Fifty Years Of Solar Events

NOAO 50th Anniversary Symposium

The Sun is never still

- Conditions change on time scales from 10^{-6} to 10^{17} seconds, spanning 23 orders of magnitude
- On the long end, secular evolution of the internal solar structure
- On the short end, explosive magnetic reconnection in flares
- In between, many different phenomena

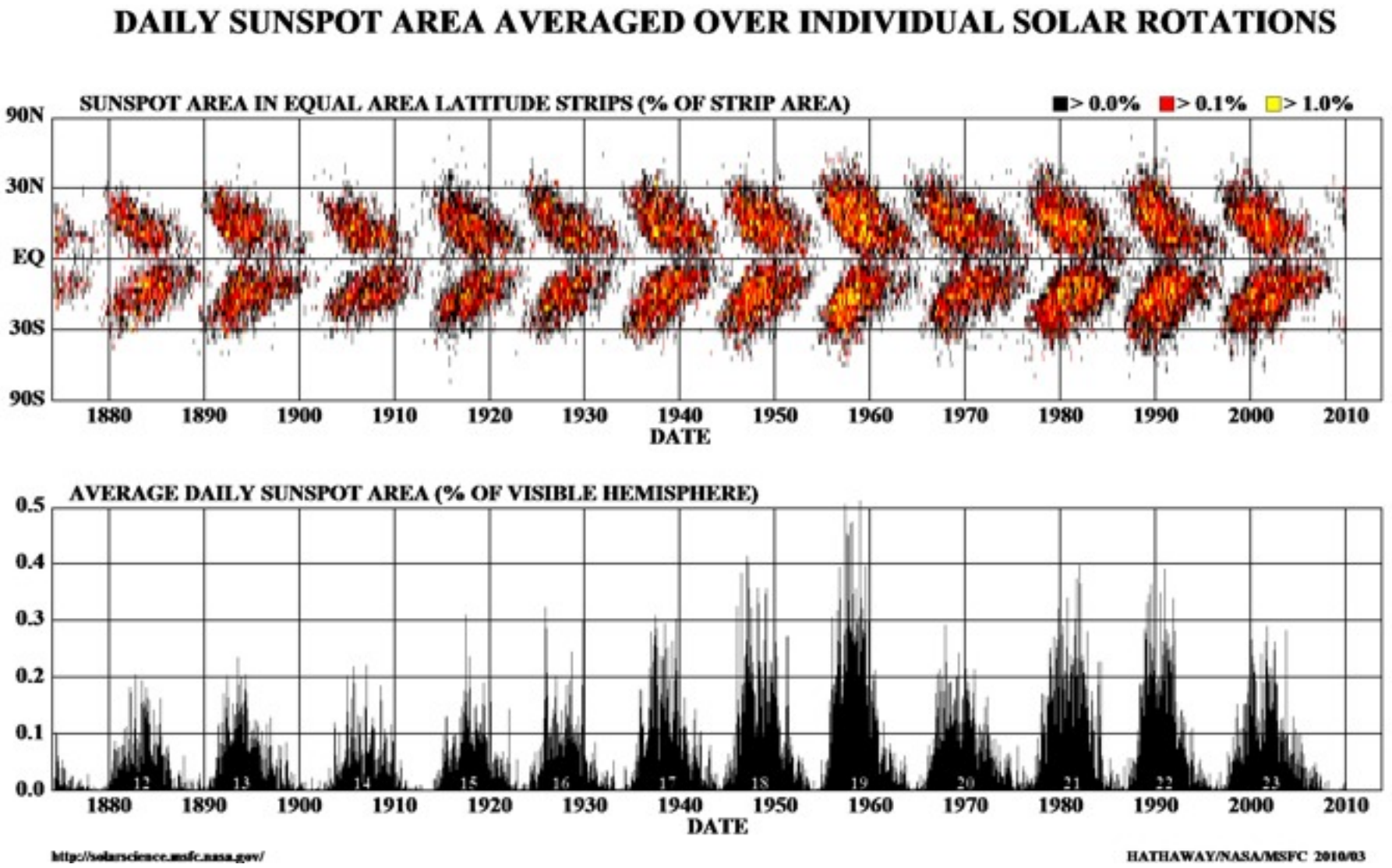
Source of solar variability

- For time scales shorter than 10^4 years, main cause of variability is the magnetic field on the surface
- This field is generated inside the Sun by plasma motions
- The most familiar phenomenon is the solar activity cycle
- Number of sunspots increases & decreases with a period of 9 to 13 years
- Dominant solar polarity flips with every sunspot cycle, so the polarity cycle is 18 to 26 years

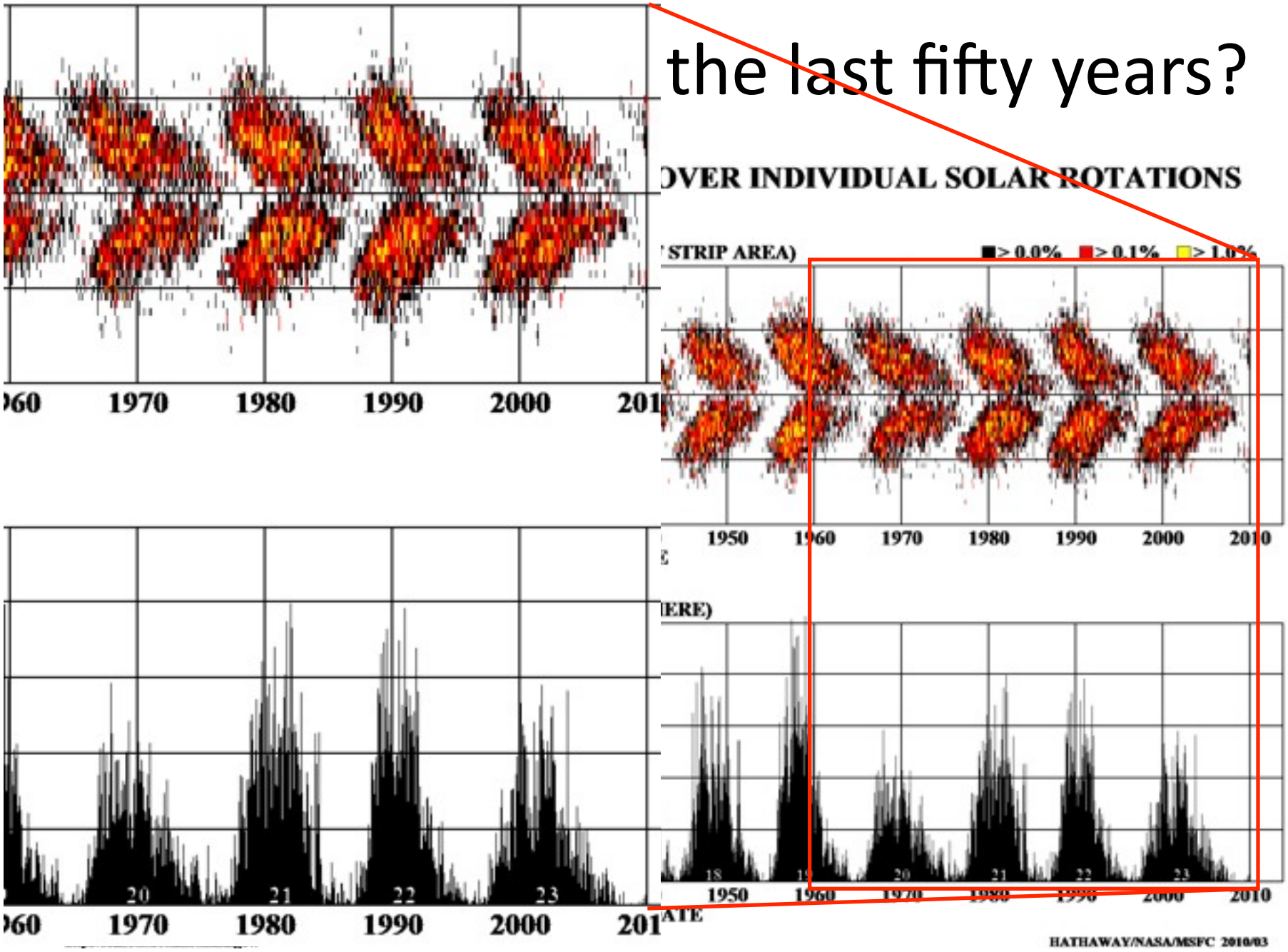
The active Sun

- High number of sunspots
- Many flares emitting energetic particles, X-rays, γ-rays, etc.
- Increased frequency of coronal mass ejections (CMEs)
- Slightly higher irradiance (0.1%)
- Rather higher irradiance in UV (20%), X-rays
- Reduced galactic cosmic ray flux
- Increased unsigned global magnetic field strength

What happened in the last fifty years?



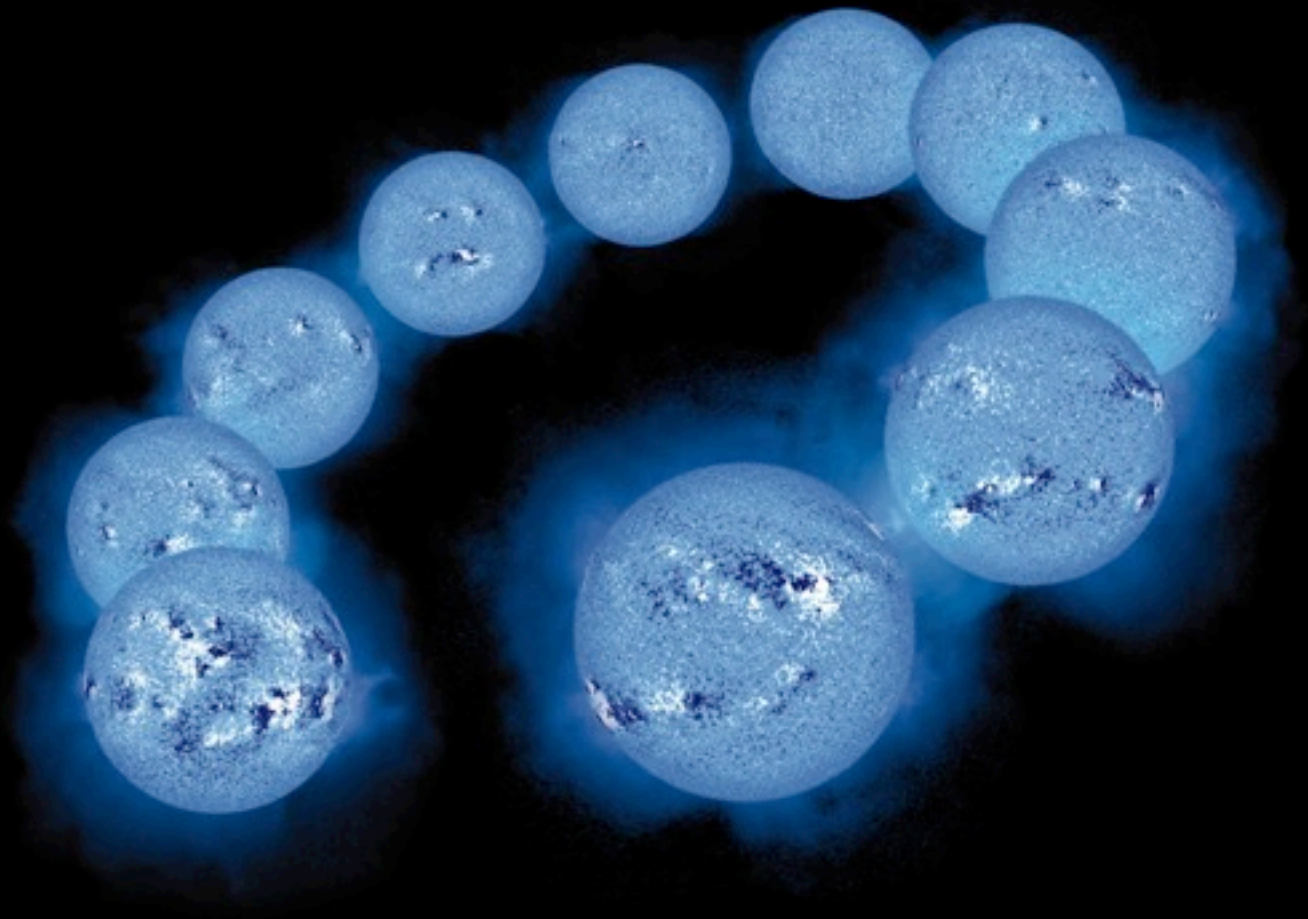
the last fifty years?



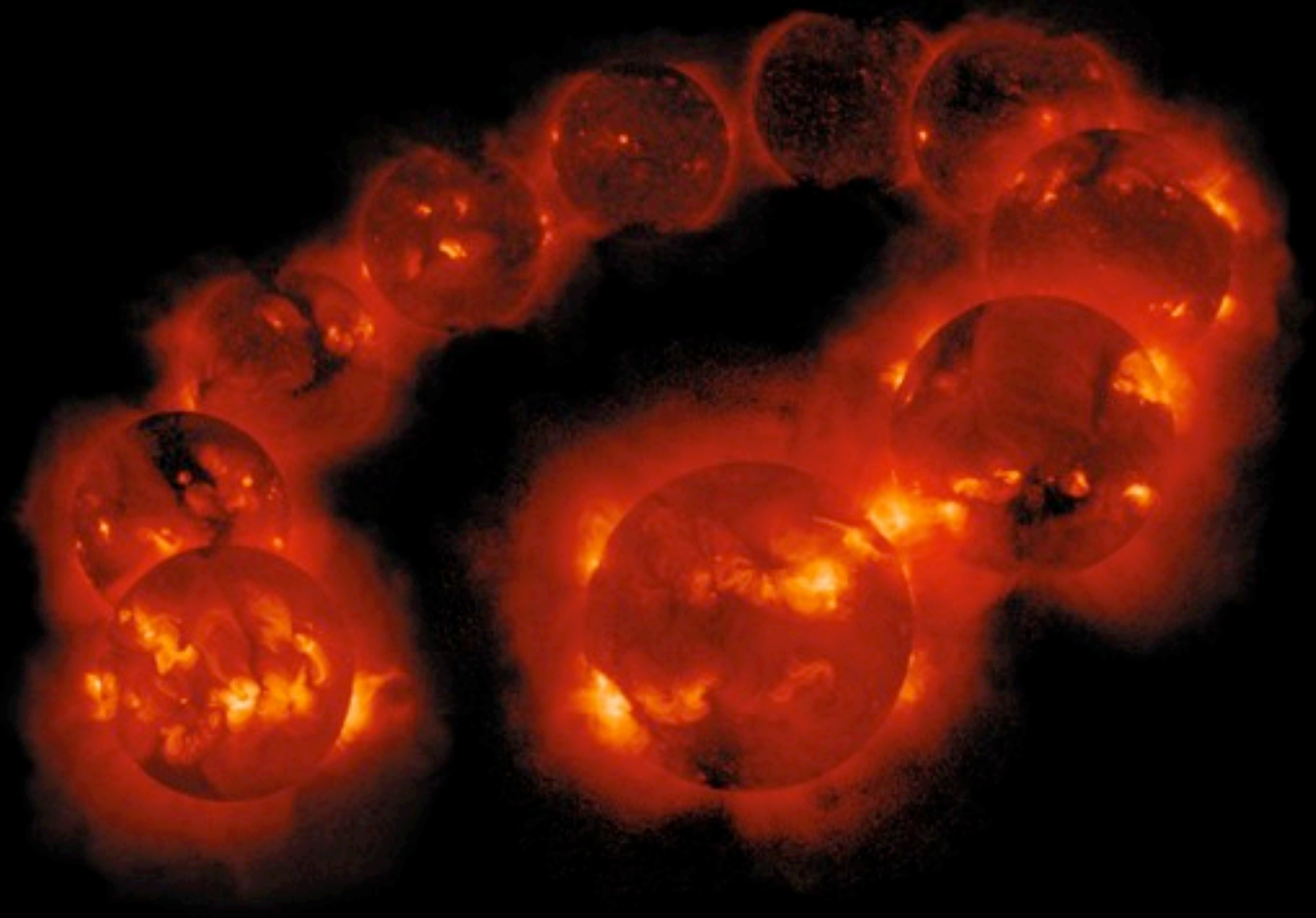
Highlights of cycles 19-24

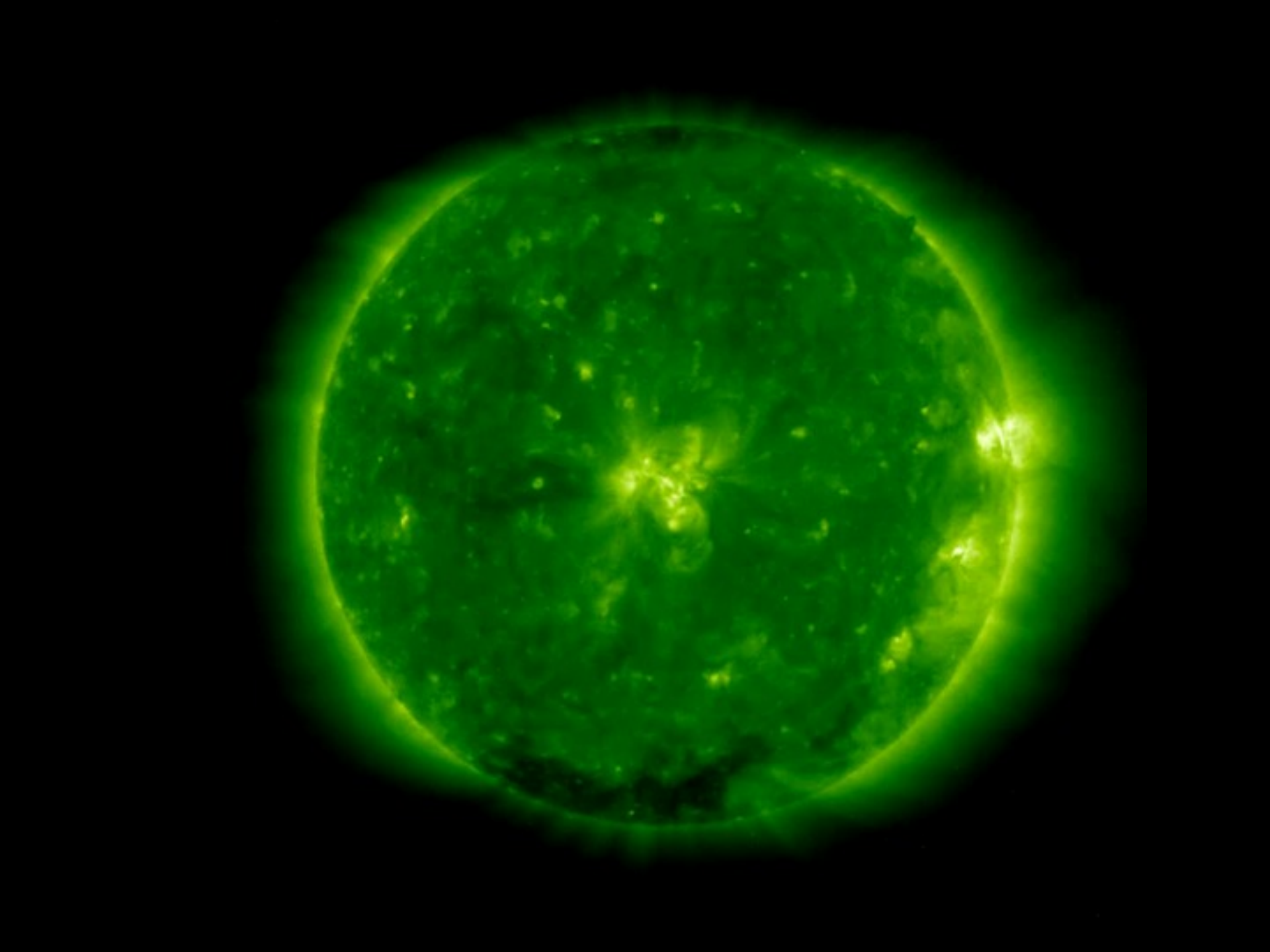
- Coincident with the birth of the space age, IGY
- Activity in cycle 19 was highest since Maunder Minimum
- Largest solar flare in modern era on November 4, 2003 (X17)
- Power grid failure March 13, 1989 in Quebec from solar activity
- Deep solar minimum just now ending

The surface magnetic field through the cycle



The solar x-ray flux through the cycle





Halloween 2003 on the Sun

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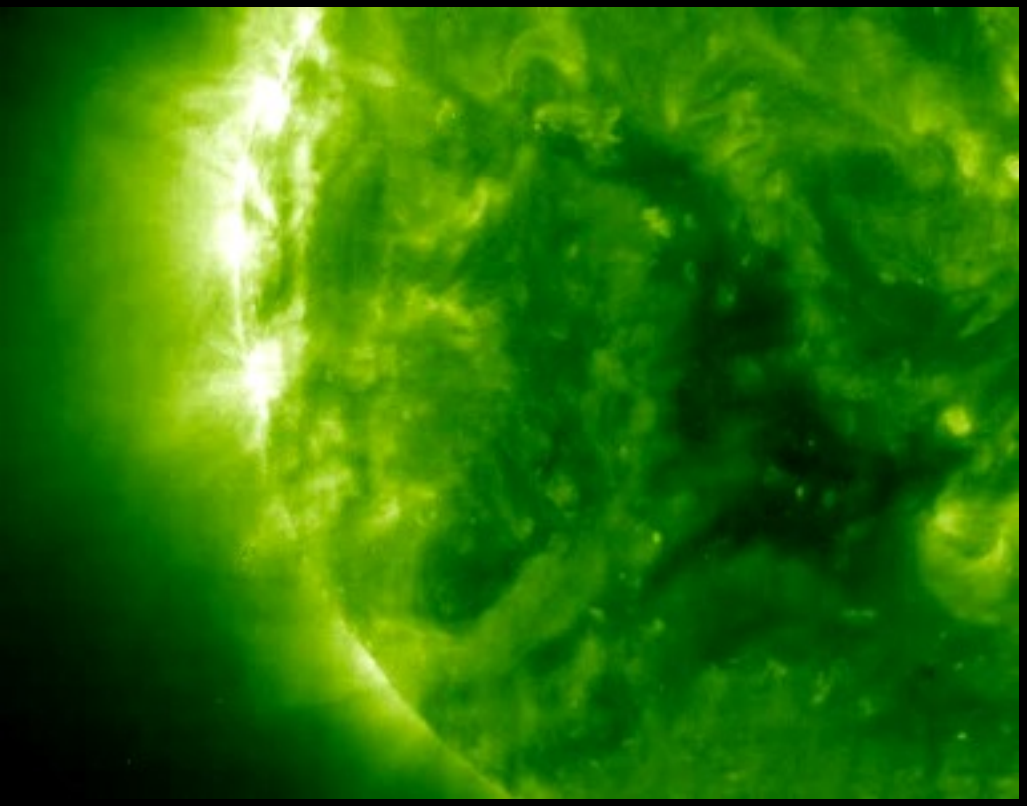
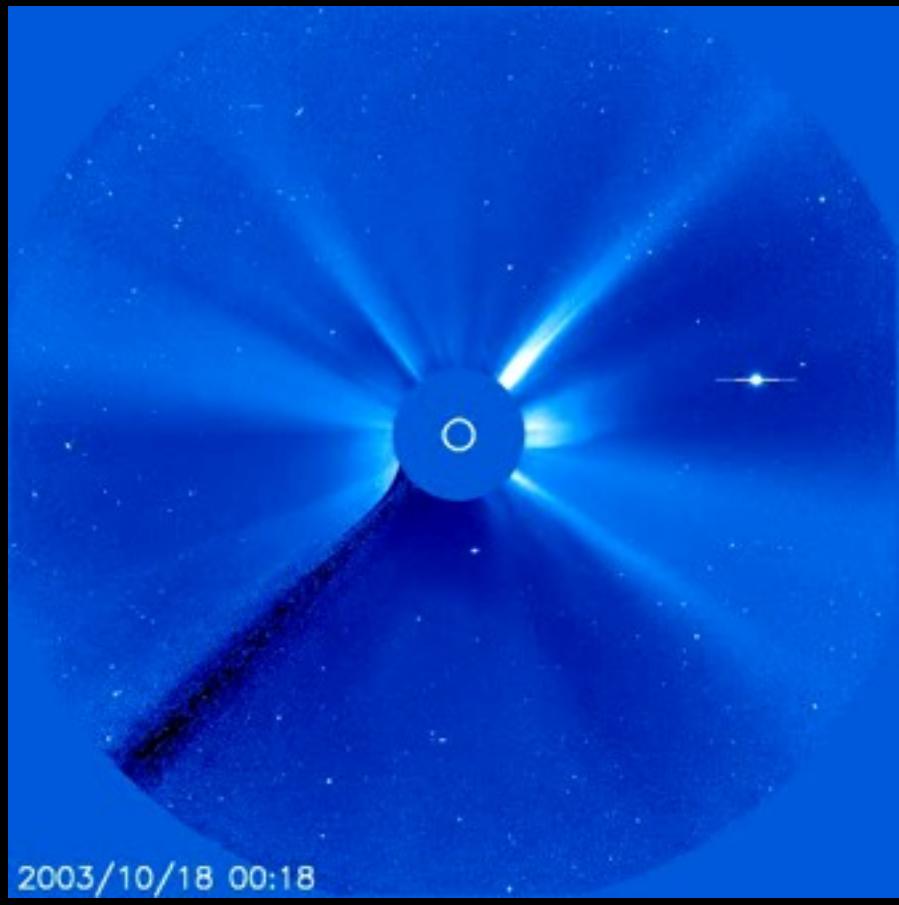
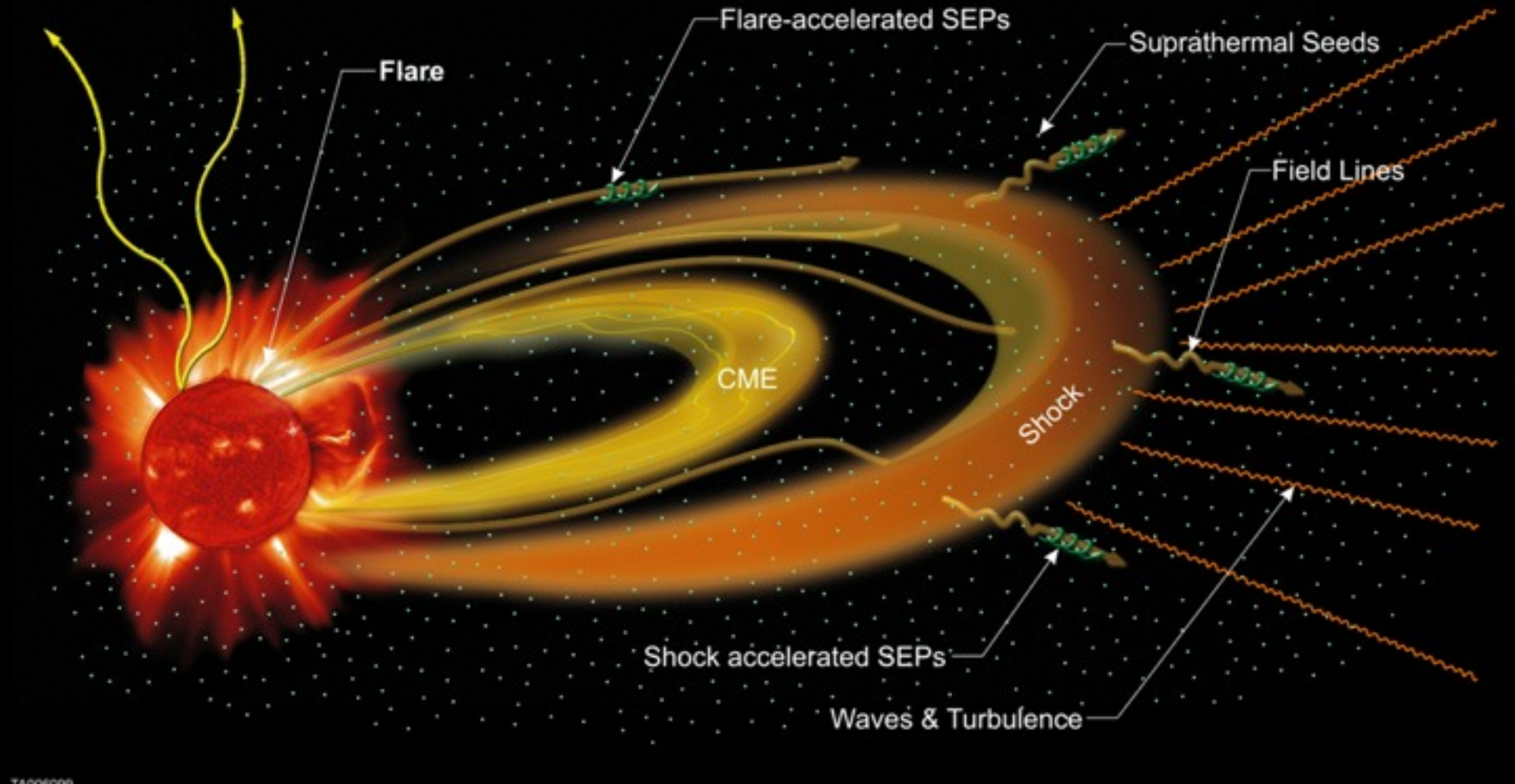
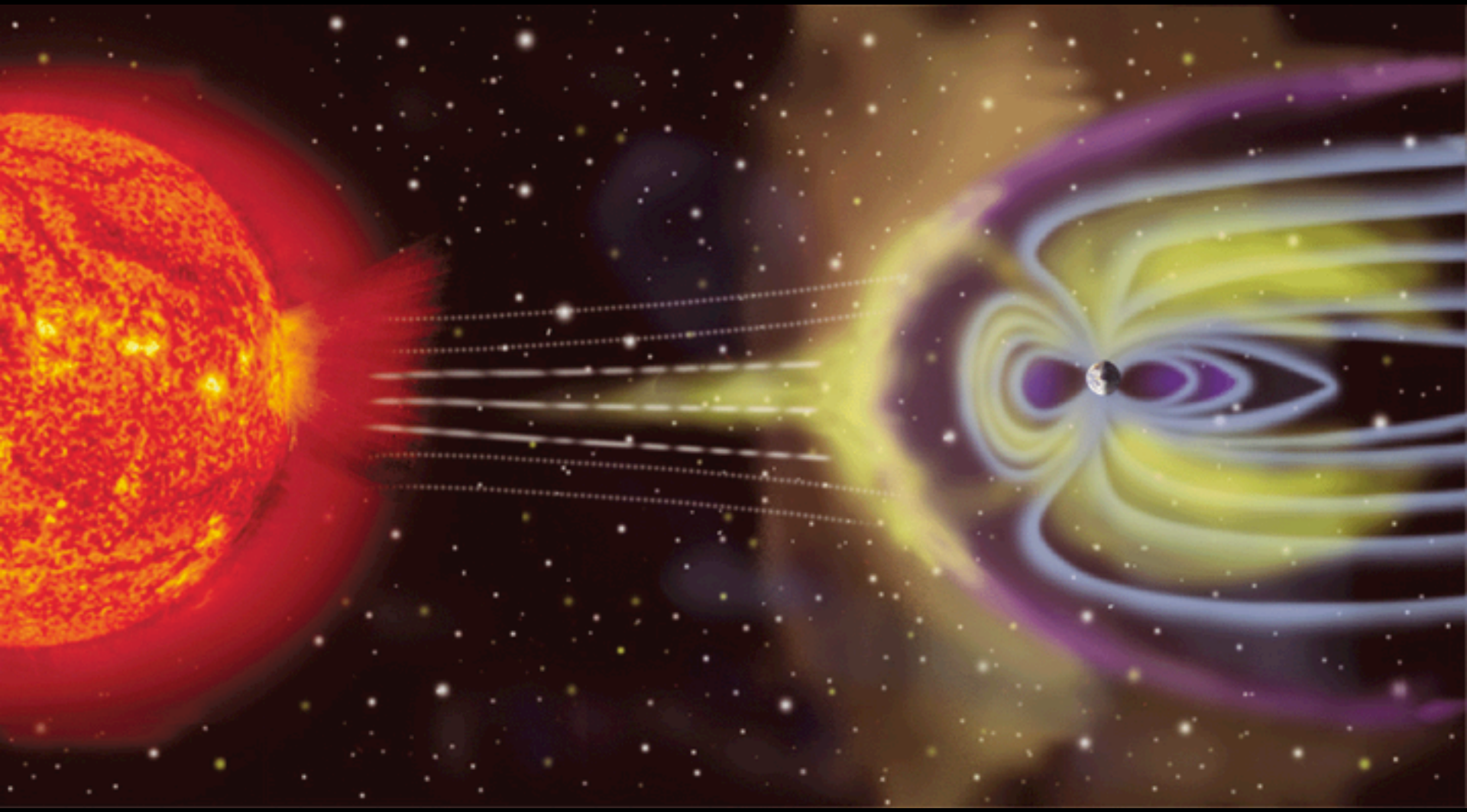




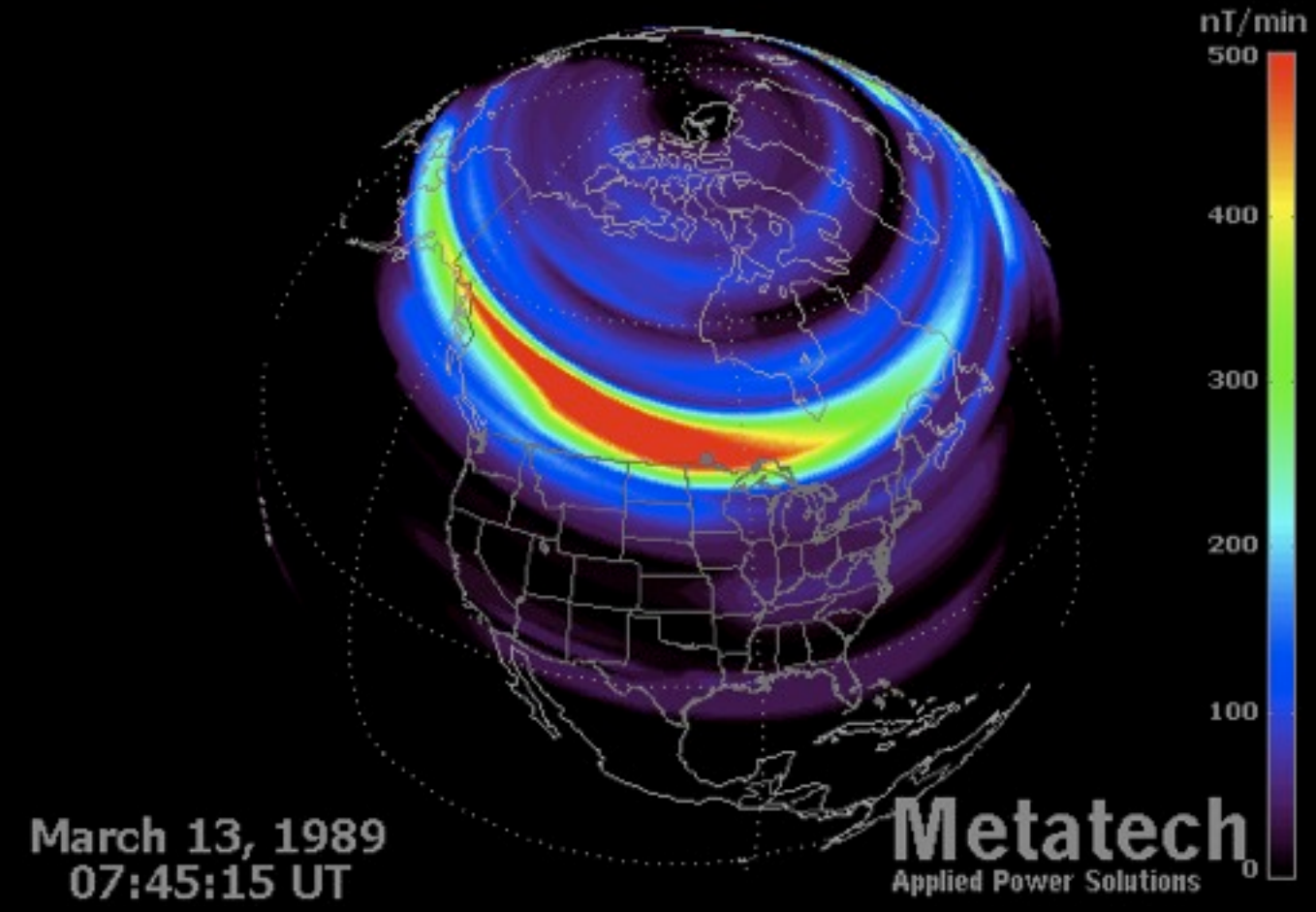
The Sun spits up a lot



Effect of the Sun on the Earth (Not to scale)



The geomagnetic storm of March 13, 1989



Quebec went dark at 7:45 UT

The current minimum is unusual

- Longer than average
- Most spotless days (so far) since cycle 15
- Lowest global solar wind pressure of the space age
- Solar magnetic field 36% weaker than last minimum
- Lowest irradiance yet measured
- Lowest sustained 10.7-cm radio flux since 1947
- Unusually high tilt of dipole field
- No classical quiescent equatorial streamer belt
- Very high cosmic ray flux
- Odd behavior of *p*-mode frequencies

- But it seems to be over….

What causes the solar cycle?

- Flux-Transport Dynamo theory:
  - Differential rotation winds up the internal poloidal (N-S) magnetic field into a toroidal (E-W) field
  - As the field is wound up, its strength increases, and it becomes buoyant
  - The field breaks through the surface, reconnects in the corona, and returns to a poloidal configuration
  - Meridional plasma flows move the field from equator to pole at the surface and pole to equator deeper down

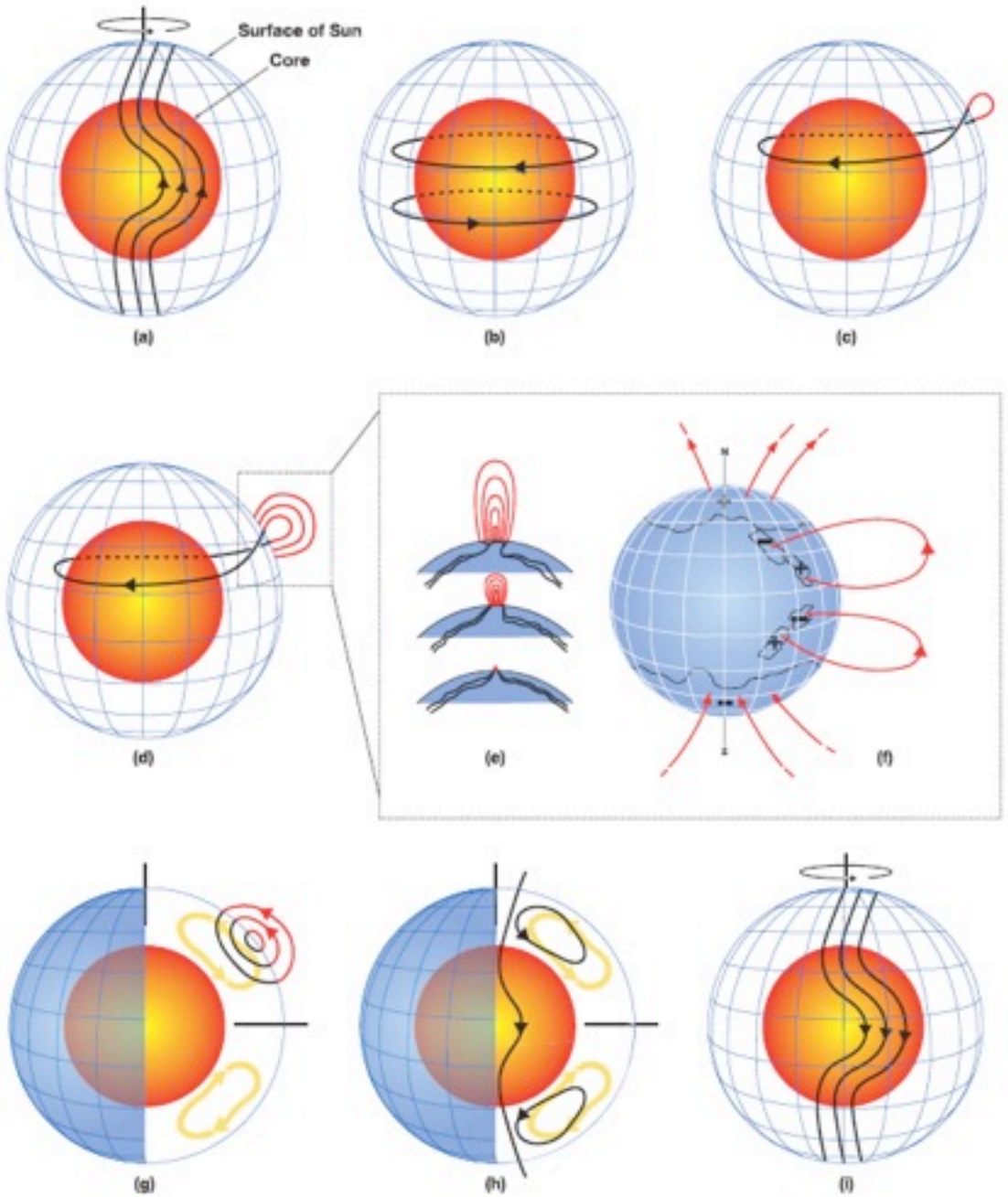
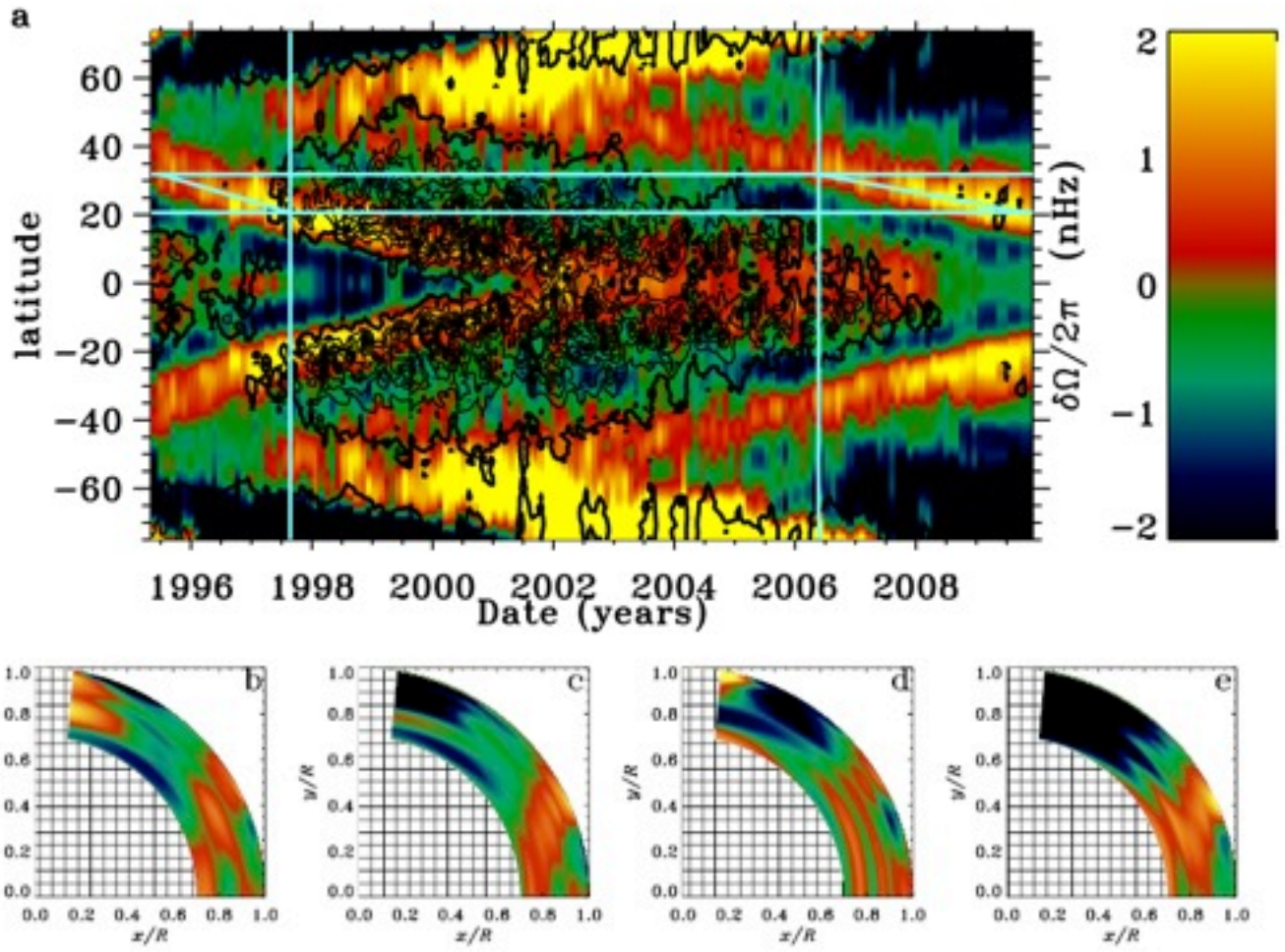


Fig. 2. Schematic of solar flux-transport dynamo processes. Red inner sphere represents the Sun's radiative core and blue mesh the solar surface. In between is the solar convection zone where dynamo resides.
(a) Shearing of poloidal field by the Sun's differential rotation near convection zone bottom. The Sun rotates faster at the equator than the pole.
(b) Toroidal field produced due to this shearing by differential rotation.
(c) When toroidal field is strong enough, buoyant loops rise to the surface, twisting as they rise due to rotational influence. Sunspots (two black dots) are formed from these loops.
(d, e, f) Additional flux emerges (d, e) and spreads (f) in latitude and longitude from decaying spots.
(g) Meridional flow (yellow circulation with arrows) carries surface magnetic flux poleward, causing polar fields to reverse.
(h) Some of this flux is then transported downward to the bottom and towards the equator. These poloidal fields have sign opposite to those at the beginning of the sequence, in frame (a).
(i) This reversed poloidal flux is then sheared again near the bottom by the differential rotation to produce the new toroidal field opposite in sign to that shown in (b).

Internal flows cause the cycle

- Differential rotation winds the field up
- Helioseismology revealed the internal pattern of rotation and discovered the tachocline
- Meridional (N-S) flow moves the field in latitude – a key ingredient for FTD
- Speed of deep meridional flow sets period and strength of cycle
- Helioseismology trying to measure the deep meridional flow, but it is difficult
- But there is also something missing from the FTD picture – the zonal (E-W) flows

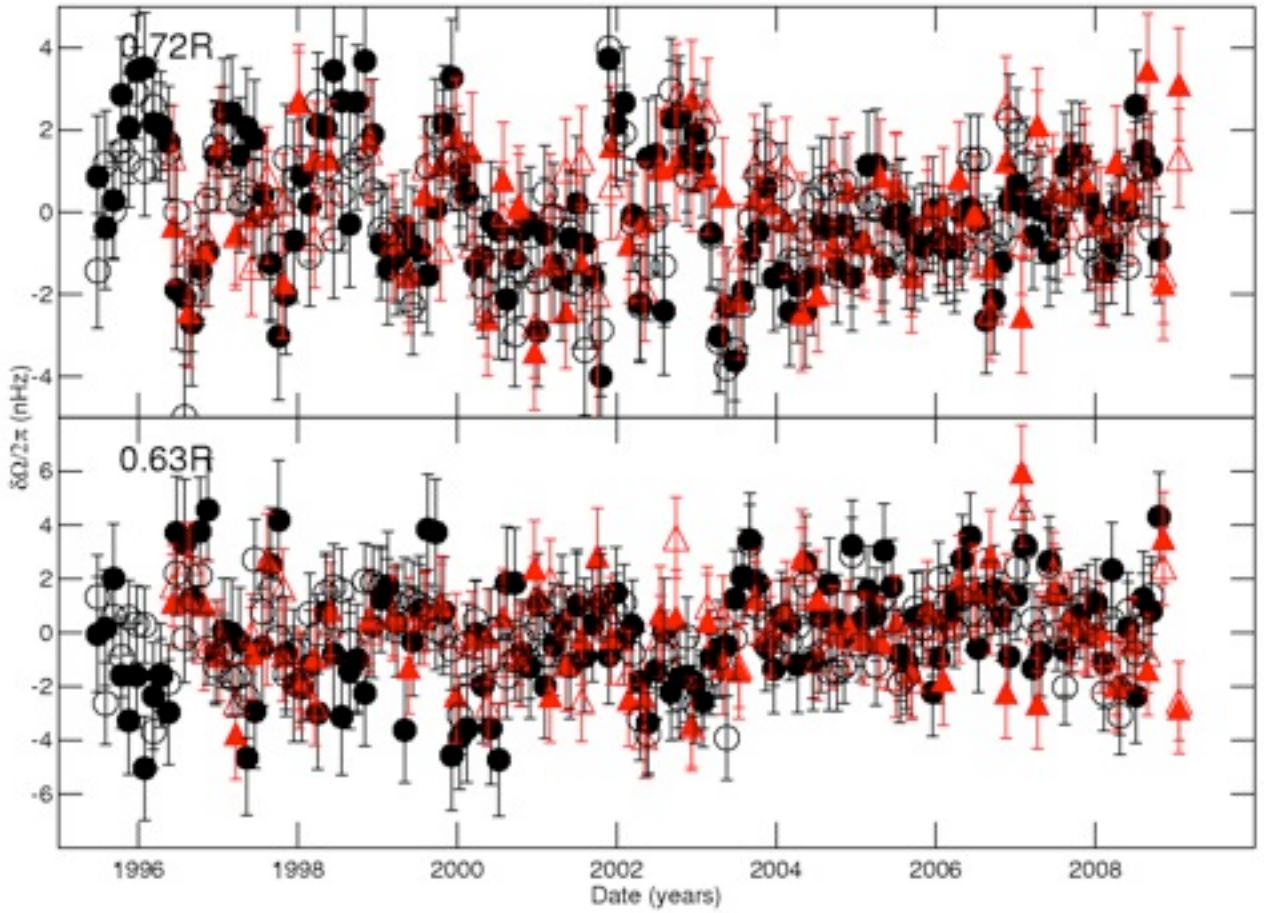
Solar cycle timing from the “torsional oscillation”



Slow migration of flow towards equator coincided with extended minimum. Predicted that when flow reached ~22°, then solar activity would increase. It did.

(R. Howe)

Another intriguing thing…



The rotation rate at the solar tachocline varied (maybe periodically) in the first part of cycle 23, but stopped. Is this related to the deep minimum preceding cycle 24?

The Sun and the Earth

- Solar activity affects the Earth and terrestrial society
  - GPS
  - Telecommunications
  - Space hardware & astronauts
  - Power grids
  - Polar airline flights
- Thus considerable interest in predicting "Space Weather"

Flows below active regions

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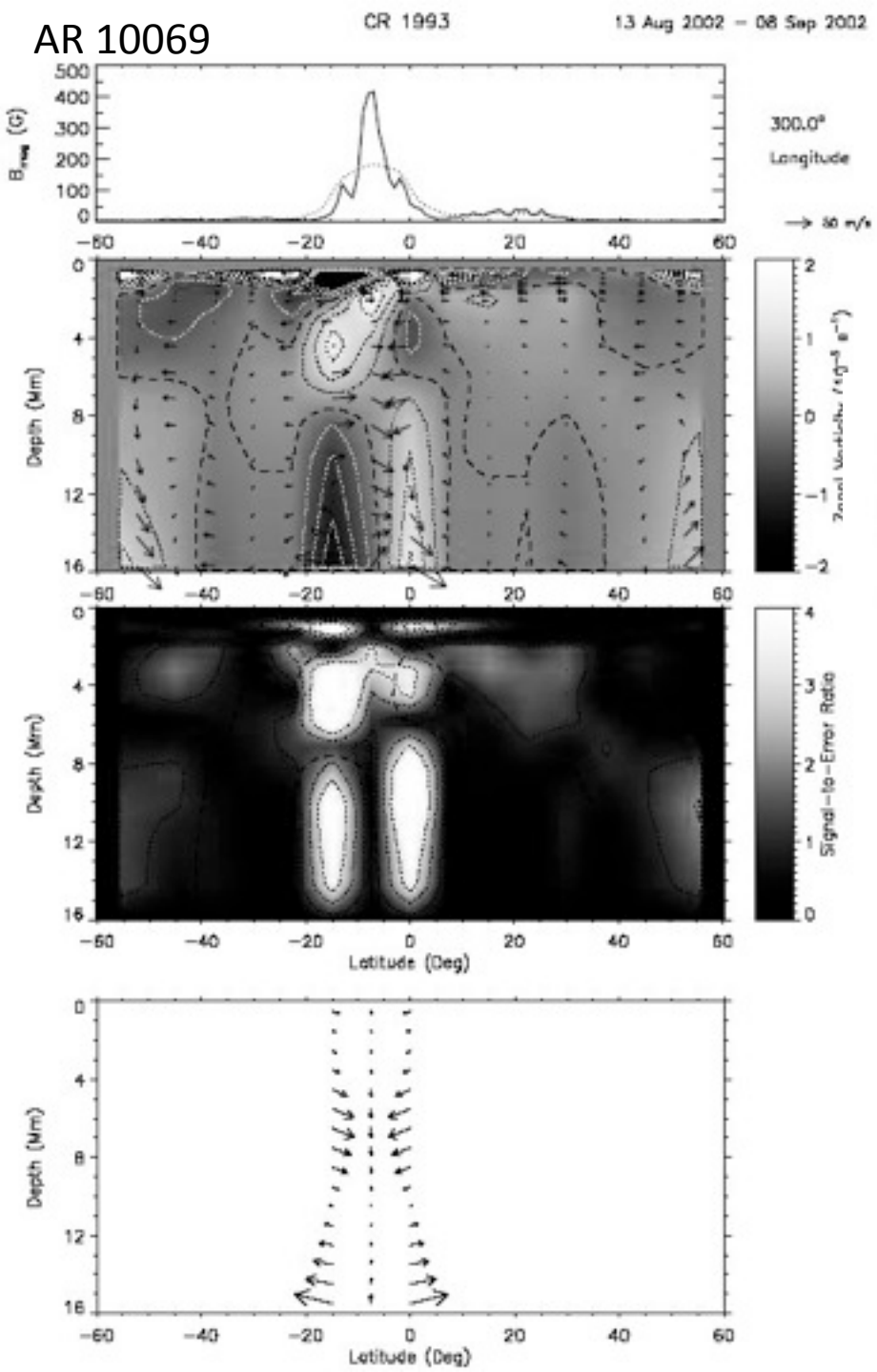
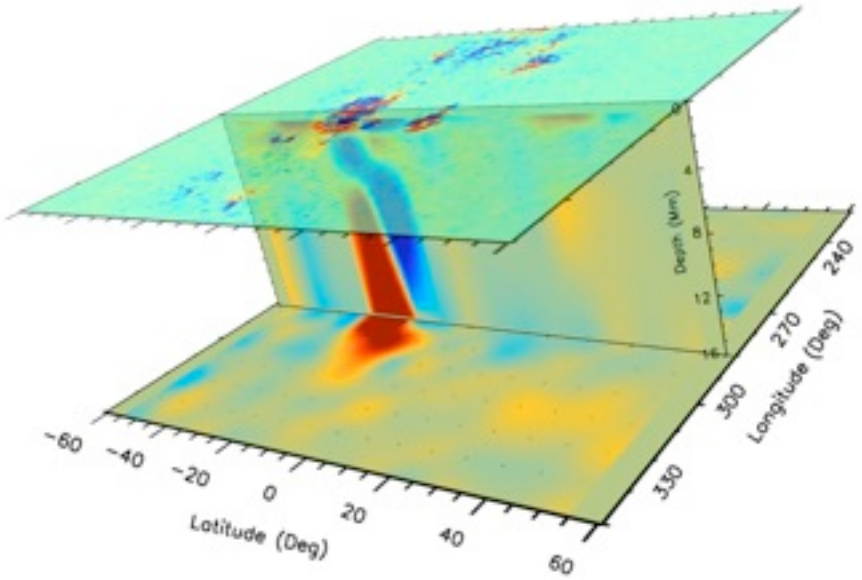


Fig. 4.— Zonal vorticity, ω_x, at 300° longitude in CR 1993 as a function of latitude and depth. *Top:* gross magnetic flux (solid line) and binned over 15° (dotted line); *2nd:* the x-component of vorticity (ω_x); *3rd:* the signal-to-error ratio. The arrows represent the meridional and vertical velocity components with the vertical one increased by a factor of 10 for visibility. *Bottom:* idealized schematic for flows below a strong active region (with arbitrary amplitudes).



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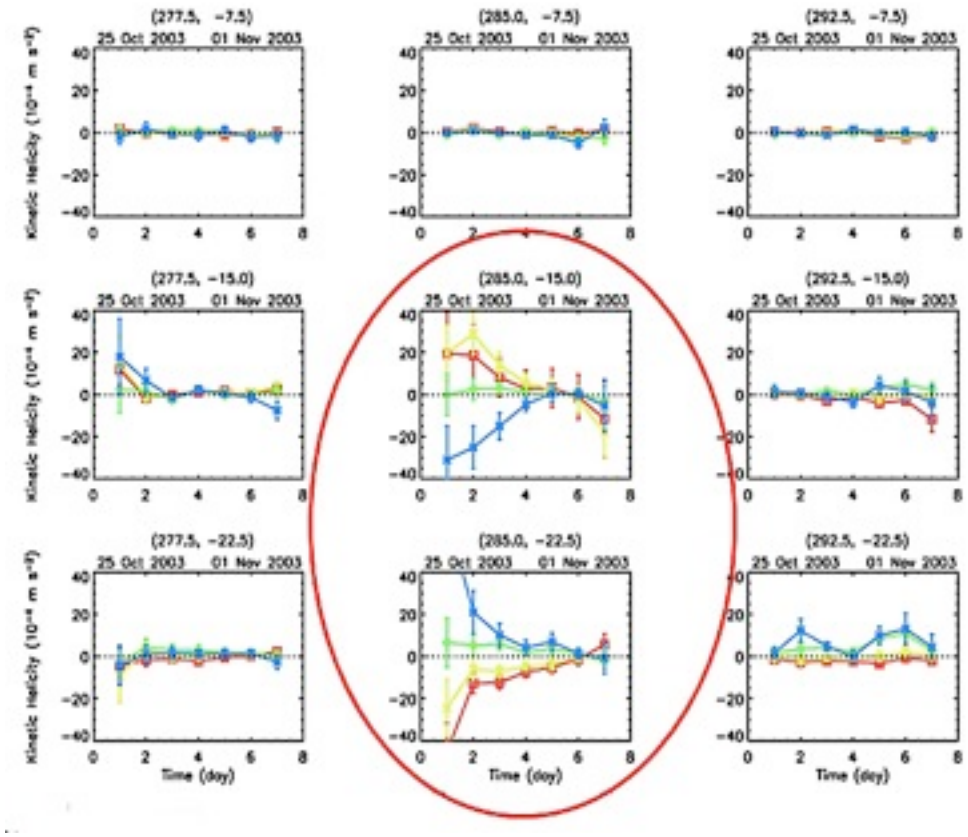
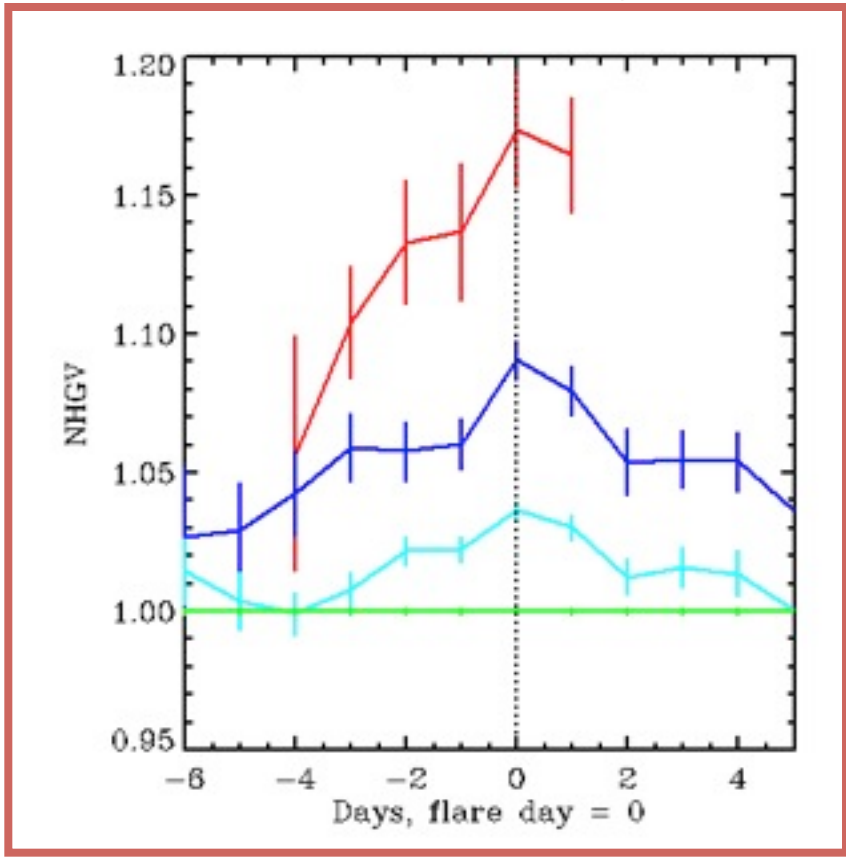
Flare forecasts from subsurface vorticity





Active regions with both strong subsurface vorticity (twisting motions) and high surface magnetic field are almost certain to produce many energetic flares

The vorticity changes rapidly before a flare occurs, starting as many as three days in advance of the flare.

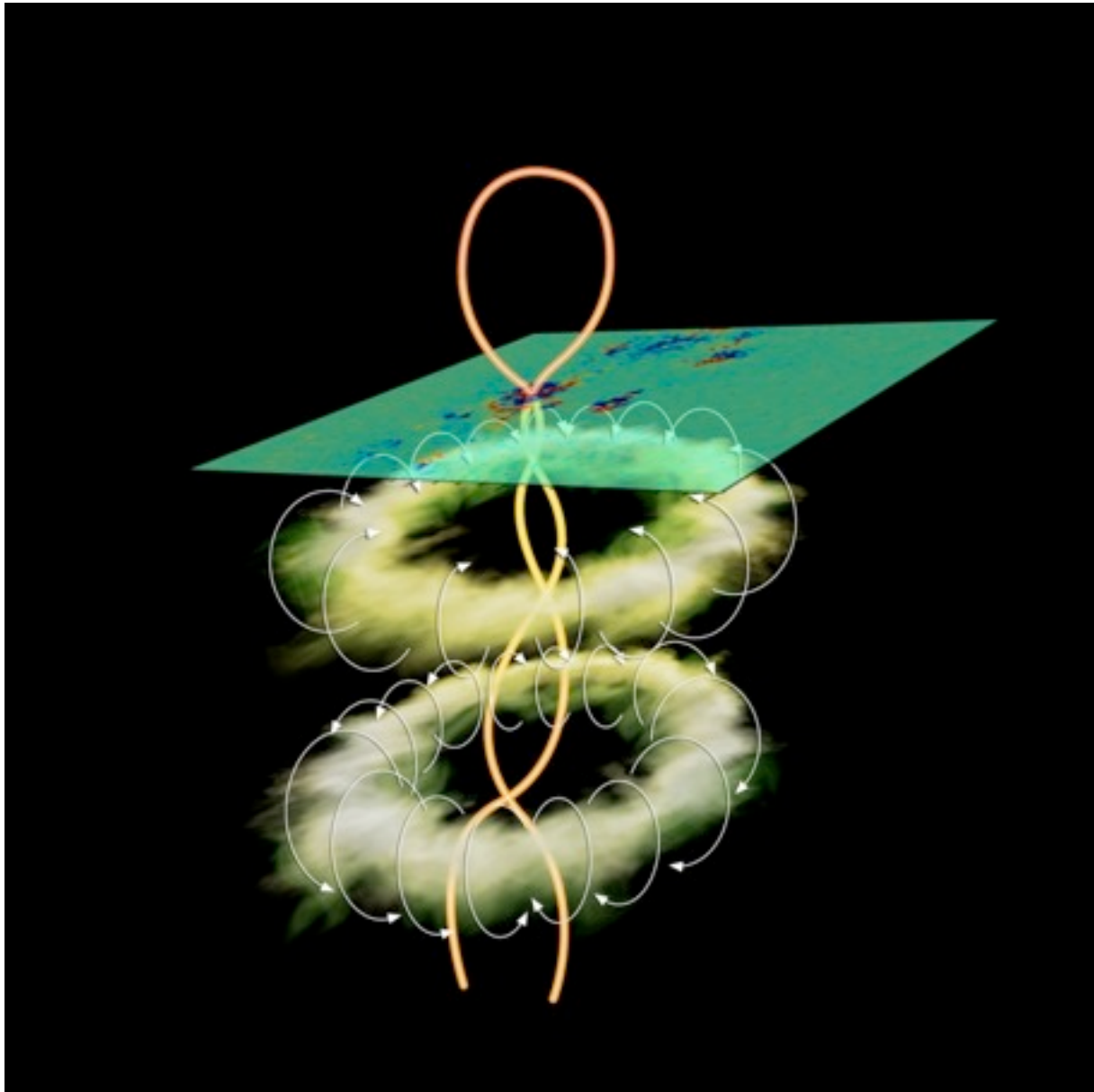
The predictive capability is twice that of current methods, and likely can be improved

A Reinard , J. Henthorn, R. Komm

Physical scenario

Convective rolls or “smoke rings” twist the flux tube

Need detailed models of the process



NOAO's contribution

- Solar events are also terrestrial events
- As society becomes more dependent on technology, the understanding of solar activity becomes more important
- NOAO, through NSO, has played a vital role in this understanding
- ATST, SOLIS and GONG will continue to be in the forefront of the science