Symposium to Celebrate the 50th Anniversary of the Princeton Plasma Physics Laboratory

Magnetic Activity of the Sun and Stars

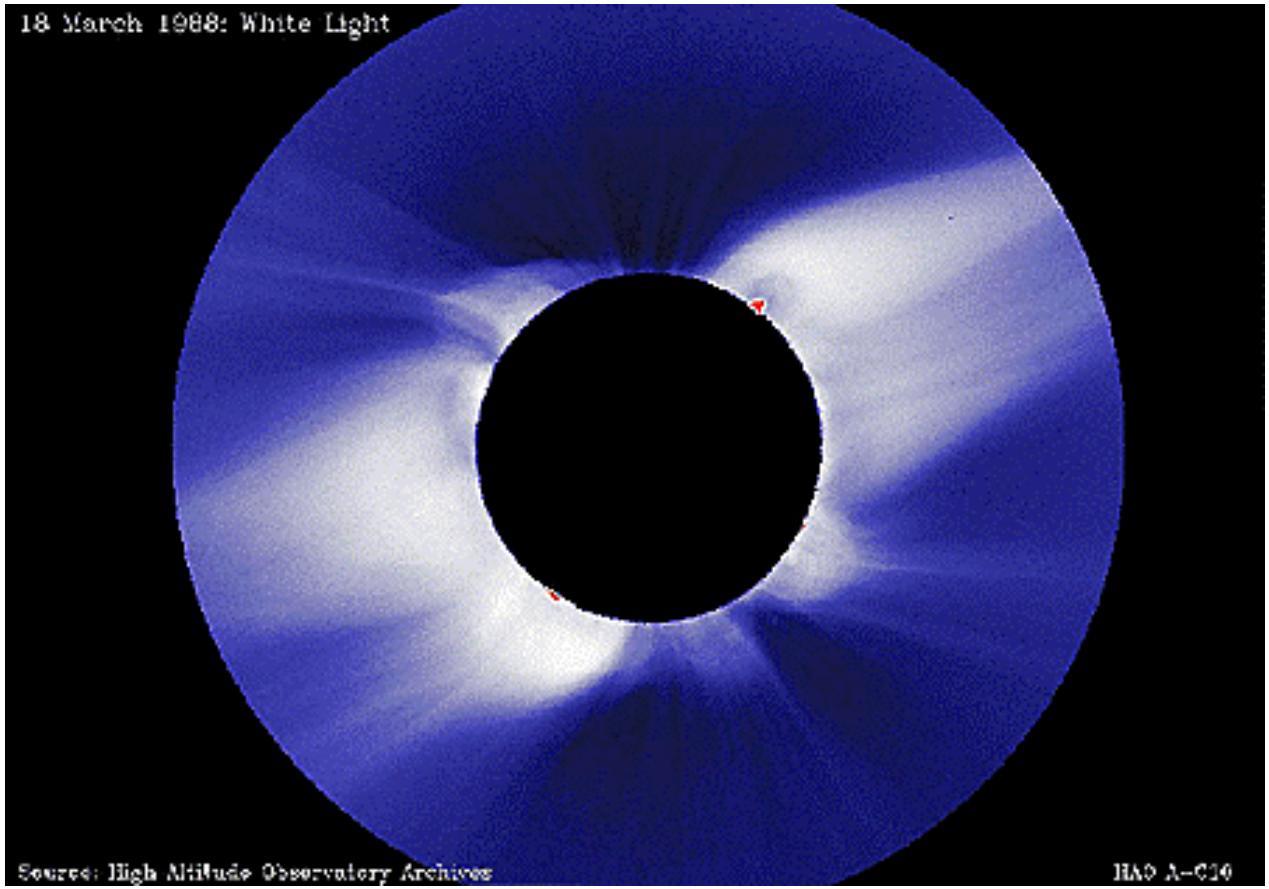
Robert Rosner
The University of Chicago

June 6, 2002
Princeton Plasma Physics Laboratory
Princeton, NJ

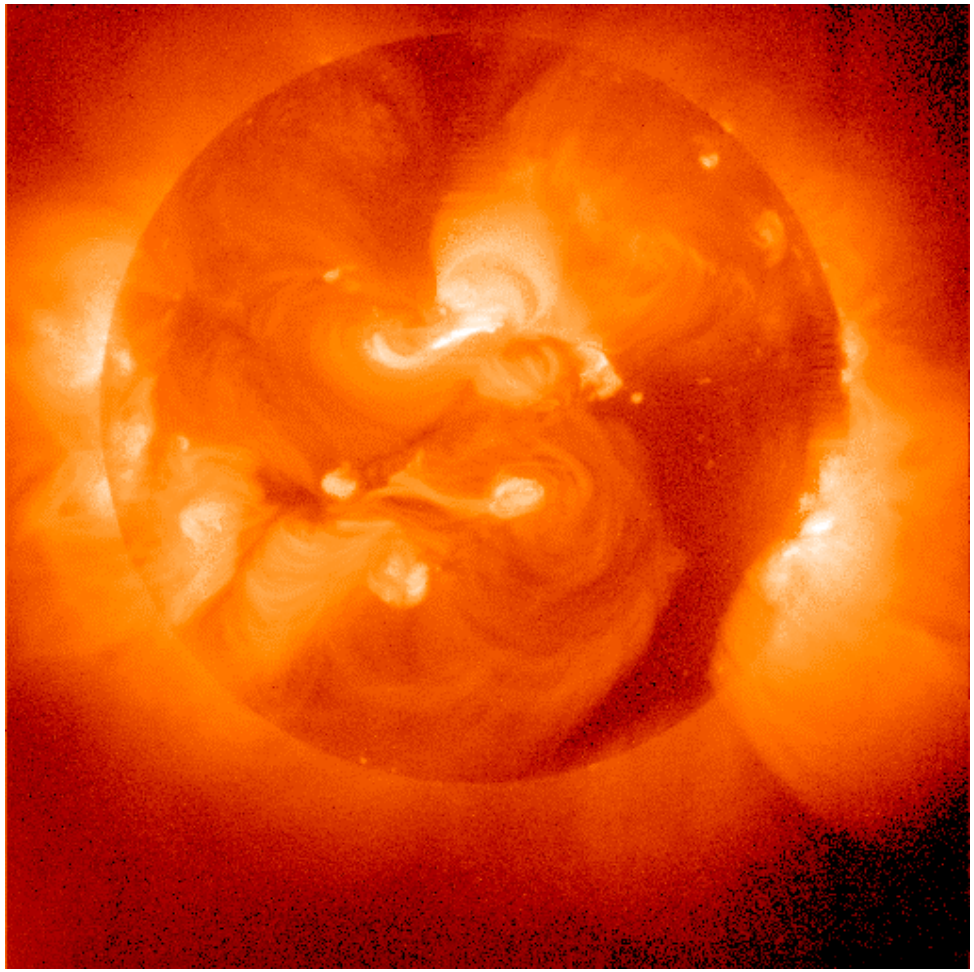
The visible Sun is “blemished” …

Image courtesy NSO

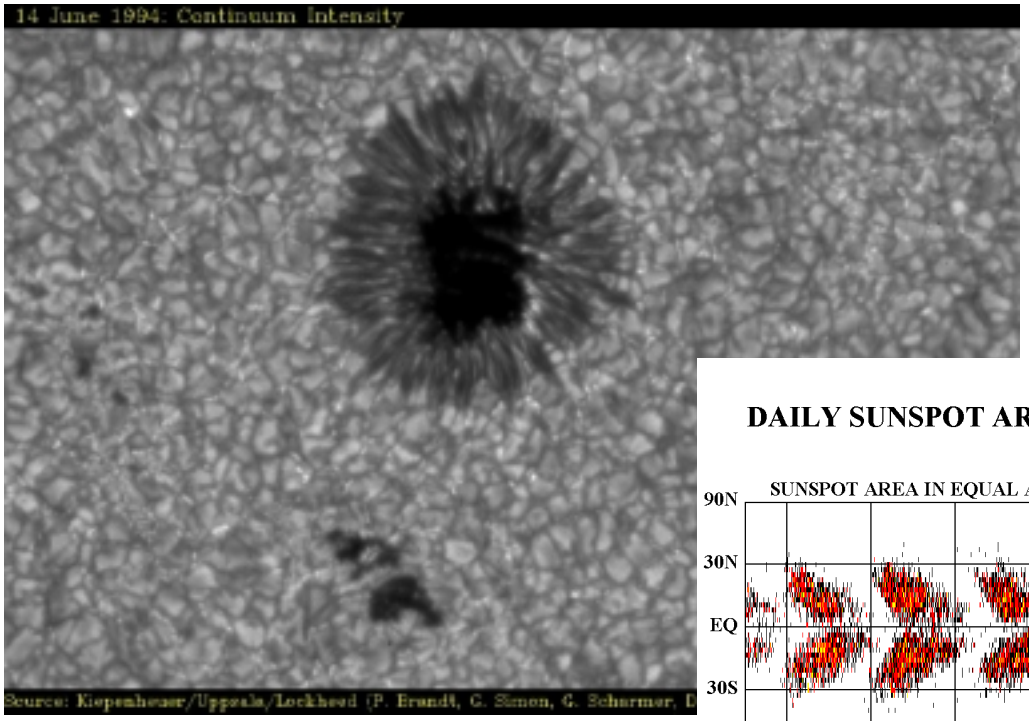
… but how is it connected with coronal activity?

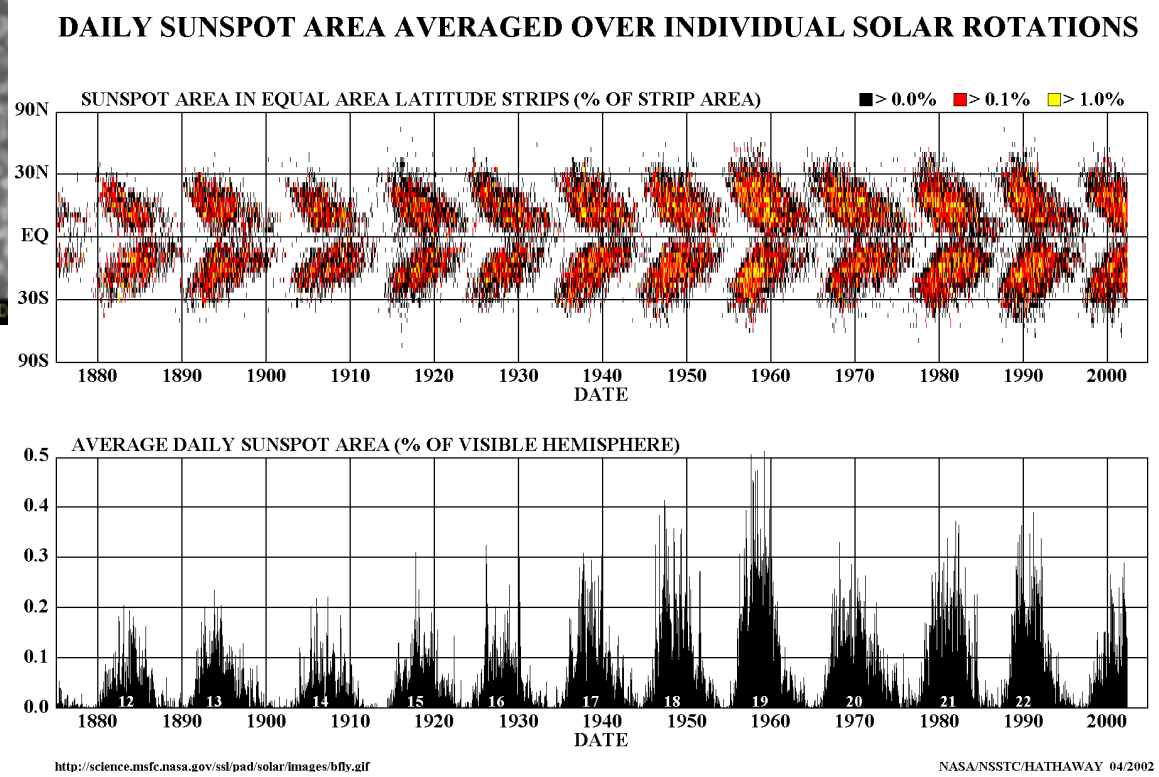


Establishing the connection: *Skylab*



Order out of chaos?

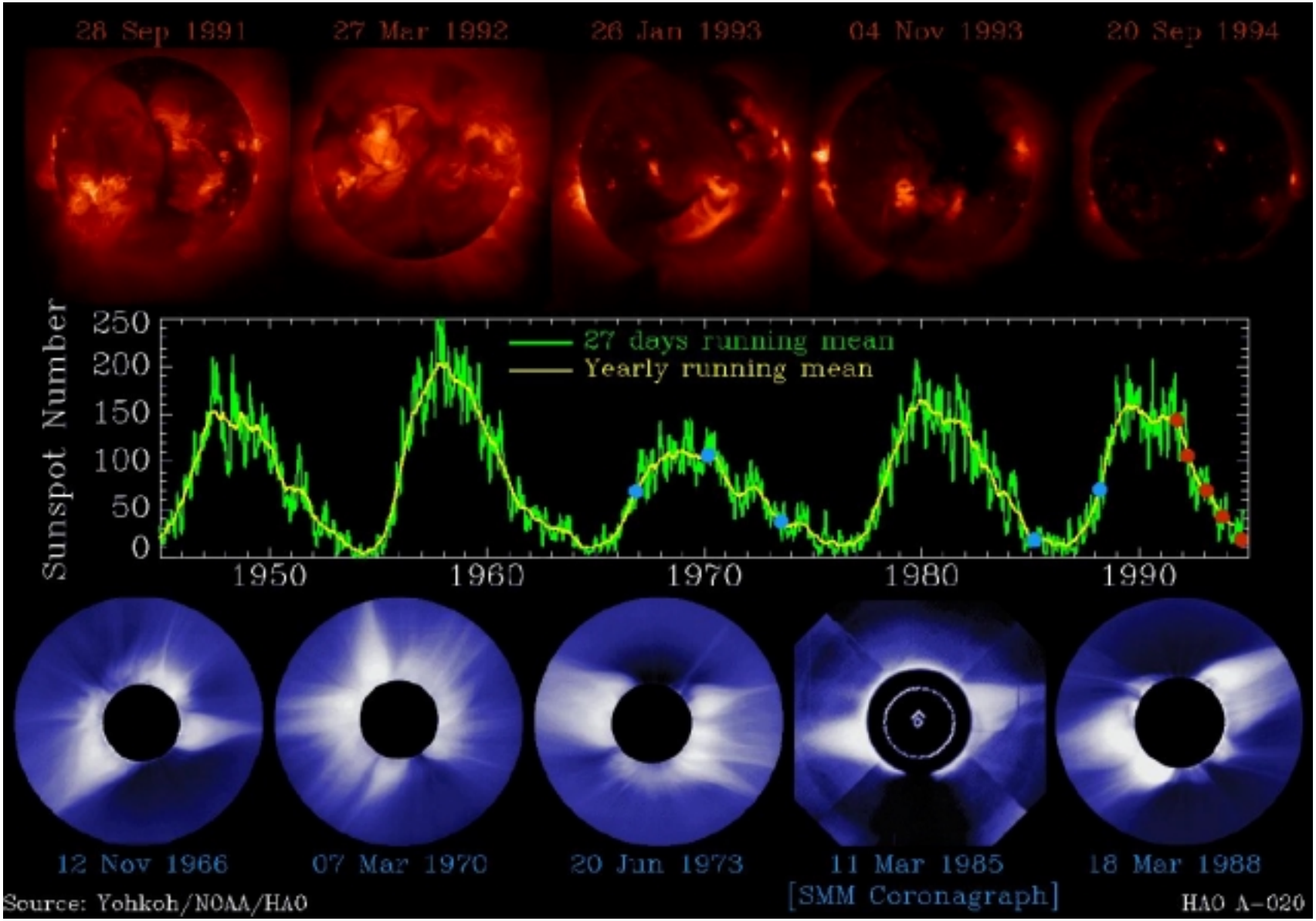




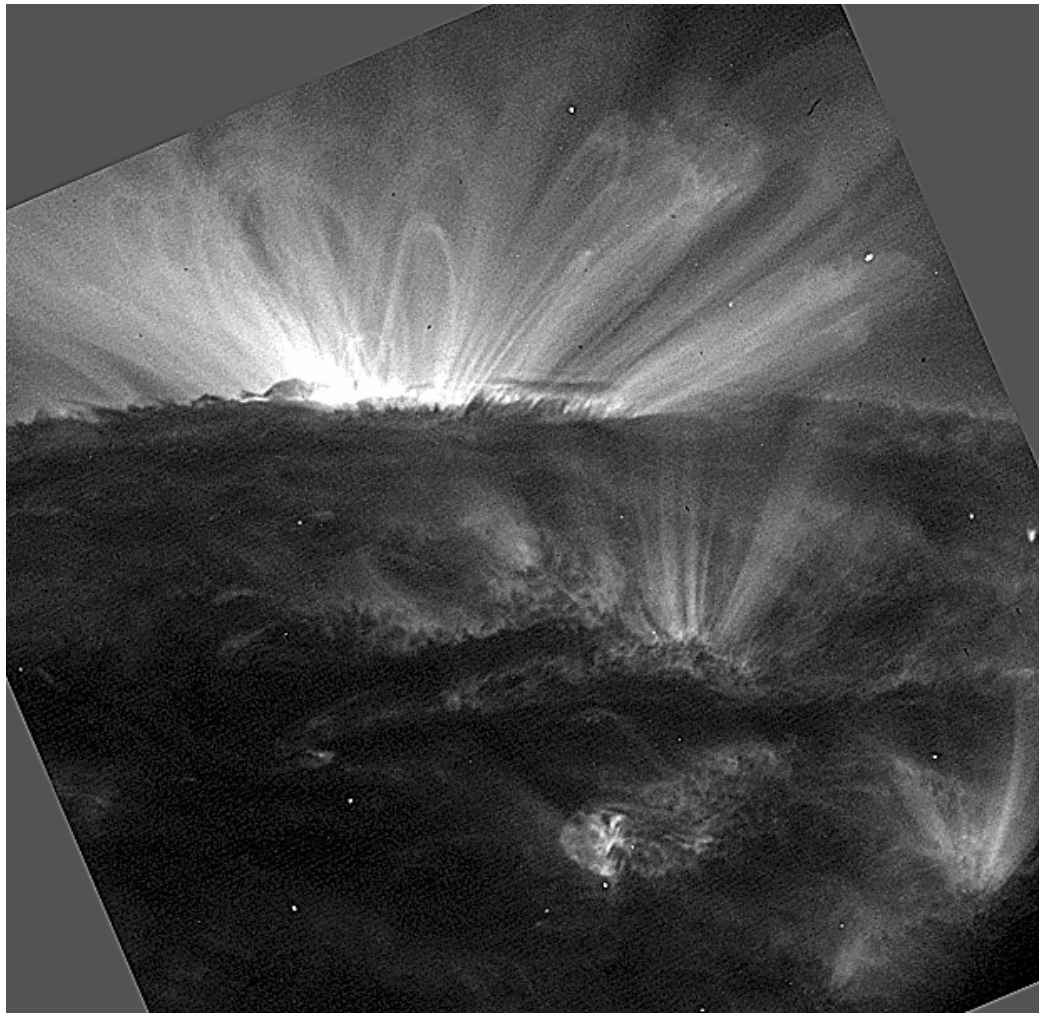
The great regularities:

- o periodicity ~ 22 yrs
- o Butterfly diagram
- o Hale polarity law

Order emerges at the coronal level as well …

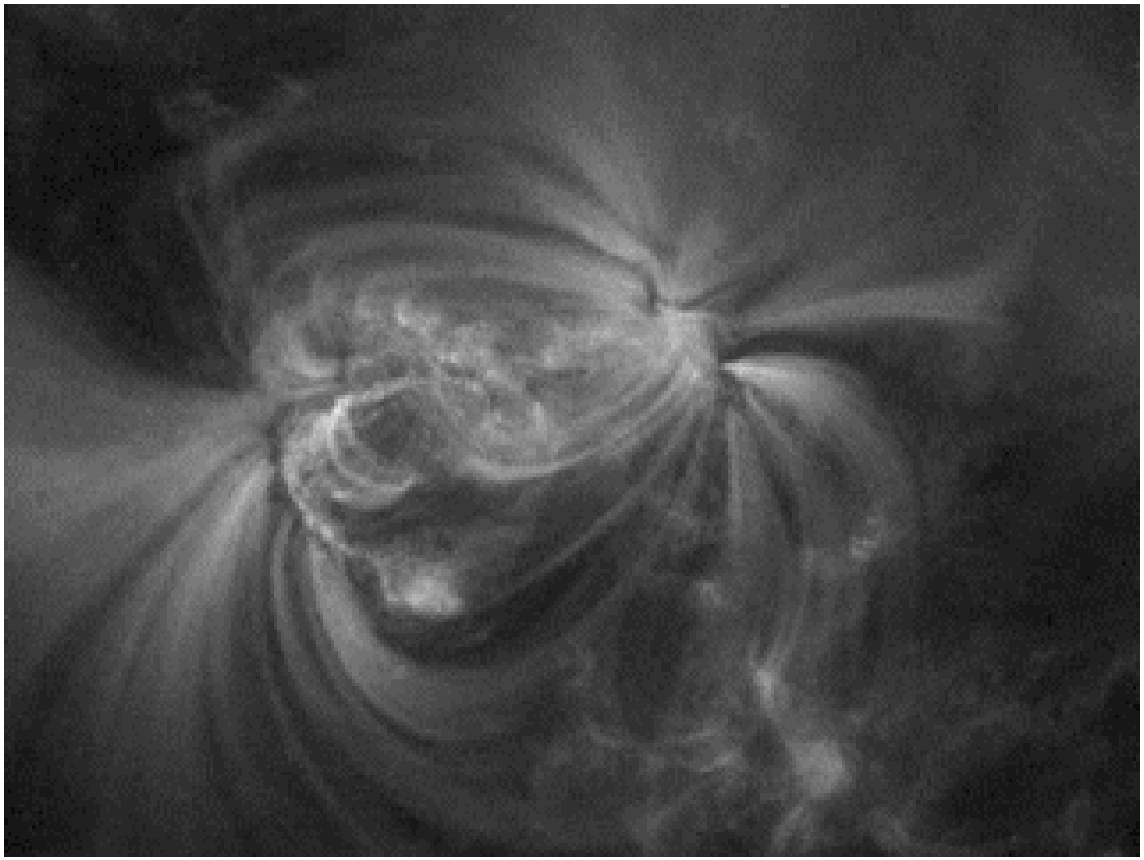


Order is even “local”: Coronal “self-organization”



Images courtesy NASA/TRACE

… but it is far from steady



What don't we know?

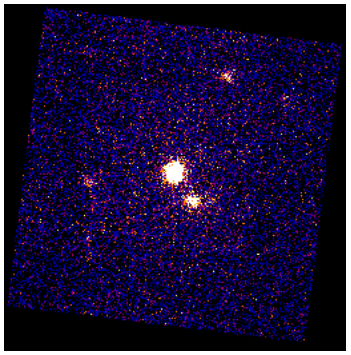
- Is the Sun typical?
- Are magnetic fields sufficient and necessary for solar activity?
  - How do magnetic fields lead to plasma heating and acceleration?
  - Are there non-magnetic mechanisms for plasma energization?
- How are solar magnetic fields created?
  - What solar properties define the field production mechanism?
  - Can we predict magnetic dynamo properties from first principles?
- How does solar activity depend on the Sun's extrinsic and intrinsic properties?
- How has solar activity varied in the Sun's lifetime?

Our ignorance has a context

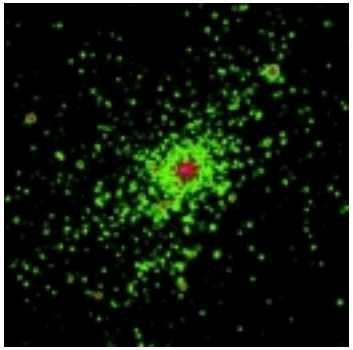
- Classical kinematic α–Ω magnetic dynamo models capture much of the behavior of observed low-order multipoles of solar magnetic activity
  - These models describe the linear regime
  - The actual physical system is surely in a fully nonlinear state
  - Nevertheless, many features of the nonlinear regime are captured
    - Periodicity
    - Butterfly diagram
    - Hale polarity law
  - Many of the unaccounted-for details within the context of the simplest model are readily explained by relatively simple modifications of the classical model
- If this is correct, we expect other stars to show similar behavior
- Other stars allow us to “turn the knobs” on our theory for solar activity
  - Stellar rotation rate
  - Stellar mass
  - Stellar age …

What have we learned from the stars?

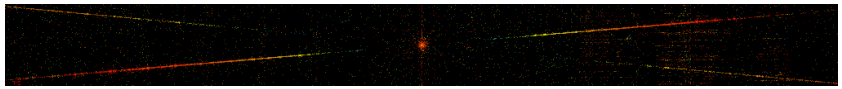
- Stellar X-ray observations were initiated by the Einstein Observatory over 20 years ago
- Since then, data from Exosat, ROSAT, XTE, Chandra, and XMM/Newton have helped to complete the picture



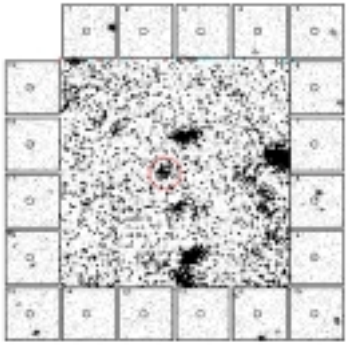
Einstein ObservatoryHyades//IPC



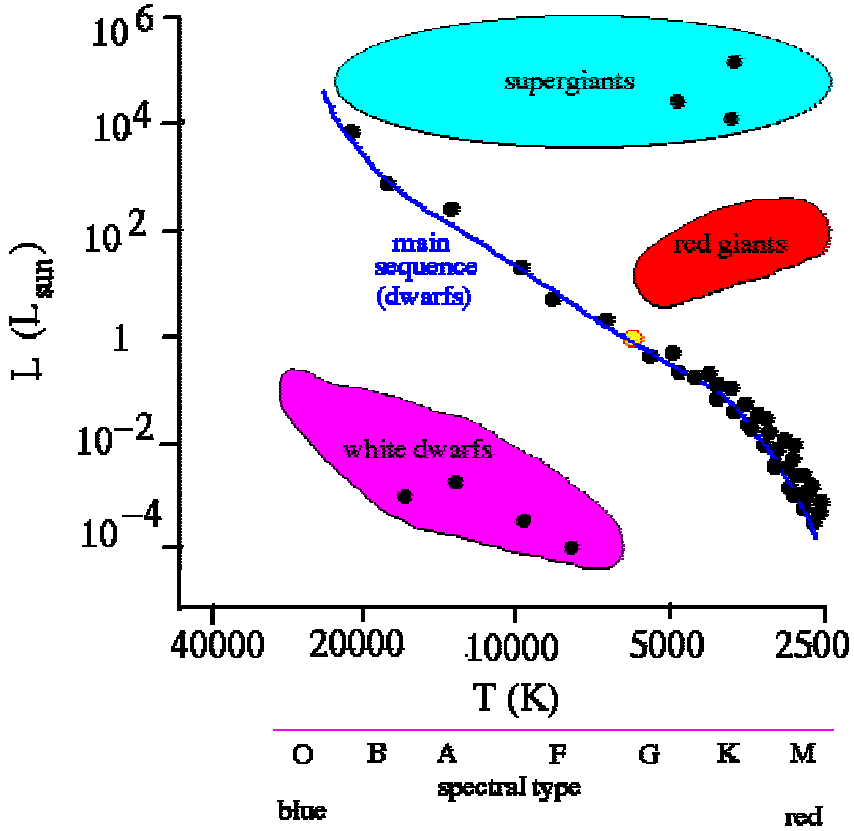
Chandra/NGC3603



Chandra/HETGS/Capella



Chandra/Orion core composite



“Turning the knobs” on stellar activity …

For stars like the Sun:

- Stellar X-ray luminosity scales with stellar rotation rate, $L_x \sim \Omega^2$
- Coronal temperatures resemble solar coronal temperatures, $T \sim 10^6\text{-}10^8$ K

For hot, young, massive stars:

- Stellar X-ray luminosity scales with stellar bolometric luminosity
- Some recent evidence for “plasma confinement”

For young (“pre-main sequence”) stars:

- Stellar X-ray luminosity scales with neither stellar rotation rate nor bolometric luminosity
- Emission extremely intermittent

Is the Sun a sensible "template"? Are stars proxies for the Sun?

- A large fraction of the phenomena encountered in other parts of the H-R diagram find their counterparts somewhere on the Sun
  - Dynamo field production, non-thermal heating of corona and chromosphere, acceleration of winds and of particles, …
  - For these processes, the Sun is often the only "laboratory" for testing the details of theoretical ideas

- Stars show virtually all of the phenomenology associated with solar magnetic activity, but under potentially very different conditions
  - Luminosity, mass, age, effective temperature, rotation, composition

- Stars exercise the limitations of solar models for activity: We should expect that models developed in the solar context will not always work
  - Activity 'saturation', shut-off of surface convection, turn-on of core convection, …

The many new puzzles

- Behavior of young stars
- Behavior of hot (massive) stars
- Behavior of low mass stars/brown dwarfs
- …

The vigorous activity of young stars

Young stars are

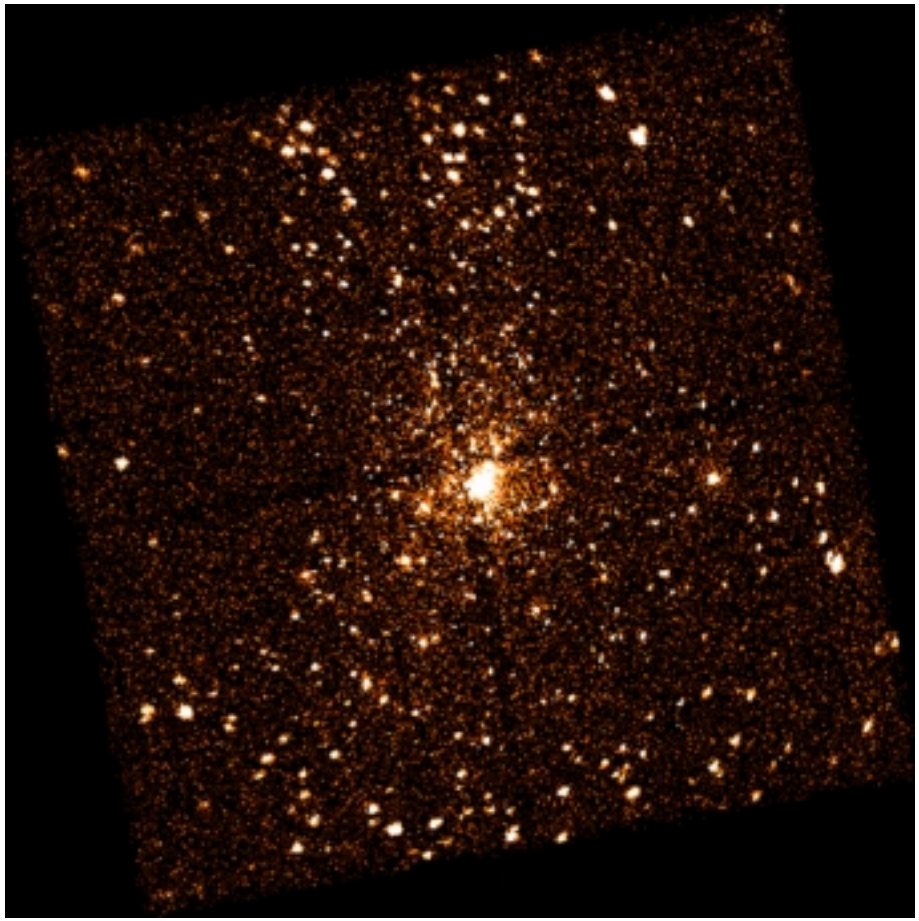
- **Bright x-ray sources ($L_x \sim 10^2$-10^3 brighter than Sun)**
- **Highly variable, with large 'flares' quite frequent**
- **Relatively hard (hot) sources**

Implications

- **Solar-like activity, but with clear evidence for complications (disk interactions, saturation, …)**
- **May explain local origin of rare isotopes such as ^{10}Be, ^{41}Ca, ^{26}Al and ^{53}Mg, among others**
- **These stars tell a story about our young Sun …**

Puzzles

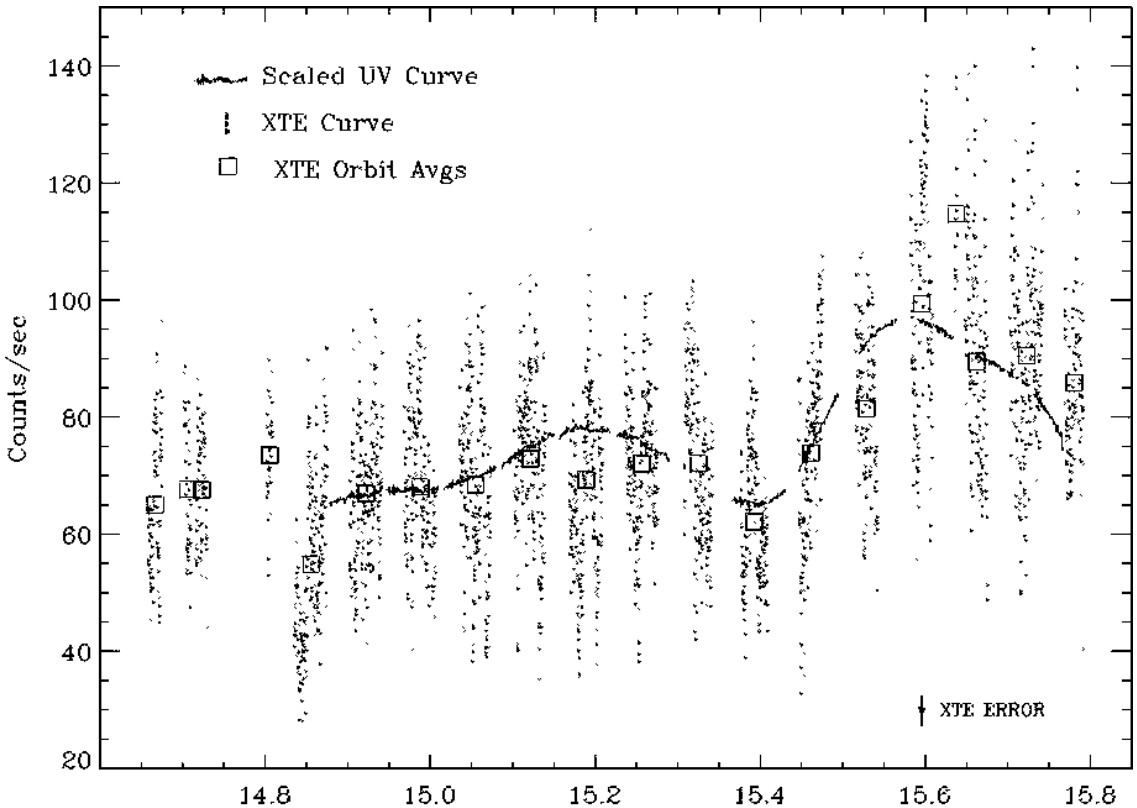
- **Where are the "seed" B fields from?**
- **How does activity "saturation" work?**
- **How do the accretion disk dissipate?**
- **…**



Orion nebula (Feigelson et al. 2001)

Do hot stars have magnetic fields?

The standard theory for explaining why hot massive stars are X-ray sources takes into account the fact that these stars have very powerful winds, and shows that wind instabilities lead to shocks, and whence hot plasma.



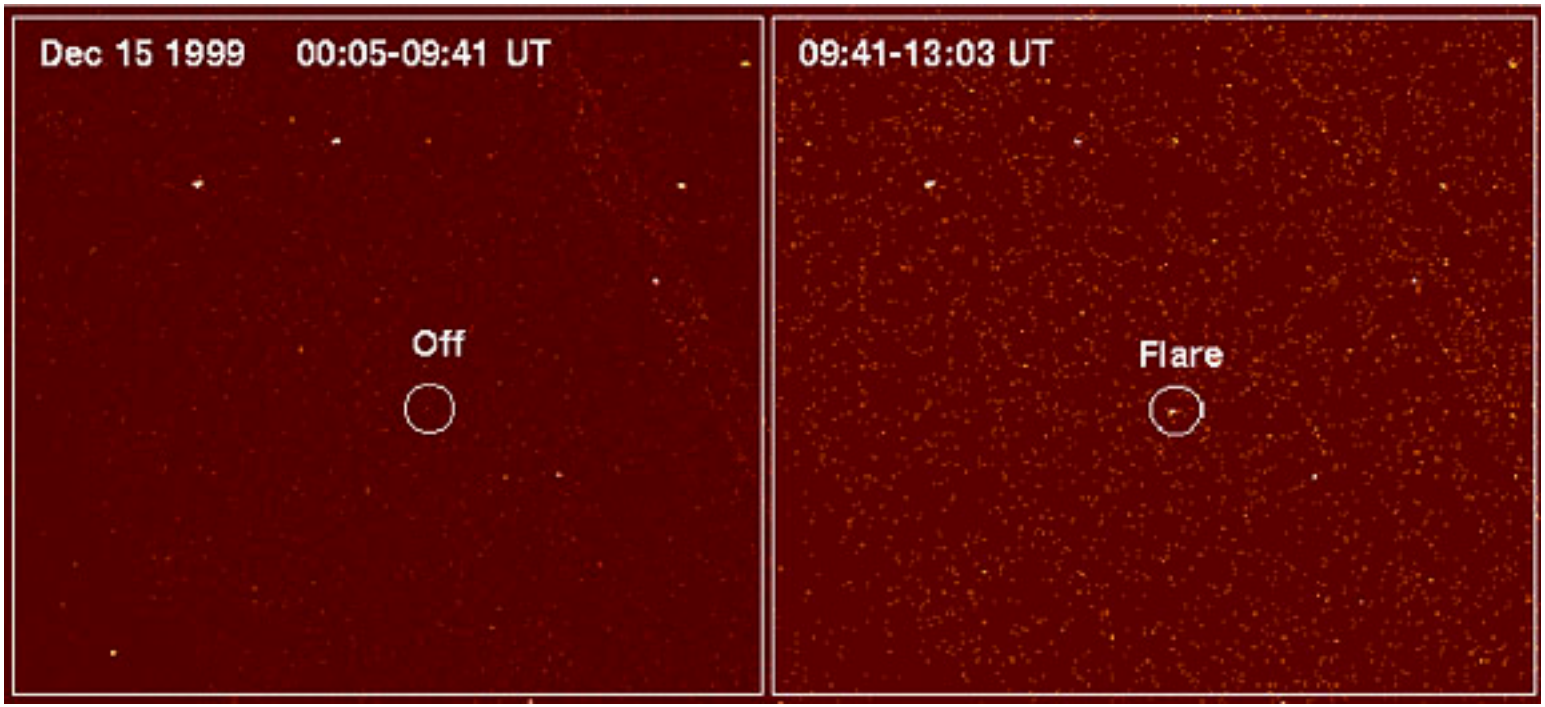
γ Cassiopeiae
(Be, Smith et al.)

<u>Puzzle</u>: Such a theory would have difficulty explaining the observation of flares - what is the origin of the magnetic fields known to lead to flares?

Brown Dwarfs do have magnetic fields …

Standard theory for stellar activity based on stellar magnetic dynamos predicted that activity should decrease significantly once stars become fully convective (at ~ M5). Until recently, there was no direct evidence for activity for very low mass (<0.1 M_o) stars.

LP944 image courtesy R. Rutledge (Caltech)



Puzzle: What is the corona of LP944 like? How does its magnetic dynamo work?

Summary

- The past 20 years have led to the founding of a new field of astronomy, in which the ideas developed by solar astronomers have been applied to other stars, and in which entirely new stellar activity phenomena have been discovered.
- The theoretical framework for solar activity has proven to be quite appropriate for discussing activity for solar-like stars
- The number of new questions which the new stellar data have given birth to is much larger than the number of questions that have been answered …
- These new questions have led to new or renewed ties to other disciplines
  - Origin of life on Earth
  - The birth of stars, and galactic “chemical” evolution
  - Atomic and nuclear physics

… and that leads us to

QUESTIONS AND DISCUSSION