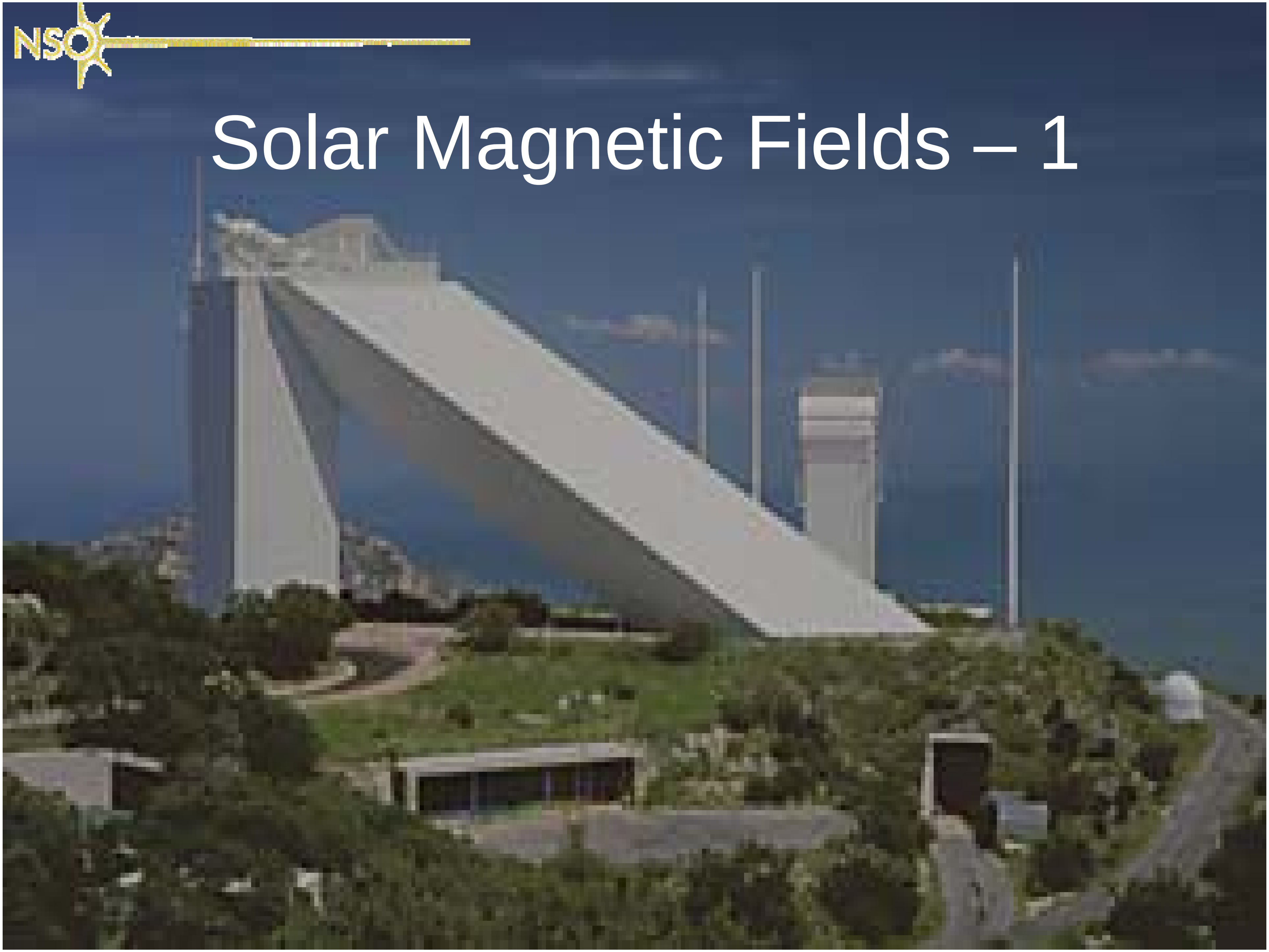
Solar Magnetic Fields – 1



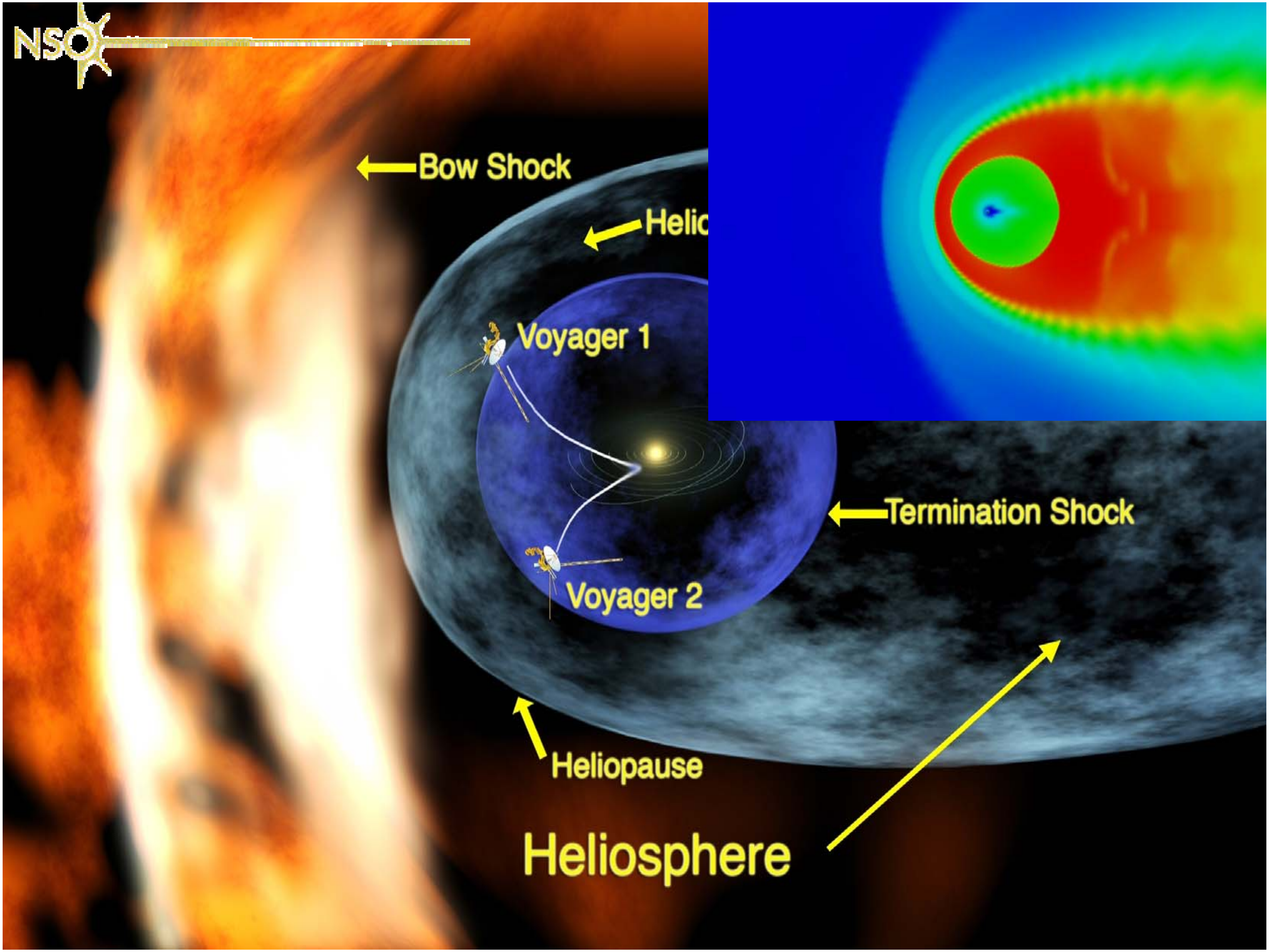

NSO
“If the sun didn't have a magnetic field, then it would be as boring a star as most astronomers think it is.”
-- Robert Leighton
N
TRACE 19/Aug/98 02:00:55 171ao
15000 km

- **Solar Magnetic Fields 1 (11 June)** – A *very qualitative* overview of the structure and evolution of the solar magnetic fields, from the outer heliopause to the solar interior.
  - Heliosphere
  - Magnetic effects caused by the interplanetary field and wind
  - Geomagnetic effects: the Sun – Earth connection
  - Corona: CMEs, flares, and recent direct magnetic measurements
  - Photosphere: magnetograms and vector maps, flux eruption
  - Interior: solar cycle changes and constraints on models.

- **Solar Magnetic Fields 2 (12 June)** – An introduction to the instruments and techniques used to remotely measure the solar magnetic field
  - Zeeman effect
  - Stokes Vectors
  - Hanle effect
  - Plans for the Advanced Technology Solar Telescope

Heliosphere

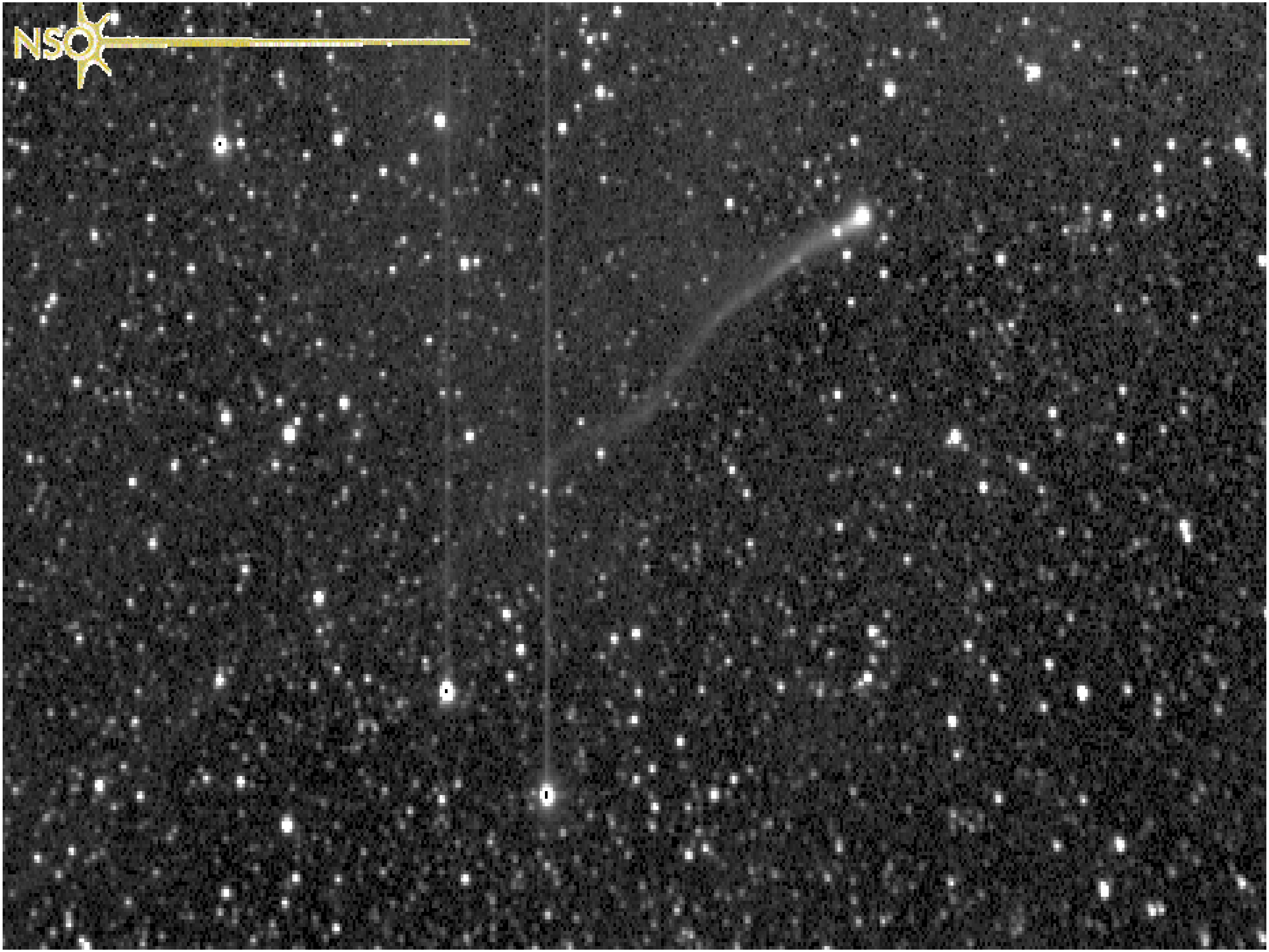
- **The heliosphere is a low density cavity carved by the solar wind into the local interstellar medium.**
- **The heliopause represents the outermost extent of the solar magnetic field, where it interacts with the magnetic field in the ISM.**
- **Heliosphere is asymmetric, extending about 100AU upstream and perhaps 200AU downstream; complex interaction of the solar and ISM winds, magnetic fields, cosmic rays and neutral atoms determine the shape.**
- **Heliosphere varies on timescales of hours to the 22-year solar cycle.**
- **Models of these interactions shows time variations**
- **Studied with very low frequency (2-3 kHz) radio emission observations from spacecraft**
- **Now in-situ measurements can be made from Voyager 1**


NSO
Bow Shock
Helic
Voyager 1
Termination Shock
Voyager 2
Heliopause
Heliosphere

- **Studies of the heliosphere have direct astrophysical applications.**

Interplanetary Magnetic Fields and Wind

- **The solar wind and magnetic field have a direct effect on objects in the solar system.**
- **The ion and neutral tails from comets provided some of the first evidence of the solar wind existence, and can still be used as probes of the wind and magnetic storms.**
- **A fleet of spacecraft routinely monitor the solar wind and magnetic storms from many different locations in the solar system; this includes the Ulysses spacecraft, which orbits the polar regions of the Sun.**
- **Recent observations of Jupiter, Mercury and the Moon show changes caused by magnetic storms in the solar wind.**



Interplanetary Magnetic Fields and Wind

- **Work from Potter et al. from McM/P have shown emission from sodium atoms that are blown off the surface of Mercury, forming an exosphere and a comet-like tail.**
- **Rapid variations in the sodium intensity (factor of 3 during 6 days) seem correlated with solar magnetic storms.**

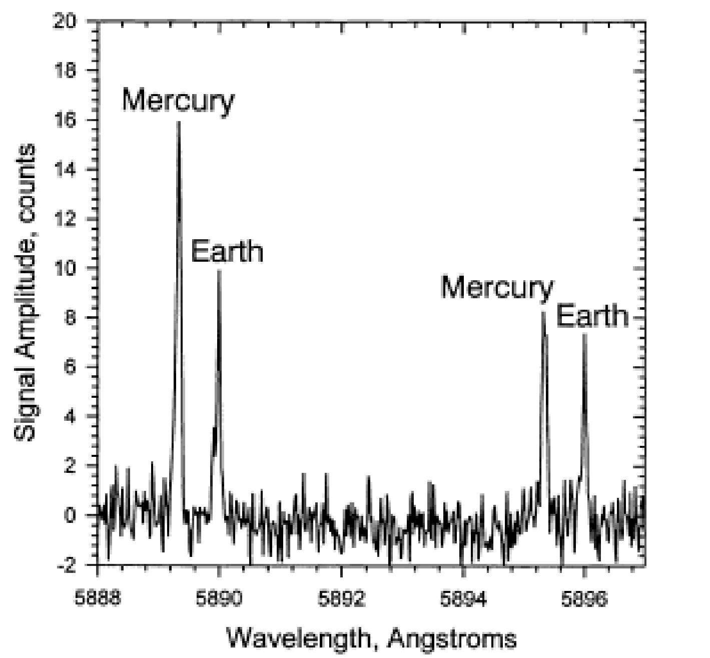


FIG. 1. The spectrum of sodium D lines at a location 33 000 km downstream of Mercury on 0300 U.T. 2001 May 26. The sodium lines from Mercury are shifted 0.62 Å to shorter wavelengths from the terrestrial twilight glow lines because of the velocity of Mercury relative to the Earth.

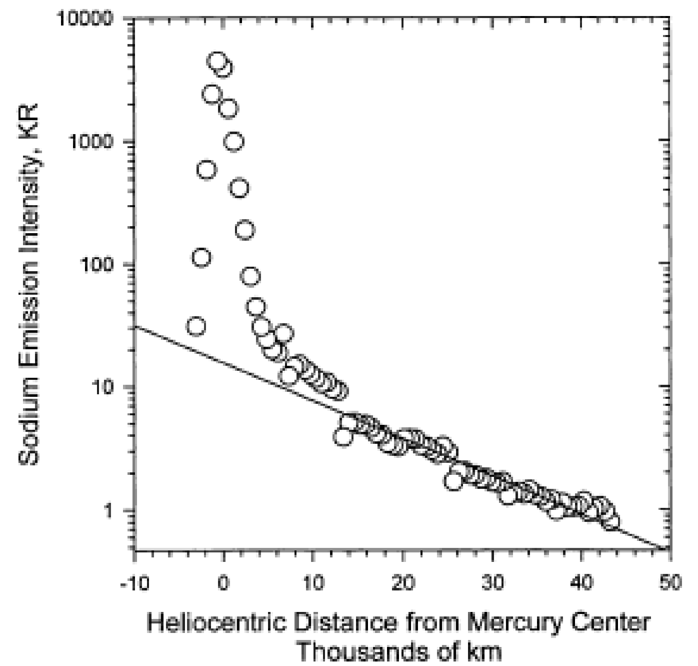
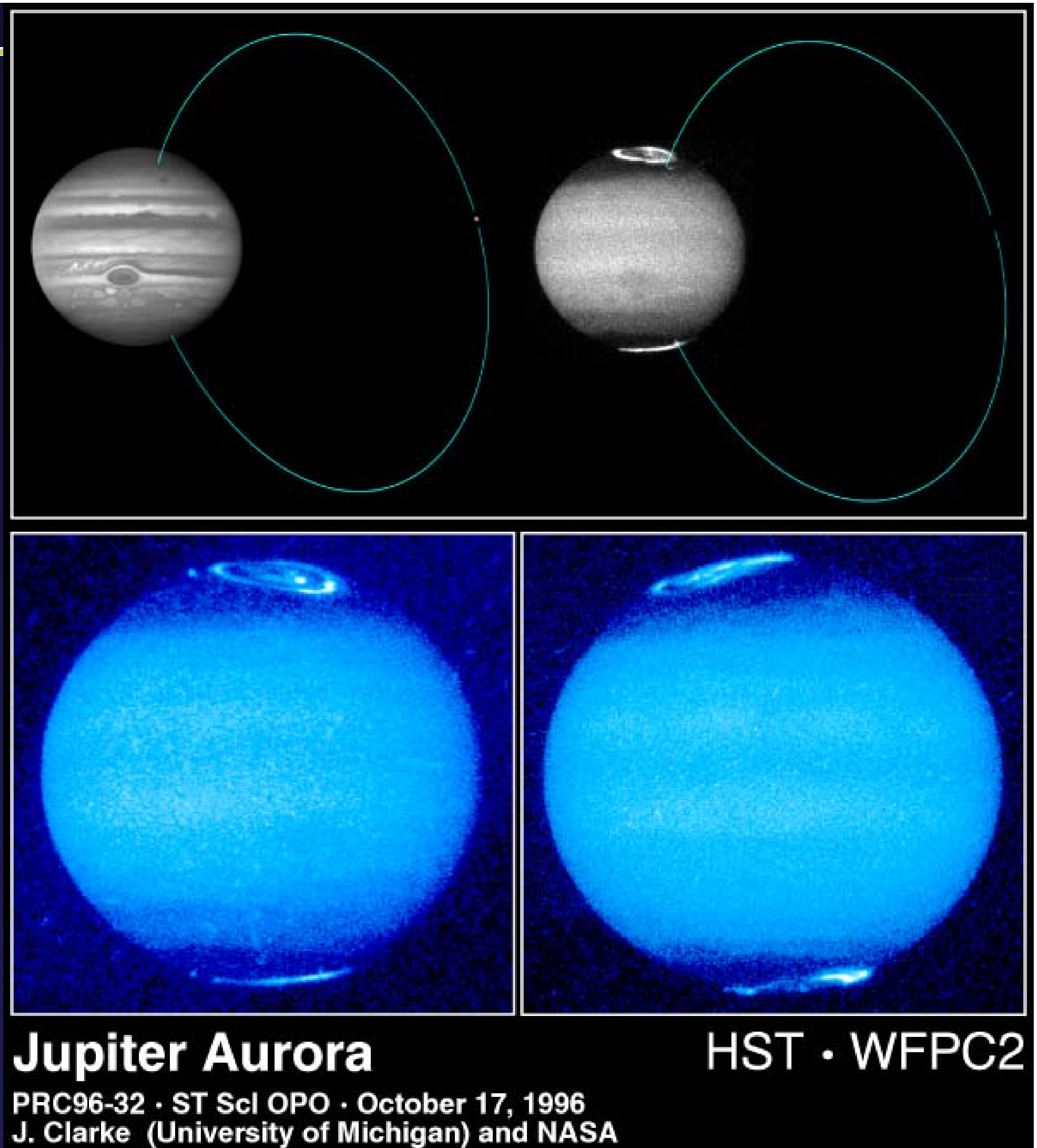


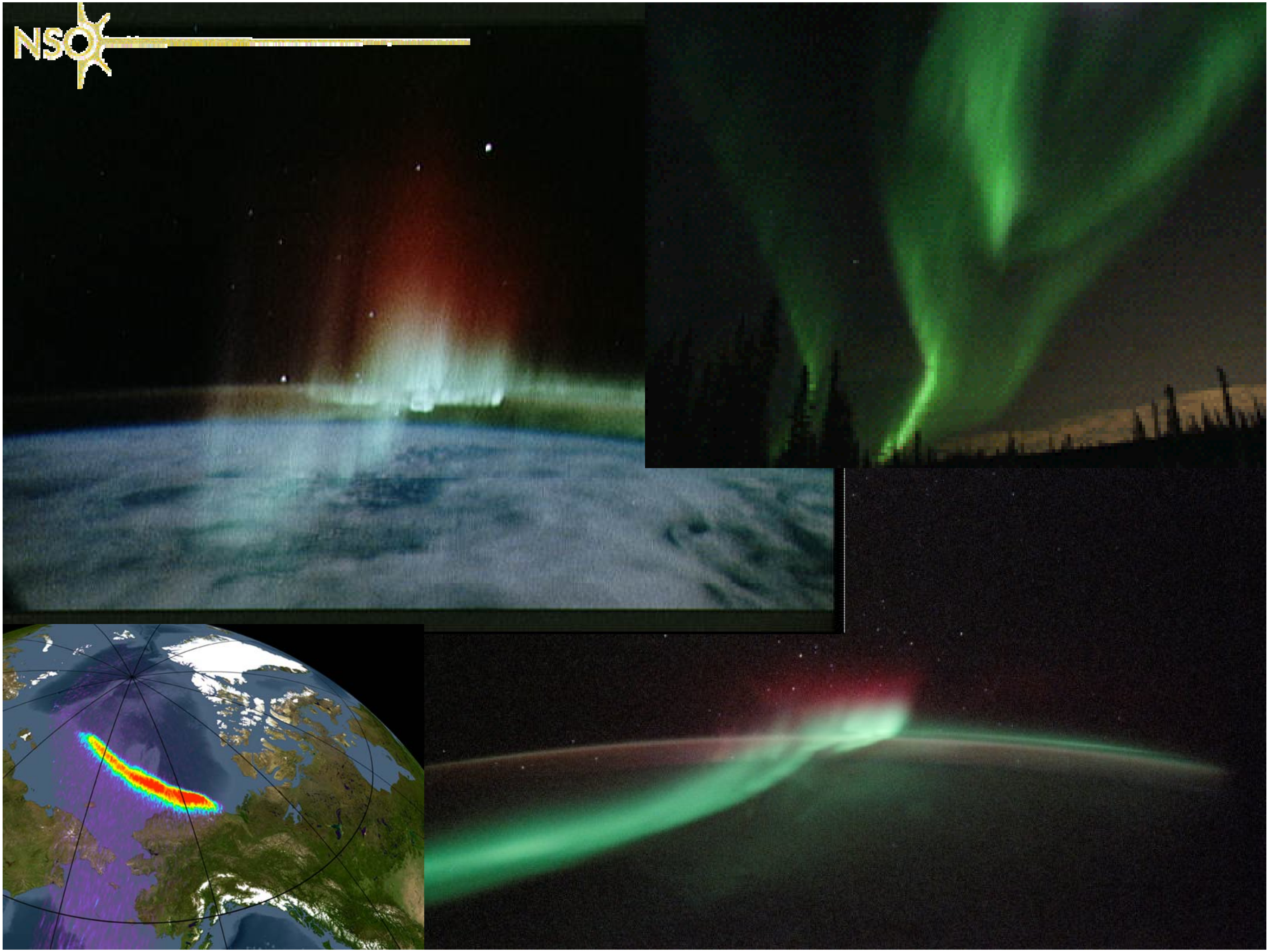
FIG. 3. The emission intensity in kilorayleighs (kR) along the axis of the Mercury sodium tail at 0300 U.T. 2001 May 26. The line-of-sight distances have been converted to heliocentric distances. The semilogarithmic plot becomes linear at distances greater than ~15 000 km, with a slope of 0.031 $\log_{10}$ kR (10^3 km)$^{-1}$.


Jupiter Aurora
HST • WFPC2
PRC96-32 • ST ScI OPO • October 17, 1996
J. Clarke (University of Michigan) and NASA

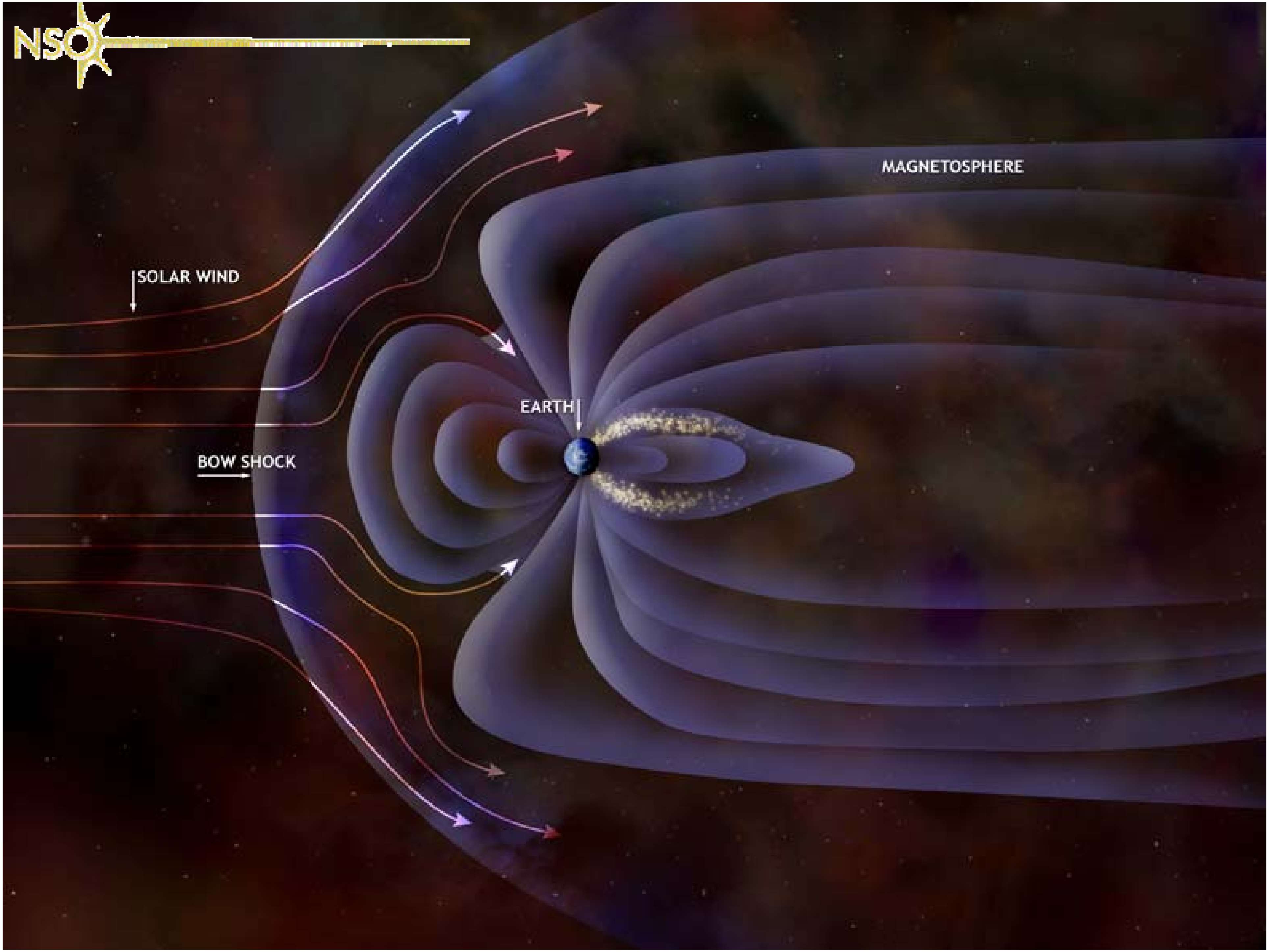
11 Jun 07

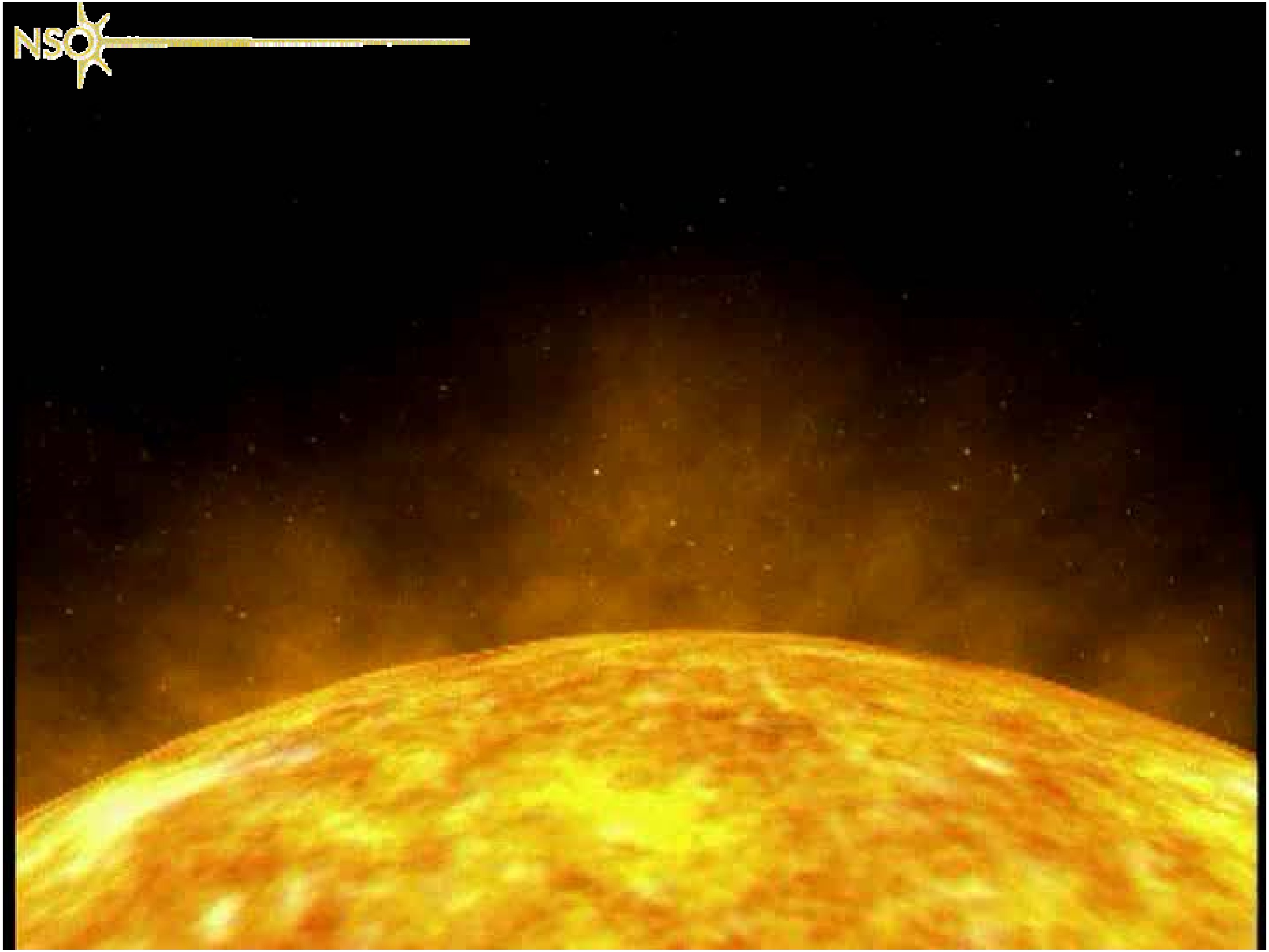
Geomagnetic Effects

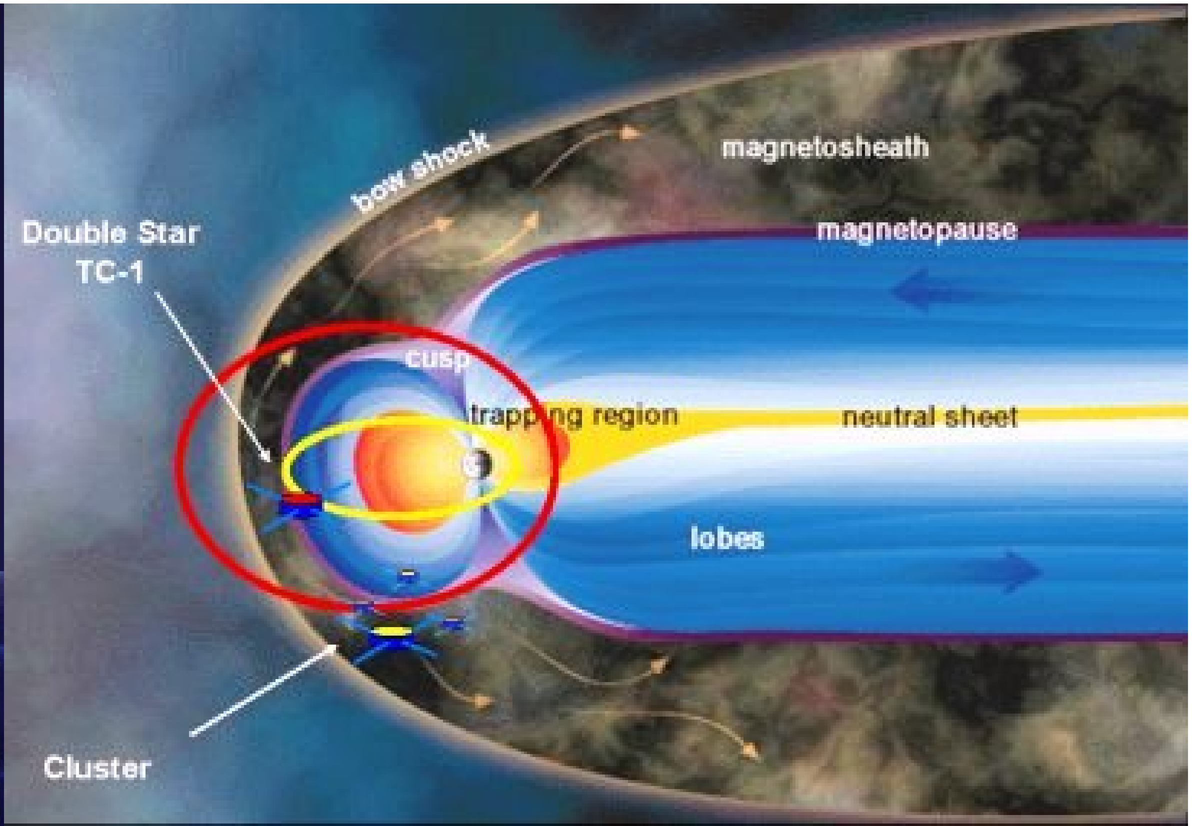
- Effects of solar magnetic storms on the Earth can be profound, and have been known for many years.
- Direct interaction of solar particles with the Earth is limited to the magnetic cusp regions.
- Larger interaction occurs when the geomagnetic field is compressed, expanded or reconnected by the solar magnetic storms.
- Aurora are usually caused when particles are accelerated in reconnection events in the geomagnetic field, and now spacecraft can image aurora and other plasma changes in the near-Earth environment.
- Rapid changes in the geomagnetic field can induce currents on the Earth, and have caused fires in telegraph offices.
- Modern problems include damage to large-scale power grids, compromising GPS signals and destruction of improperly shielded spacecraft electronics.

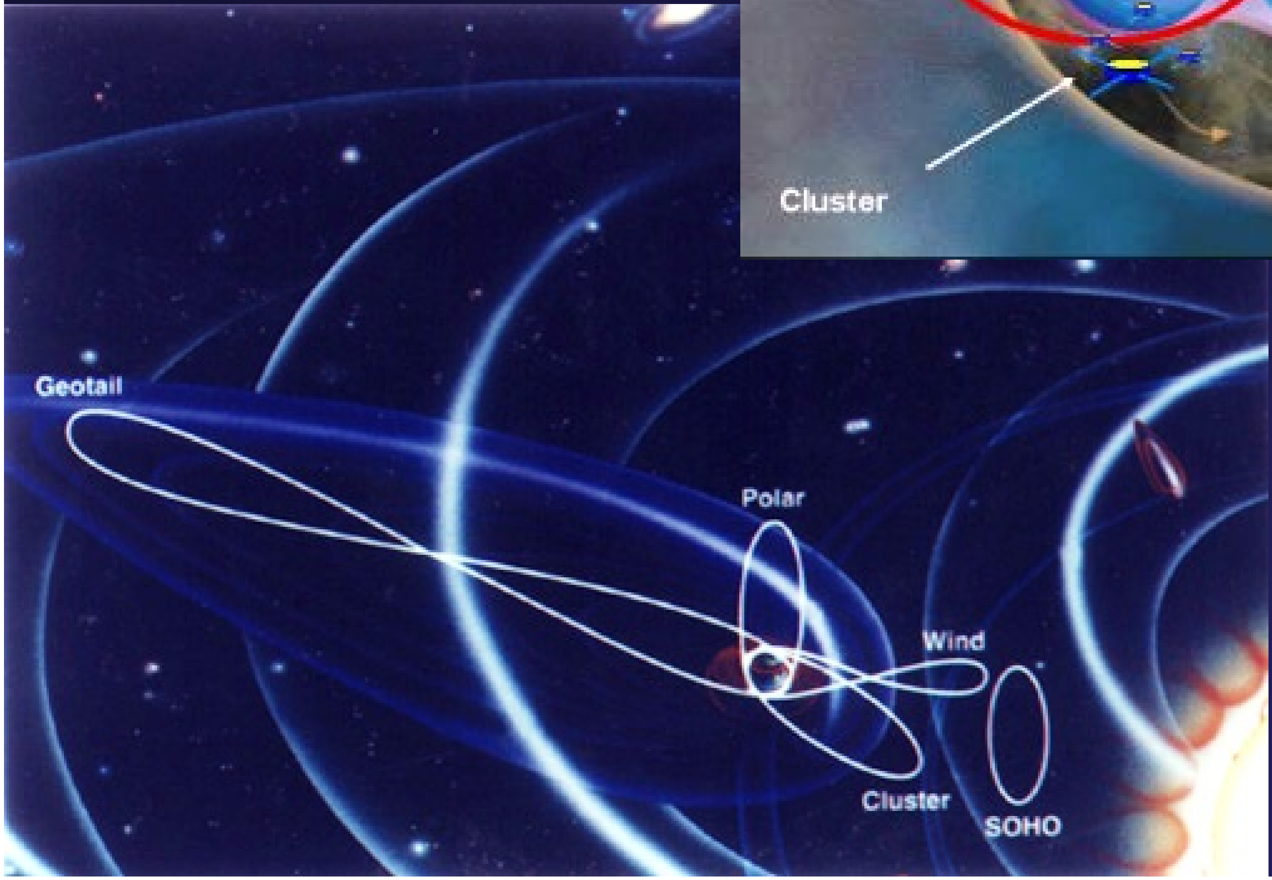


"An electric storm: Widespread disturbances" The impact of the storm was reported to be felt throughout the country. It is the worst storm of its kind in years, and extends throughout the US and Canada. A report from New York says that Europe was also affected. The switchboard at the Chicago Western Union office was set on fire several times, and much damage to equipment was done. From Milwaukee, the 'volunteer electric current' was at one time strong enough to light up an electric lamp. **[Savanah Morning News, November 18, 1882, p. 1]**

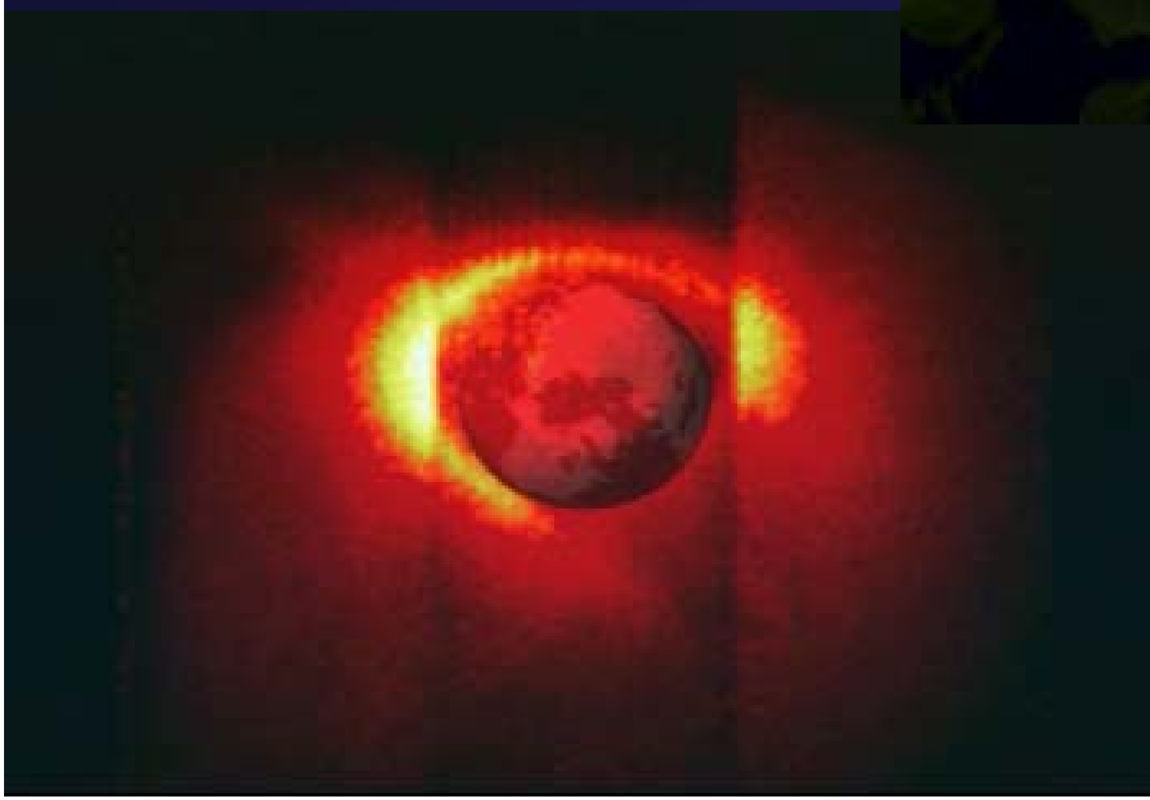

NSO
MAGNETOSPHERE
SOLAR WIND
EARTH
BOW SHOCK




bow shock
magnetosheath
magnetopause
Double Star
TC-1
cusp
trapping region
neutral sheet
lobes
Cluster


Geotail
Polar
Wind
Cluster
SOHO

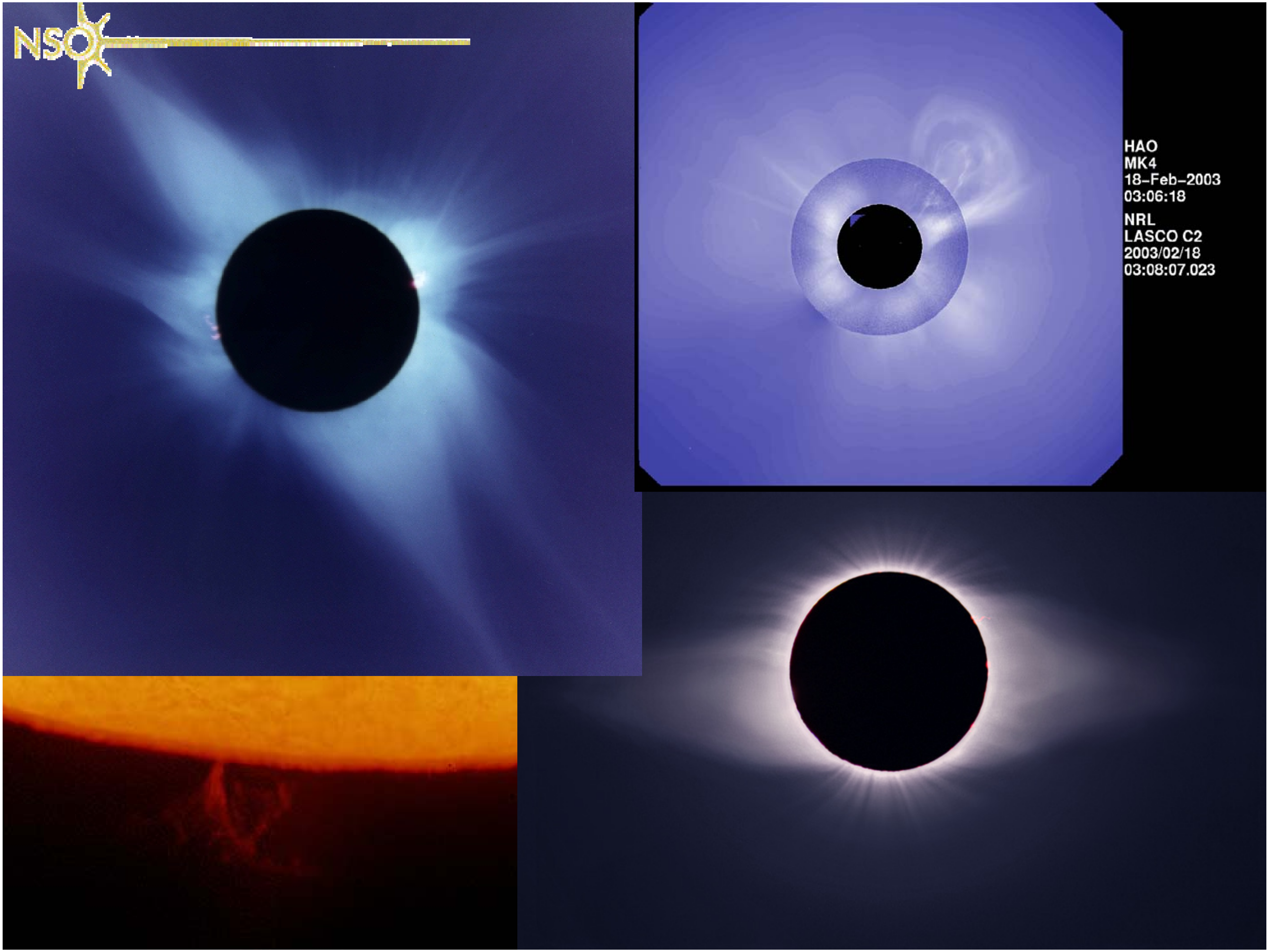
Changes in the plasma in the near-Earth environment are imaged in this short time sequence.



Rarely, energetic particles can cause reconnection and breach the geomagnetic field to hit the Earth, such as in this proton aurora. The proton aurora is the bright spot centered in the frame, the usual electron aurora is the arc.

Corona

- **The evolution of the coronal magnetic field is the source of solar flares and coronal mass ejections.**
- **The kinetic energy density in the corona is much lower than magnetic energy density so the magnetic fields control the plasma dynamics.**
- **Observations of the hot plasma (10^6 K temperatures) in the solar corona are difficult since in the visible, the coronal surface brightness is 10^{-6} of the disk brightness.**
- **Observations of the cold plasma (10^4 K temperatures) is easier since the intensities are 10^{-3} of the disk brightness.**


NSO
HAO
MK4
18–Feb–2003
03:06:18
NRL
LASCO C2
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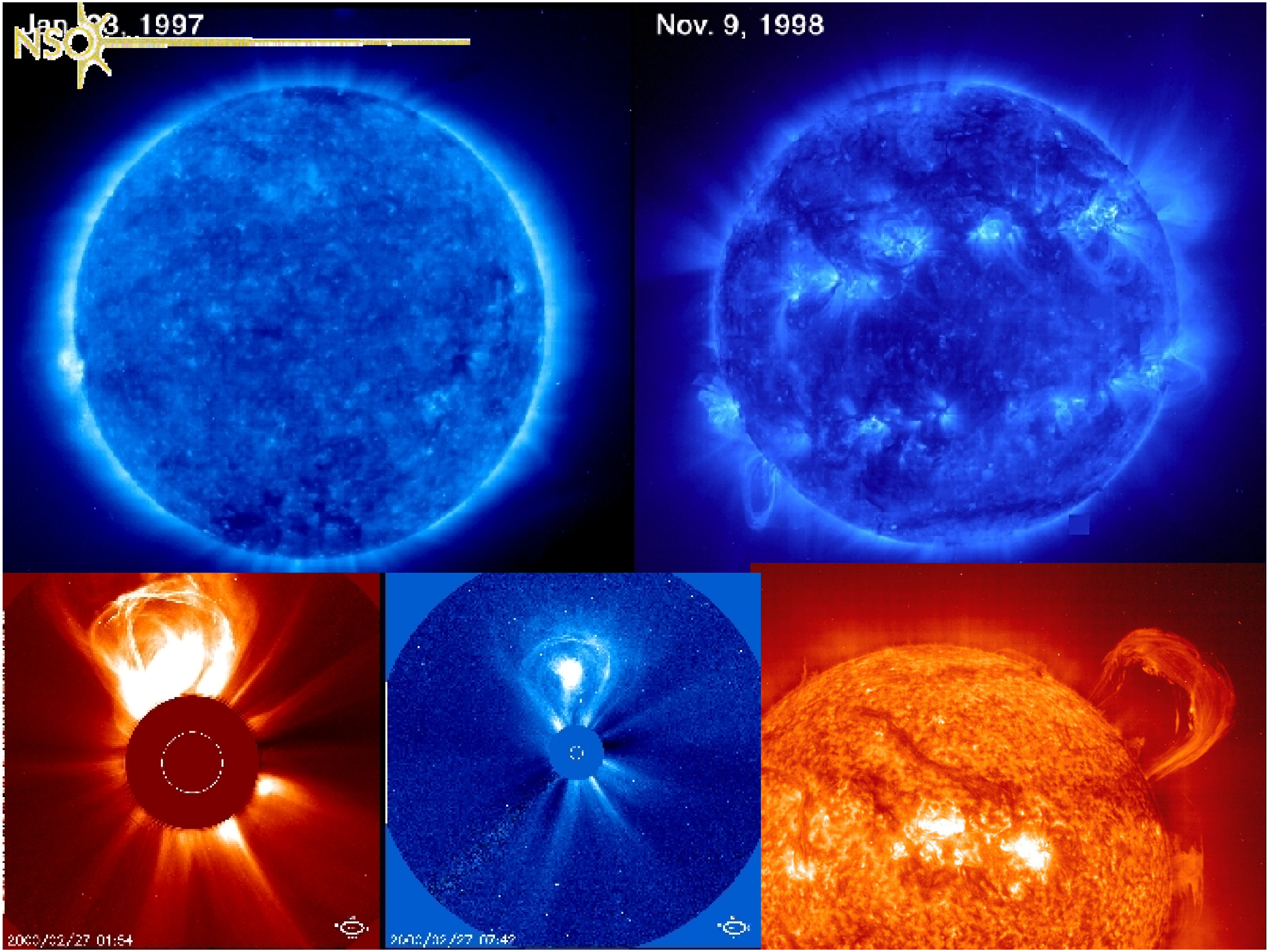
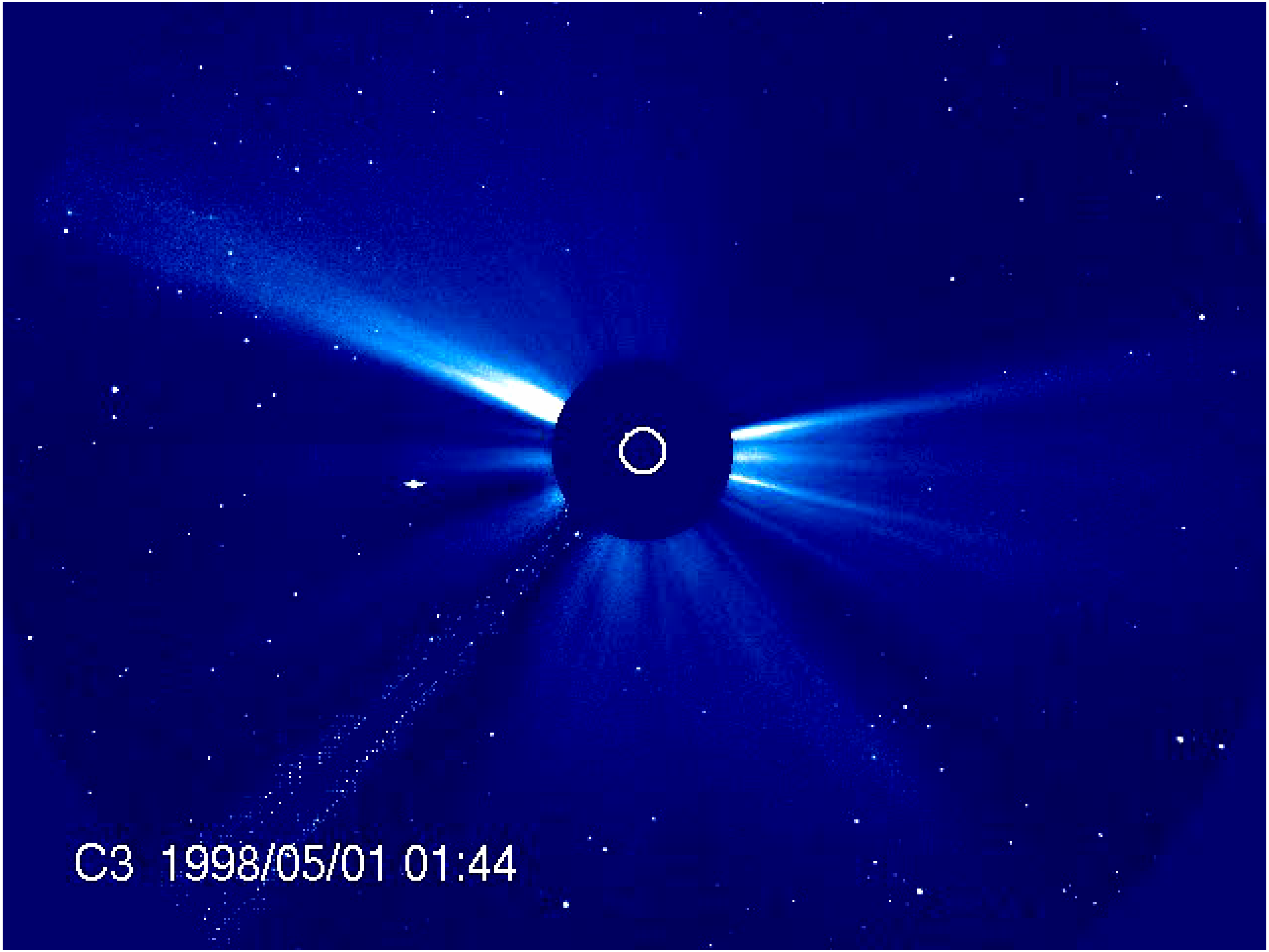
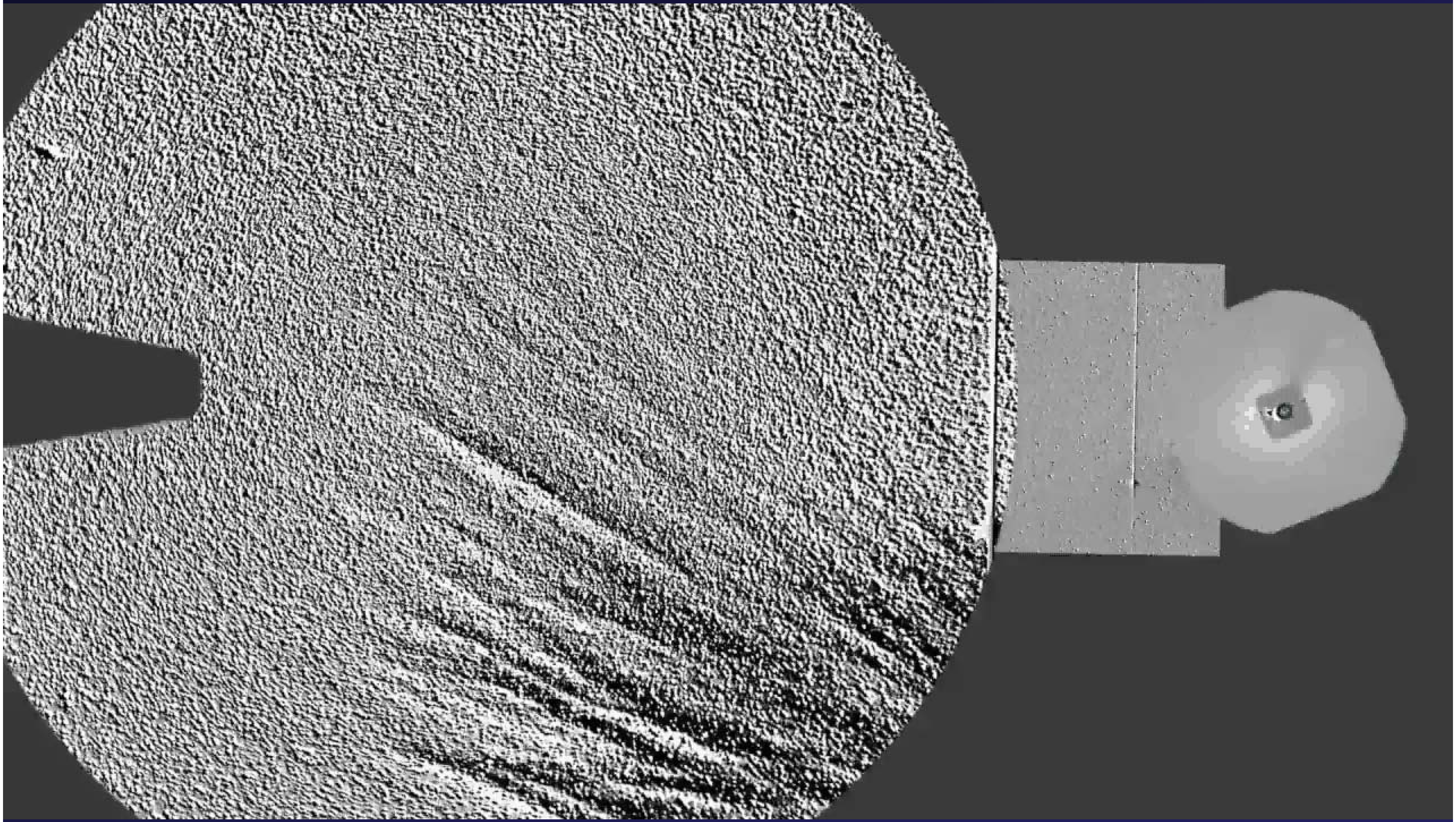


Nov. 9, 1998
2000/02/27 01:54
2000/02/27 07:42

Coronal Mass Ejections

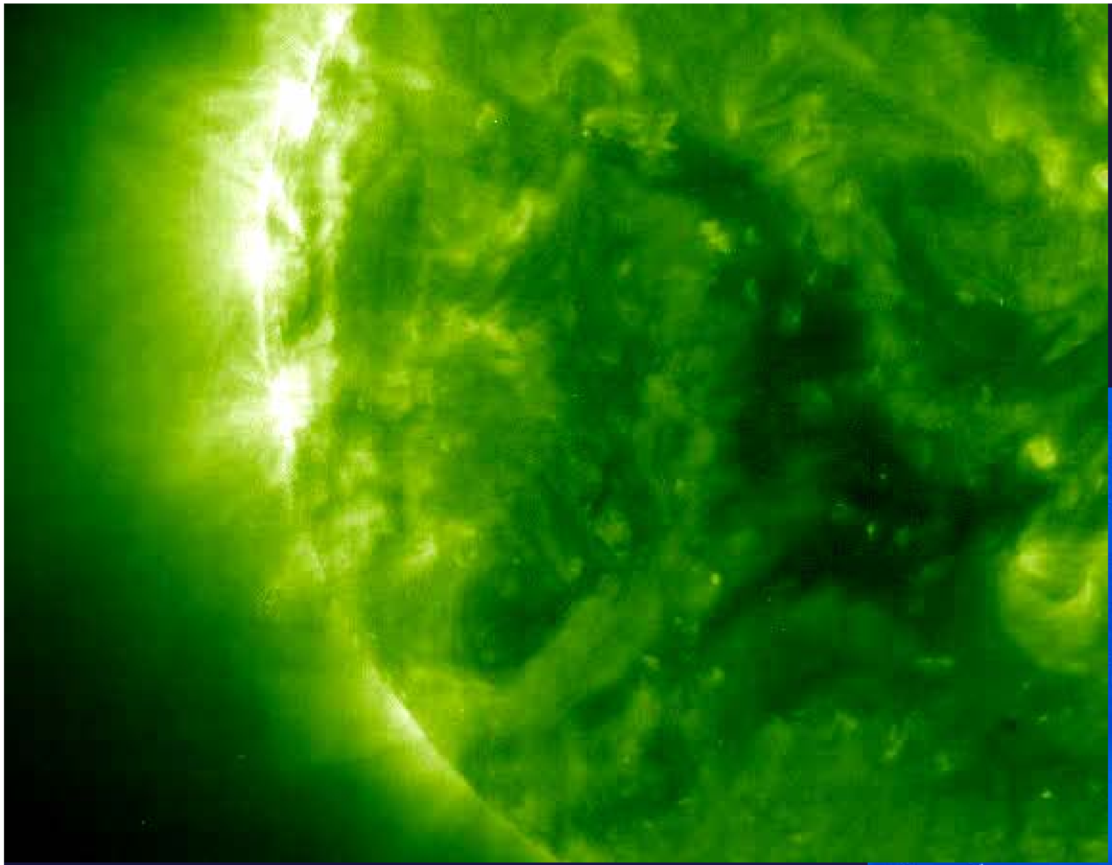
- Coronal Mass Ejections (CME) are eruptions of enormous amounts of plasma (10^{16} gm) and magnetic fields from the Sun.
- CMEs are often associated with eruptions of cool filament material in the solar corona.
- CMEs are also often associated with solar flares, which involve rapid heating of the solar corona, chromosphere and sometimes photosphere, emission of energetic photons and particles, and ejection of mass and magnetic fields from the Sun.
- CMEs have been observed from the ground, but the best observations have been from spacecraft.
- SoHO has a suite of coronagraphs (C2 and C3), Stereo Secchi has another set, and the SMEI mission also images CME material; now we can watch the material on its trip from the solar atmosphere all the way to the near-Earth environment.

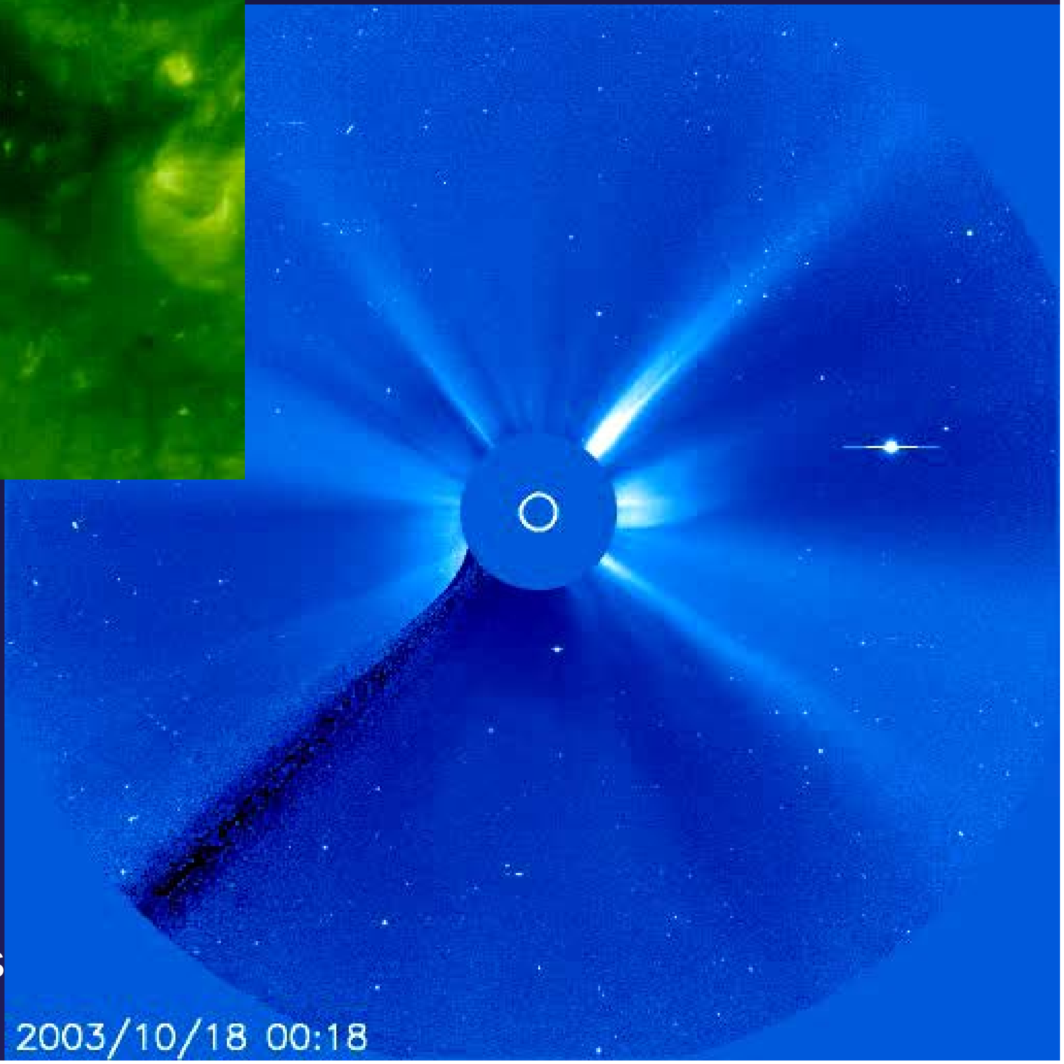

C3 1998/05/01 01:44



October 2003 Flares

- **A set of several very large (X-class) flares occurred late in 2003 at the end of the last solar cycle**
- **Several CMEs were directed at the Earth, and large auroral disturbances were observed from the ground and from space.**

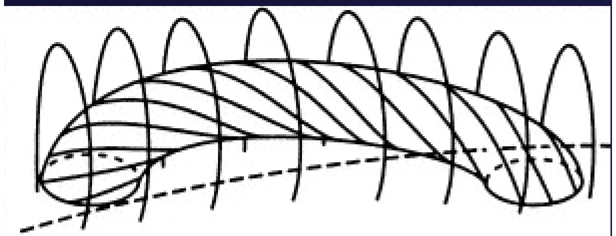


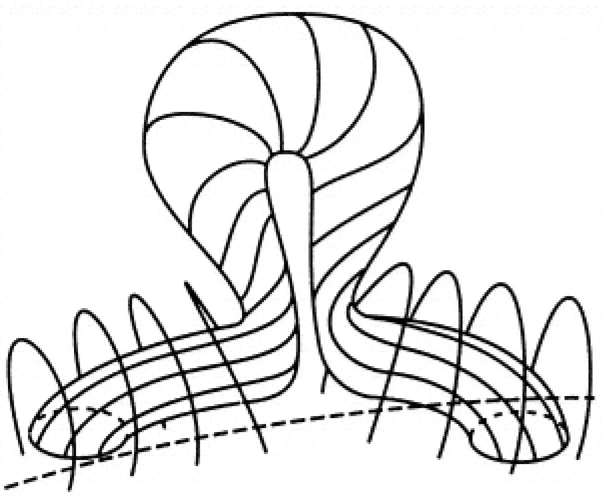

2003/10/18 00:18

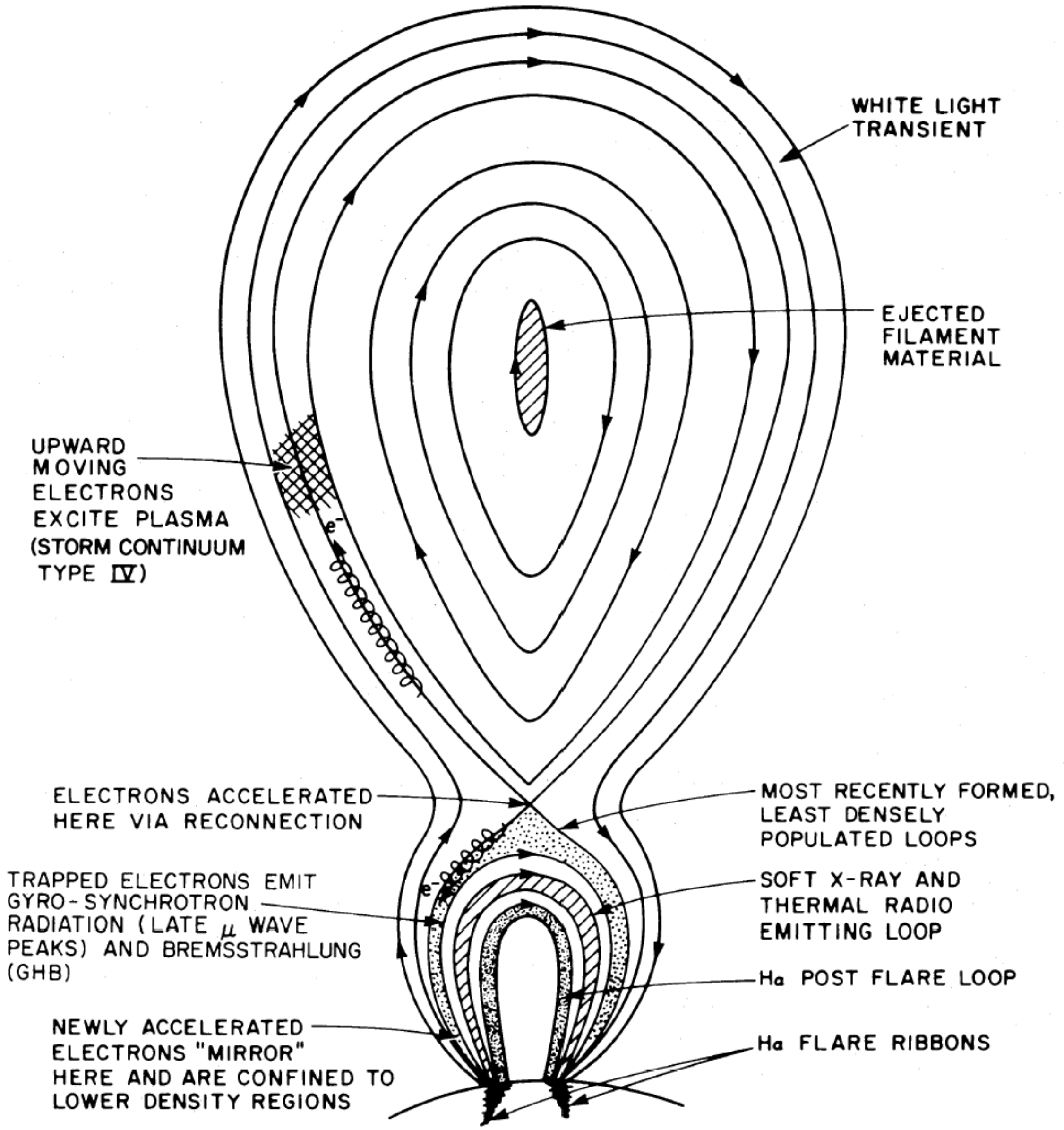

NSO
Oct 29 2003 05:44:53

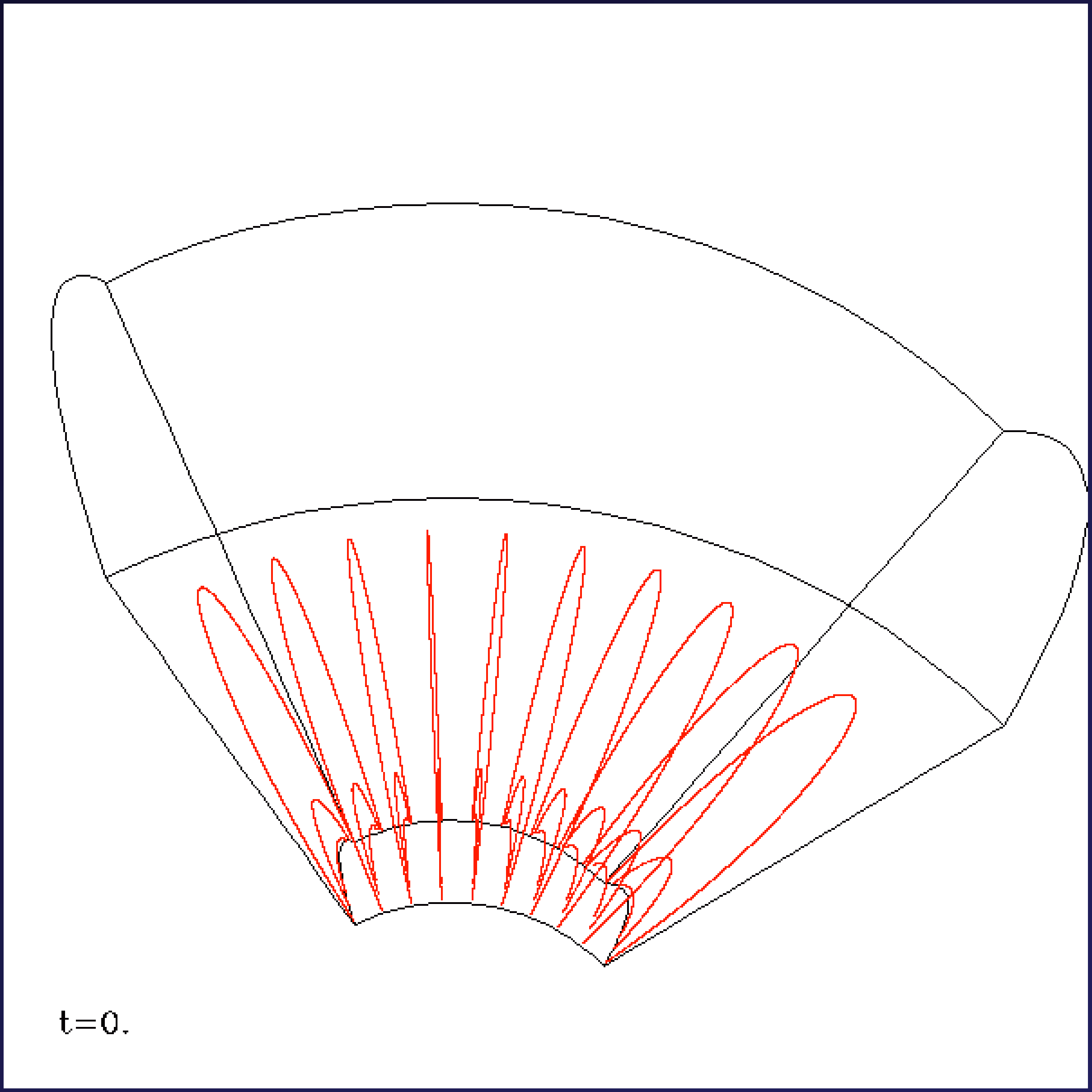
Coronal Mass Ejection: Models

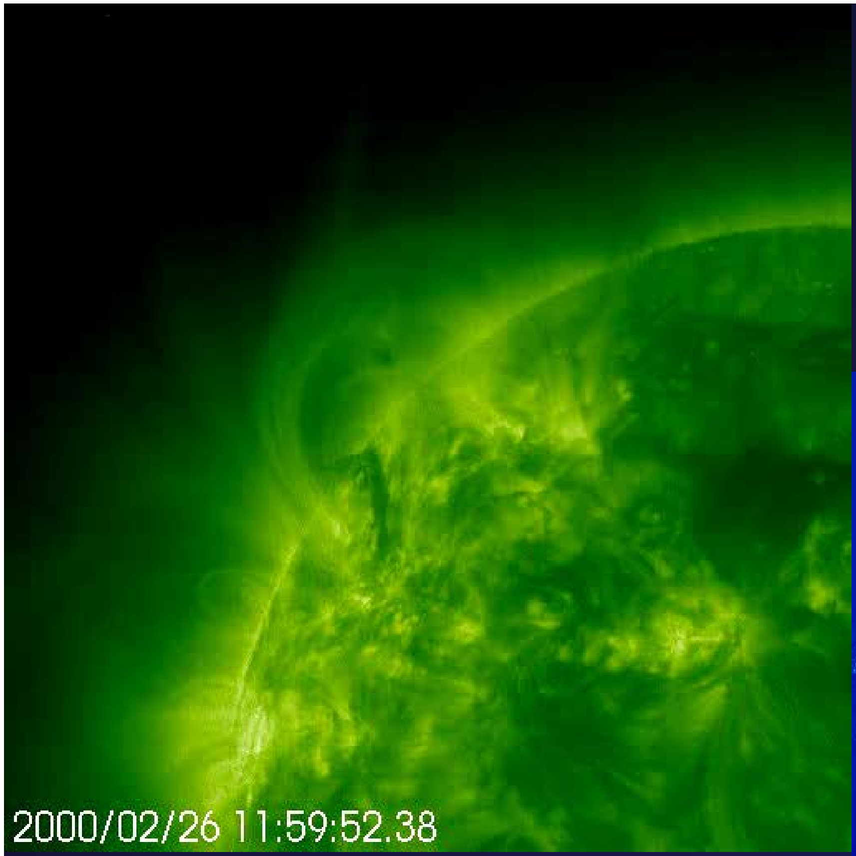
- **Magnetic modeling to explain some of the features of CMEs has been done.**
- **One type of model involves the eruption of a filament containing magnetic fields after it breaches an overlying arcade of magnetic field loops.**
- **Cartoon diagrams can help explain several of the features observed in CMEs, and now 3-d magnetic field models are beginning to reproduce the observed features as well.**

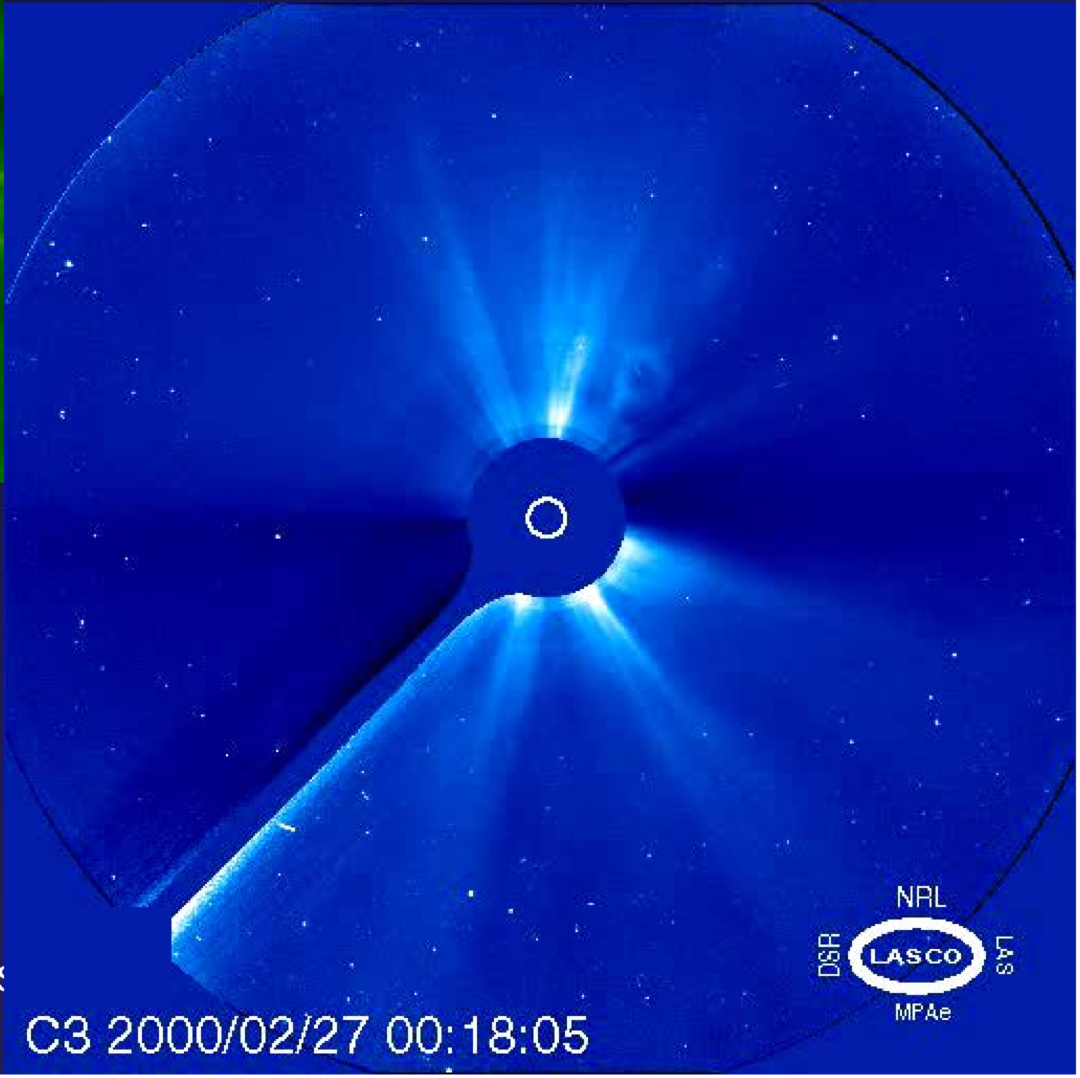





WHITE LIGHT TRANSIENT
EJECTED FILAMENT MATERIAL
UPWARD MOVING ELECTRONS EXCITE PLASMA (STORM CONTINUUM TYPE IV)
ELECTRONS ACCELERATED HERE VIA RECONNECTION
MOST RECENTLY FORMED, LEAST DENSELY POPULATED LOOPS
TRAPPED ELECTRONS EMIT GYRO-SYNCHROTRON RADIATION (LATE μ WAVE PEAKS) AND BREMSSTRAHLUNG (GHB)
SOFT X-RAY AND THERMAL RADIO EMITTING LOOP
Hα POST FLARE LOOP
NEWLY ACCELERATED ELECTRONS "MIRROR" HERE AND ARE CONFINED TO LOWER DENSITY REGIONS
Hα FLARE RIBBONS

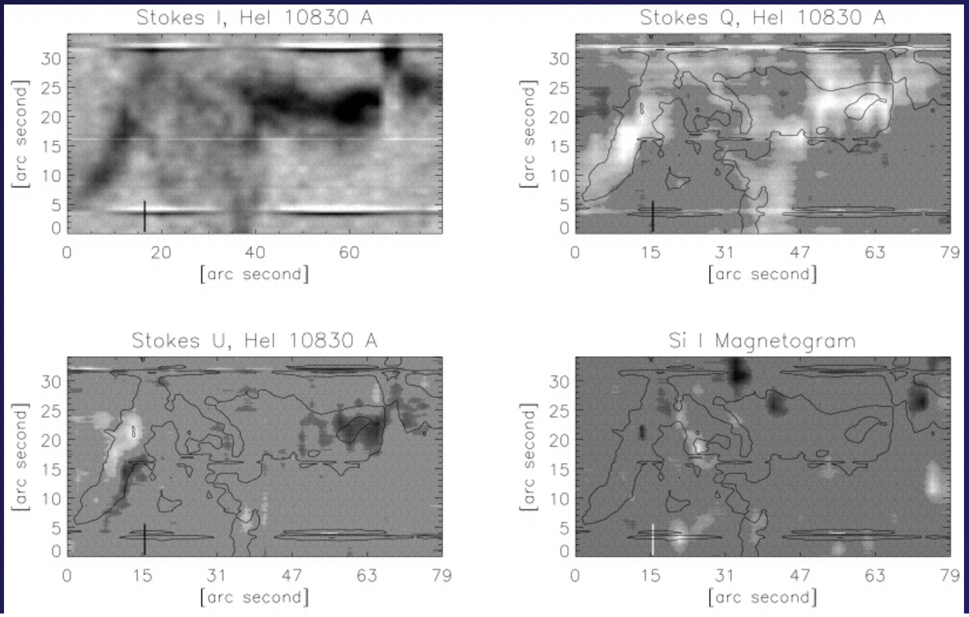

t=0.


2000/02/26 11:59:52.38


NRL
DSR
LASCO
LAS
MPAe
C3 2000/02/27 00:18:05

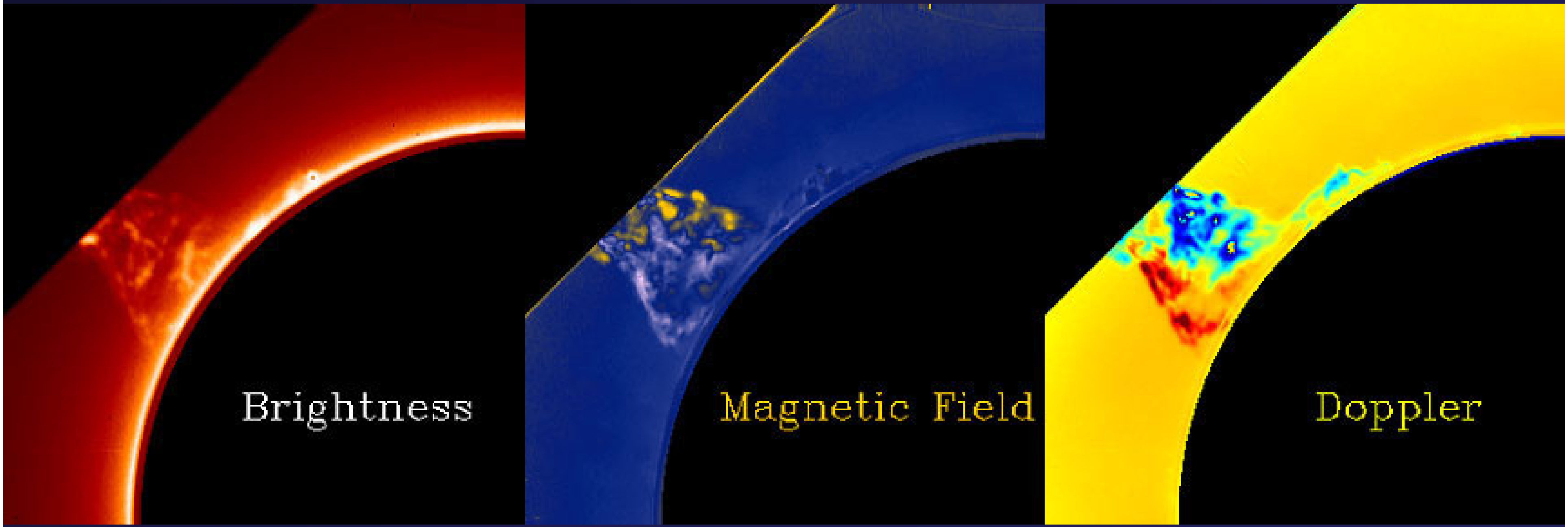
Coronal Magnetic Field: Cold Plasma

- **Observations of the magnetic field in the corona from the ground started with Leroy in the 1980s; his technique used the scattering Hanle effect, and he measured the average magnetic field in a prominence for several years.**
- **Lin, Penn and Kuhn (1998) mapped the magnetic field in a filament (seen against the disk of the Sun) and developed some simple expressions for the Hanle effect in filaments. Results suggested that the filament was imbedded in a tipped arcade of coronal magnetic field lines.**



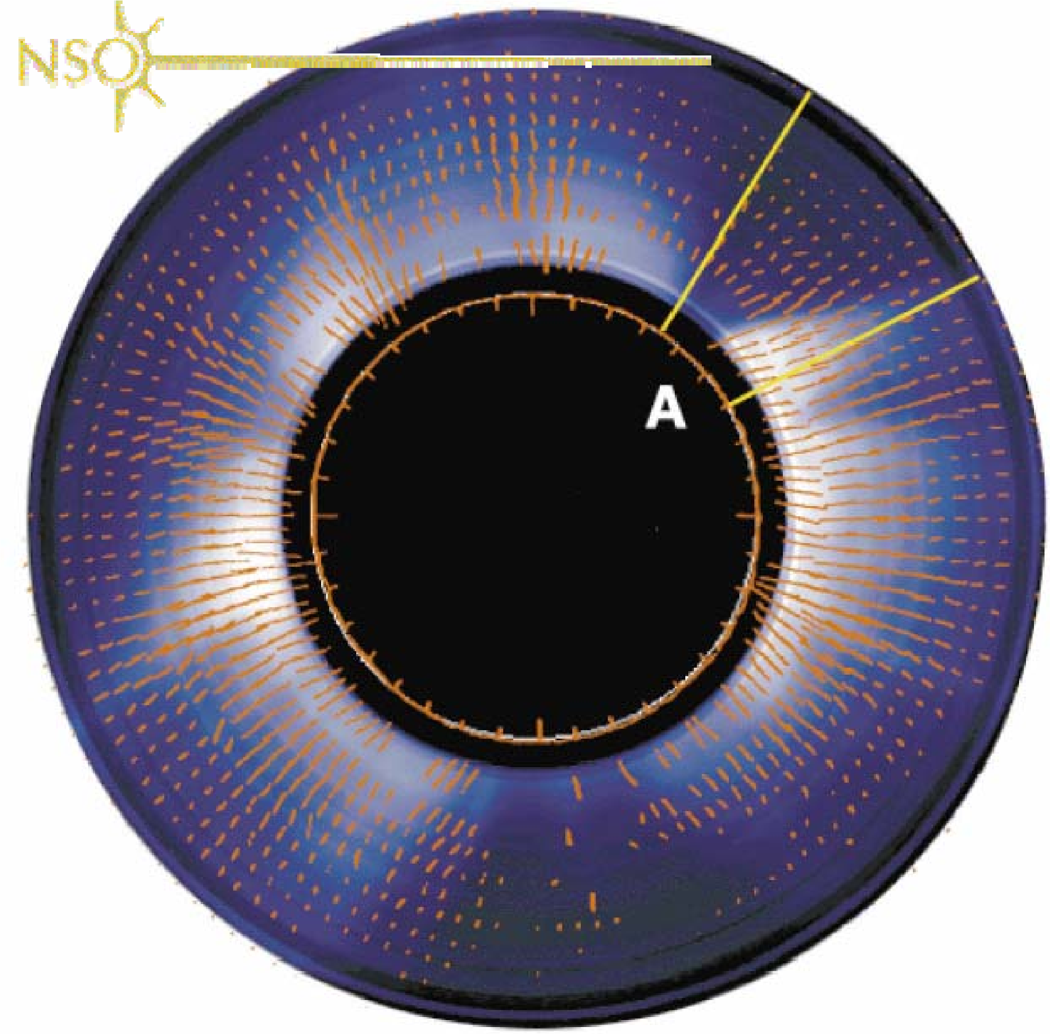
Coronal Magnetic Field: Cold Plasma

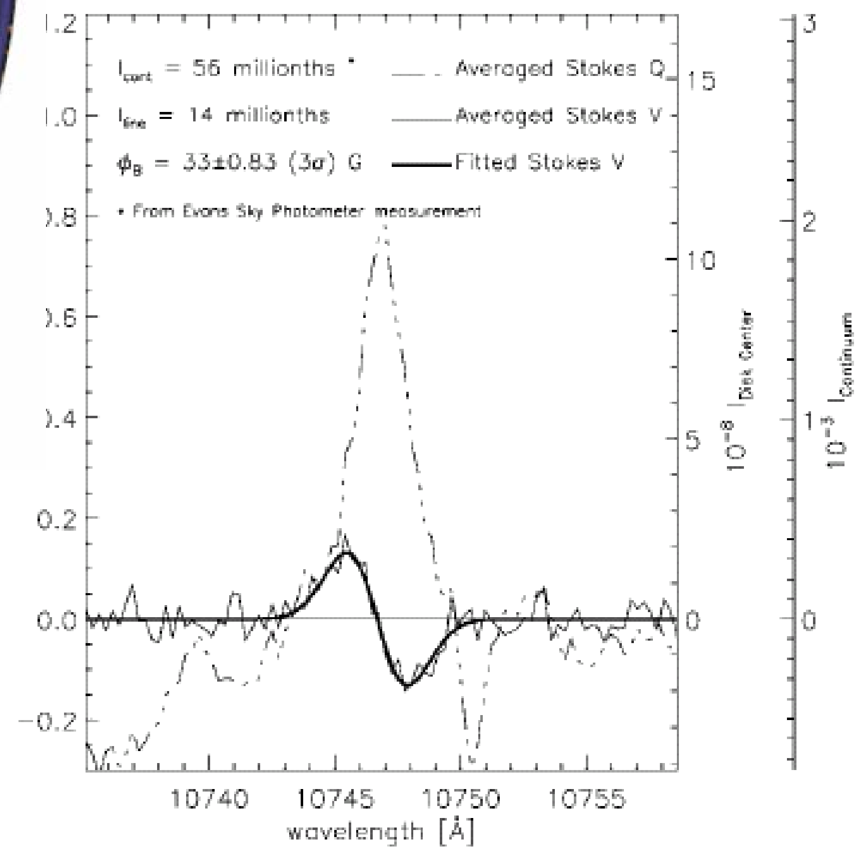
- **Recently Tomczyk et al. have used an imaging filter instrument (COMP) at Sac Peak to map the magnetic field signal from the Zeeman effect in an erupting limb prominence.**

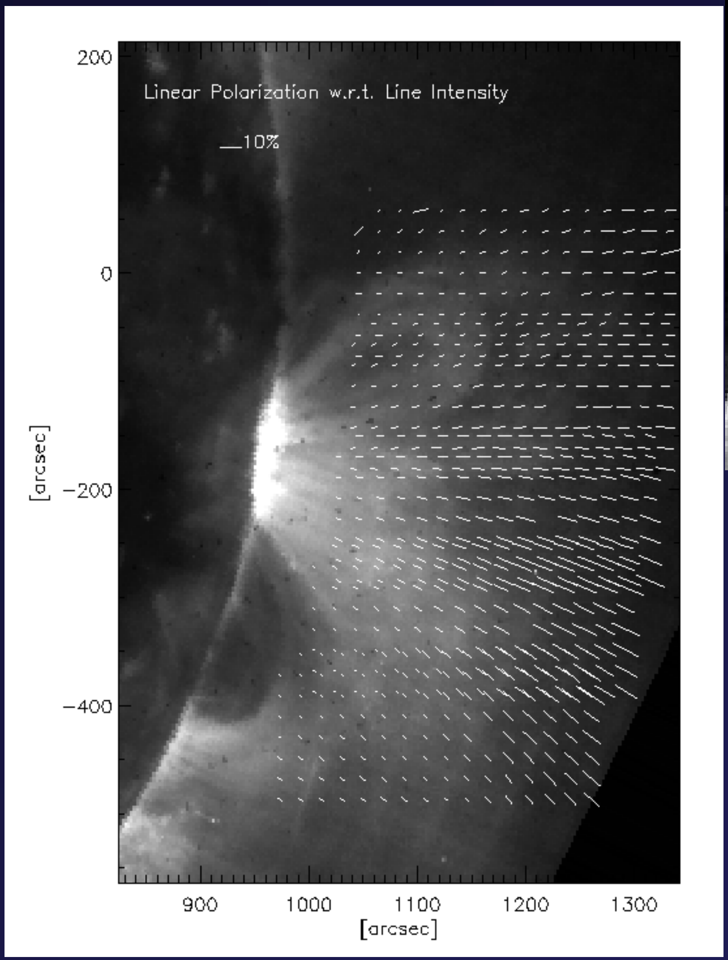


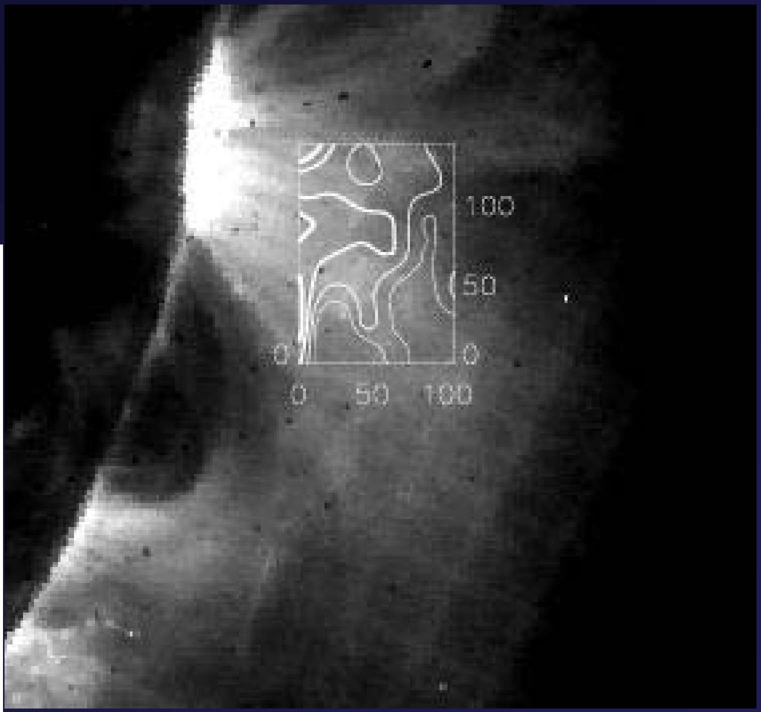
Coronal Magnetic Field: Hot Plasma

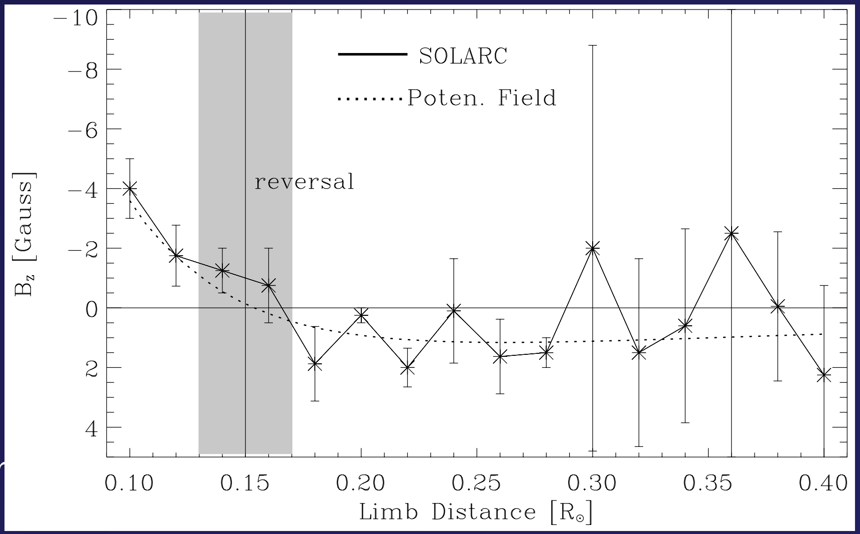
- **Observations of the magnetic field in the corona are possible using the Hanle technique; this technique gives only the direction of the magnetic field, and was used in the 1980's at Sac Peak.**
- **Magnetic field strength observations in the hot plasma are possible using some radio observations. This technique is limited to a small region in height, directly over a sunspot.**
- **Observations of the coronal magnetic field strength at larger heights were done by Harvey (1969) with spectral lines in the visible spectrum, and then Kuhn (1998) used an infrared spectral line to set an upper limit.**
- **Lin, Penn and Tomczyk (2000) used the same infrared spectral line, and with a long integration obtained spectra to measure the full magnetic vector at a point in the corona.**
- **Lin et al. (2004) have recently made the first vector maps of the coronal magnetic field, comparison with models is favorable.**

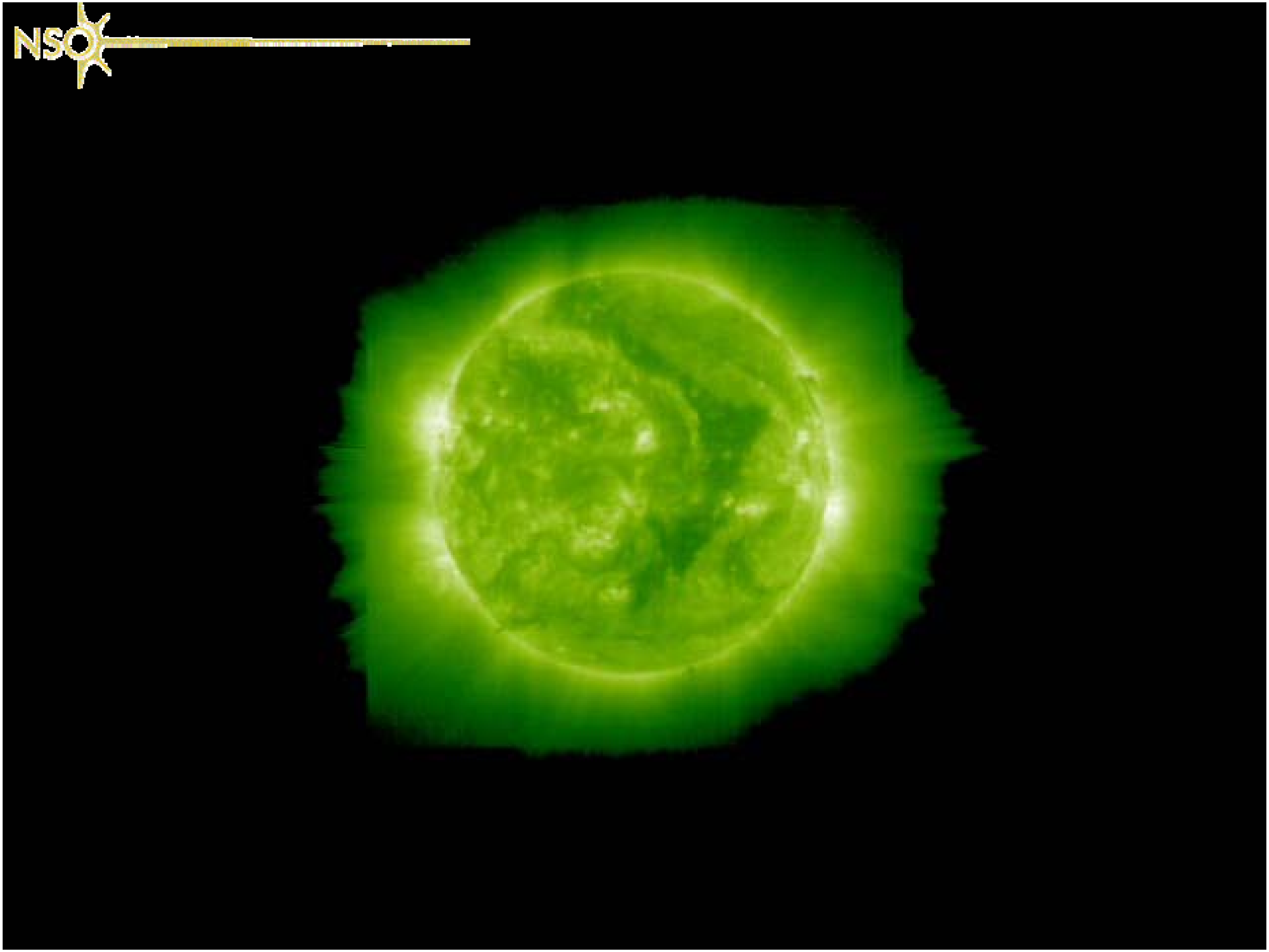

NSO
A


I_{cont} = 56 millionths *
I_{line} = 14 millionths
ϕ_B = 33±0.83 (3σ) G
* From Evans Sky Photometer measurement
Averaged Stokes Q
Averaged Stokes V
Fitted Stokes V
wavelength [Å]
10^{-8} $I_{Disk\ Center}$
10^{-3} $I_{Continuum}$


Linear Polarization w.r.t. Line Intensity
10%
200
0
−200
−400
[arcsec]
900
1000
1100
1200
1300
[arcsec]

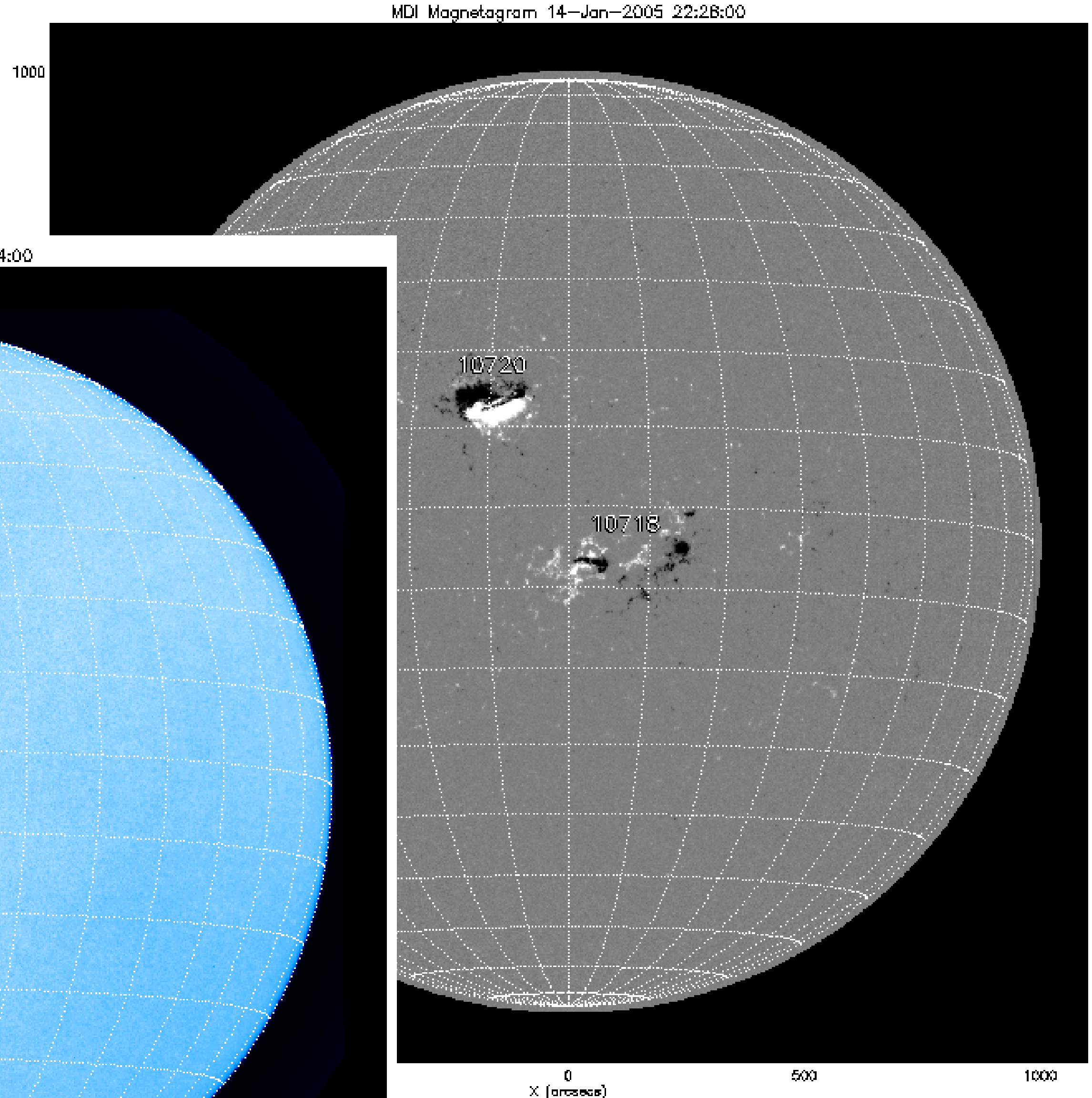

100
50
0
0
0
50
100

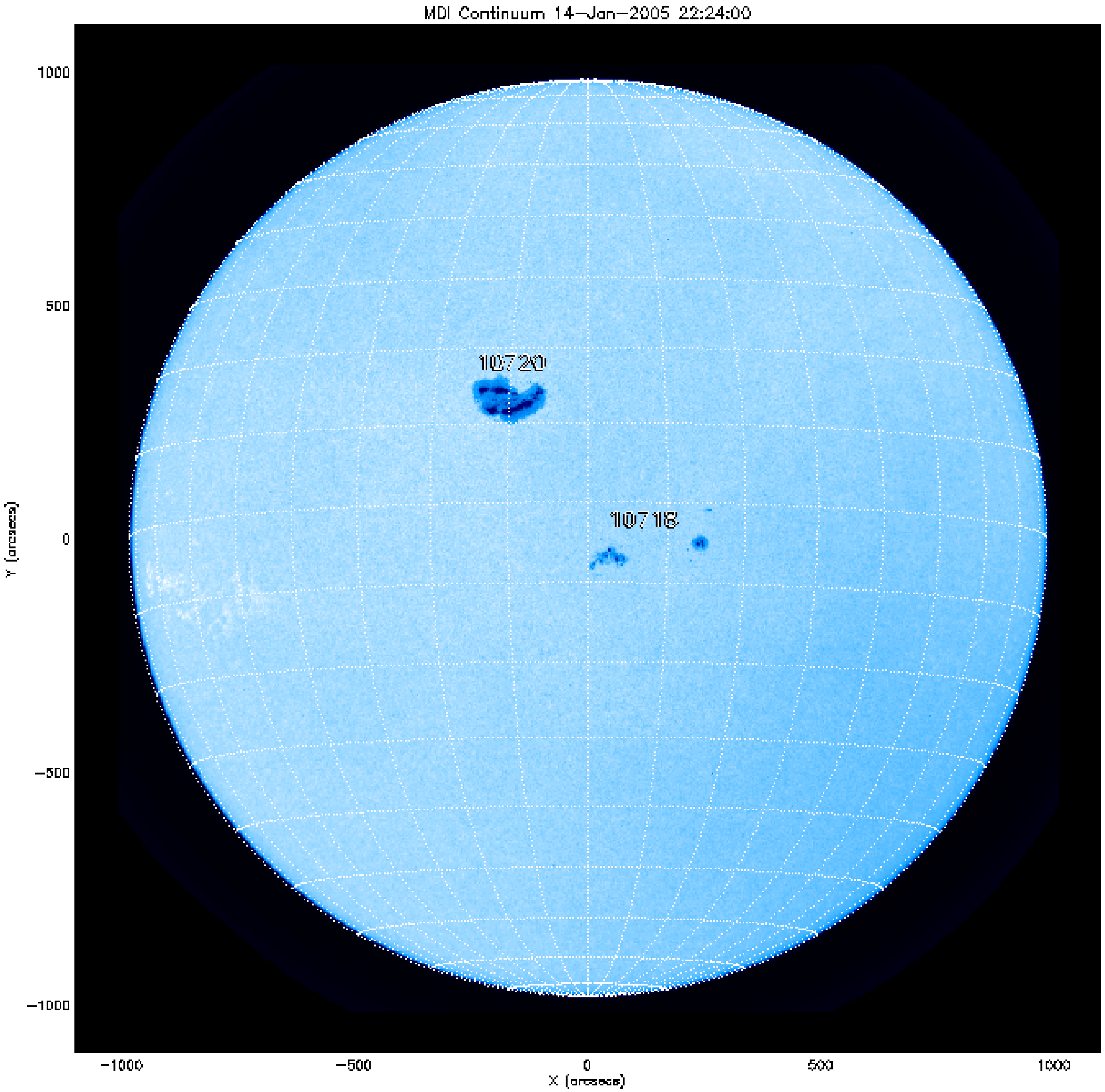

SOLARC
Poten. Field
reversal
B_z [Gauss]
Limb Distance [$R_\odot$]
−10
−8
−6
−4
−2
0
2
4
0.10
0.15
0.20
0.25
0.30
0.35
0.40



Photospheric Magnetic Field

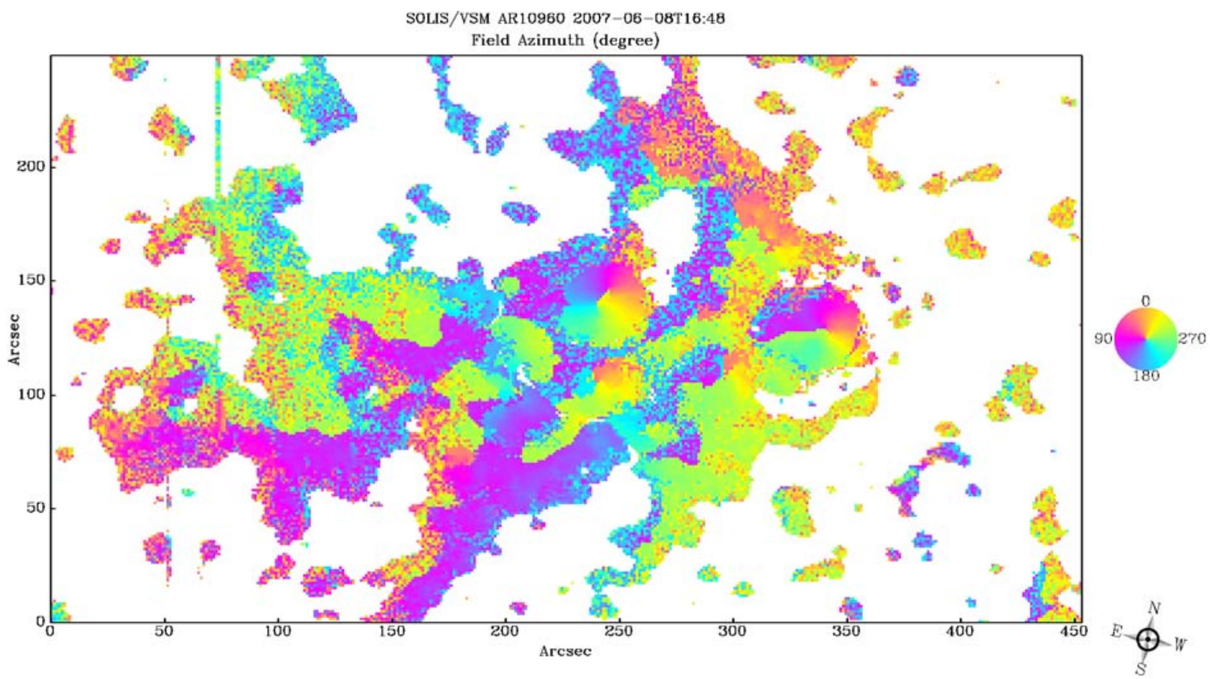
- The full vector magnetic field in the photosphere is measured using the Zeeman effect, by examining the polarization signal from solar absorption lines.
- Different spectral lines probe different layers of height in the solar photosphere, and some lines can probe the solar chromosphere.
- Measurements of the line-of-sight component of the magnetic field vector are the easiest, and such magnetograms have been made for many years.
- The other vector components of the magnetic field are more difficult to measure, and there are some problems with determining the exact direction of the field – there is a 180-degree ambiguity.
- Recently infrared spectral lines have been used, and these lines allow us to precisely measure the magnetic field strength, rather than measuring it with spectral line fits (and the inherent assumptions).


MDI Magnetogram 14-Jan-2005 22:28:00
1000
10720
10718
0
500
1000
X (arcsecs)

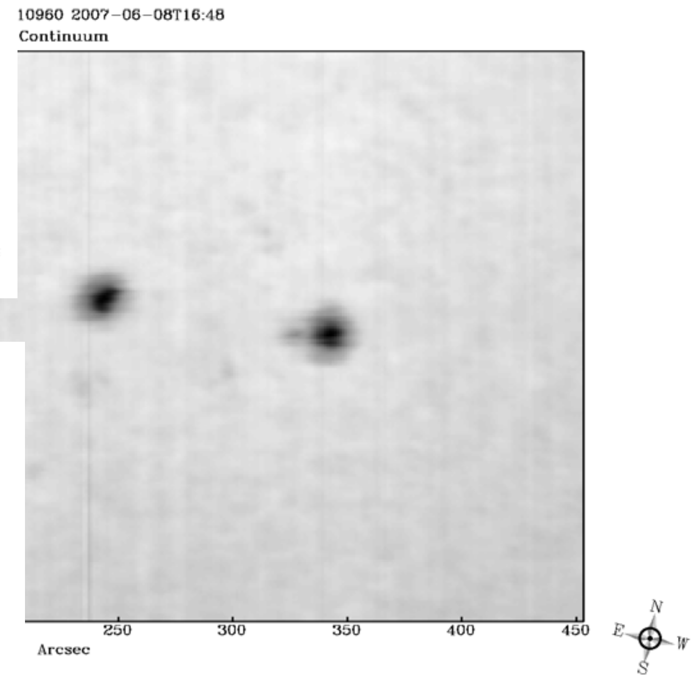

MDI Continuum 14-Jan-2005 22:24:00
1000
500
0
−500
−1000
Y (arcsecs)
10720
10718
−1000
−500
0
500
1000
X (arcsecs)

SOLIS: full-disk vector magnetic field measurements

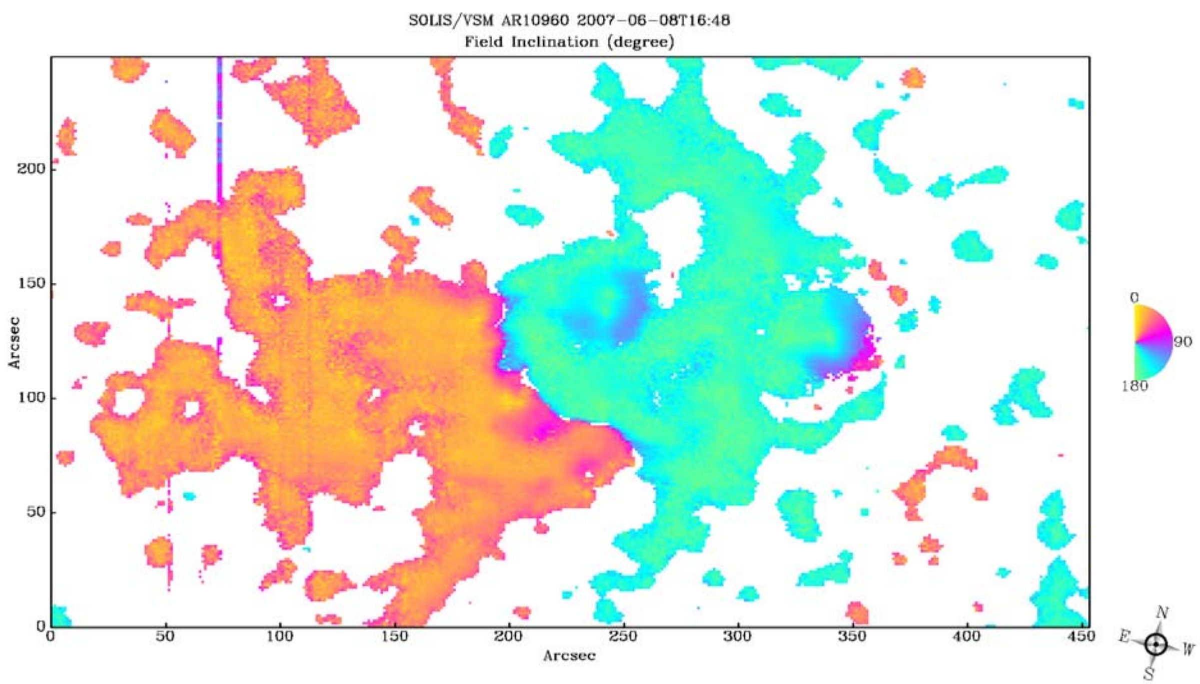
- The SOLIS project from NSO includes the Vector Spectromagnetograph which produces daily vector magnetic field measurements of the whole solar disk.
- Recent results: Hinode sees horizontal field everywhere, SOLIS sees horizontal field at the limb… these are not associated with bright points.
- “Turbulent” field as observed with Hanle effect?



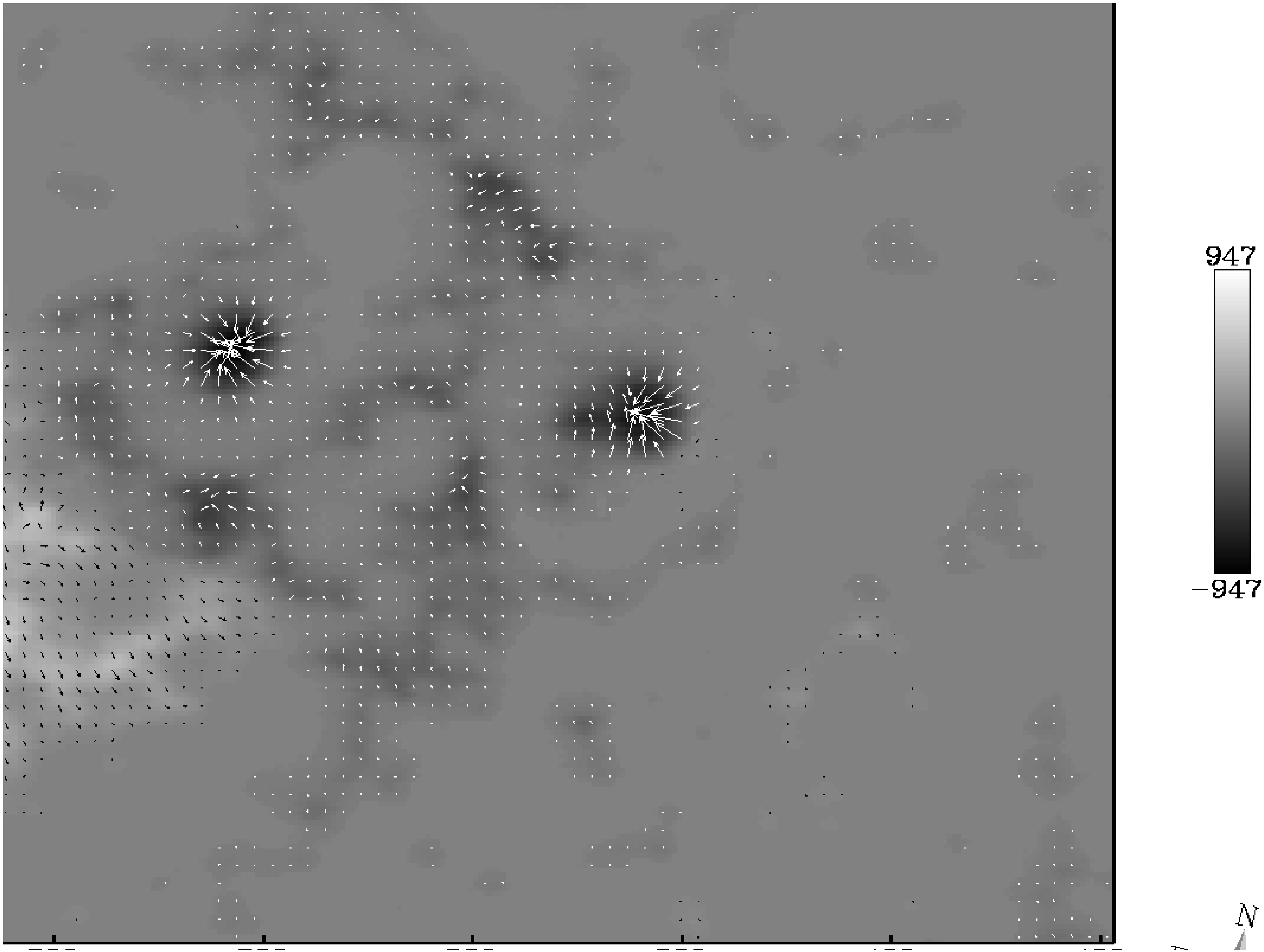
SOLIS/VSM AR10960 2007-06-08T16:48
Field Azimuth (degree)
Arcsec
Arcsec
0
90
270
180
N
E
W
S



10960 2007-06-08T16:48
Continuum
Arcsec
N
E
W
S



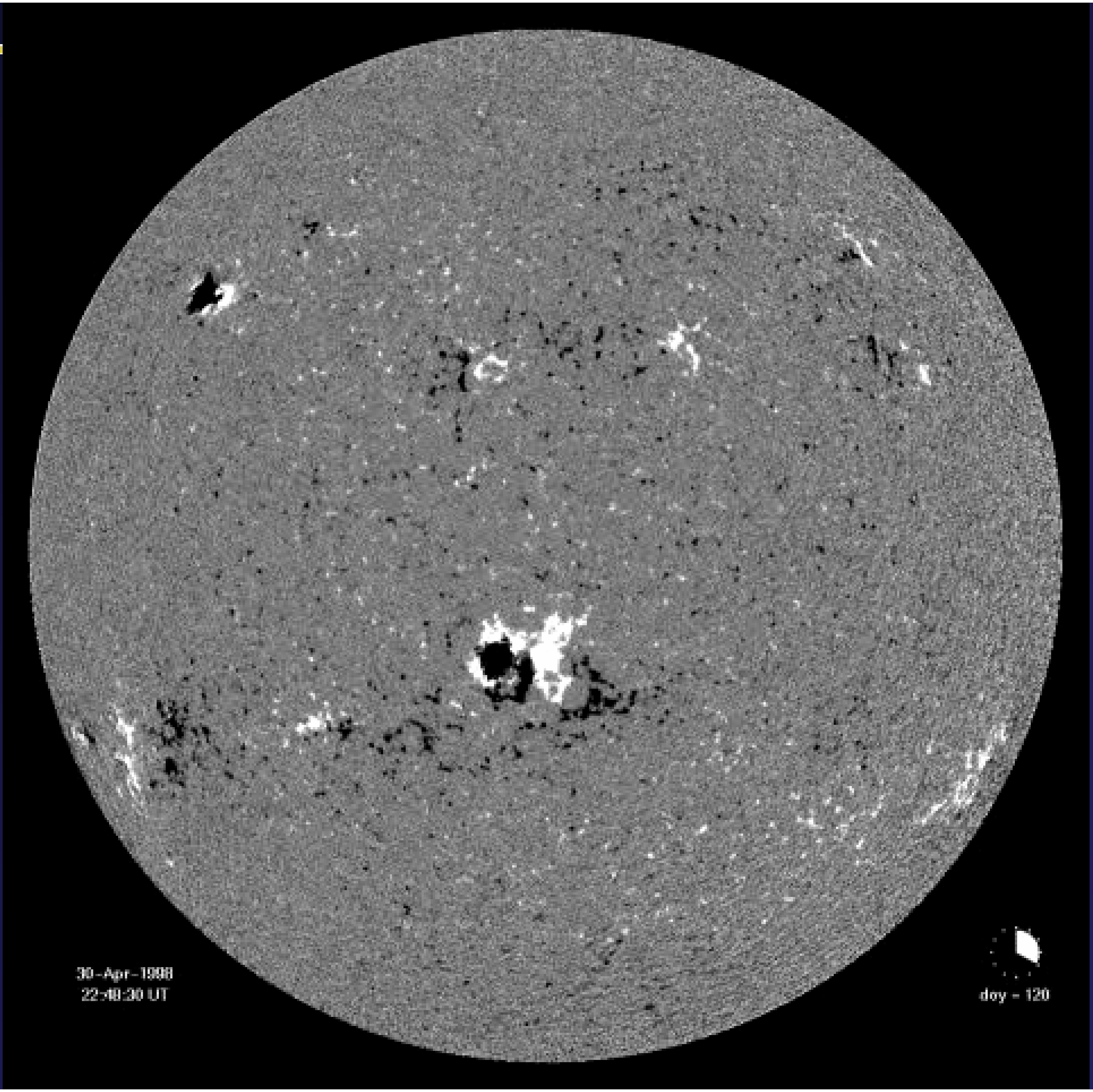
SOLIS/VSM AR10960 2007-06-08T16:48
Field Inclination (degree)
Arcsec
Arcsec
0
90
180
N
E
W
S



947
−947
N

Sunspot magnetic flux eruption

- **The magnetic flux associated with sunspots erupts at the surface in some sort of a bipolar configuration (not very simple!).**
- **The magnetic fields carry twist, and particular orientations (Joy's Law) which they may acquire during their rise through the convection zone.**
- **Spot magnetic fields evolve on small spatial scales.**
- **Magnetic fields are also seen away from spots in the "quiet sun"; often as bright regions in the solar photosphere.**



30-Apr-1998
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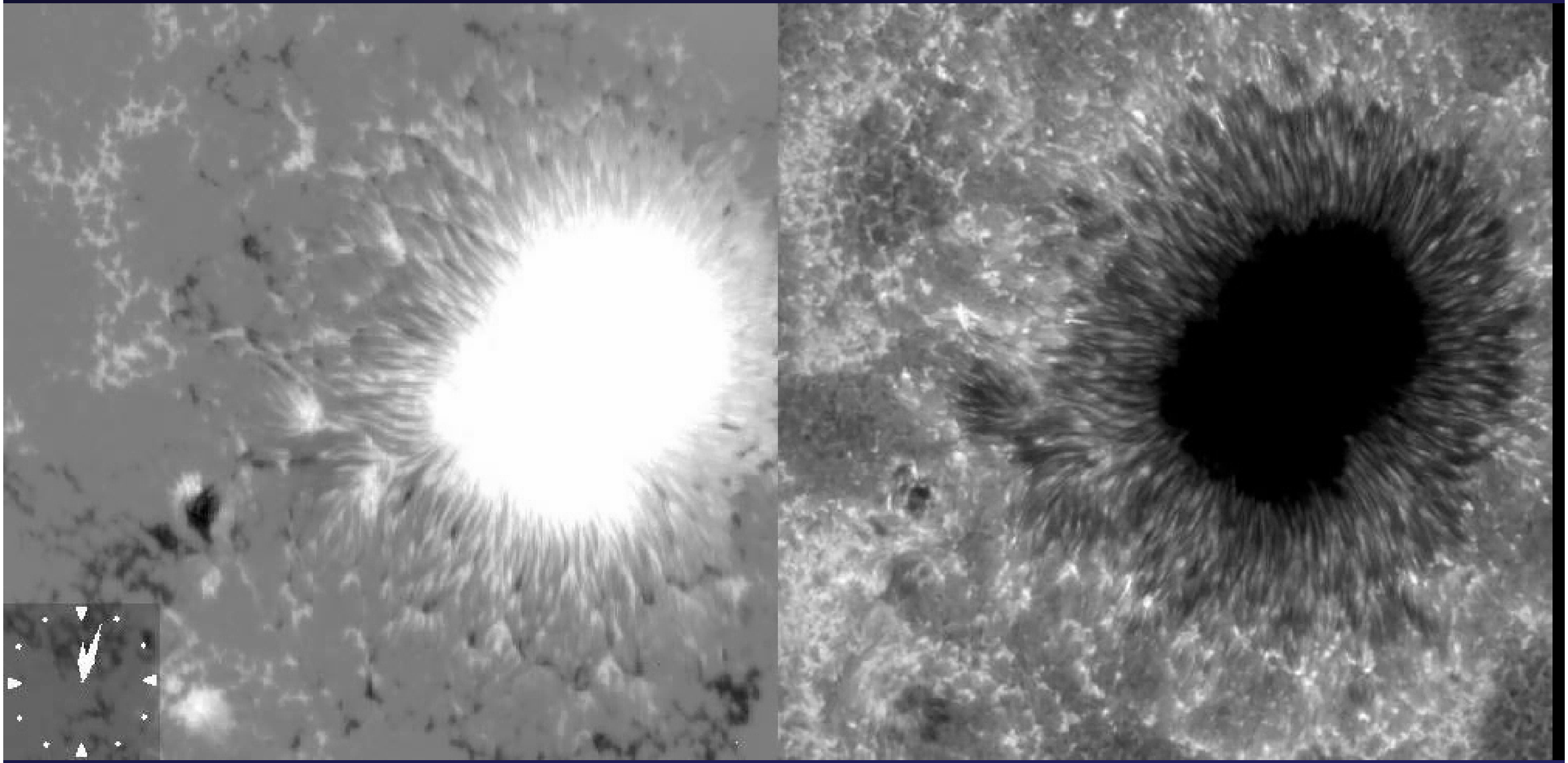
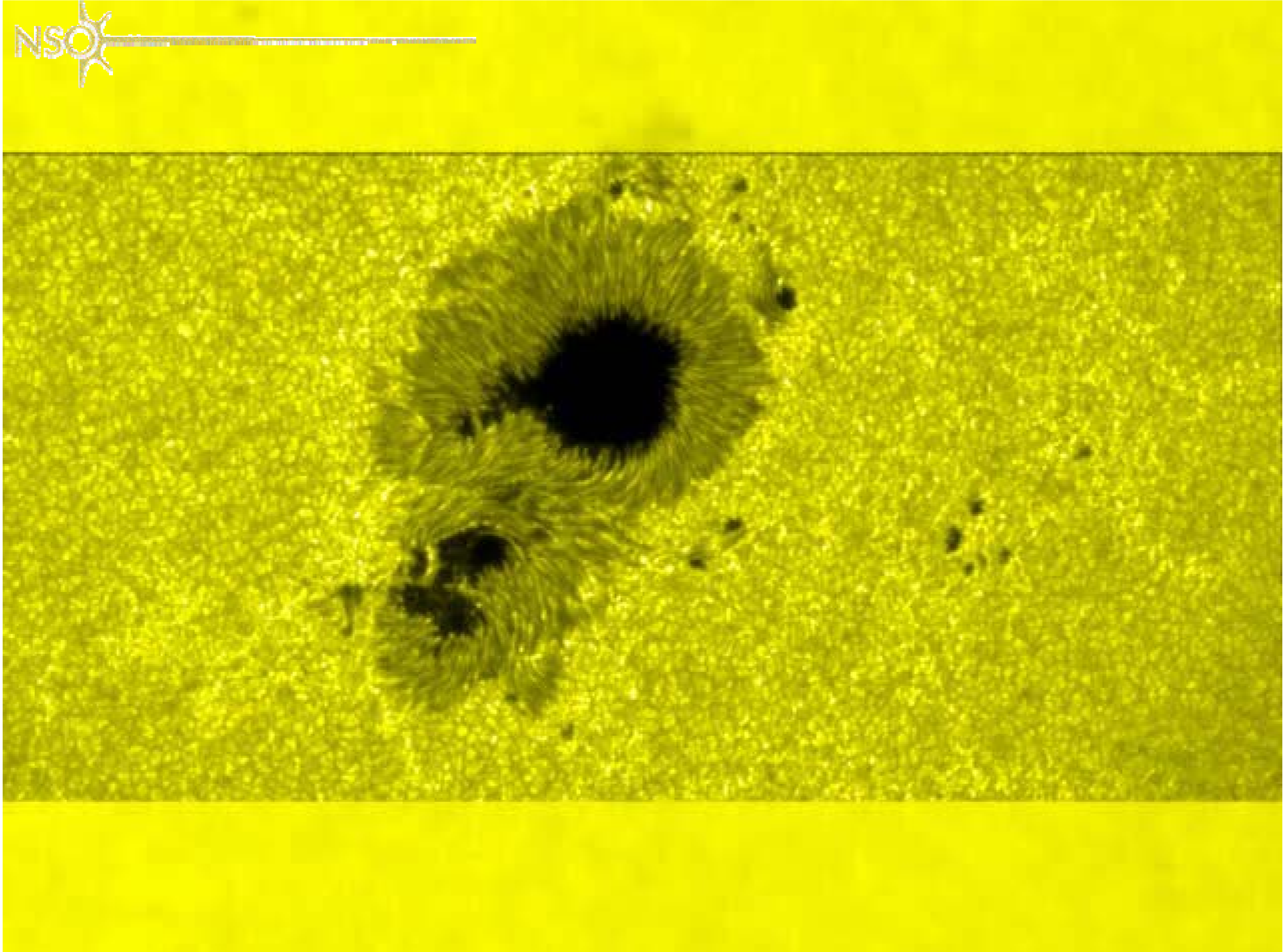
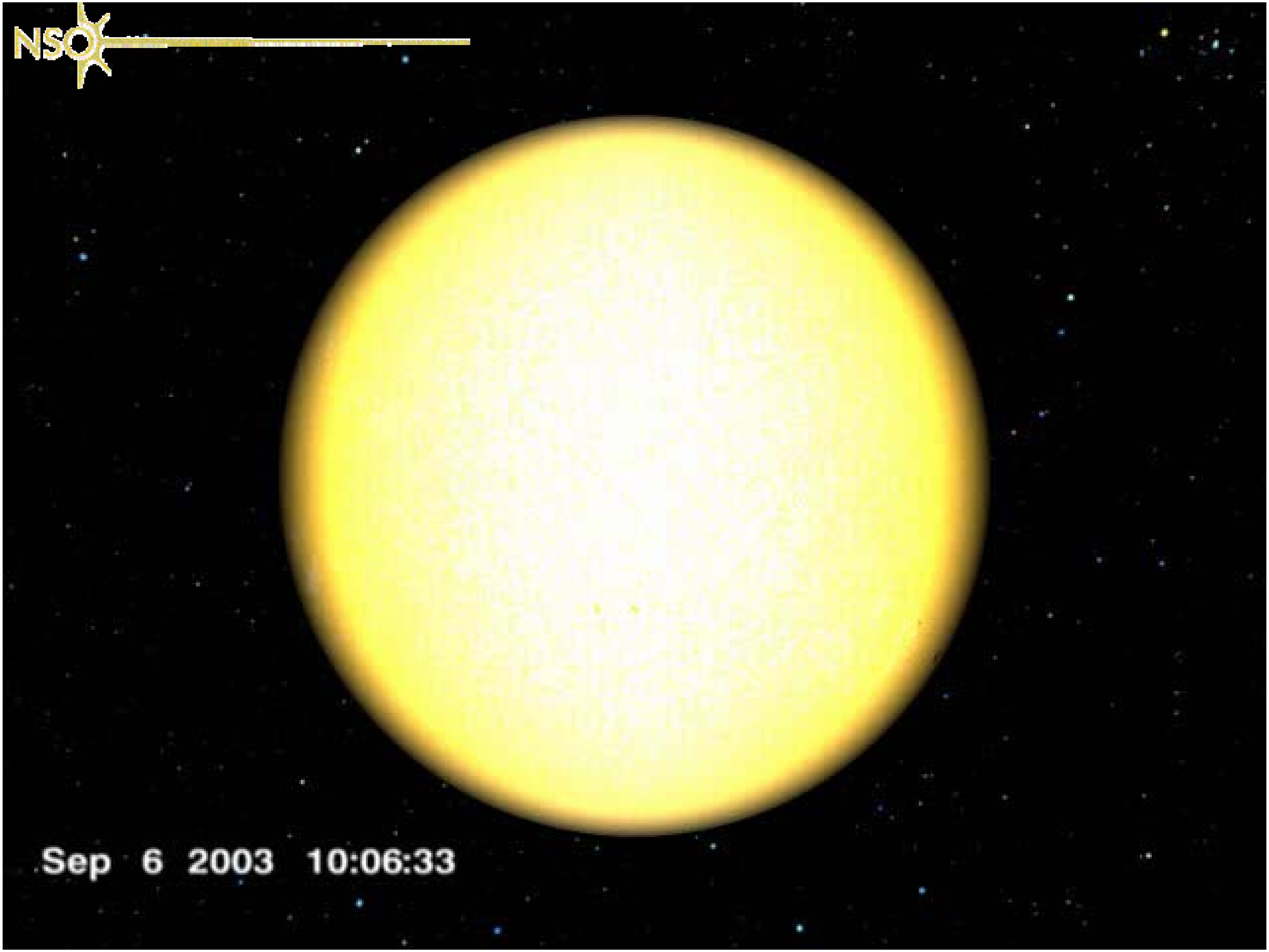
day - 120




NSO

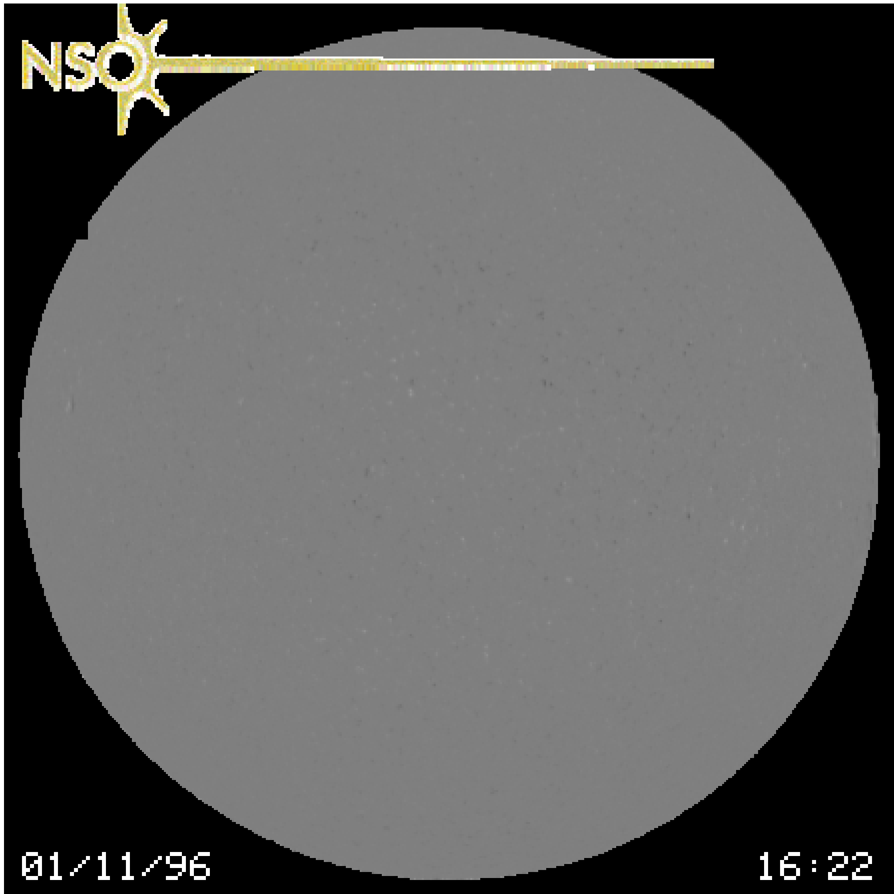
Magnetic fields absorb solar oscillations

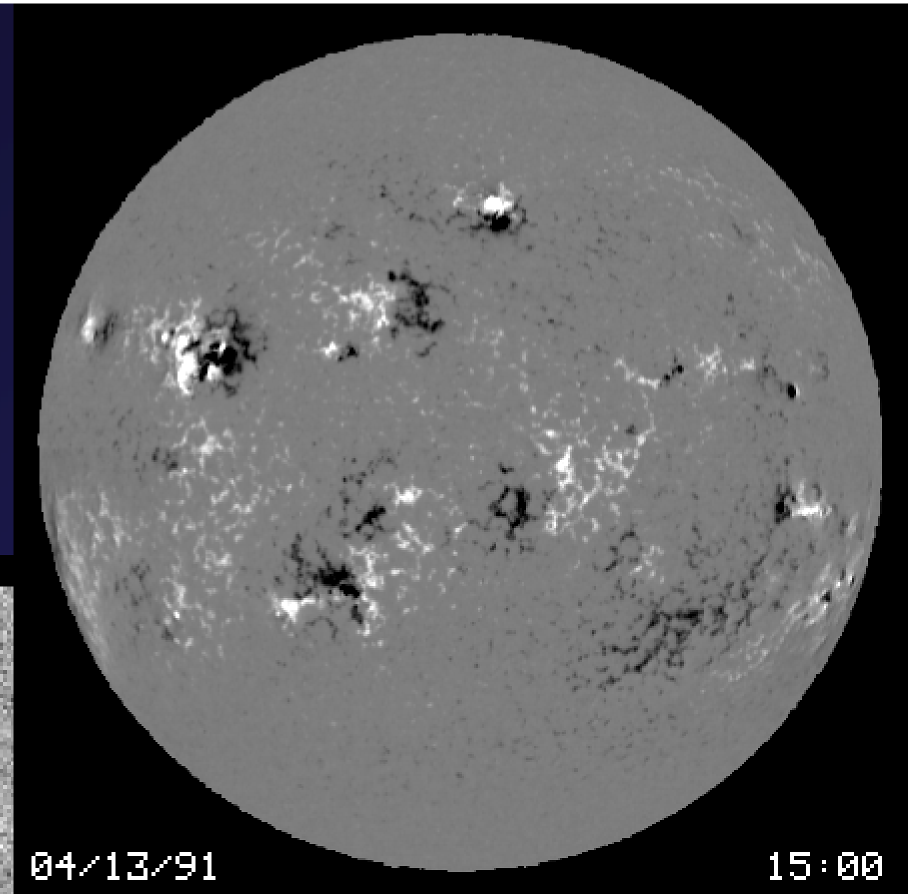
- **Braun, Duvall and LaBonte showed that sunspots absorb the p-mode oscillation waves seen on the surface of the Sun.**
- **These oscillations are global: the waves wrap around the Sun.**
- **Studies of the wave power on the near-side of the solar surface can reveal information about the magnetic fields on the far-side of the Sun.**
- **Recently images of the far-side are being produced daily to image the sunspots on the far-side of the sun.**


NSO
Sep 6 2003 10:06:33

Solar magnetic cycle

- **Sunspots show an 11 year cycle in their number, but the magnetic configuration of those sunspots (Hale's polarity law) takes 22 years to complete a cycle.**
- **Magnetic fields erupt at high latitudes early in the cycle, and low latitudes late in the cycle.**
- **At the surface, magnetic flux migrates from the spots to the solar poles and changes the magnetic polarity there.**
- **Surface observations of the magnetic field provide important contraints on models of the magnetic field generation inside the sun, the magnetic dynamo models.**


NSO
01/11/96
16:22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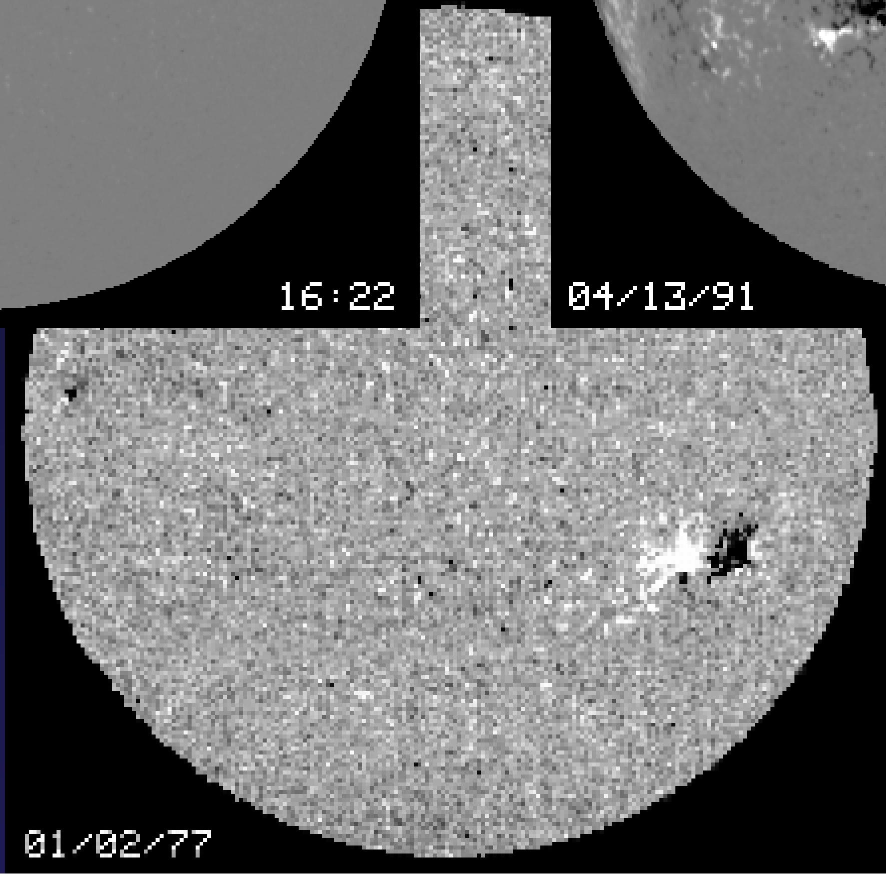
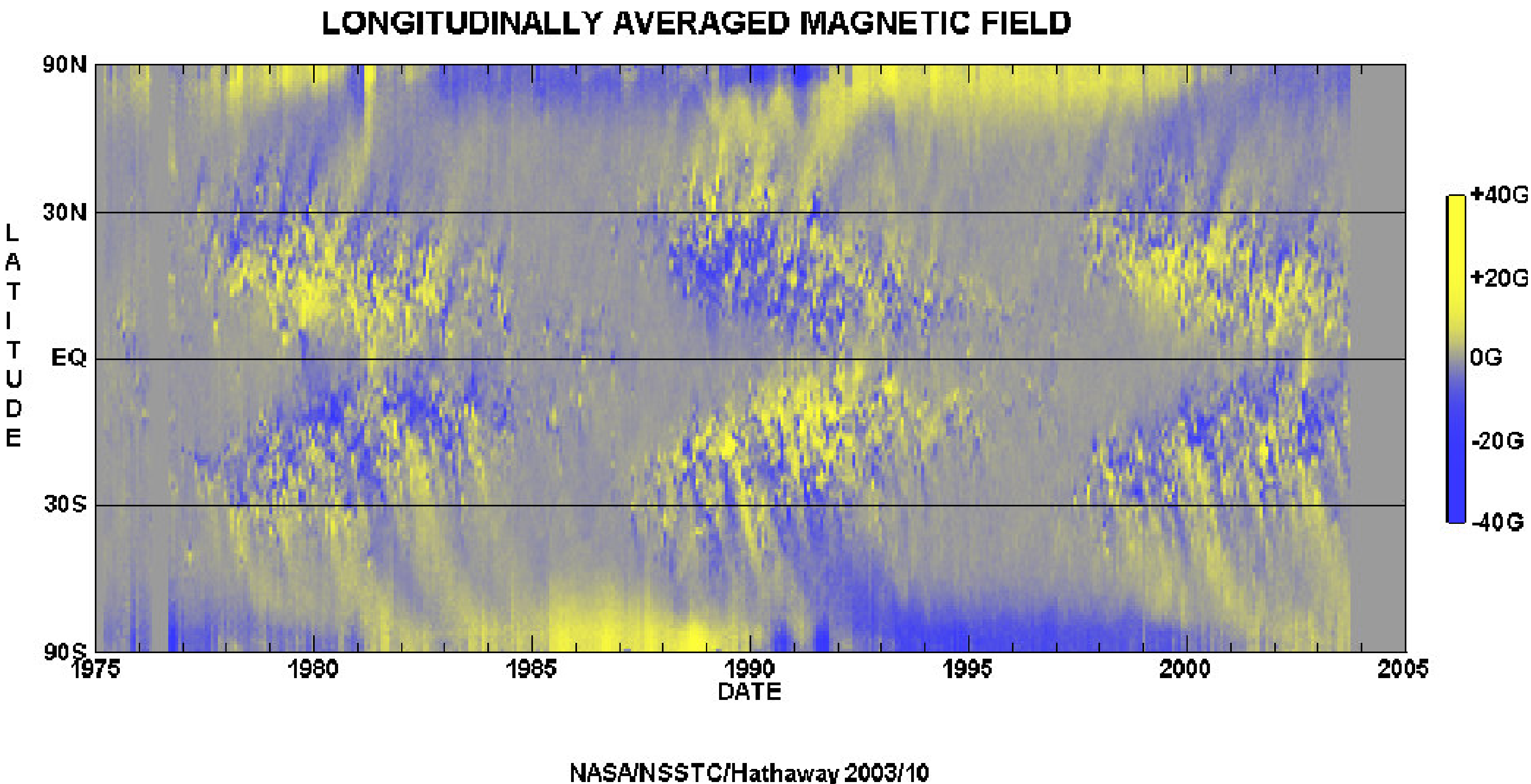
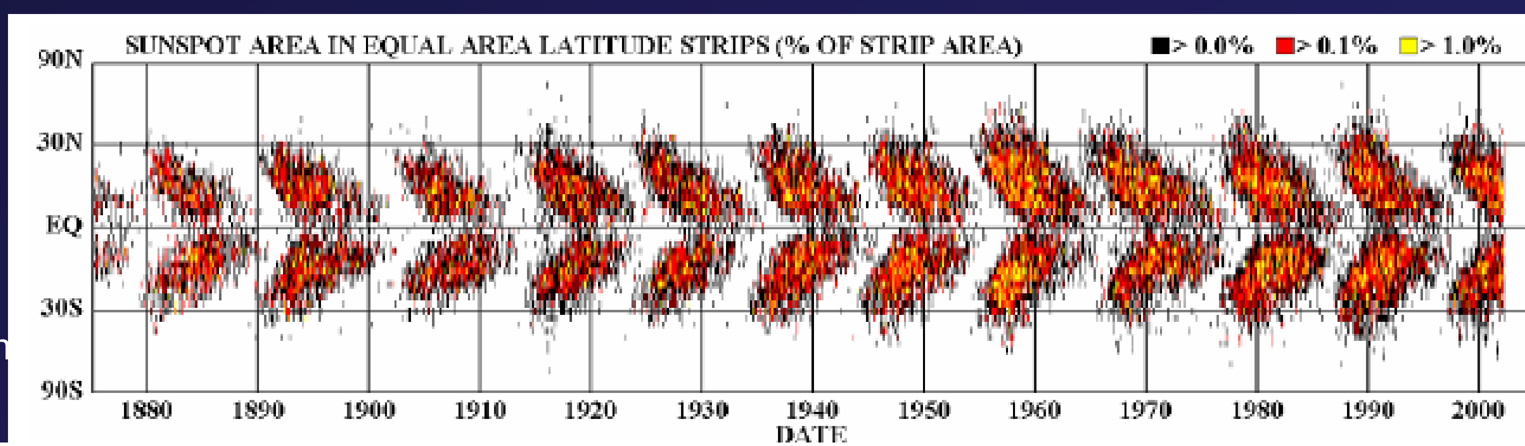
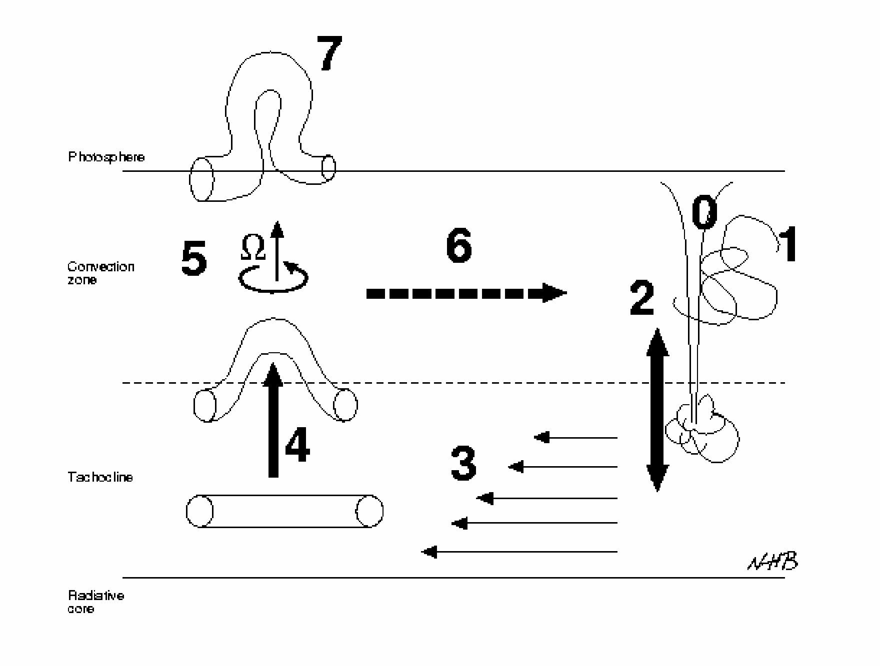

01/02/77


LONGITUDINALLY AVERAGED MAGNETIC FIELD
90N
30N
EQ
30S
90S
LATITUDE
1975
1980
1985
1990
1995
2000
2005
DATE
+40G
+20G
0G
-20G
-40G
NASA/NSSTC/Hathaway 2003/10


SUNSPOT AREA IN EQUAL AREA LATITUDE STRIPS (% OF STRIP AREA)
> 0.0%
> 0.1%
> 1.0%
90N
30N
EQ
30S
90S
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
DATE


7
Photosphere
0
1
5
6
Convection zone
2
4
3
Tachocline
NHB
Radiative core

- **Solar Magnetic Fields 1 (11 June)** – A *very qualitative* look at the structure and evolution of the solar magnetic fields, from the outer heliopause to the solar core.
  - Heliosphere
  - Magnetic effects caused by the interplanetary field and wind
  - Geomagnetic effects: the Sun – Earth connection
  - Corona: CMEs, flares, and recent direct magnetic measurements
  - Photosphere: magnetograms and vector maps, flux eruption
  - Interior: solar cycle changes and constraints on models.

- **References:**
  - **Scientific Visualization Studio: http://svs.gsfc.nasa.gov/Gallery/NASAsSun-EarthGallery.html**
  - **SoHO movie web page: http://sohowww.nascom.nasa.gov/bestofsoho/Movies/movies2.html**
  - **Trace movies: http://soi.stanford.edu/results/SolPhys200/Schrijver/index.html**
  - **Solar Model Cartoons: http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/**
  - **NSO Solis Web page: http://solis.nso.edu/**
  - **Hinode data and movies: http://solar-b.nao.ac.jp/latest_e/**
  - **Lin, Penn, Kuhn 1998, ApJ 493, 978**
  - **Lin, Penn, Tomczyk 2000, ApJ 541, L83**
  - **Lin, Kuhn, Coulter, 2004, ApJ 613, L177**
  - **NSO KPVT data archive: http://synoptic.nso.edu/**