THE INCONSTANT SUN

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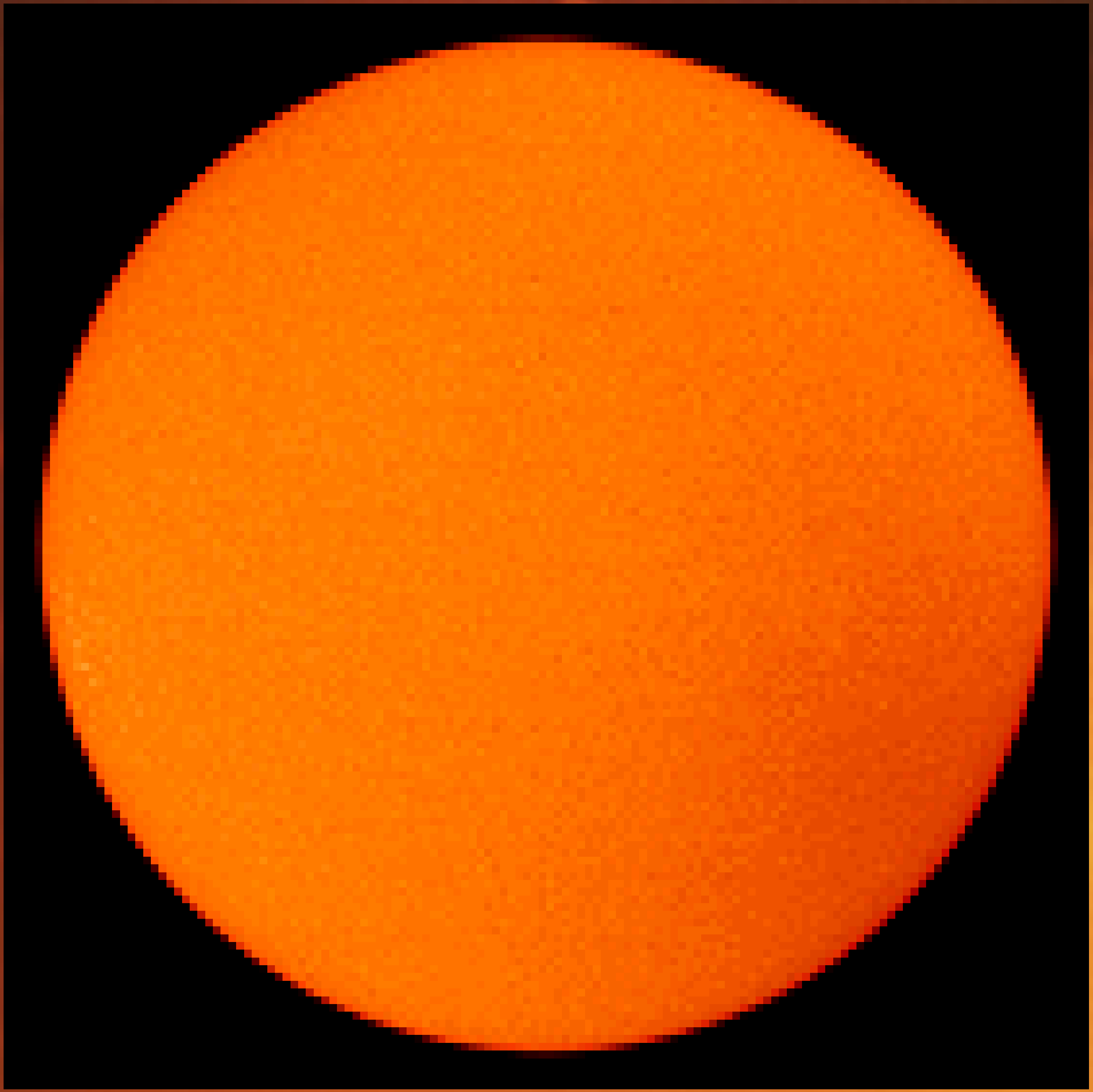


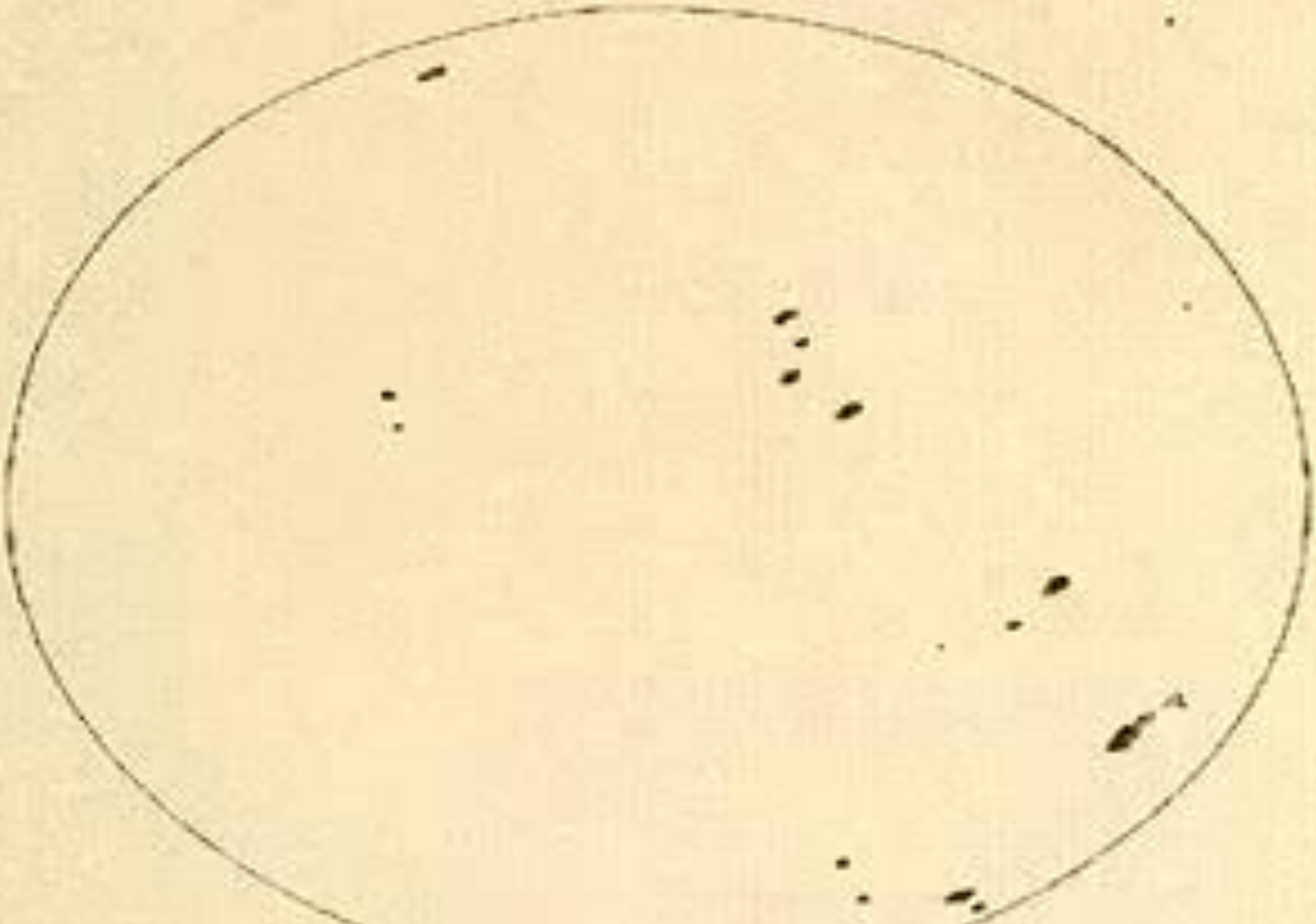


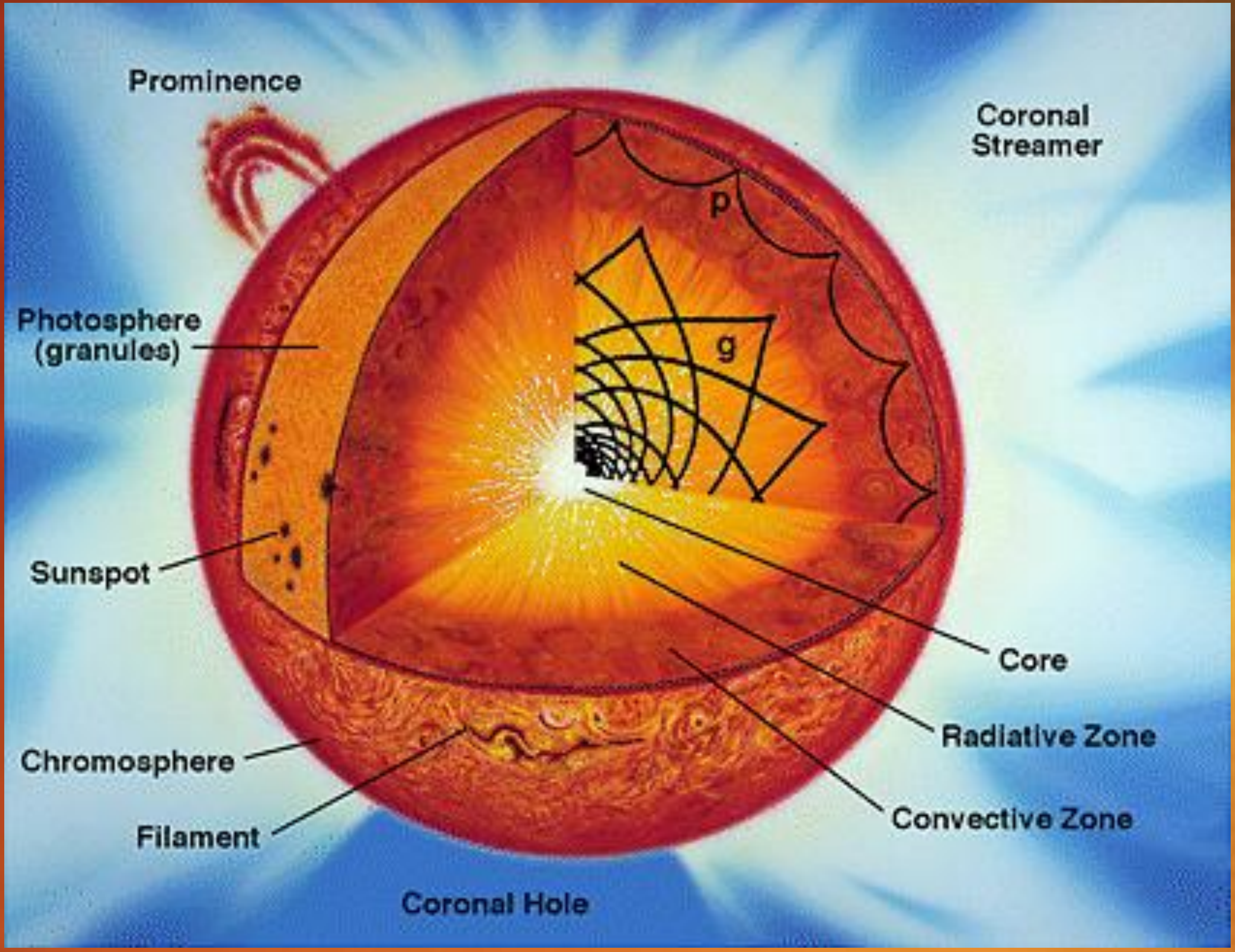
Fig. D. 2.

Overview of Solar Structure

The Sun is made mostly of HYDROGEN and HELIUM and a little admixture of heavy elements

Main Parts:

- Corona
- Chromosphere
- Photosphere
- Convection Zone
- Radiative Zone
- Core



Internal structure of the Sun is governed by

- Mechanical equilibrium
- Thermal equilibrium

- **Auxiliary input physics**

	Opacity of solar material
Microphysics:	Nuclear energy generation in the core
	Equation of state of matter
	Turbulent convection
Macrophysics:	Diffusion of helium and heavy elements
……………………..	

STRUCTURAL EQUATIONS FOR SPHERICAL SUN

$$\frac{dP(r)}{dr} = -\frac{GM(r)}{r^2}\rho(r) \ ,$$

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r) \ ,$$

$$\rho T \frac{dS(r)}{dr} = -\frac{1}{r^2}\frac{d}{dr}\left(r^2(F_{\mathrm{rad}} + F_{\mathrm{conv}})\right) + \rho\epsilon \ ,$$

$$F_{\mathrm{rad}} = -K_{\mathrm{rad}}\frac{dT}{dr} \ , \qquad (K_{\mathrm{rad}} = \frac{4acT^3}{3\kappa\rho})$$

$$F_{\mathrm{conv}} = -\kappa_{\mathrm{turb}}\rho T \frac{dS(r)}{dr} \ , \qquad (\kappa_{\mathrm{turb}} \approx wl)$$

Is there any way of checking the correctness of theoretical solar models?

We can probe the solar interior with the help of diagnostics provided by:

- Neutrinos - temperature, composition
- Seismic Waves – sound speed, density, rotation, ..

pp cycle

$$
\begin{array}{lrcll}
 & p + p & \rightarrow & d + e^+ + \nu_e & (\leq 0.42\ \mathrm{MeV}) \\
 & p + e^- + p & \rightarrow & d + \nu_e & (1.44\ \mathrm{MeV}) \\
 & p + d & \rightarrow & {}^3\mathrm{He} + \gamma & \\
\text{pp-I :} & {}^3\mathrm{He} + {}^3\mathrm{He} & \rightarrow & {}^4\mathrm{He} + 2p & \\
 & {}^3\mathrm{He} + p & \rightarrow & {}^4\mathrm{He} + e^+ + \nu_e & (\leq 18.8\ \mathrm{MeV}) \\
\text{pp-II :} & {}^3\mathrm{He} + {}^4\mathrm{He} & \rightarrow & {}^7\mathrm{Be} + \gamma & \\
 & {}^7\mathrm{Be} + e^- & \rightarrow & {}^7\mathrm{Li} + \nu_e & (0.38,\ 0.86\ \mathrm{MeV}) \\
 & {}^7\mathrm{Li} + p & \rightarrow & {}^8\mathrm{Be} + \gamma & \\
 & {}^8\mathrm{Be} & \rightarrow & 2\ {}^4\mathrm{He} & \\
\text{pp-III :} & {}^3\mathrm{He} + {}^4\mathrm{He} & \rightarrow & {}^7\mathrm{Be} + \gamma & \\
 & {}^7\mathrm{Be} + p & \rightarrow & {}^8\mathrm{B} + \gamma & \\
 & {}^8\mathrm{B} & \rightarrow & {}^8\mathrm{Be} + e^+ + \nu_e & (\leq 14.6\ \mathrm{MeV}) \\
 & {}^8\mathrm{Be} & \rightarrow & 2\ {}^4\mathrm{He} &
\end{array}
$$

CNO cycle

$$
\begin{aligned}
{}^{12}\mathrm{C} + p &\rightarrow {}^{13}\mathrm{N} + \gamma \\
{}^{13}\mathrm{N} &\rightarrow {}^{13}\mathrm{C} + e^{+} + \nu_e \qquad (\leq 1.2\ \mathrm{MeV}) \\
{}^{13}\mathrm{C} + p &\rightarrow {}^{14}\mathrm{N} + \gamma \\
{}^{14}\mathrm{N} + p &\rightarrow {}^{15}\mathrm{O} + \gamma \\
{}^{15}\mathrm{O} &\rightarrow {}^{15}\mathrm{N} + e^{+} + \nu_e \qquad (\leq 1.7\ \mathrm{MeV}) \\
{}^{15}\mathrm{N} + p &\rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}
\end{aligned}
$$

OR

$$
\begin{aligned}
{}^{15}\mathrm{N} + p &\rightarrow {}^{16}\mathrm{O} + \gamma \\
{}^{16}\mathrm{O} + p &\rightarrow {}^{17}\mathrm{F} + \gamma \\
{}^{17}\mathrm{F} &\rightarrow {}^{17}\mathrm{O} + e^{+} + \nu_e \qquad (\leq 1.7\ \mathrm{MeV}) \\
{}^{17}\mathrm{O} + p &\rightarrow {}^{14}\mathrm{N} + {}^{4}\mathrm{He}
\end{aligned}
$$

RESULTS

EXPT:	CHLORINE	GALLIUM	SK	SNO
Threshold (MeV)	0.834	0.233	5	5
R	**0.33 ± 0.03**	**.55 ± 0.03**	**0.465 ± 0.015**	**0.36 ± 0.015**
			(0.36 ± 0.015)*	**(1.0 ± 0.1)****

R = (Measured neutrino flux) / (Predicted model neutrino flux)

* Neutral current corrected neutrino flux

** Total neutrino flux measured by neutral current reaction

HELIOSEISMOLOGY

Sun continually shakes and rings: its entire surface churns like an ocean, undergoing mechanical vibrations. These are seismic waves generated through bulk of the solar body which carry information about the physical conditions within.

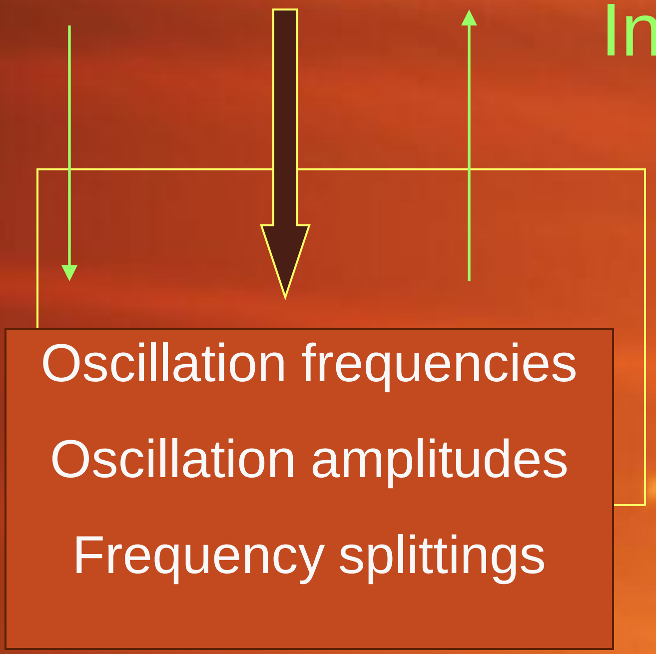
Analogous to geoseismology, it is possible to infer from the frequencies of solar oscillations the sound speed, density, composition and rotation profiles through practically most of the solar interior.

HELIOSEISMOLOGY

Solar structure and dynamics

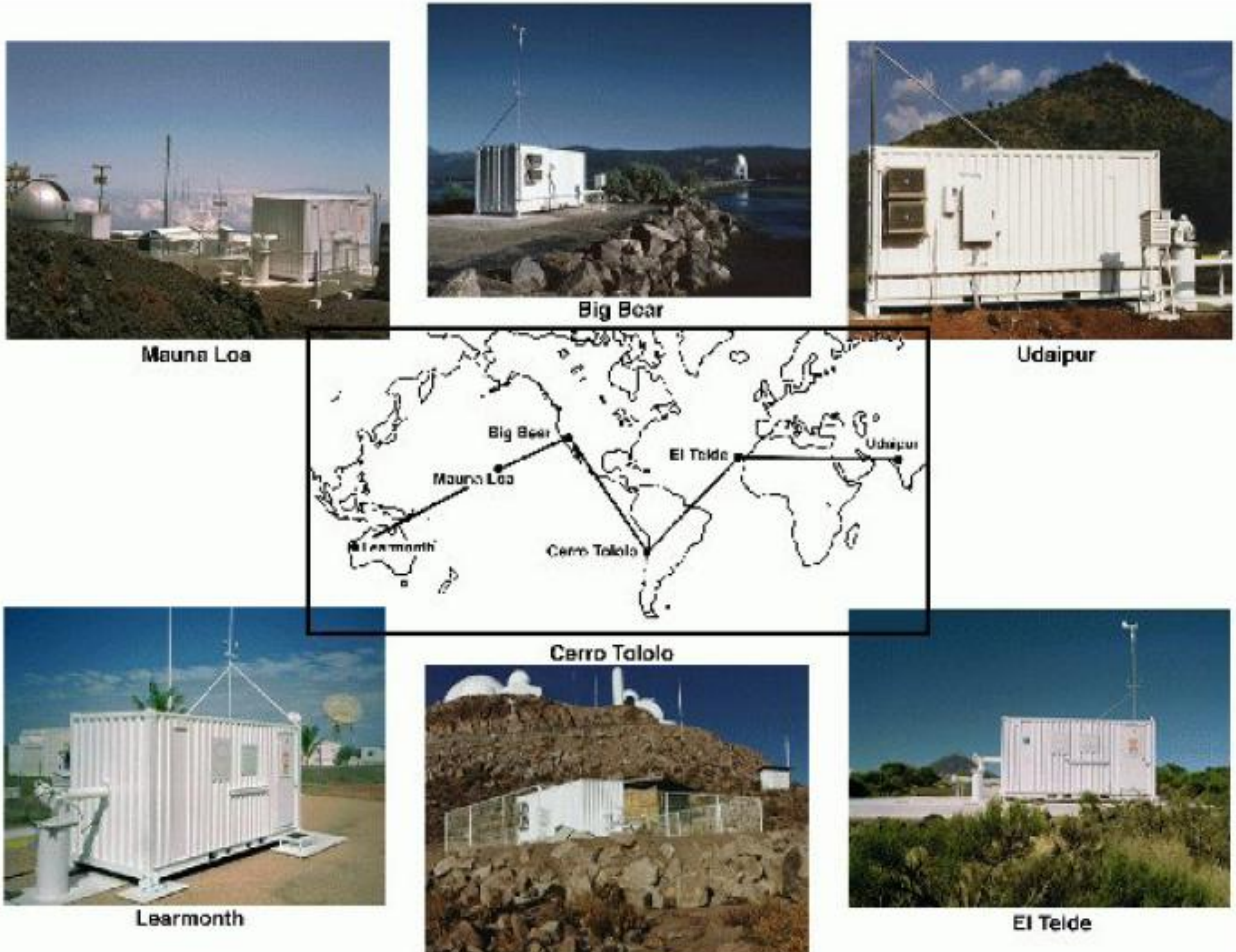
Forward method

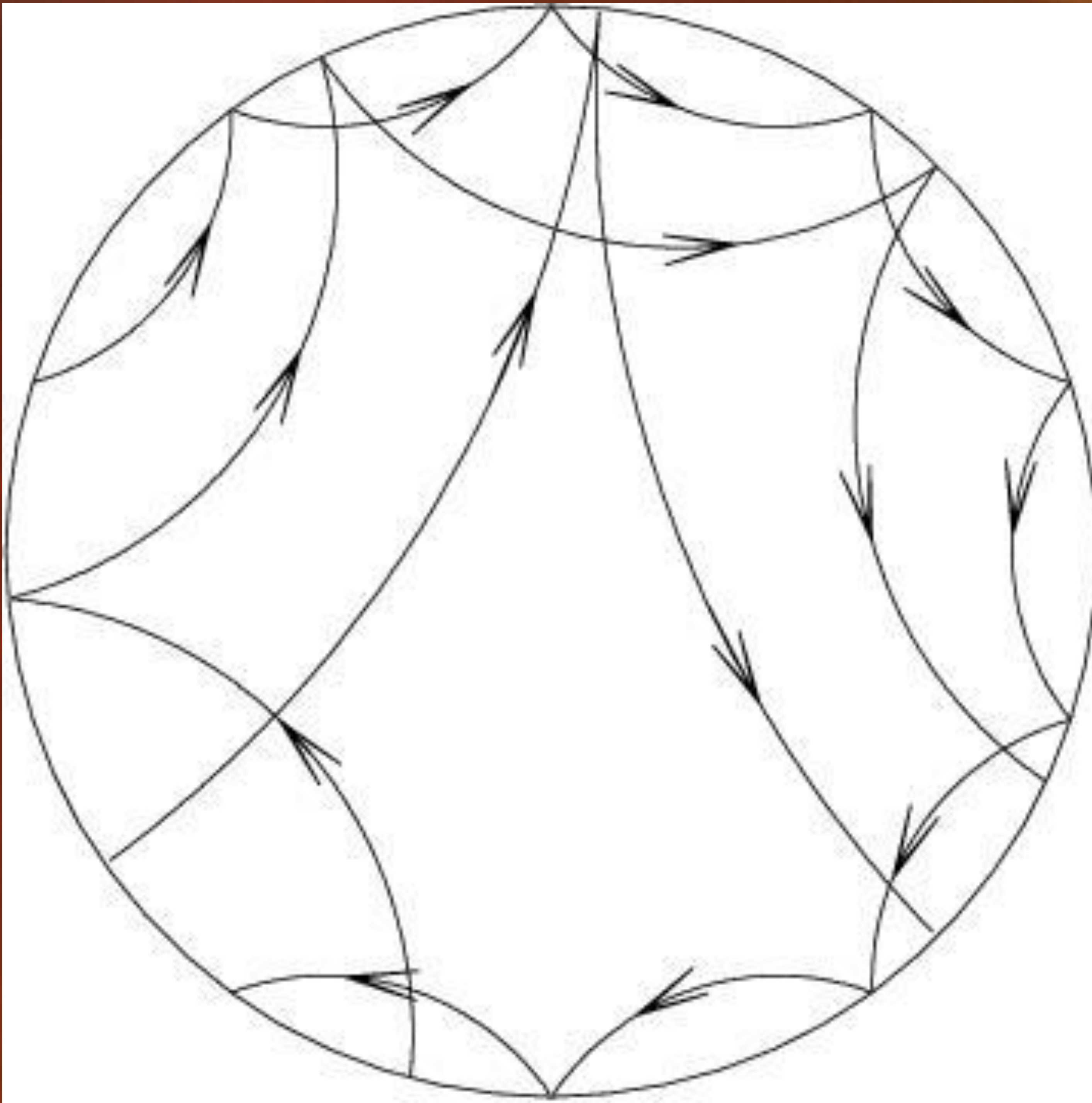
Inverse method

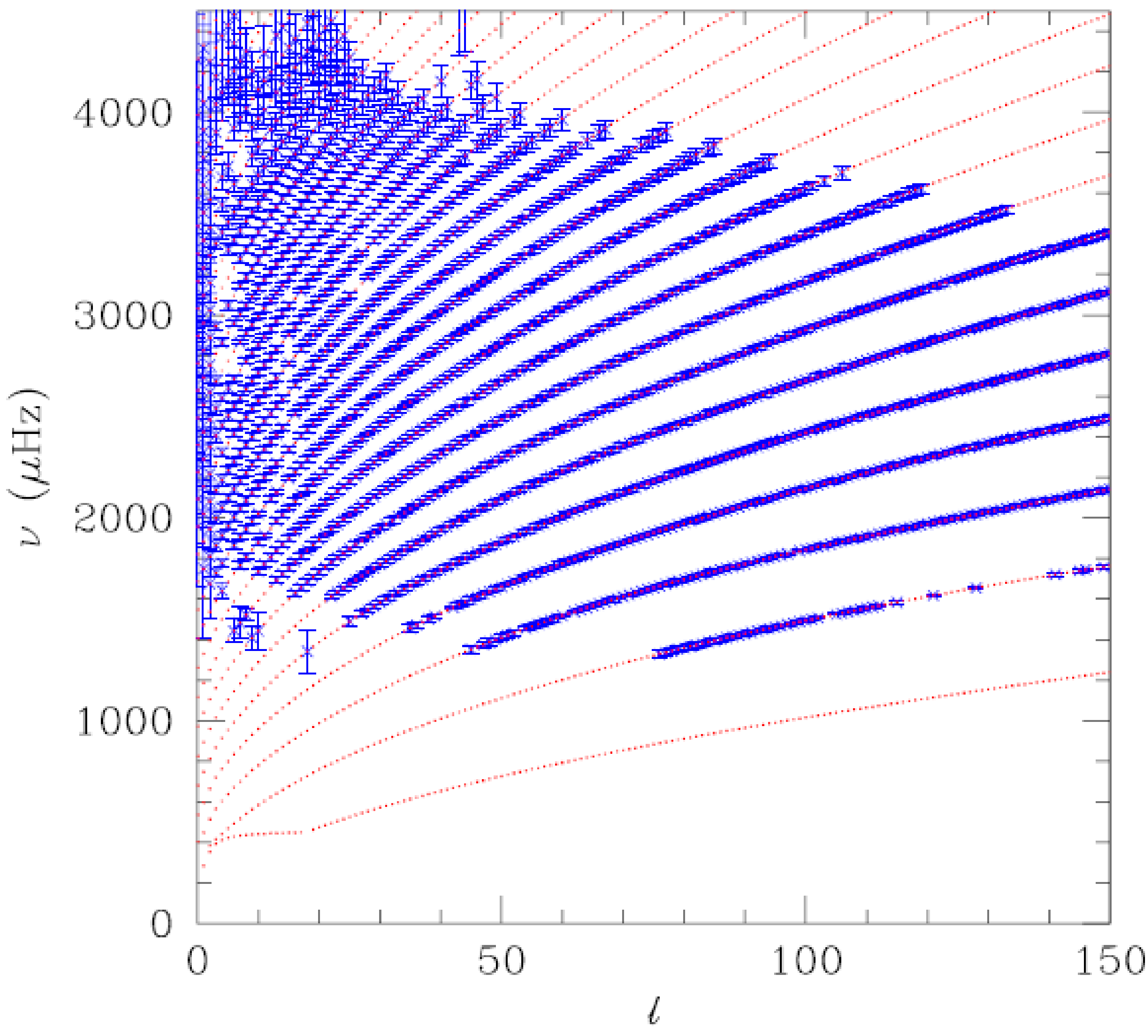


$f(r,\theta,\phi,t) = f(r)\, Y_l^m(\theta,\phi)\, e^{i\omega t}$ (Spherical geometry)

Degree (l), Azimuthal order (m), Radial order (n)


Mauna Loa
Big Bear
Udaipur
Big Bear
El Teide
Udaipur
Mauna Loa
Learmonth
Cerro Tololo
Cerro Tololo
Learmonth
El Teide





4000
3000
2000
1000
0
ν (μHz)
0
50
100
150
ℓ

INVERSION

Using equations of mechanical equilibrium

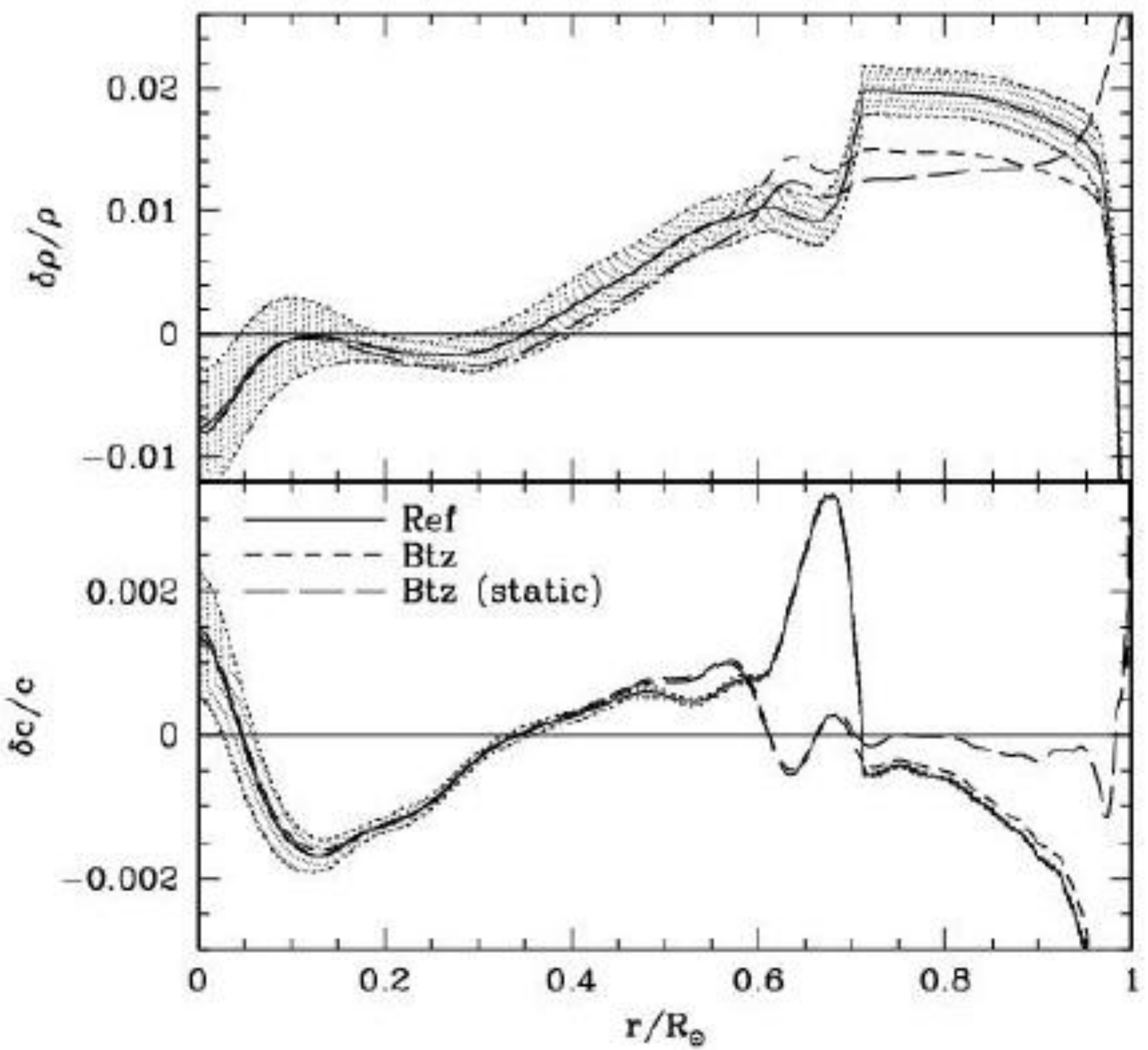
$$\frac{\delta\nu_{n\ell}}{\nu_{n\ell}} = \int_0^R \mathcal{K}^{n\ell}_{c^2,\rho}(r)\frac{\delta c^2}{c^2}(r)\, dr + \int_0^R \mathcal{K}^{n\ell}_{\rho,c^2}(r)\frac{\delta\rho}{\rho}(r)\, dr + \frac{F(\nu_{n\ell}}{E_{n\ell}}$$

where

$$E_{n\ell} = \frac{4\pi \int_0^R (|\xi(r)|^2 + \ell(\ell+1)|\eta(r)|^2)\rho_0 r^2\, dr}{M(|\xi(R_\odot)|^2 + \ell(\ell+1)|\eta(R_\odot)|^2)} ,$$

$F(\nu_{n\ell})$ is surface term

$\mathcal{K}^{n\ell}(r)$ are the kernels



0.02
0.01
δρ/ρ
0
−0.01
Ref
Btz
Btz (static)
0.002
δc/c
0
−0.002
0
0.2
0.4
0.6
0.8
1
r/R⊙

CONSTANT SUN

No significant temporal variation detected over a solar cycle in

- Sound speed, density in the Sun's interior
- Depth of the convection zone
- Extent of overshoot beneath convection zone
- Solar radius!
- Solar oblateness (Quadrupole moment)
- Position and thickness of the tachocline

INVERSION RESULTS

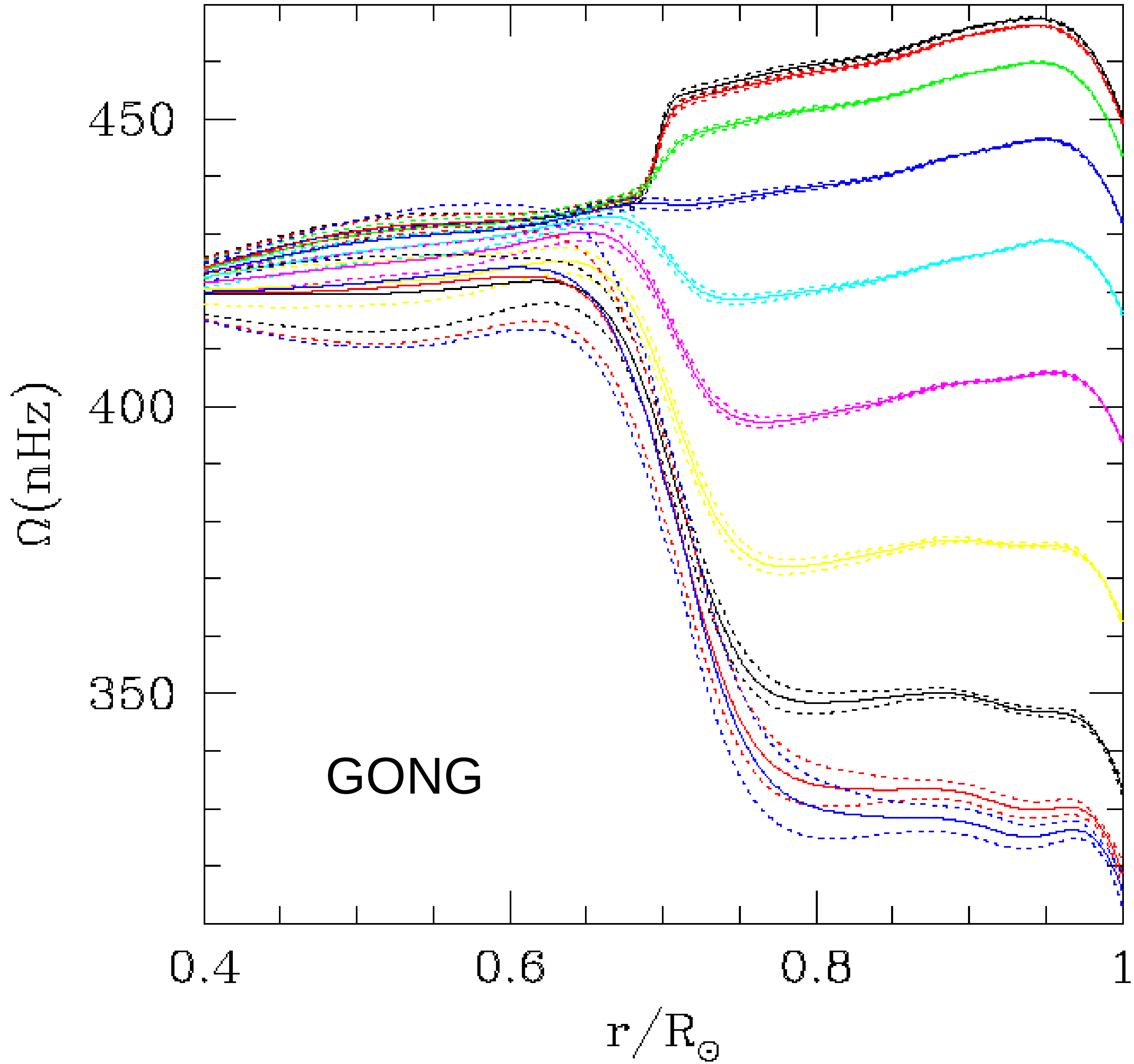
- Thickness of the convection zone $(0.2865 \pm 0.0005)R_\odot$
- Abundance of helium in solar envelope 0.249 ± 0.003
- Significant ($\approx 15\%$) increase in opacity values near base of the convection zone
- Central temperature of the Sun $(15.6 \pm 0.4) \times 10^6$ K
- Extent of overshoot beneath convection zone < 0.05 (local pressure scale-height)

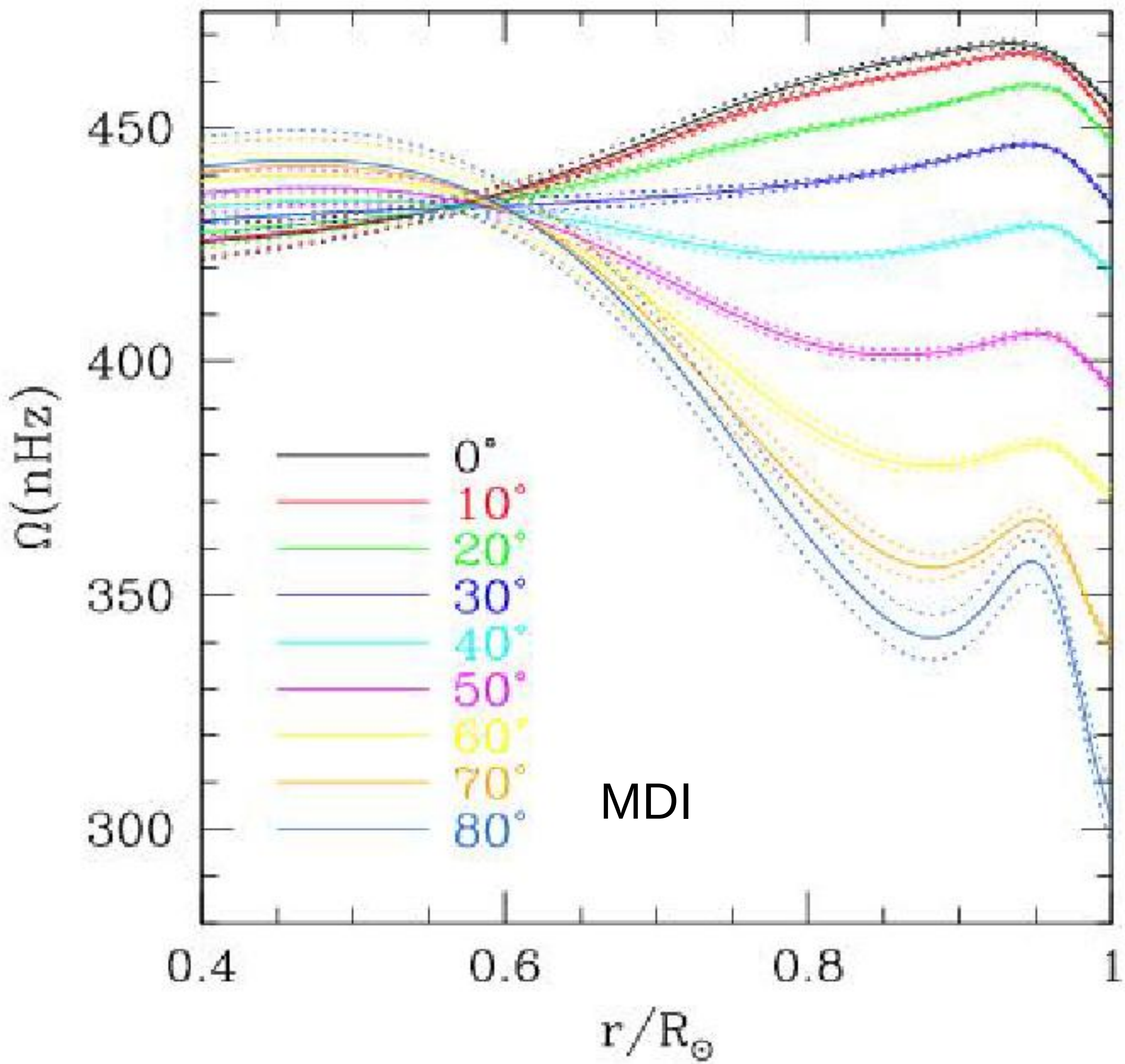
Rotation rate in the solar interior

- Rotational splittings can be inverted to calculate the rotation rate $\Omega(r,\theta)$. Only odd order splitting coefficients are required.

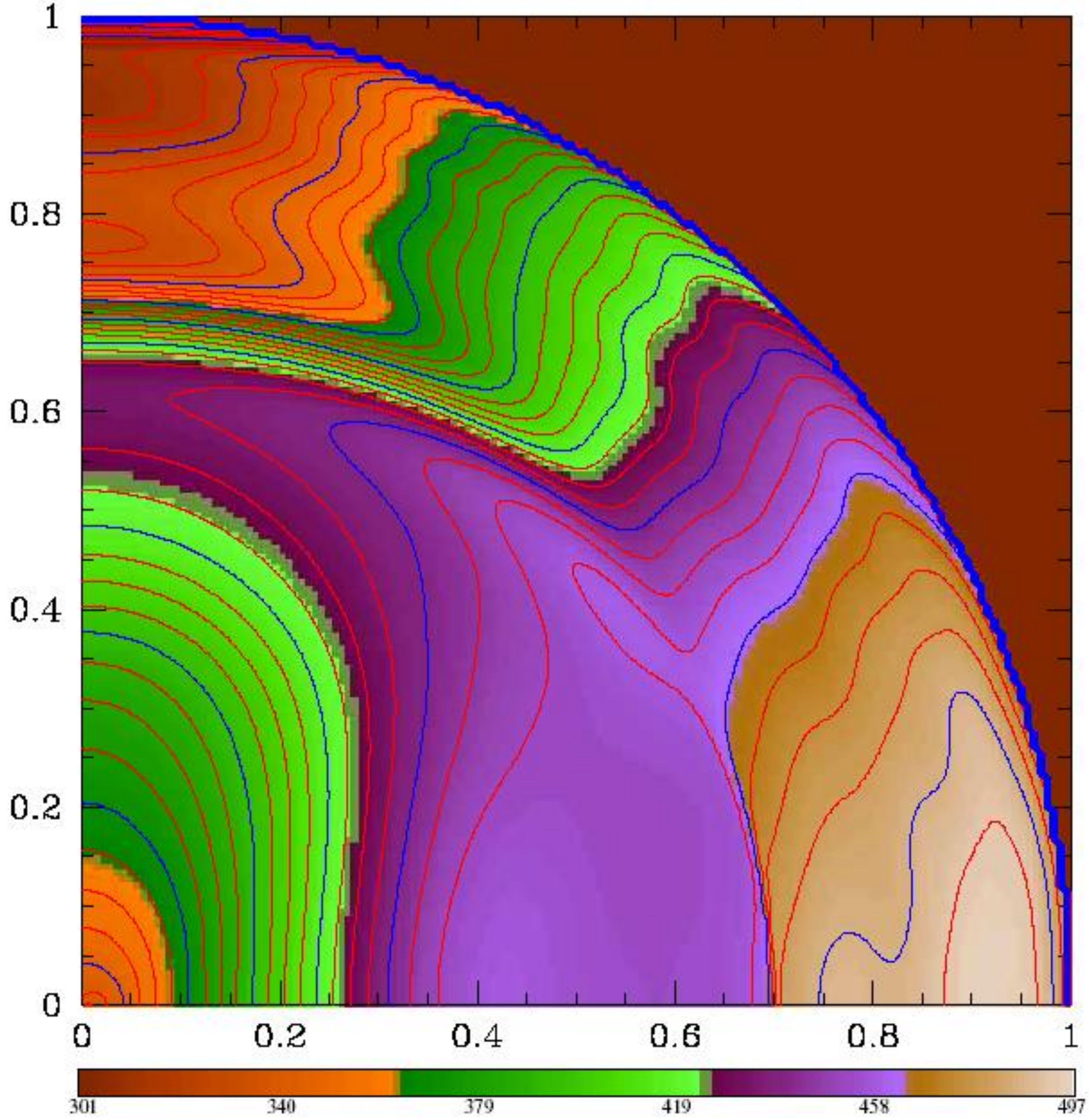
- Rotational splittings are related by

$$D_{n\ell m} = \frac{\nu_{n\ell m} - \nu_{n\ell -m}}{2m} = \int_0^1 \int_0^1 dr\, d\cos\theta\, K_{n\ell m}(r,\theta)\Omega(r,\theta)$$


450
400
350
Ω(nHz)
GONG
0.4
0.6
0.8
1
r/R⊙



450
400
350
300
0.4
0.6
0.8
1
Ω(nHz)
r/R⊙
0°
10°
20°
30°
40°
50°
60°
70°
80°
MDI



1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
301
340
379
419
458
497

RESULTS

- Radial & latitudinal rotation rate profile through the solar interior implying presence of sub-surface shear layer, the tachocline and nearly uniformly rotating radiative interior) solar oblateness = -5.8×10^{-6} and solar quadrupole moment = $(2.18 \pm 0.06) \times 10^{-7}$

- Precession of perihelion of Mercury’s orbit amounting to 0.03 arcsecond per century

CONSTANT SUN

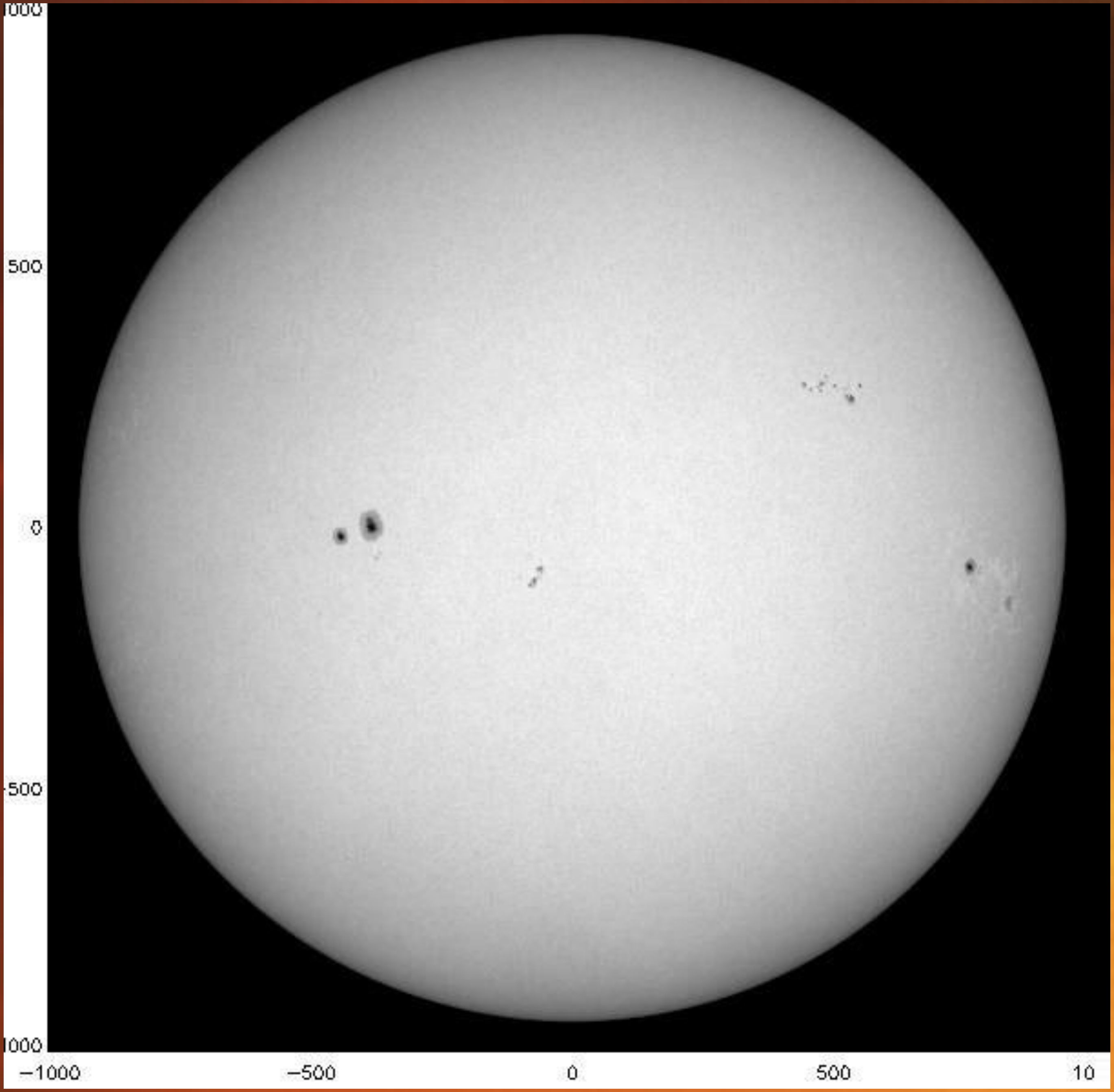
No significant temporal variation detected over a solar cycle in

- Sound speed, density in the Sun’s interior
- Depth of the convection zone
- Extent of overshoot beneath convection zone
- Solar radius!
- Solar oblateness (Quadrupole moment)
- Position and thickness of the tachocline

INCONSTANT SUN

Significant temporal variations observed with solar activity cycle in

- Sunspot number
- Kitt Peak magnetic index
- Total flare index
- 10.7 cm radio flux
- Mg II core-to-wing ratio
- p-mode & f-mode oscillation frequencies
- Rotation rate in bulk of the convection zone: Zonal bands of slower and faster than average rotation
- Solar R.M.S. magnetic fields
- Solar irradiance
- Coronal line intensity
- Coronal mass ejection rate and speed



1000
500
0
-500
1000
−1000
−500
0
500
10

SOLAR ACTIVITY CYCLE

Sunspots - probably the best known example of solar activity cycle

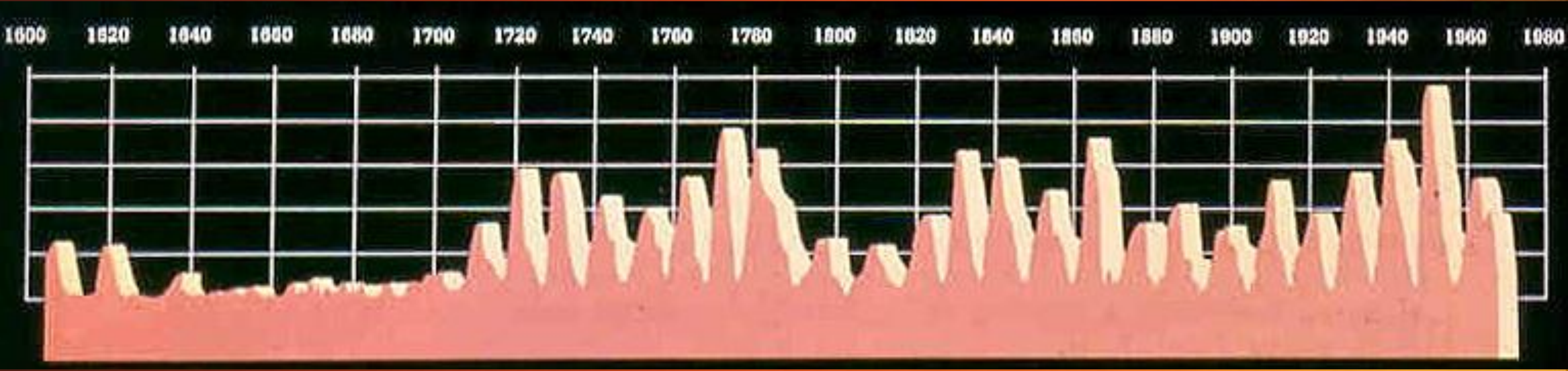
:First observed by Chinese astronomers over 2000 years ago ,but systematically studied by Galileo in 1610 after invention of telescope. Two centuries later Schwabe (1843) discovered 11-year cyclic variation of sunspot numbers and later Carrington(1858) noted gradual drift of spots from mid-latitudes towards the equator.

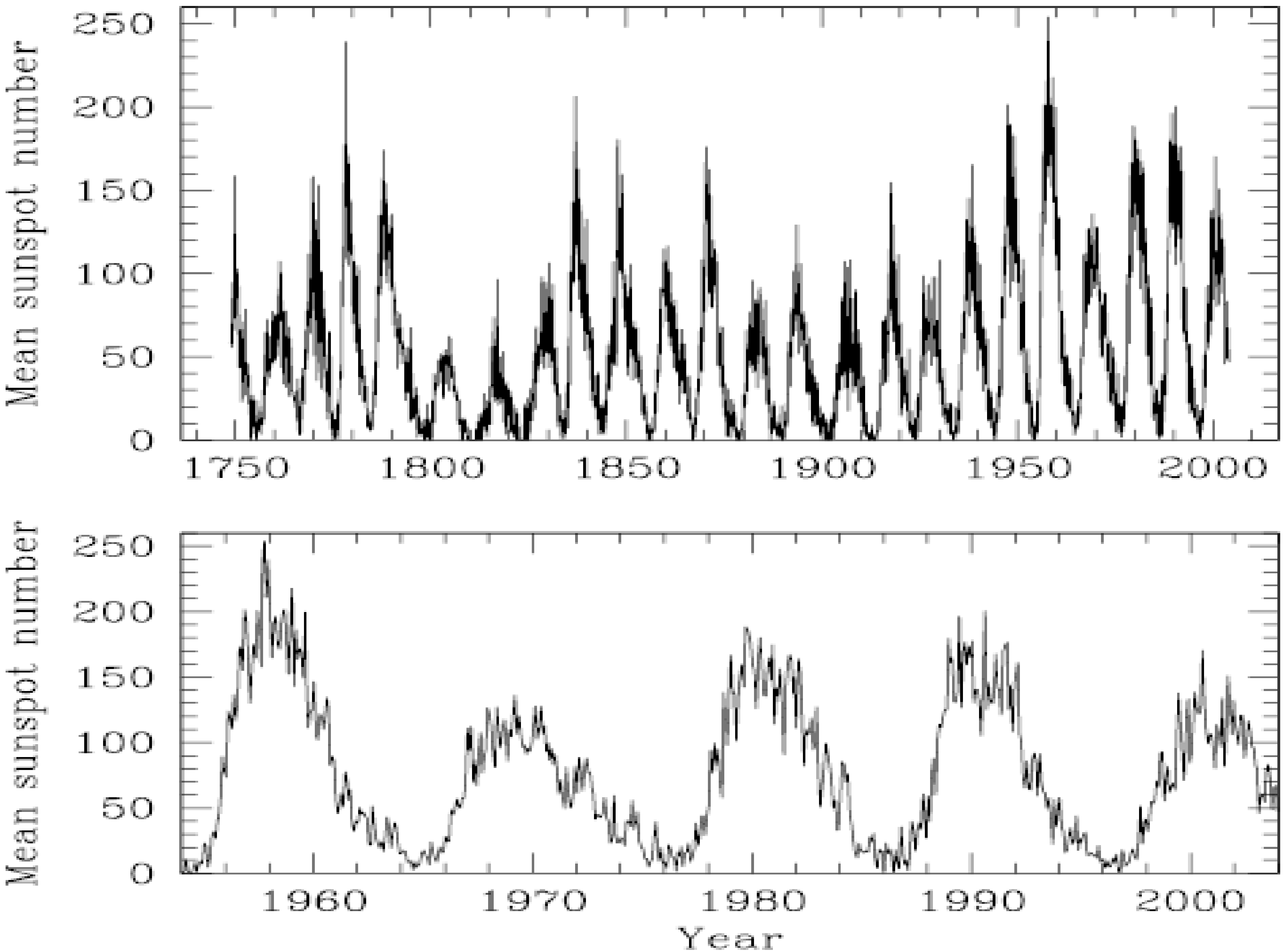
* Sunspot number on solar disc varies with period of 8 to12 years

* Average number of spots at peak of activity ranging from 100 to 200 with period and amplitude changing from cycle to cycle

*Alternation of magnetic polarities in successive cycles-reversal of global magnetic field of the Sun with approximate period of 22 years

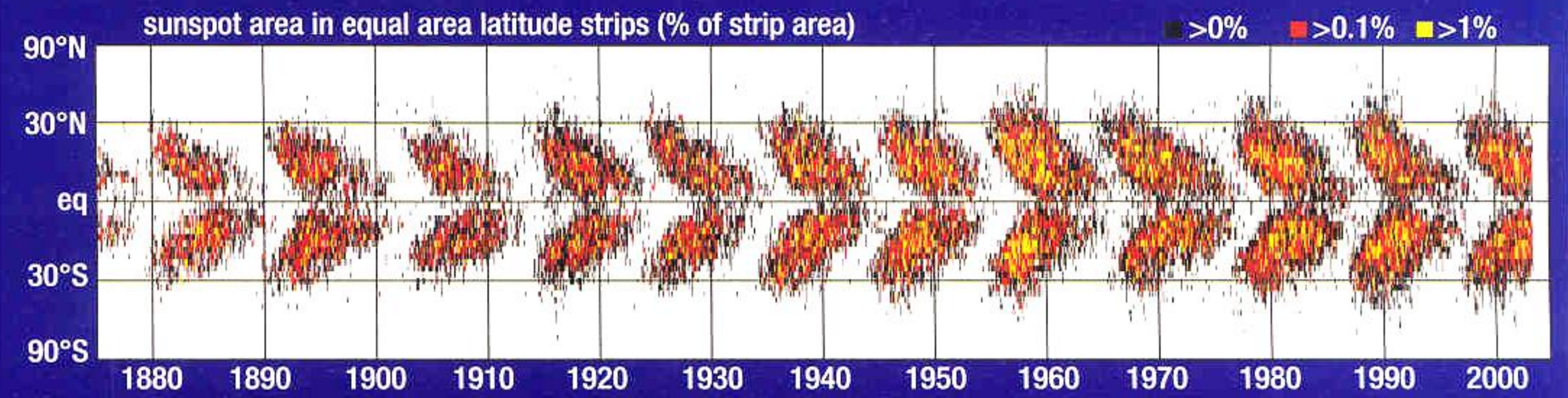
Sunspot number vs. time





Mean sunspot number
250
200
150
100
50
0
1750
1800
1850
1900
1950
2000
Mean sunspot number
250
200
150
100
50
0
1960
1970
1980
1990
2000
Year

Butterfly Diagram

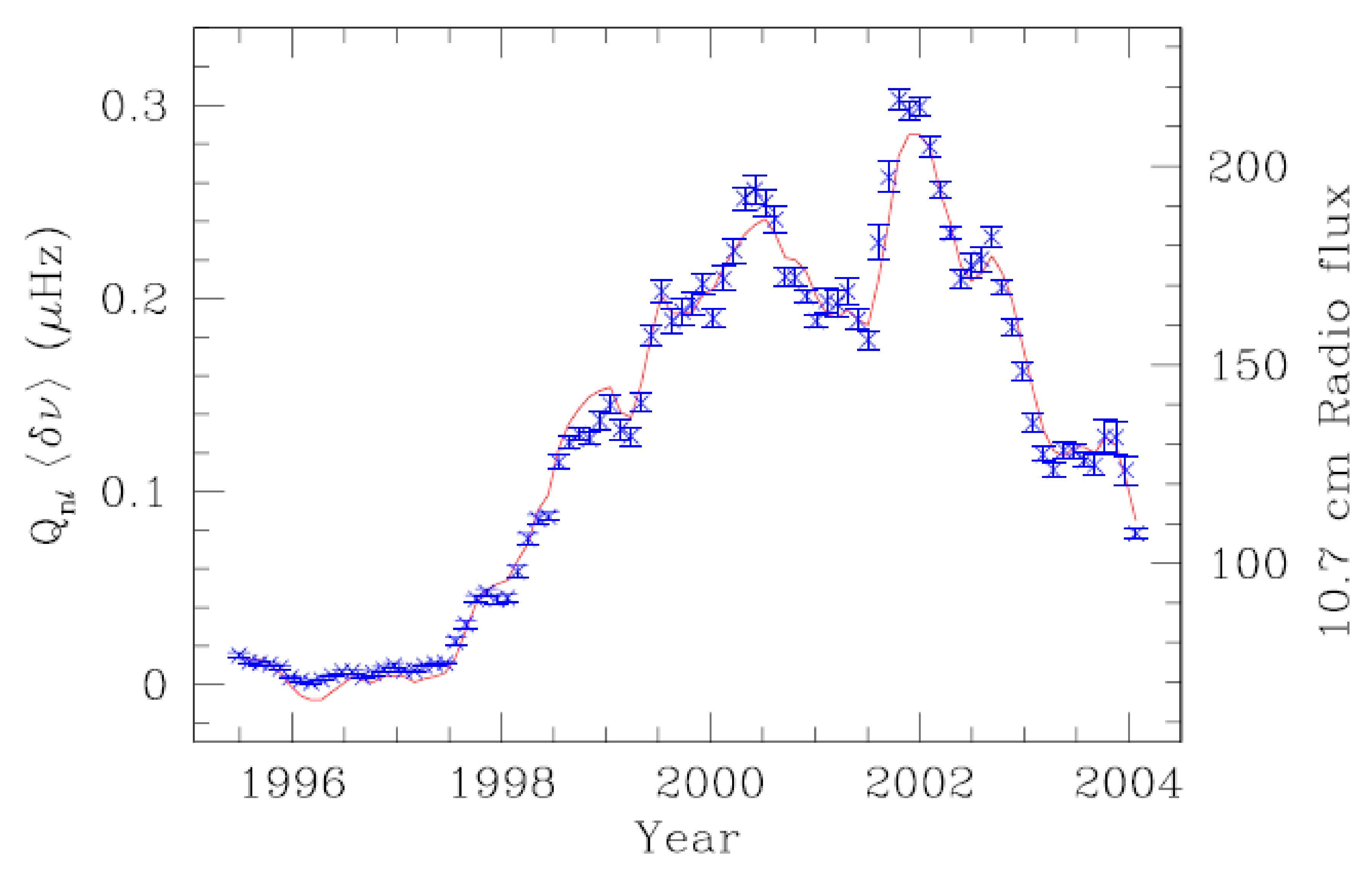


1: The butterfly diagram: a latitude versus time plot of the sites where sunspots appear. At the start of each cycle, sunspots emerge at mid-latitudes. As the cycle progresses, the locations where emerging spots appear move towards the equator. After about 11 years the magnetic field reverses and the sunspots reappear at higher latitudes. (Courtesy D H Hathaway, NASA/NSSTC.)

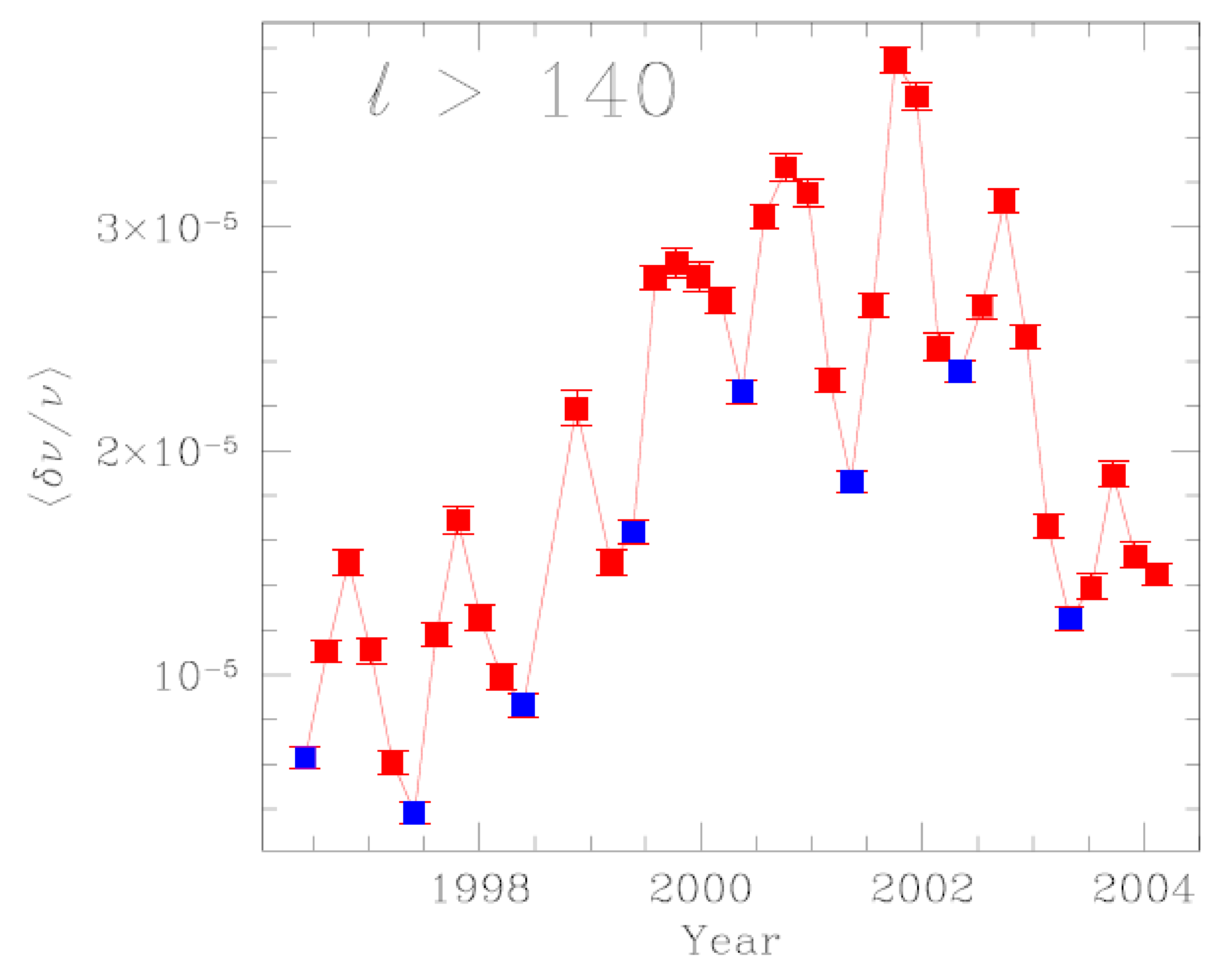
SOLAR CYCLE

Solar activity cycle manifests most strikingly through number of spots on the solar surface varying with an approximate period of 11 years.

Likely to be driven by the interaction between Sun's differential rotation, magnetic field and convection/ circulation!



0.3
0.2
0.1
0
$Q_{nl}\ \langle\delta\nu\rangle\ (\mu Hz)$
200
150
100
10.7 cm Radio flux
1996
1998
2000
2002
2004
Year



l > 140
3×10⁻⁵
2×10⁻⁵
10⁻⁵
⟨δν/ν⟩
1998
2000
2002
2004
Year

f-mode variation can be resolved into 2 components:

- Oscillatory component with ~ 1 year period

- Slowly varying component correlated with solar activity cycle, probably caused by temporally varying RMS B ~20 G in the top ~4 Mm layer of the Sun. Thermal fluctuations at the solar surface unlikely to account for observed f-mode frequency shifts.

Temporal variation of p- & f-mode frequencies

- Frequency shifts in phase with solar cycle
- Steep frequency dependence with high-frequency modes (which are reflected near the surface) experiencing greater shifts than low-frequency modes (which are reflected in deeper layers)

$$\Downarrow$$

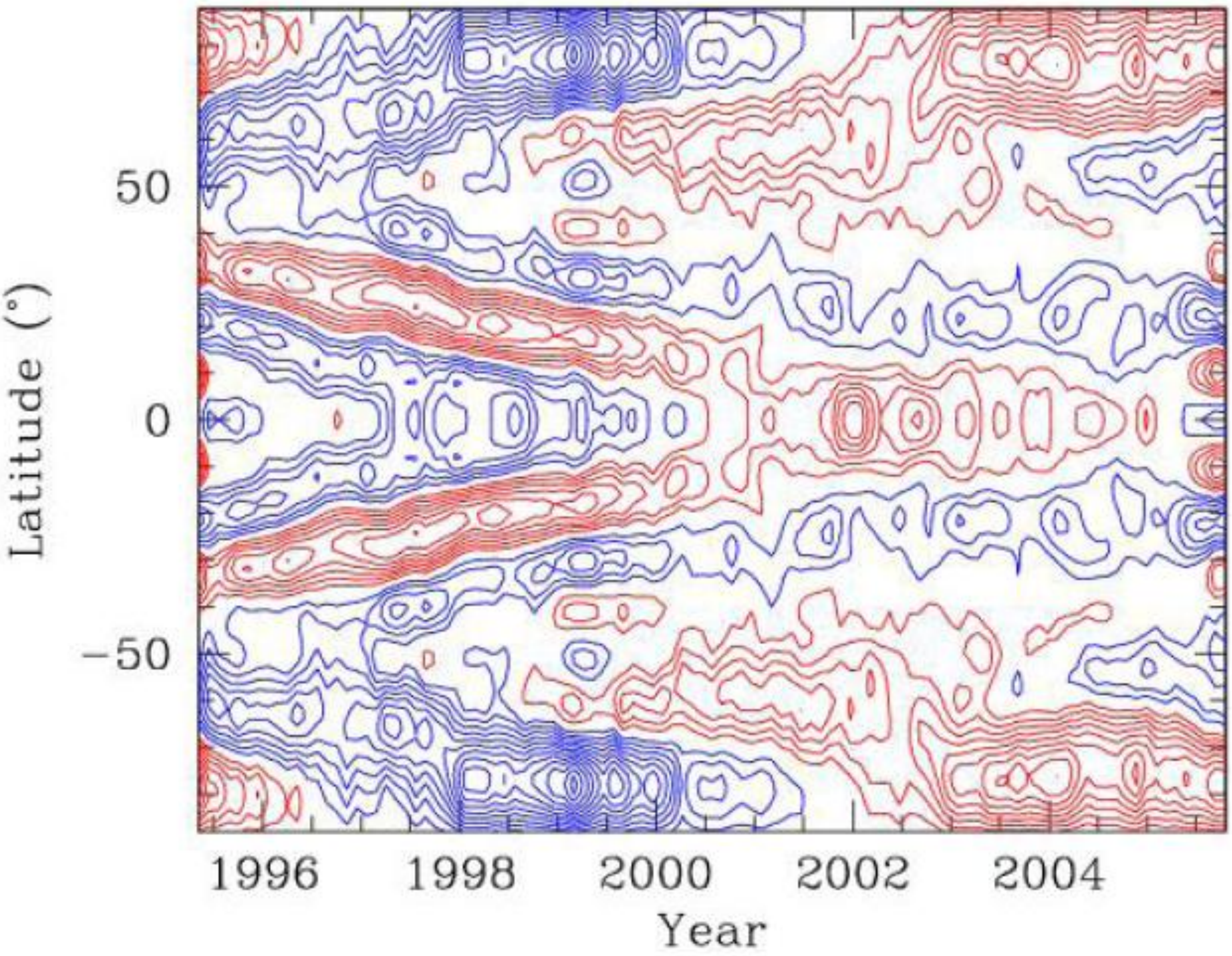
Likely cause: Time-dependent perturbations residing in near-surface layers (e.g., temporally varying magnetic fields)

SOLAR CYCLE VARIATION OF ROTATION RATE

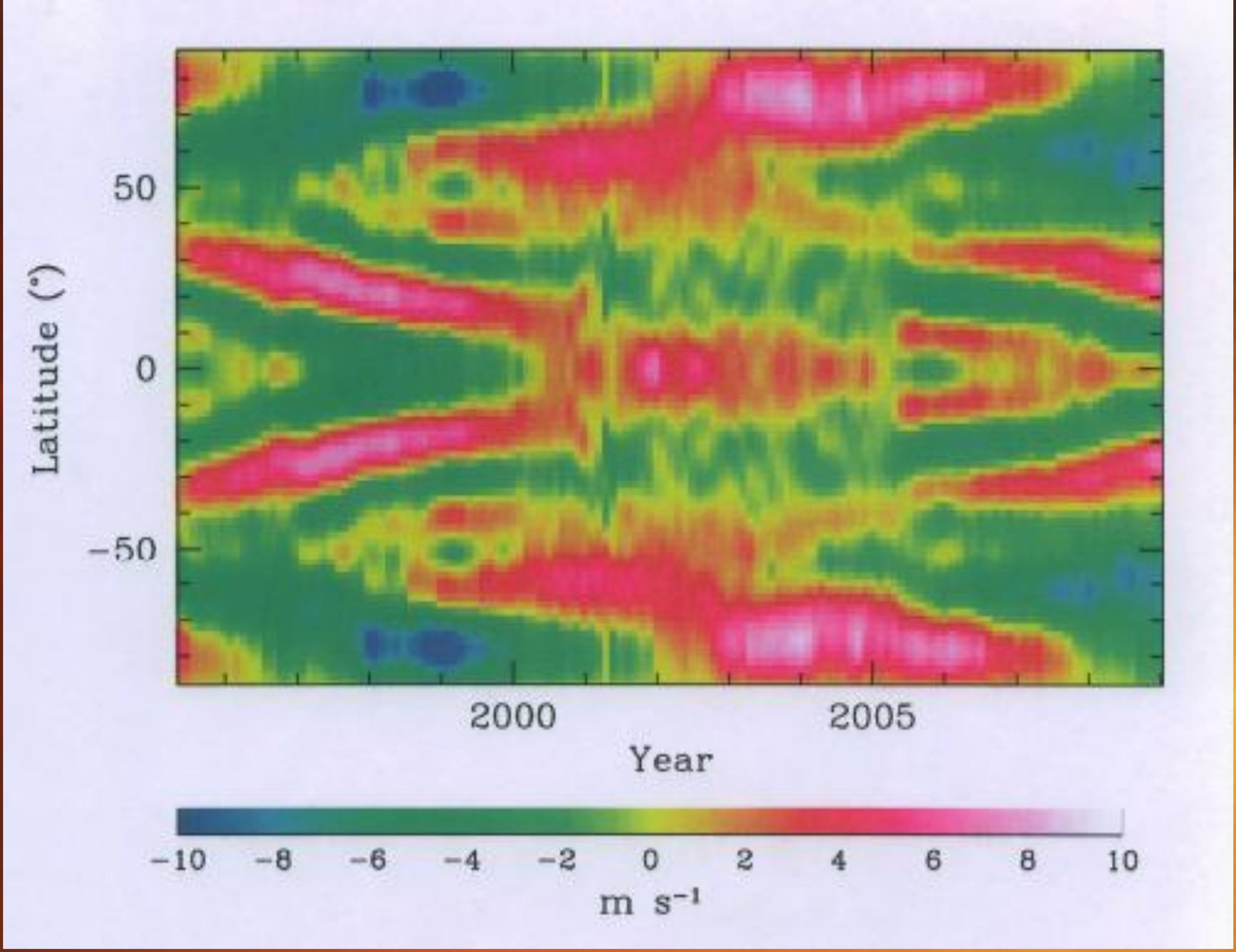
• Total change in rotation rate ~4 nHz (out of the average rotation rate ~450 nHz) over a solar cycle

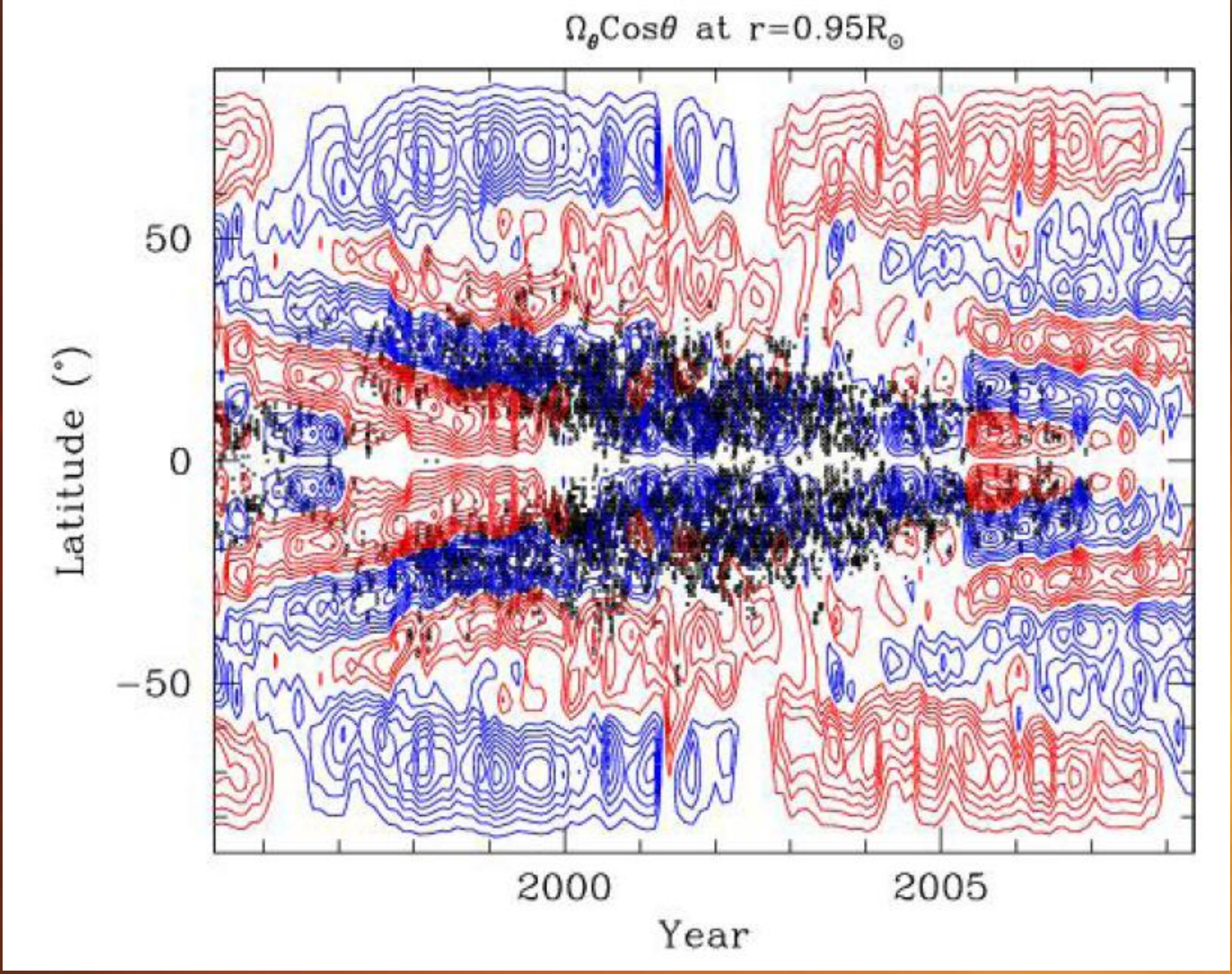
• ZONAL FLOWS:

Bands of faster — and slower — than average rotation rate with equatorial migration of low-latitude branch and strengthening drift of high-latitude branch of torsional oscillations with solar activity cycle, reminiscent of classical “butterfly diagram” for sunspots/ active regions and latitudinal drift of polar faculae, crown of polar prominences, magnetic neutral lines, filaments, . . .


50
0
−50
Latitude (°)
1996
1998
2000
2002
2004
Year

GONG

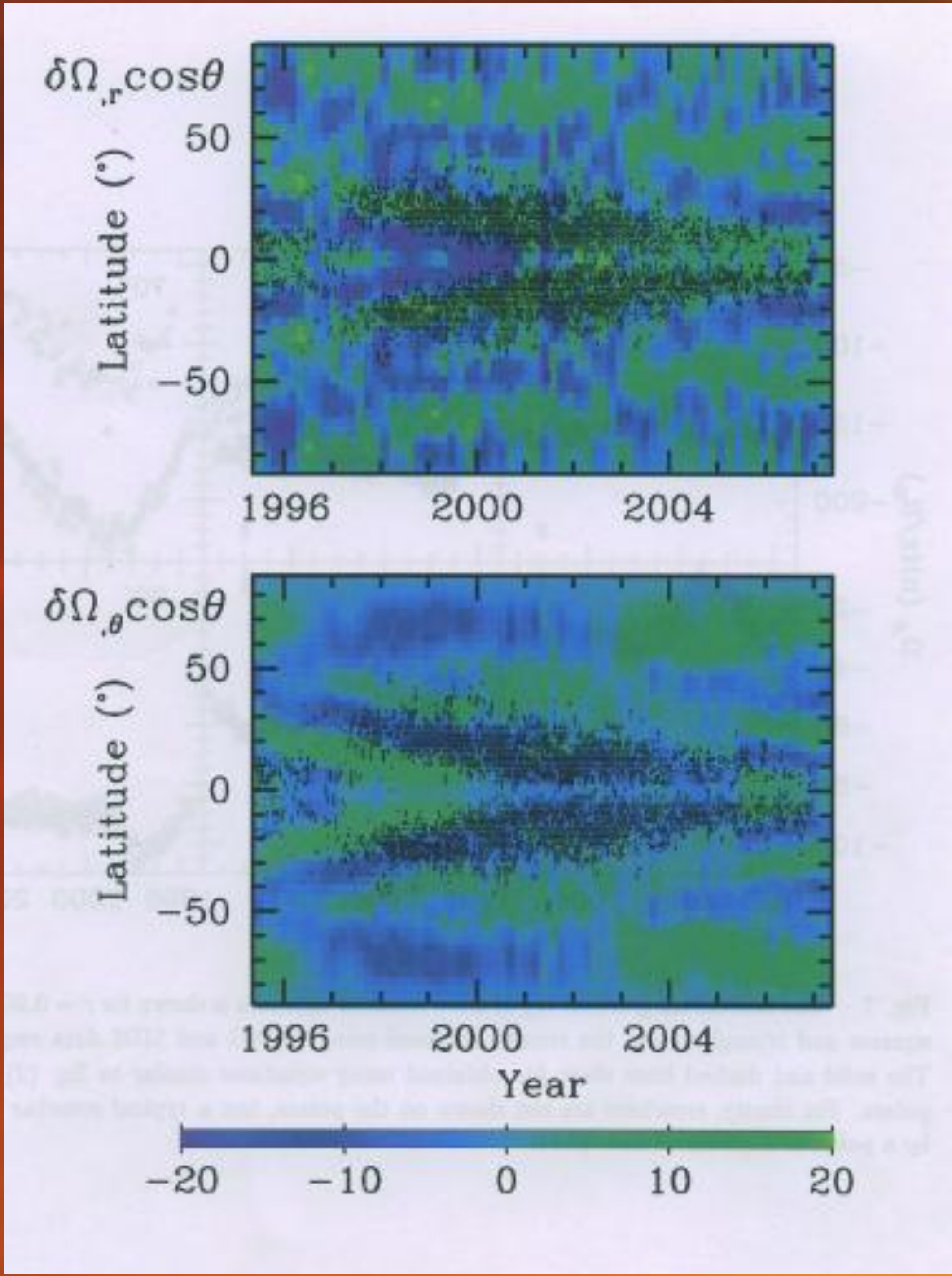




$\Omega_\theta \mathrm{Cos}\theta$ at $r=0.95R_\odot$
50
0
−50
Latitude (°)
2000
2005
Year

Radial Gradient

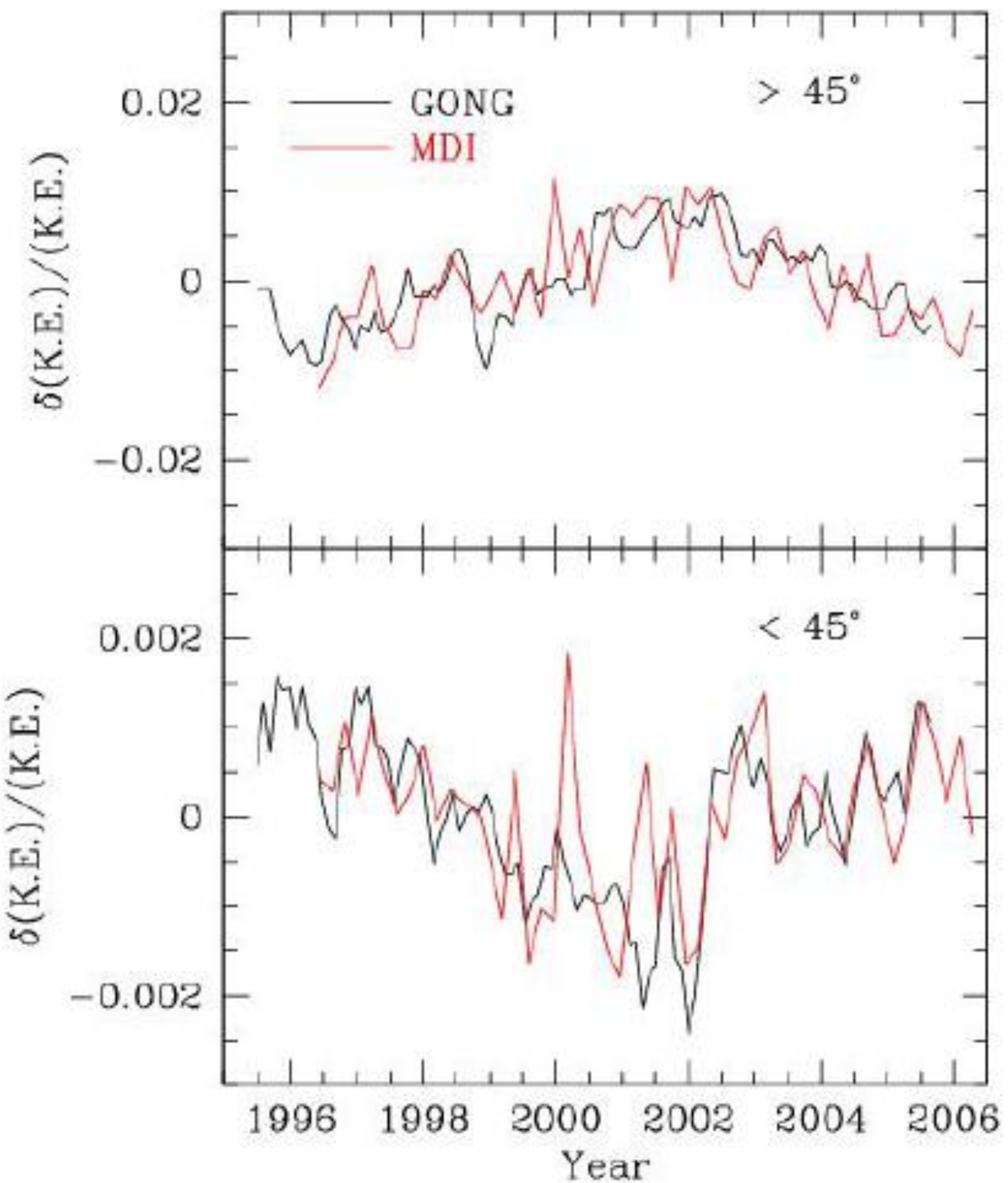
Lat. Gradient



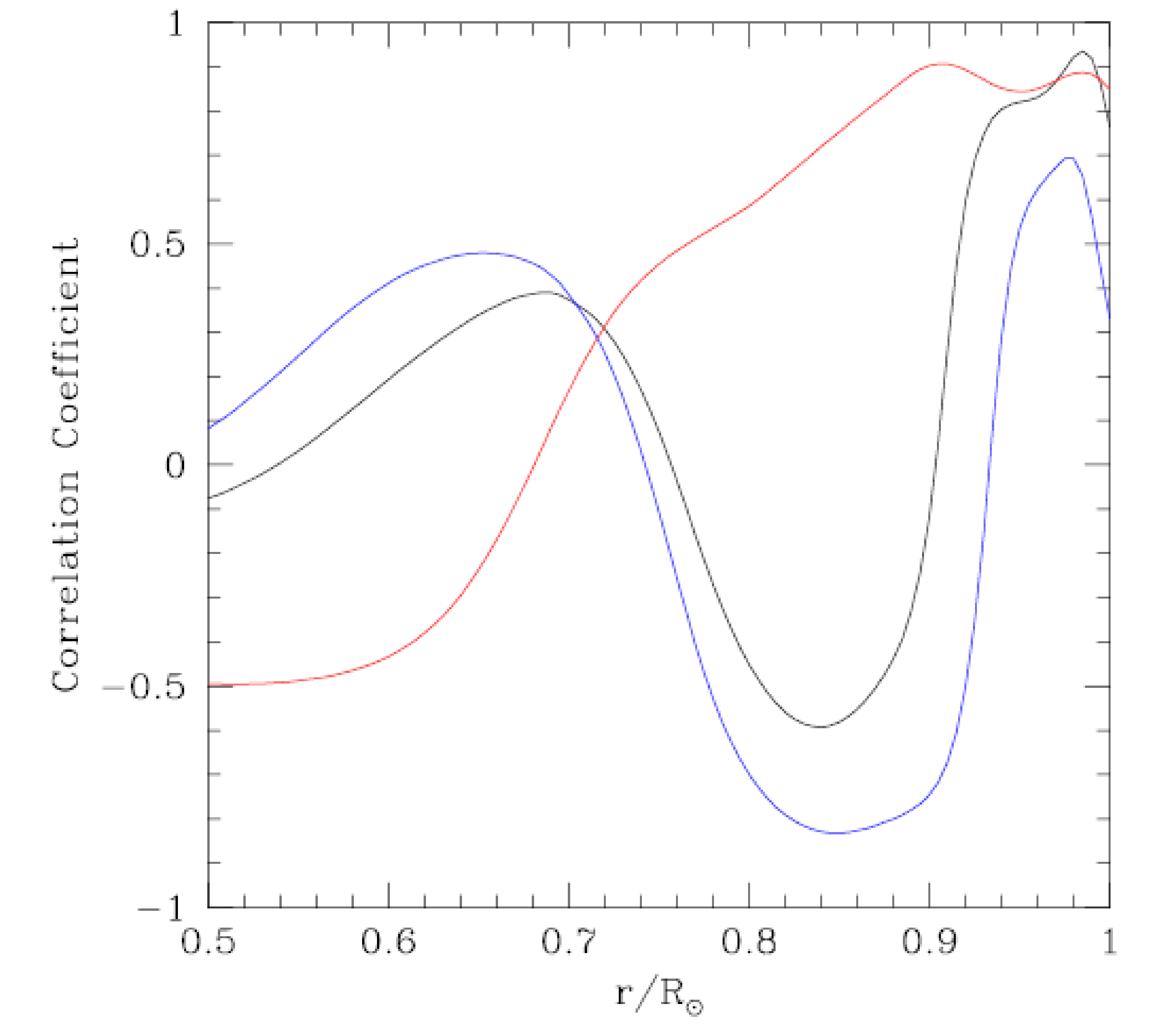
TEMPORAL VARIATION IN ROTATIONAL K. E.

- Relative variation in residual K. E. of rotation is about 0.1% of total rotational energy. Remarkably, relative variation in rotational K. E. in polar latitudes is an order of magnitude larger than that in equatorial latitudes

- Over bulk of the convection zone (0.7–1.0 $R_\odot$) residual K. E. of rotation at high latitudes is correlated with solar activity, while in low latitudes it is anticorrelated over the region 0.7–0.95 $R_\odot$.



GONG
MDI
> 45°
< 45°
0.02
0
−0.02
0.002
0
−0.002
δ(K.E.)/(K.E.)
δ(K.E.)/(K.E.)
1996
1998
2000
2002
2004
2006
Year



1
0.5
0
−0.5
−1
0.5
0.6
0.7
0.8
0.9
1
Correlation Coefficient
r/R⊙

Radial distribution of rotational kinetic energy and RMS magnetic fields

Radial Distance	**Rot K.E. (ergs)**	**RMS Mag. Field (G)**	**Thermal energy (ergs)**
$.99 < r/R_{\odot} \leq 1$	5.3×10^{37}	250	2×10^{41}
$.95 < r/R_{\odot} \leq .99$	6.5×10^{39}	1400	2.4×10^{43}
$.85 < r/R_{\odot} \leq .95$	9.3×10^{40}	3700	1.4×10^{45}
$.75 < r/R_{\odot} \leq .85$	2.0×10^{41}	6100	7.6×10^{45}
$.65 < r/R_{\odot} \leq .75$	2.6×10^{41}	7900	2.2×10^{46}

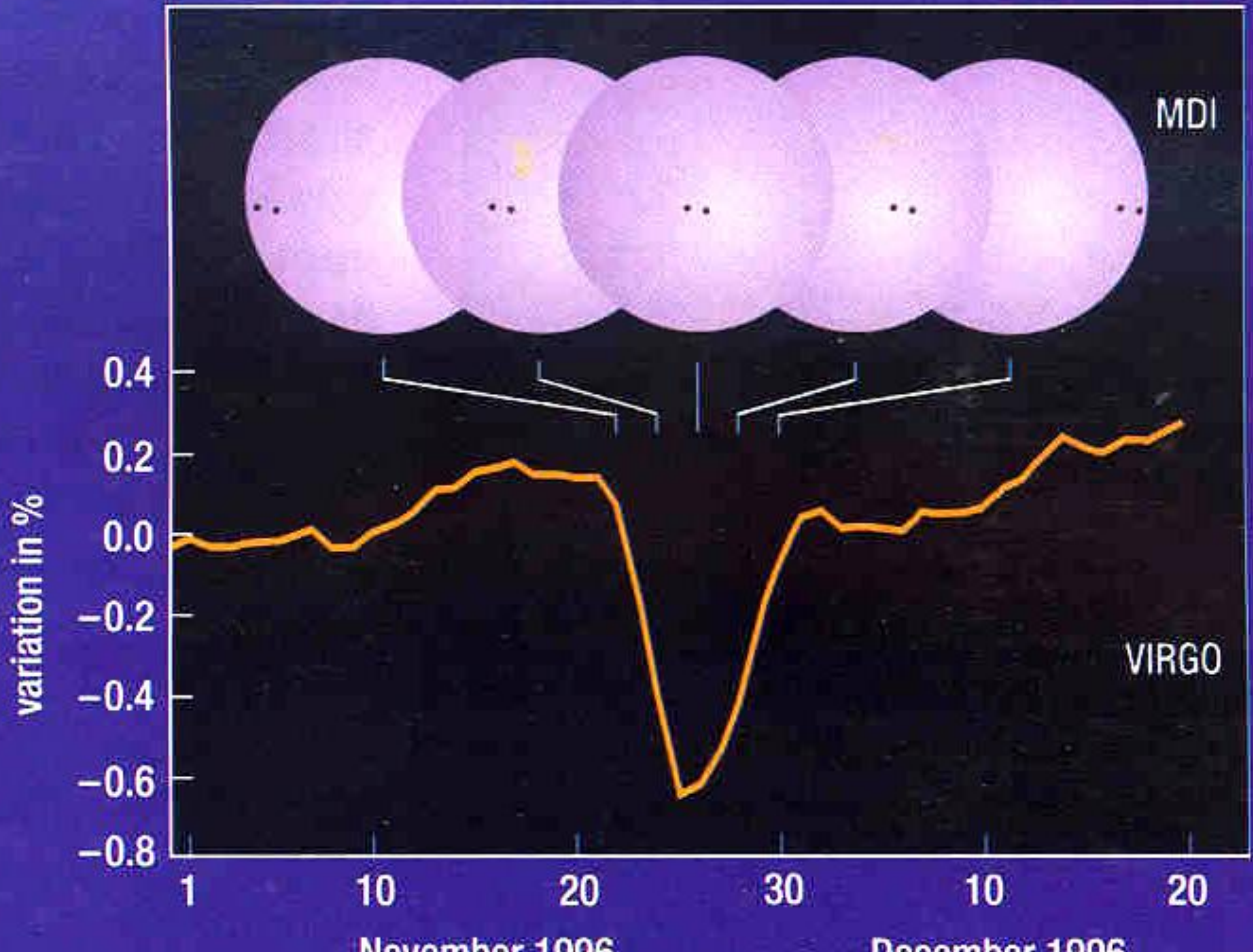
Over convection zone, amplitude of temporal variation in residual K. E. of rotation

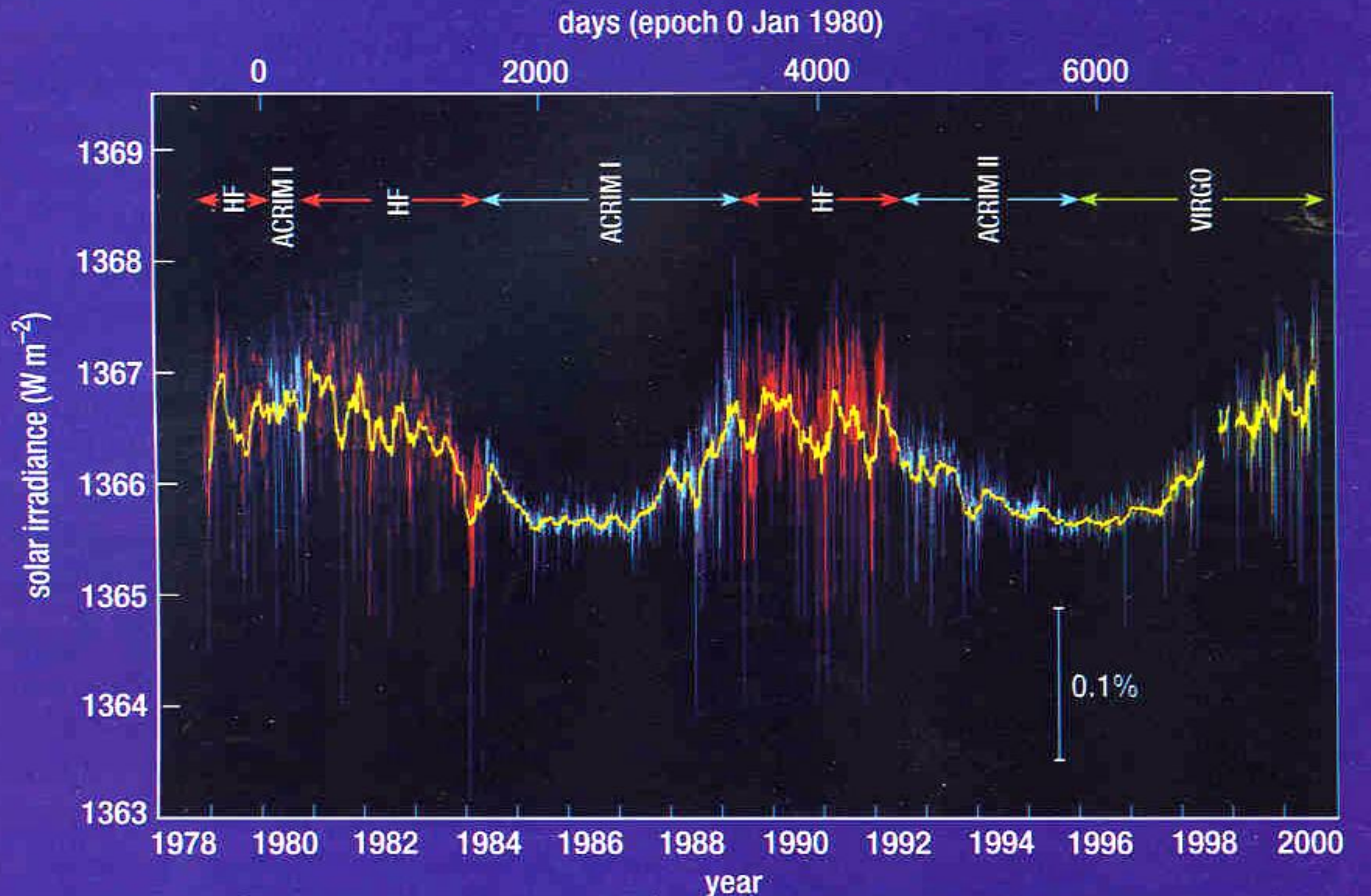
$$\delta T \approx 5 \times 10^{38}\ \text{erg}$$

During half the solar cycle, this would yield rate of variation

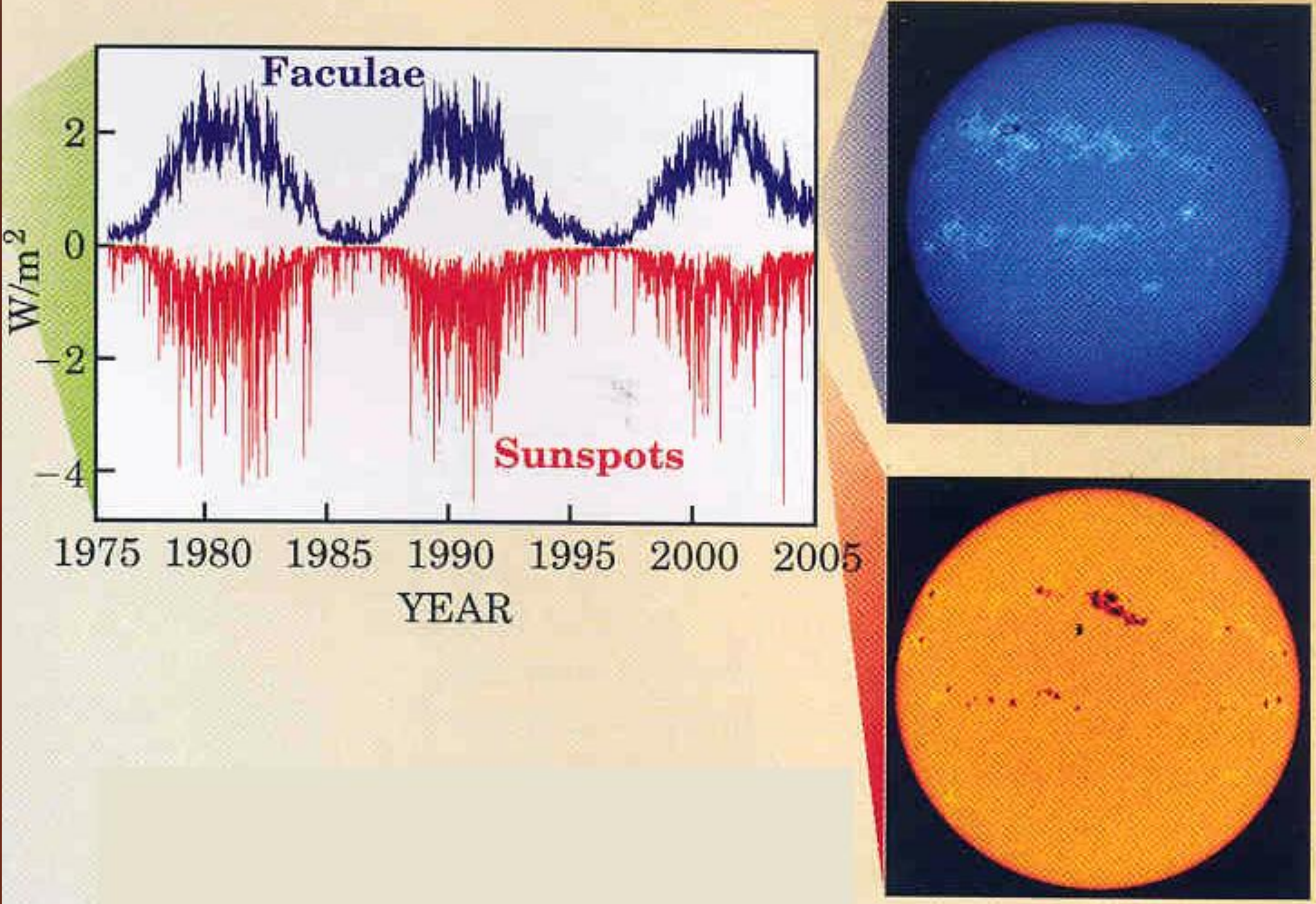
$$\frac{\delta T}{P} \approx 3 \times 10^{30}\ \text{erg s}^{-1} \approx 0.001 L_{\odot}$$

7: Dip in total solar irradiance measured by the VIRGO instrument on the SOHO spacecraft (orange curve). The face of the Sun in white light on five selected days during the dip is also shown. Note the sunspots on the solar disc.

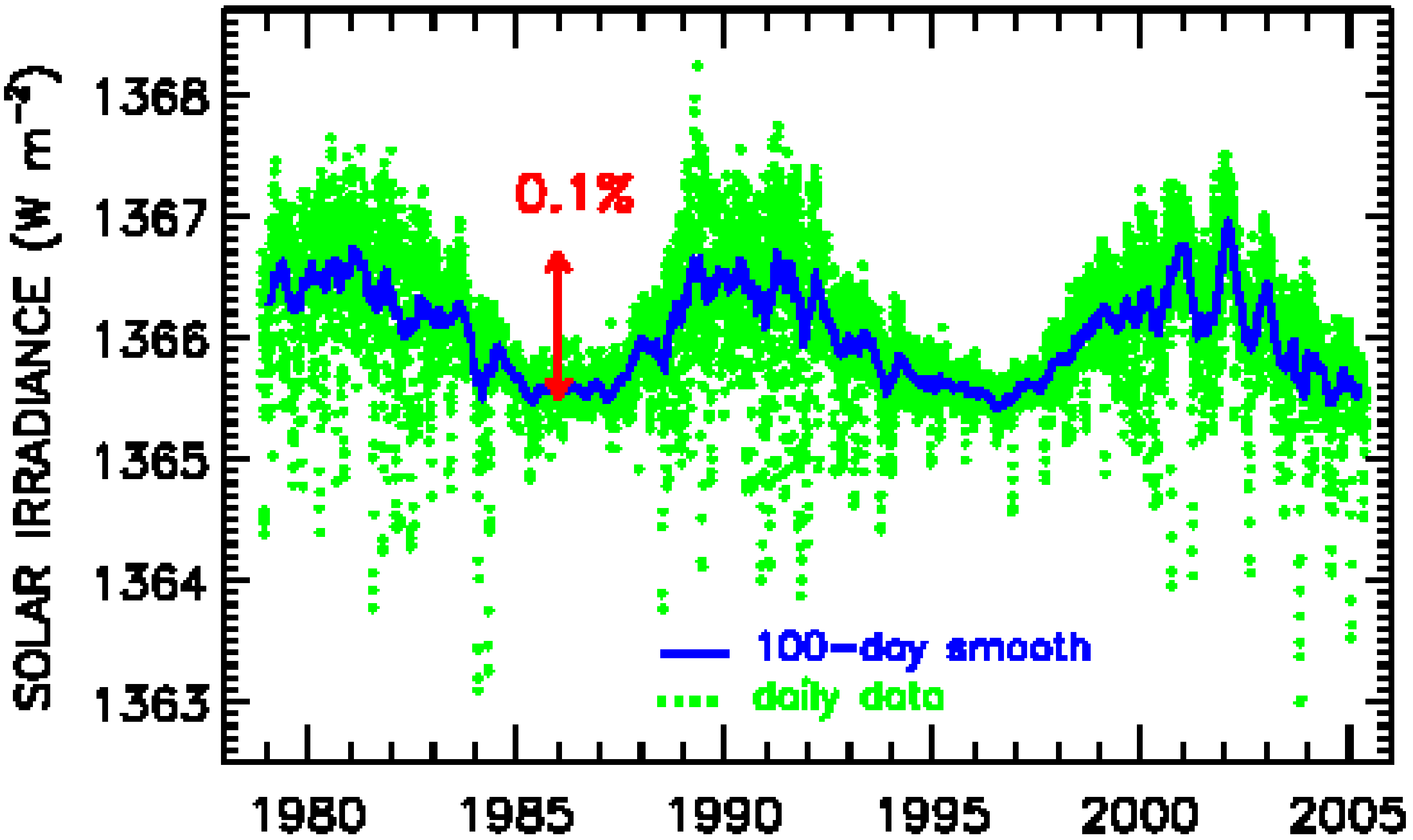




6: Composite of total solar irradiance covering more than two solar cycles, as measured by radiometers flying on spacecraft. Data from four instruments have been used to create this composite. Details of the procedure employed to merge the data sets are provided by Fröhlich and Lean (1998).



The irradiance cycle arises from the competing effects of sunspots and bright areas called faculae; the two features are evident in the solar images on the right and produce the effects on daily irradiance shown above.



SOLAR IRRADIANCE (W m^{-2})
1368
1367
1366
1365
1364
1363
1980
1985
1990
1995
2000
2005
0.1%
100-day smooth
daily data

AGENTS RESPONSIBLE FOR TOTAL SOLAR IRRADIANCE VARIATION

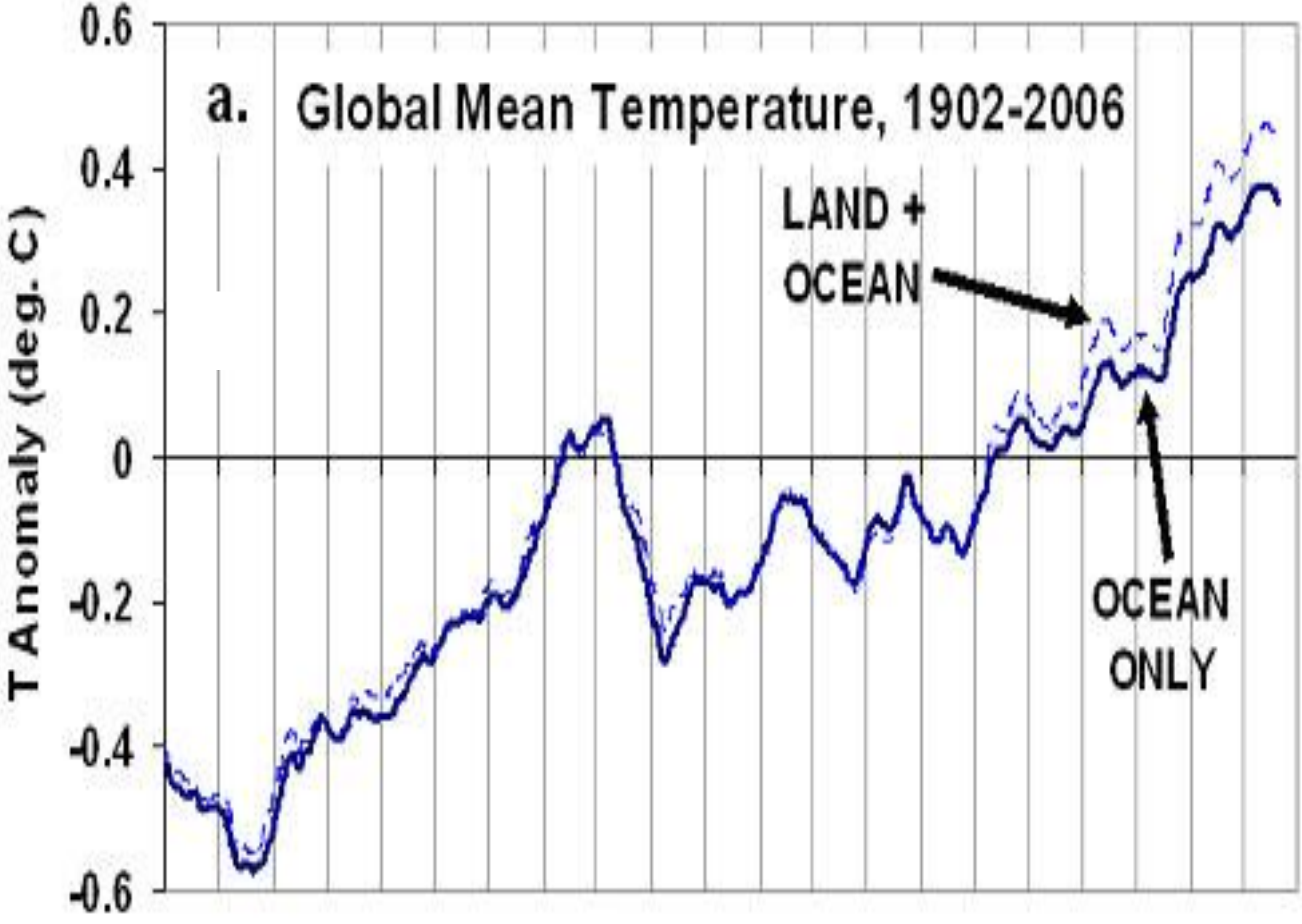
- SUNSPOTS
- FACULAE
- MAGNETIC NETWORK
- MODULATION OF THERMAL ENERGY
- FLUCTUATIONS OF ROTATIONAL & MAGNETIC ENERGY

TOTAL SOLAR IRRADIANCE VARIATIONS

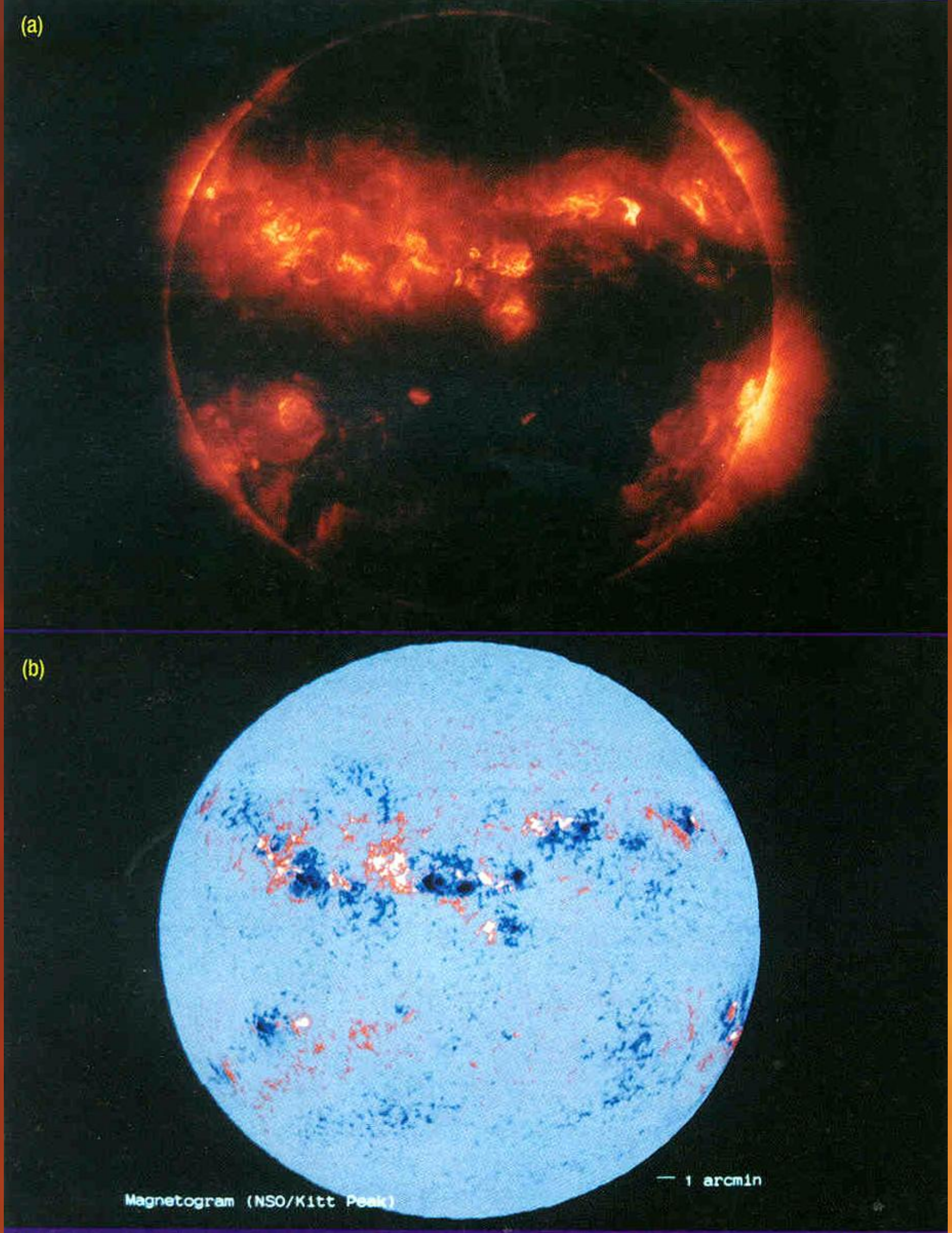
- 5-minute oscillations ~ 0.003%
- 27-day Solar Rotation ~ 0.2%
- 11-year Solar Cycle ~ 0.1%
- Longer-term variations ~ !

- Total solar irradiance variations unlikely to be caused solely due to superficial effects like sunspots, faculae, rather there should be comparable contribution from modulation of thermal energy stored in outer regions of convection zone ($r \geq 0.90\ R_{\odot}$) which is shared between K.E. of zonal flows and magnetic energy.

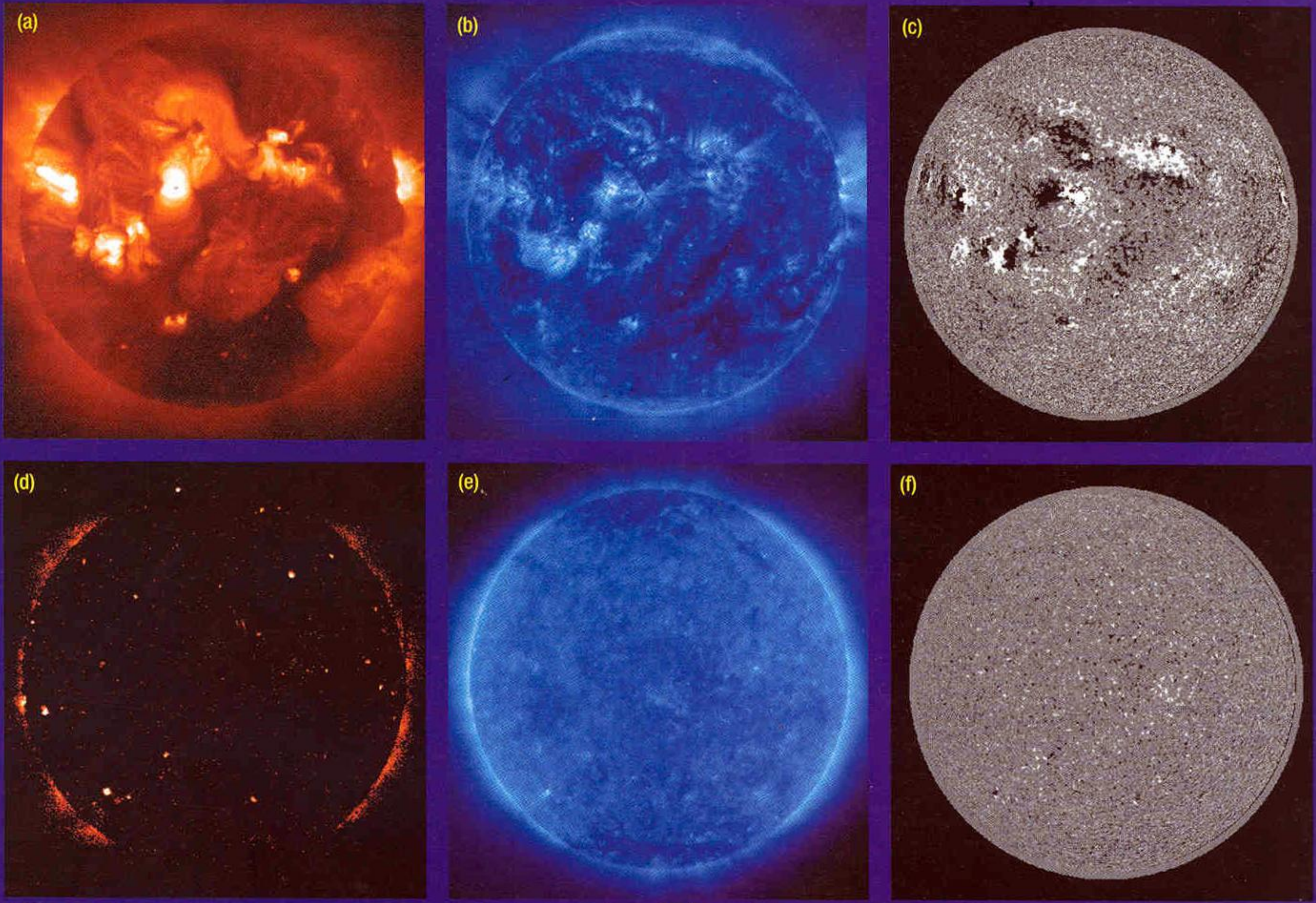
- Tempting to speculate if temporal variations in residual K.E. of rotation has a significant role in total solar irradiance modulation with activity cycle and whether zonal flows are in some way responsible for reversals of magnetic fields in successive cycles!



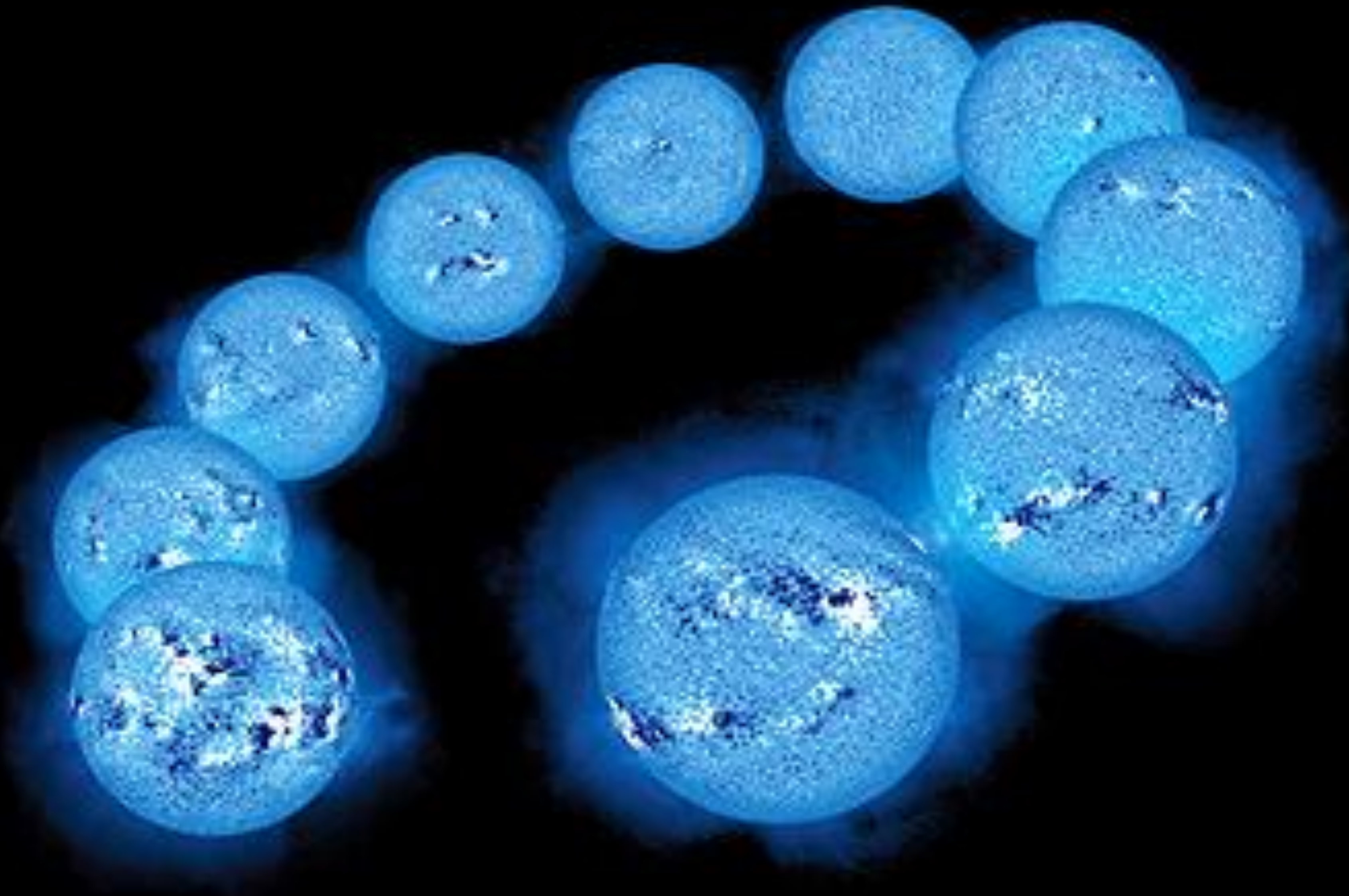
a. Global Mean Temperature, 1902-2006
T Anomaly (deg. C)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
LAND + OCEAN
OCEAN ONLY

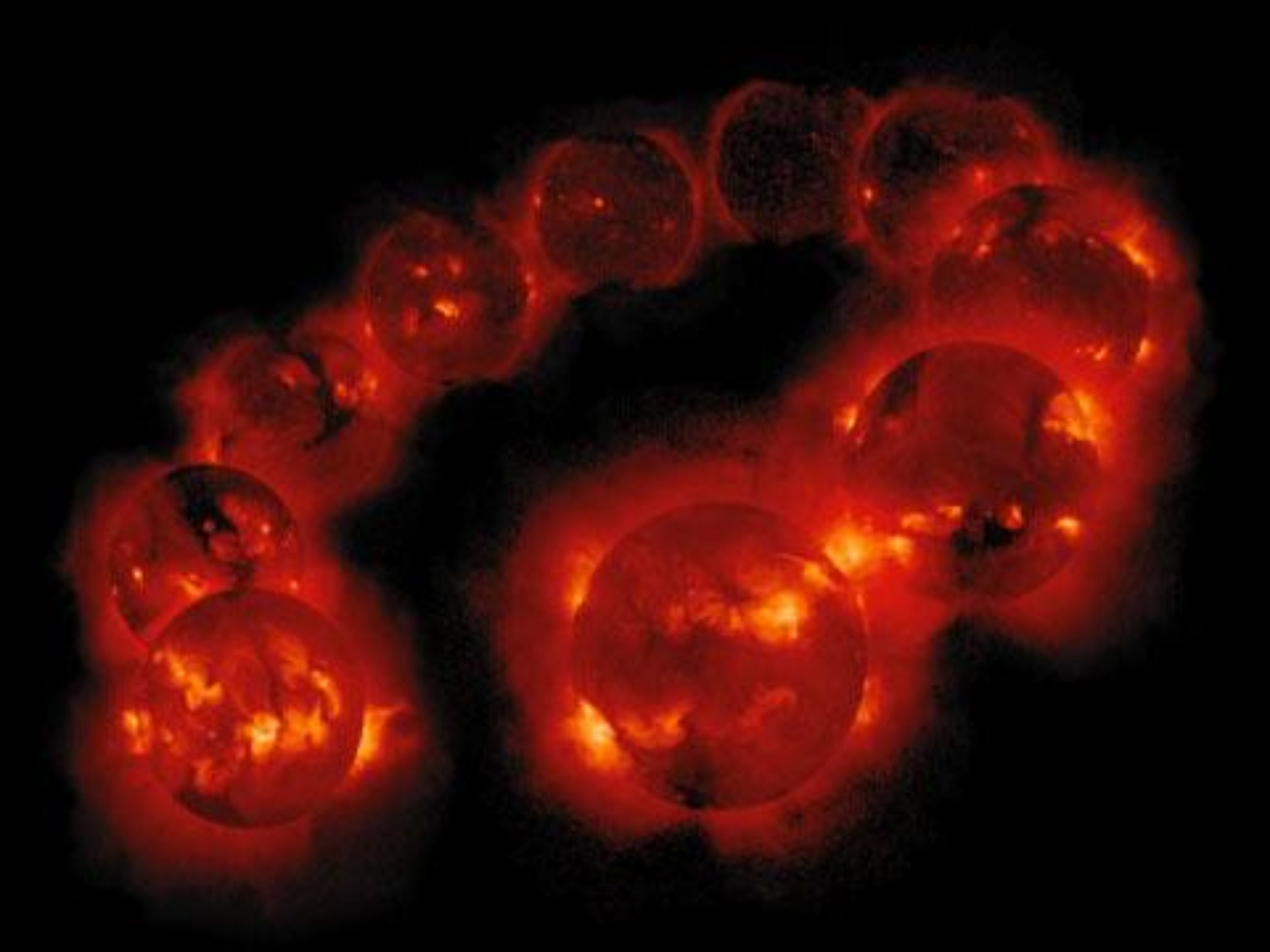


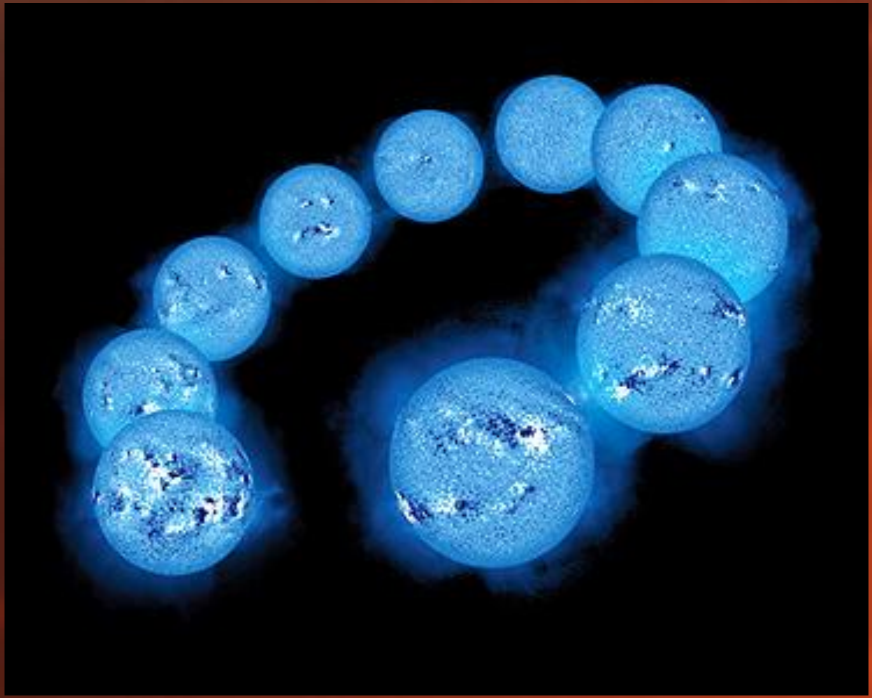
5: X-ray emission from the hot corona of the Sun maps magnetic fields at the solar surface. (a) A soft X-ray image of the Sun, obtained with the Normal Incidence X-ray Telescope on a rocket flight on 11 September 1989. (b) The corresponding magnetogram, from Kitt Peak National Observatory, shows oppositely directed fields as blue and red against a lighter neutral background. (Courtesy of L Golub.)



2: Images of the solar atmosphere at solar maximum (a–c) and solar mimimum (d–f). From left to right: Yohkoh SXT image ($2\times10^6 < T < 6\times10^6$ K), SOHO EIT image ($T \approx 10^6$ K) and SOHO MDT magnetogram of the magnetic field in the photosphere.

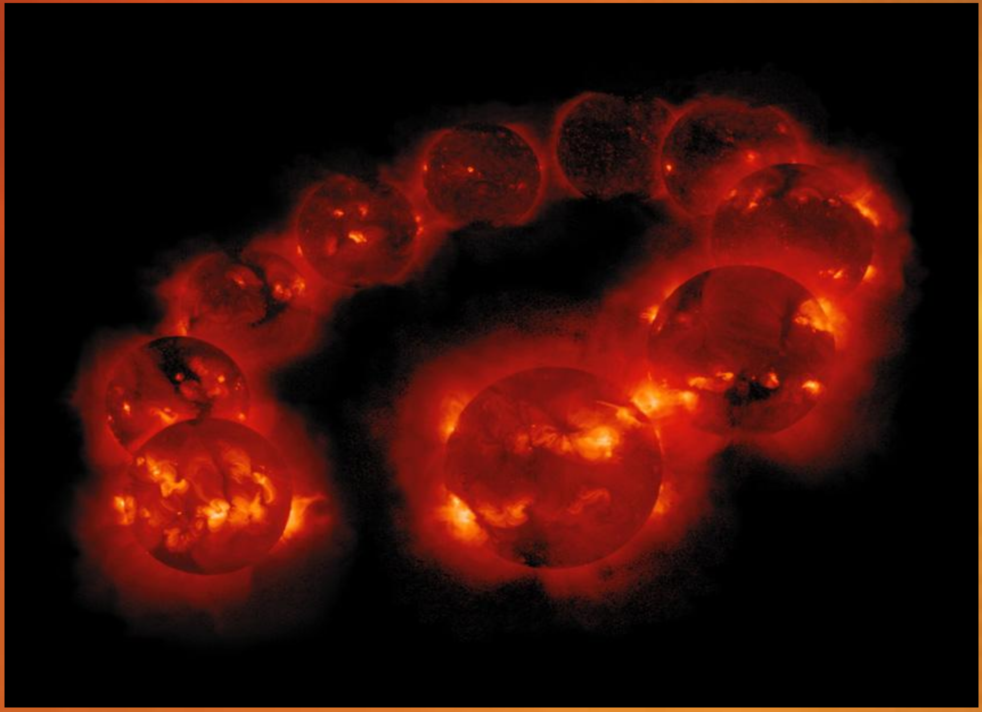


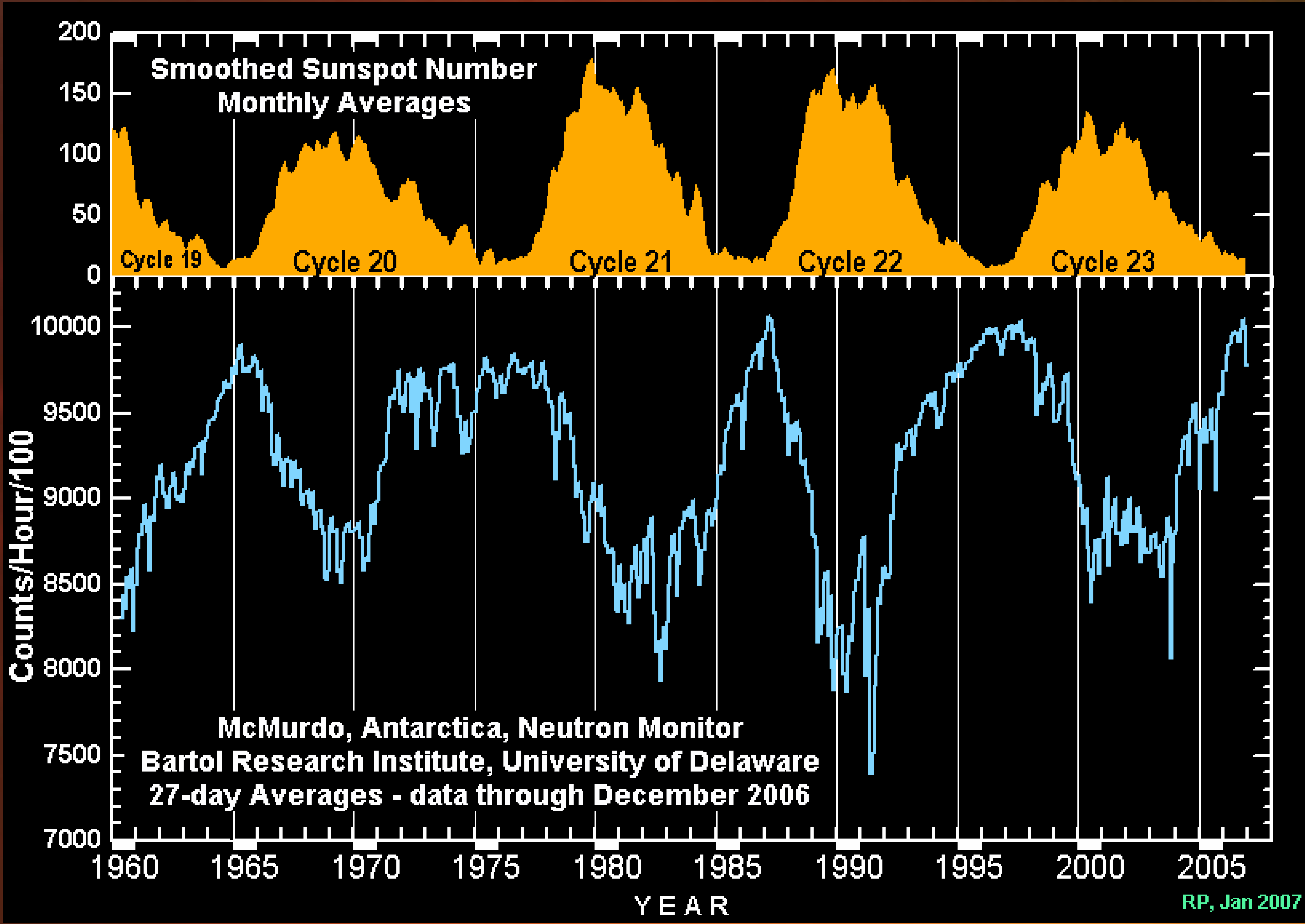




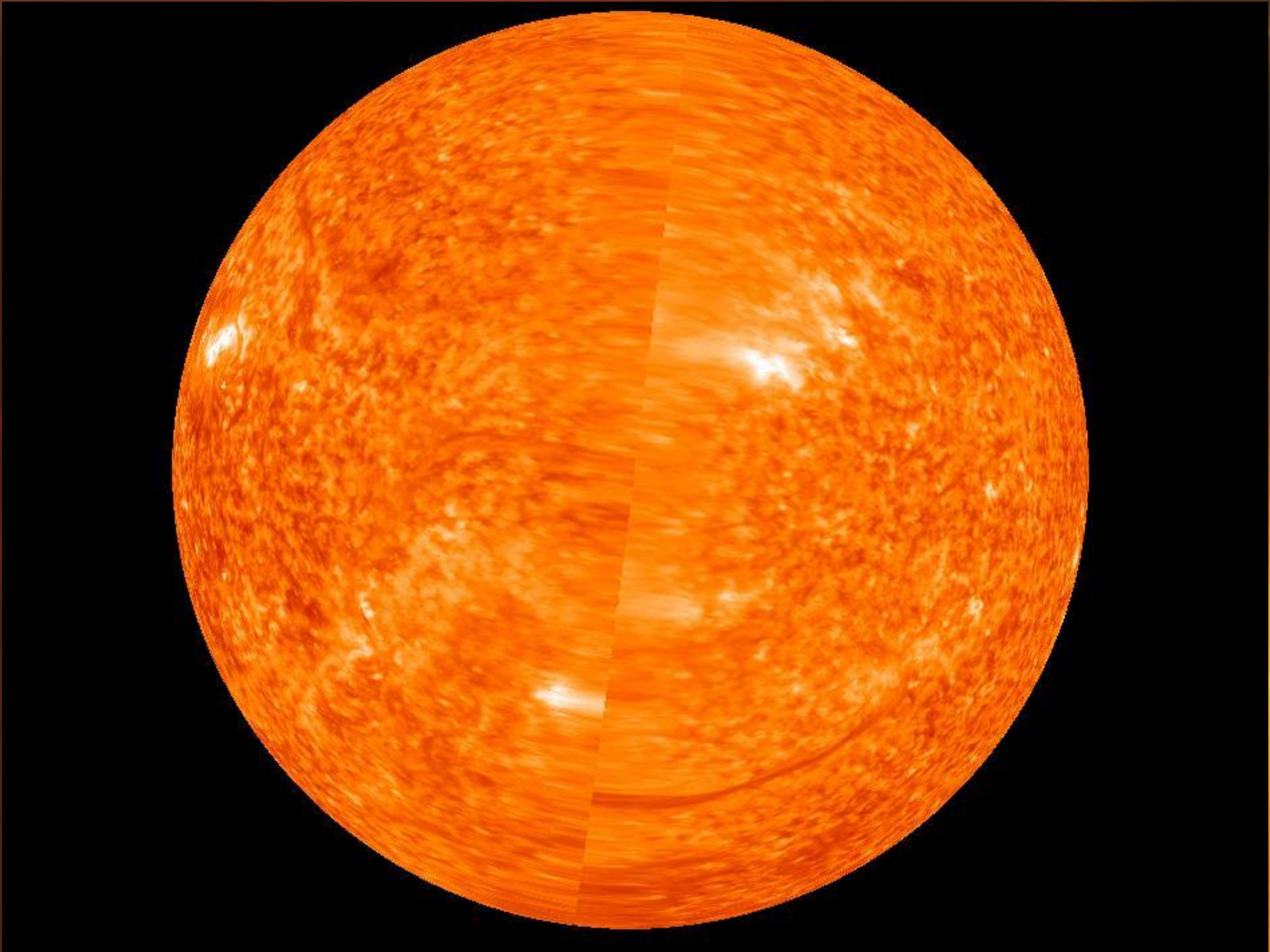
Evolution of Solar Magnetic Field over a cycle

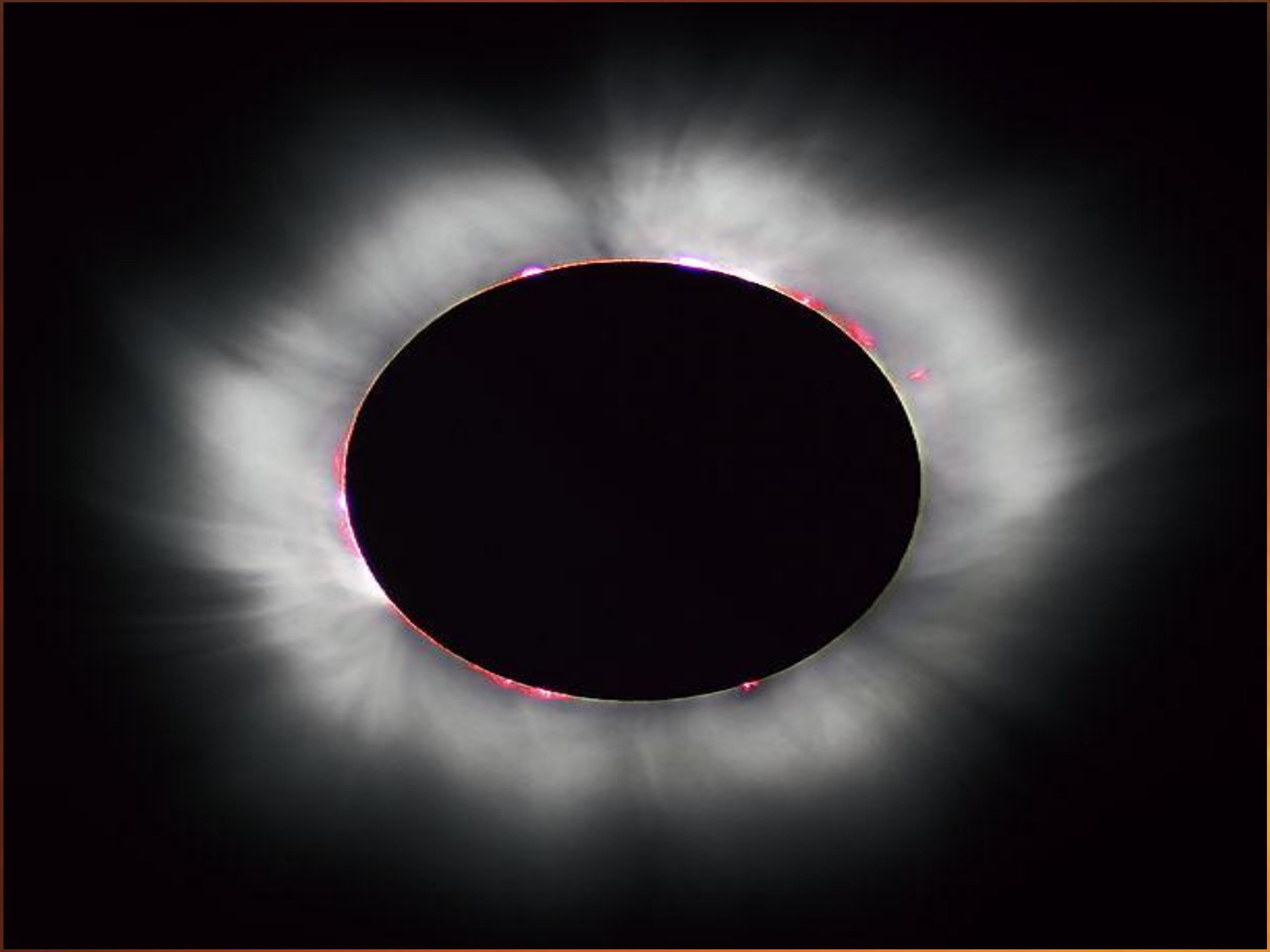
Evolution of Solar Corona over a cycle

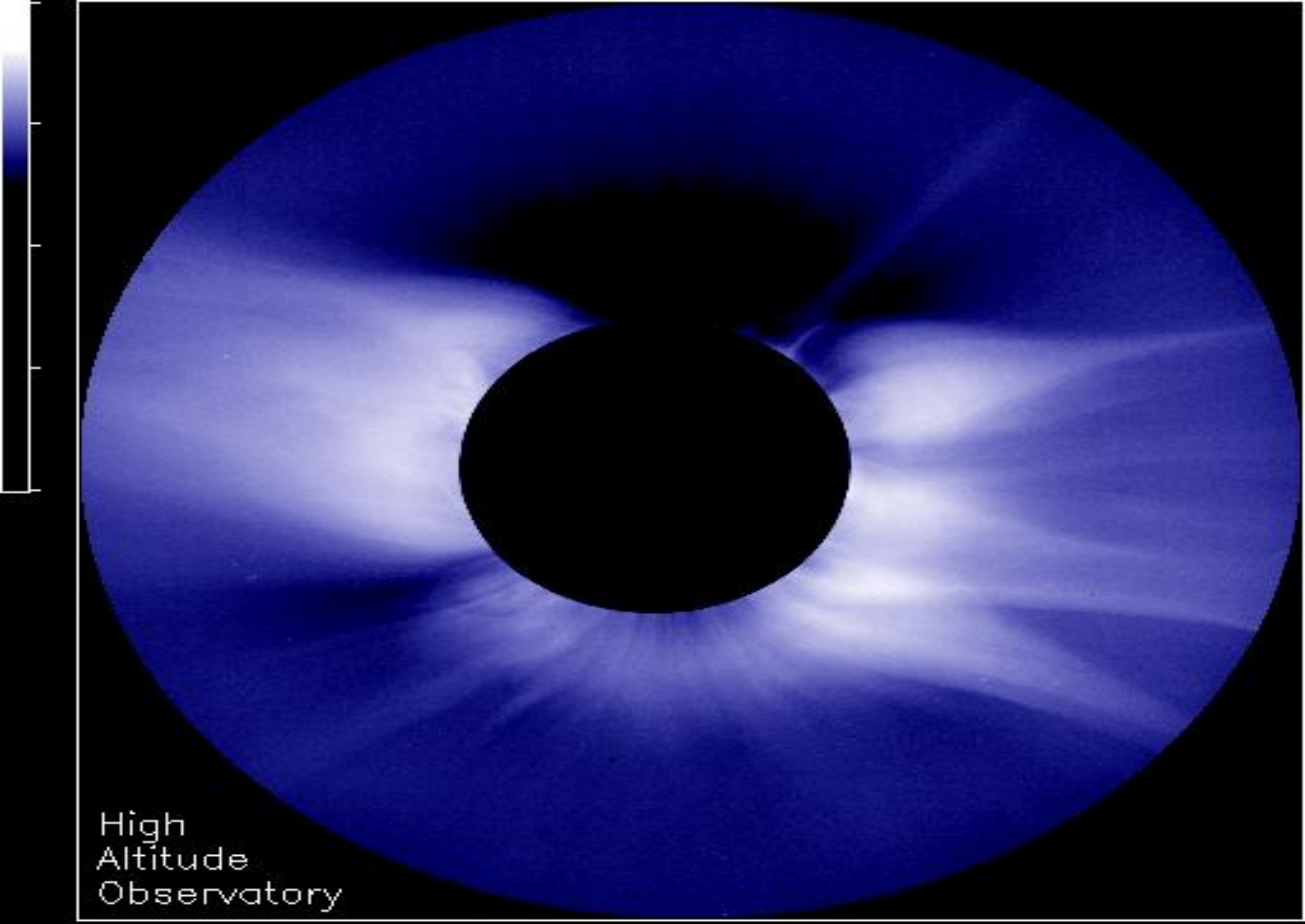




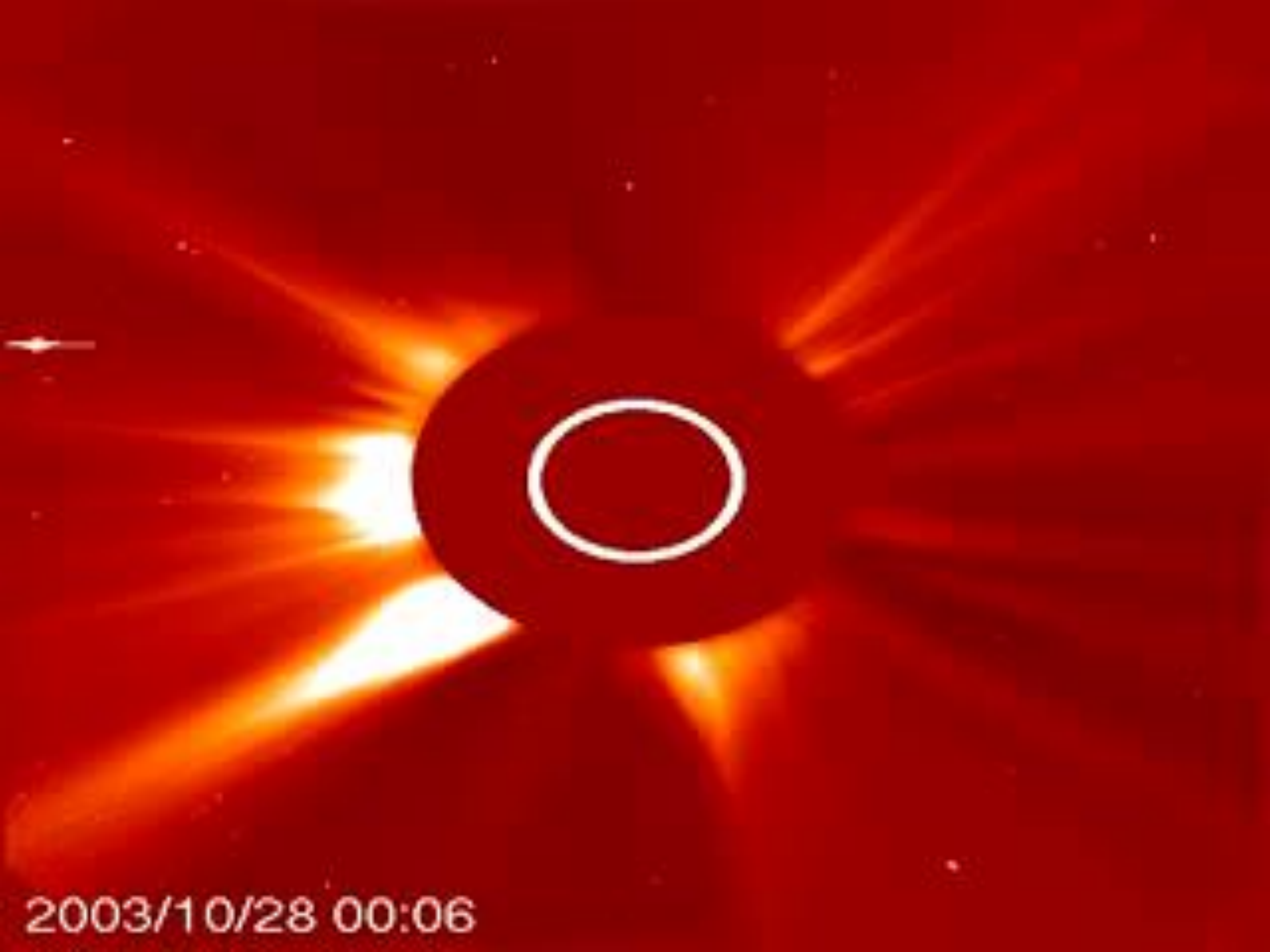
Smoothed Sunspot Number
Monthly Averages
200
150
100
50
0
Cycle 19
Cycle 20
Cycle 21
Cycle 22
Cycle 23
10000
9500
9000
8500
8000
7500
7000
Counts/Hour/100
McMurdo, Antarctica, Neutron Monitor
Bartol Research Institute, University of Delaware
27-day Averages - data through December 2006
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
YEAR
RP, Jan 2007







20 June 1973 – Total Solar Eclipse – Loiengalani, Kenya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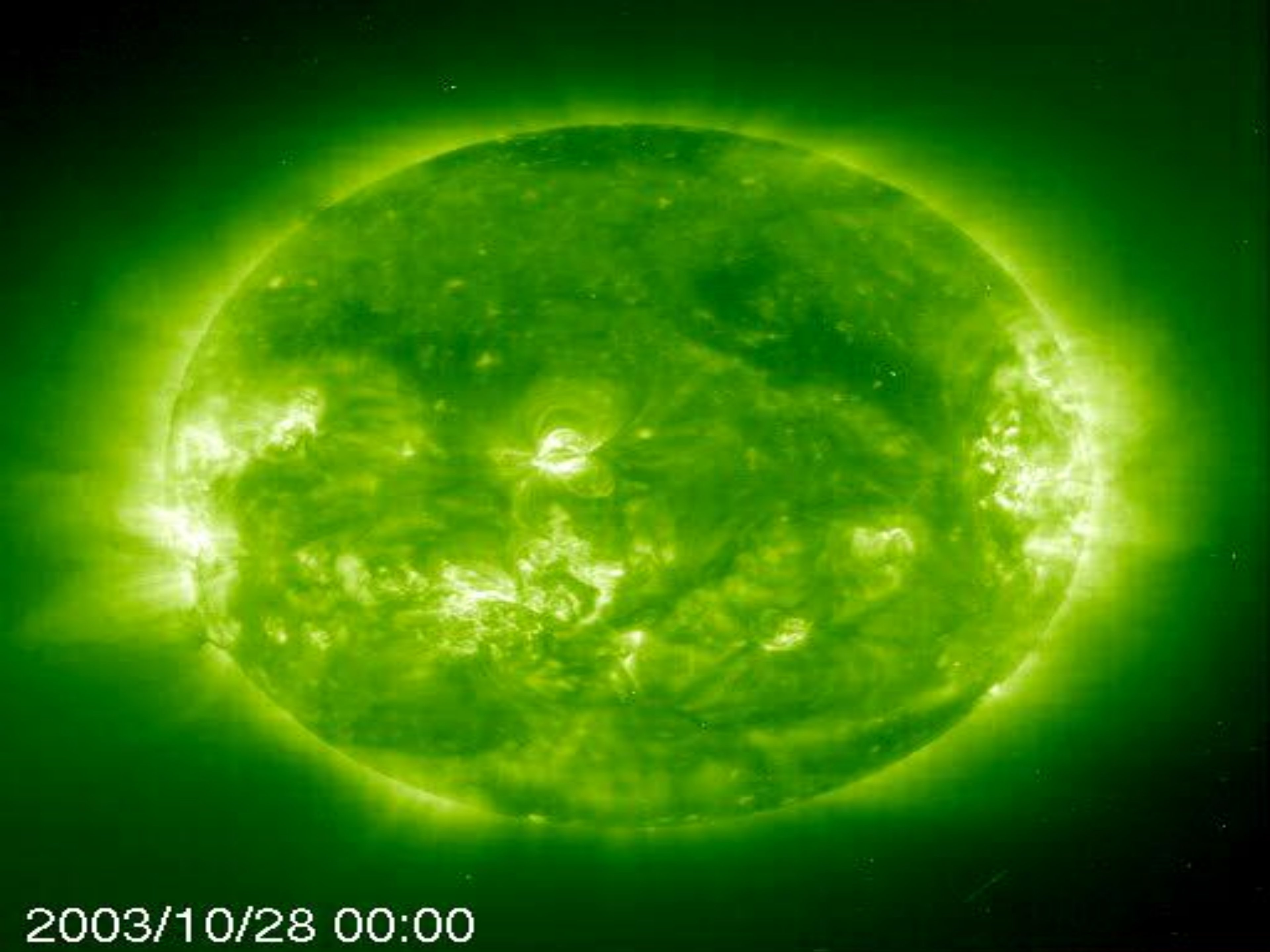
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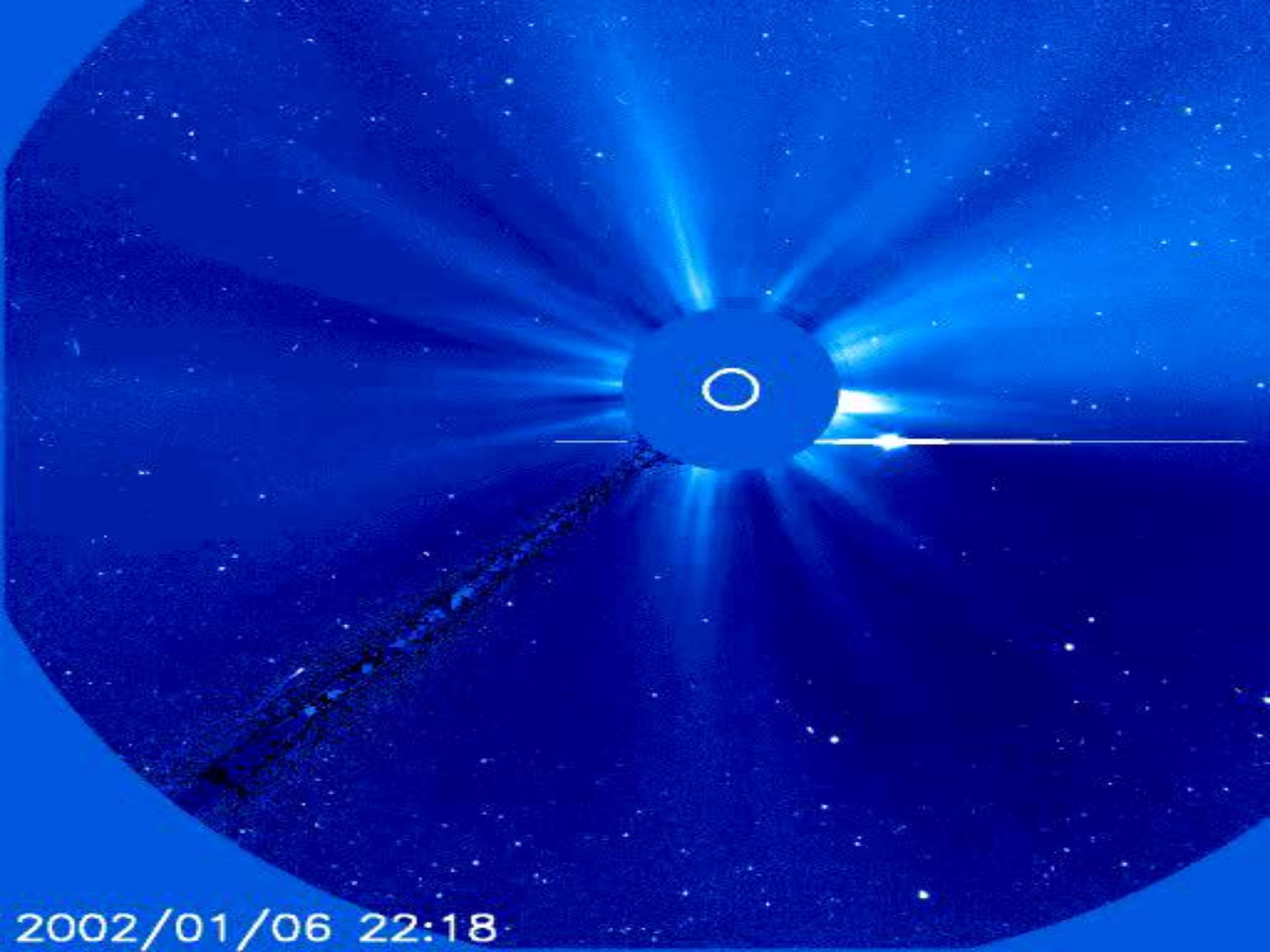
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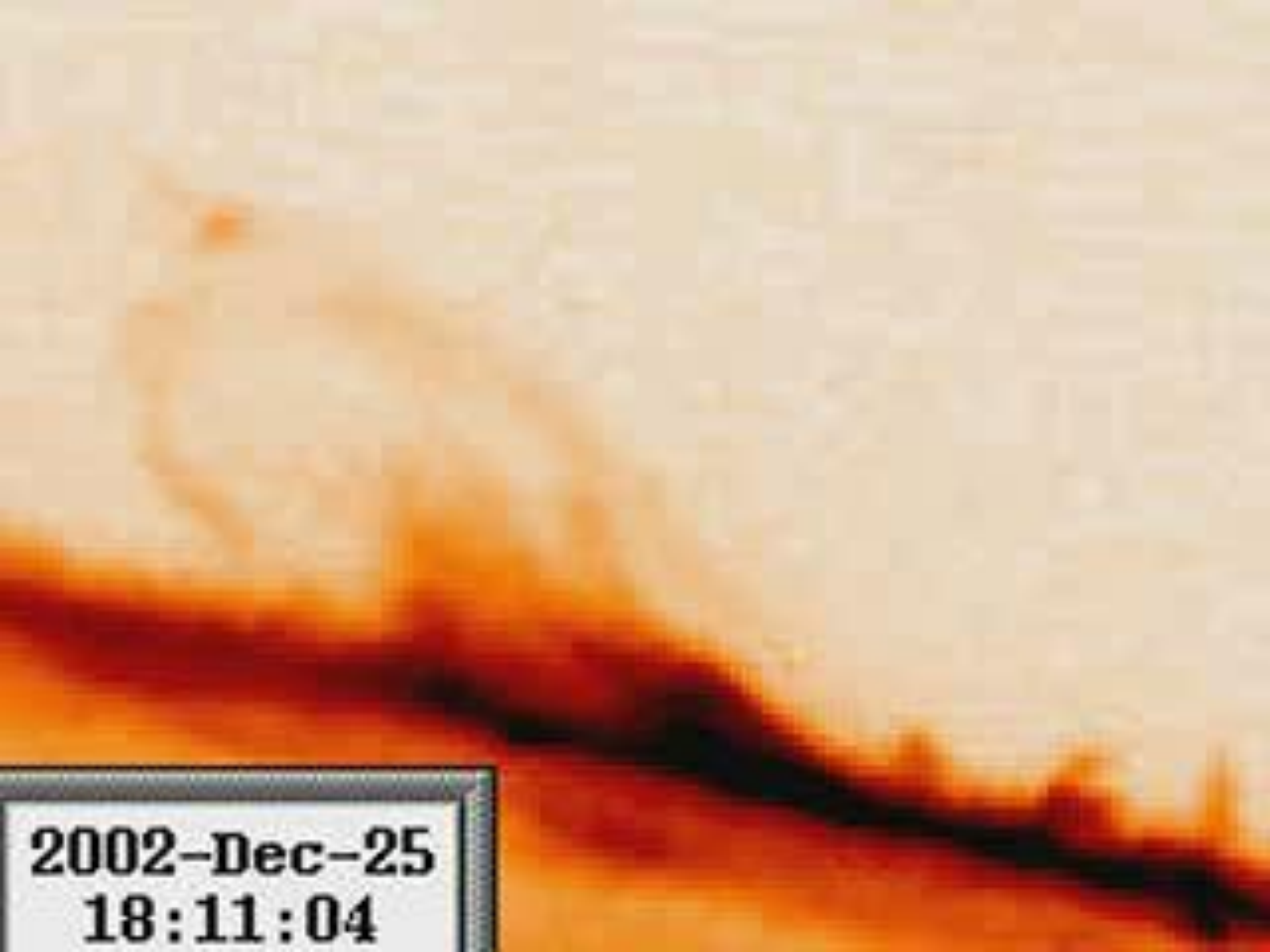
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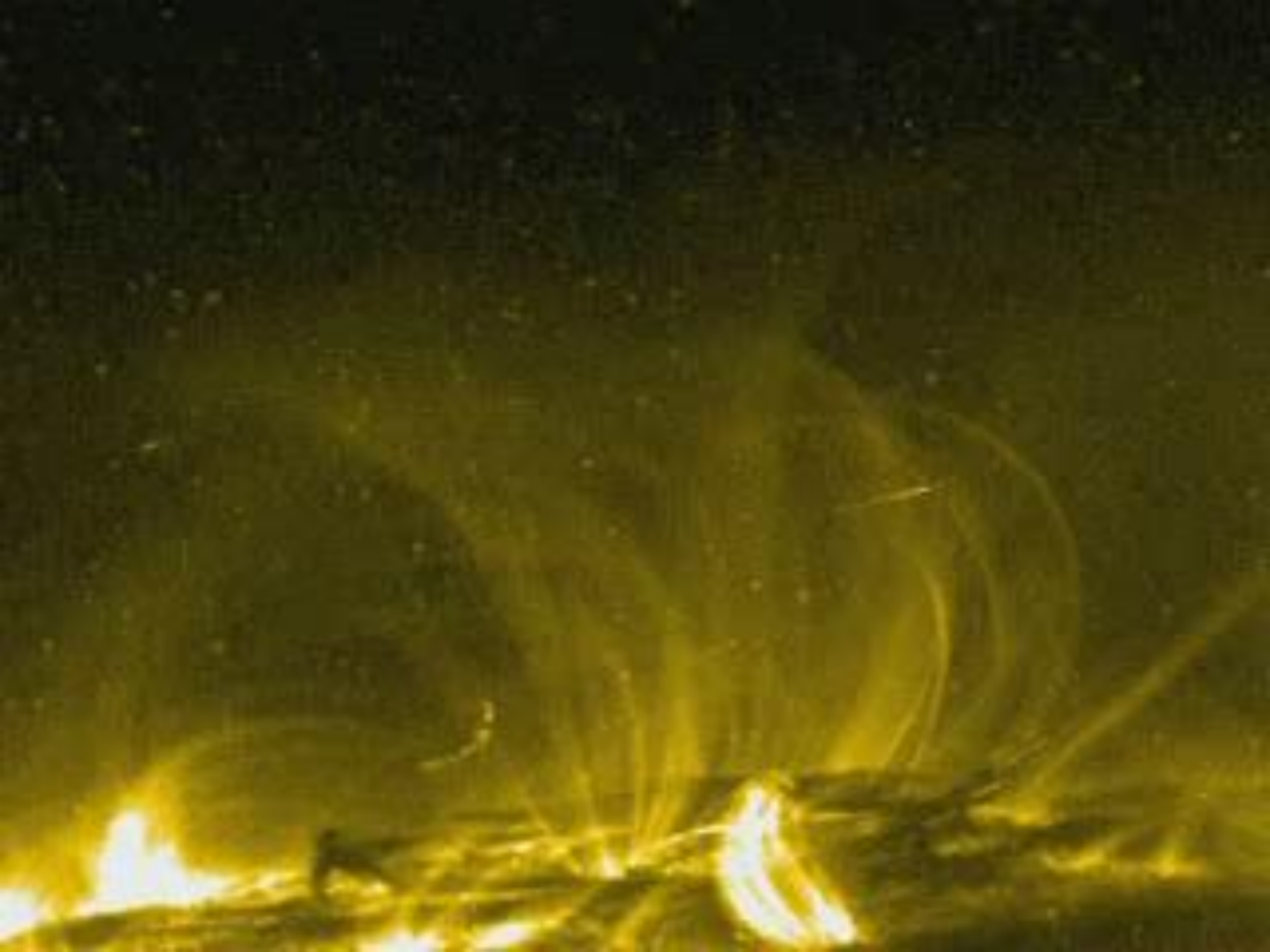
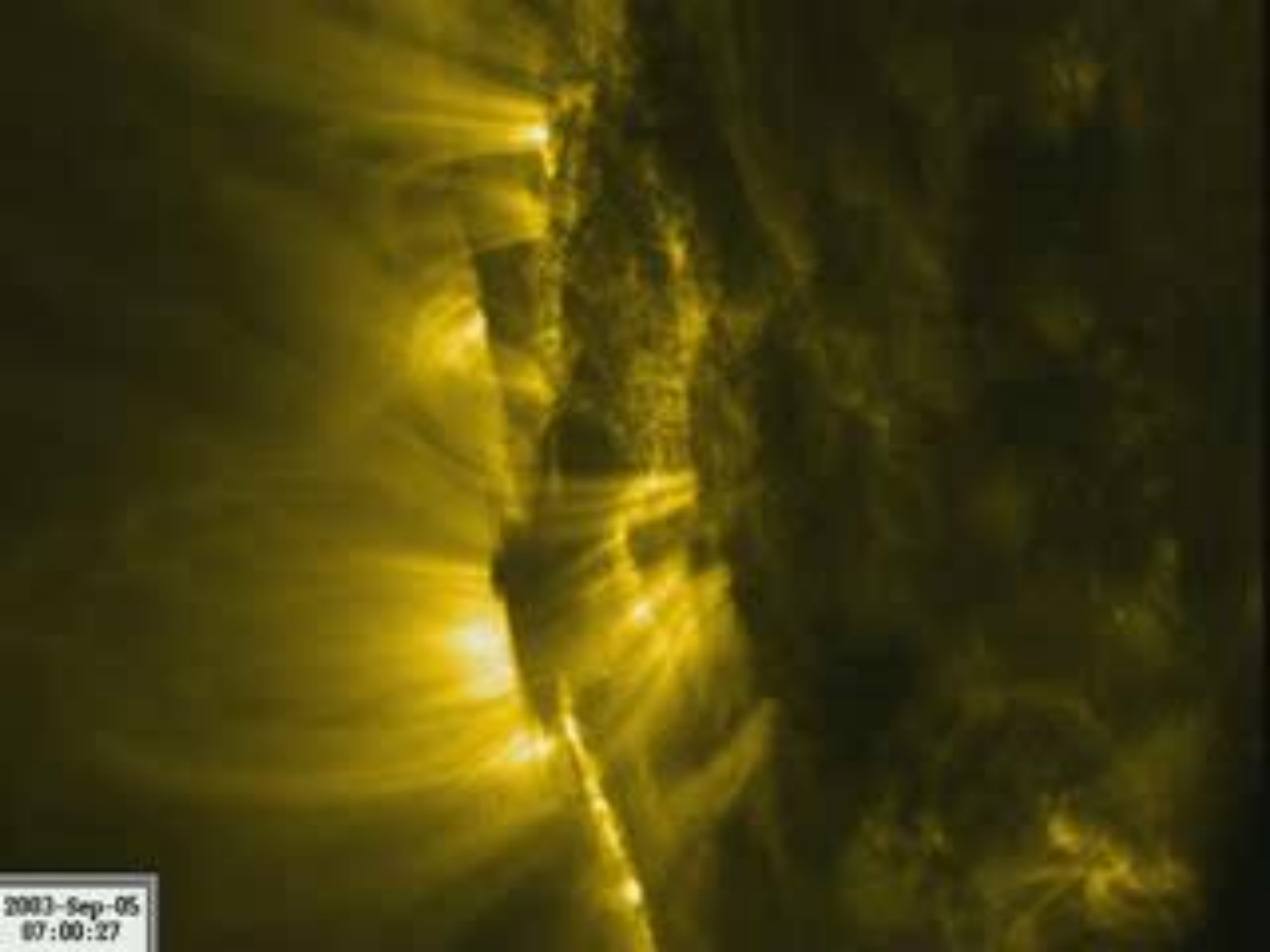
18:11:04

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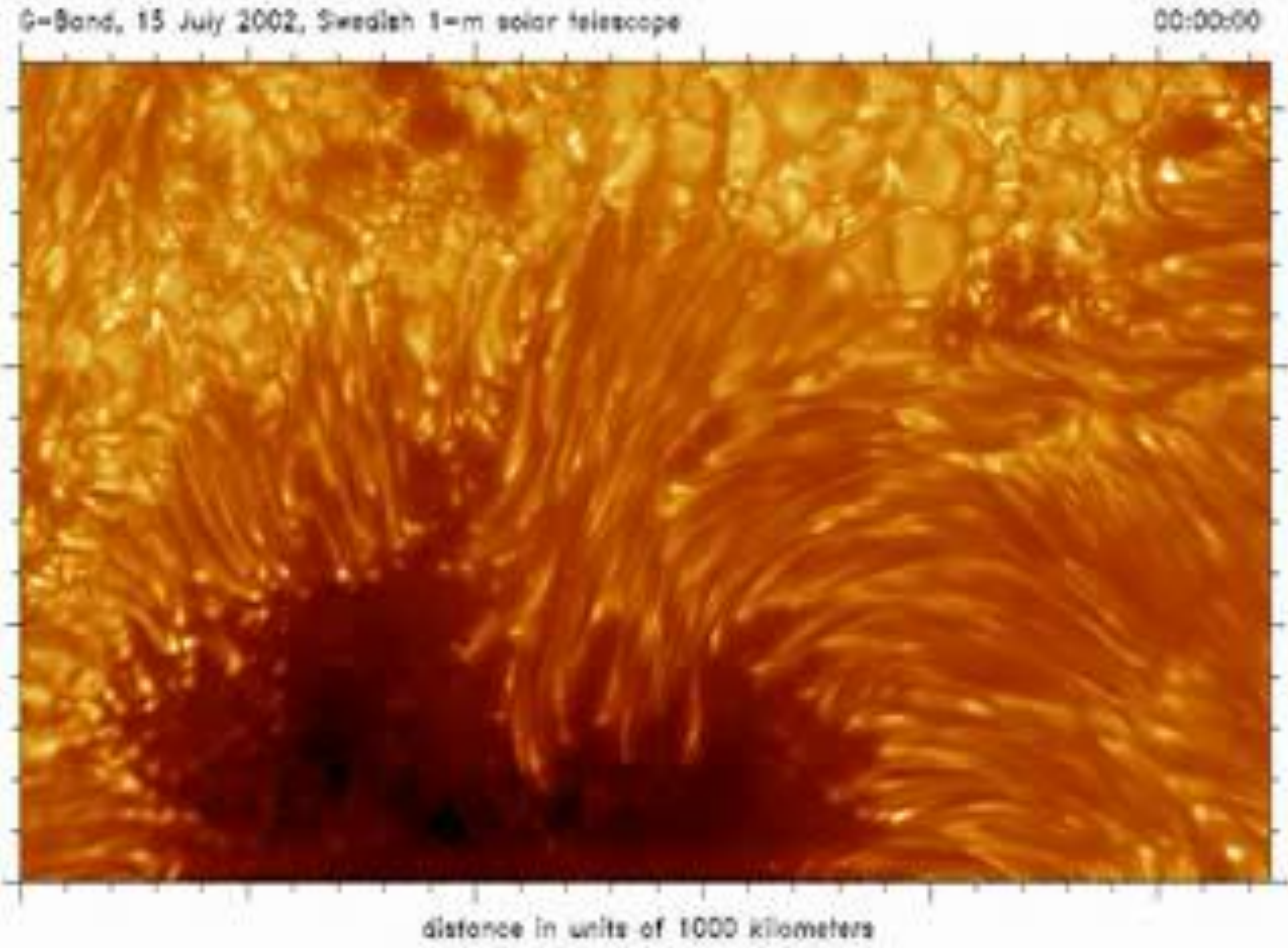
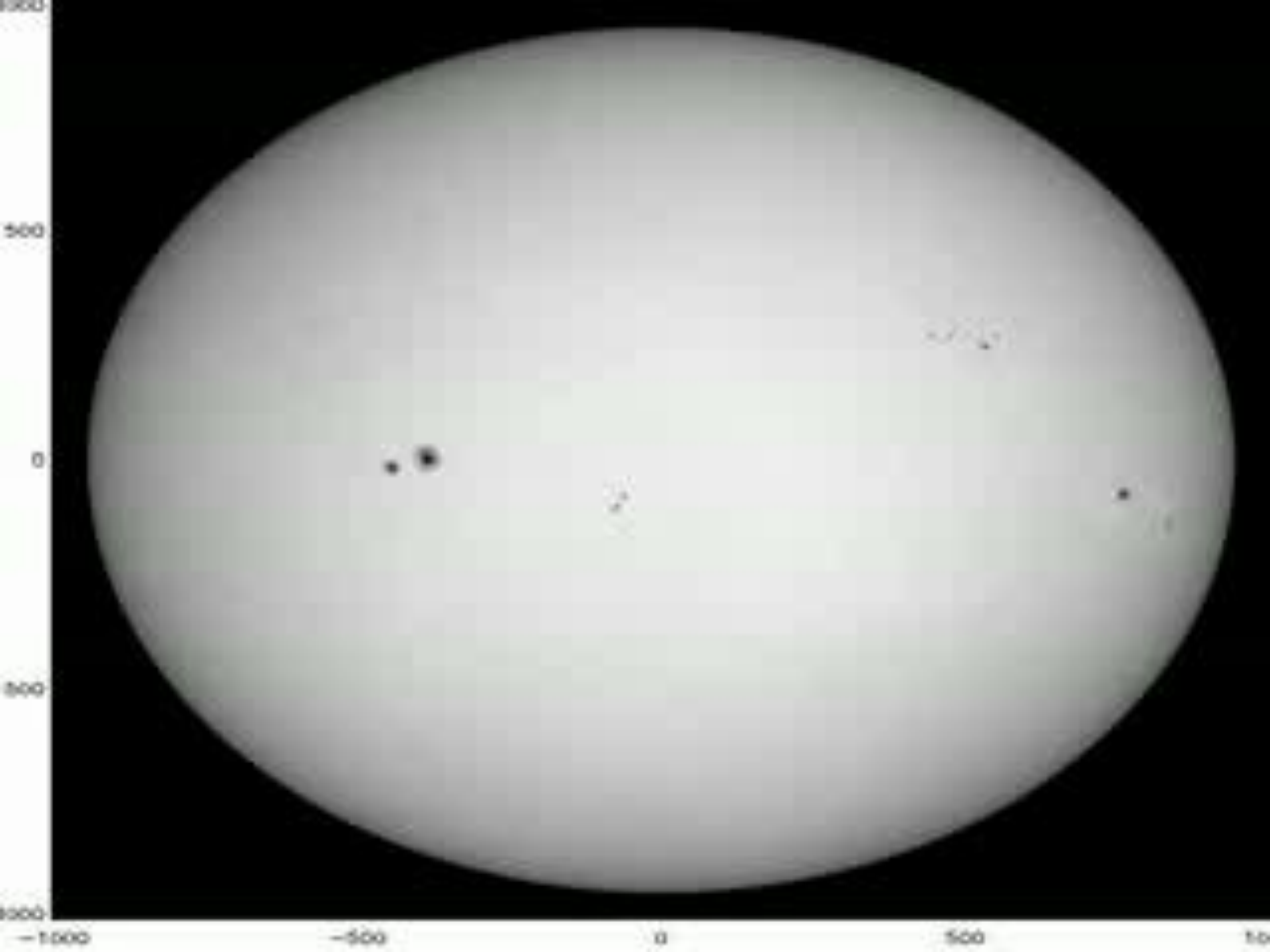


G-Band, 15 July 2002, Swedish 1-m solar telescope
00:00:00
distance in units of 1000 kilometers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0
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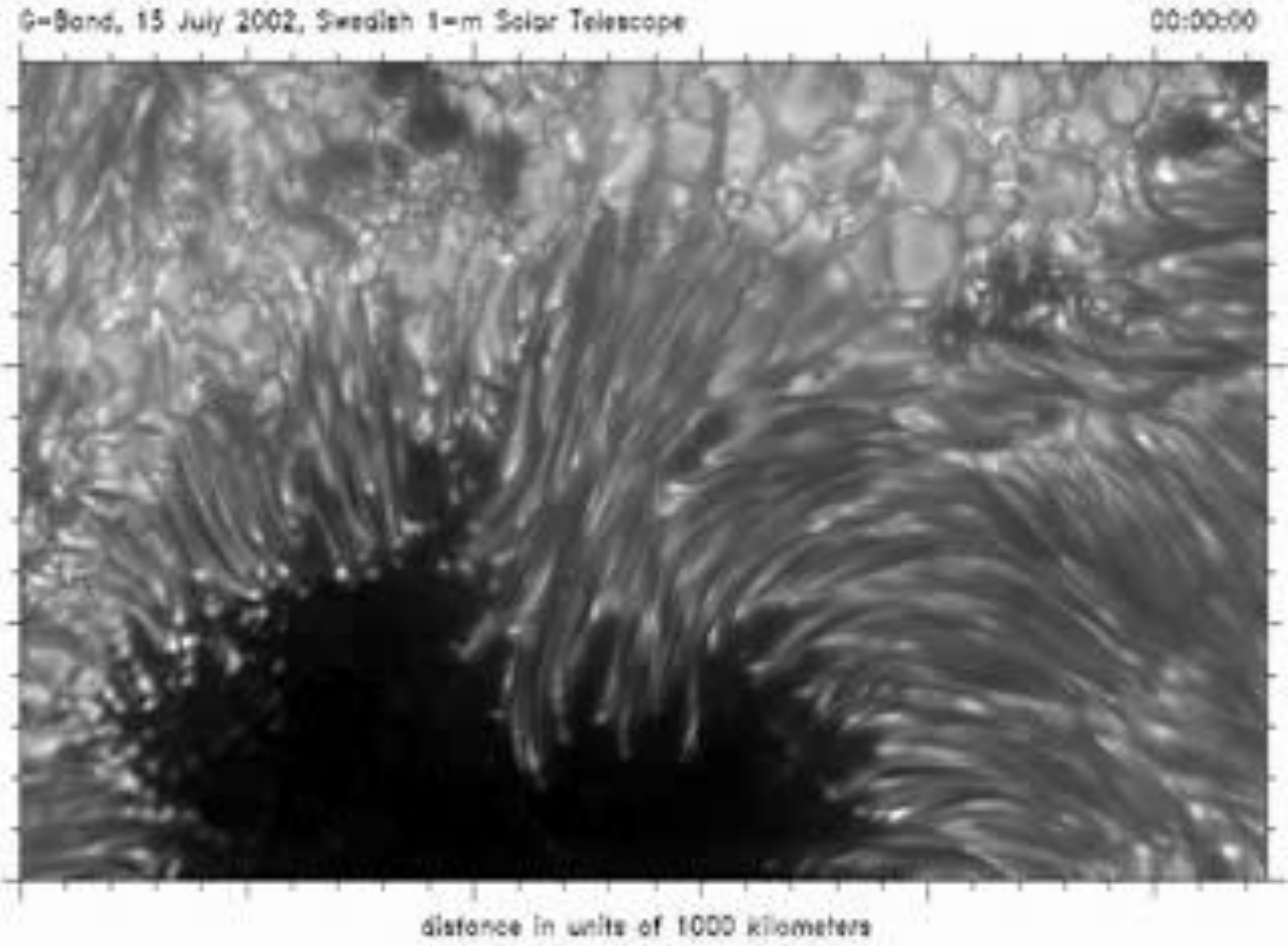
−500
0
500


G-Band, 15 July 2002, Swedish 1-m Solar Telescope
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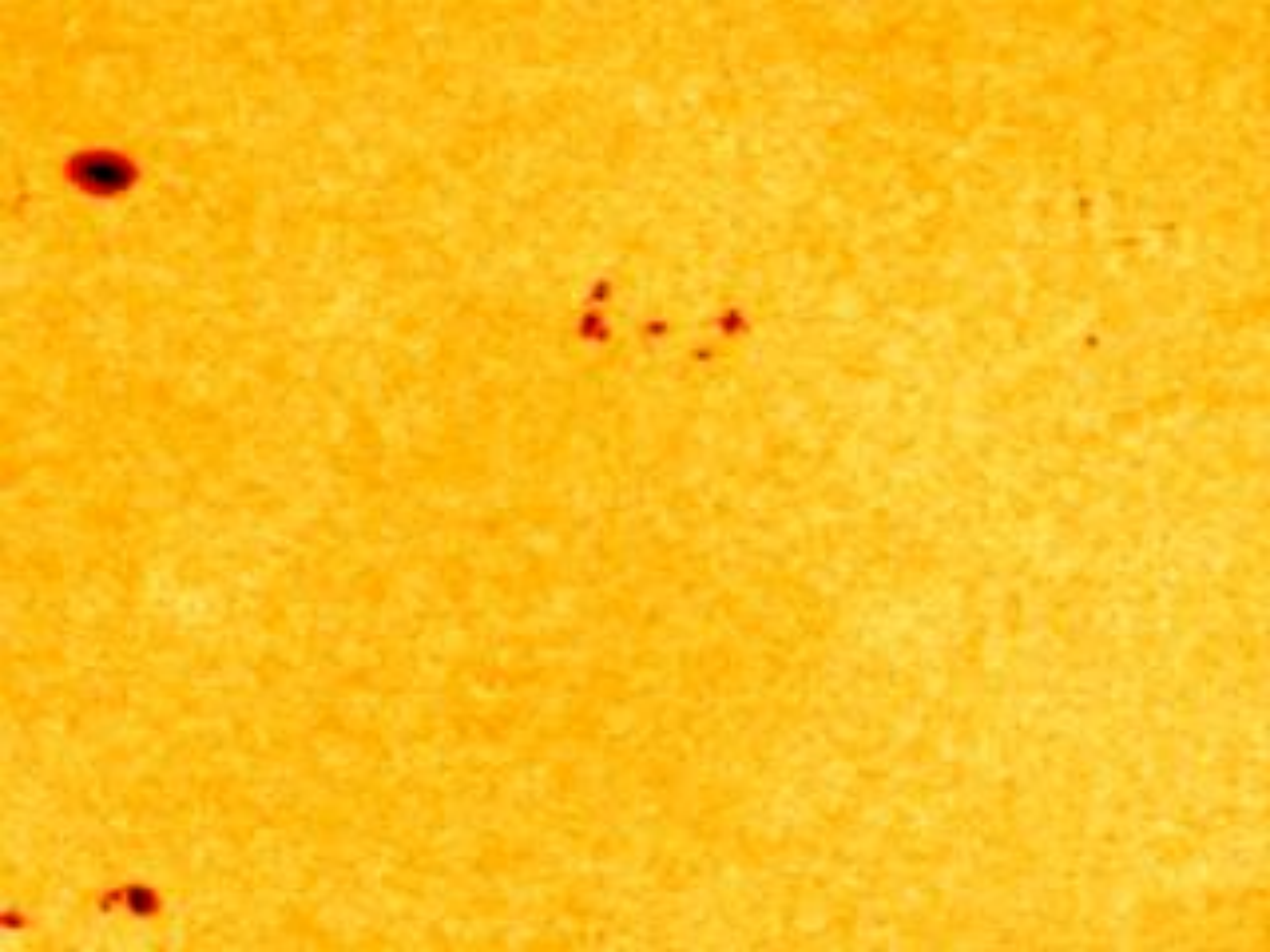
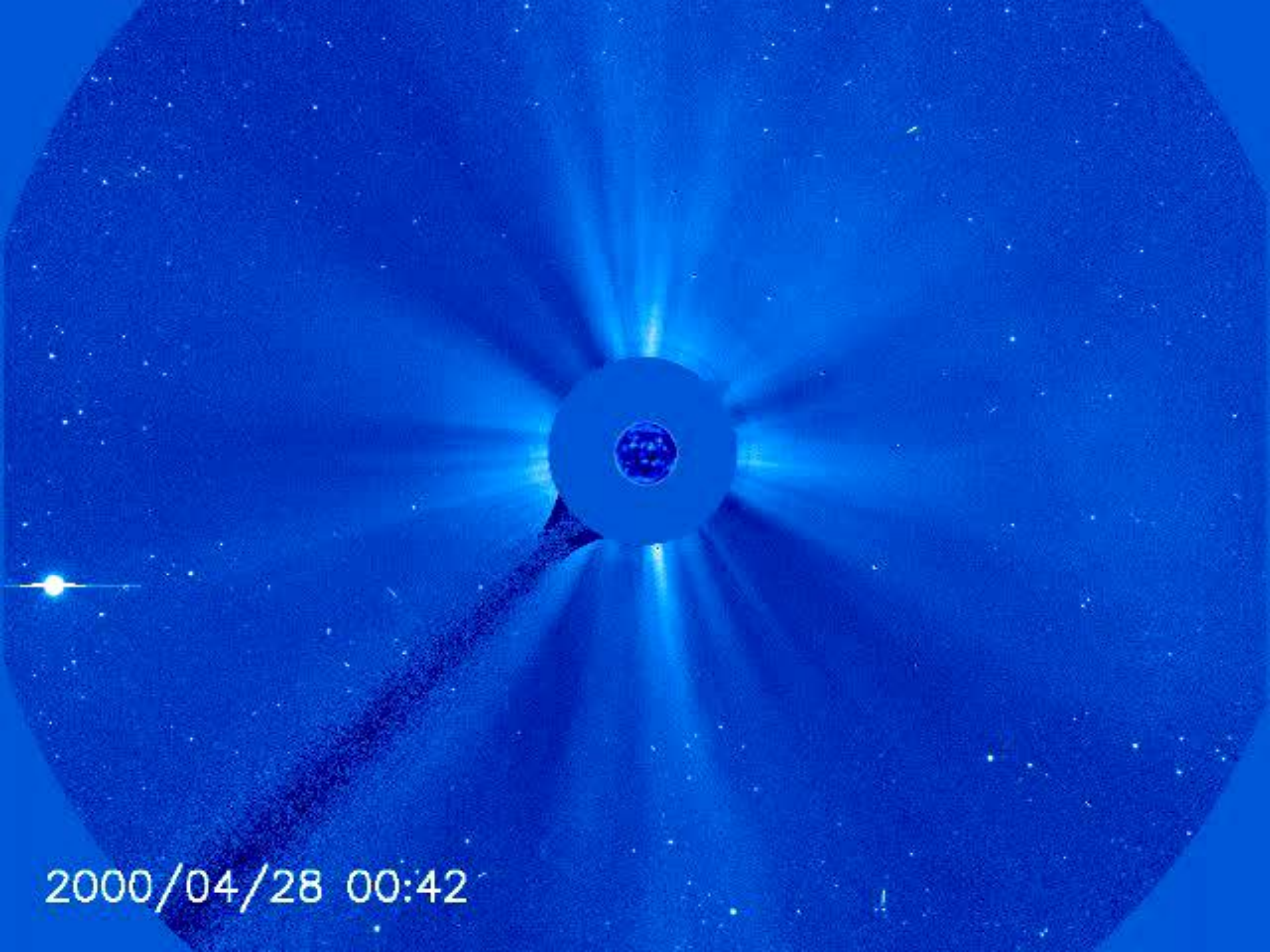



Prominence Eruption
1945 June 28
High Altitude Observatory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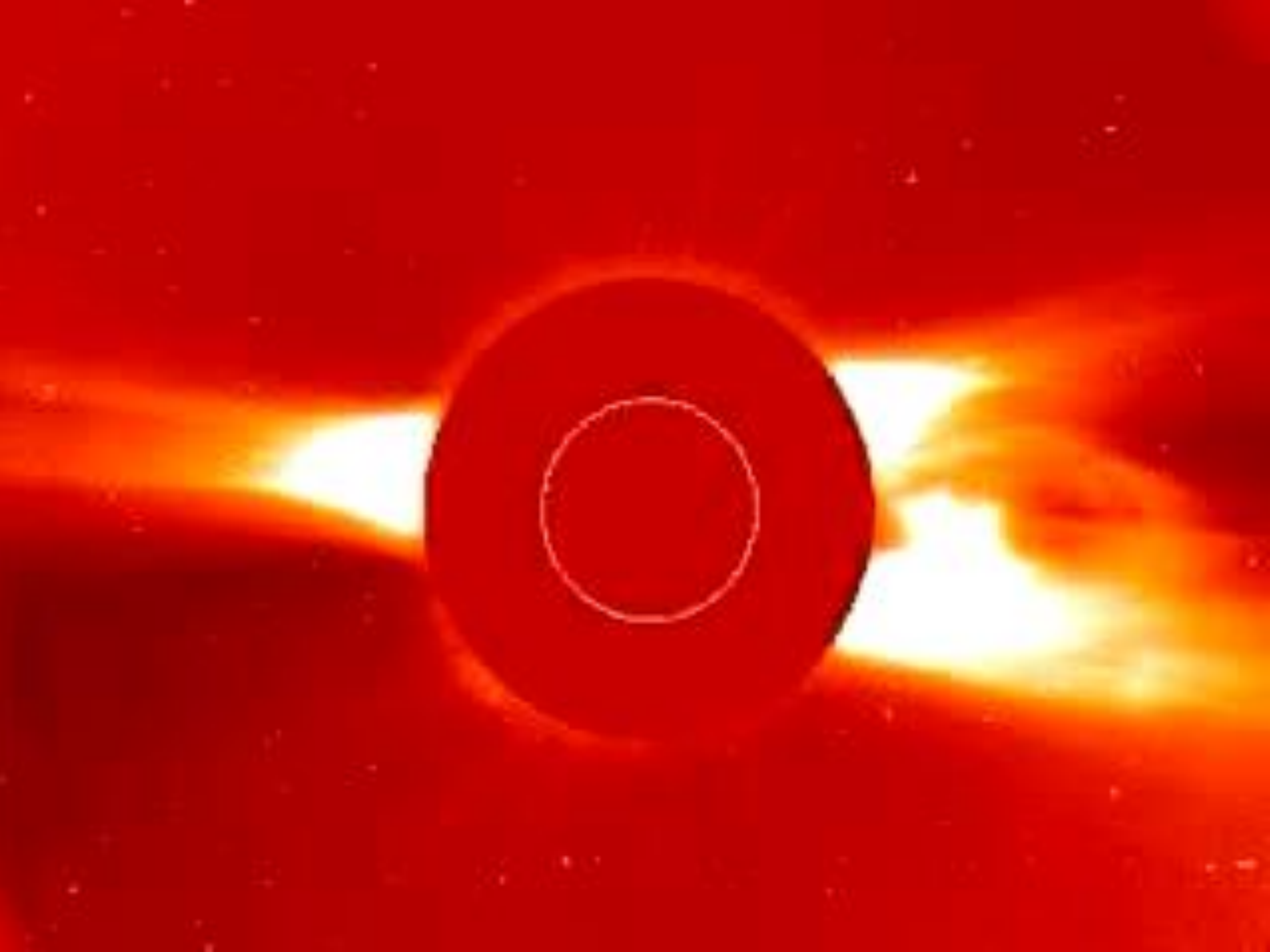
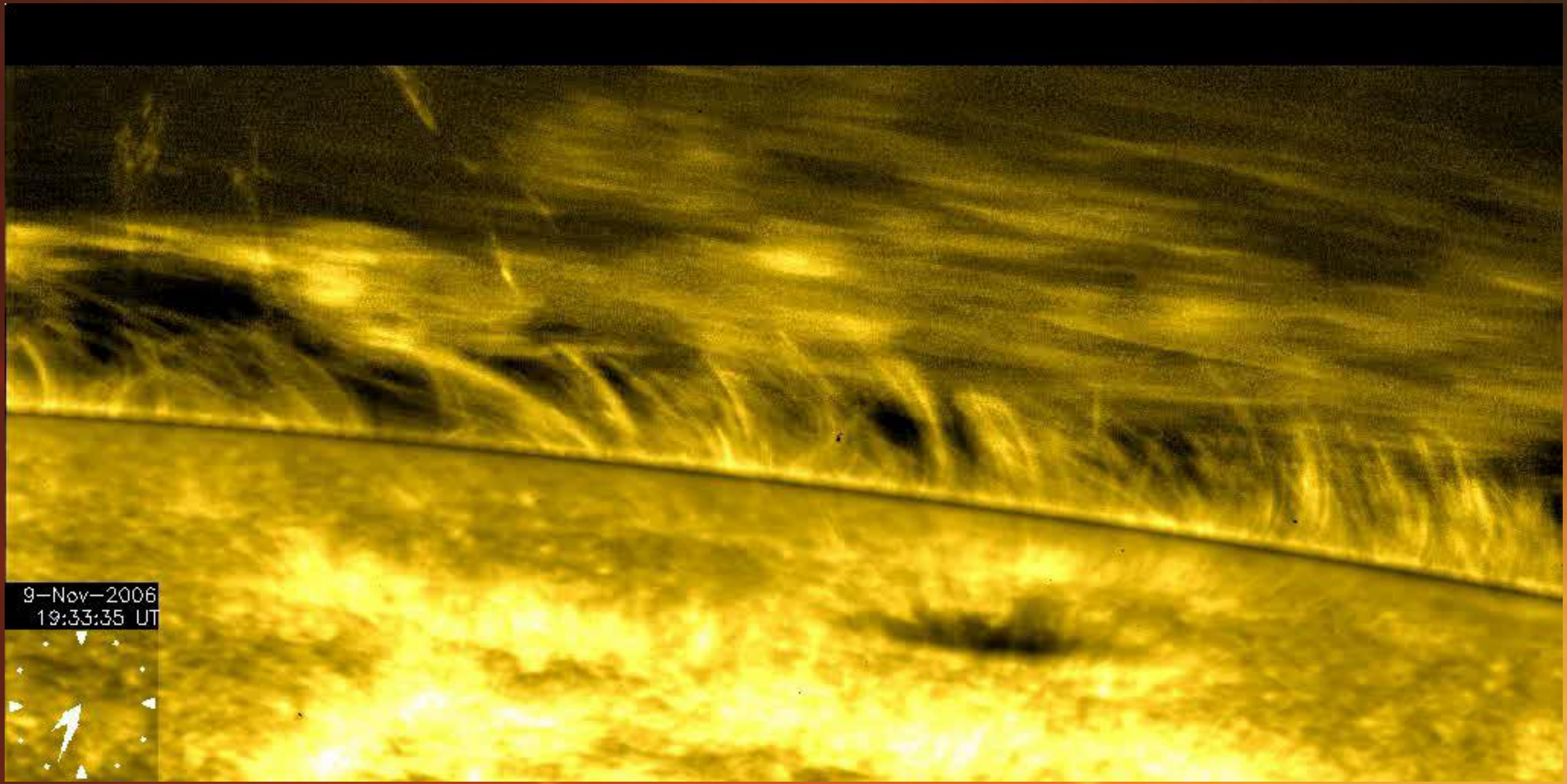
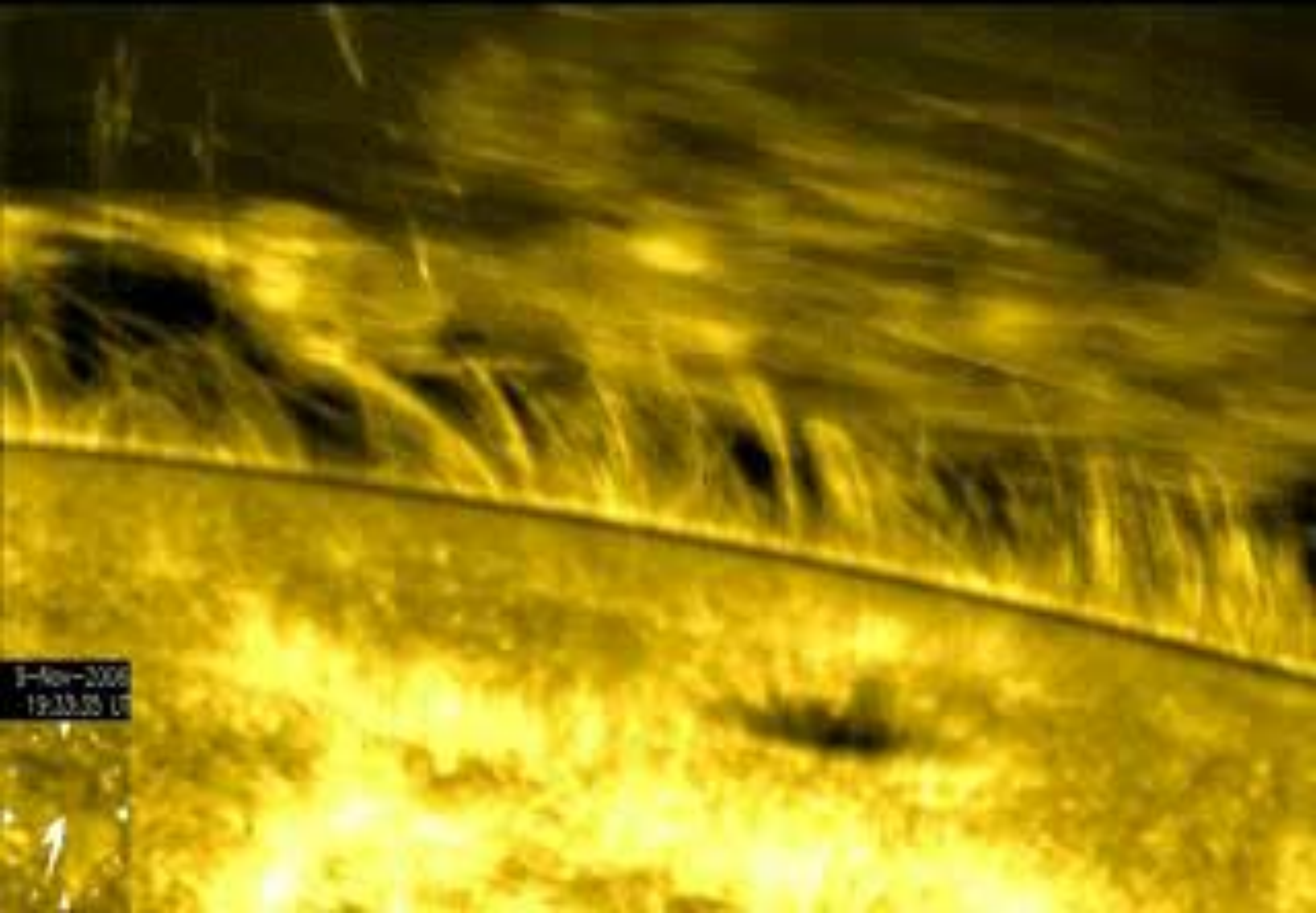
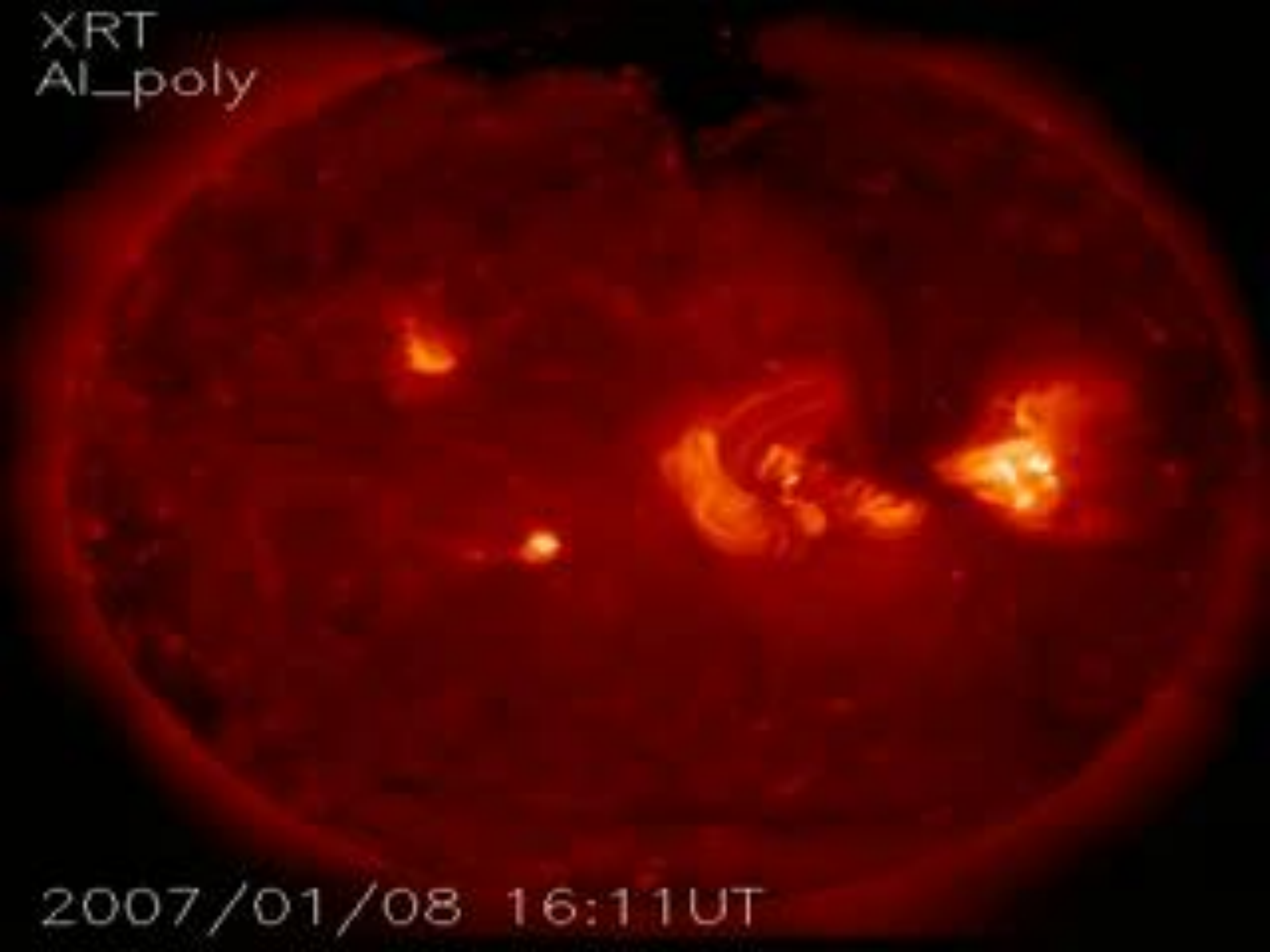



9-Nov-2006
19:33:35 UT




XRT
Al_poly
2007/01/08 16:11UT


28-AUG-92 00:17:34

MAGNETOSEISMOLOGY

- Origin & distribution of magnetic fields in solar interior
- Seat of solar dynamo & underlying mechanism governing solar activity
- Temporal evolution of magnetic fields in sub-surface layers and its relation to transient events in overlying solar atmosphere.

- Role of rapidly evolving magnetic field in explosive release of energy and acceleration of energetic particles at reconnection sites

- Identification of drivers for solar wind flows, CMEs, PEs, . . .

- Response of solar corona to time-varying magnetic activity at Sun’s surface

CONCLUSIONS

- Variations of p- & f-mode oscillation frequencies with solar activity cycle likely to result from time-varying subsurface magnetic fields of strength 20 G

- Plausible mechanism responsible for simultaneous variations of oscillation frequencies, total solar irradiance, magnetic fields and effective temperature with solar activity cycle probably reside in the sub-surface shear layer

"What we are doing is mainly a cultural and intellectual contribution – minute though it may be - to the sum total of human knowledge. And, that is why we do it and perhaps, this is our apology for what we are doing. If it should happen to have practical applications, that is very well - fine and dandy! But we think it is important that the human race understands where the sunlight comes from."

- William A. Fowler

Oh life-giving Sun,
offspring of the Lord of Creation,
Solitary star of heavens,
Spread thy light
and withdraw thy blinding Splendour
that I might behold thy radiant form.

-the Upnishads

THANK YOU