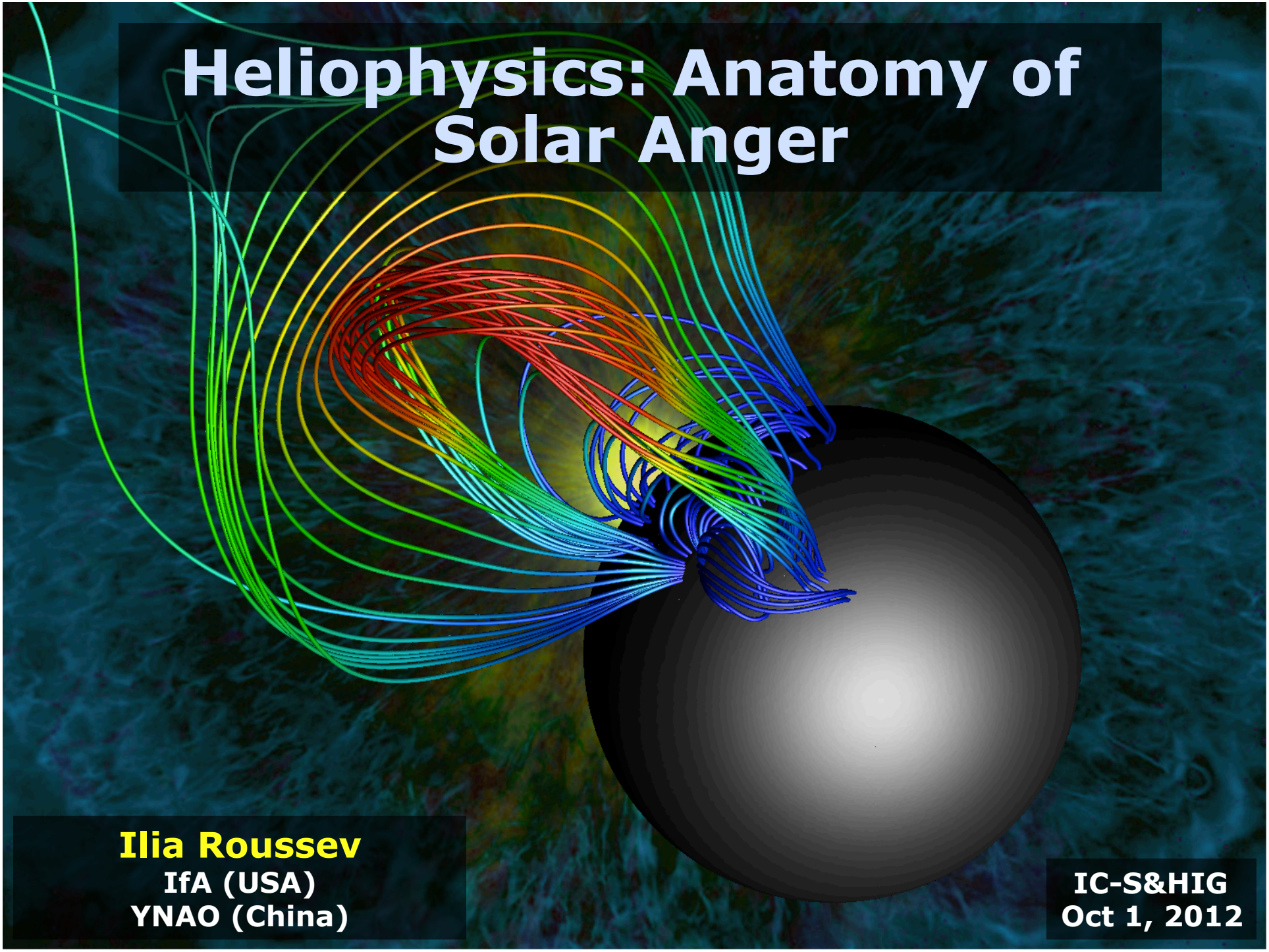
Heliophysics: Anatomy of Solar Anger



Ilia Roussev
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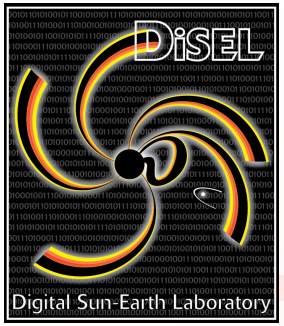
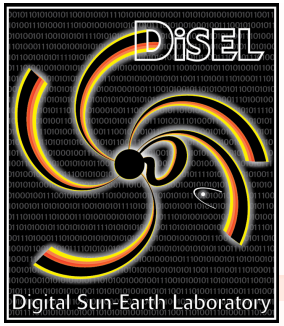
IC-S&HIG
Oct 1, 2012



Little Bit of History…

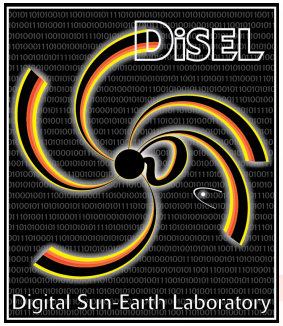
- During the Space Race (1957-1975) it was realized that "weather" in outer space can be quite stormy.
  - In 1958, first NASA satellite, Explorer 1, discovered Van-Allen radiation belts.
    - Geiger counter onboard spacecraft knocked out.
  - In 1959, Soviet satellite Luna 1 provided first detection of solar wind.
  - In 1972, major solar storm occurred between Apollo 16 (Apr) and Apollo 17 (Dec) missions.
    - Apollo 17 mission would have suffered massive failure if astronauts were to walk on Moon on Aug 4 instead of Dec 11.
    - While on the Moon for few hours, astronauts Schmidt and Cernan would have been hit by an incredible blast of radiation well over 1,000 rem! (Accumulated radiation in a typical 70-year lifespan is 0.25 x 70 = 18 rem.)
  - In 1973, new solar phenomenon named *coronal transients* (later on renamed to *coronal mass ejections*) was discovered during the Skylab mission.
- Since 1972, no more NASA astronauts walked on the Moon again…



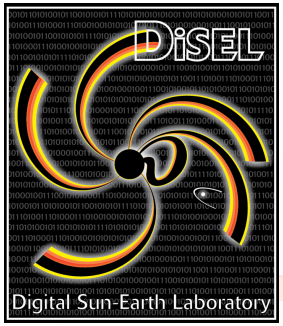
What Is Heliophysics?

- **Heliophysics** encompasses the study of Sun's heliosphere and objects that interact with it (planetary atmospheres and magnetospheres, interstellar medium, etc.).
- **Heliophysics** combines several other disciplines, including magnetospheric physics, ionospheric physics, and plasma physics.
- **Heliophysics** is closely tied to the study of **Space Weather** and the phenomena that affect it.
- **Space Weather** is the concept of changing environmental conditions in near-Earth space.

System Sun–Earth is tightly coupled which is why there can be stormy weather in outer space!



How Does the Sun Affect Us?



Psychoanalysis of Sun

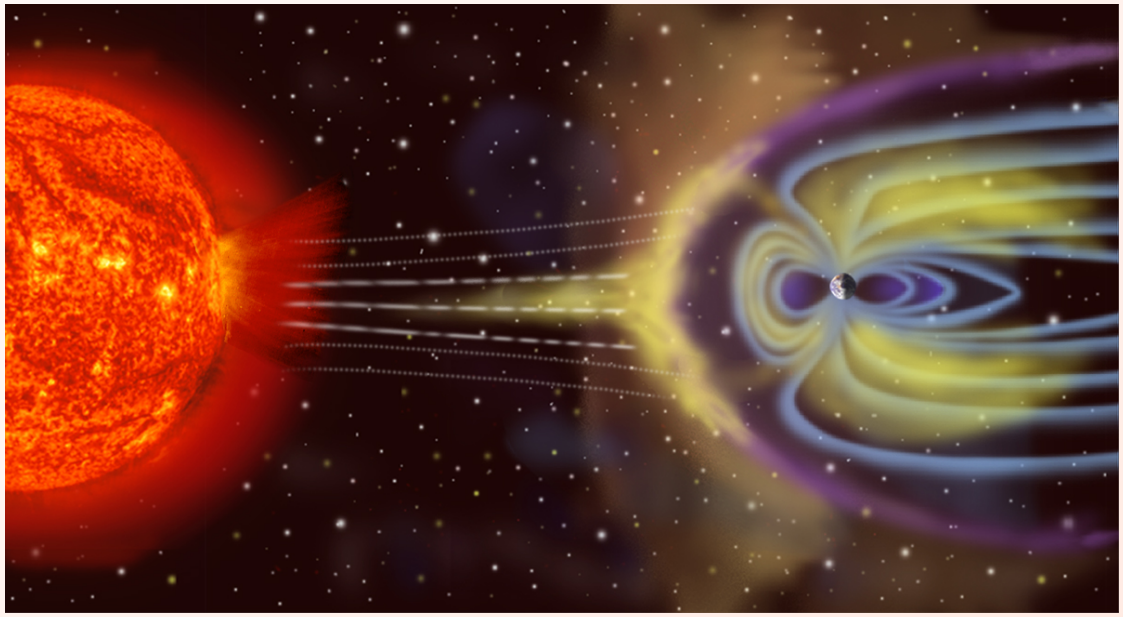
What do we know about Sun?

- Sun suffers from **MANIC-DEPRESSIVE PSYCHOSIS:** this behavior is characterized by occurrence of mania/euphoria (solar maximum) alternated with bouts of depression (solar minimum).
- Cycle of this behavior is 11 years, also known as **Solar Cycle**.

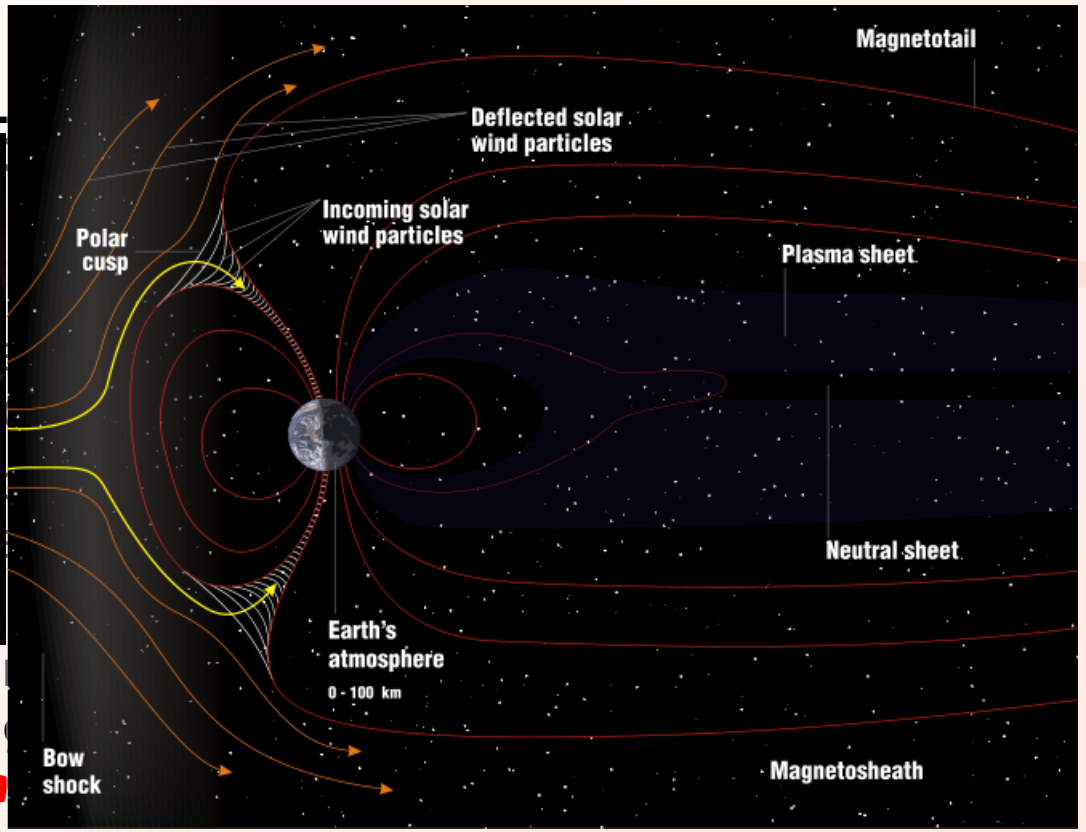
What is difficult to predict about Sun's behavior?

- **SOLAR ANGER** which includes two phases:
  - Misplaced anger (accumulative, or implosive, stage for later explosive behavior).
  - Excessive anger (explosive phase – yields **Flares** and **Solar Eruptions**).

Living With Active Sun



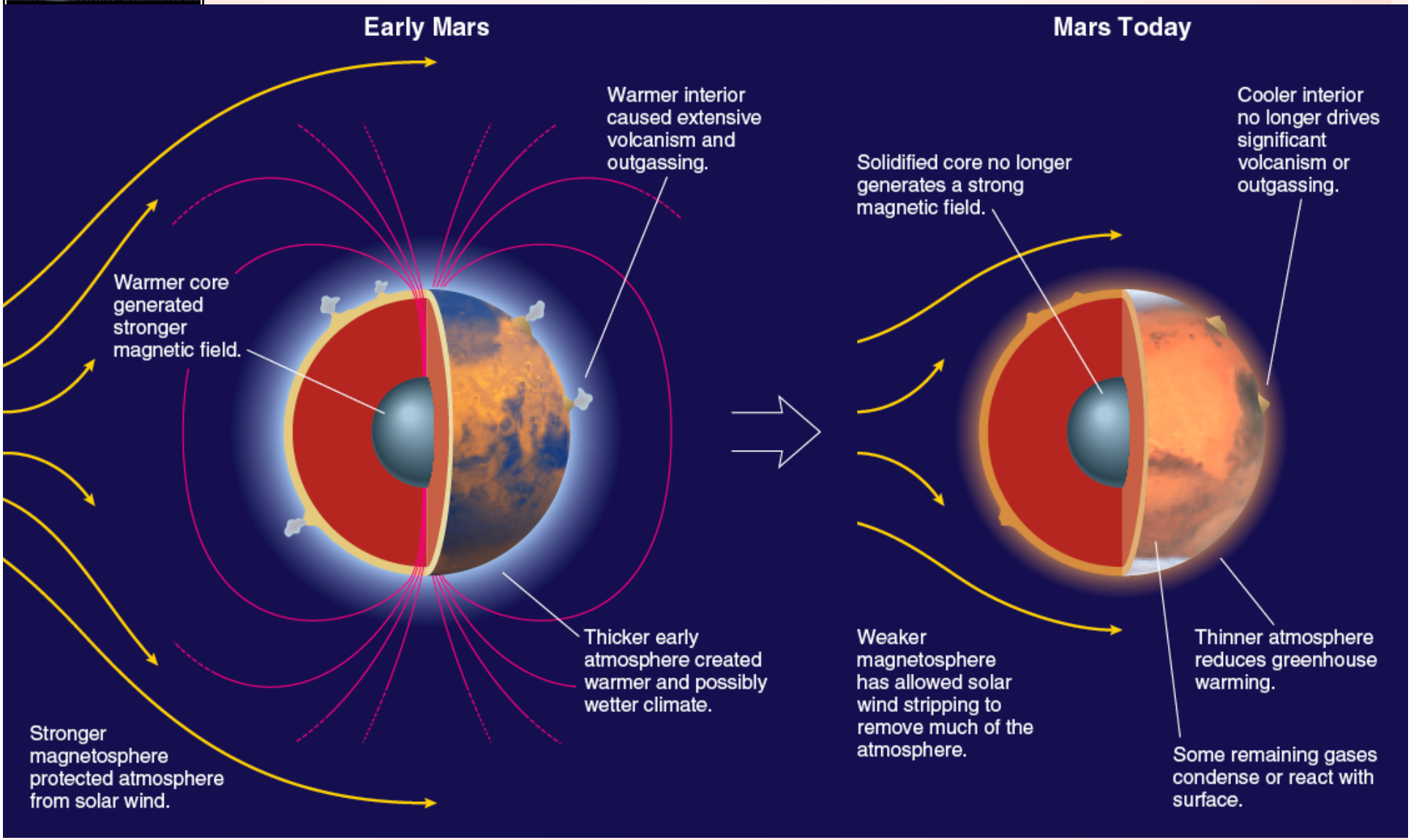
- Sun's atmosphere expands into space to form the ***solar wind***.
- Throughout its 11-year ***cycle of activity***, Sun produces numerous ***flares*** and ***coronal mass ejections***, which perturb the steady solar wind flow and may create ***shock waves*** in heliosphere.
- Shock waves in heliosphere act as powerful ***accelerators*** of charged particles.

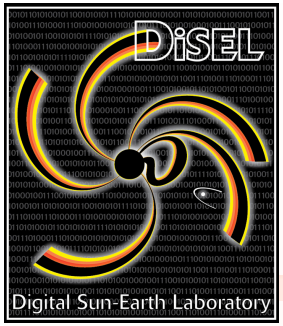


- Some of this electric curre
  atmosphere, which can li
  mysterious and beautiful ***a***
- Earth's magnetosphere and atmosphere act like ***protective shields*** for us from the solar wind and other kinds of ***solar and cosmic radiation***.
  - Mars might have been habitable world now if it did not lose its large-scale magnetic field few billion years ago!

One of our principal goals at DiSEL is to better understand and predict the space environment conditions in outer space, the *Space Weather*.

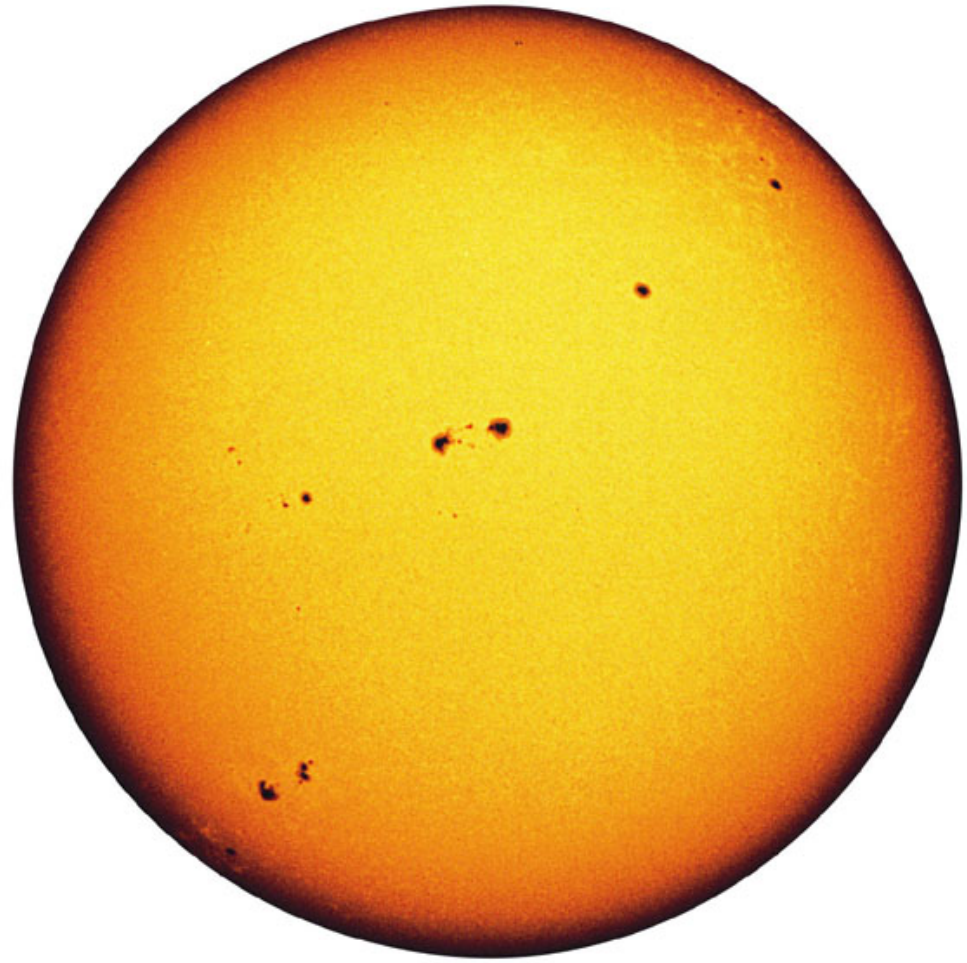
How Did Mars Change?





Sources of Solar Activity

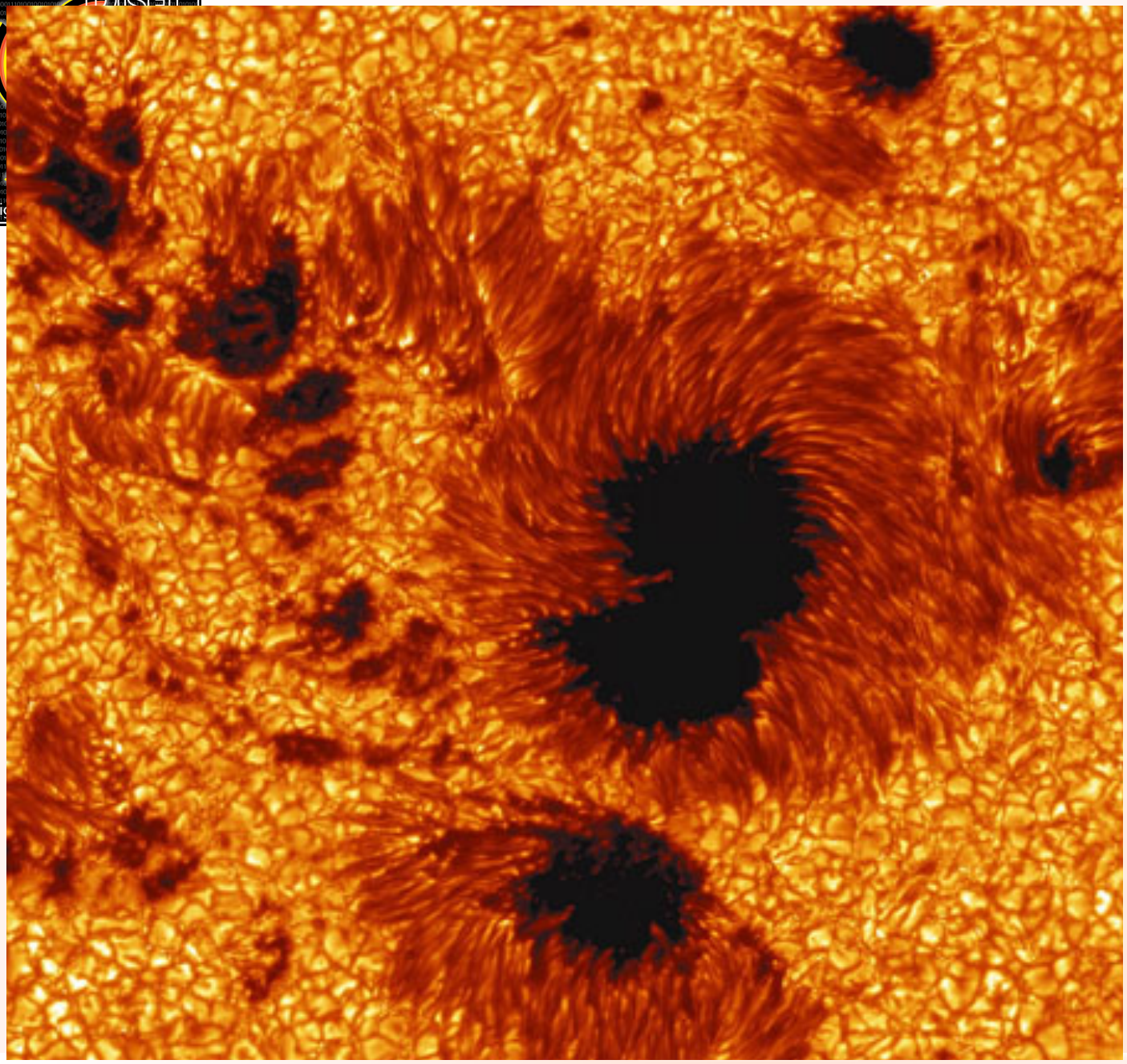
Sun: Big, Powerful, Dangerous



- Sun serves to provide light in the solar system… as well as danger for life and technology.
- Sun is the most powerful source of EM and particle radiation.
- Sun is biggest laboratory in solar system.
- Unlike any other laboratory on Earth, we cannot conduct controlled experiments on Sun.
- That is why it is very difficult to study Sun.

Sun's "Beauty Spots"

- ***Sunspots***, like those seen as dark areas in visible-light images of the Sun, are responsible for the intense ***X-ray emission*** from the corona.
- Sunspots are ***active regions*** where hot, dense material (plasma) becomes energized to yield ***flares*** and ***coronal mass ejections.***



Sunspots:

Are ***cooler*** (and that is why ***darker***) than other parts of the Sun's surface (~6,700 °F)

These are regions of ***strong magnetic field!***

Magnetic field suppresses motion of hot rising gas from below the surface.

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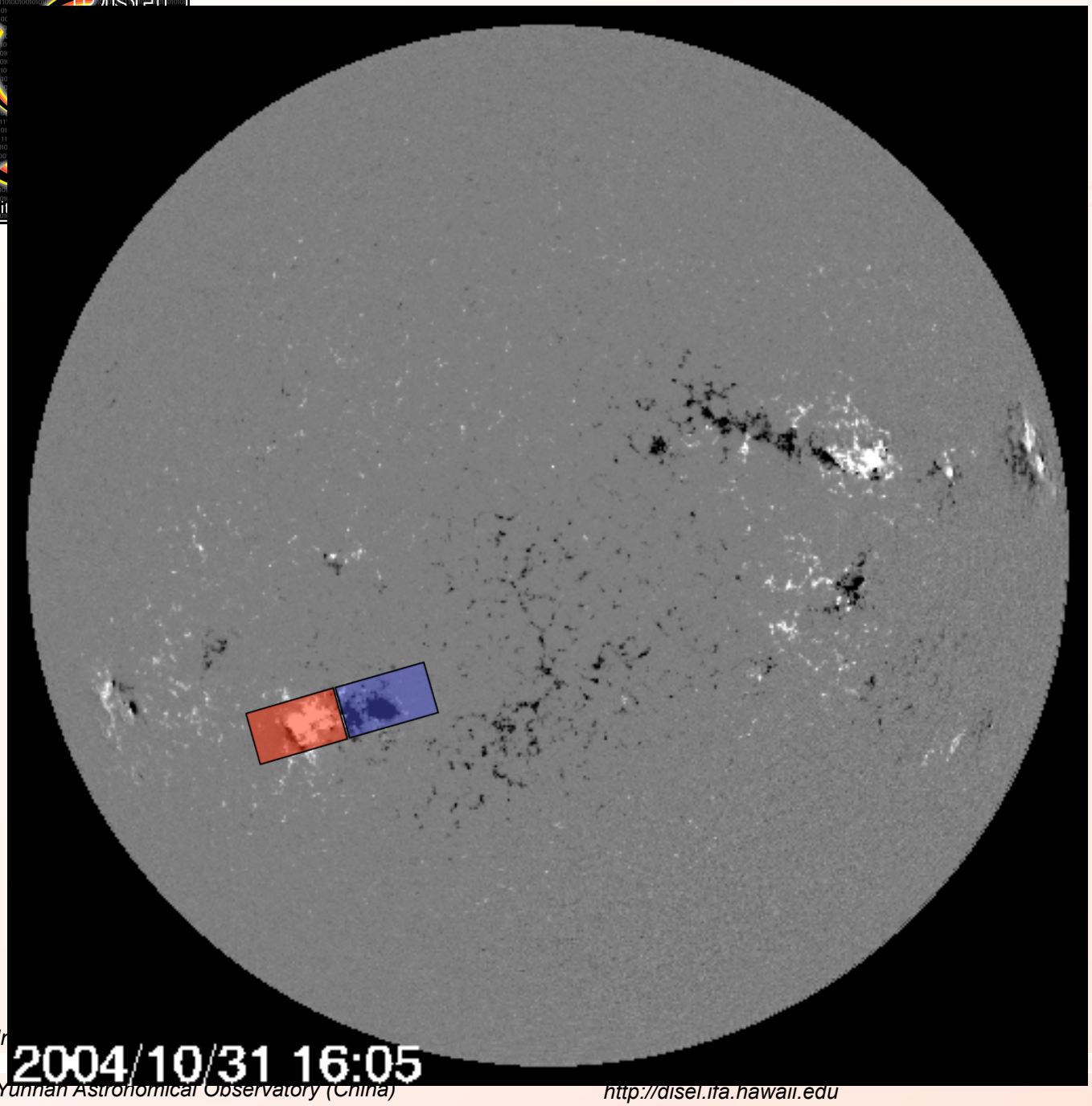
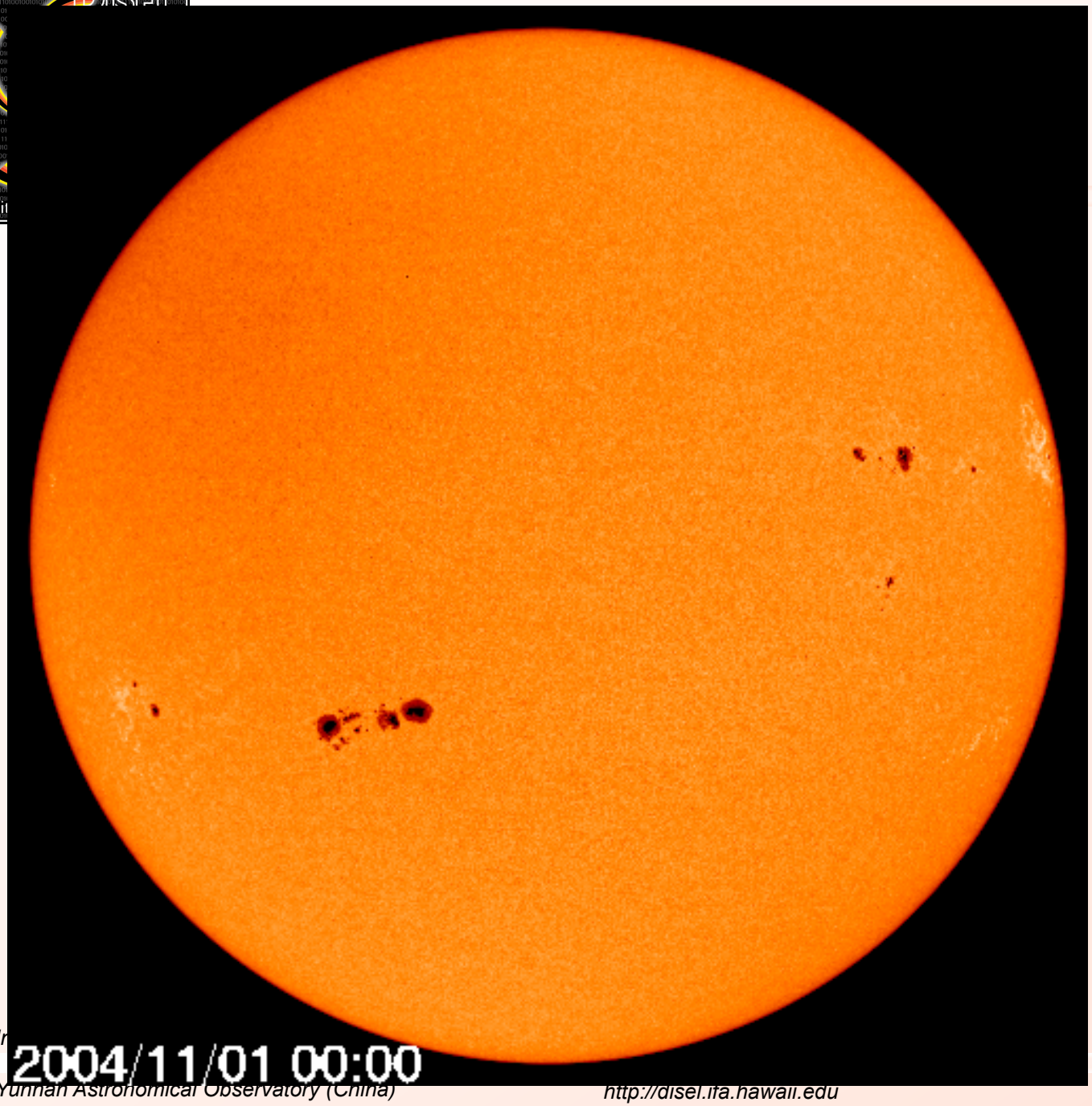
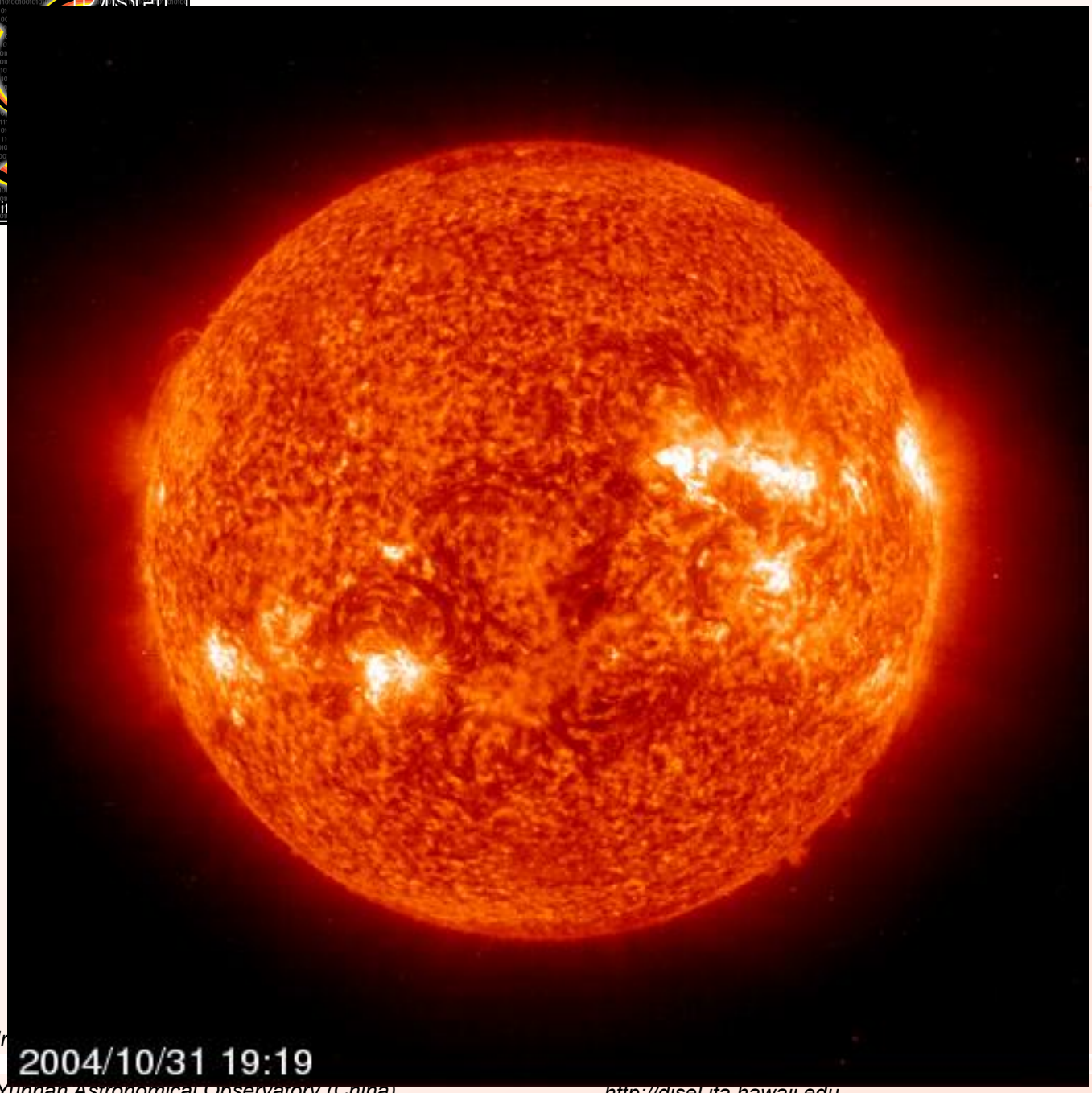


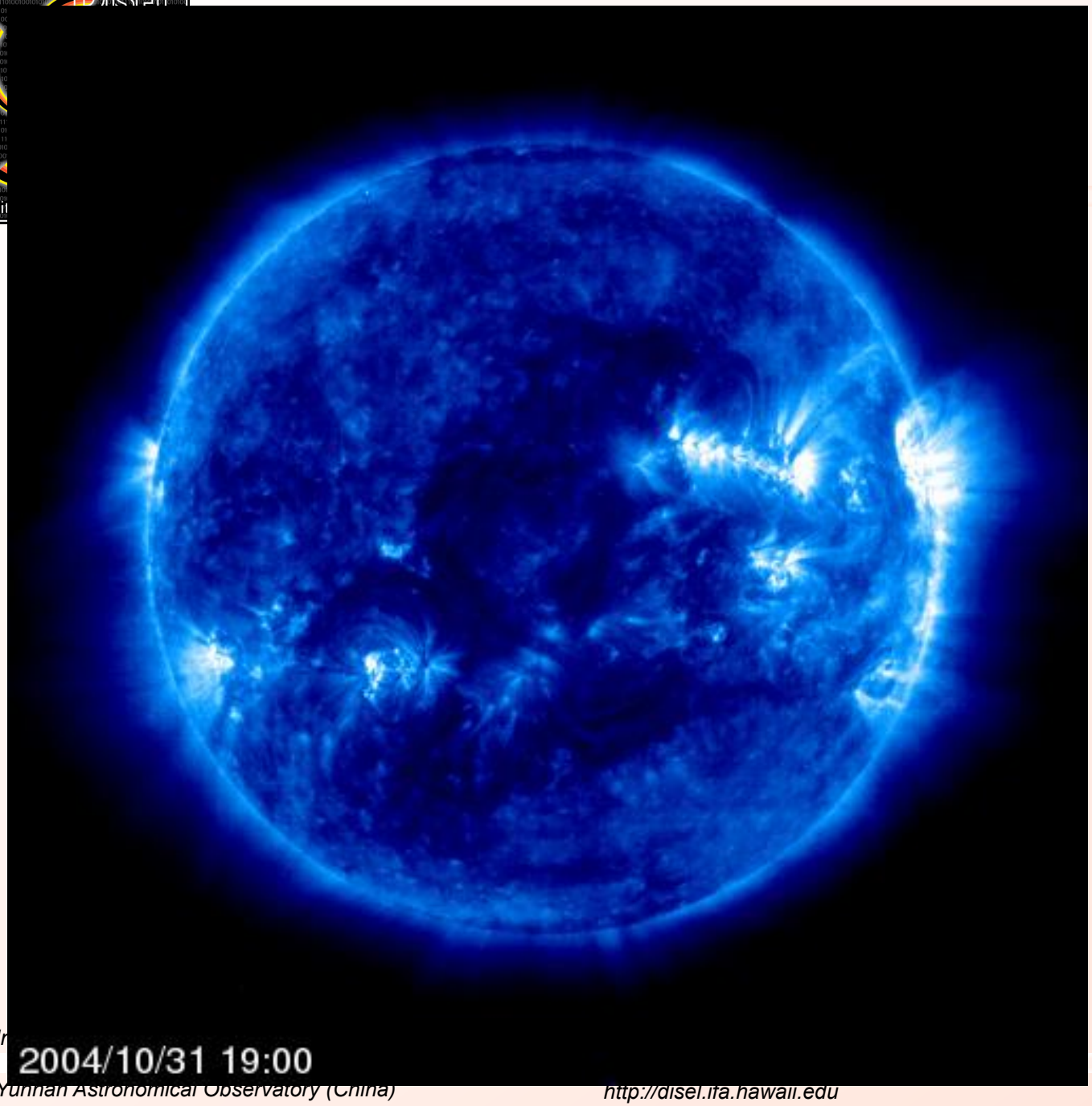
Photospheric Magnetic Field – SOHO/MDI



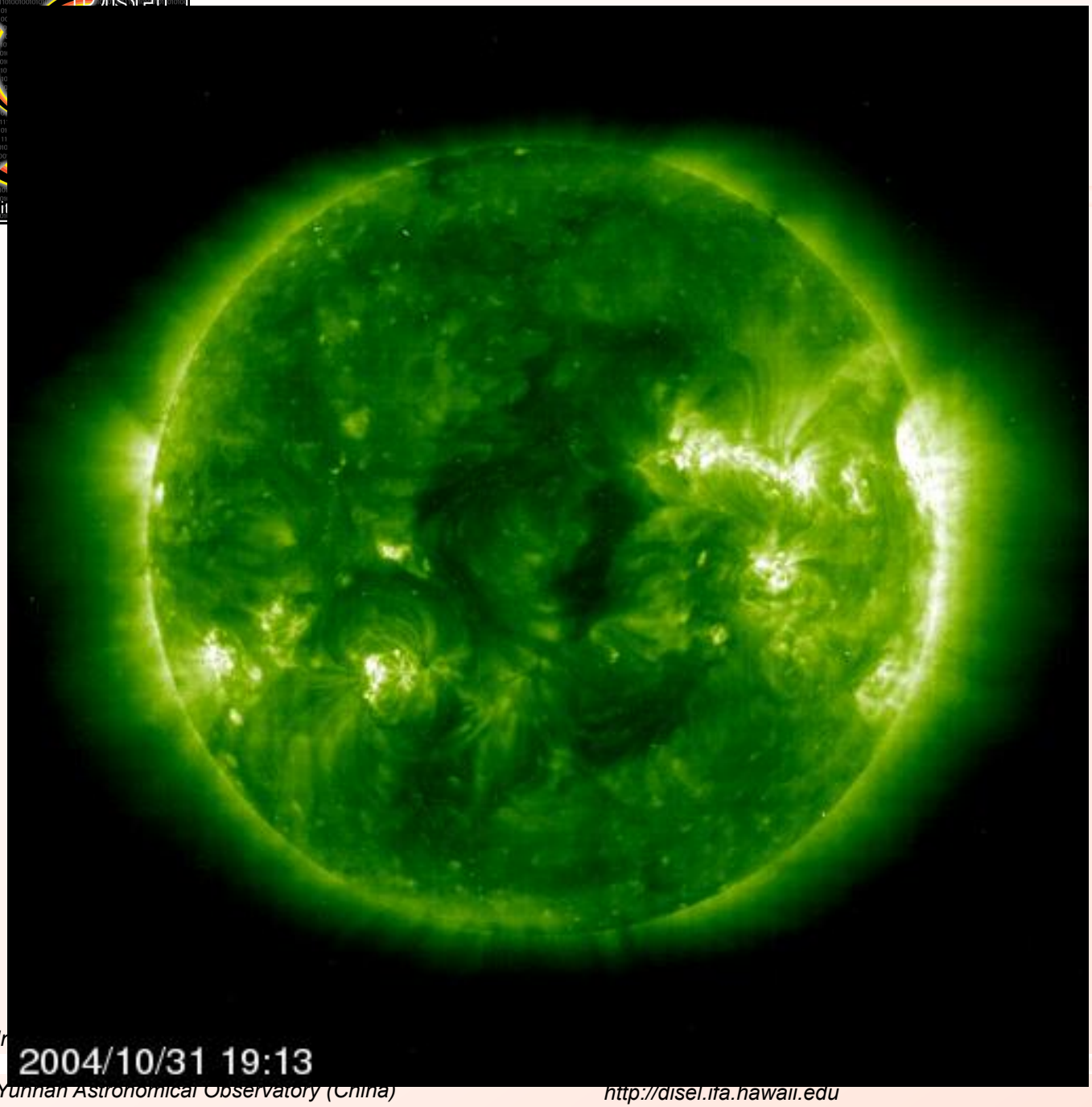
SOHO/MDI Continuum



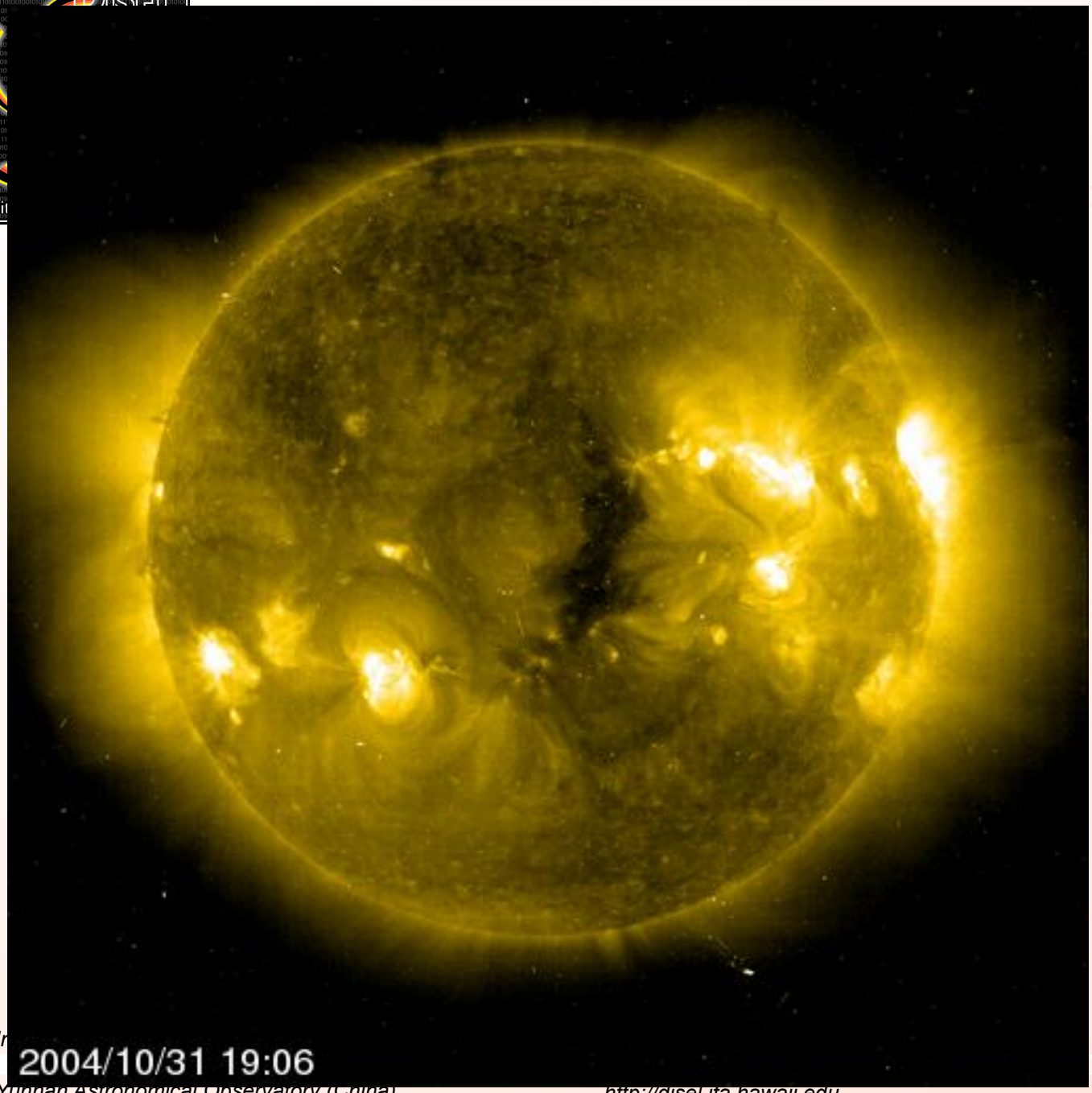
Chromosphere @ 5-8x10^{4}K – SOHO/ EIT 304Å



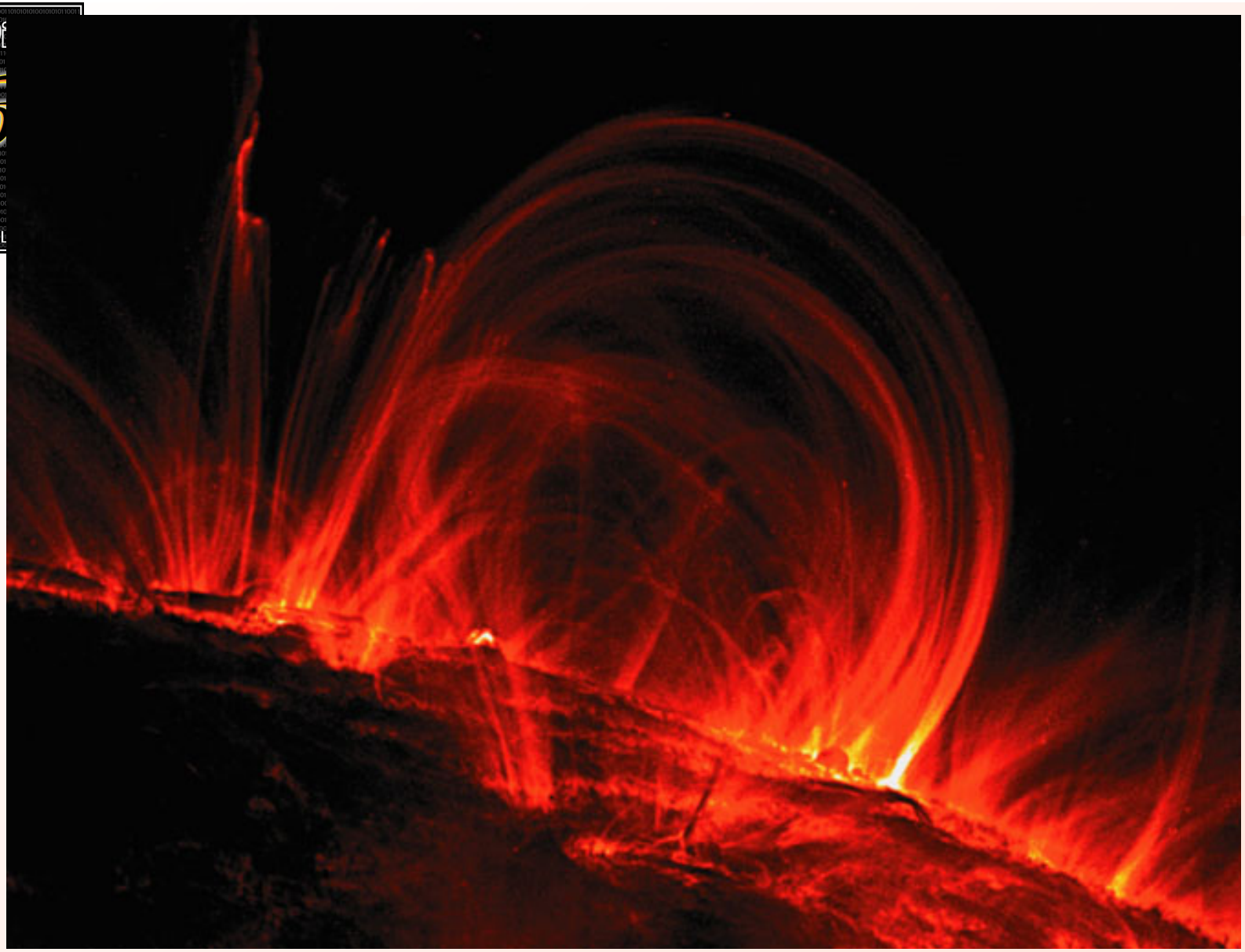
Corona @ 1.3MK – SOHO/EIT 171Å



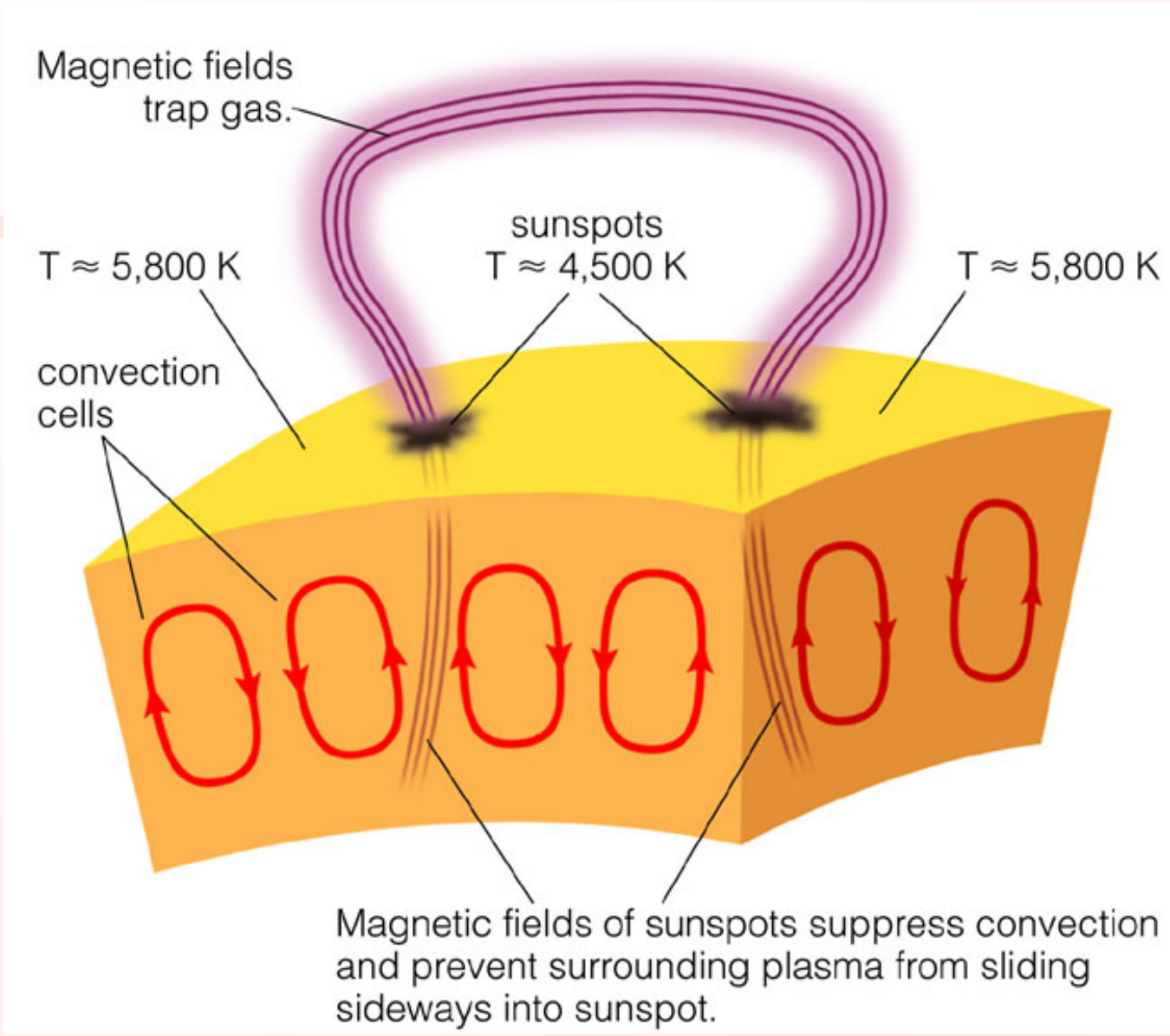
Corona @ 1.6MK – SOHO/EIT 195Å



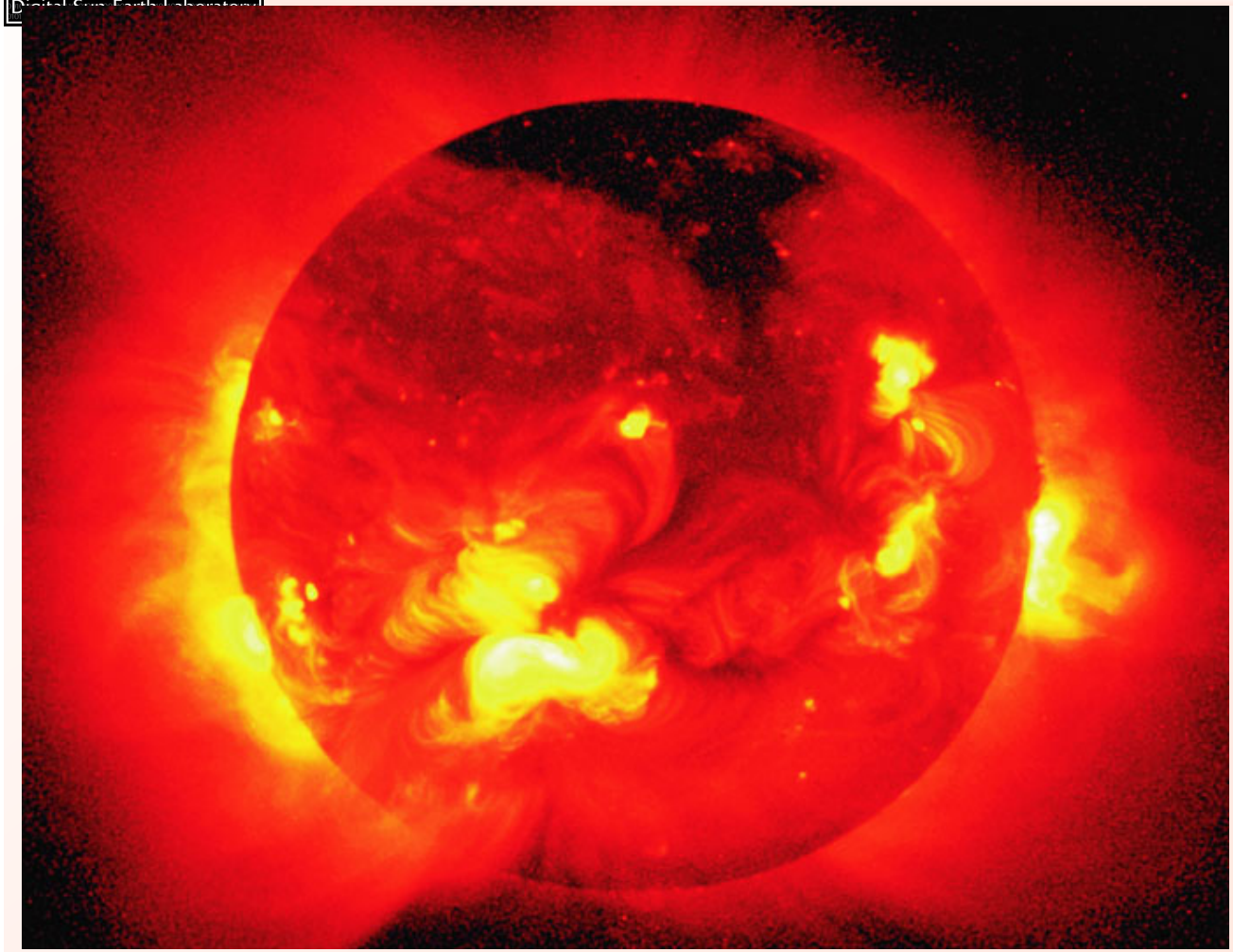
Corona @ 2.0MK – SOHO/EIT 284Å



Loops of bright gas in solar corona connect _sunspot pairs_.

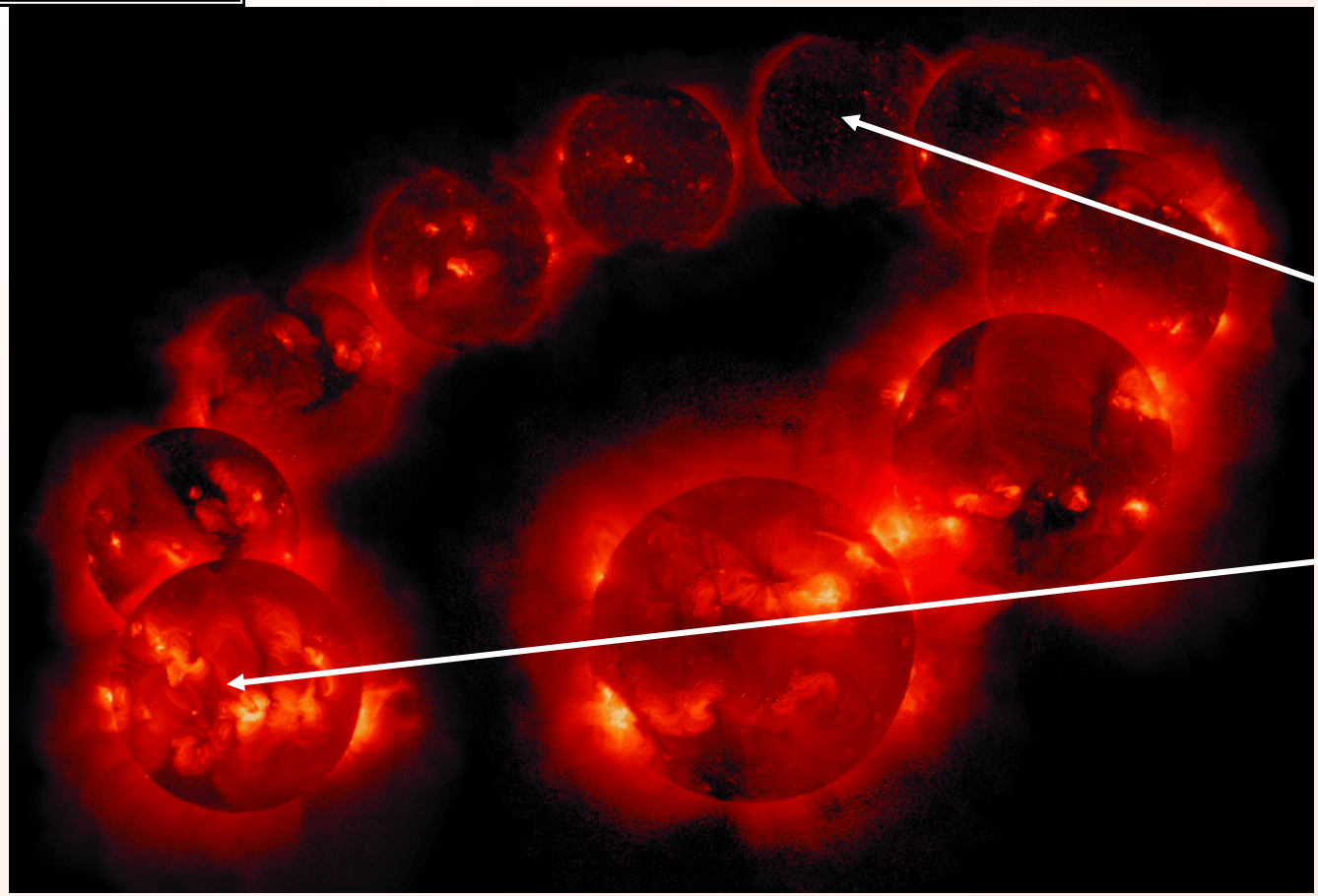


Coronal loops trace magnetic field lines.



Solar corona appears bright in X-ray images in places where magnetic field traps hot gas of solar corona.

Solar Cycle



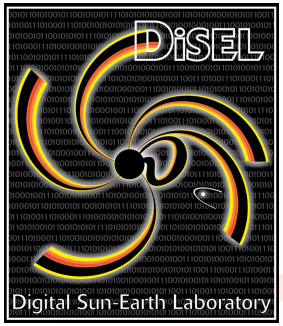
Sun is now approaching maximum of Solar Cycle 24!

Sun follows an ***11-year*** cycle of activity called the ***solar cycle***.

There are times when the Sun is not very active – ***solar minimum***.

About 6 years later, the Sun becomes very active – ***solar maximum***.

Solar cycle is related to the generation of magnetic field inside the Sun – ***solar dynamo***.



Consequences of Active Solar Magnetism: Flares and Coronal Mass Ejections

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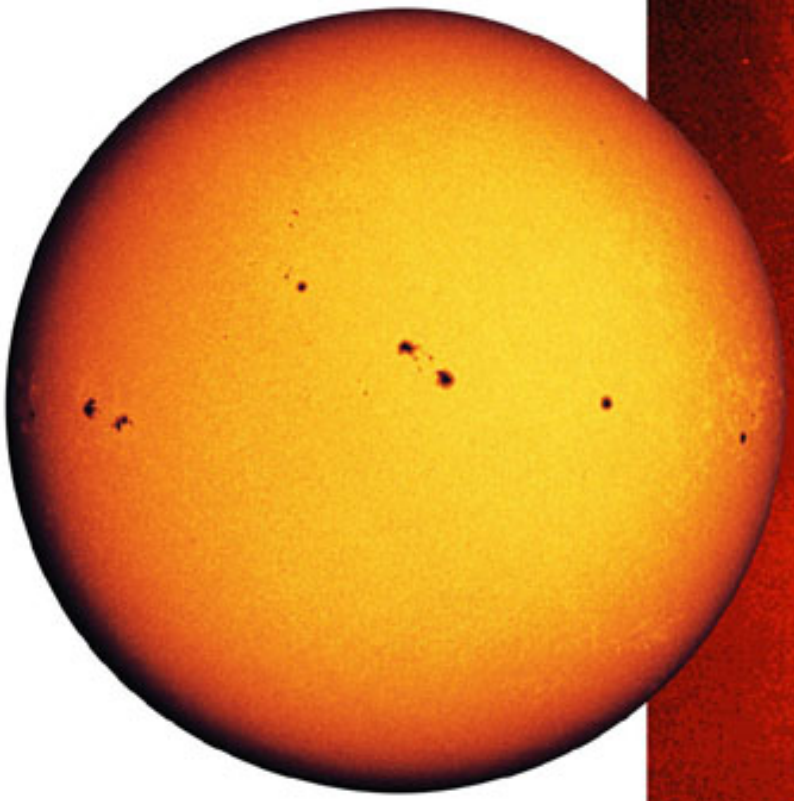
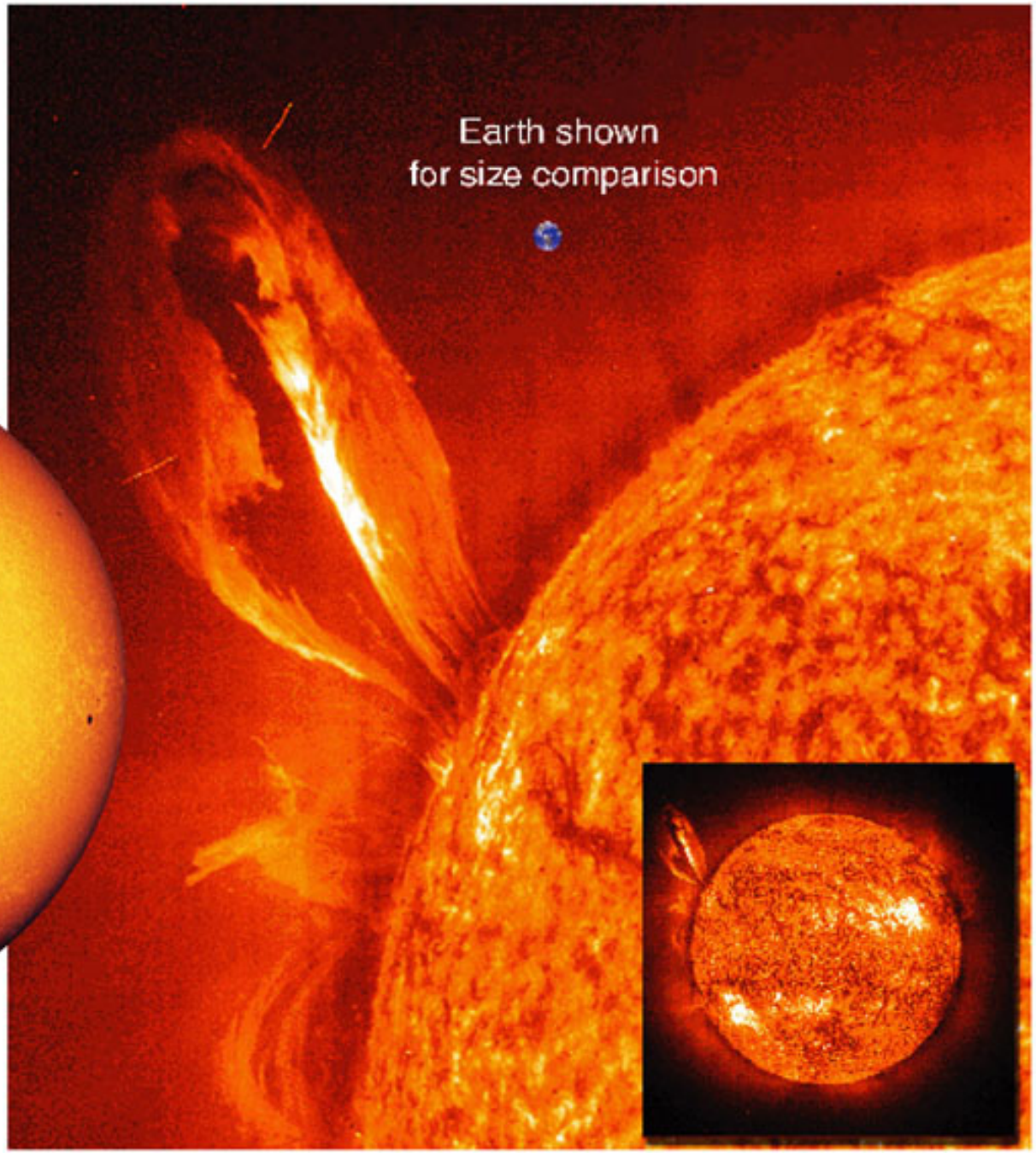
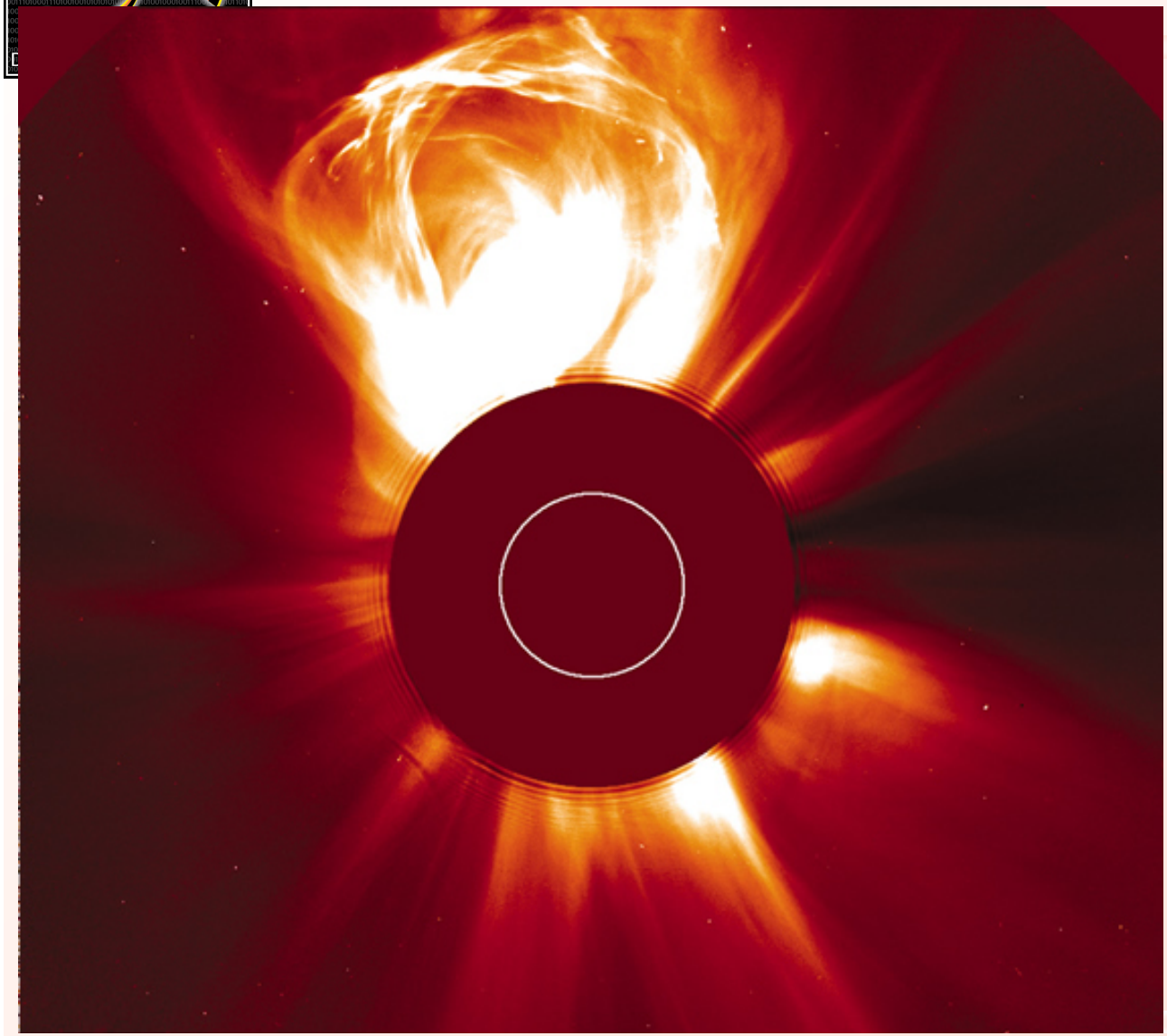
Oct 1, 2012

Sun powers flares and CMEs





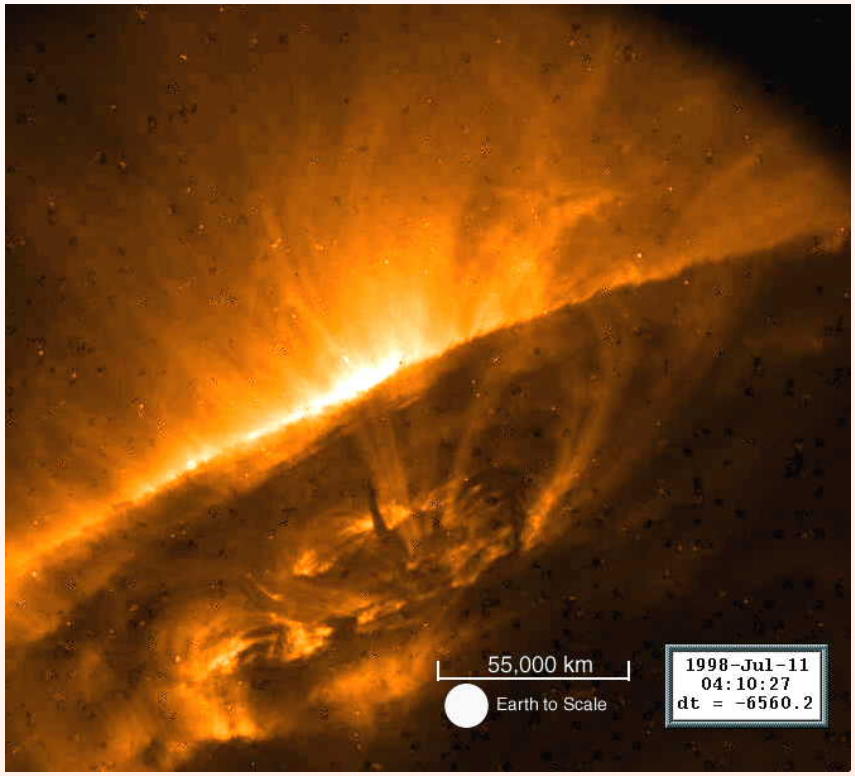


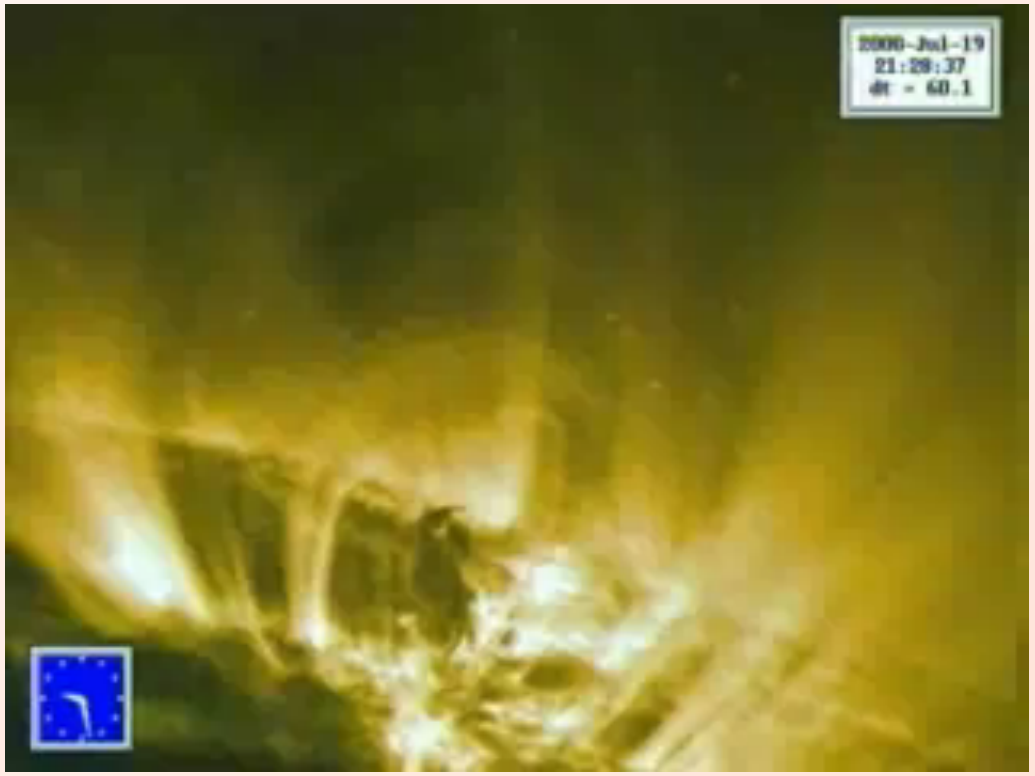
Coronal mass ejections are large-scale expulsions of ***coronal material*** and ***magnetic field*** into interplanetary space.

The also generate bursts of ***energetic charged particles*** that traverse the solar system.

CME Observations

Coronal Mass Ejections (CMEs) are the most powerful manifestation of solar activity in which vast amounts of magnetic flux (10^{21-23} Mx) and solar plasma (10^{15-16} g) are ejected from low corona into heliosphere.





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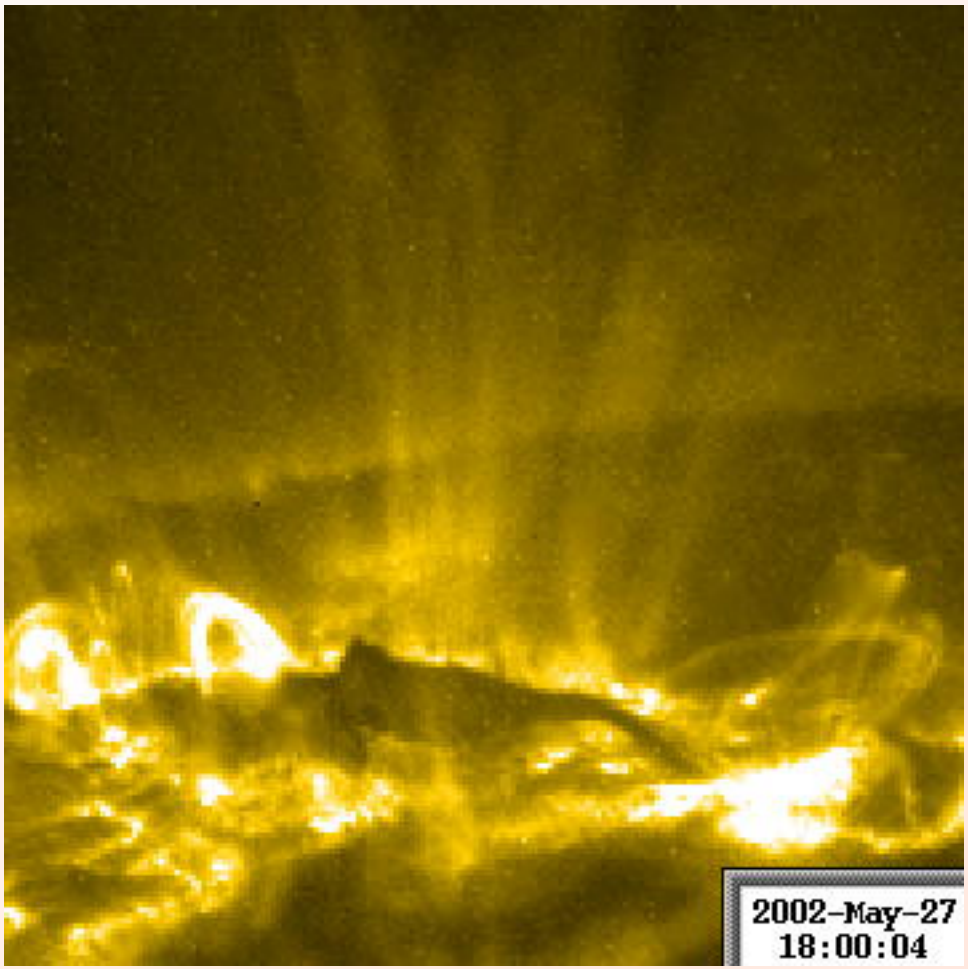
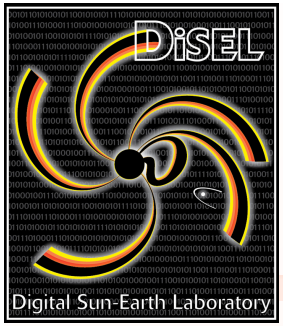
CME Observations (Cont.)

- CMEs are full-fledged solar phenomenon.
- CMEs and solar flares are interrelated.
  - ~20% of large flares are associated with CMEs.
- CMEs may be important for reconfiguring large-scale magnetic field of the Sun.

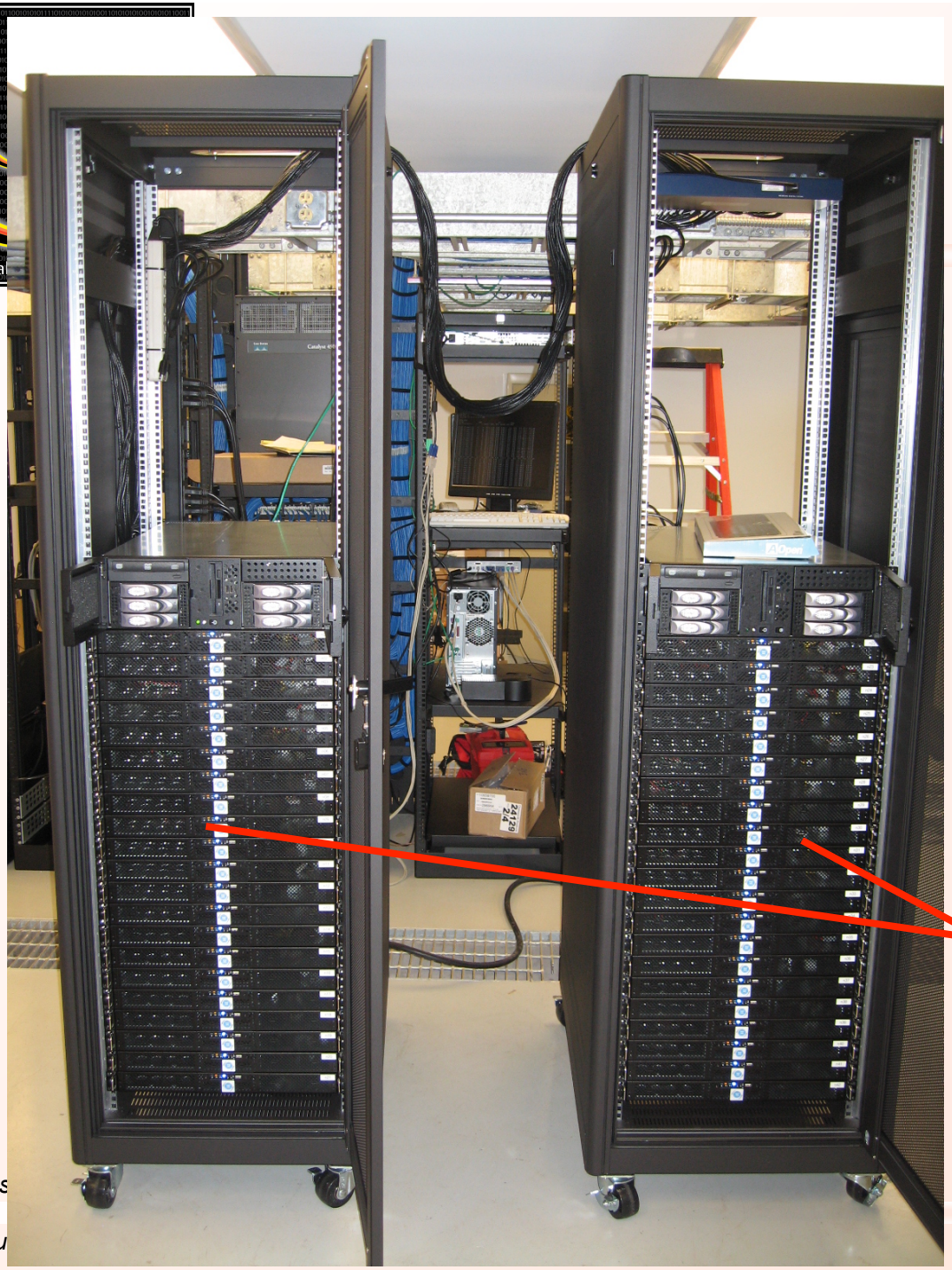
Failed CMEs



Not all CMEs succeed, some fail.



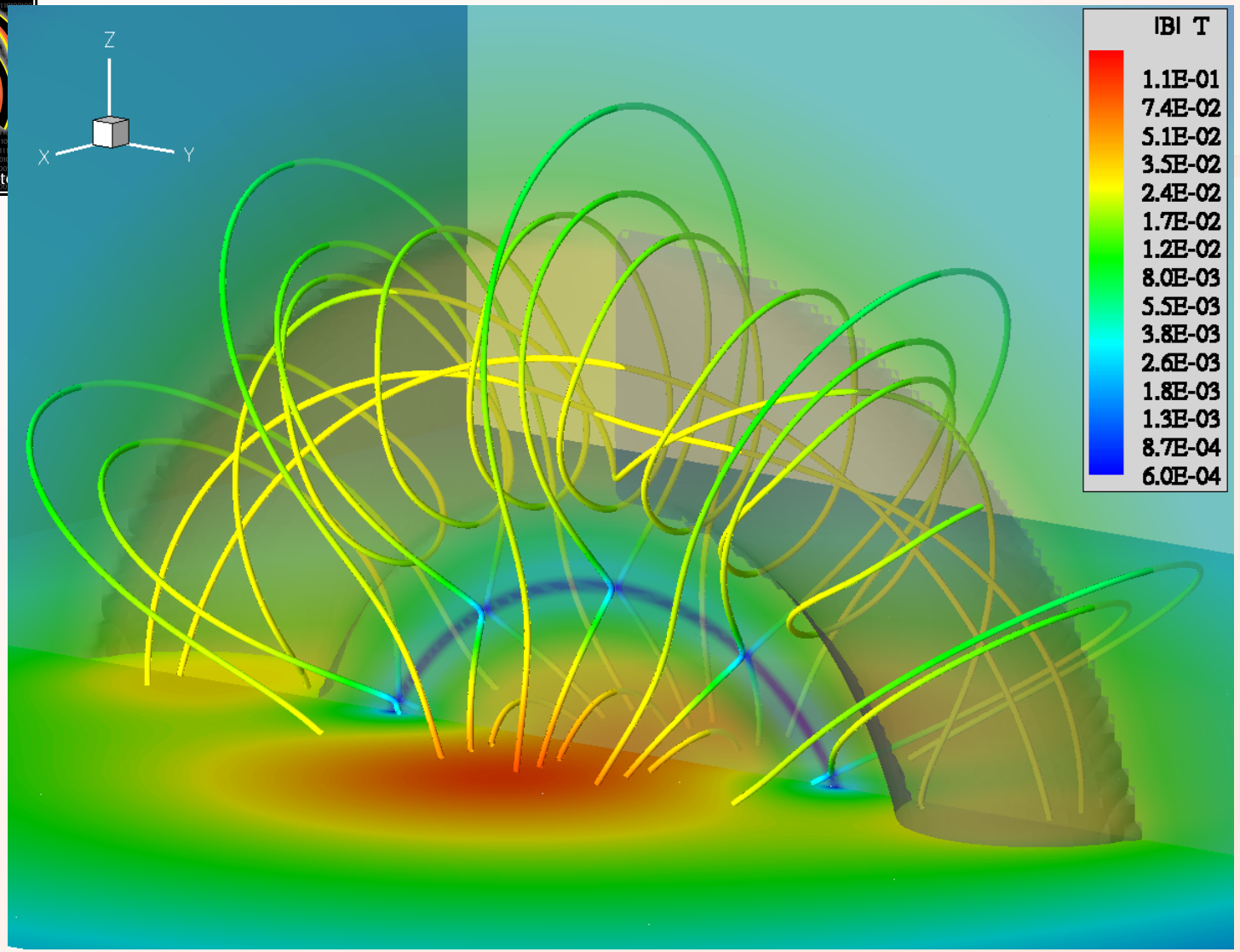
How Do We Study CMEs at IfA and YNAO?



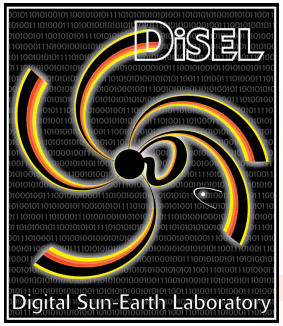
We develop sophisticated numerical codes describing the physical processes taking place in the solar atmosphere.

We run these programs on computer clusters, or supercomputers.

One such cluster, Jotun, operates at the IfA's building on Maui.



Model of CME's magnetic field.



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Welcome to the Digital Sun-Earth Laboratory (DiSEL)

The Digital Sun-Earth Laboratory (DiSEL) is a group of scientists from the US and Europe with common research goals. They investigate, by means of 3-D data-driven computer simulations: (i) the initiation and evolution of coronal mass ejections (CMEs); (ii) the production and transport of solar energetic particles (SEPs); (iii) the physical causes of coronal heating and the origin of the solar wind; and, (iv) the solar drivers of Space Weather and other topics pertaining to Heliophysics.

DiSEL is headed by Dr. Ilia Roussev from the Institute of Astronomy (IfA) at the University of Hawaii at Manoa (UH). The virtual Lab consists of Dr. Noe Lugaz (University of New Hampshire), Dr. Elena Moise (Institute of Geodynamics of the Romanian Academy), Dr. Cooper Downs (Predictive Sciences, Inc.), and graduate students Mrs. Nada Al-Haddad (K.U. Leuven), Mr. Gabriel Dima (UH IfA), and Mrs. Katie Whitman (UH Physics).

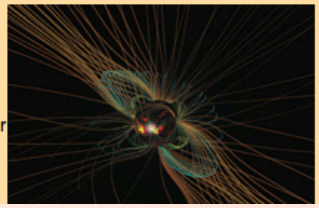
(Click logo to download or view larger version.)

"Explaining fast ejections of plasma and exotic X-ray emission from the solar corona". *Nature Physics*, 23 September 2012

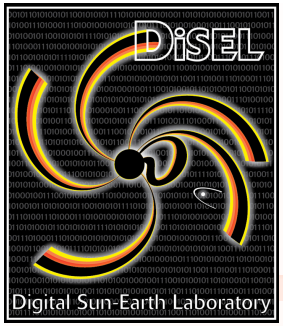
New science from DiSEL scientists and collaborators has been published in *Nature Physics* on September 23, 2012, as announced in a press release from the University of New Hampshire. The paper (abstract below) can be accessed online at the Nature Physics link http://www.nature.com/nphys/journal/vaop/ncurrent/abs/nphys2427.html. A "News and Views" article describing the new science, entitled **Coronal Mass Ejection The Birth of a Solar Eruption** written by Stefaan Poedts, also appears in the latest edition of *Nature Physics*. The second article can be accessed at this link: http://www.nature.com/nphys/journal/vaop/ncurrent/full/nphys2446.html.

Explaining fast ejections of plasma and exotic X-ray emission from the solar corona

Ilia I. Roussev, Klaus Galsgaard, Cooper Downs, Noé Lugaz, Igor V. Sokolov, Elena Moise & Jun Lin
Nature Physics (2012) doi:10.1038/nphys2427

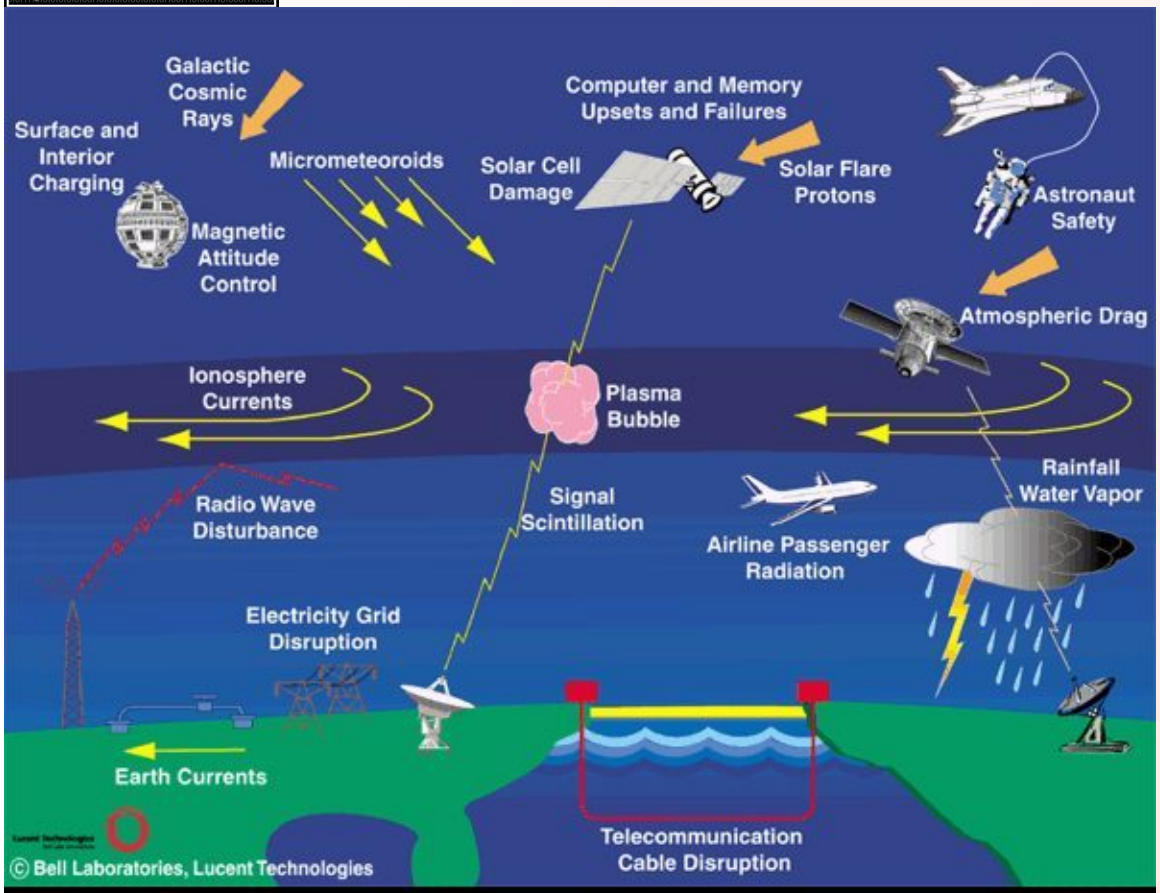


Coronal mass ejections (CMEs) are the most energetic events in the solar system and can make near-Earth space a hazardous place. However, there is still no consensus as to what physical mechanisms are responsible for these solar eruptions. Here we demonstrate a fundamental connection between the emergence of magnetic flux into the solar atmosphere and the formation of solar eruptions. We present a model of the dynamics of the solar atmosphere and inner solar wind region using a realistic representation of the electric field at the photosphere, calculated from flux-emergence computer simulations, as the boundary conditions. From this, we show how



Impacts of Space Weather on Life and Technology

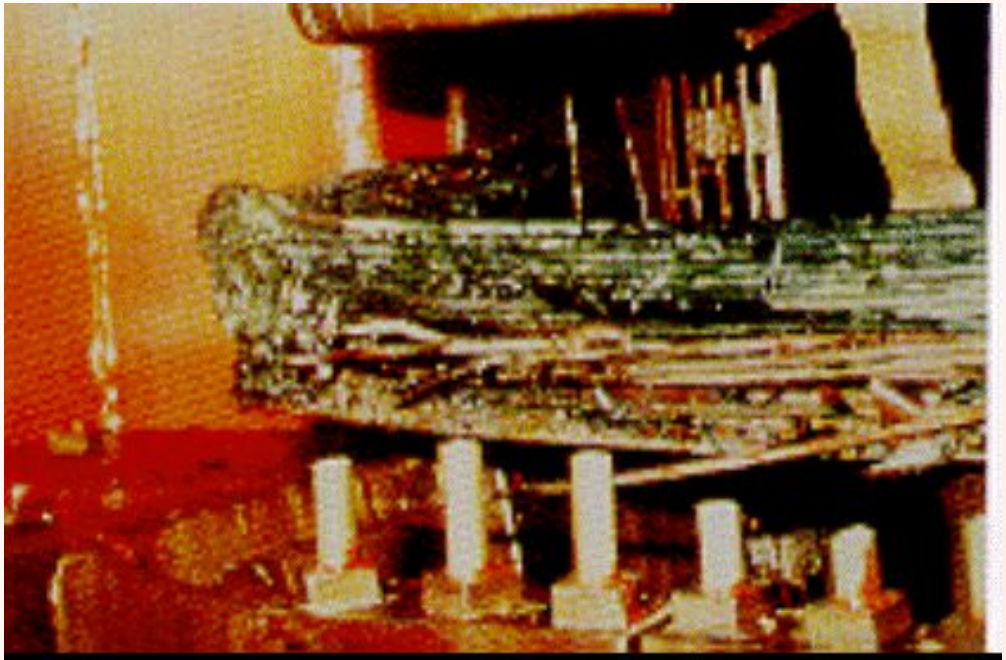
What Can Space Weather Do?



The graphic above shows many ways in which space weather affects our near-space environment. Courtesy Lou Lanzerotti, Lucent Technologies.

- Solar storms do not directly harm life on Earth, but they do affect the way we live!
- Space weather can pose a ***radiation hazard*** for astronauts.
- Space storms disturb the ***radiation belts***: they become filled with ***"killer electrons"*** that can pierce the the skin of an astronaut.
- Space weather can distort radio signals and disturb navigation devices such as ***GPS***.
- Solar storms can disrupt and cut short the work of ***satellites***.

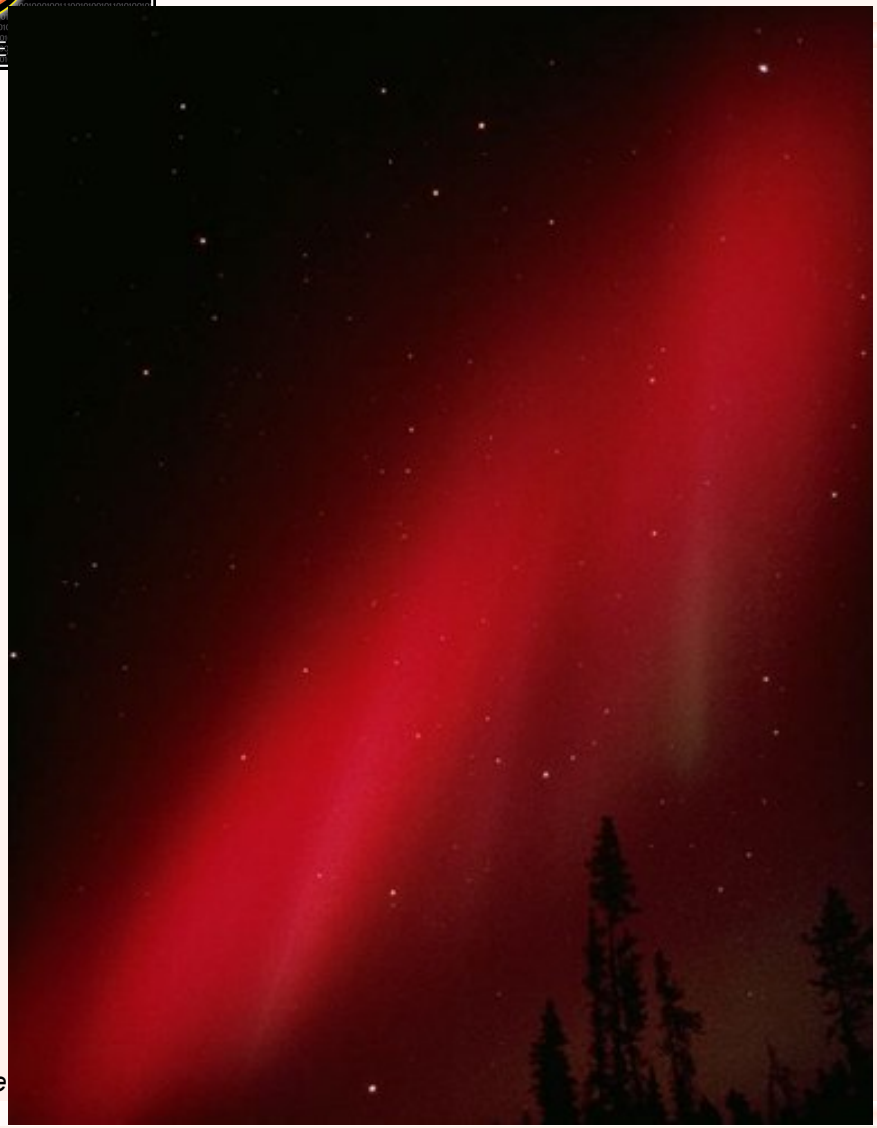
What Can Space Weather Do?



An electric power transformer destroyed by induced currents during a large magnetic storm. In April 1994, five transformers in the Chicago area failed in association with elevated geomagnetic activity.

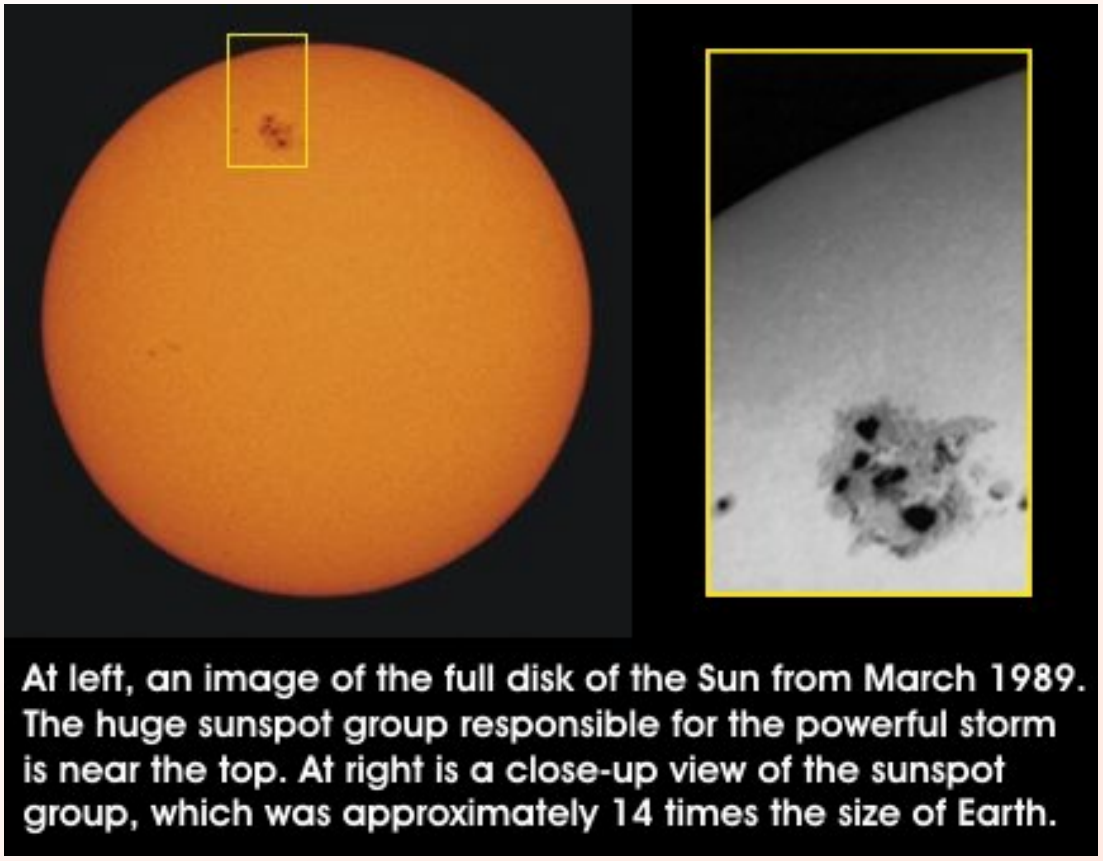
Magnetic storms can ***pump extra electricity*** into our power lines and pipelines, causing blackouts and fuel leaks!

Example of Space Weather Event



- In March 1989, a scientist observed Aurora from Arizona (Kitt Peak National Observatory)!
- Occurrence of northern lights at the latitude of Tucson was due to a strong magnetic storm caused by a series of very powerful events at the Sun.
- Magnetic storm caused a blackout of the Hydro-Quebec power system in Canada, leaving 6 million people in Canada and the US without power for nine hours!

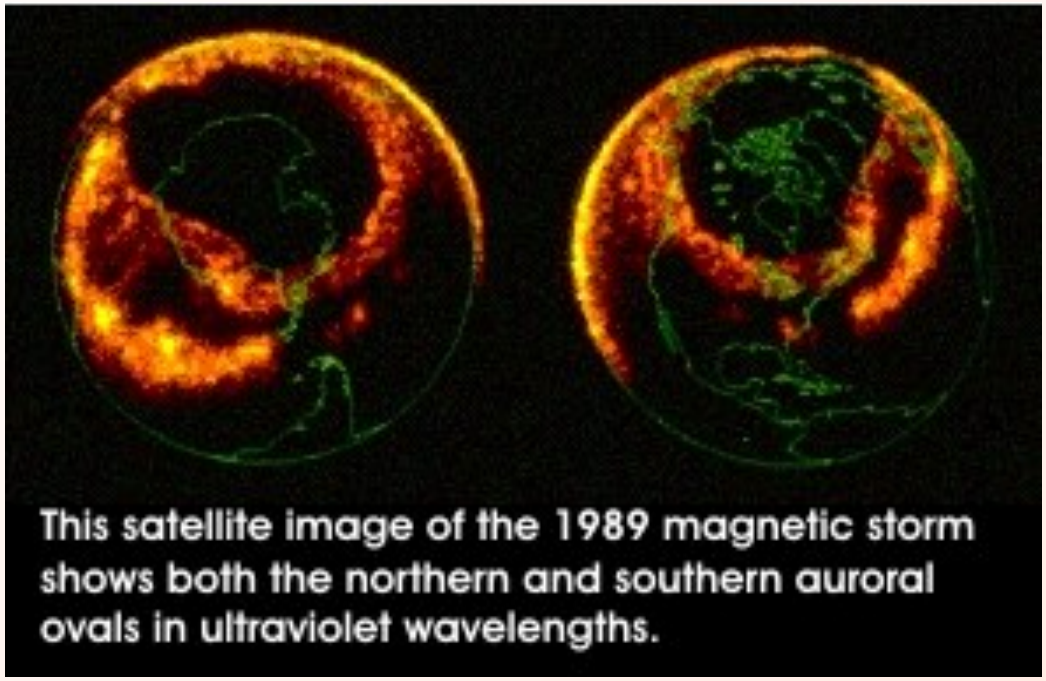
What Exactly Happened?



At left, an image of the full disk of the Sun from March 1989. The huge sunspot group responsible for the powerful storm is near the top. At right is a close-up view of the sunspot group, which was approximately 14 times the size of Earth.

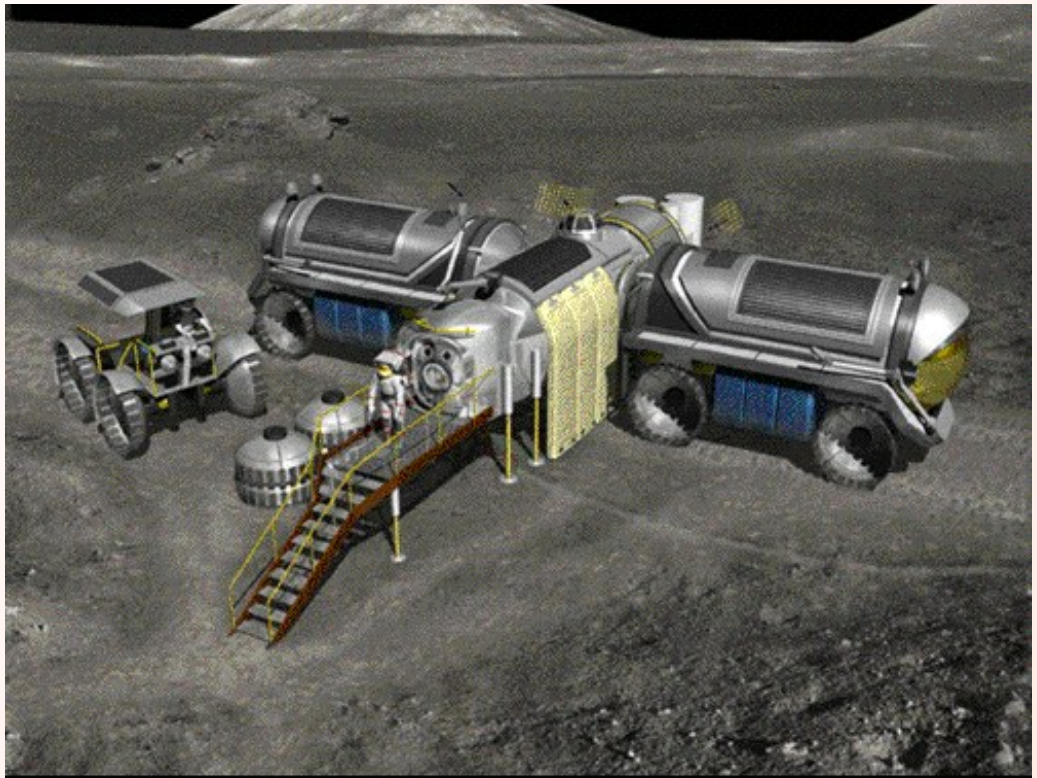
- In March of 1989, an immense area of Sunspots (large enough to contain 14 Earths!) had come into view around the eastern edge of the Sun.
- Created by intense magnetic fields, the giant Sunspot group suddenly brightened and expanded to cover hundreds of thousands of square miles!
- The solar flare was accompanied by a huge burst of EM radiation and a large CME.

What Was the Aftermath?



- CME traveled through the solar wind at a speed of several ***million km/h.***
- When the CME arrived at Earth, it caused the generation of huge sheets of electrical current above Earth's surface.
- These currents produced magnetic field changes, and they led to the ***complete collapse of the Hydro-Quebec power grid***.
- Damage caused by this storm alone was estimated to be around ***$50 million!***

Space Explorers Are Bathed in Radiation

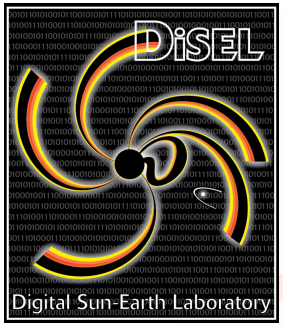


Crews of future missions to the Moon and Mars will be at risk from space storms. When a space storm hits, astronauts will have to take over in a "storm shelter."

- Astronauts in outer space are not protected against radiation.
- Radiation exposure may cause ***cancer***, or ***instant death*** in extreme circumstances.
- In 1 year, an astronaut on the Moon's surface would be exposed to ***200 times*** the radiation dose allowed by the EPA–the equivalent of ***2,000 chest X-rays!***
- As of today, we have not found strong enough shields to protect astronauts during long space missions through the solar system.

Summary

- We live in a dynamic environment governed by the ***magnetic activity*** of the Sun.
- We try to develop predictive capability for the "weather" in outer space, which we call ***space weather***.
- We use many different satellites and ground-based stations around the world to ***monitor*** the Sun and the ***space environment conditions*** near the Earth.
- We utilize sophisticated numerical codes and powerful computers to ***simulate space weather events***.
- We work in synergy with a large number of space scientists from around the globe to develop reliable ***space weather forecast tools*** in the near future.



Thank you!