Lecture 17

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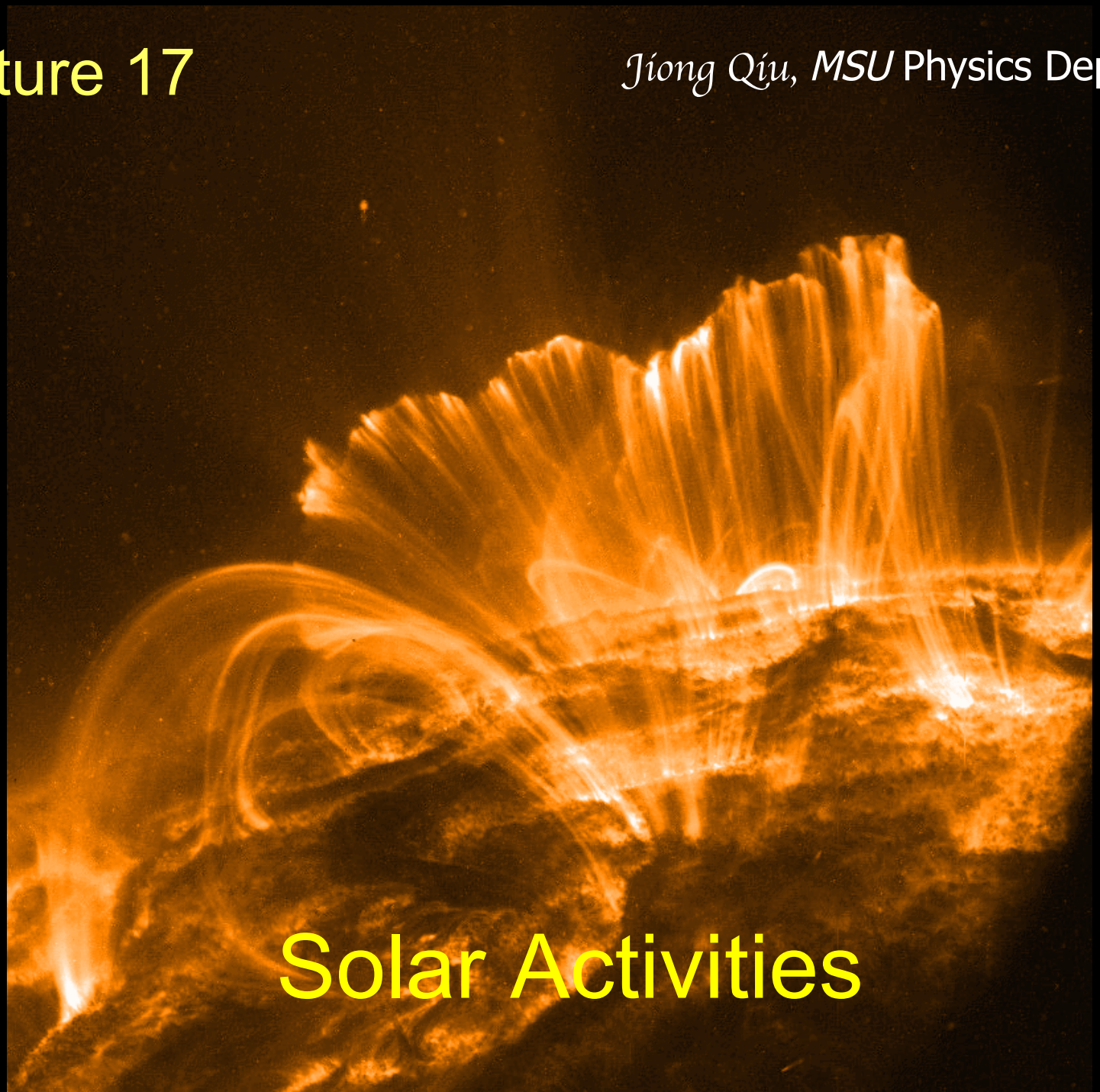
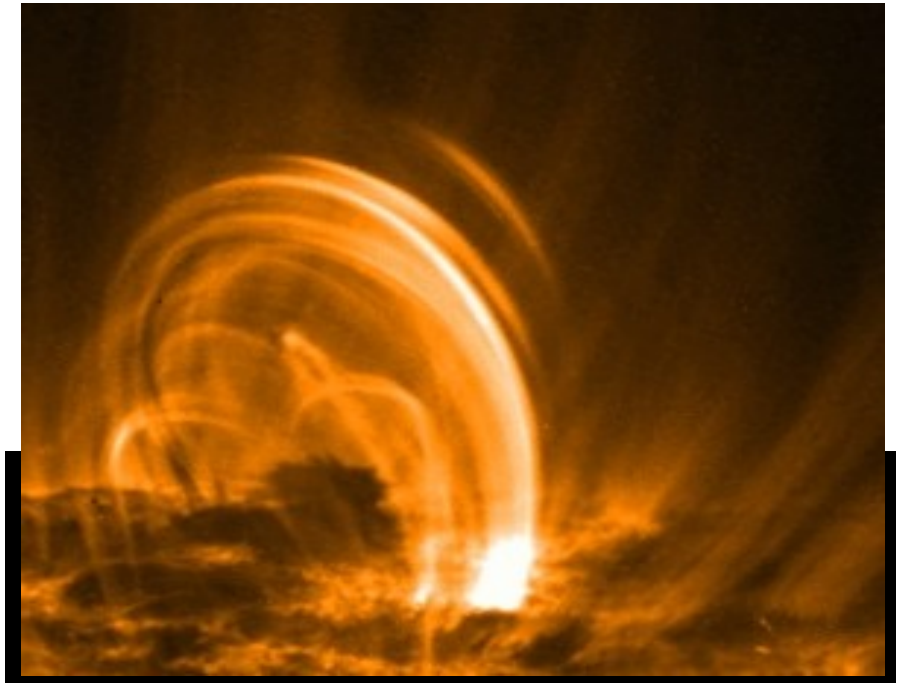


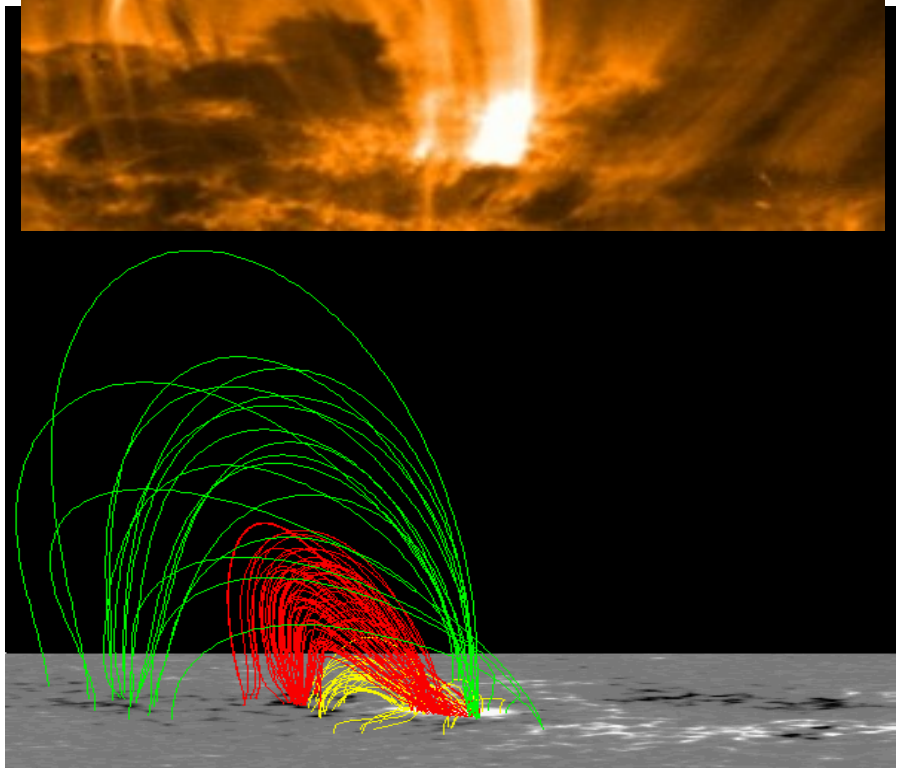
Solar Activities

Guiding Questions

1. What are solar active regions? How do we know that sunspots are regions of strong magnetic field? How is magnetic field of the Sun measured?
2. What is the magnetic structure of a sunspot? Why are sunspots dark?
3. Can we observe magnetic field in the corona? How do we study coronal magnetic field?
4. What is a solar flare? What is the connection between solar flares and magnetic field? Where comes the energy of a solar flare?
5. What is our current understanding of the physical mechanism of solar flares? How can we be convinced that flares are driven by magnetic reconnection?
6. What is a Coronal Mass Ejection (CME)?

The sun's atmosphere is highly structured and dynamic, and is filled with magnetized plasmas.





Examples:

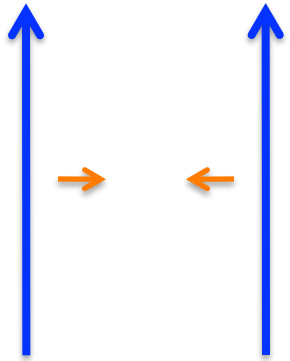
- coronal loops: confinement and heating
- Filaments: magnetic support
- Spicules: dynamics
- flares and CMEs: energetics
- solar winds: geometry and particle acceleration
- sunspots
- solar cycle …….

"If the Sun did not have a magnetic field, it would be as uninteresting a star as most astronomers believe it to be." R. Leighton.

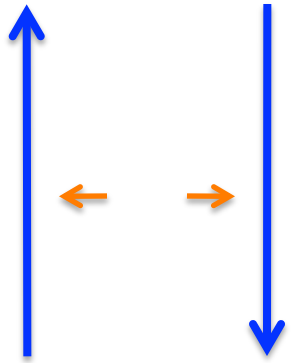
16.1 Magnetic Field and Force

Magnetic field may be viewed as being generated by electric currents. Like electric field, magnetic field applies a force on charged particles that are **moving** with a velocity perpendicular to the magnetic field.

A current applies a repulsive or attractive force on another current through the magnetic field, just like a mass applies a force to another mass through the gravitational field.

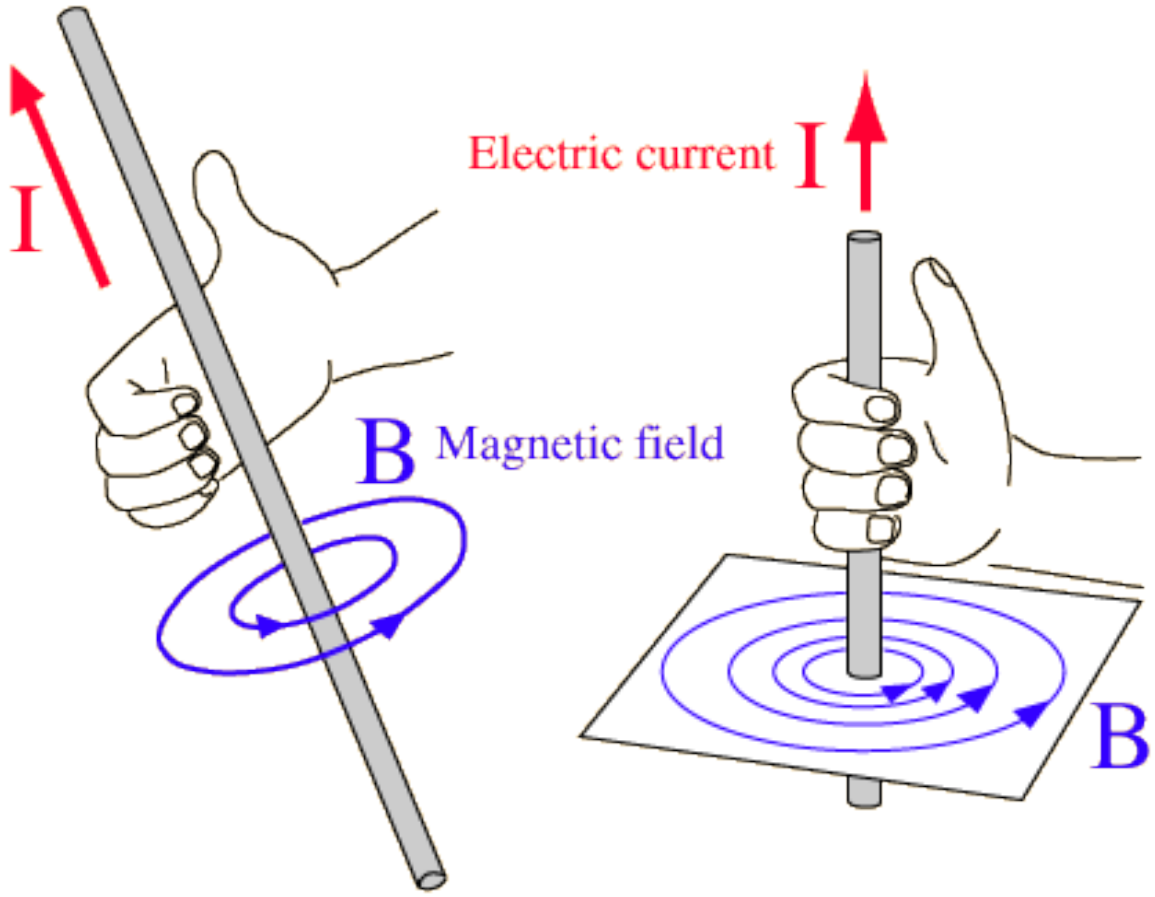


Parallel currents attract

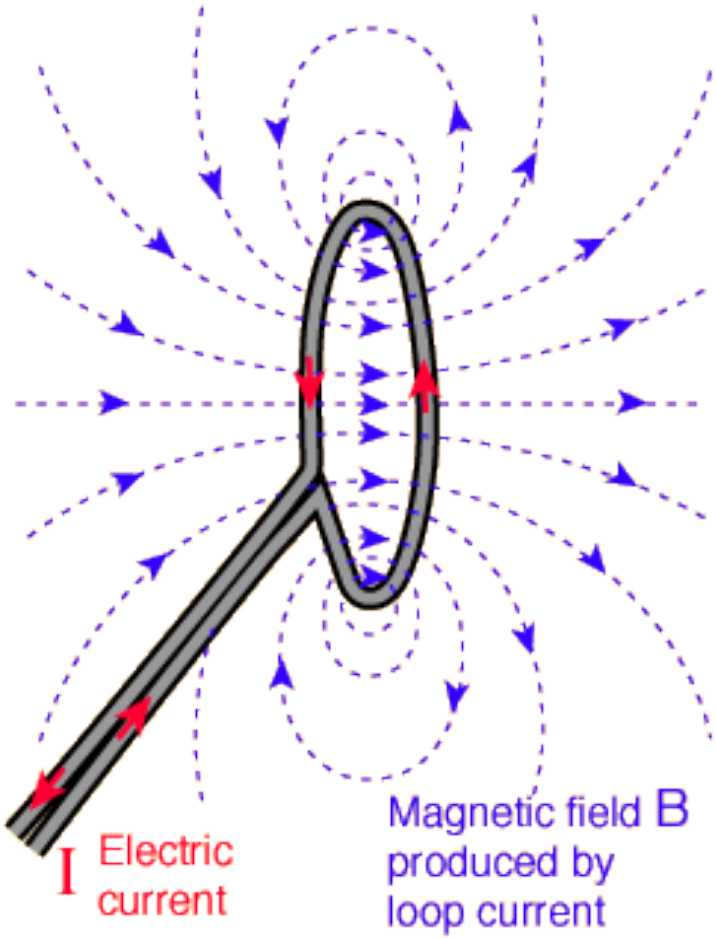


Anti-parallel currents repel

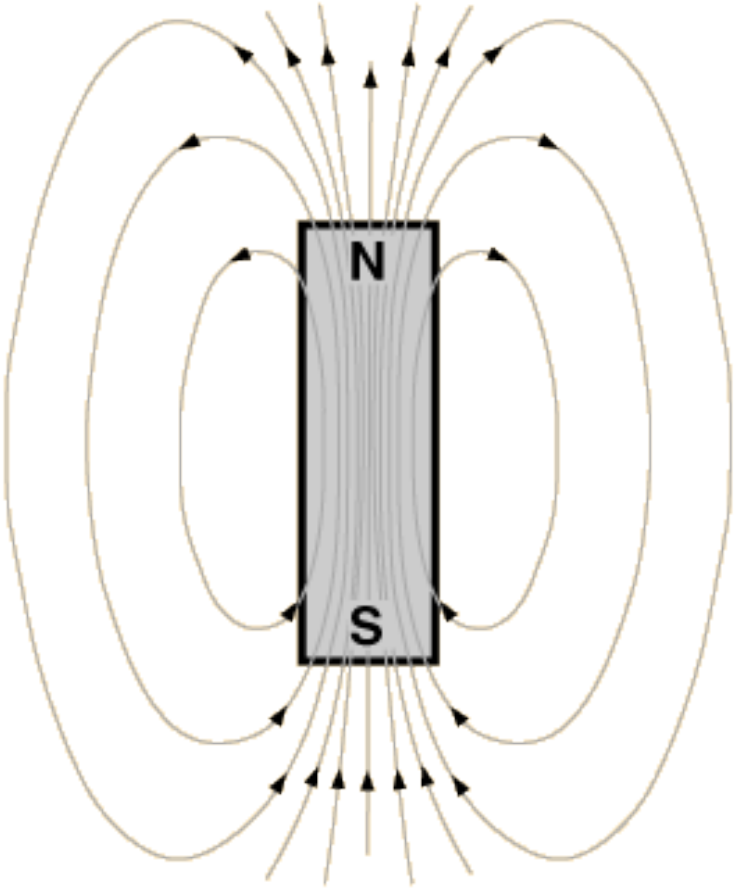
Ex 1: magnetic field generated by electric currents.
(all figures from http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magcon.html#c1)

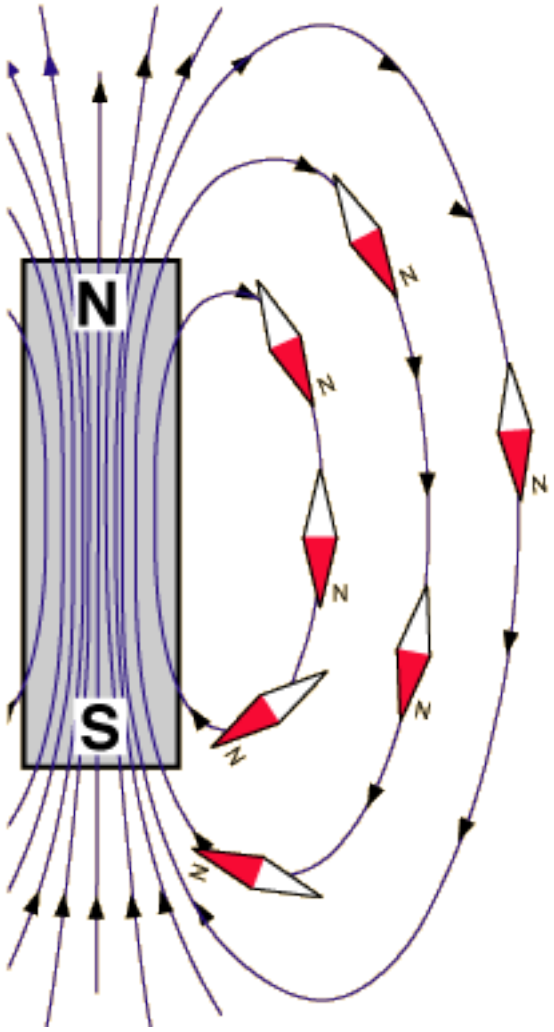


Magnetic field by a straight line current

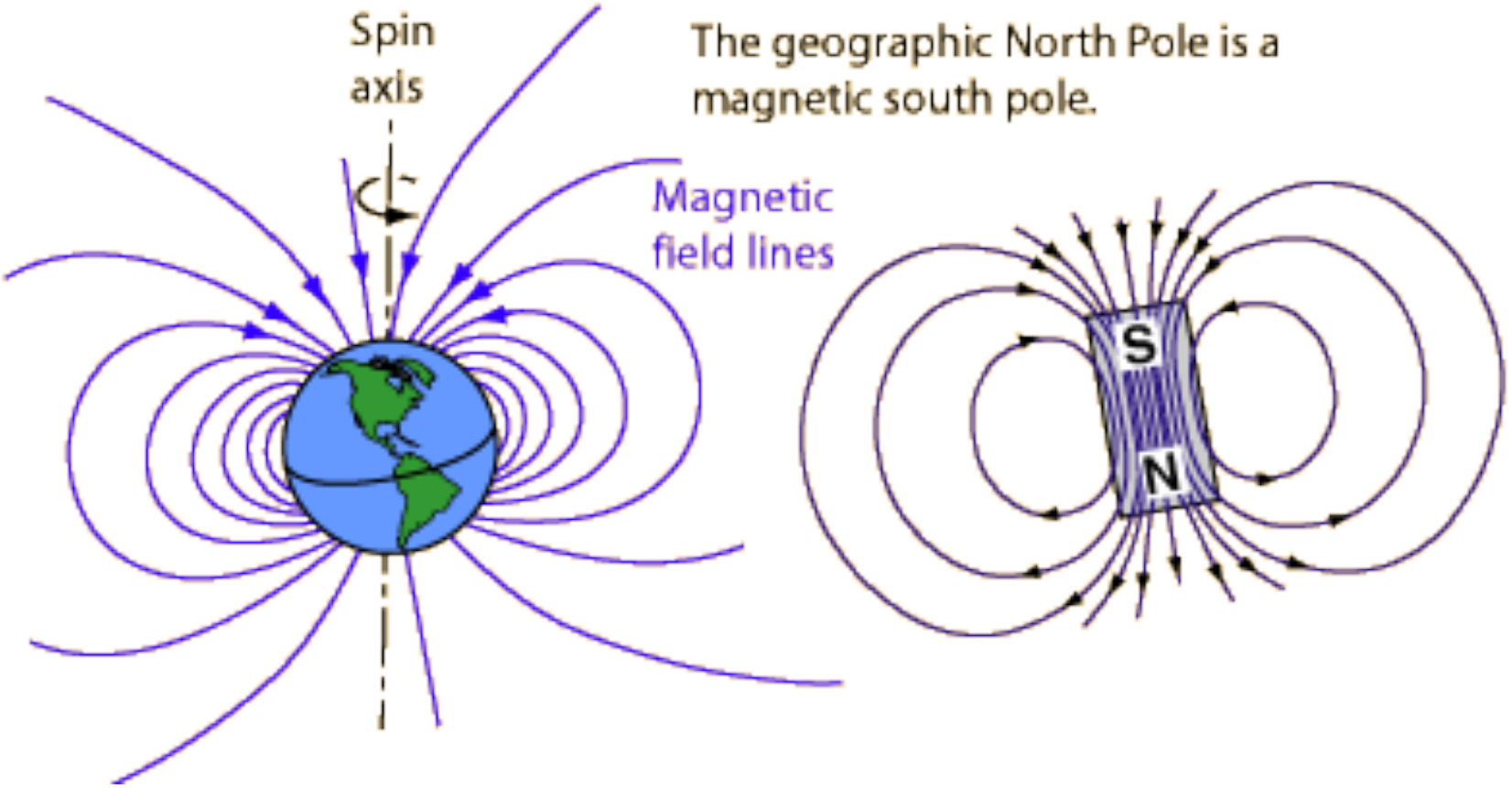


Magnetic field by a loop current





Magnetic field by a bar magnet - where is the current?



Earth's Magnetic field

Magnetic field traps charged particles by Lorentze force. Therefore, plasmas may move along magnetic field lines but not across.

Ex 2: examples of plasma – magnetic field interaction in the solar system (including the Sun).

- magnetospheres and aurorae on planets
- comet's ion tail
- sun's coronal loops and solar wind

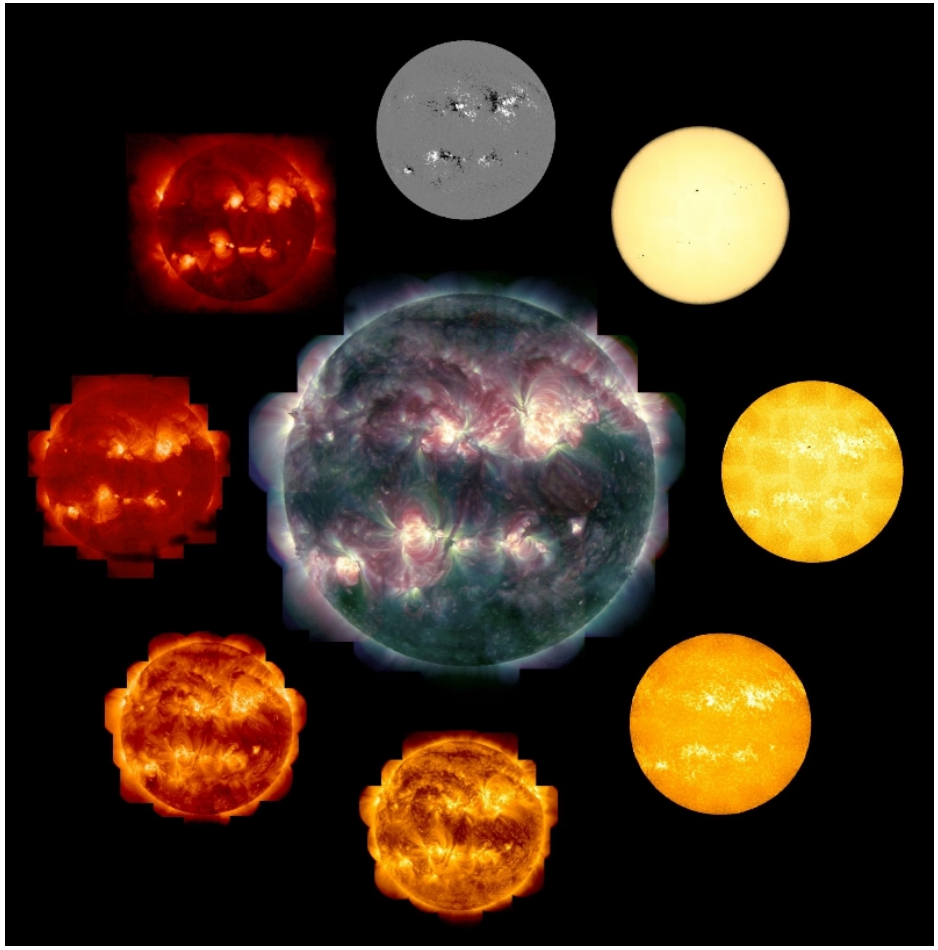
On the other hand, plasmas can also push and pull magnetic field (??)

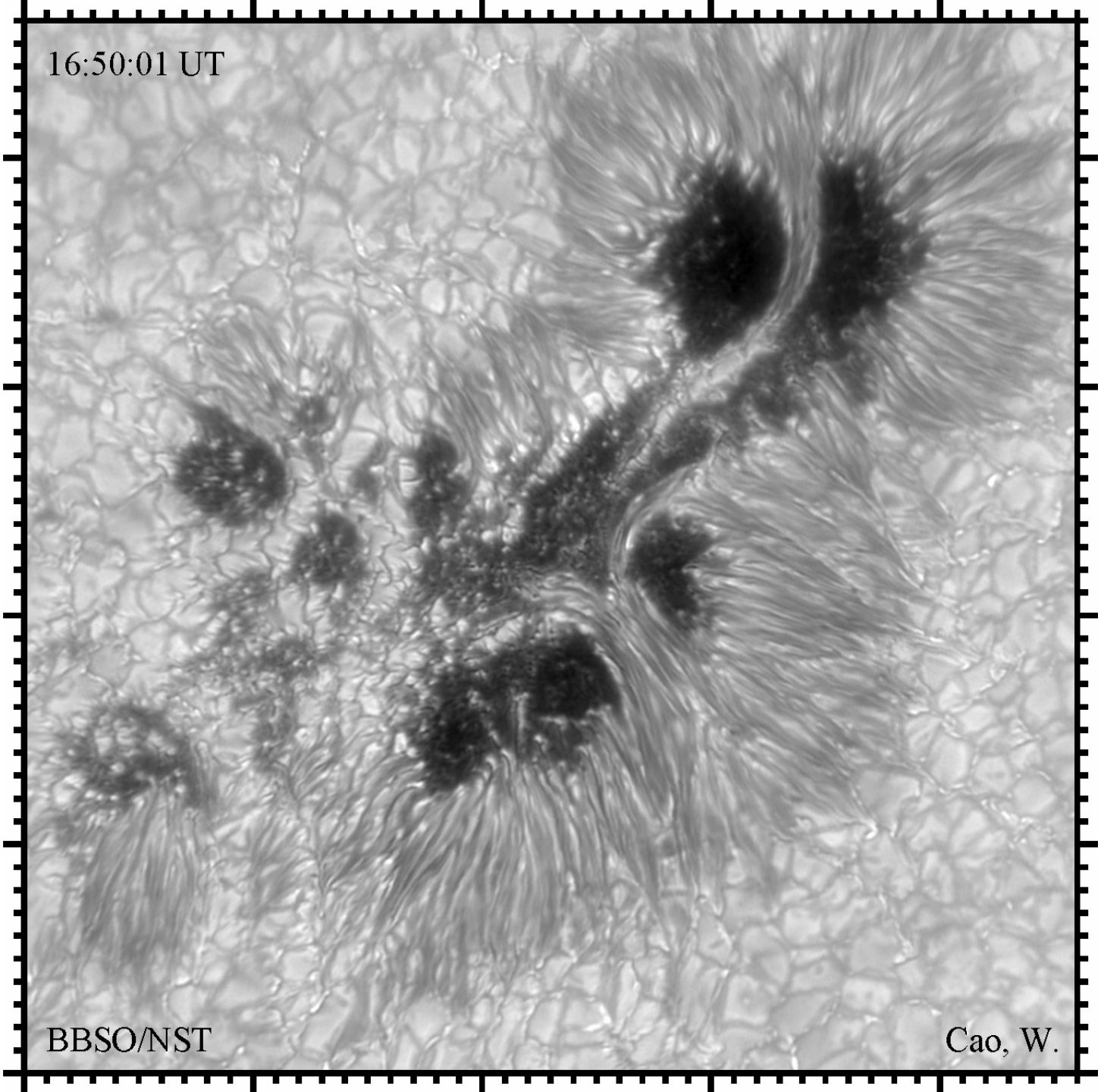
16.2 Solar active regions and magnetic fields

Active regions are where the atmosphere is most "active", or hotter and more dynamic. These are regions of concentration of **magnetic field**. Sunspots are often found in active regions.

Active regions are bright at nearly all altitudes and wavelengths.

Active regions tend to reside in low-mid latitudes in both hemispheres.

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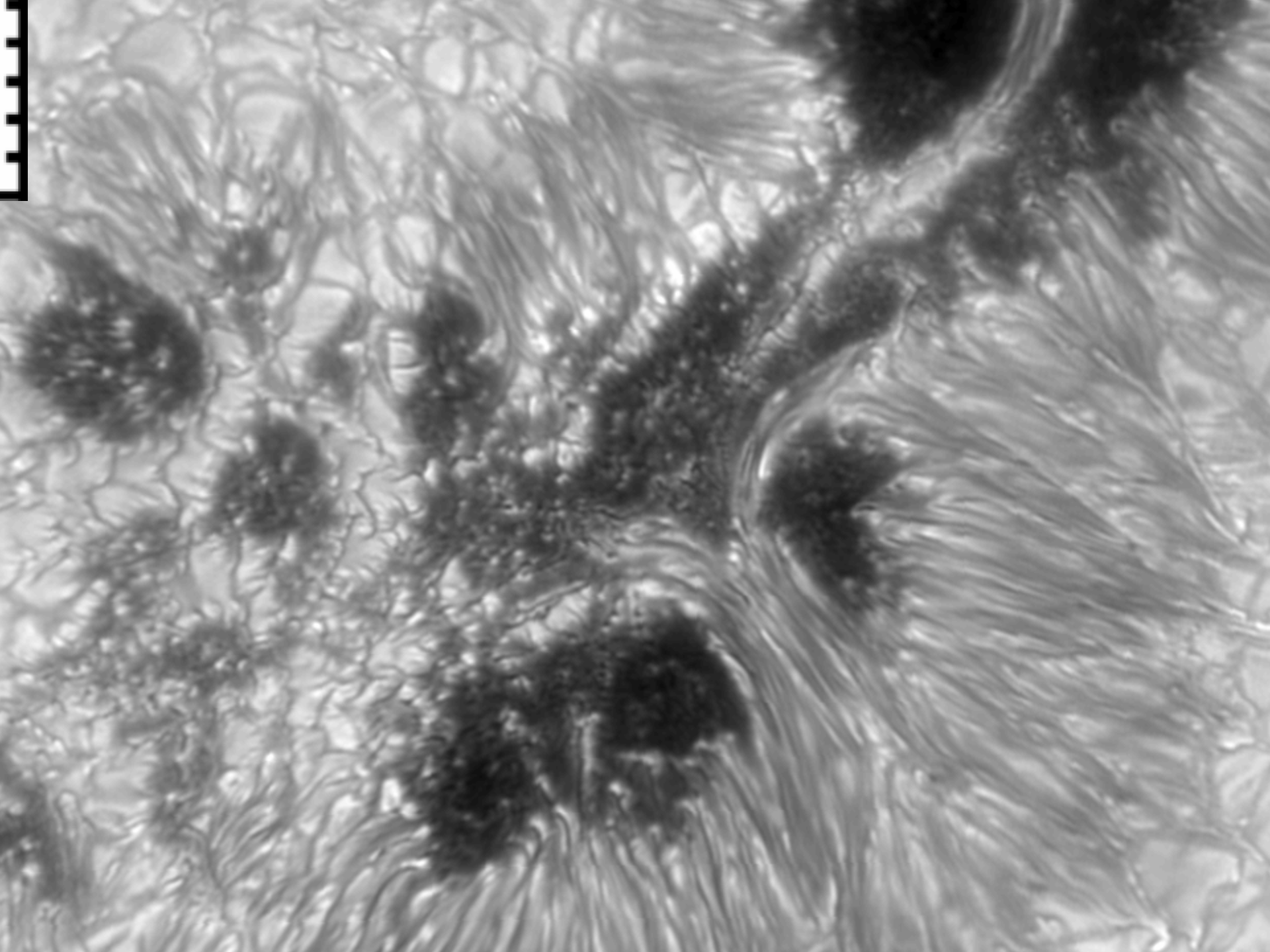
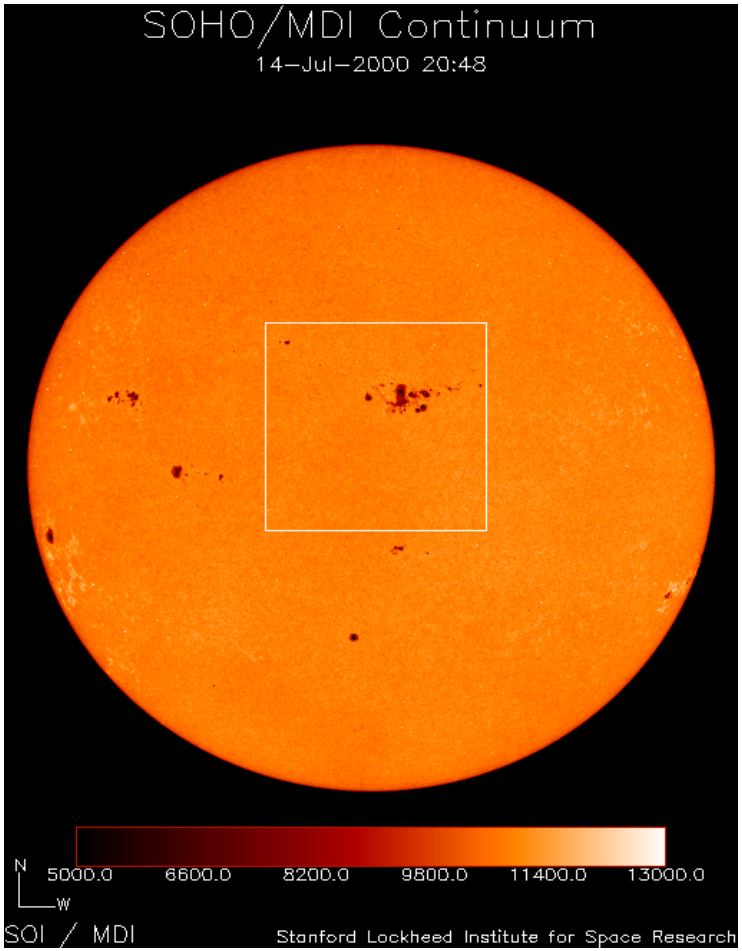
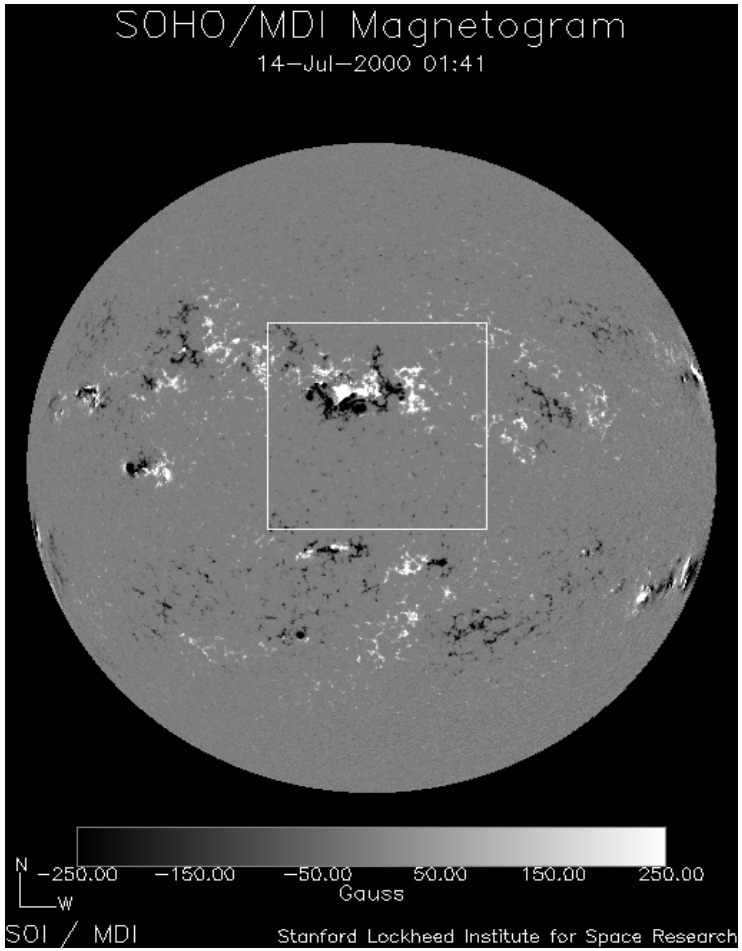
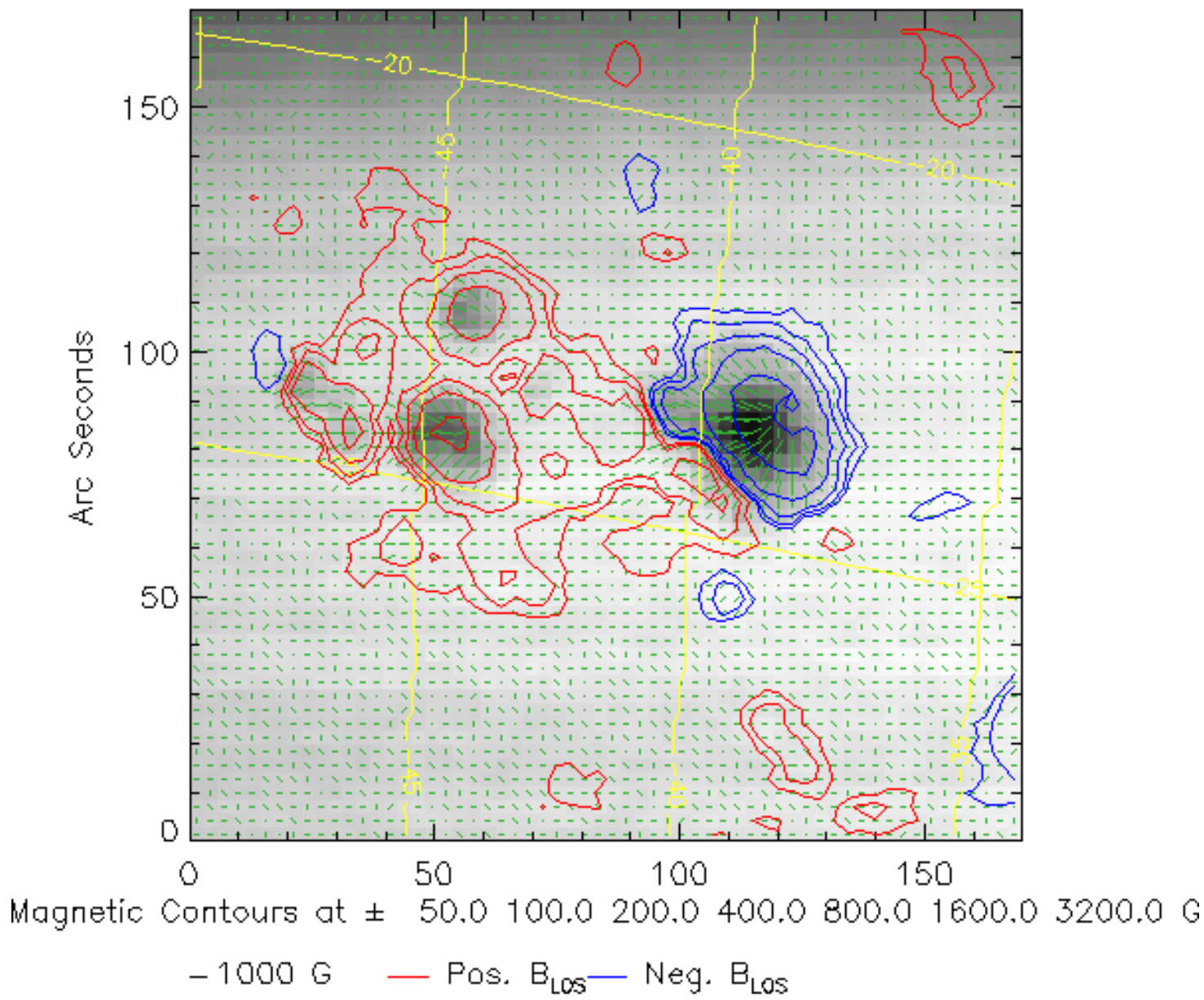


Sun spots are cool regions of strong magnetic fields (a few hundred to a few thousand Gauss: 1 Gauss = 0.0001 Tesla) in the photosphere.



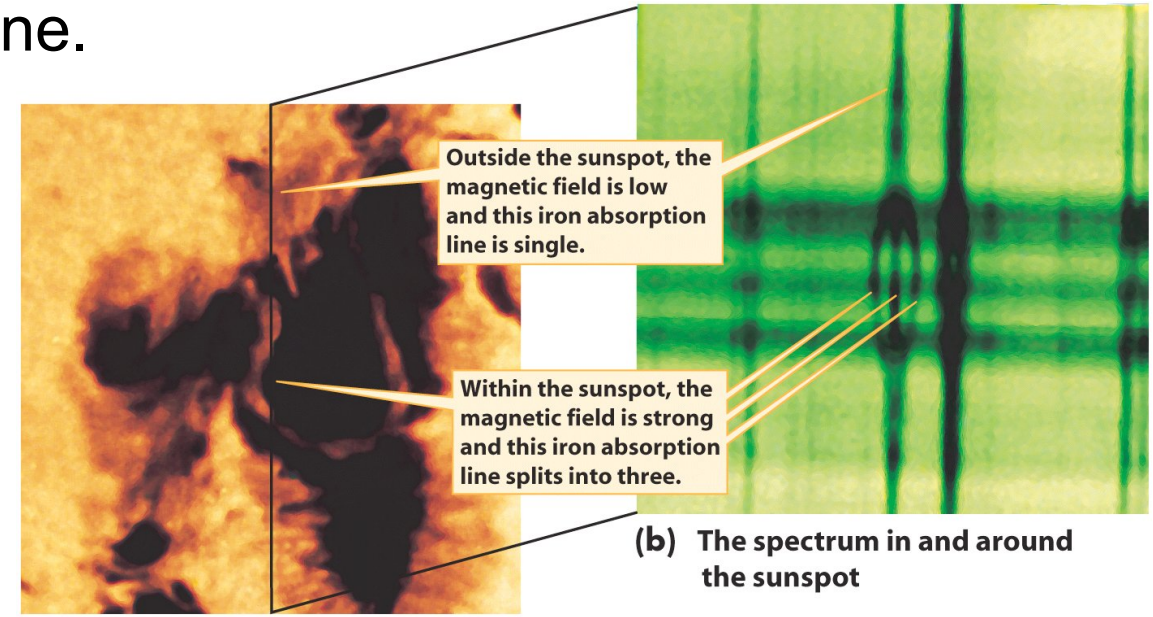


Intensity and longitudinal magnetic field maps observed by Michelson Doppler Imager. White/dark indicates field lines pointing outward/inward.



a vector magnetogram

Magnetic fields are observed/measured by **Zeeman effect,** or split and polarization of a magnetically sensitive spectral line.



Ex.3: Zeeman effect: the amount of line split is roughly proportional to the magnitude of magnetic field: $\Delta\lambda \sim B$

Magnetic field is a vector. All three components of magnetic field can be measured according to their polarization properties to produce a **vector magnetogram.**

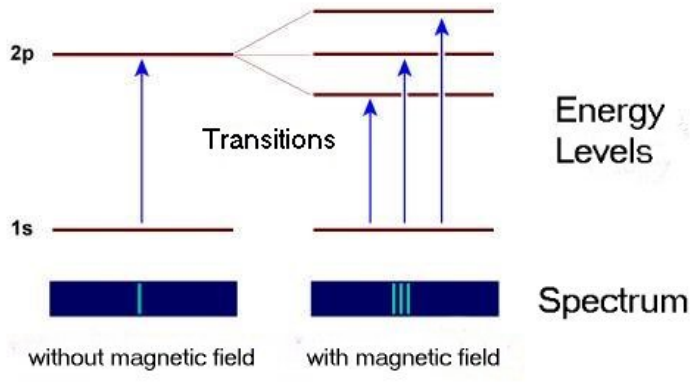
Technique Highlights

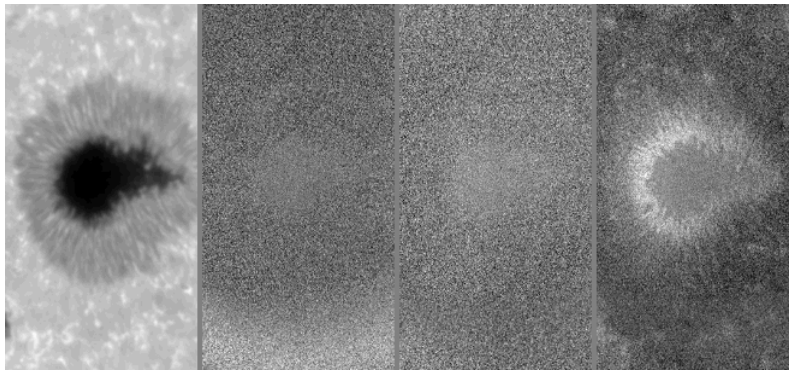
- Solar magnetic field measurement based on Zeeman effect

$$\Delta\lambda_B = \frac{e\lambda^2 gB}{4\pi m_e c^2} = 4.67\times10^{-13}\lambda^2 gB$$

- Available Zeeman sensitive lines in NIR
  - *FeI 0.630 μm, λg = 1575 nm, photosphere*
  - *TiI 2.231 μm, λg = 5578 nm, photosphere*
  - *FeI 4.064μm, λg = 5080 nm, photosphere*
  - *SiI 4.143 μm, λg = 9321 nm, photosphere*
  - *CaI 3.697 μm, λg = 4067 nm, chromosphere*
  - *MgI 3.682 μm, λg = 4307 nm, chromosphere*

- The highest precision magnetic field measurement in solar chromosphere
- The only fully cryogenic NIR solar spectrograph





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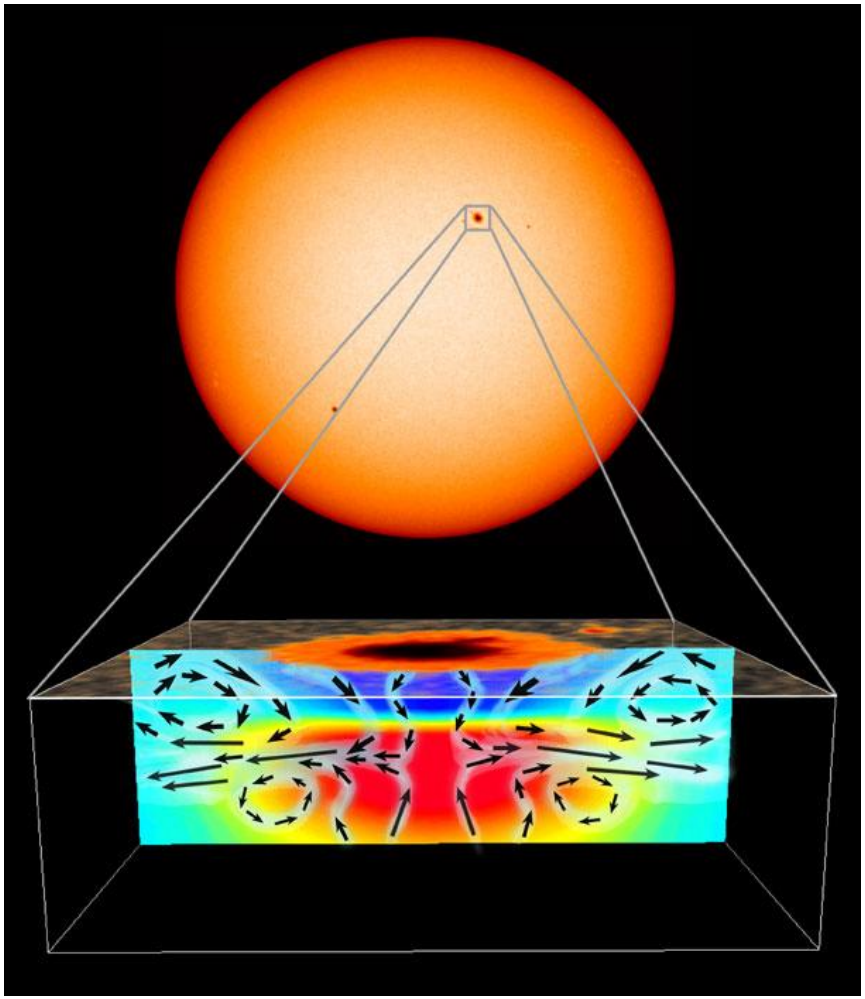
Chromospheric magnetic field measurement with Ca II 854.2 nm

Q: why are sunspots dark?



The temperature of a sunspot is lower than the quiescent photosphere temperature.

$T_{spot} = 4000\ K < 6000\ K = T_{pho}$

$F_{spot}/F_{pho} = (4000/6000)^4 = 0.2$

Redder and less bright!

Ex.4: around the sunspot, the force balance is maintained between gas pressure and **magnetic pressure**.

Gas pressure : $P_g = nkT$

P_g : gas pressure in N/m^2

n : particle number density in m^{-3}

k : Boltzmann constant $= 1.38 \times 10^{-23}$ J/K

T : temperature in K degree

Magnetic pressure : $P_m = \dfrac{B^2}{2\mu_0}$

P_m : magnetic pressure in N/m^2

B : magnetic field in Tesla : 1 Tesla $= 10^4$ Gauss

μ_0 : permeability of vacuum $= 4\pi \times 10^{-7}$ N A^{-2}

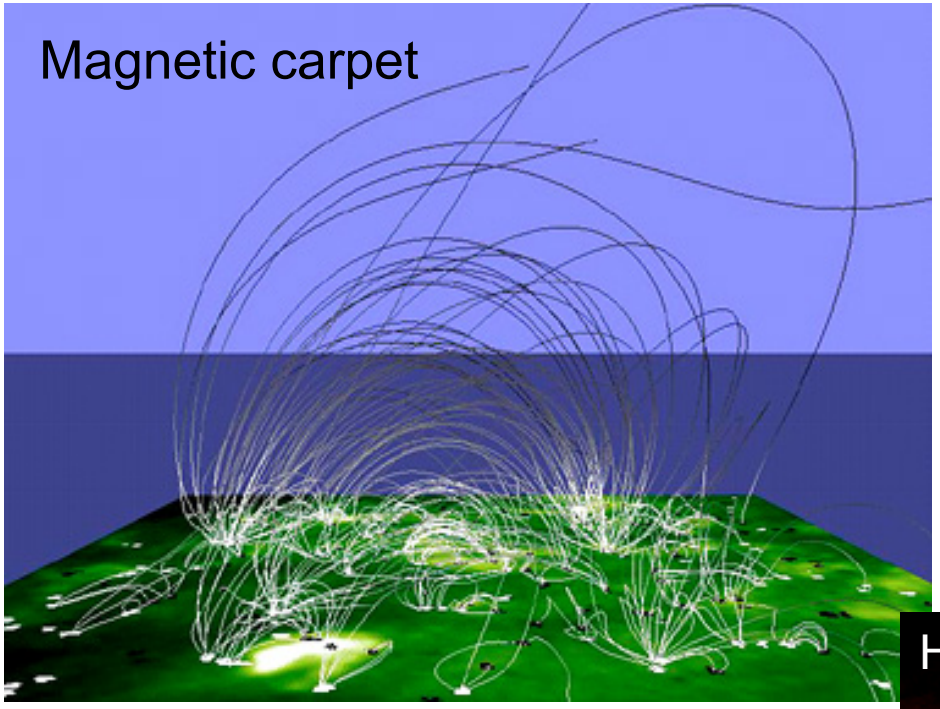
The ratio of gas (plasma) pressure to magnetic pressure is defined as the plasma β.

$$\beta = \frac{P_g}{P_m} = \frac{nkT}{B^2/2\mu_0}$$

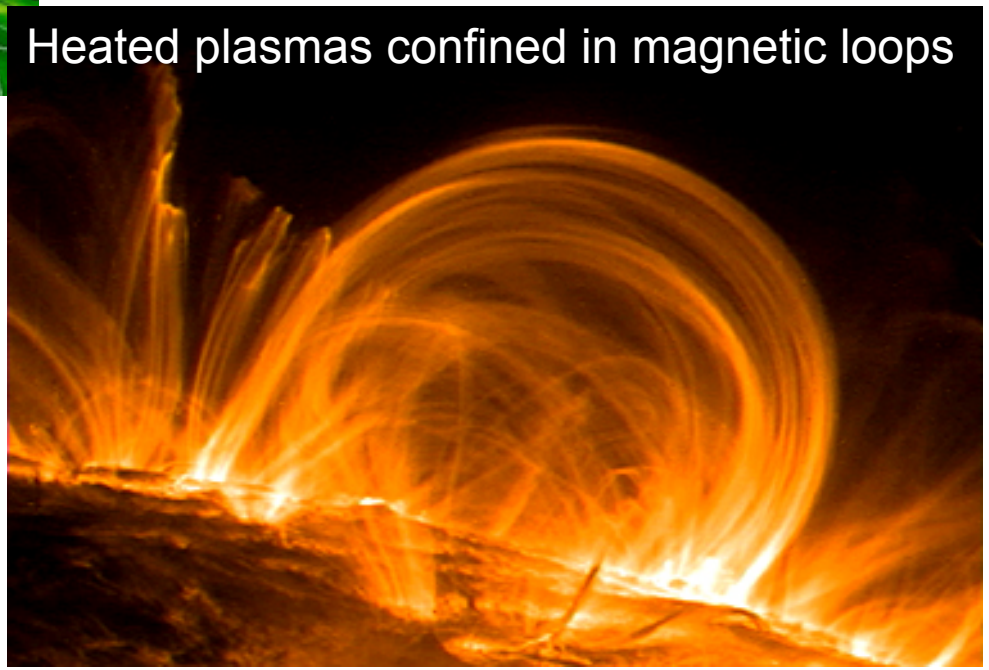
Ex 5: the magnetic field at Earth's surface is about 0.5 Gauss (or 5 x10^{-5} Tesla). How does the magnetic pressure at Earth's surface compare with the air pressure (eg. at the sea level, 1atm = 1.013x10^5 N/m^2)? What is the β value?

The Sun's photosphere is of high β, and the corona is of low β (find this out in your homework). Therefore, in and below the photosphere, gas pushes magnetic field (e.g., dynamo); and in the corona, magnetic field pushes gas.

16.3 Magnetized atmosphere



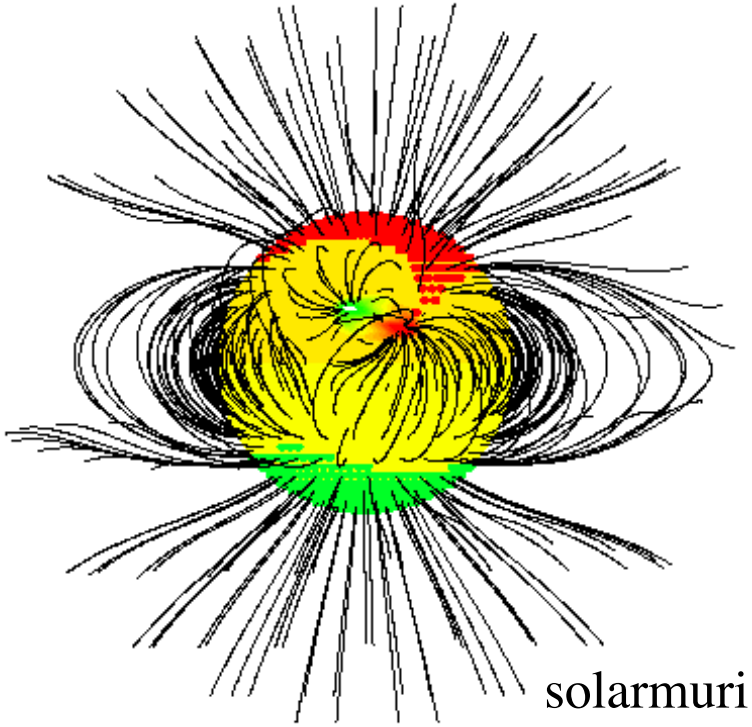
Magnetic field rooted from below the photosphere expands upward and governs the upper atmosphere properties, such as **coronal heating**.



In solar corona, where the **magnetic pressure** dominates the **gas pressure,** magnetic fields are in control.

It is very difficult to directly observe and measure magnetic field in other than the photosphere, because the field becomes very weak upward, producing little Zeeman splitting.

The coronal magnetic field is reconstructed by **extrapolation** from photospheric magnetograms.



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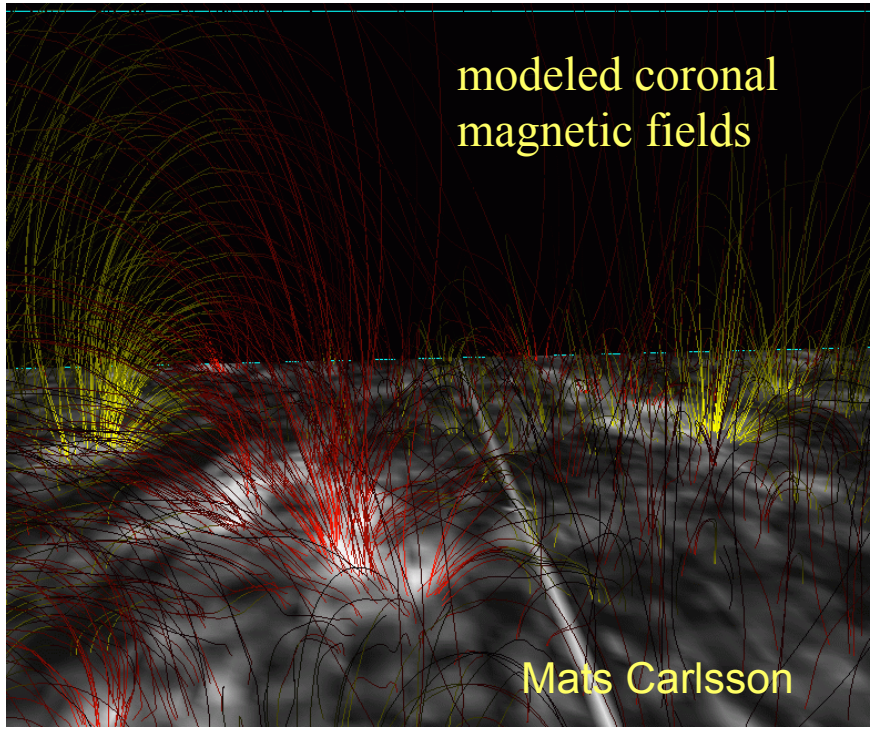
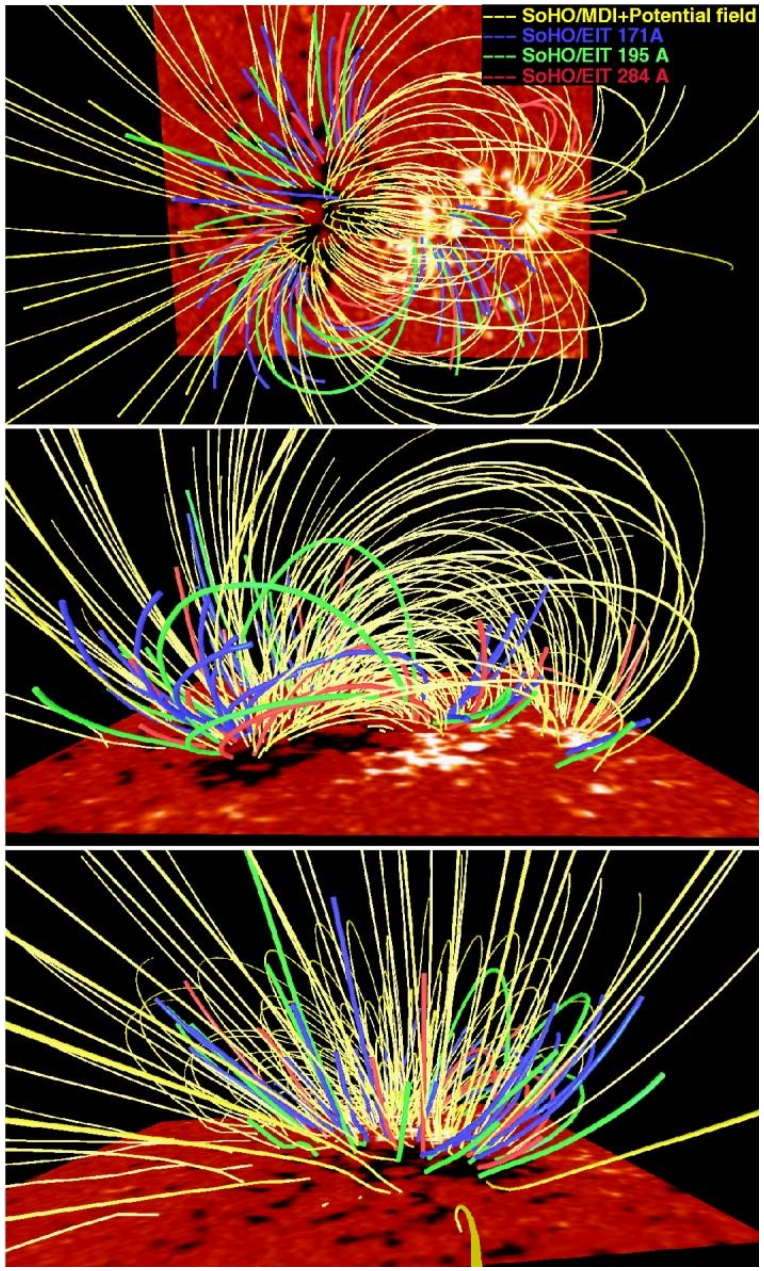


top view

side view

another side view



Coronal magnetic field reconstructed by extrapolation: numerically determine the magnetic field at each altitude, following physical principles, with some assumptions and observational constraints.

Q: can a magnetic field line break and end somewhere in the air?

Q: Why do we care about magnetic fields in the corona?

- magnetic field governs behavior of plasmas (low β)
- magnetic field provides energy for solar activities.

Ex.6: Magnetic field deviating from a **potential field** (no electric current) contains **free magnetic energy** to fuel energetic solar activities. E.g. a twisted rubber band contains more mechanical energy and strives to return straight.

magnetic energy in a volume :

$$W_B = \int \frac{B^2}{2\mu_0} d\tau$$

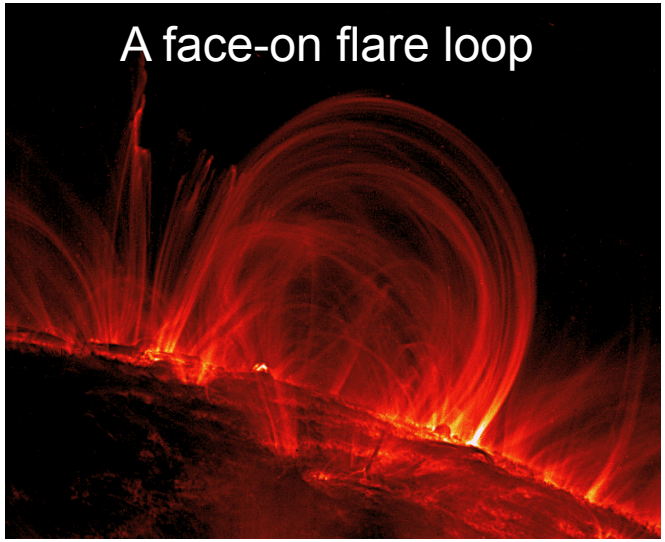
$$\Delta W_B = W_B{}^{np} - W_B{}^{p} = E_{flare} + E_{CME}$$

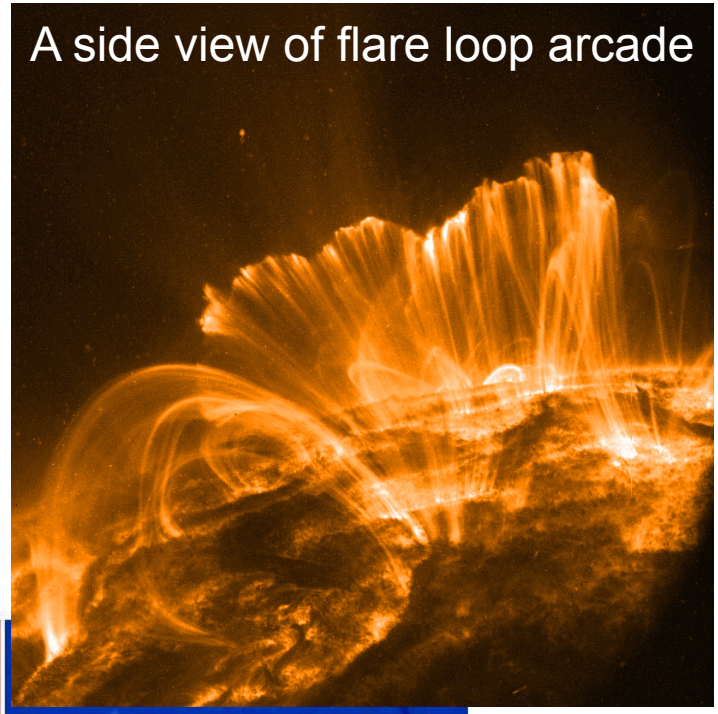
16.4 Solar flares and magnetic reconnection

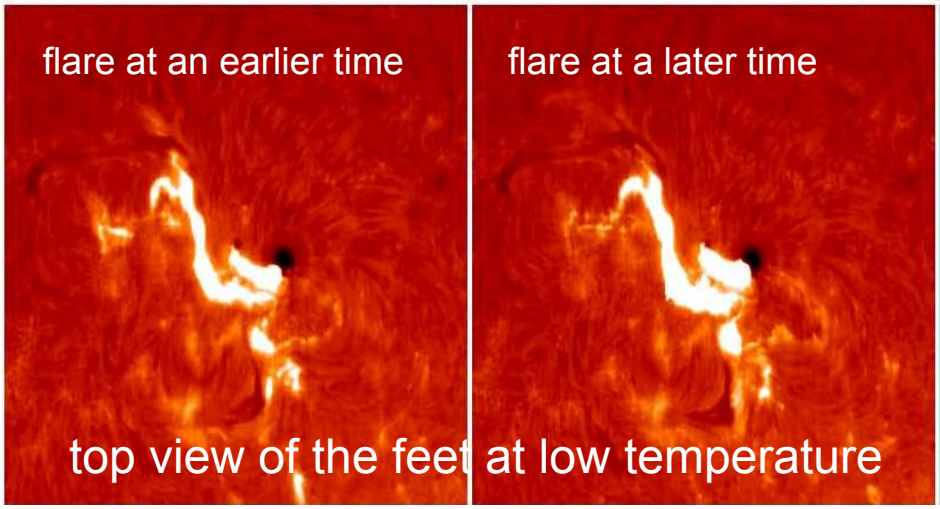
The fire and the storm: explosive energy release from the Sun.

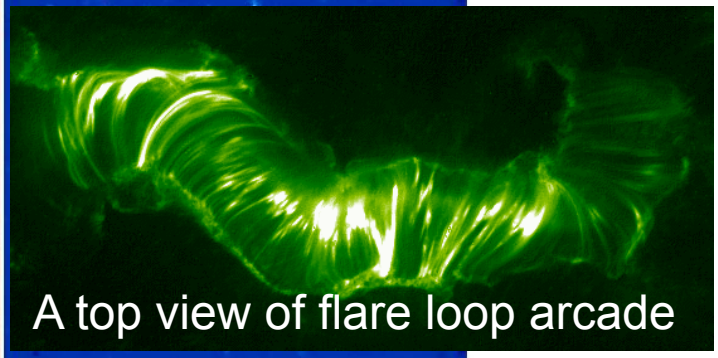
EUV image of the Sun's corona by SDO.

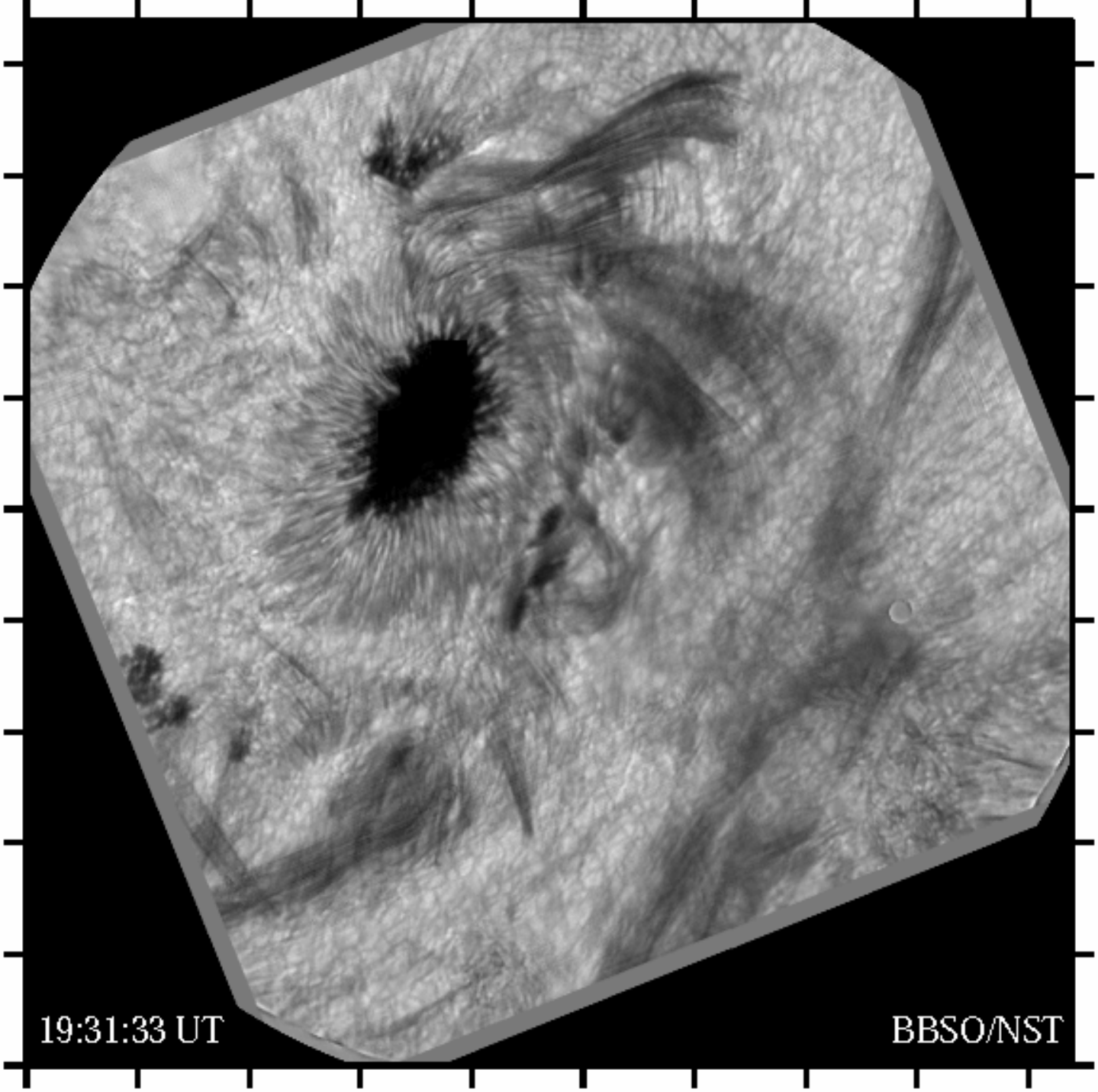
Ex.7: live observations of flares







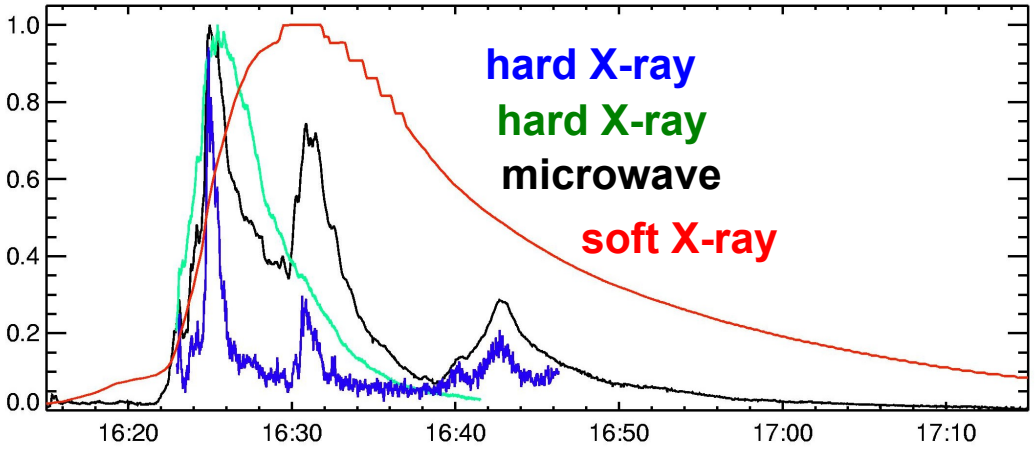




A C9.5 flare on July 5, 2012

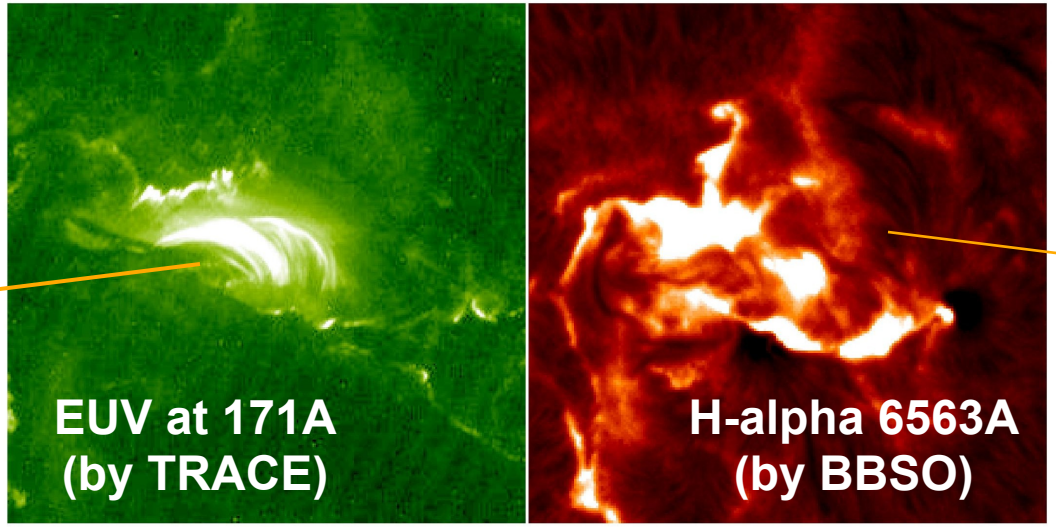
A M1.2 flare on August 17, 2013

flares: a spectacular form of violent solar energy release.



A typical flare releases energy of $10^{21\text{-}25}$ joules in 10^{0} -10^{2} minutes. It heats plasmas and produces beams of particles with high energies.

flare loops in the corona

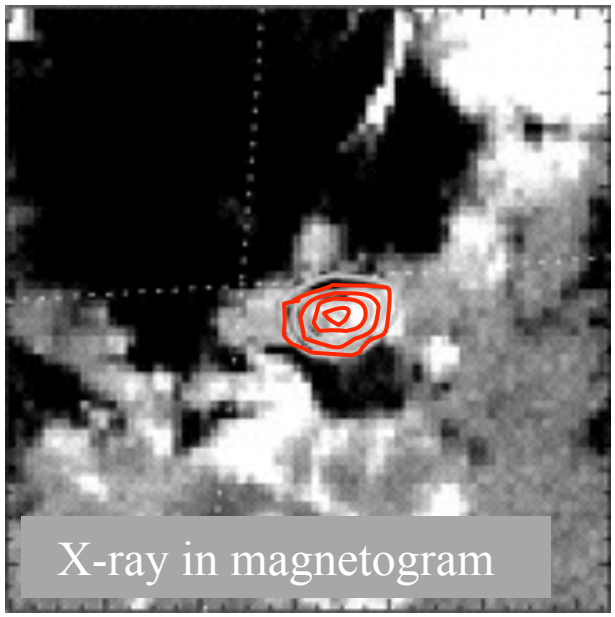


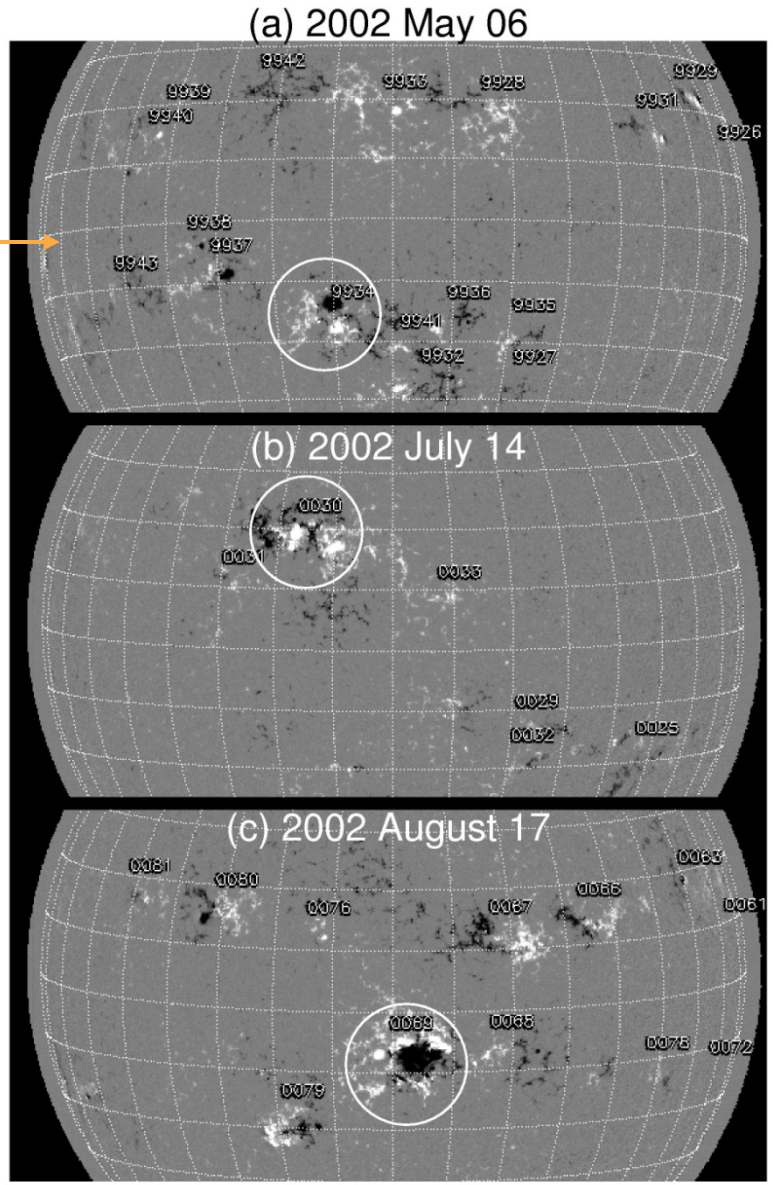
flare ribbons in the chromosphere

a large flare observed in different wavelengths

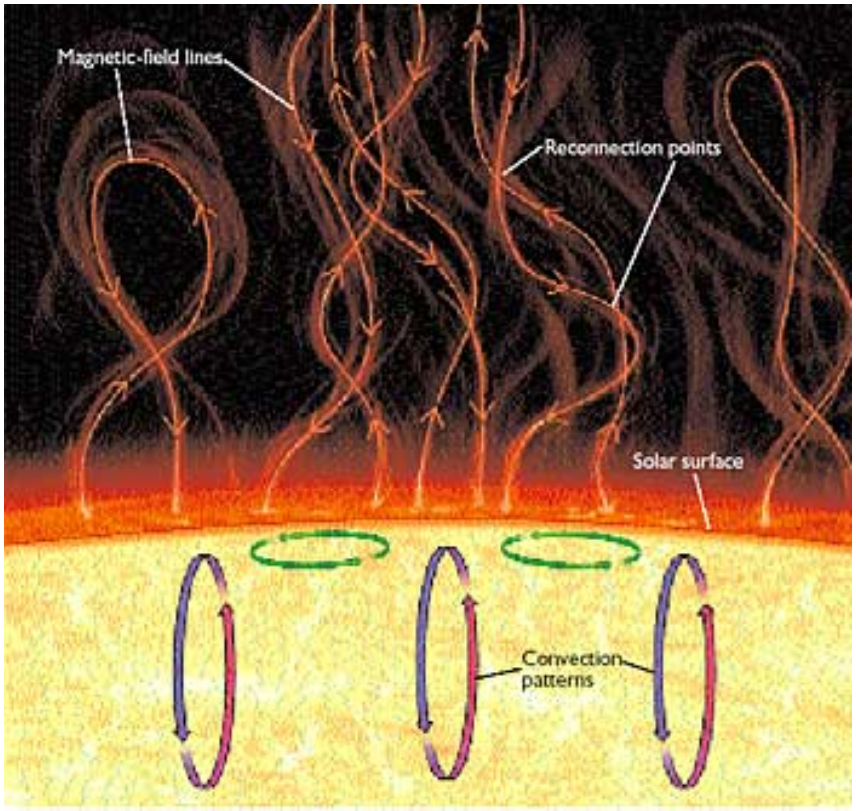
Most flares occur in **active regions** where magnetic fields concentrate and are complex.

They are located at where the polarity of magnetic fields reverses.

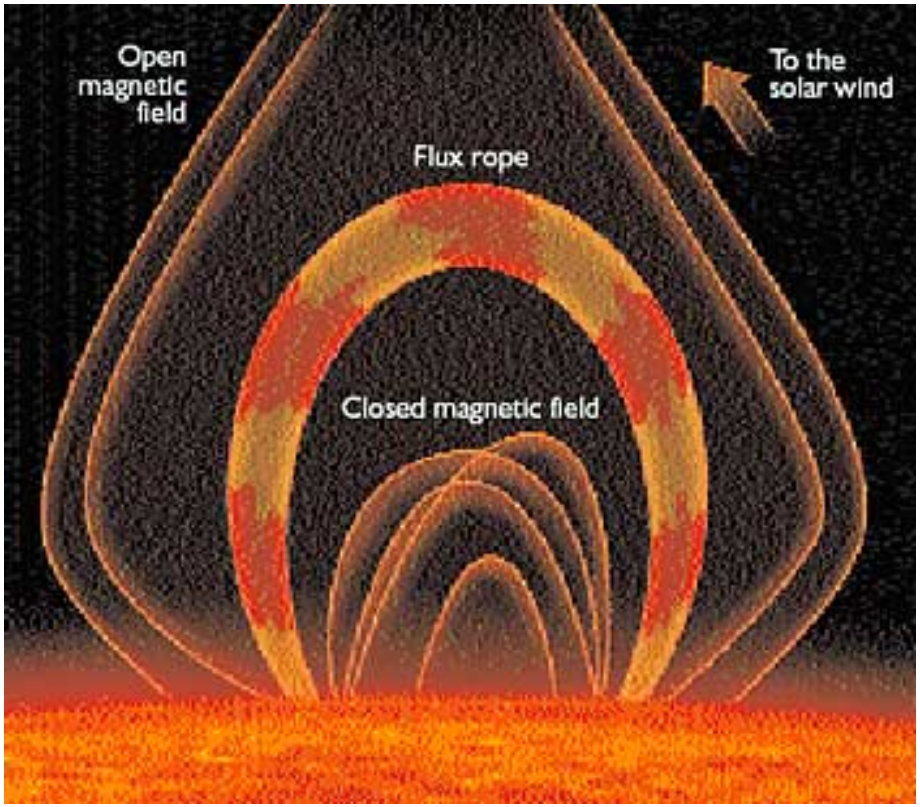




Flares are **magnetic reconnection** events.

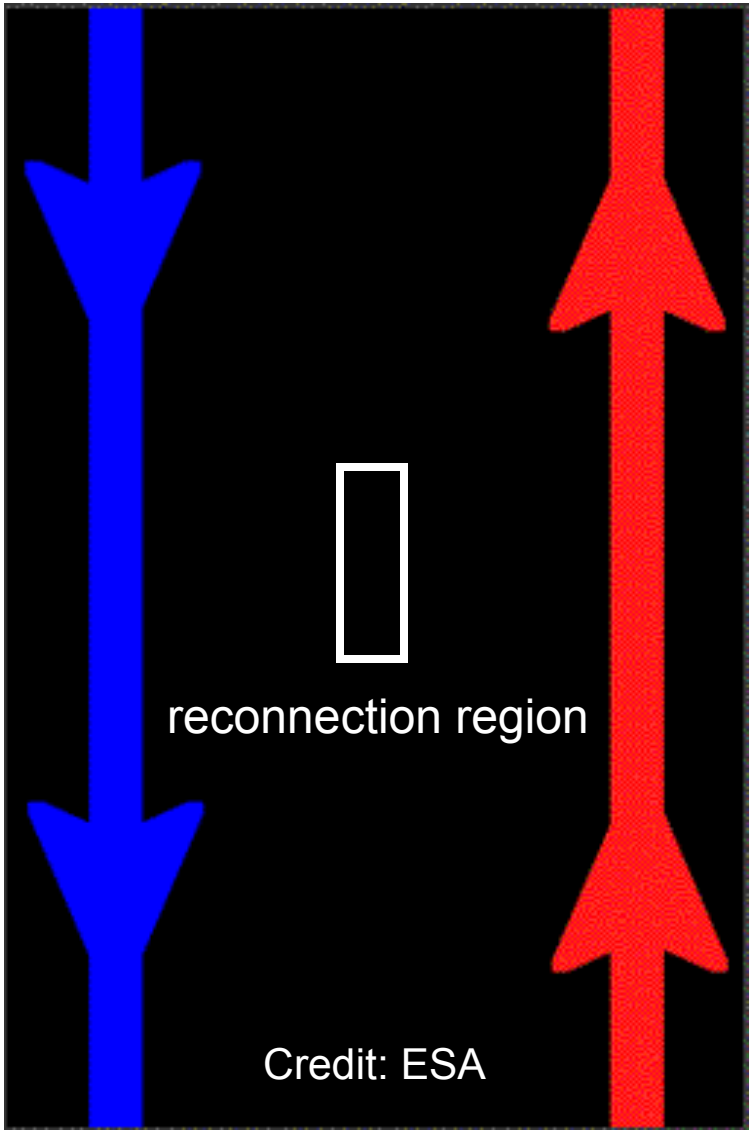


a. Solar magnetic-field lines, anchored in the turbulent convective zone beneath the surface, become tangled and braided, building up magnetic stress and energy. (Tom Moore)



b. Reconnection between tangled field lines releases the stress and energy, forming "closed-field", or flare loops. (Tom Moore)

magnetic reconnection is considered to release energy at observed rate.

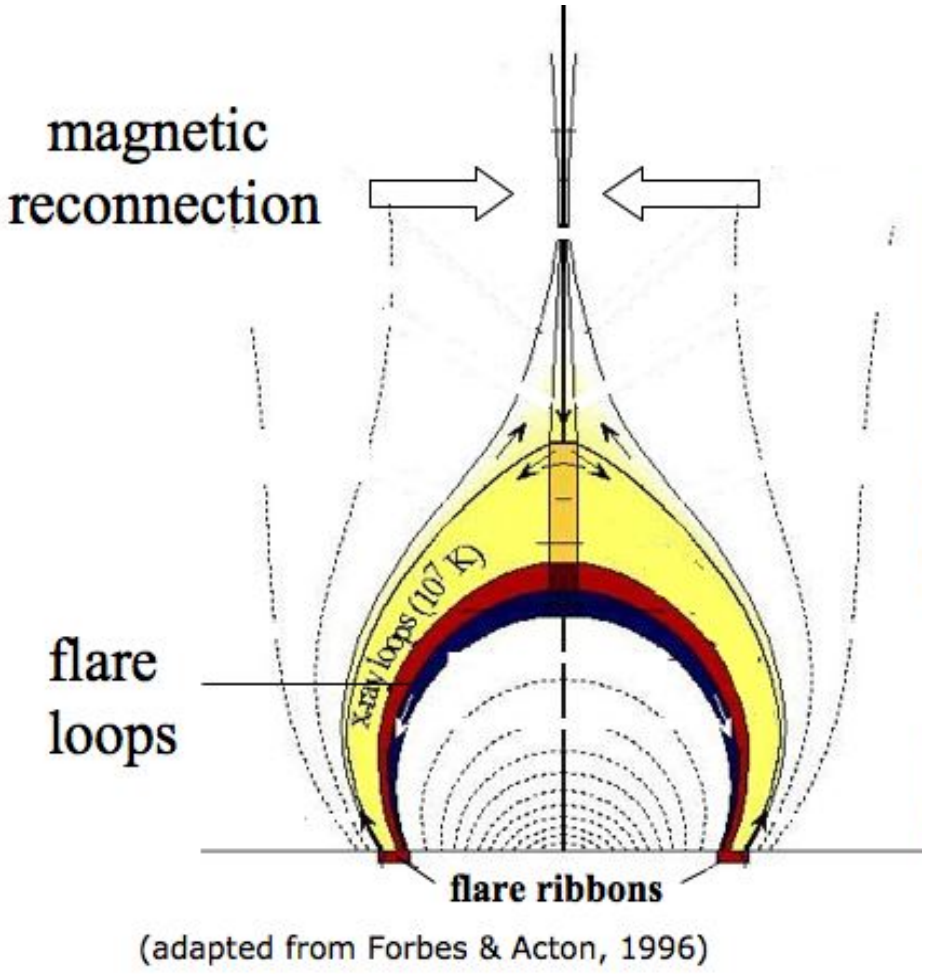


- Magnetic field has a special property: it does not have a source or sink. Therefore, magnetic field lines cannot break.

- Anti-parallel magnetic field lines, when pushed close, exchange connectivities. This is **magnetic reconnection**.

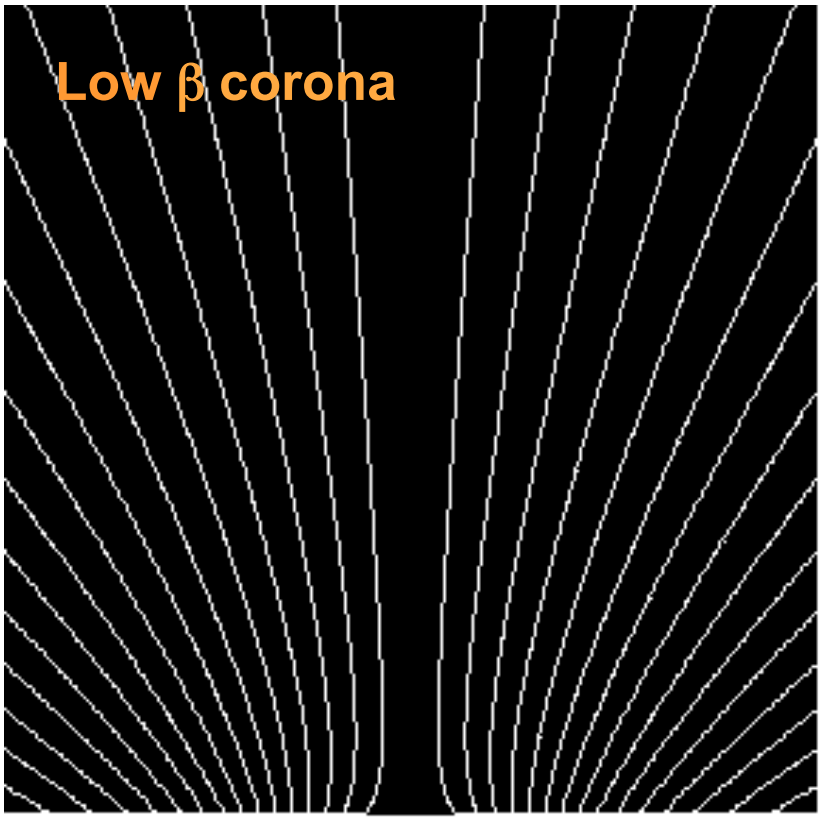
- Magnetic reconnection so occurs that the magnetic configuration after reconnection has less energy than before reconnection.

"observe" magnetic reconnection in a standard flare configuration



(adapted from Forbes & Acton, 1996)

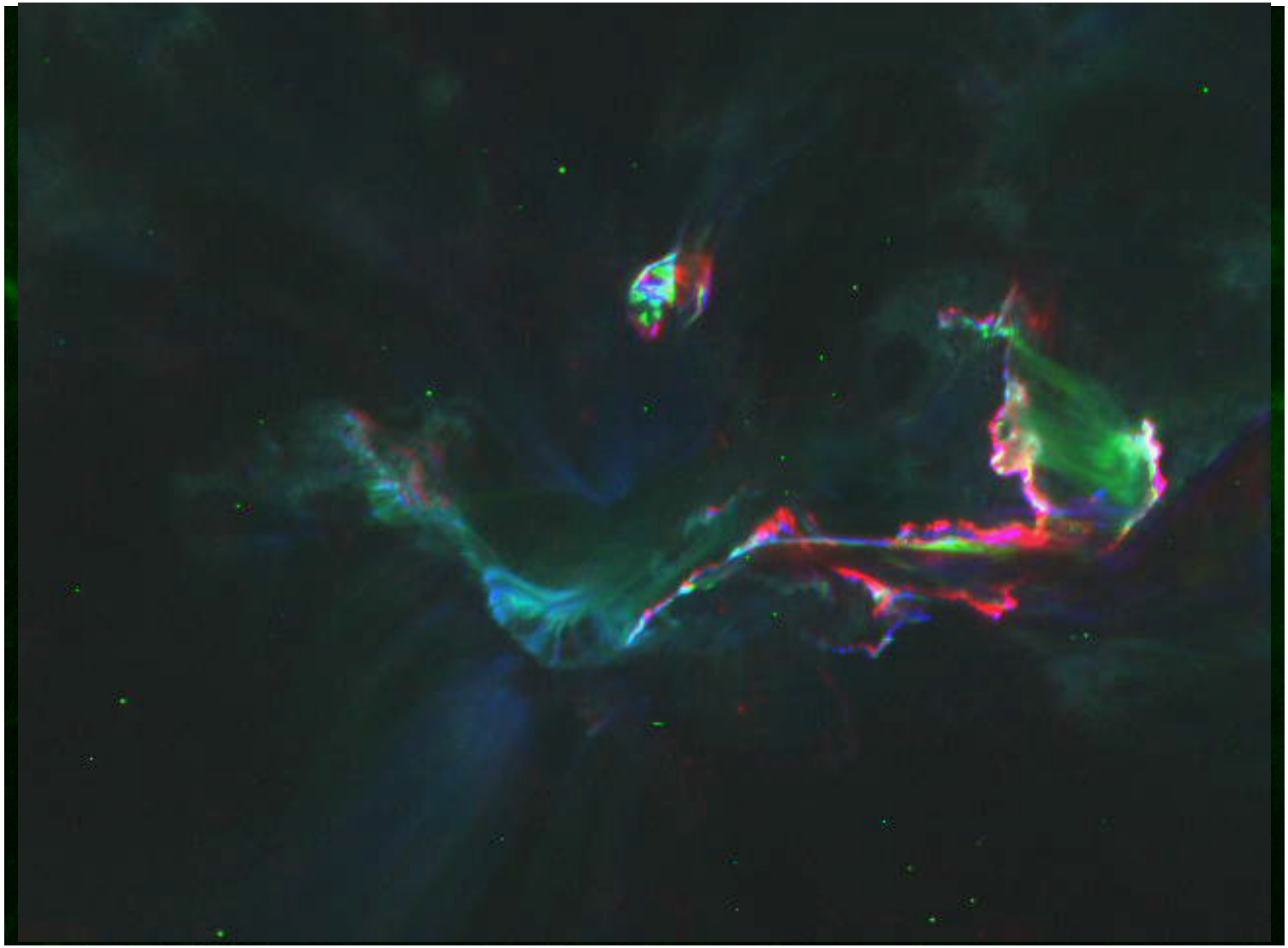
front view



High β surface

(Forbes)

As taller flare loops form in the corona, their feet (flare ribbons) expand on the surface.



A grand solar flare in progress

Magnetic reconnection is an important topic in plasma physics applied to astrophysics, space physics, and fusion research.

Ex.8: how is the reconnection released energy used and manifested on the Sun?

magnetic energy in a volume :

$$W_B = \int \frac{B^2}{2\mu_0} d\tau$$

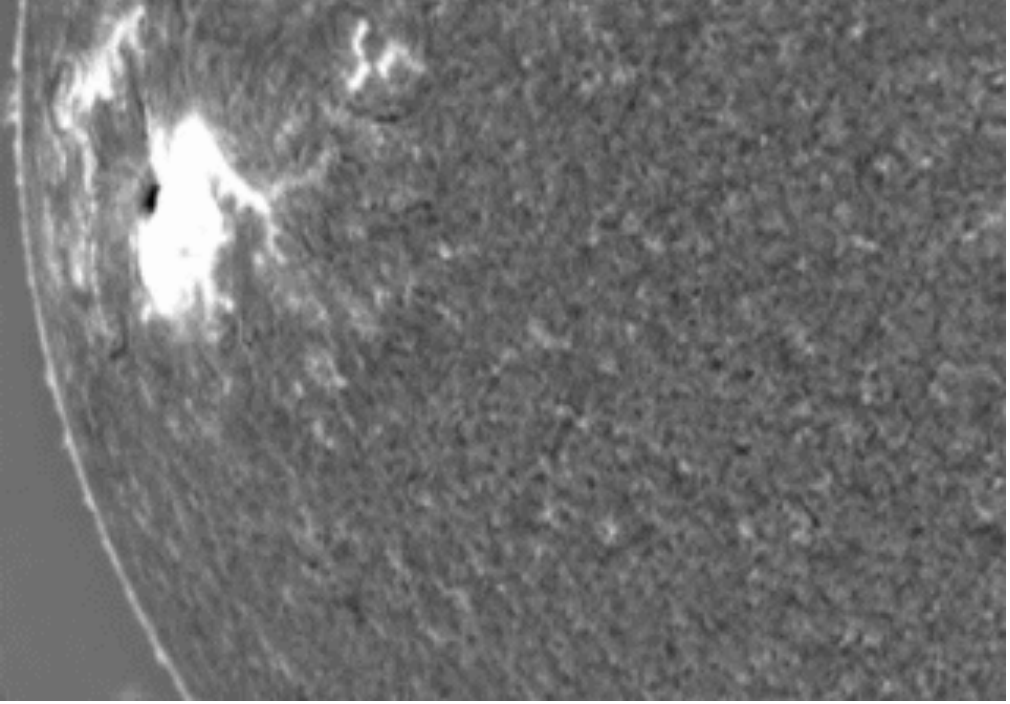
$$\Delta W_B = W_B{}^{np} - W_B{}^{p}$$

$$= E_{flare} + E_{CME}$$

- push gas to move or eject → kinetic energy → measured in time lapse movies or Dopplergrams.
- heat plasmas → thermal energy → measured from continuum or line emissions.
- accelerate charged particles → non-thermal energy → measured from microwave emission when particles spiral around magnetic field lines or hard X-ray emission when particles lose their energy by colliding with high-density plasmas.

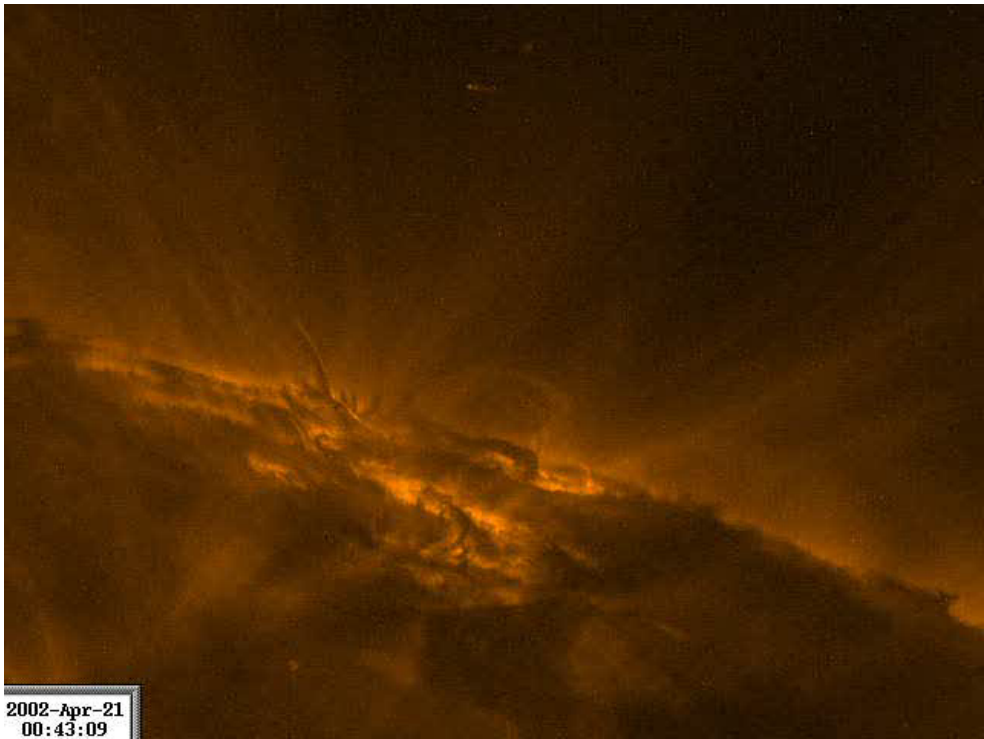
Guiding Questions

1. What are solar active regions? How do we know that sun spots are regions of strong magnetic field? How is magnetic field of the Sun measured?
2. What is the magnetic structure of a sun spot? Why are sunspots dark?
3. Can we observe magnetic field in the corona? How do we study coronal magnetic field?
4. What is a solar flare? What is the connection between solar flares and magnetic field? Where comes the energy of a solar flare?
5. What is our current understanding of the physical mechanism of solar flares? How can we be convinced that flares are driven by magnetic reconnection?
6. What is a CME? What is the connection between CMEs and the space weather? In what ways can we possibly predict the space weather?

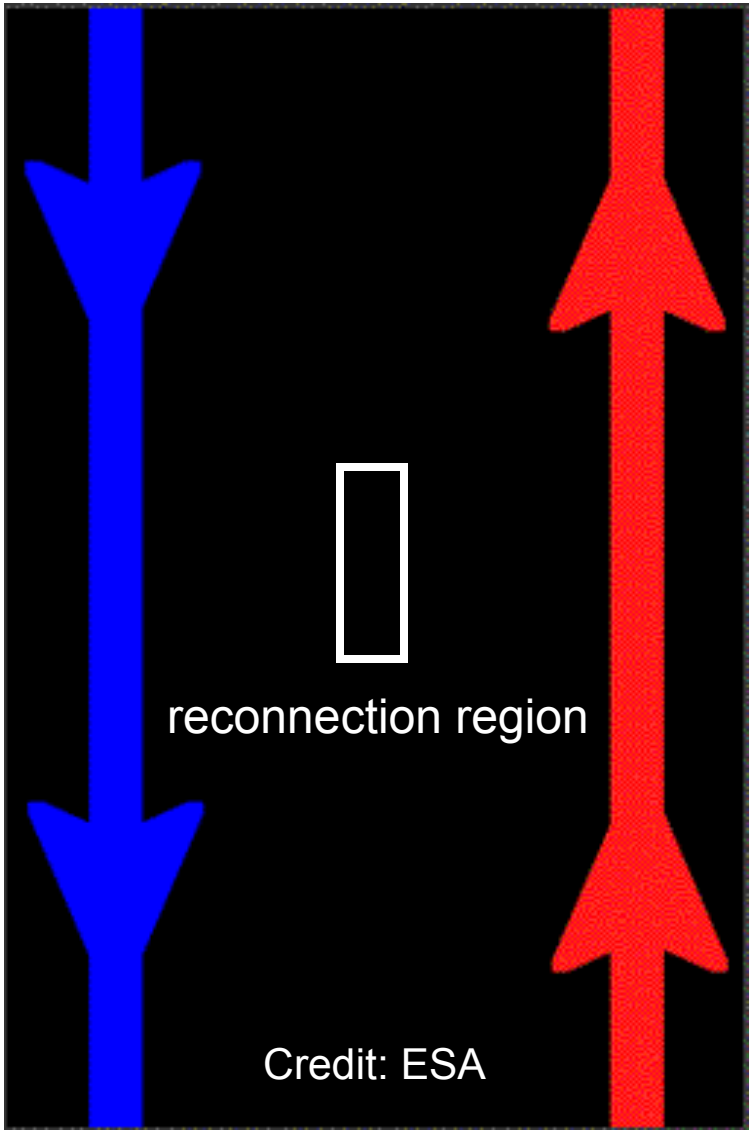


Energy Release during Flares

Human beings are unable to predict solar flares events!



magnetic reconnection is considered to release energy at observed rate.



- Magnetic field has a special property: it does not have a source or sink. Therefore, magnetic field lines cannot break.

- Anti-parallel magnetic field lines, when pushed close, exchange connectivities. This is **magnetic reconnection**.

- Magnetic reconnection so occurs that the magnetic configuration after reconnection has less energy than before reconnection.

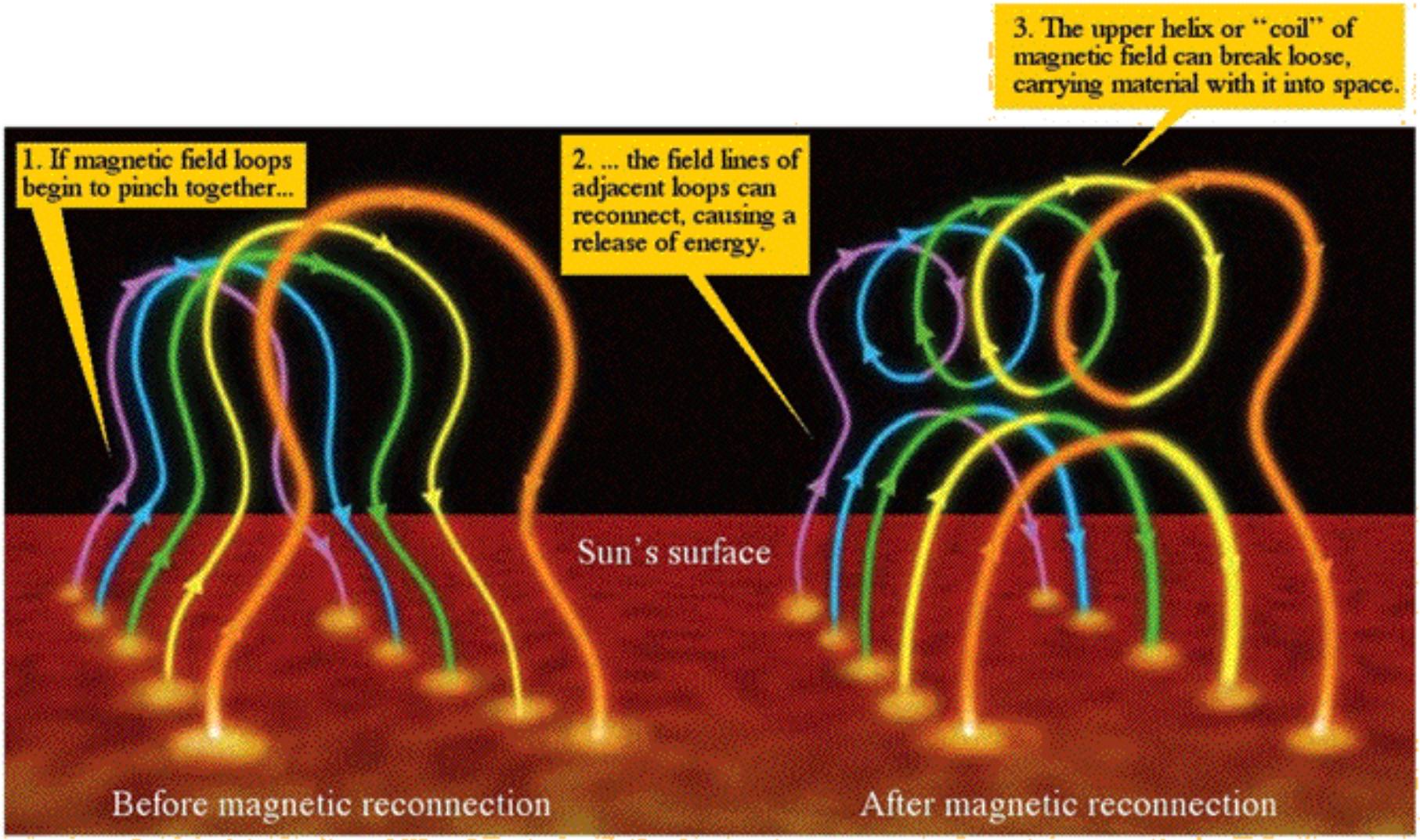
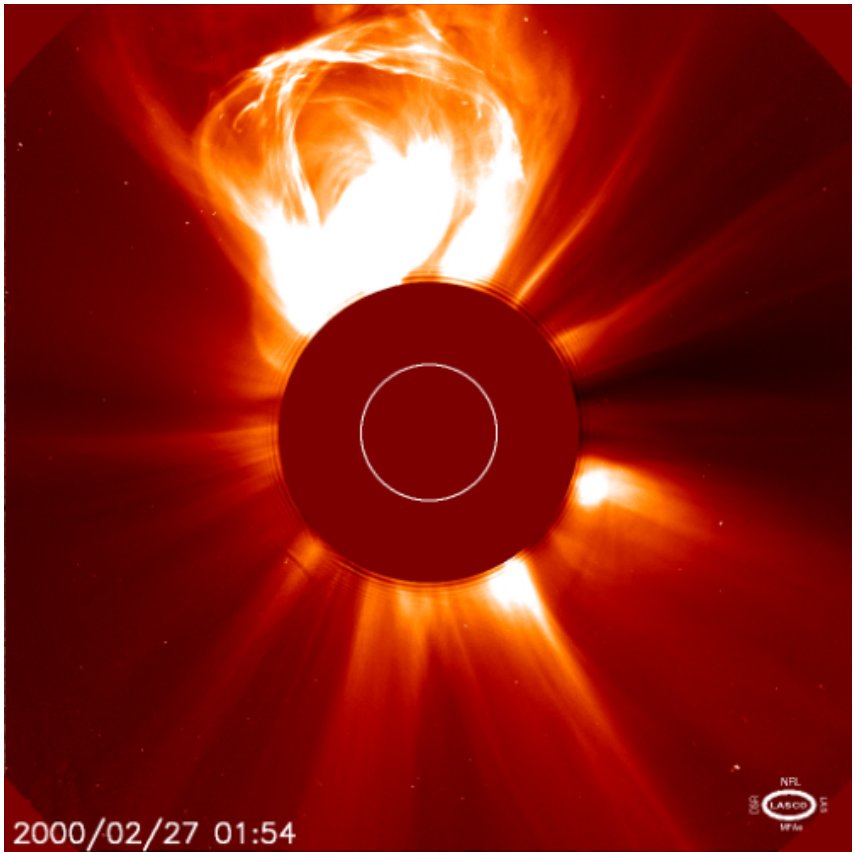


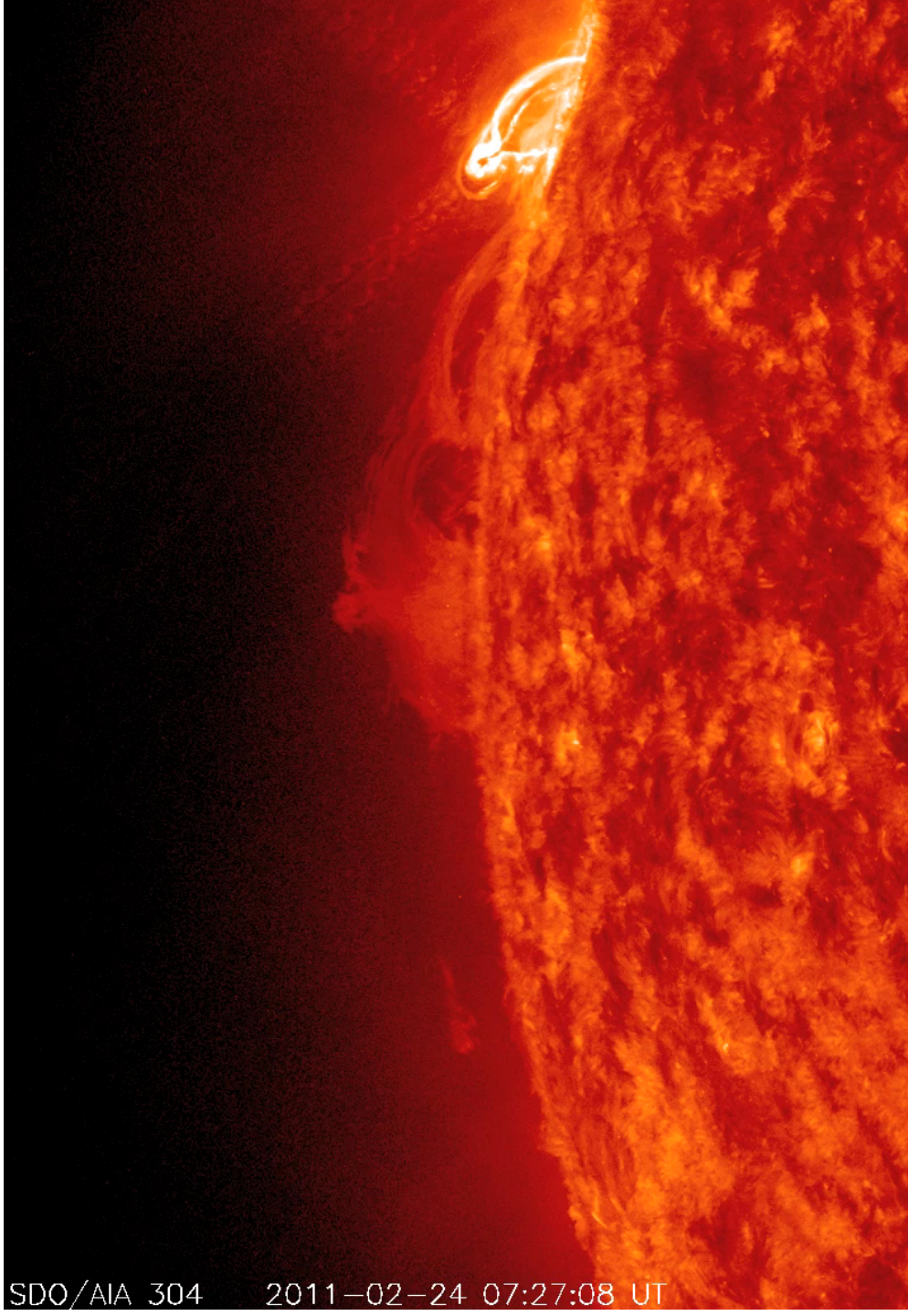
Figure 16-25b
Universe, Eighth Edition

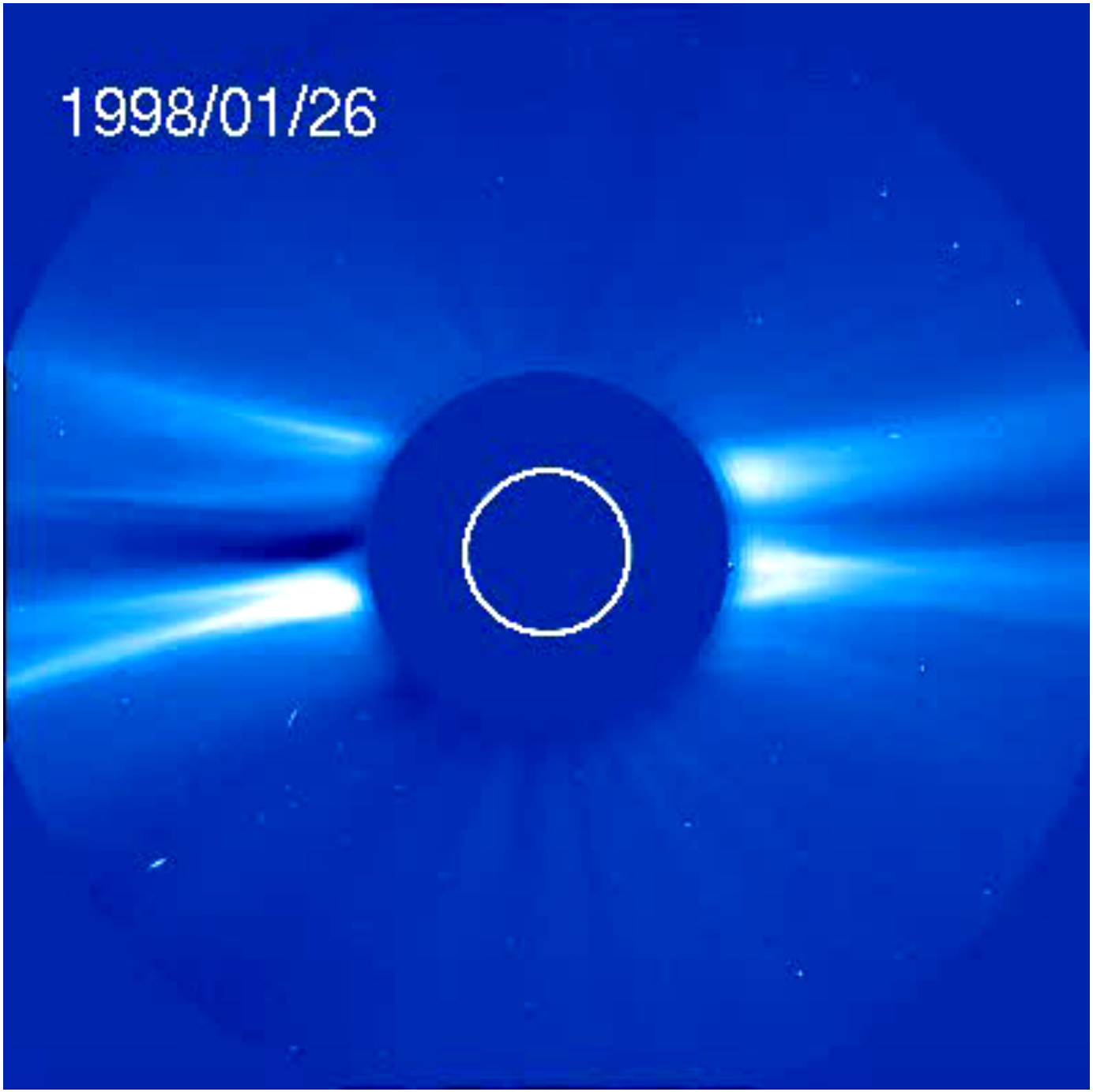
Reconnection may also produce the upper bundle of twisted fields, called "flux ropes", and release them to interplanetary space.

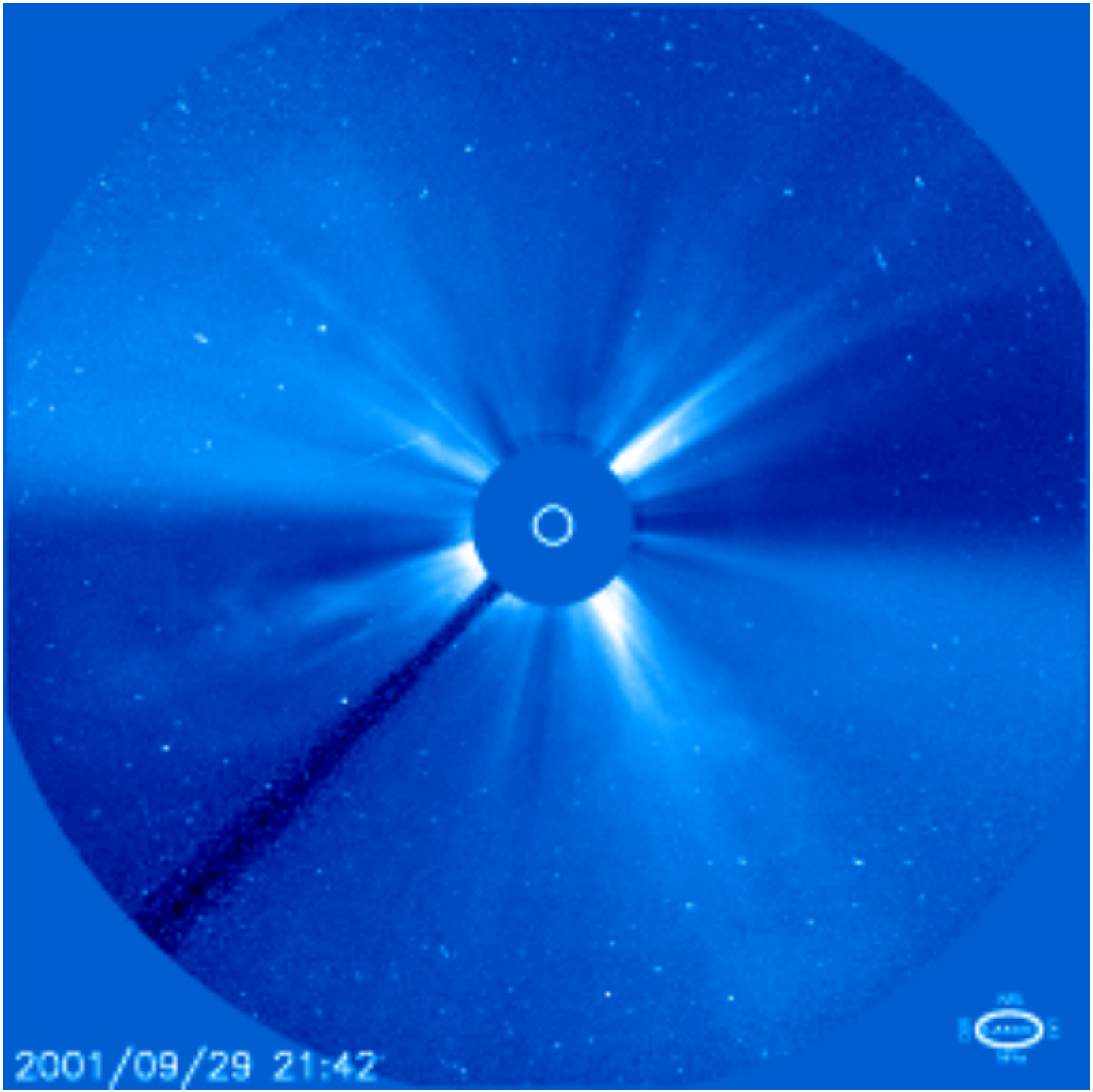
Coronal Mass Ejections

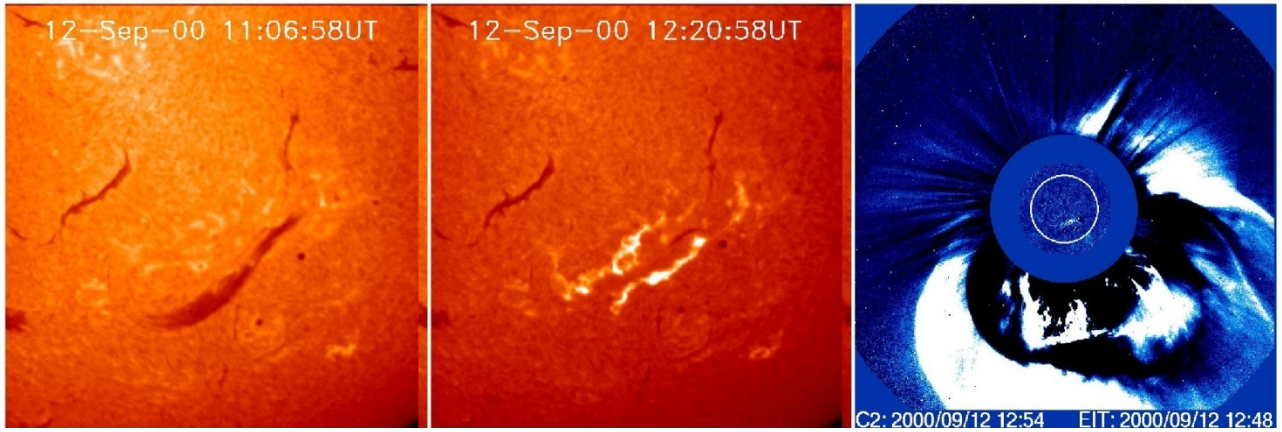
The most violent solar activity is reflected in events called **Coronal Mass Ejections,** or **CME**s.





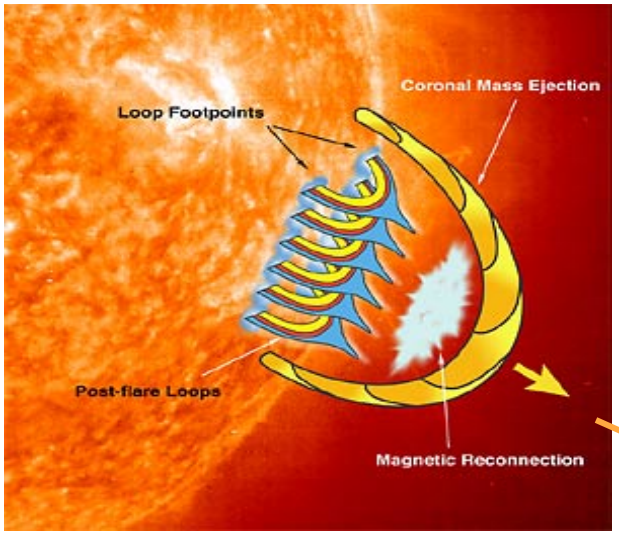

1998/01/26


2001/09/29 21:42

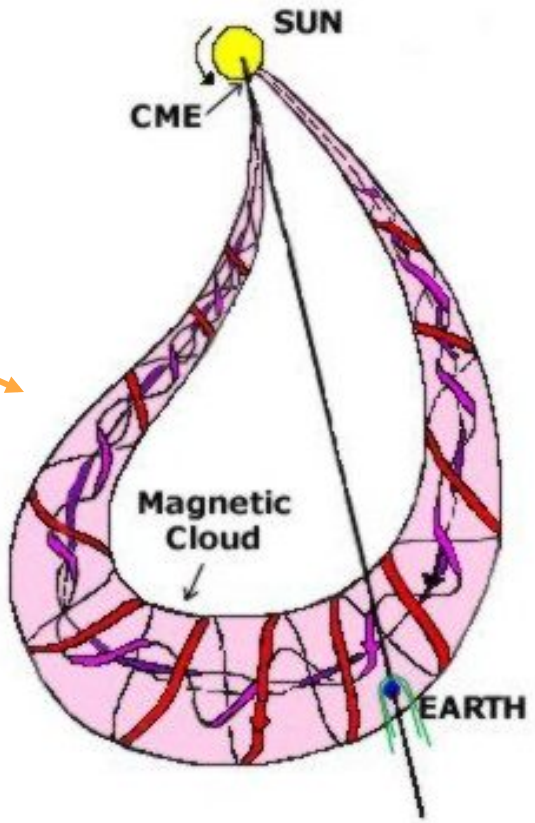


The most energetic flares are often associated with coronal mass ejections,

Coronal mass ejections may carry magnetized plasmas to the Earth and be measured as a complicated magnetic structure, a “magnetic cloud”, by satellites crossing the cloud.



A complicated magnetic structure forms on the Sun and is ejected out of the Sun.



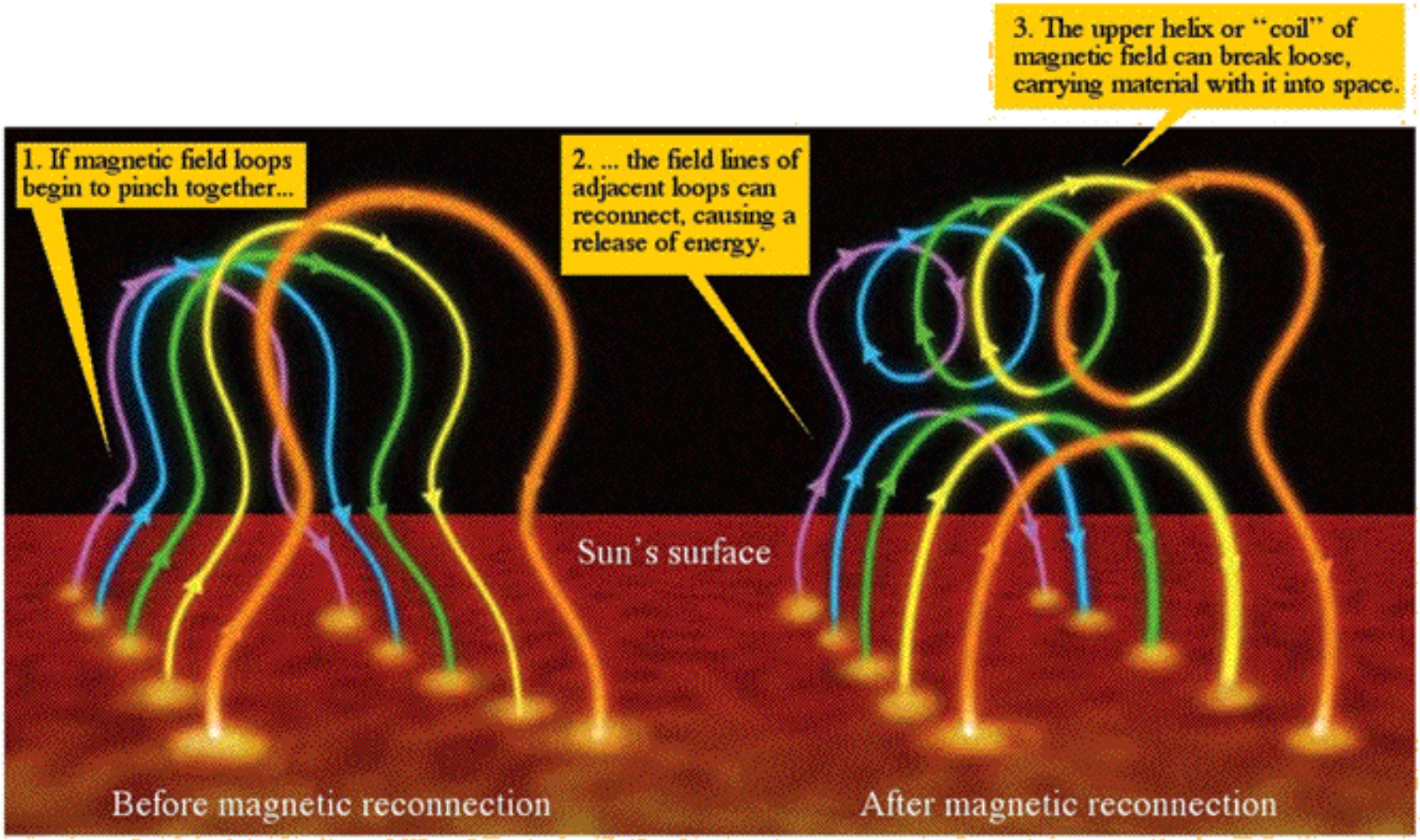
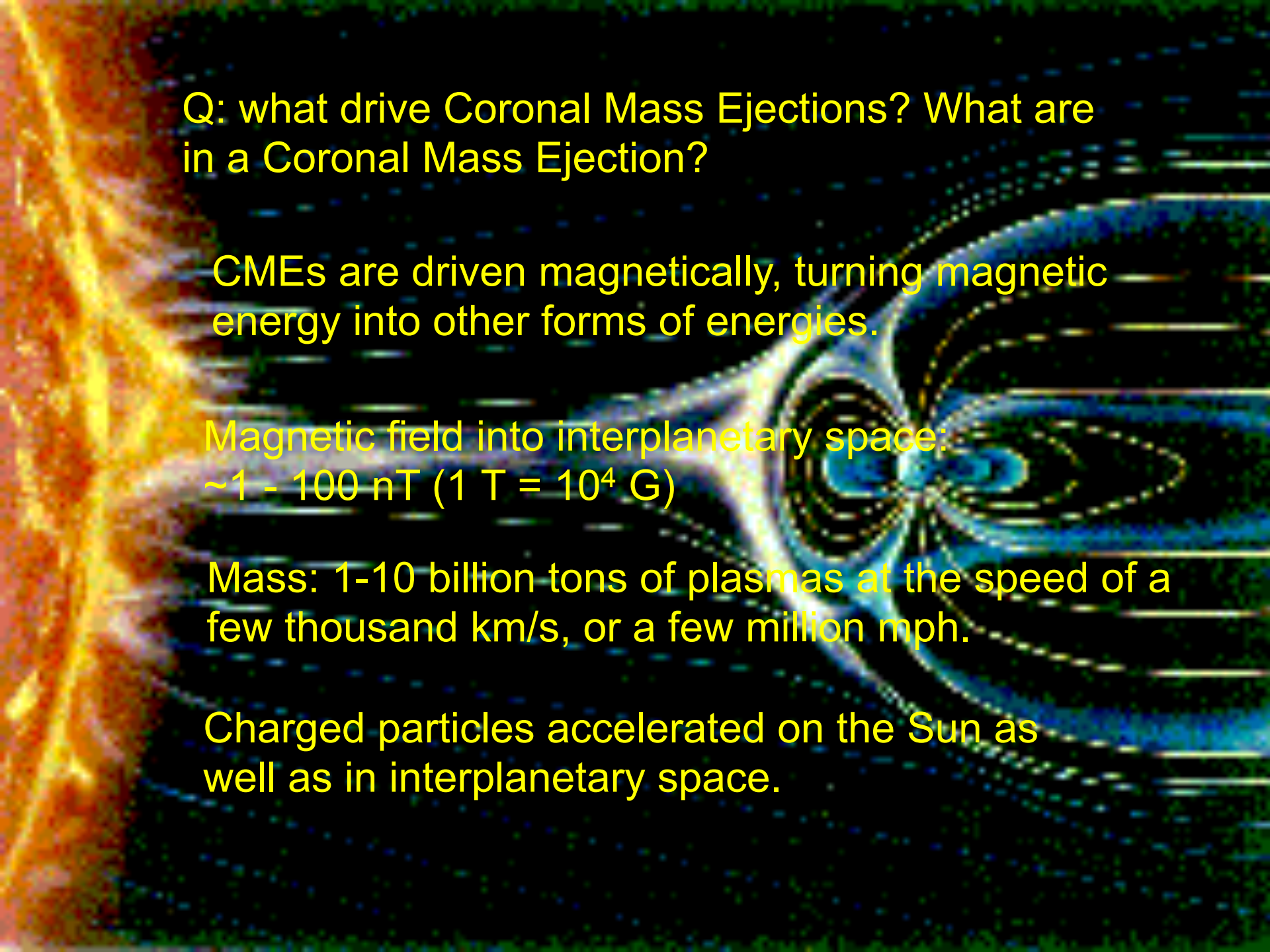


Figure 16-25b
Universe, Eighth Edition

Reconnection may also produce the upper bundle of twisted fields, called "flux ropes", and release them to interplanetary space.



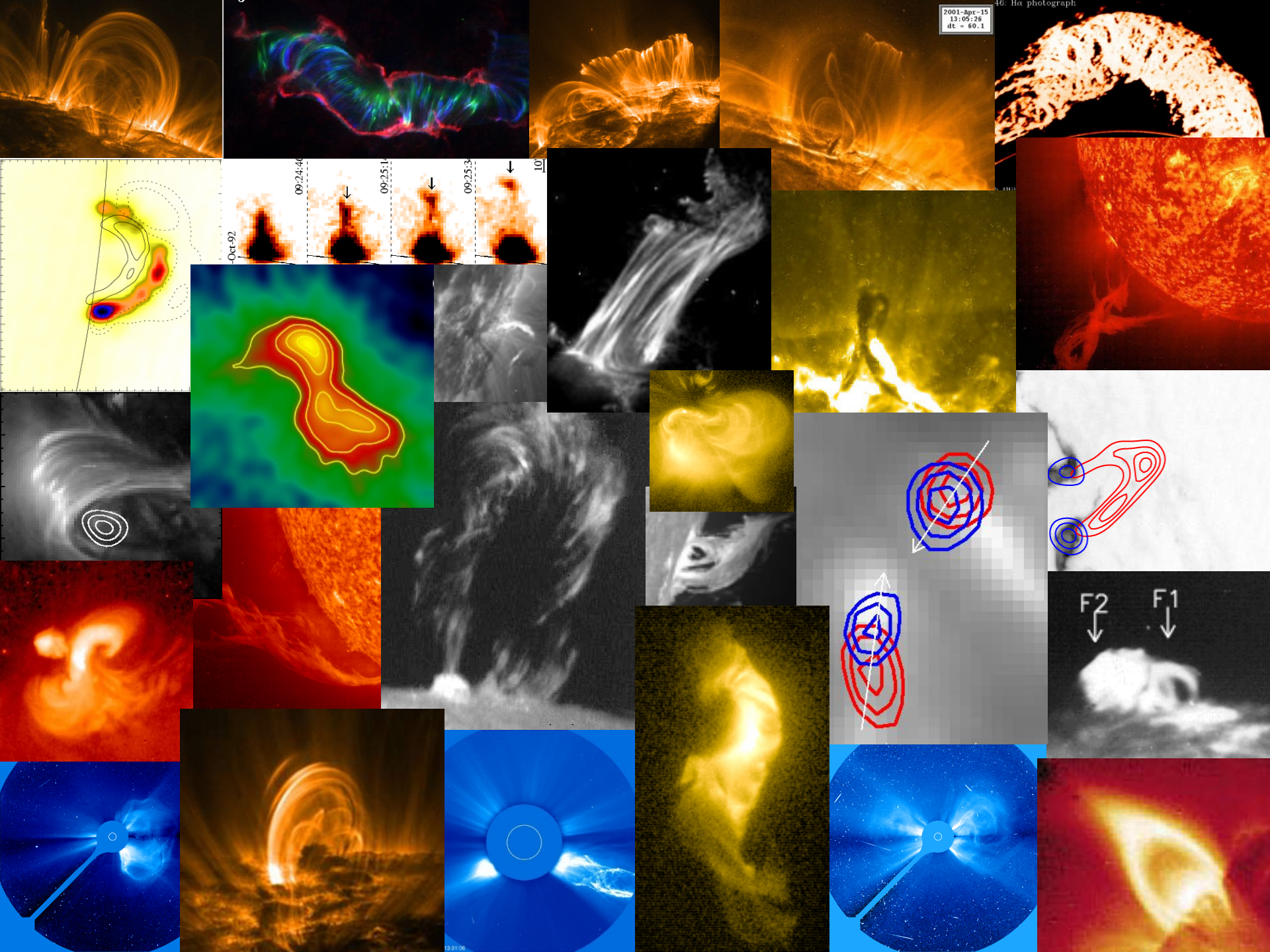
Q: what drive Coronal Mass Ejections? What are in a Coronal Mass Ejection?

CMEs are driven magnetically, turning magnetic energy into other forms of energies.

Magnetic field into interplanetary space: ~1 - 100 nT (1 T = 10^4 G)

Mass: 1-10 billion tons of plasmas at the speed of a few thousand km/s, or a few million mph.

Charged particles accelerated on the Sun as well as in interplanetary space.


2001-Apr-15
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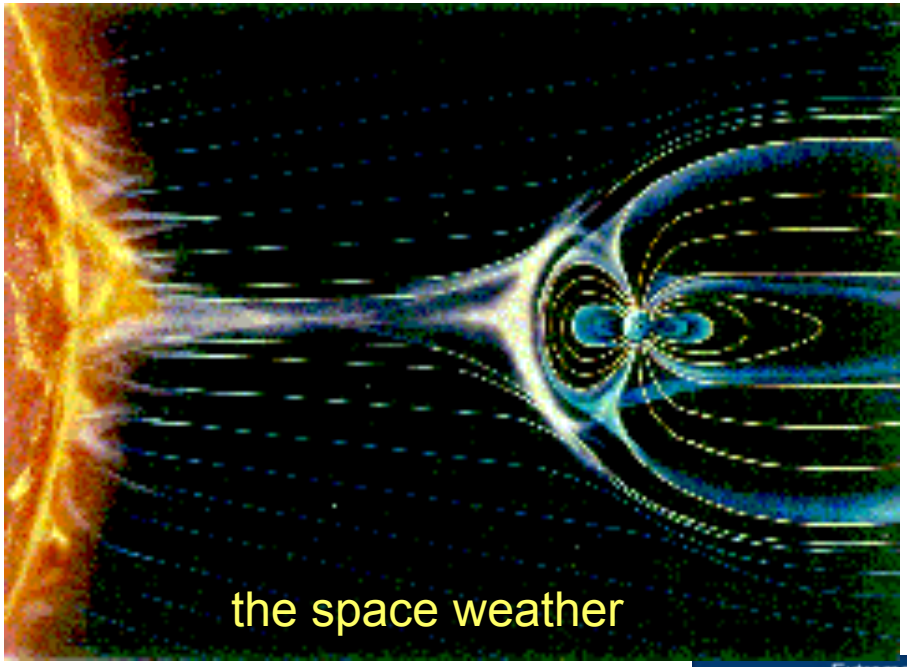
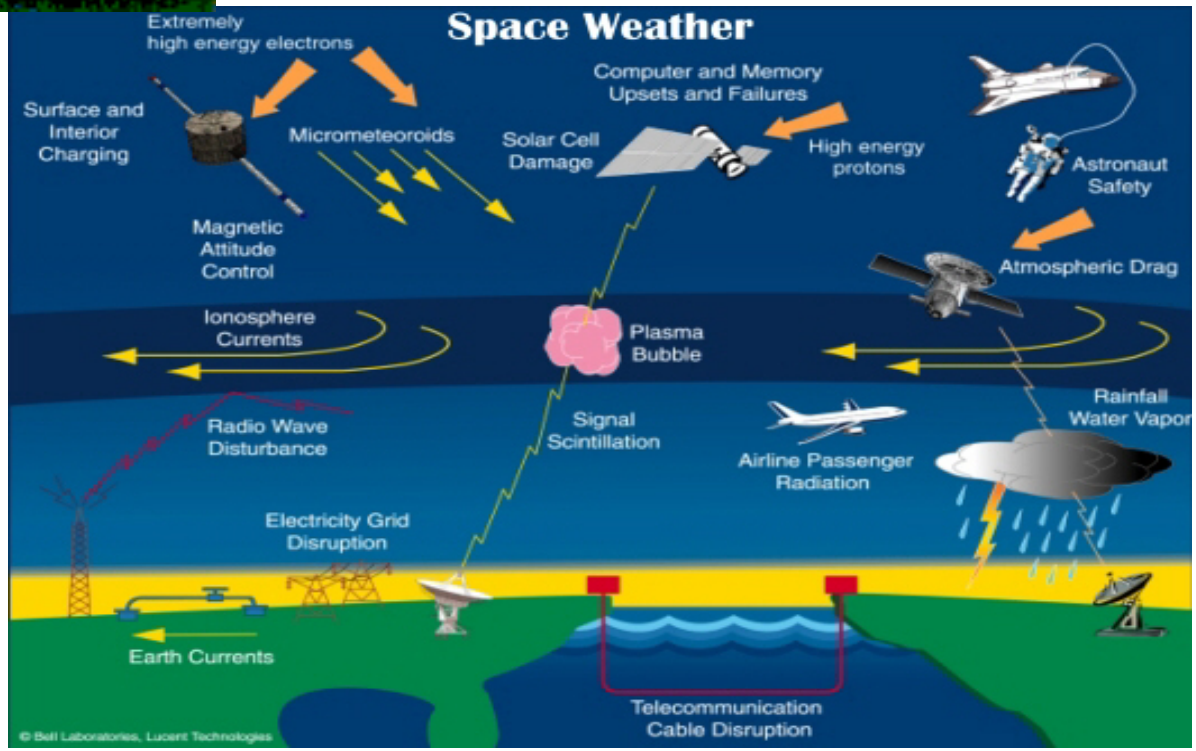
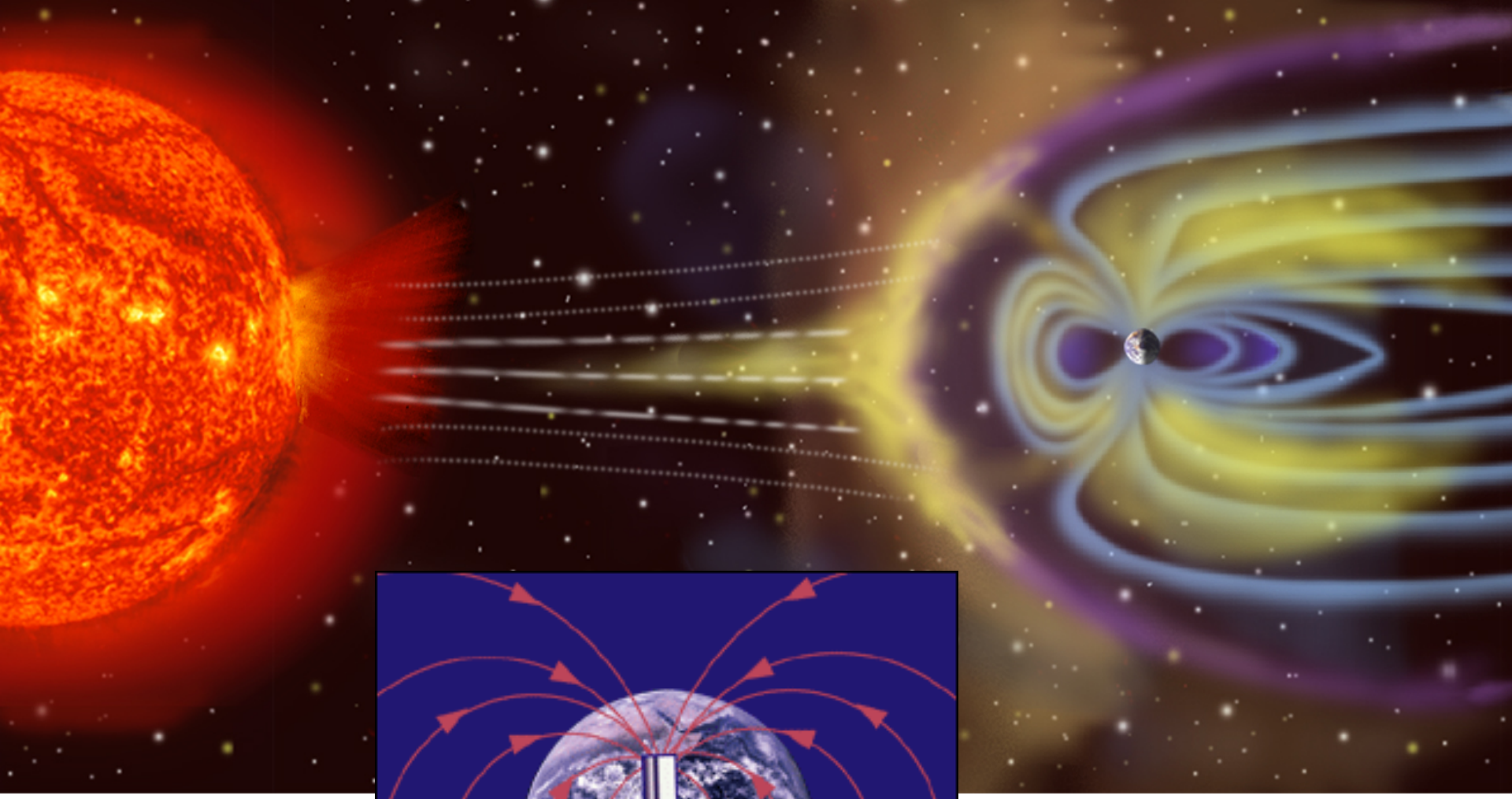
dt = 60.1
46: Hα photograph
09:24:46
09:25:14
09:25:3
Oct-92
F2
F1

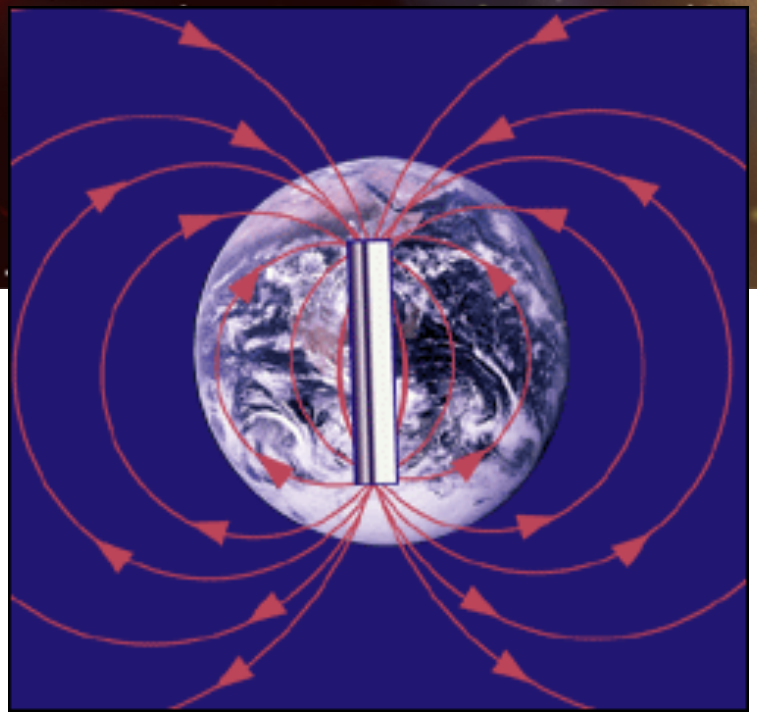


Why study the CMEs? Streams of charged particles from the Sun lead to adverse **space weather** and pose threat to our ambition to explore the outer space and solar system.

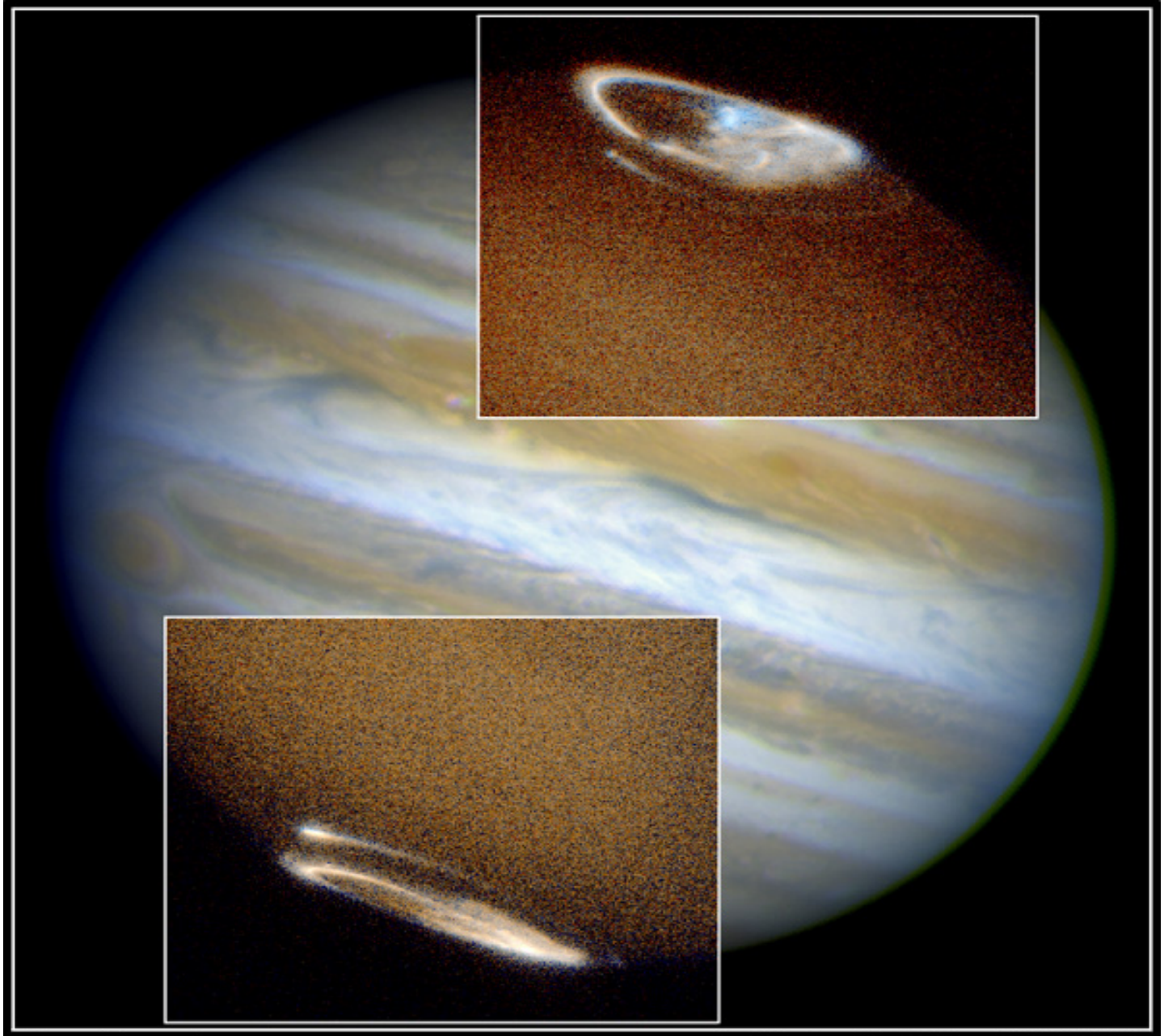
We may predict space weather by a good understanding of the Sun's magnetic field and its evolution.





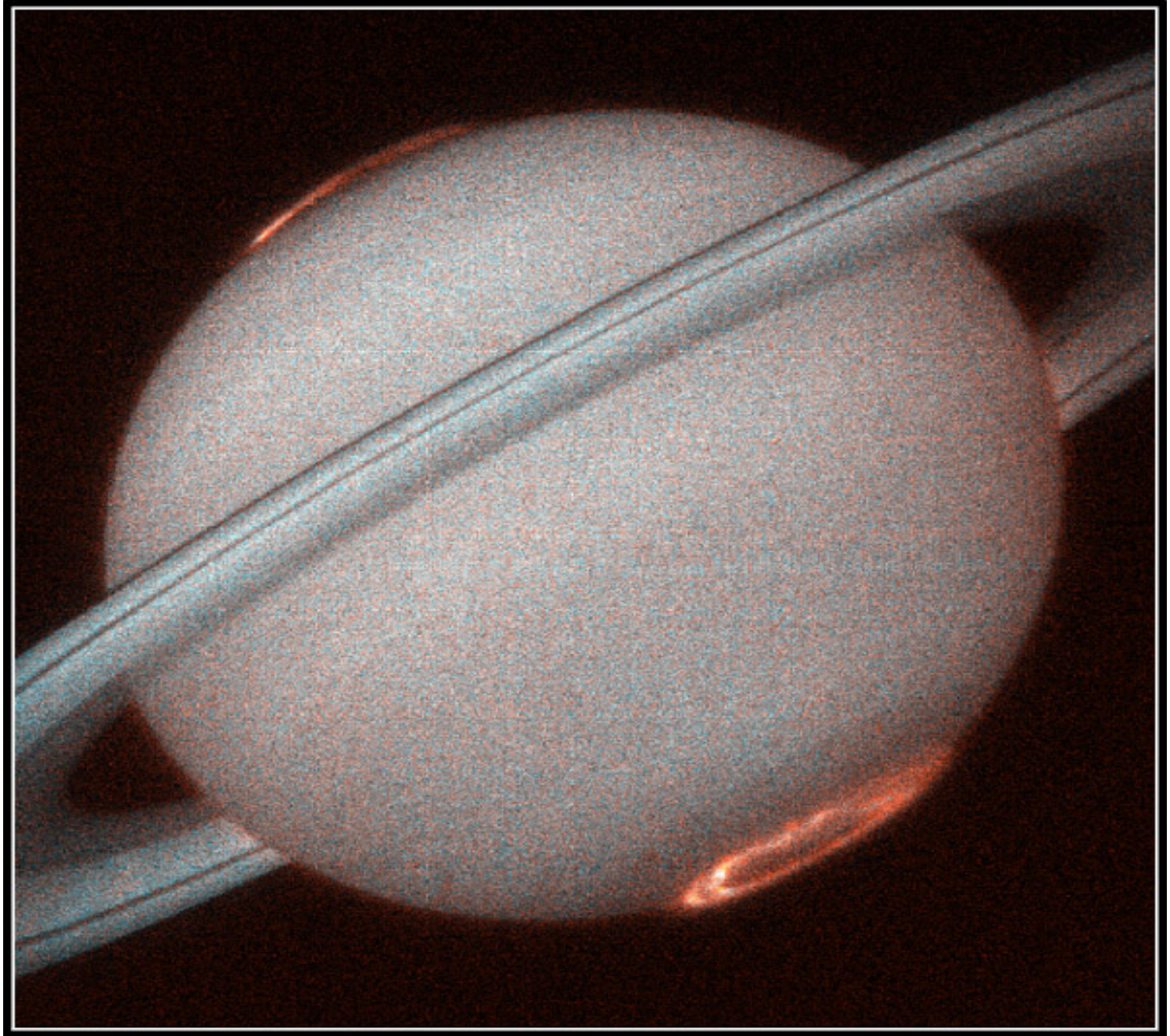


Space Weather



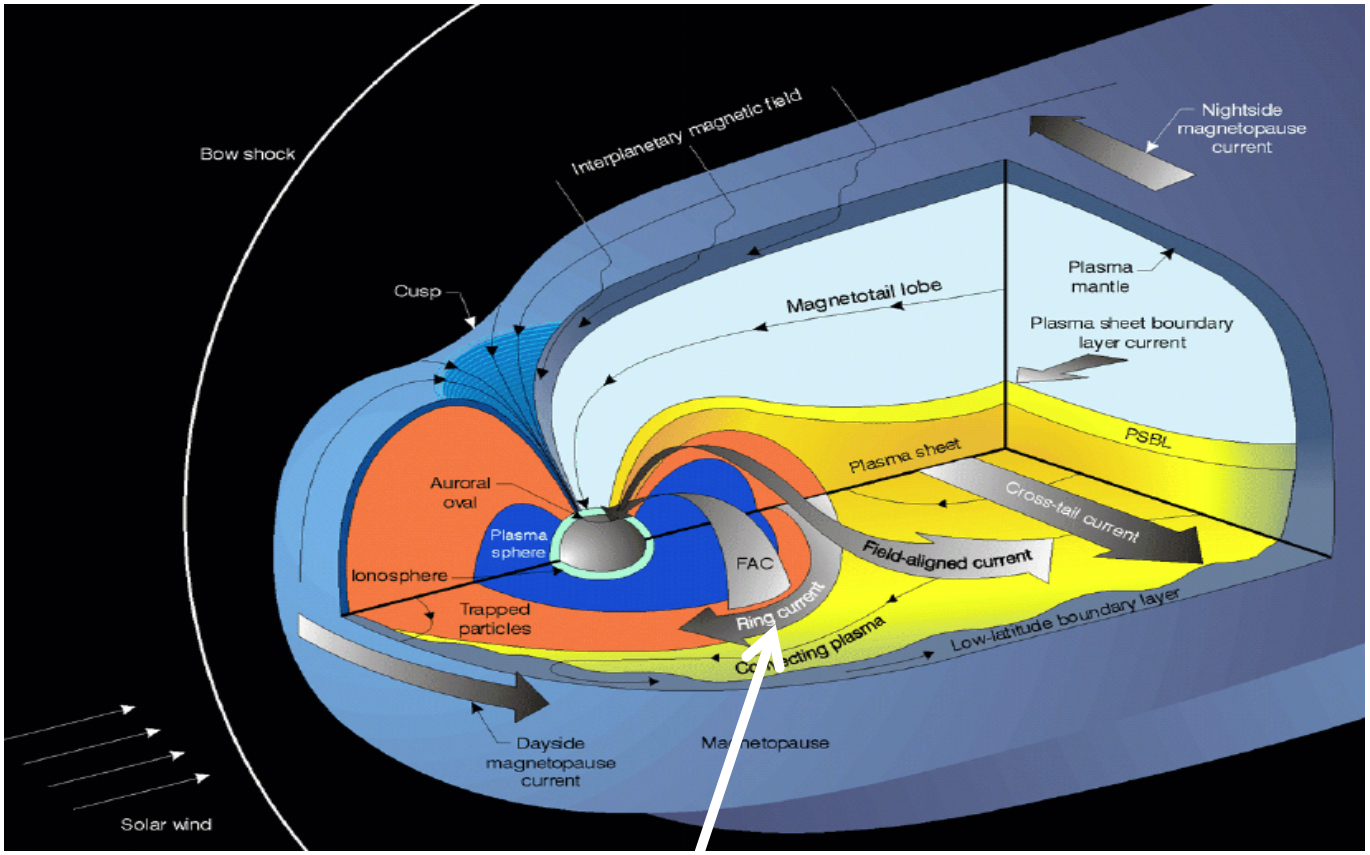
Jupiter Aurora HST • STIS • WFPC2

PRC98-04 • ST ScI OPO • January 7, 1998
J. Clarke (University of Michigan) and NASA



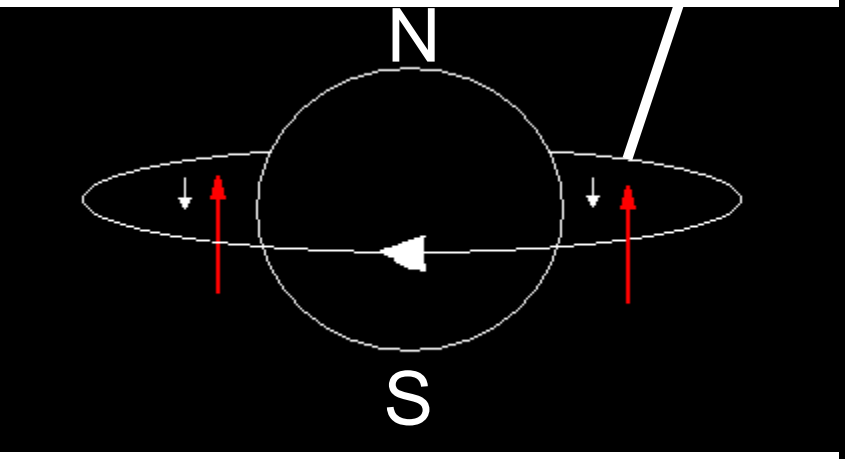
Saturn Aurora HST • STIS

PRC98-05 • ST ScI OPO • January 7, 1998 • J. Trauger (JPL) and NASA


Bow shock
Interplanetary magnetic field
Nightside magnetopause current
Cusp
Magnetotail lobe
Plasma mantle
Plasma sheet boundary layer current
PSBL
Plasma sheet
Auroral oval
Plasma sphere
Ionosphere
Trapped particles
FAC
Field-aligned current
Cross-tail current
Ring current
Low-latitude boundary layer
Dayside magnetopause current
Solar wind

磁暴

~ (2 – 24 小时)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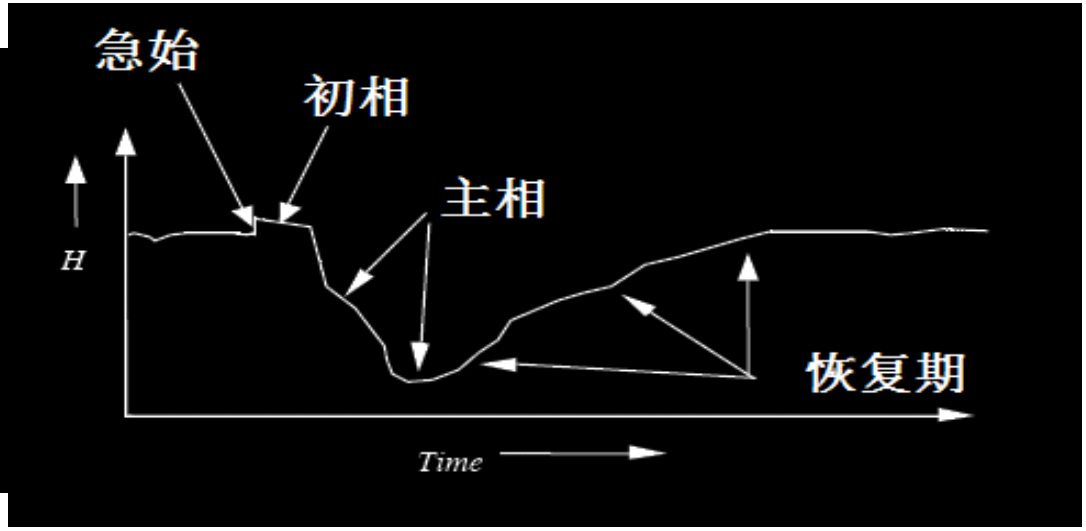
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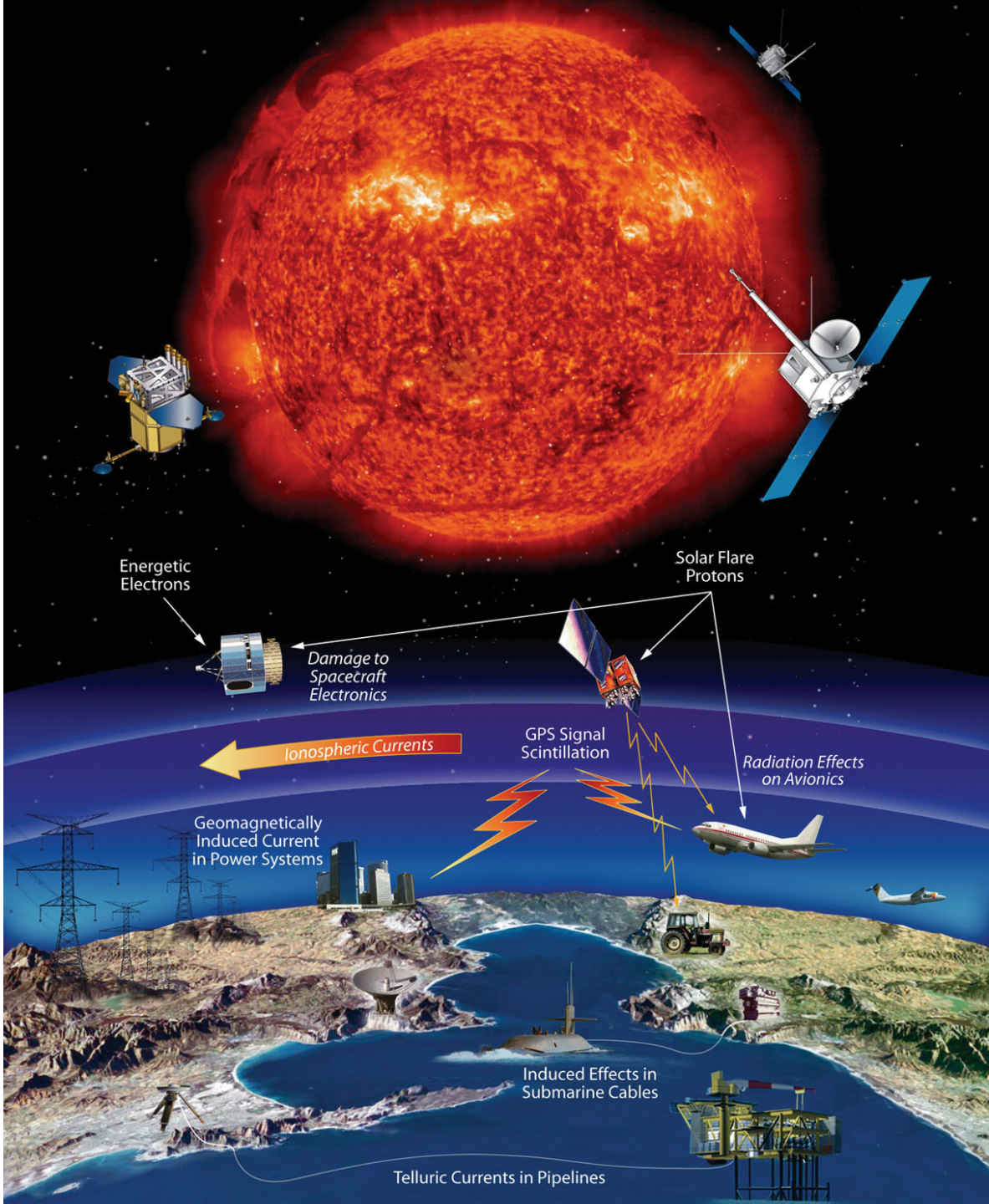
Time

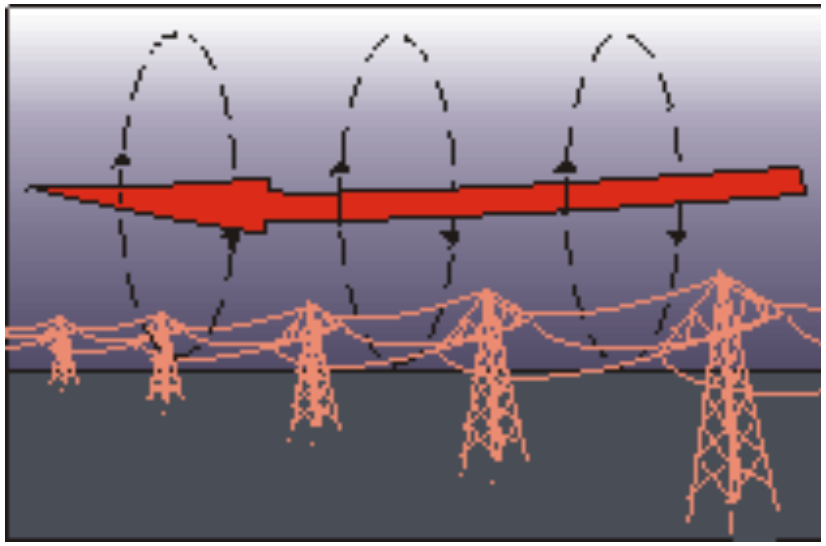
space weather

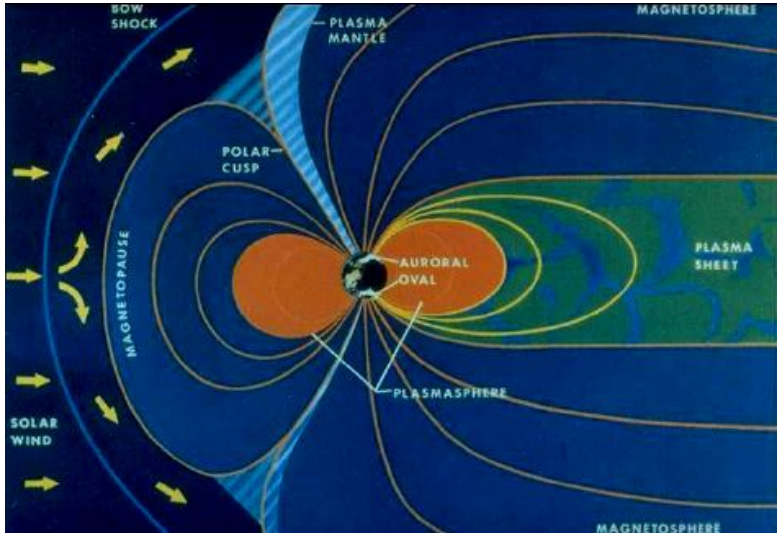
Why study the Sun? Streams of charged particles from the Sun lead to adverse **space weather** and pose threat to our ambition to explore the outer space and solar system.

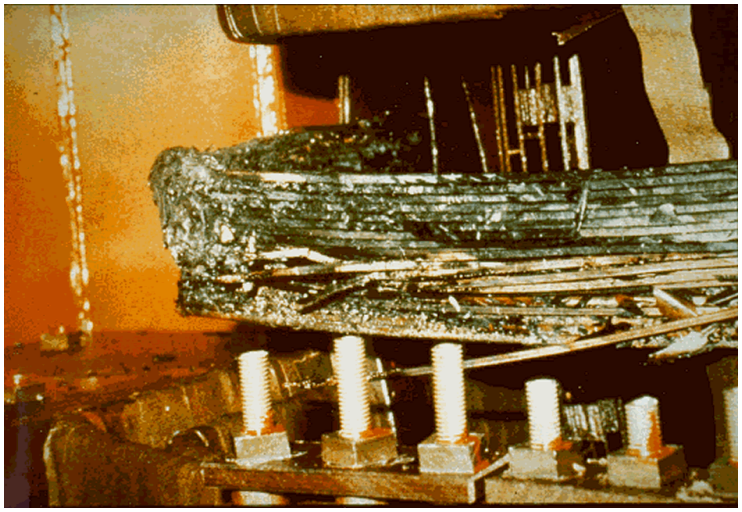
- **Induced Current**
- **Radio communication**
- **GPS**
- **Spacecraft, satellites**
- **Radiations**



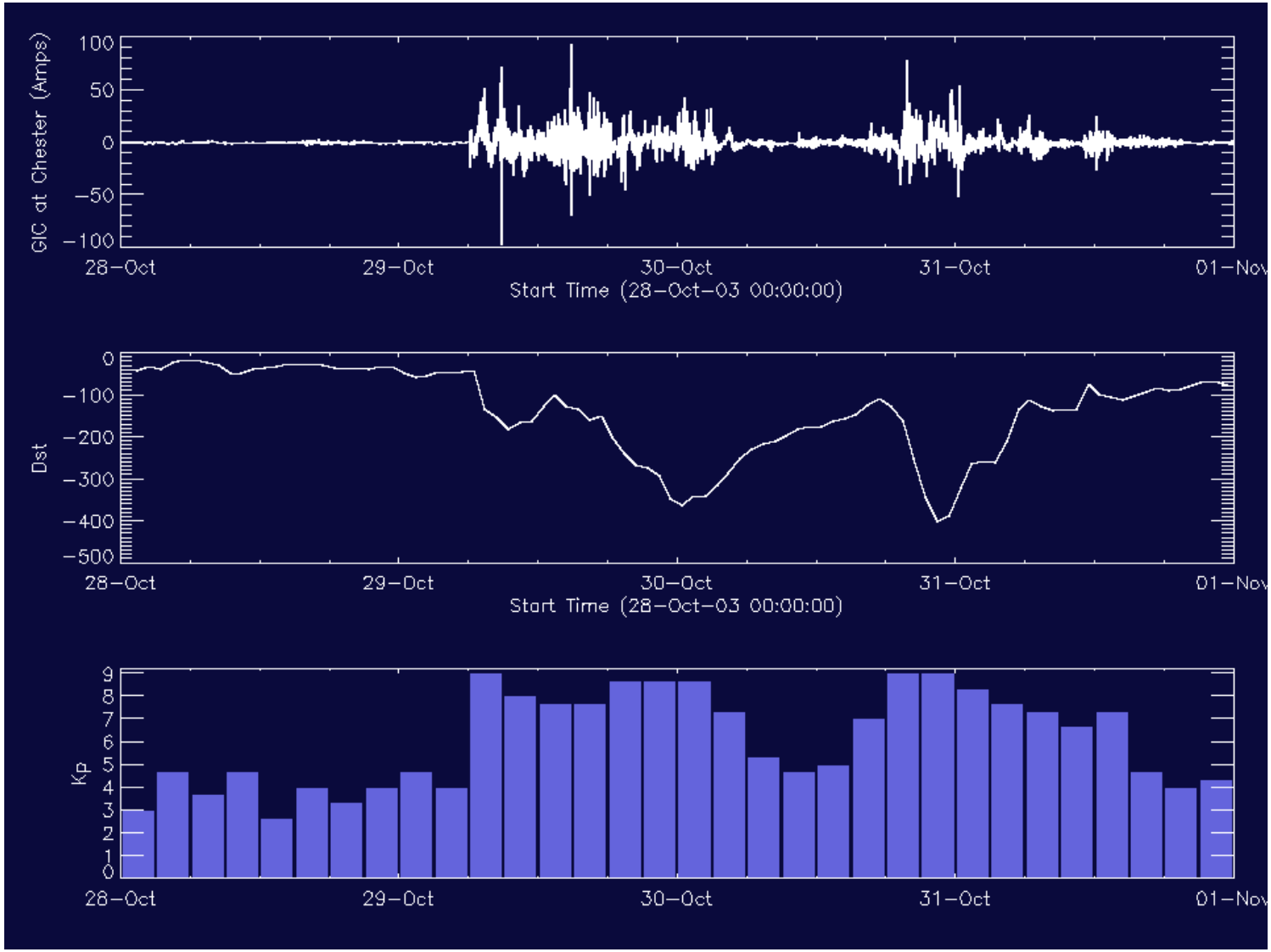
Induced Current in Power System







Induced Current in Power System



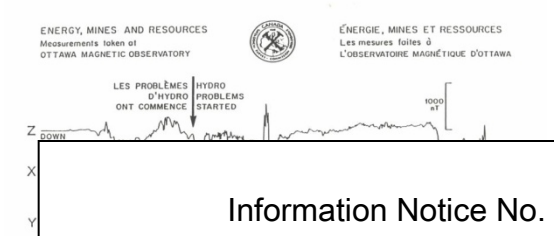
Significant grid problems have occurred…

HYDRO-QUEBEC PRESS RELEASE

Direction Relations Publiques
HYDRO-QUEBEC
MONTREAL, CANADA

MARCH 13 BLACKOUT CAUSED BY AN EXCEPTIONALLY STRONG MAGNETIC STORM

Montreal, March 15, 1989 - Hydro-Quebec confirms that the March 13 blackout was caused by the strongest magnetic storm ever recorded since the 735-kv power system was commissioned. At 2:45 AM the storm, which resulted from a solar flare, tripped five lines from James Bay and caused a generation loss of 9,450 MW. With a load of some 21,350 MW at that moment, the system was unable to withstand this sudden loss and collapsed within seconds, thereby causing the further loss of generation from Churchill Falls and Manio-Outardes.



Information Notice No. 90-42:
FAILURE OF ELECTRICAL POWER EQUIPMENT DUE TO SOLAR MAGNETIC DISTURBANCES

Specific events occurred at the Three Mile Island Unit 1, Hope Creek Unit 1, and Salem Unit 1 nuclear power plants. At Three Mile Island 1, the licensee observed tripping of capacitor banks in the 500-kilovolt substation. At Hope Creek 1, the licensee observed swings in reactive electrical power and six operations of the main generator…

…in a subsequent inspection of the generator step-up transformer… severe overheating, melted low -voltage service connections in phases A and C, and insulation discoloration in phase B. On September 19, at Salem Unit 2 nuclear power plant, a second solar storm damaged the generator step-up transformer.

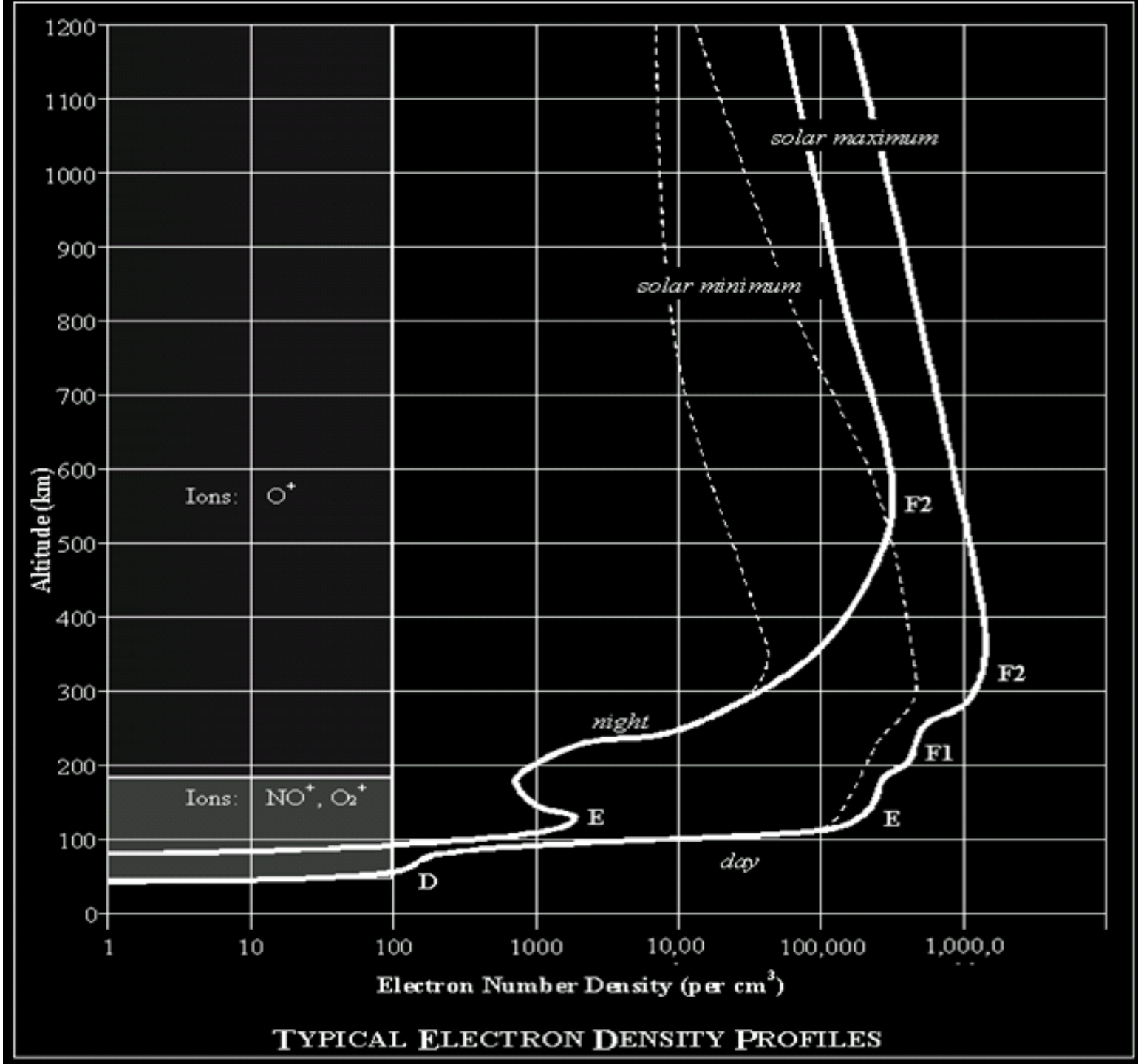
Department of Homeland Security
Information Analysis and Infrastructure Protection
Daily Open Source Infrastructure Report for 03 November 2003

Current Nationwide Threat Level is
ELEVATED
Significant Risk of Terrorist Attacks
For info click here
www.whitehouse.gov/homeland

Energy Sector

Current Electricity Sector Threat Alert Levels: Physical: Elevated, Cyber: Elevated
Scale: LOW, GUARDED, ELEVATED, HIGH, SEVERE [Source: ISAC for the Electricity Sector (ES-ISAC) - http://esisac.com]

October 31 ***- Sun storm causes problems for Swedish power system. The solar storm has caused technical glitches in Sweden's power system in the past few days and may be to blame for a blackout that affected 50,000 people on Thursday, October 30.*** *Magnetic solar storms can wreak havoc with electricity grids, and the effects continued to be felt on Friday, October 31, in the Nordic region, particularly in Sweden where problems with transformers at a nuclear station and in the grid were observed, officials said. Power was cut around 9 p.m. on Thursday in the southern Sweden city of Malmo and lasted 20 minutes to a half hour, utility Sydkraft said in a statement. "We have not 100 percent identified the solar storm as the cause, but it might have been," said Sydkraft official Peter Sigenstam. A spokesperson for Sweden's national grid, Svenska Kraftnat said that two transformers had malfunctioned, but the problems were quickly fixed and had not caused power outages to consumers.*



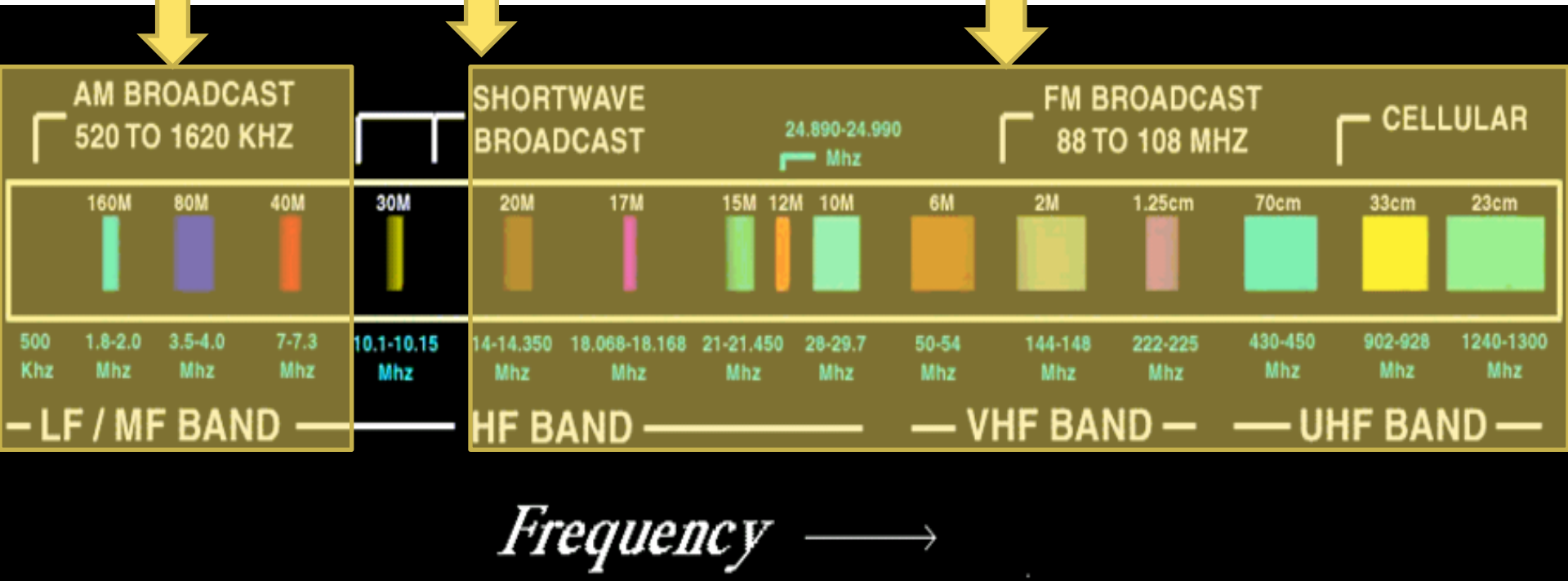
TYPICAL ELECTRON DENSITY PROFILES

Radio communication

Ionization enhancement during solar storm in D-level

$F_{muf} = 9 \times 10^{-3} N^{-1/2} / \sin\alpha$

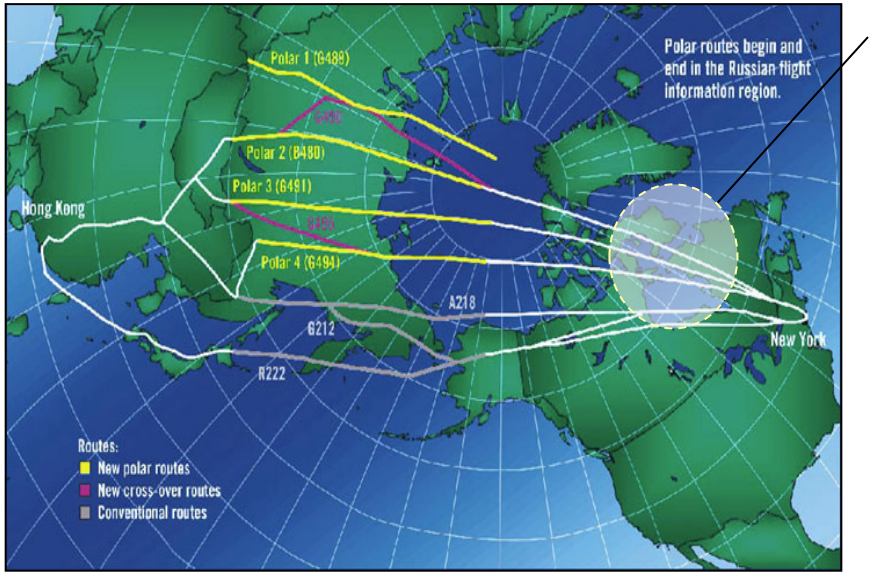
Penetrating magnetosphere

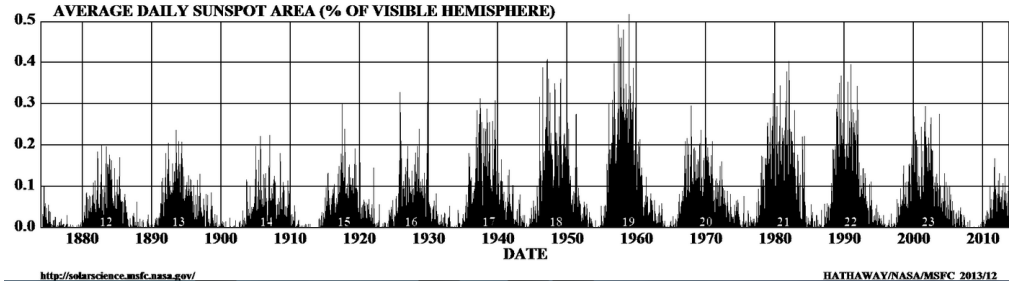


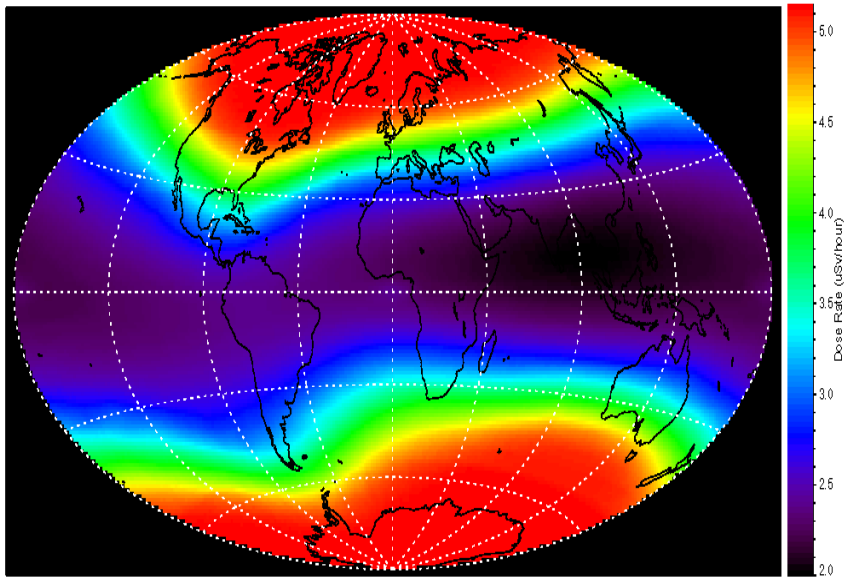
Aircrafts across poles

1. HF(3-30MHz) communication
2. Radiation harmful to pilots and passengers
3. GPS and satellites failures

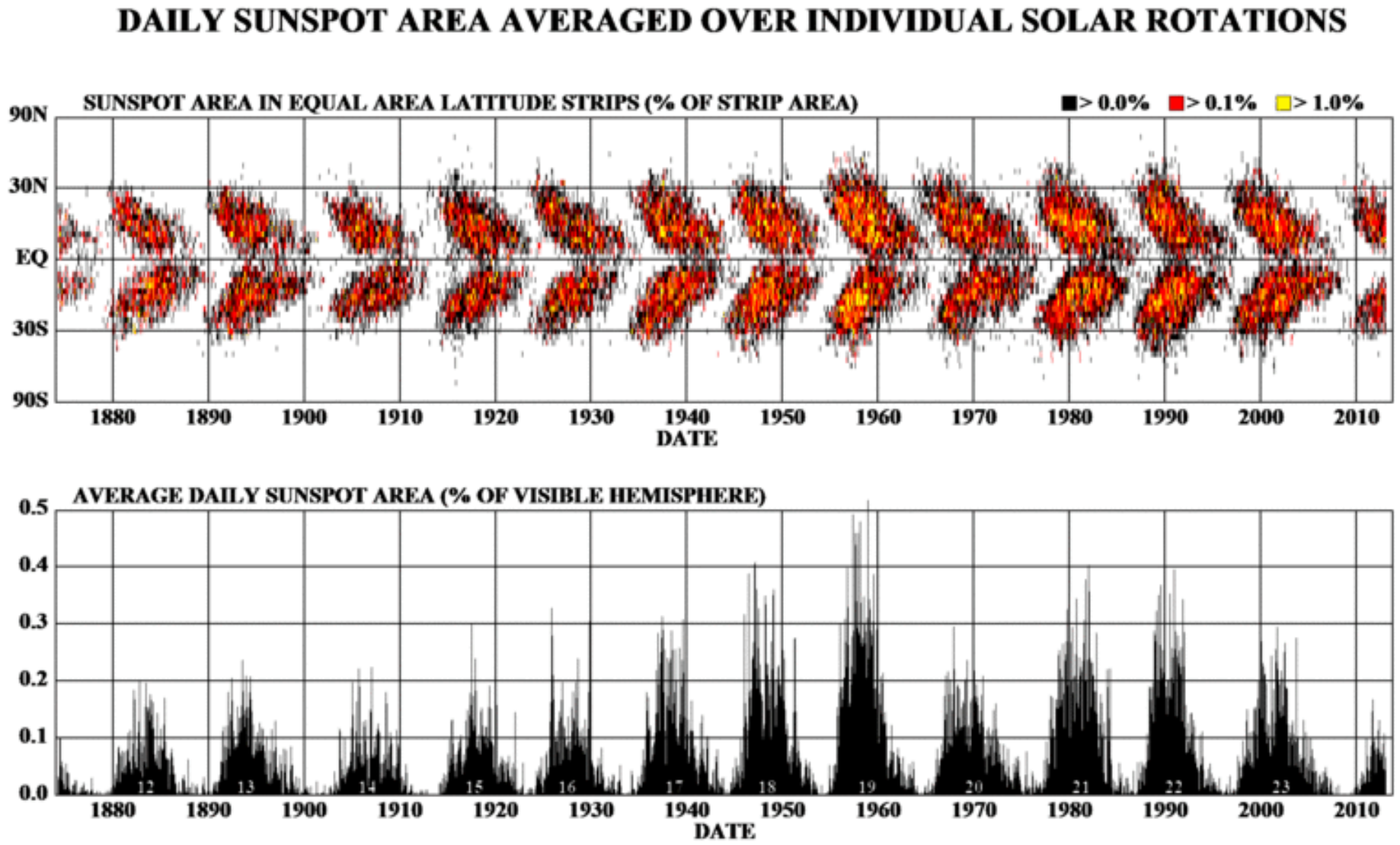
HF Communication only



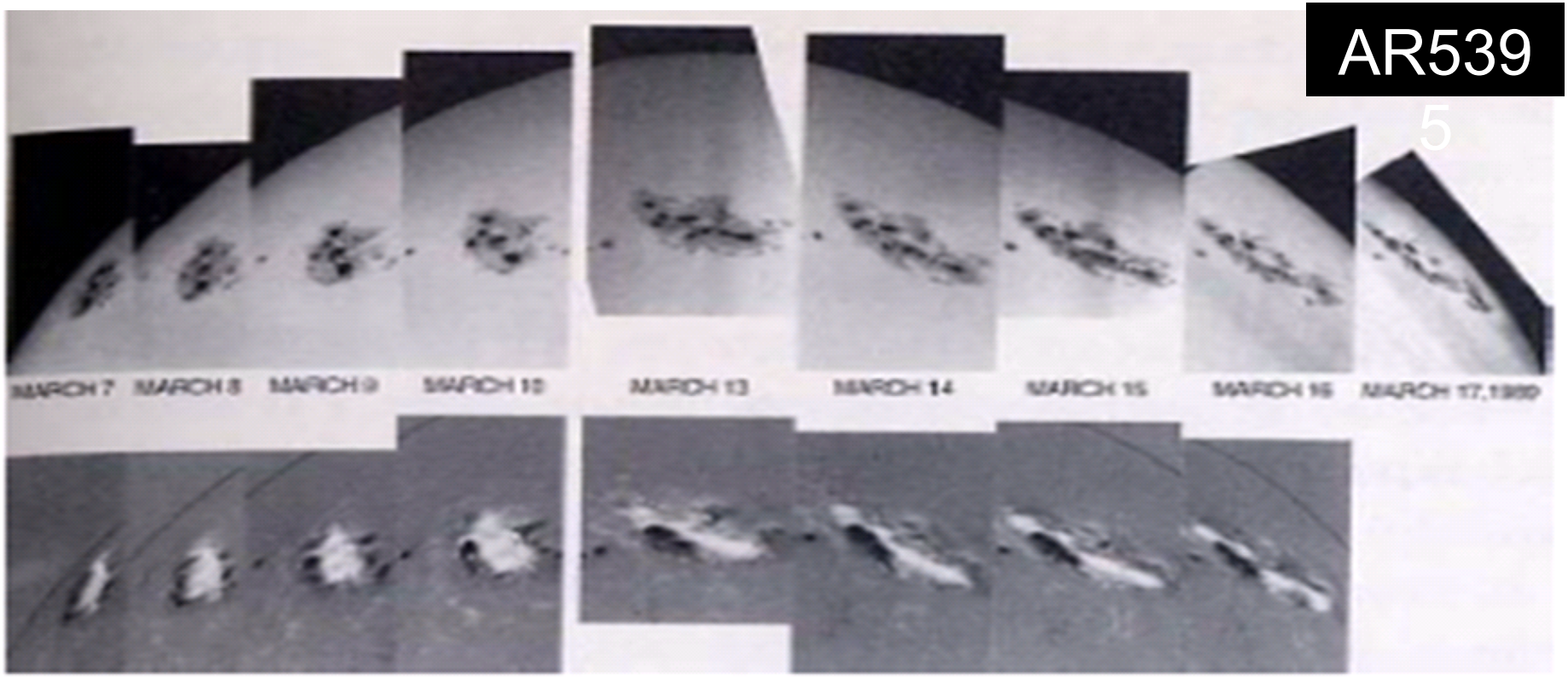




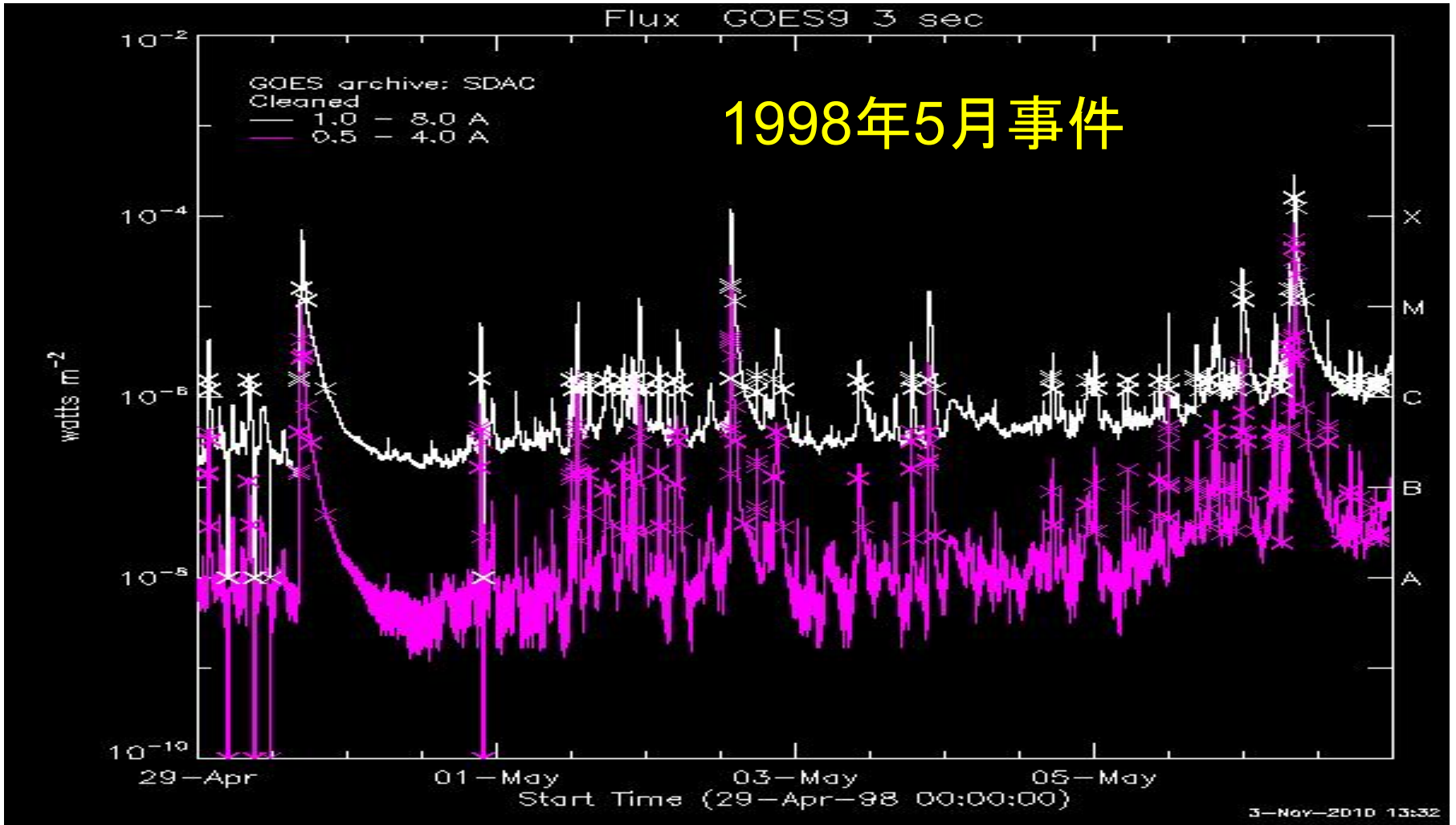
Solar Cycle and Space Weather



1989年3月6-19日，耀斑和强磁暴造成卫星SMM等轨道高度下降，日本和美国通讯卫星发生异常，美国GOES-7卫星的太阳电池损失了一半的能源，致使卫星寿命减少一半，全球无线电通信异常，轮船，飞机的导航系统失灵，美国核电站变压器烧毁，加拿大北部电网烧毁，美国，瑞典以及日本的电力系统也受到不同程度的损害，引起国际社会的震惊和对空间灾害性天气的强烈关注。



1998年4月29日至5月6日SOHO/LASCO探测到了多个CMEs爆发事件，5月2日的一个CME事件还伴随着一个X1级大质子耀斑。随后几天地球磁层发生了强地磁暴以及磁层粒子暴。在此期间多颗飞行器发生异常或者失效，包括5月1日德国科学卫星Equator-S中央处理器失效,5月6日Polar飞船6个小时数据的损失和5月19日银河IV号失效，最显著的是银河IV号通讯卫星的失效，它造成美国80%的寻呼业务的损失，无数的通讯中断，并使金融交易陷入混乱。由于这一时期发生的太阳，行星际，地磁扰动事件较多，这里重点介绍5月4日的特大地磁暴及其相关的太阳行星际扰动事件。



Dangers lurk in growing reliance on satellites

Satellite's death puts millions out of touch

By Steve Rosenbush
USA TODAY

NEW YORK — The biggest telecommunications failure in recent years continued on ...

"I have no idea at this time ... why the system failed," PanAmSat CEO Frederick Landman told reporters. He all but ruled out sabotage, leaving a range of possible causes, from space debris to a software glitch.

PanAmSat is telling customers not to count on the return of Galaxy IV, which is indefinitely out of commission. It's switching traffic to a nearby satellite known as Galaxy VI.

That's no simple matter. Hundreds of thousands of antennas scattered across the USA must be redirected by hand, using an army of at least ... The process won't be finished un-...

COVER STORY

Radio, TV faced 'serious situation'

By David Lieberman
USA TODAY

MEDIA

Loss shows key role of satellites

By Steve Rosenbush
USA TODAY

Problem triggers pager stock sell-off

By David Rynecki
USA TODAY

STOCK MARKET

Outage interrupted many convenient ways to pay

By Chris Woodyard and Lorrie Grant
USA TODAY

RETAIL/BANKING

PanAmSat Scrambles To Restore Service

Galaxy 4 Failure Stretches Fleet to Limit

By SAM SILVERSTEIN

WASHINGTON — The sudden failure last week of PanAmSat Corp.'s Galaxy 4 communications satellite forced the Greenwich, Conn., company to push its satellite fleet to the limit as it scrambled to restore service.

But Fred Landman, PanAmSat's chief executive officer, said May 20 that when the report was filed, "there was no reason to believe the satellite would spin out," and said PanAmSat had projected that ... years of useful life remained ...

The Day the Beepers Died

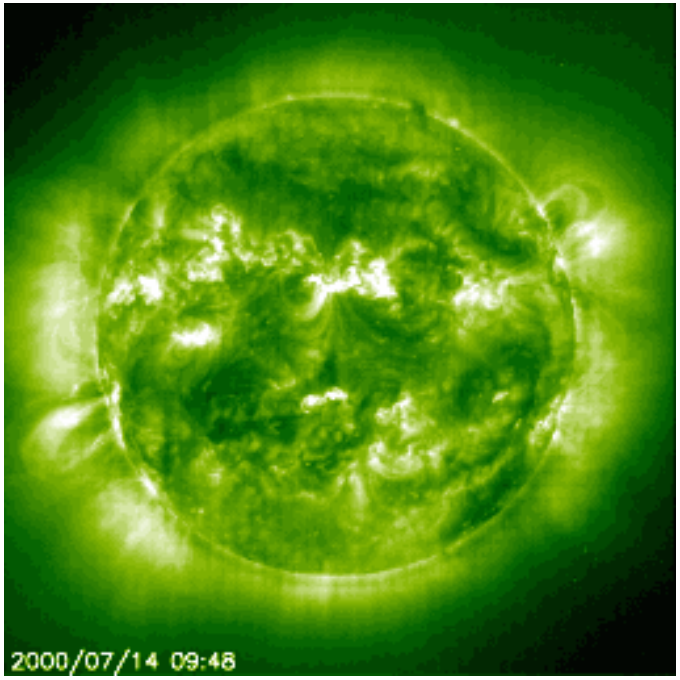
A satellite glitch reveals a high-tech bottleneck

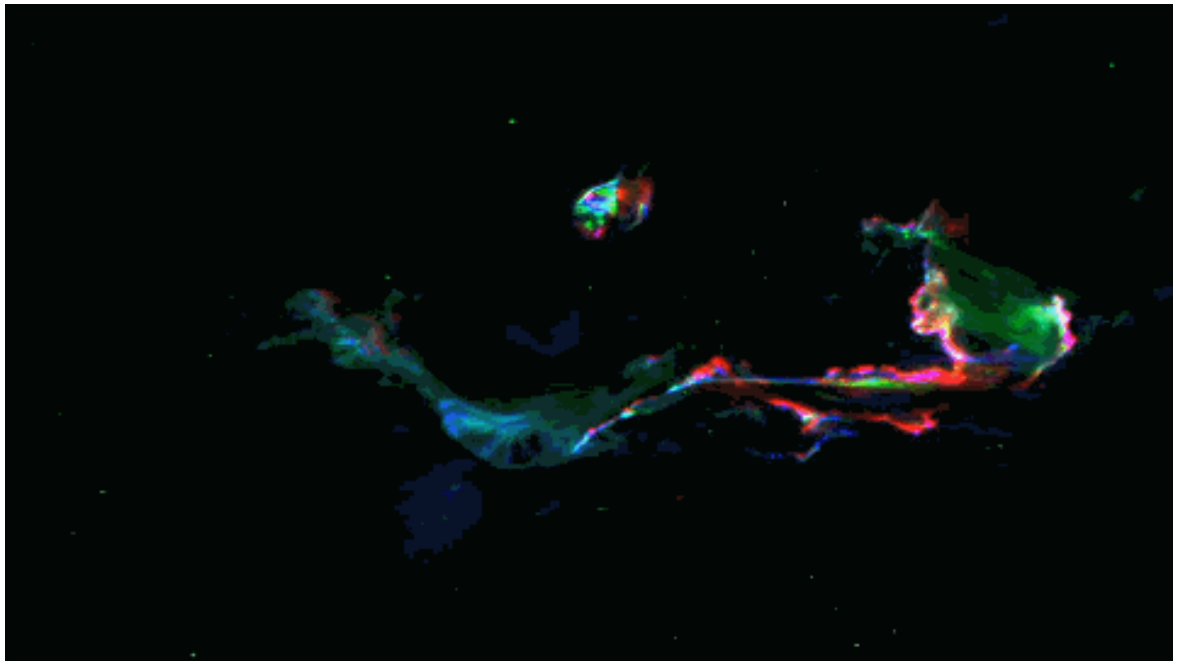
By Adam Rogers

When a key part of the wireless world fell silent last Wednesday, Chuck Woodford had a wireless solution—that's wireless as in Marconi, vacuum tubes, the Shadow and Fireside Chats. After beepers suddenly stopped working nationwide because of a satellite glitch, Woodford, morning deejay at KXPK in Denver, offered to relay messages for listeners on the air. "One of the people that called, his wife was going into labor. They were just running out to the car, didn't have a cell phone and couldn't page their midwife," says Woodford. "It was a very short phone call, needless to say."

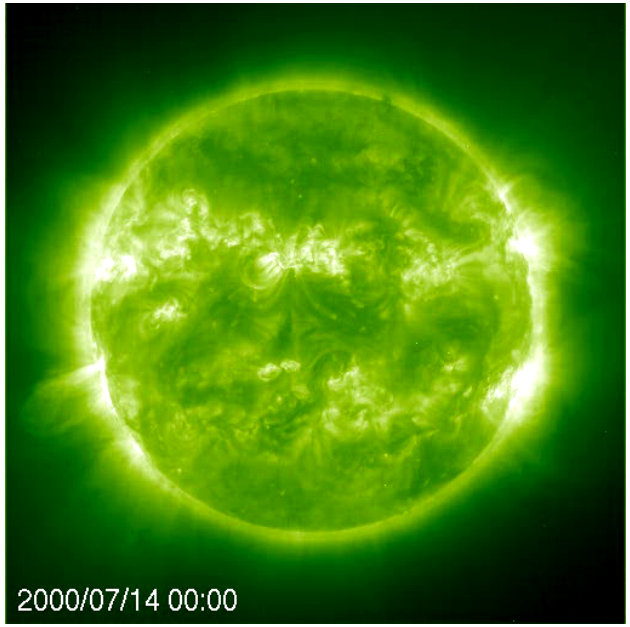
Please stand by: A silenced pager

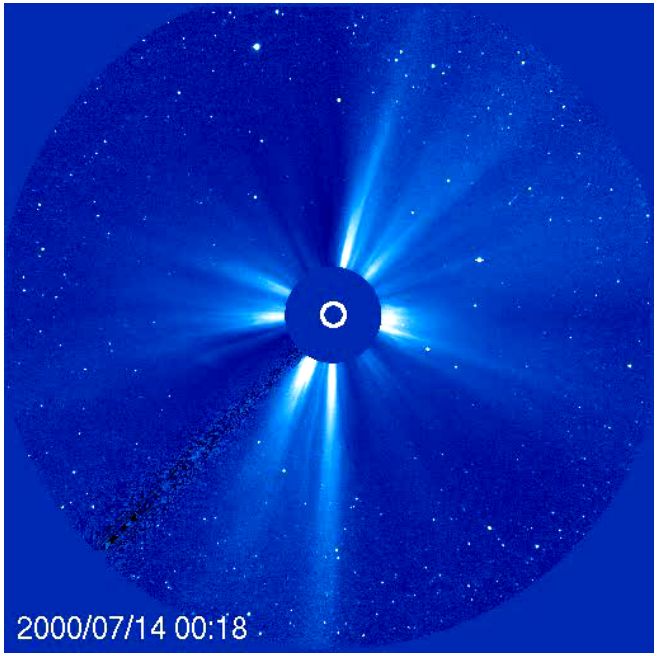
2000年7月14日发生的巴士底日事件，是几十年来发生的最大的太阳耀斑和日冕物质抛射事件之一，引起了超强地磁暴，地球同步轨道高能粒子流量非常大，地球电离层受到强烈干扰，短波通讯中断。GOES, ACE, SOHO, WIND, NEAR等重要科学卫星受到严重损害，国际空间站轨道下降了15Km,日本卫星ASCA丢失，另一颗卫星Akebono控制系统失灵等等。

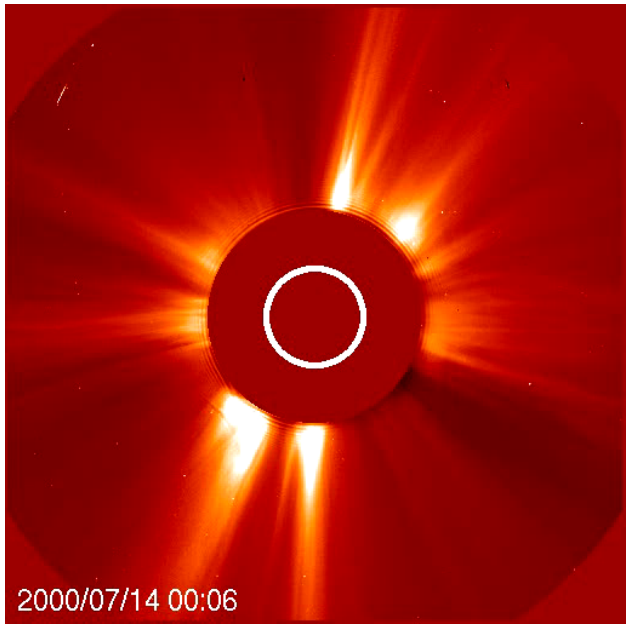


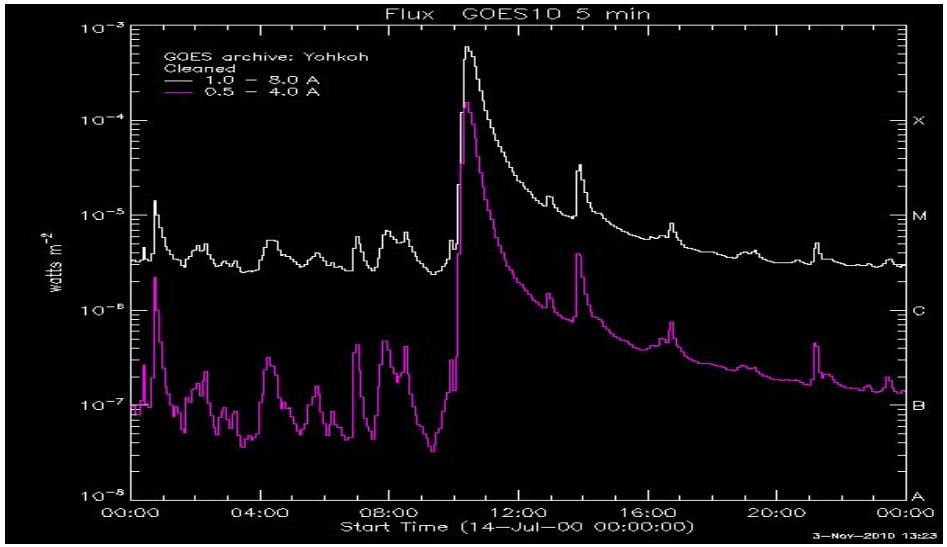


Bastille Day Event on July 14, 2000



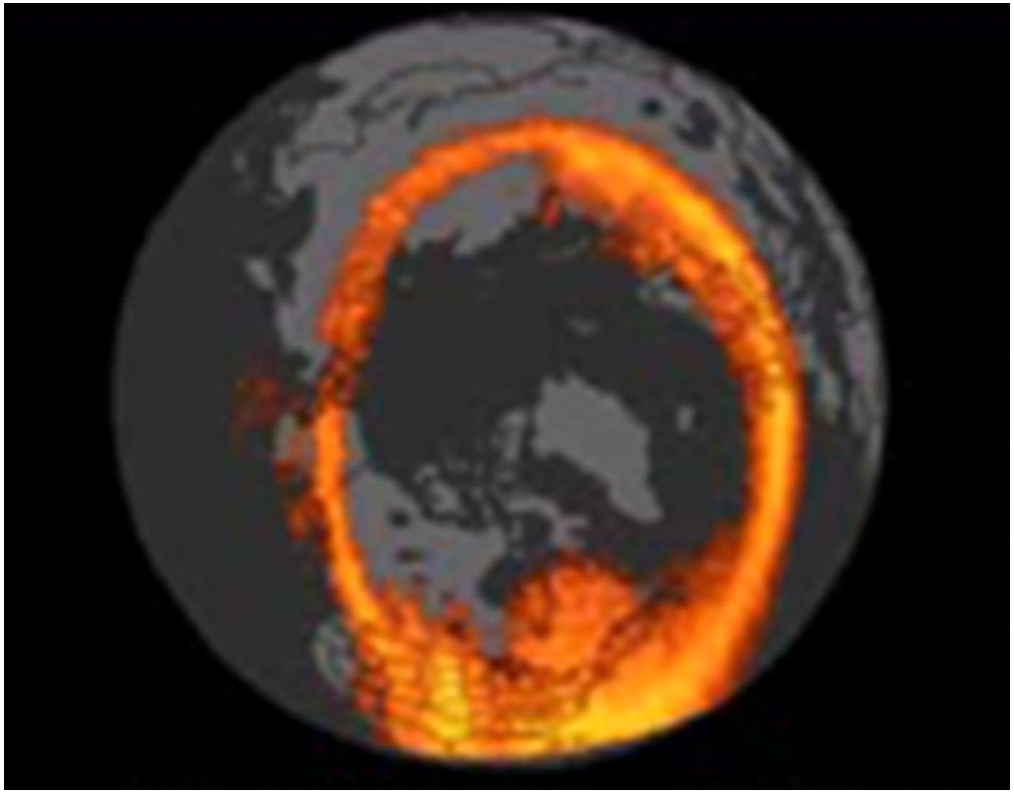




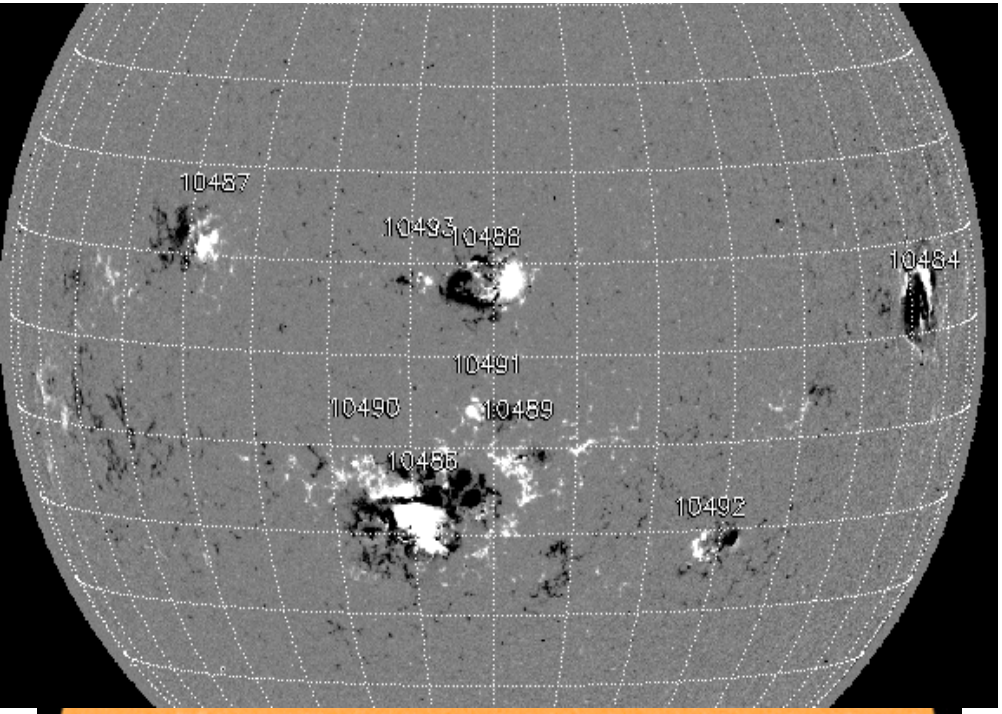


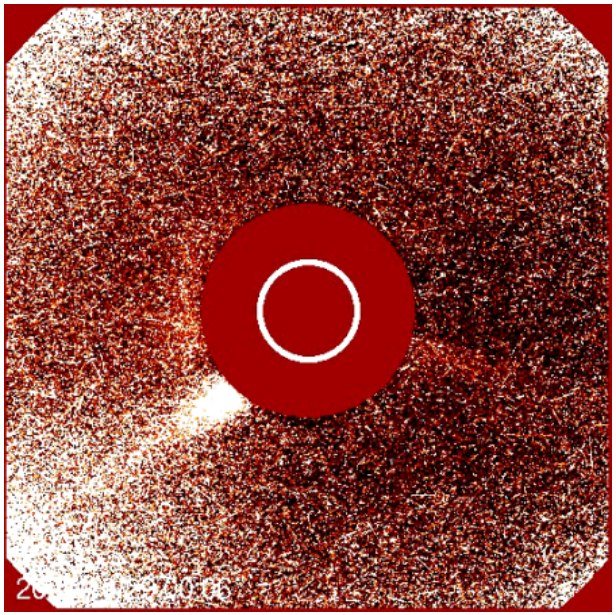
Aurora over the polar region

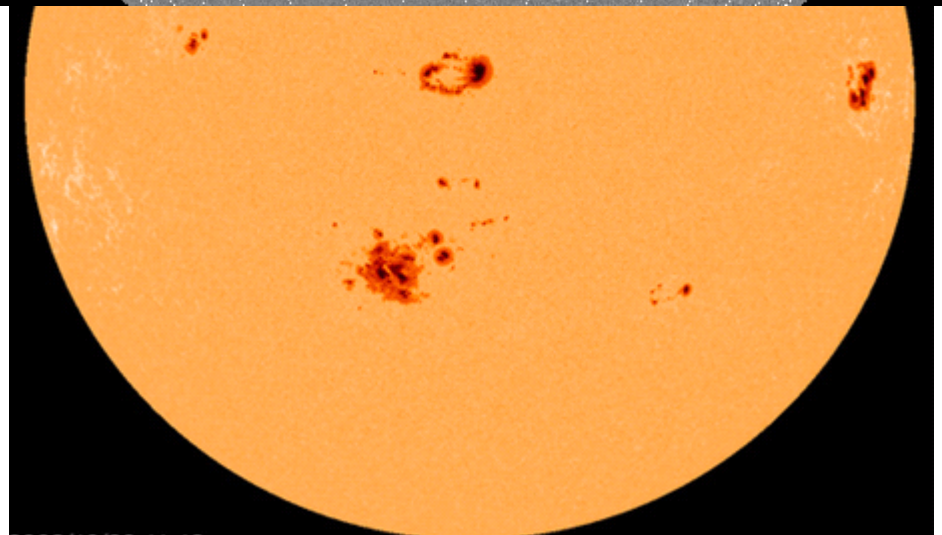
During strong storms, aurorae appear in the polar region and extend to area of low altitude (even visible in Florida)

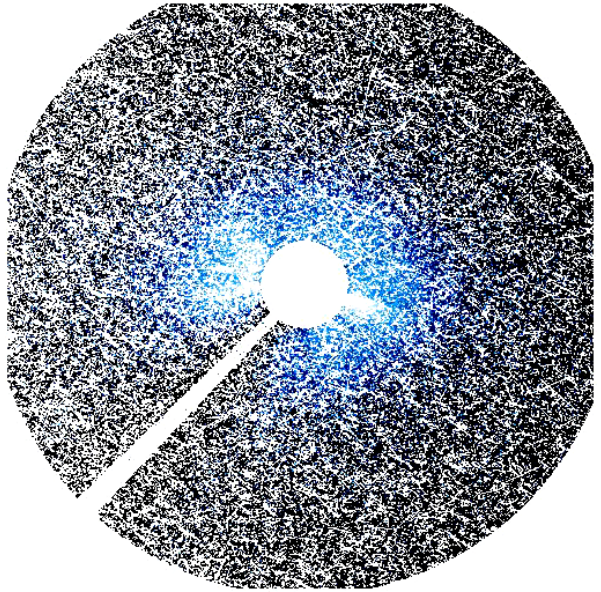


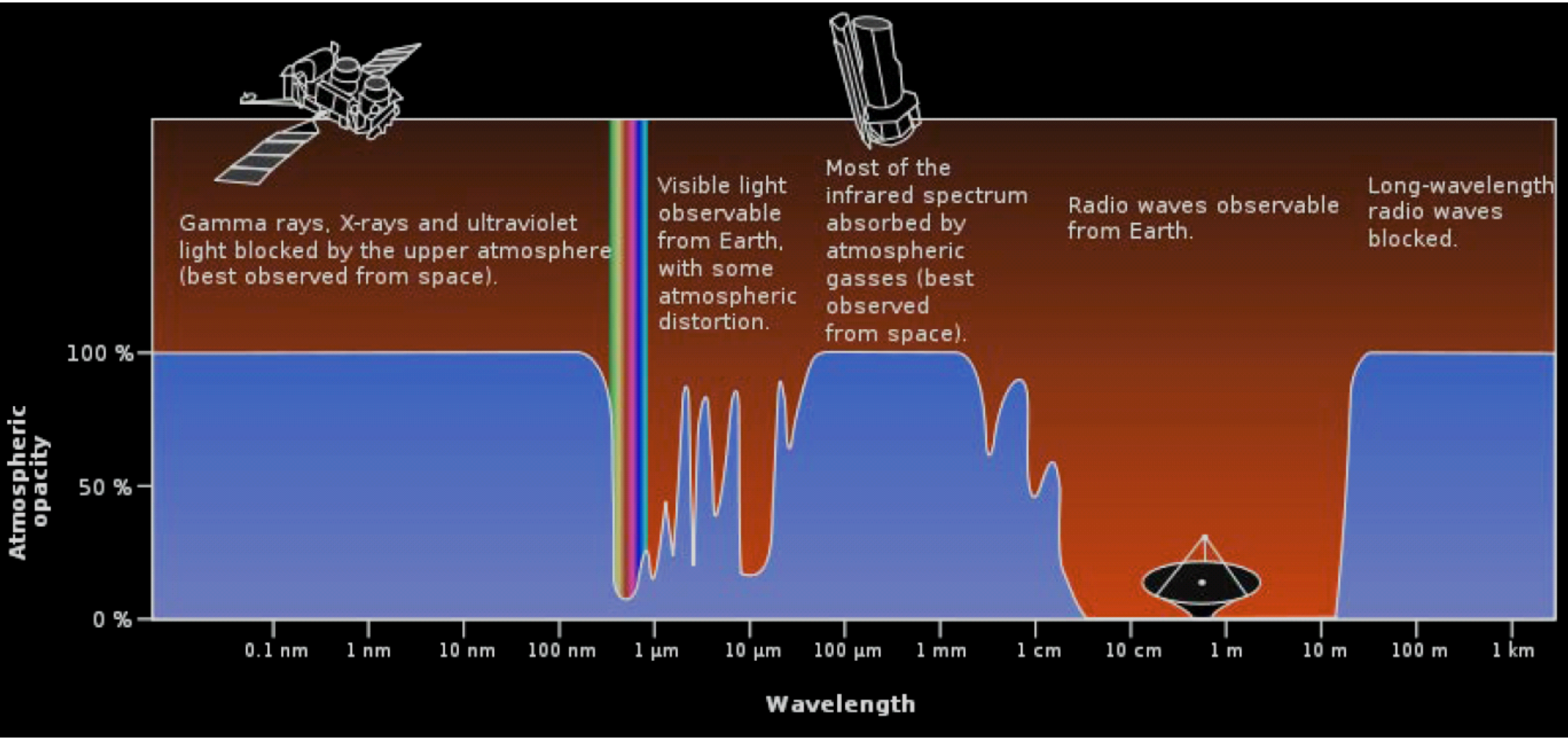
Flares during 2003.10 -11



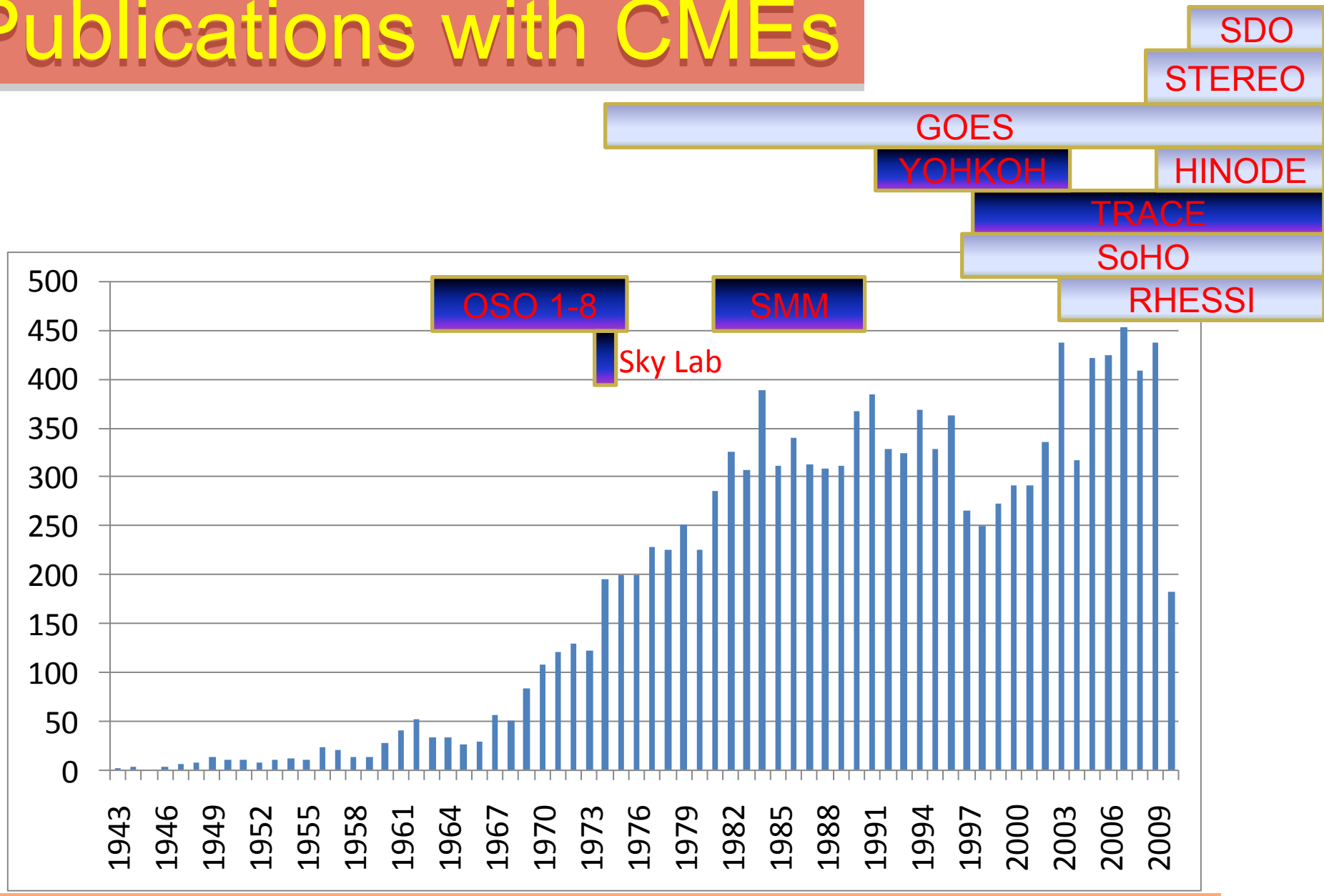






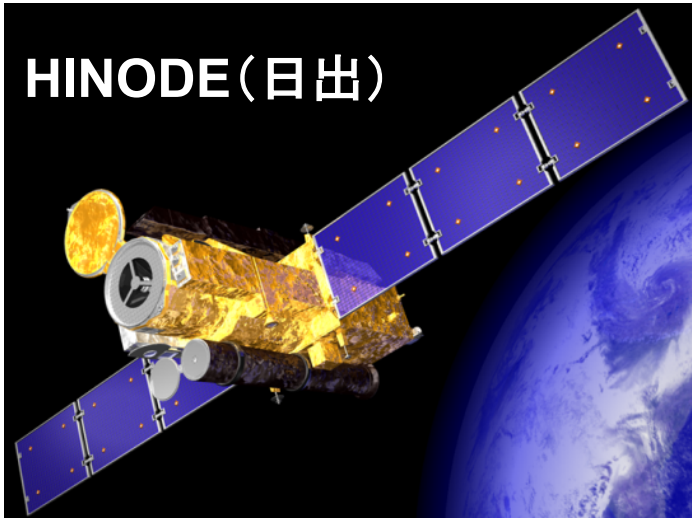

Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).
Visible light observable from Earth, with some atmospheric distortion.
Most of the infrared spectrum absorbed by atmospheric gasses (best observed from space).
Radio waves observable from Earth.
Long-wavelength radio waves blocked.
100 %
50 %
0 %
Atmospheric opacity
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength

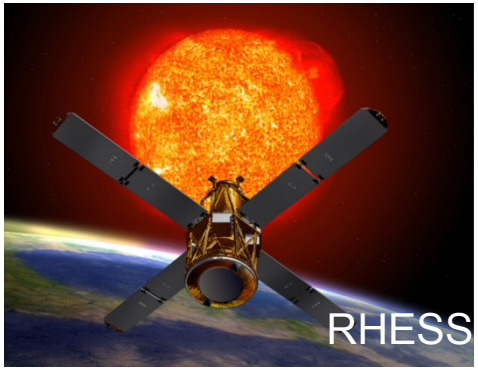
Publications with CMEs

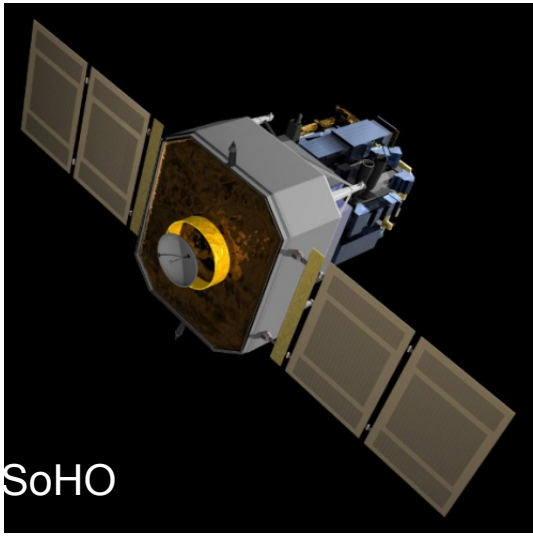


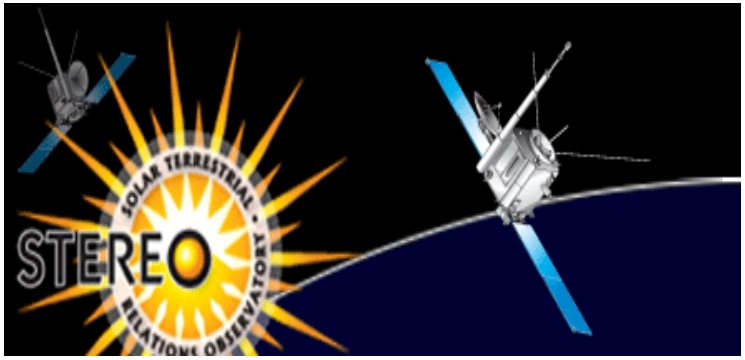
Articles published during 1940-2009 (from ads)

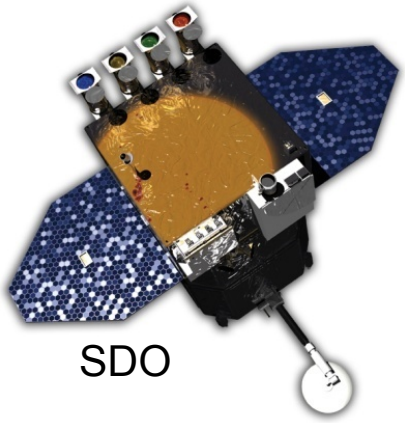
Solar Space Satellites



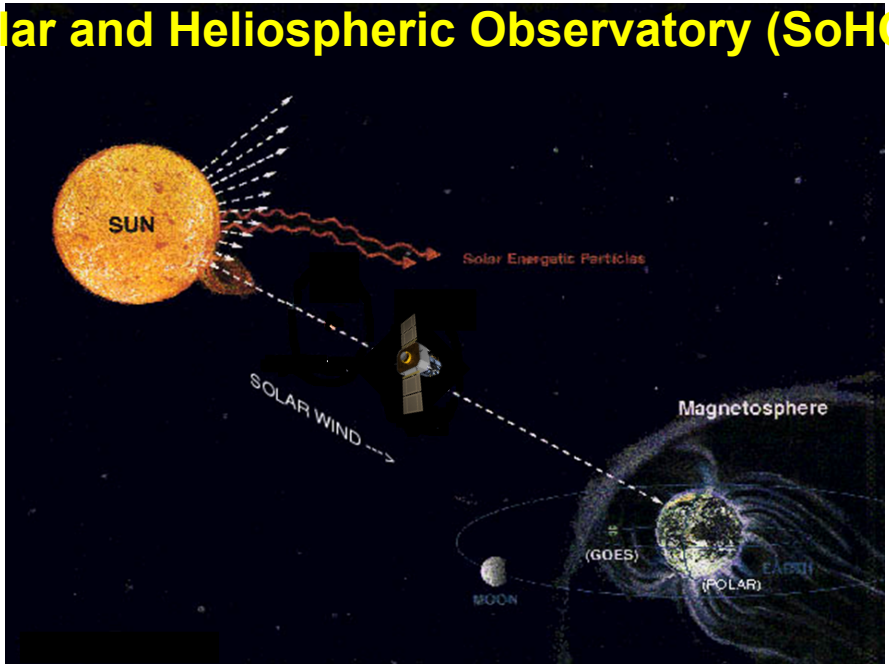


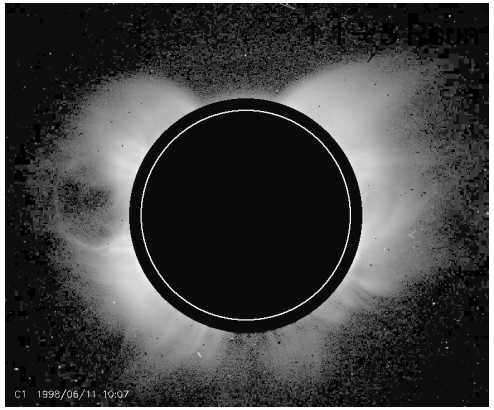






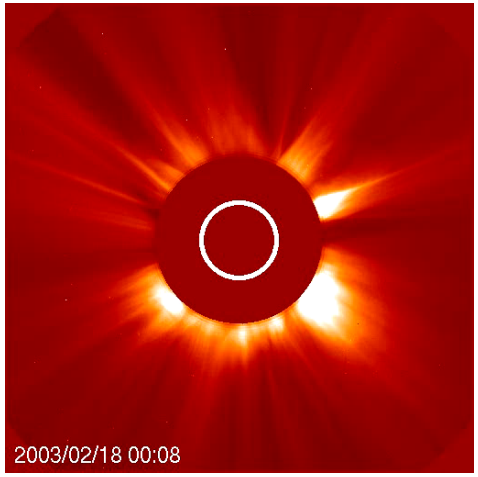
olar and Heliospheric Observatory (SoHO)

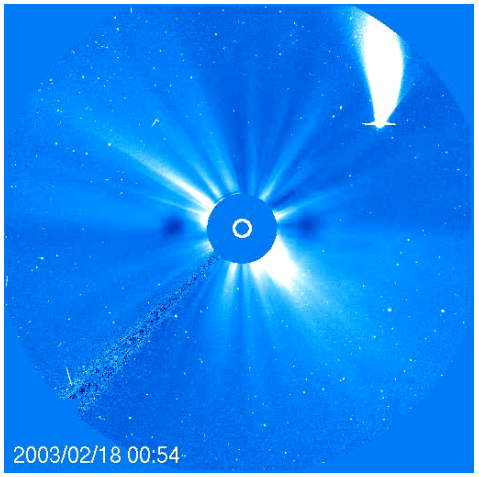




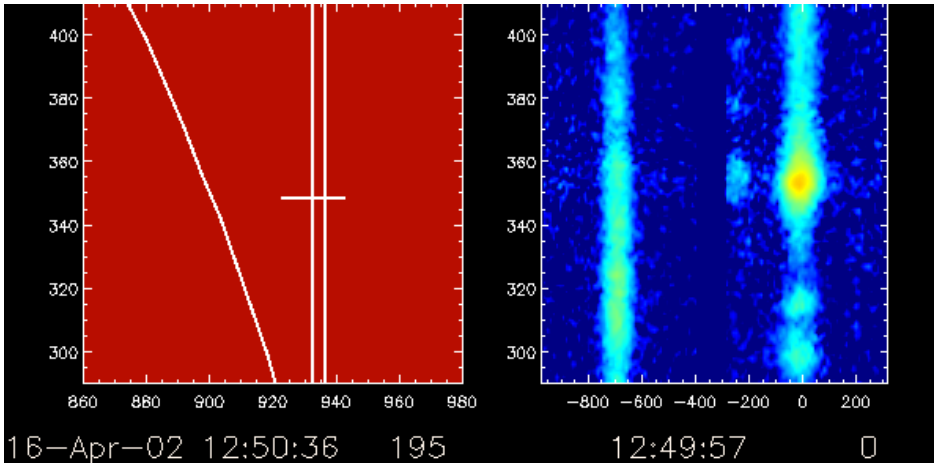
2－6 Rsun

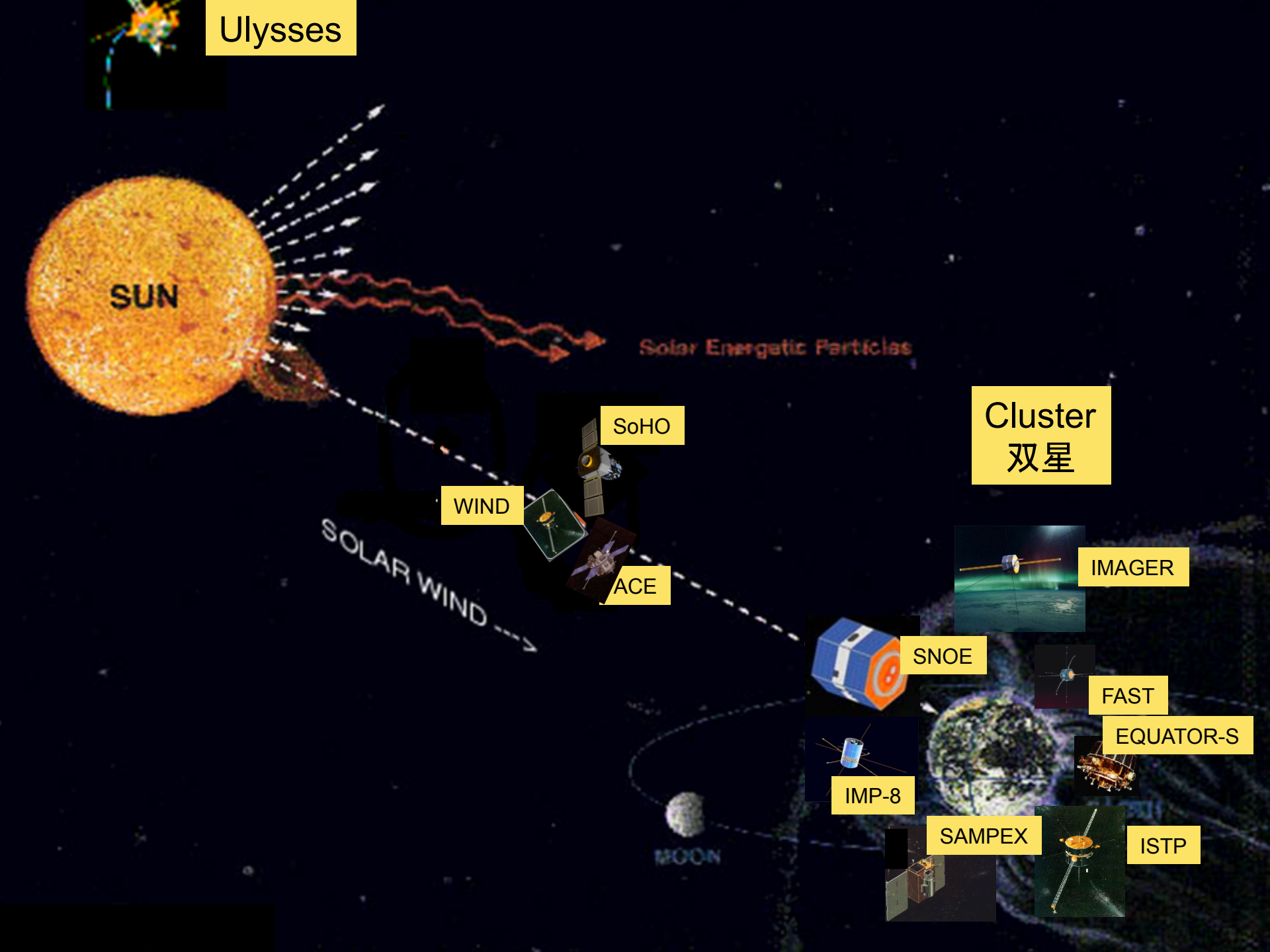
3.7－32 Rsun





MDI: Magnetic fields and velocity fields
LASCO C1 C2 C3: CMEs
EIT: EUV Imaging
SUMMER: UV Spectrum in corona
CDS: UV spectrum in corona and chromosphere
UVCS: UV spectrum in solar winds




Ulysses
SUN
Solar Energetic Particles
SoHO
WIND
ACE
SOLAR WIND
Cluster
双星
IMAGER
SNOE
FAST
EQUATOR-S
IMP-8
SAMPEX
ISTP
MOON

Key Words

- active regions
- coronal heating
- coronal mass ejection
- filament eruption
- flares
- free magnetic energy
- gas pressure
- magnetic field
- magnetic pressure
- magnetic potential field
- magnetic reconnection
- magnetogram
- non-thermal radiation
- particle acceleration
- plasma
- sunspot umbra
- sunspot penumbra
- space weather
- Zeeman effect

summary

- Solar **active regions** have strong **magnetic fields** , which produce enhanced heating and dynamics in the atmosphere. The solar atmosphere is magnetized.
- Magnetic field in the photosphere is studied by measuring the split and polarization of magnetically sensitive spectral lines, or the **Zeeman effect.**
- Magnetic field governs activities on the Sun. Violent energy release events like flares and CMEs are fueled by **free magnetic energy**.
- **Magnetic reconnection** is thought to be the driver of solar flares. Free magnetic energy is release by reconnection to heat plasmas and accelerate charged particles, which lead to impulsively enhanced radiation at nearly all altitudes and wavelengths.
- Streams of charged particles from the Sun lead to adverse **space weather.** Understanding the Sun's magnetic field is critical to space weather forecast.