Long-term evolution of magnetic activity of Sun-like stars

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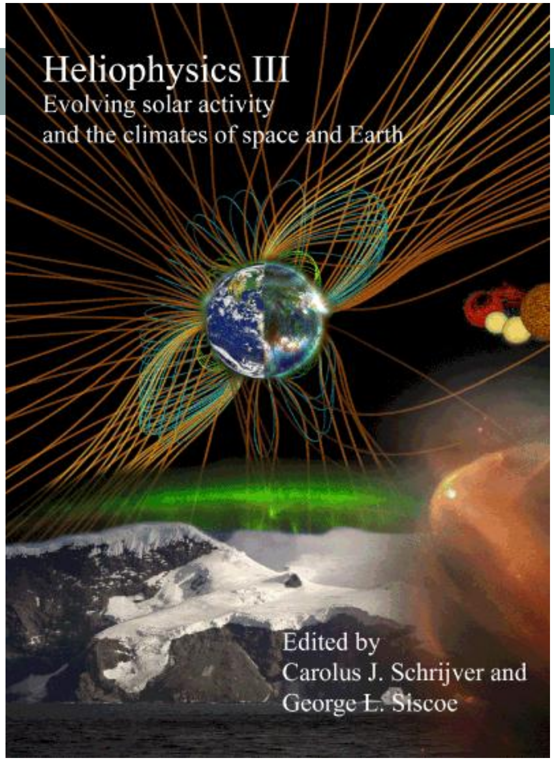
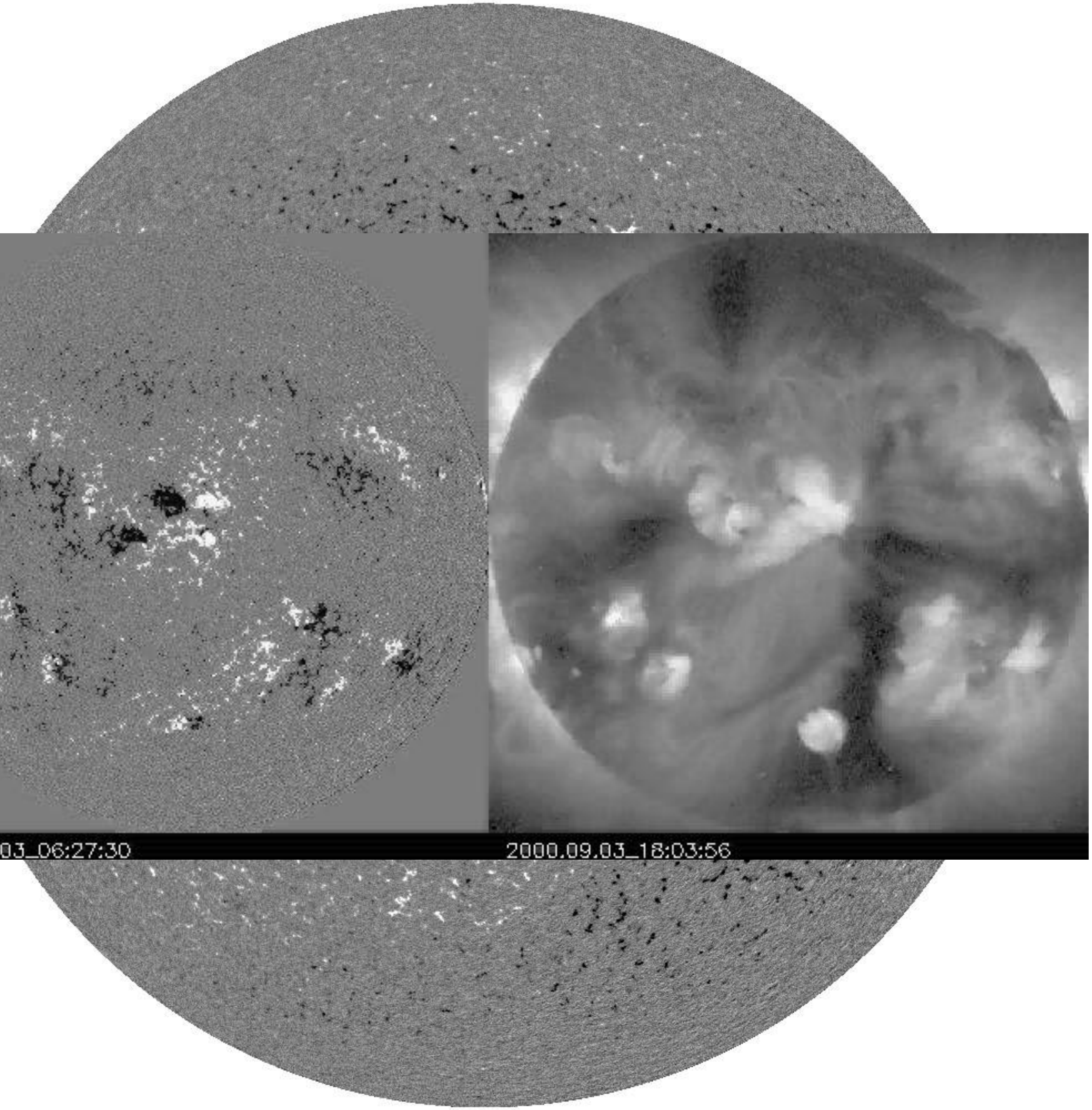


Topics

- Elements of solar activity
- The sunspot cycle
- Atmosphere, radiance, variability
- Stars and their evolution
- Evolution, rotation, activity
- Variable activity and stellar radiance
- Magnetic breaking
- Starspots
- Solar and stellar flares
- The Sun in time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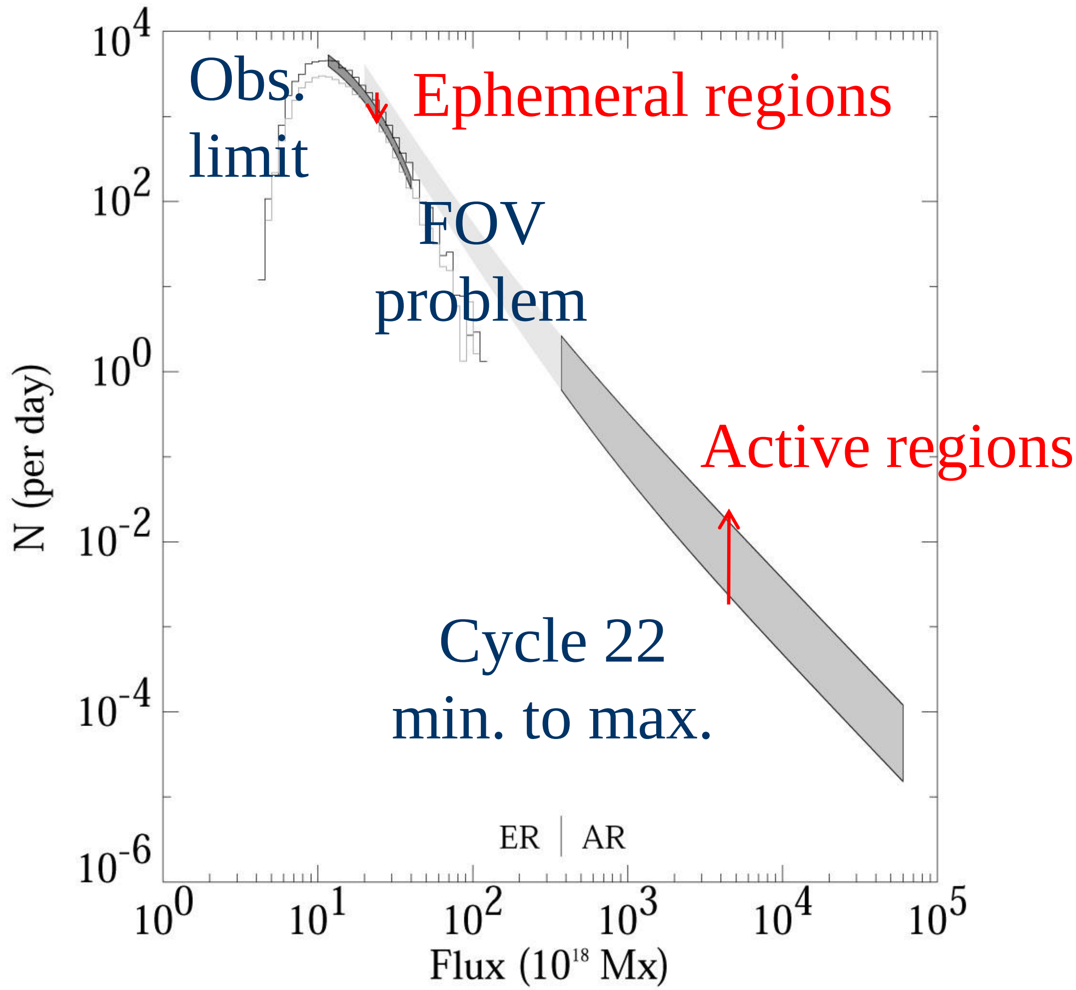
Spectrum of emerging bipolar regions

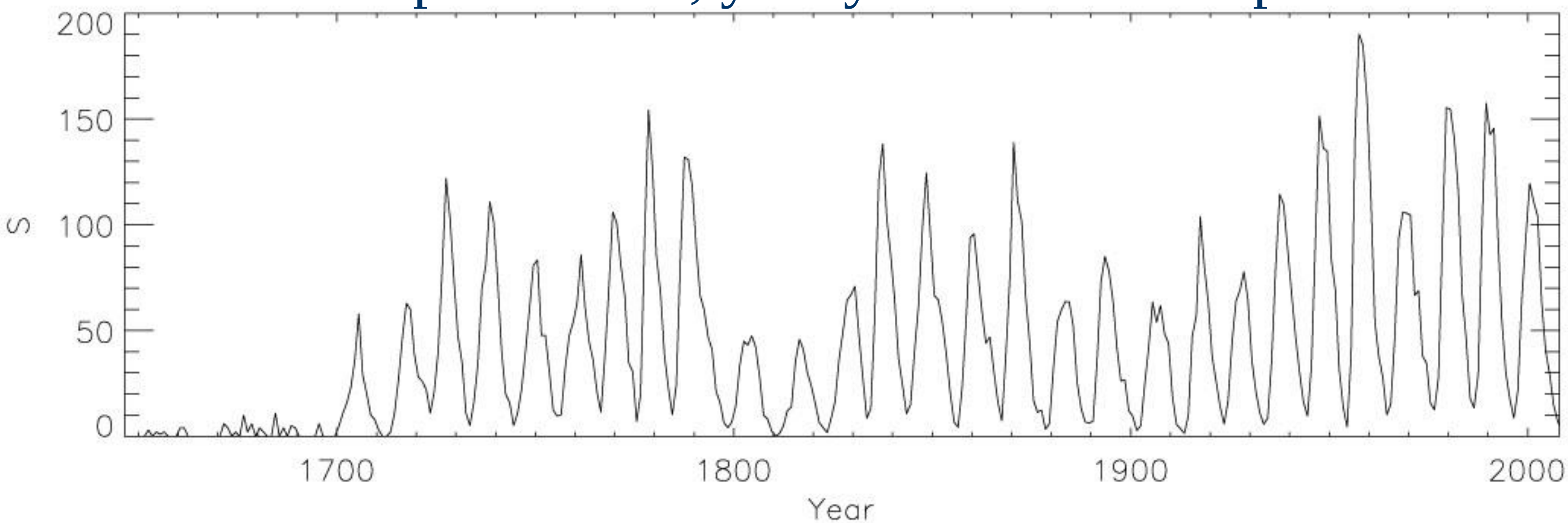
- Bipolar regions form a continuum from large active regions to small ephemeral regions, and perhaps even smaller "intranetwork field":
- Regions with less flux
  - Increased spread in latitude and orientation;
  - Less cycle dependence, perhaps slight anticorrelation



Sunspot records

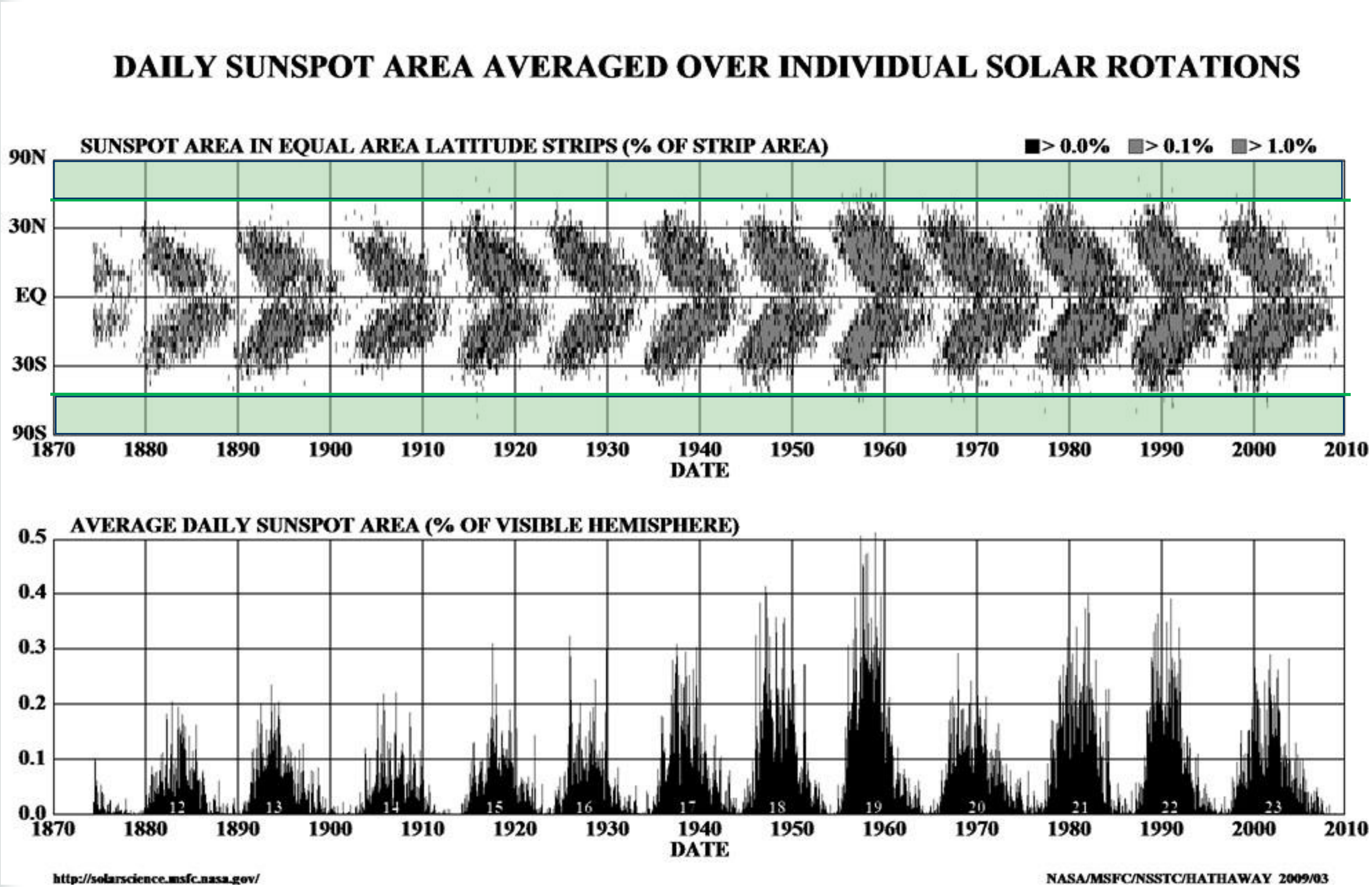
- Sunspot cycles vary in strength, duration, shape, overlap, …

Historical sunspot records; yearly smoothed sunspot number

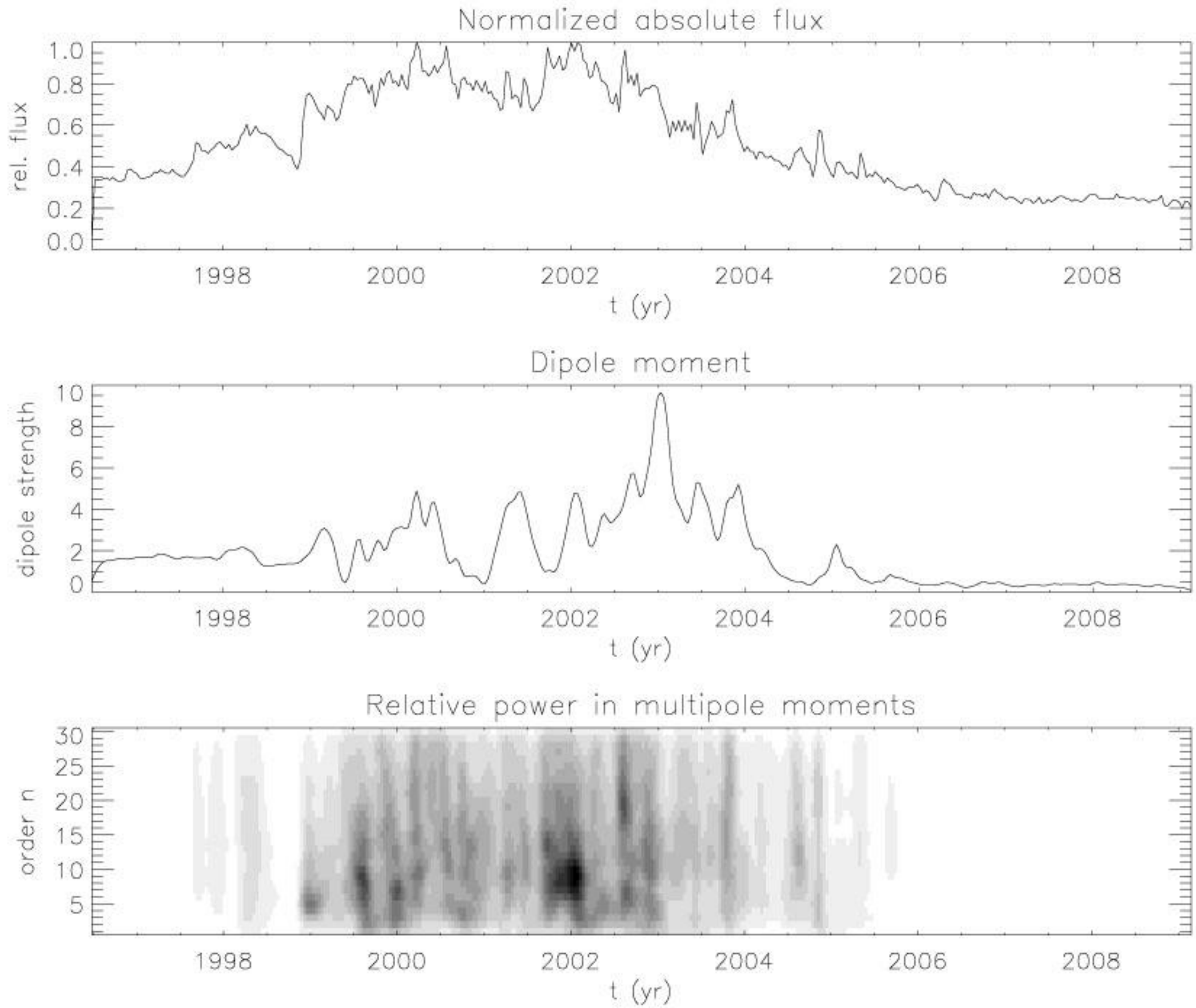


e.g, http://sidc.oma.be

Sunspot cycle



Global activity, bipole, & multipole



Simulating photospheric activity

Flux emergence

Random stepping

Diff. Rot. & Merid. flow

Flux frag- mentation

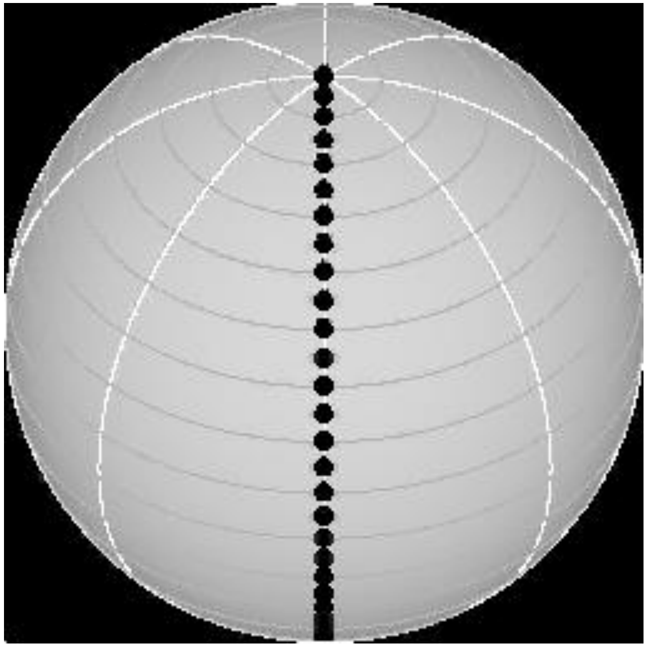
Collision & cancelation

Includes:

- magneto-convective coupling
- magneto-chemistry: fragmentation and collisions
- ephemeral-region population

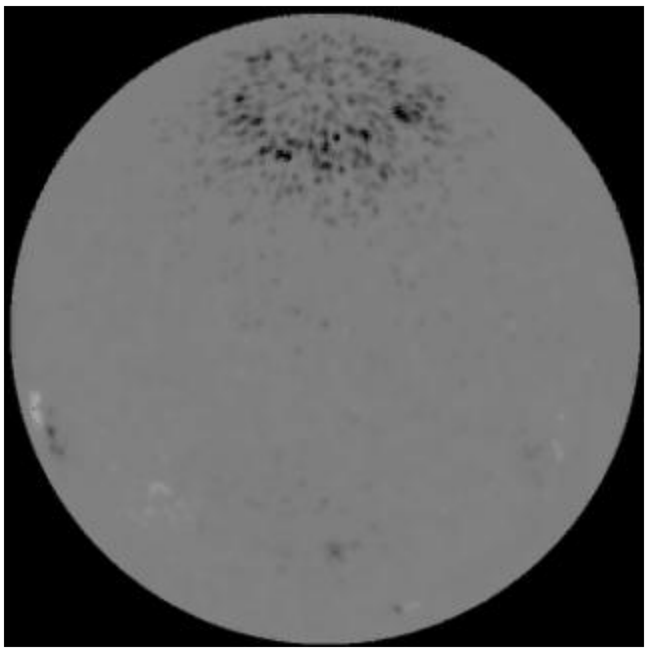
Effects of large-scale flows

Differential rotation and meridional flow only, as viewed from 40°N



Simulations of activity

Simulated "Sun" from 40°N:



Present Sun

Simulation of the solar cycle

Visualizing the evolution of the solar wind source domains, as seen in a ‘corotating’ frame, over 1-1.5 magnetic cycles:

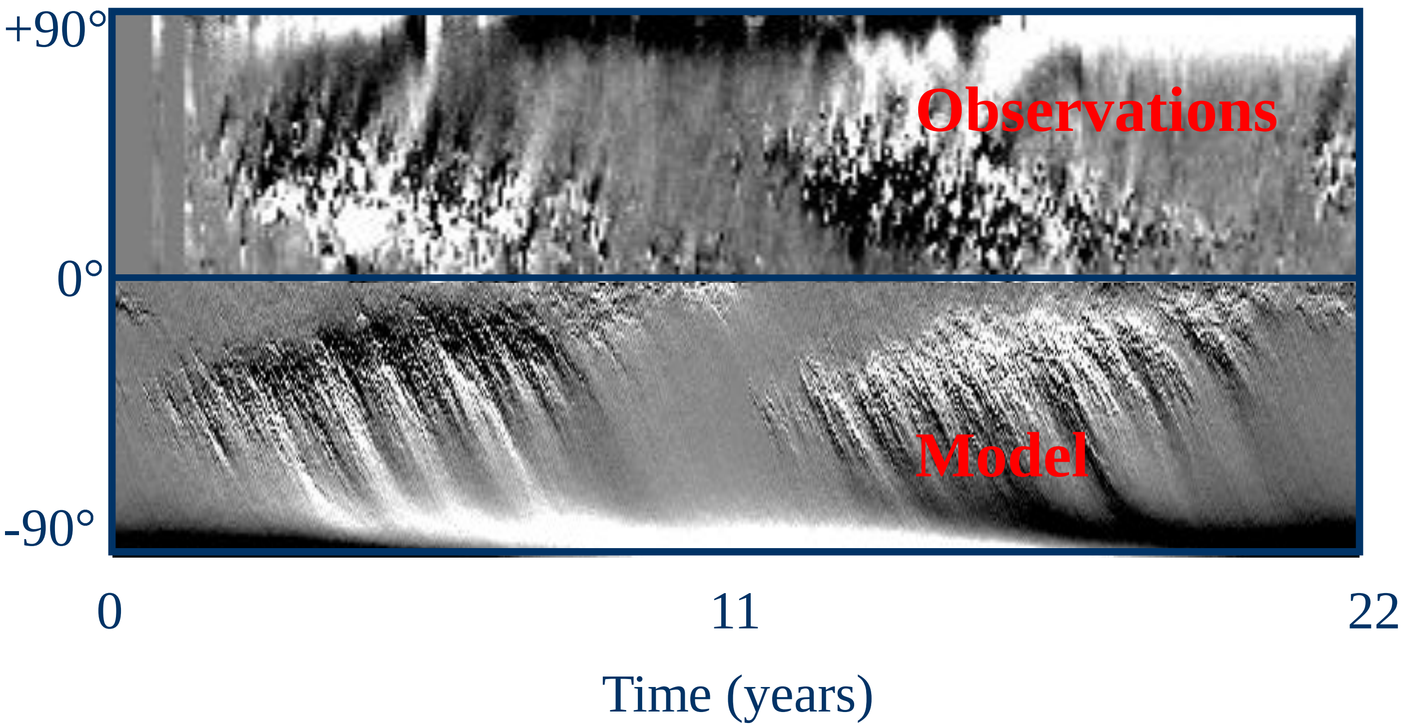
Surface view	Surface grid	Source-surf. grid
Equatorial	Equatorial	Equatorial
40 North	40 North	40 North
90 North	90 North	90 North

Streamer belt still:
From ‘Earth’:

Streamer belt envelope (27-d syn. Bartels frame):

Large-scale solar field

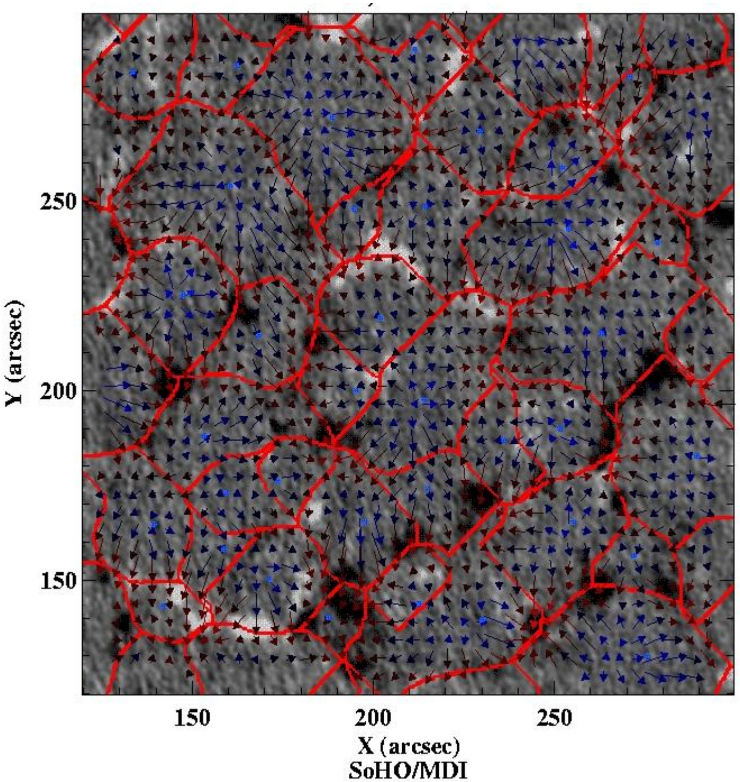
- Large-scale solar field depends on source function, dispersal, meridional flow, and differential rotation

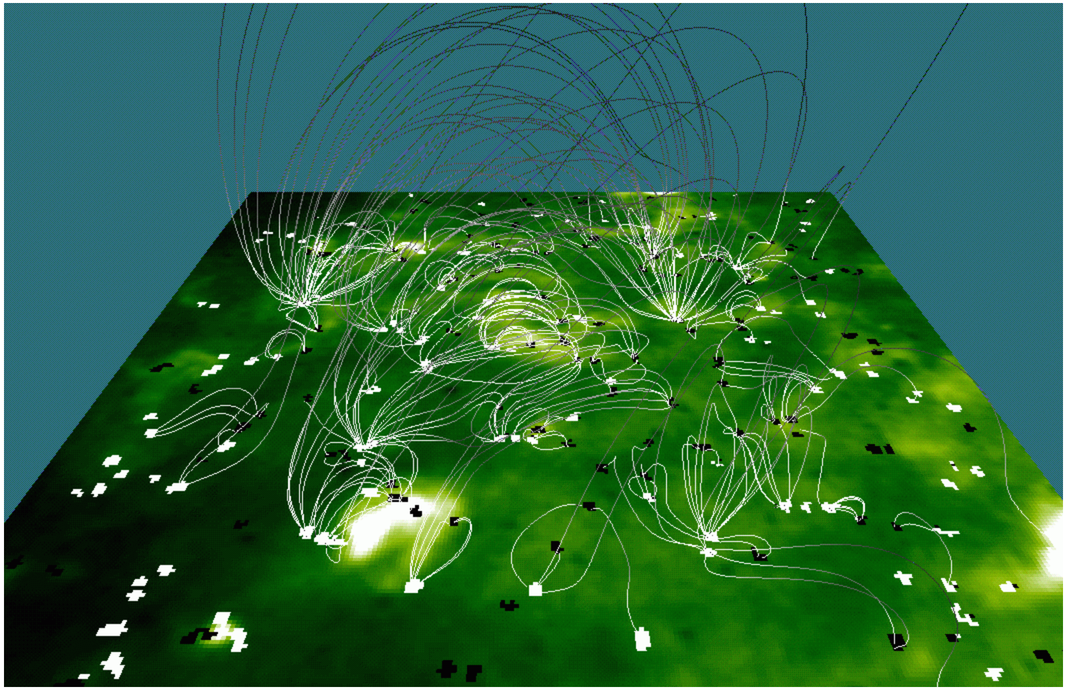


- Good approximation of large-scale flux patterns, including polar fields

And then there is the small stuff

- Quiet-Sun "magnetic carpet":
  - *Large-scale patterns survive for months* or more
  - *Network flux concentration survive for at most a few days*, and magnetic connections much less than a day, owing to emergence of many small bipoles ("ephemeral regions")

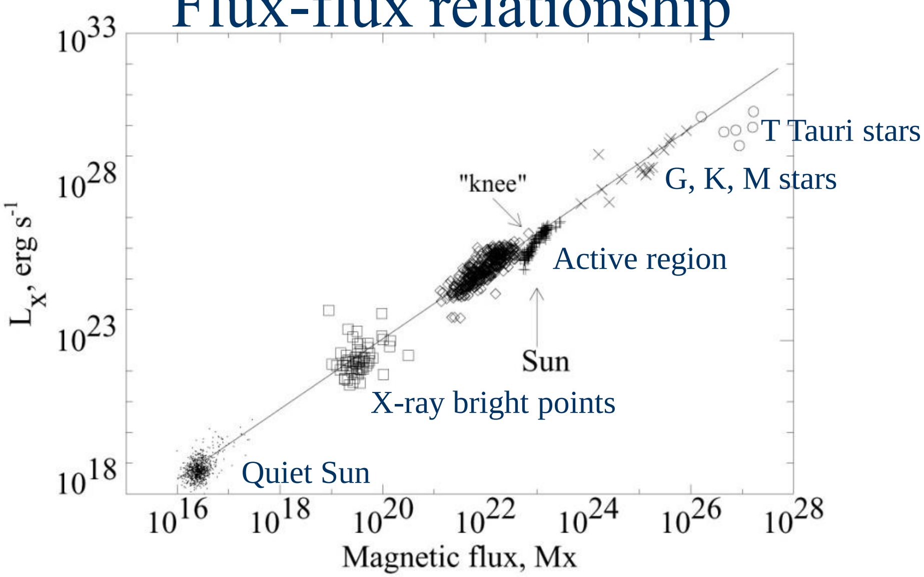




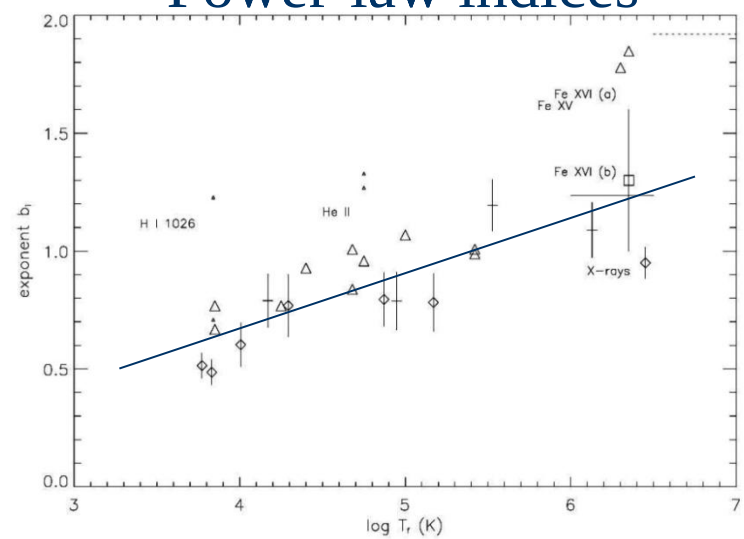
“Flux-flux relationships”

- At moderate spatial and temporal resolution, radiative losses from any thermal domain in the solar atmosphere scale with the (unsigned) magnetic flux density underneath:
  - $F_i = a <|fB|>^b$
- Coronal flux density depends nearly linearly on magnetic field, chromospheric flux density close to a square root.

“Flux-flux relationship”

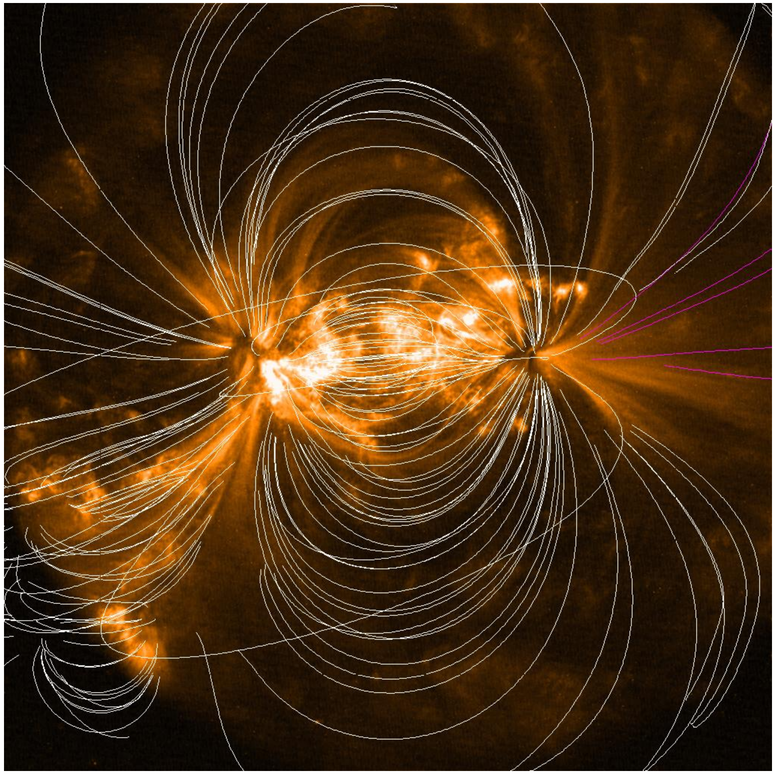


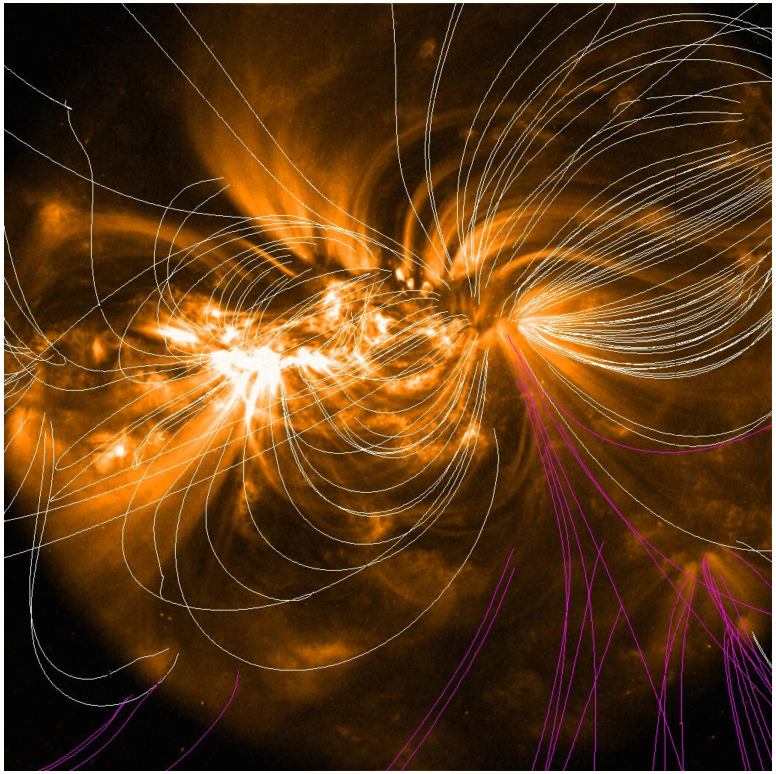
Power-law indices



Magnetic free energy in coronal field

- Significantly non-potential : ~10-30% of the regions on the surface.

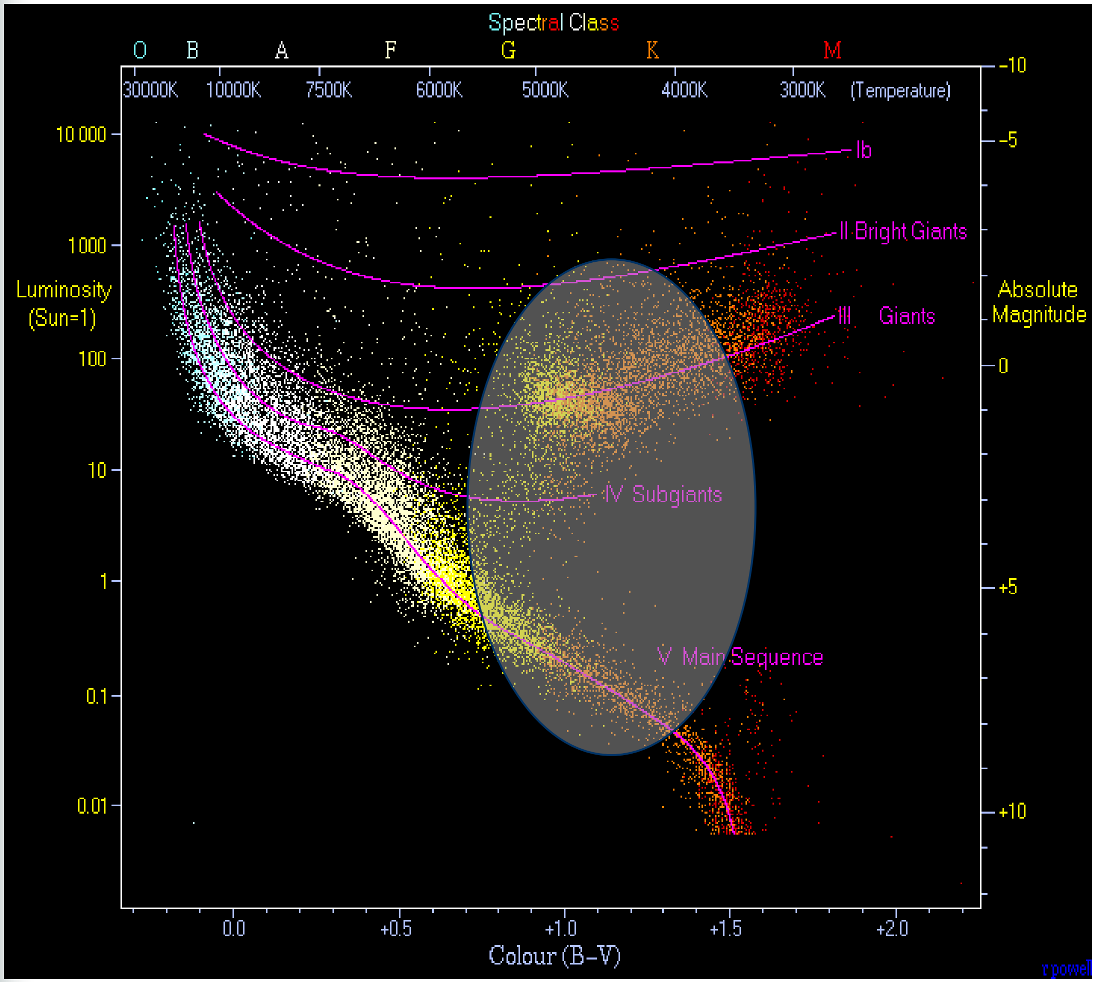


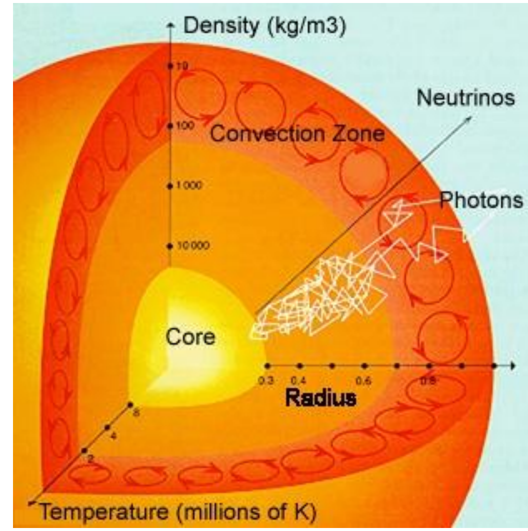


- ARs with <u>*significantly*</u>* non-potential coronae are <u>*~3x*</u> more likely to produces CMX flares that on average are <u>*~3x*</u> more energetic.

** based on a subjective comparison of images and field extrapolations.*

Solar-like stellar activity

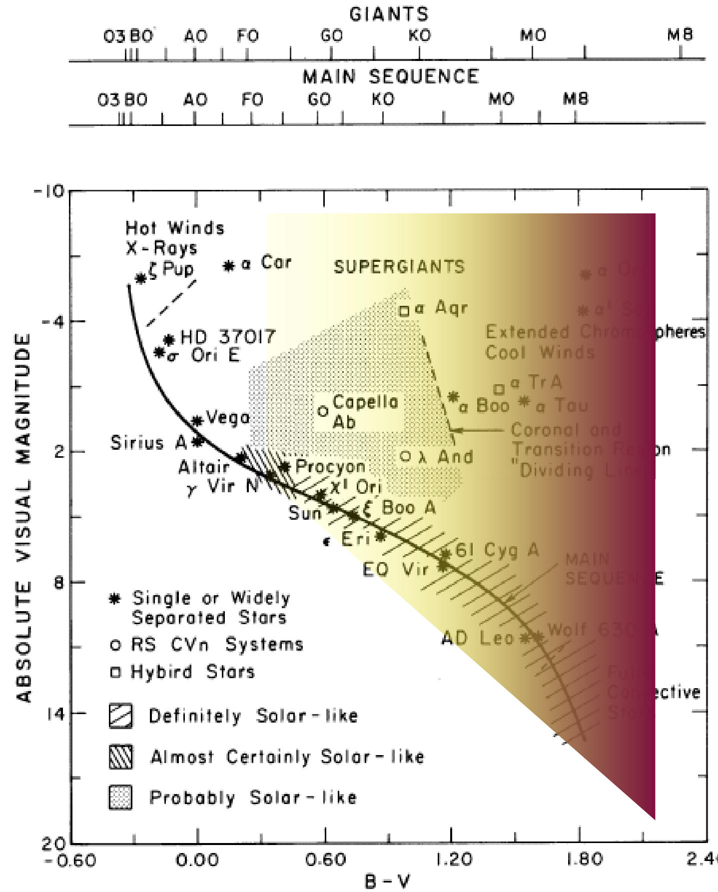


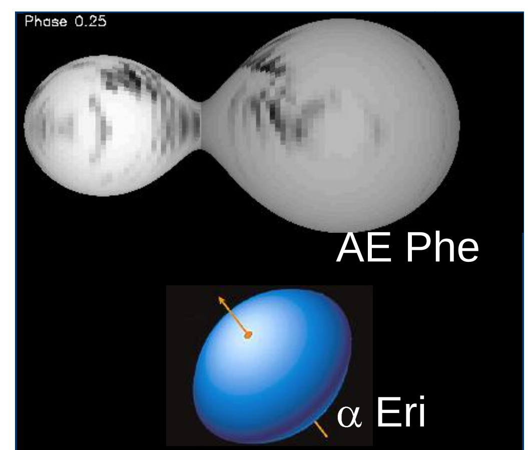


All rotating stars with convective envelopes exhibit atmospheric magnetic activity.

The Sun among the stars

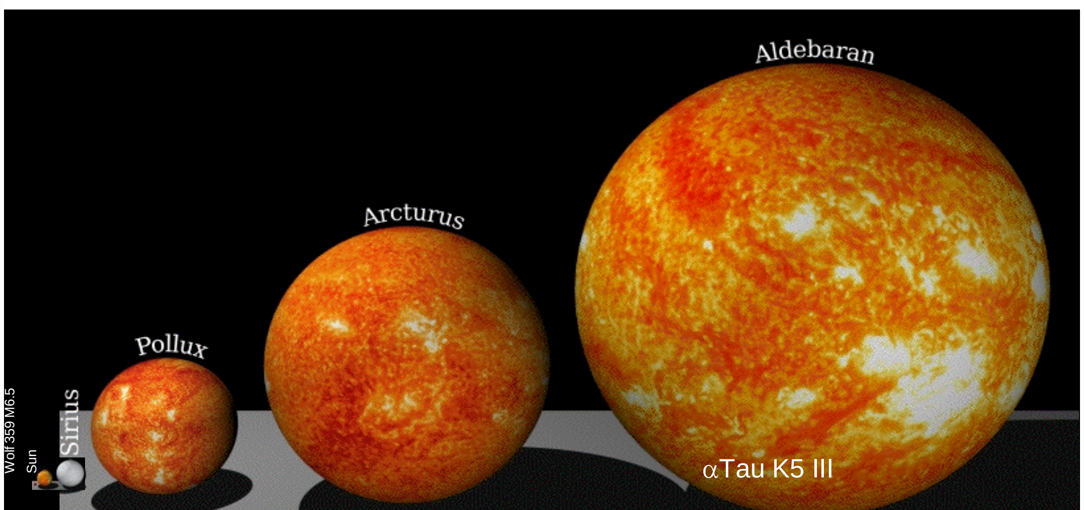
- The Sun is a typical member of the population of “magnetically active stars”, i.e., “cool stars”☐with variable coronae, chromospheres, and photospheres.
- The Sun’s near-twins (like 18 Scorpii) behave like, but not identically to, the Sun.
- Essential ingredients for activity: rotation, convective envelope.

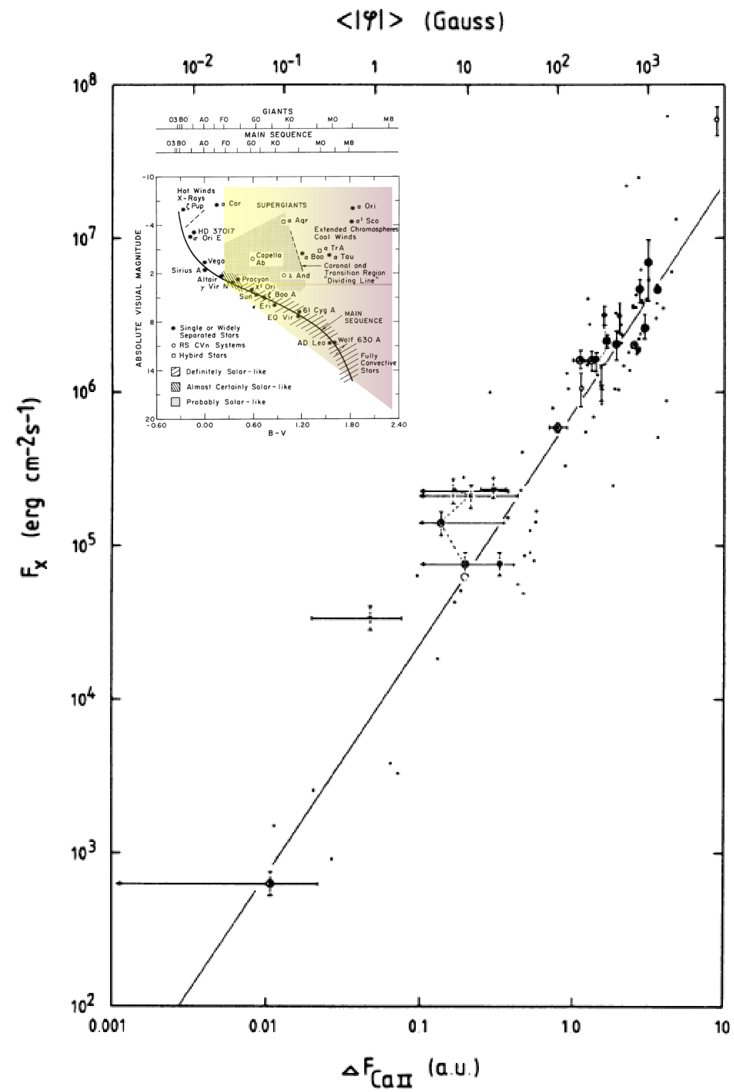




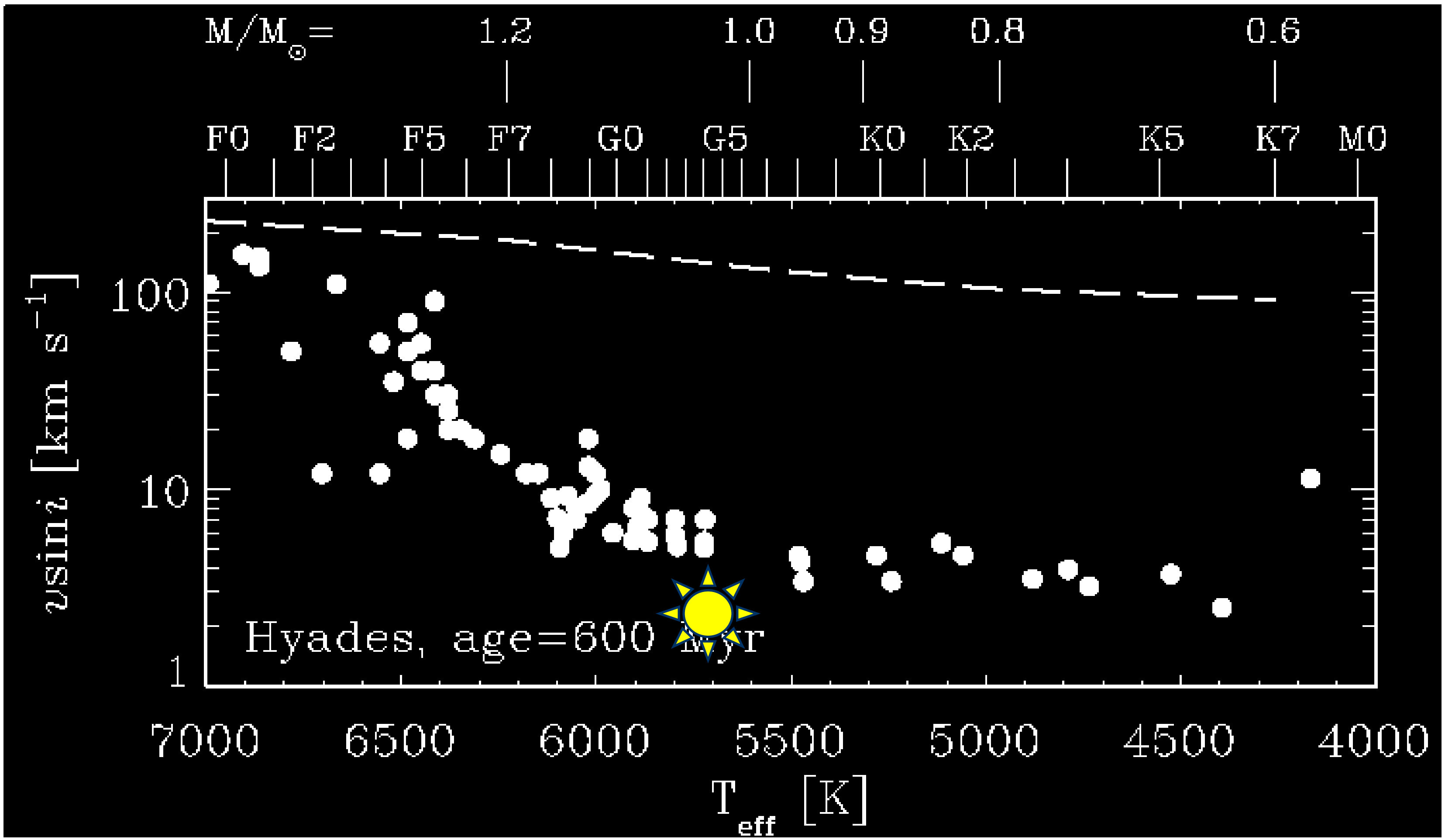
Magnetic energy conversion in stellar atmospheres

- Chromosphere and corona form an integrated system *($E_{chr./TR} \approx 30 E_{cor./hel.}$; $M_{chr./TR} \approx 50 M_{cor./hel.}$)*
  - power-laws; over 100,000x in flux density at Röntgen wavelengths.
- Basal "background" heating:
  - Adequate wave power, acoustic tunneling, magnetic carpet, magneto-acoustic couplings, …?

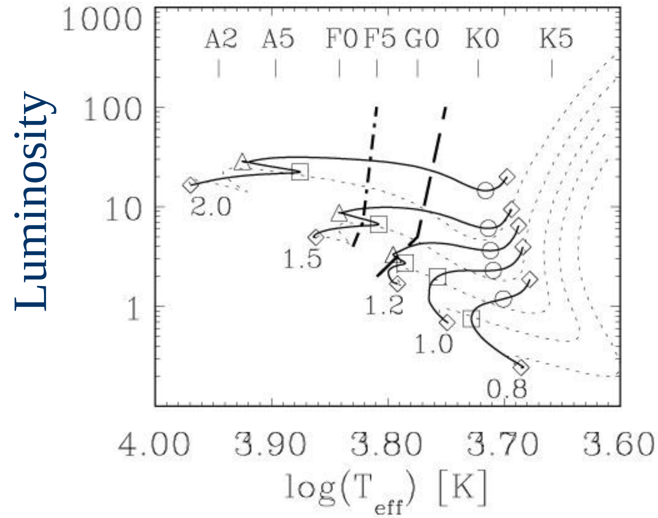




Rotation and age

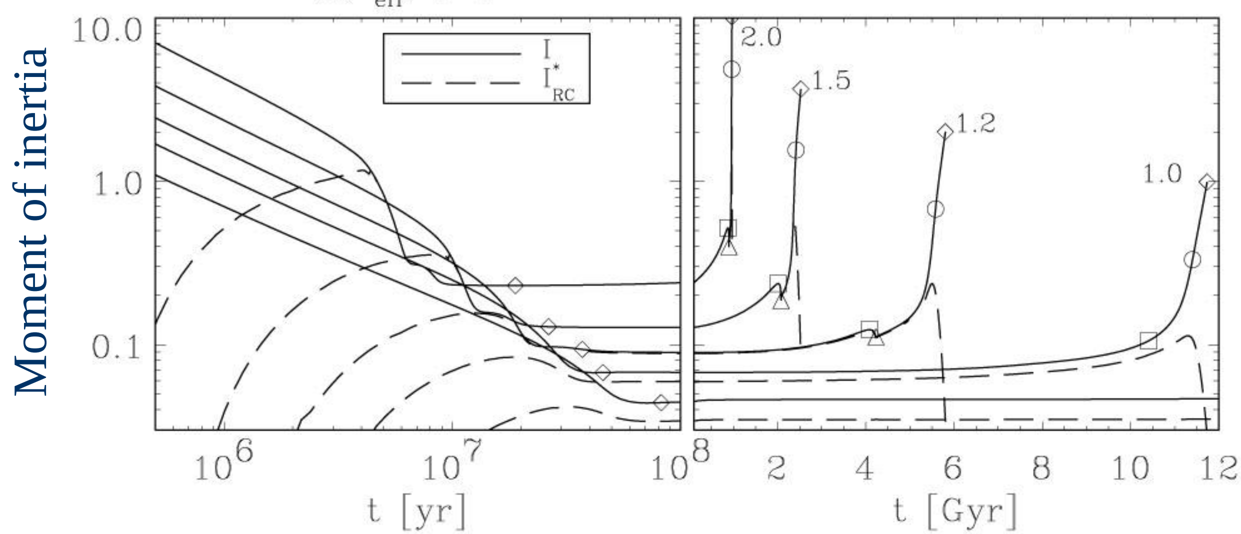


Evolution and angular momentum



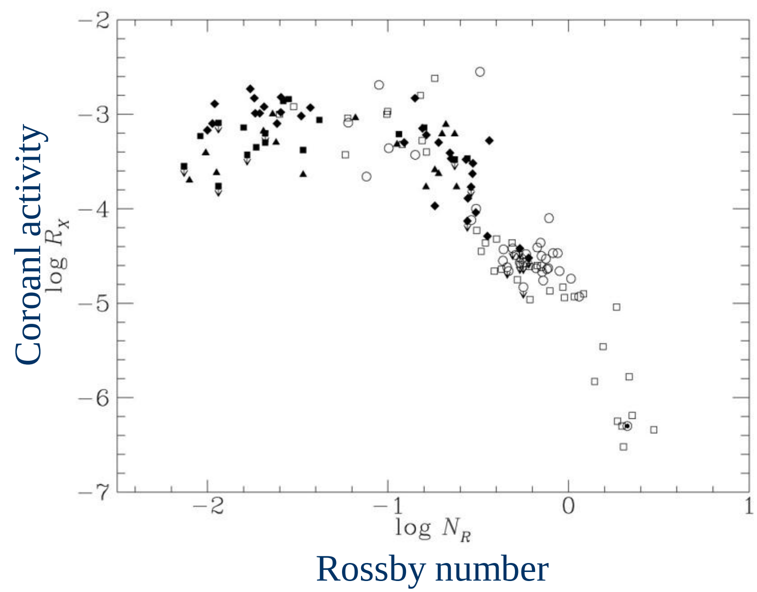
	t [Gyr]				
	2.0	1.5	1.2	1.0	0.8
◇	0.019	0.026	0.037	0.046	0.082
□	0.870	2.009	4.083	10.41	23.60
△	0.898	2.078	4.230		
○	0.959	2.417	5.579	11.40	26.75
◇	0.965	2.527	5.802	11.73	27.32

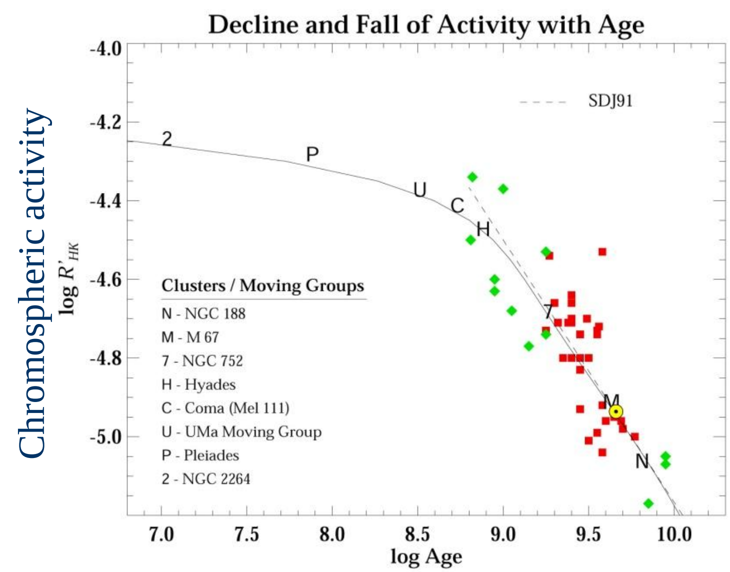
[X=0.6985 Z=0.0197 α=1.81]



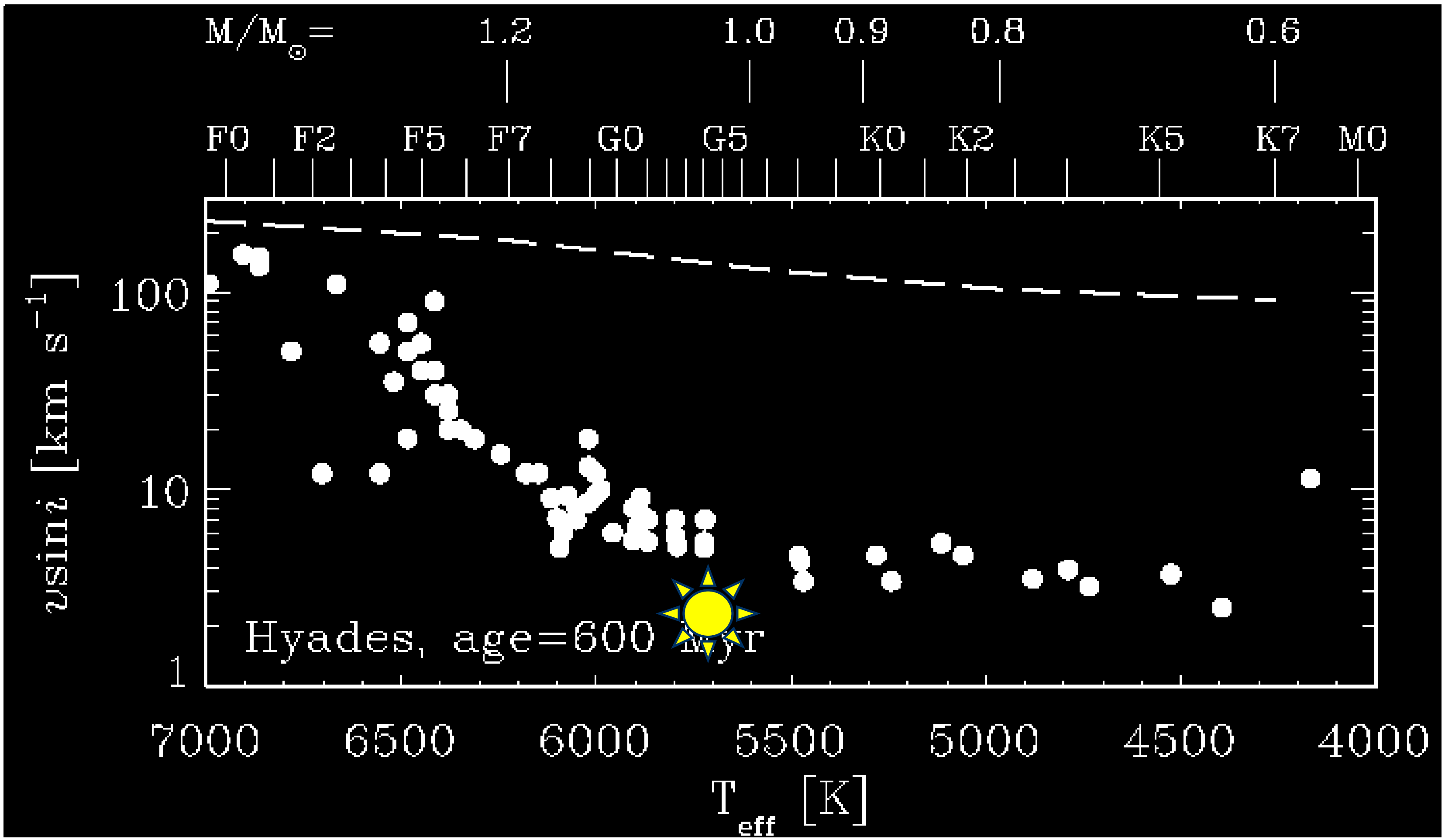
Activity, rotation, age

- Activity decreases with decreasing rotation and increasing age.
- Note “saturation” and “supersaturation” for short rotation periods.





Rotation and age: evolution and mass loss



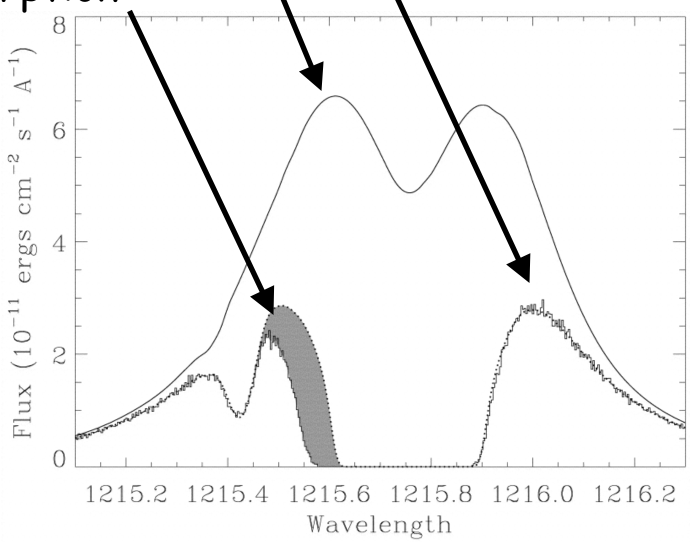
Asterospheres, stellar winds, and rotational breaking

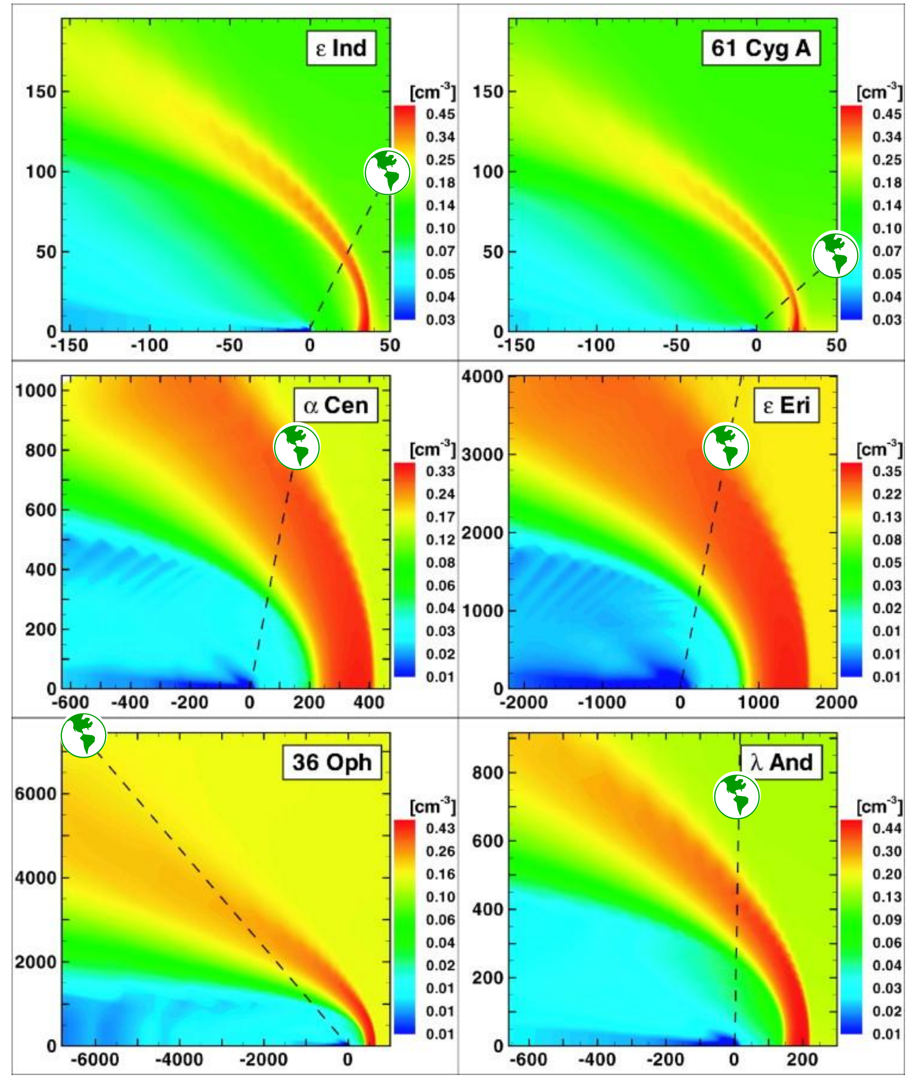
Combine observed Ly α profiles with models of wind-ISM inter-action to derive mass loss rates:

Observed after inter-/ circumstellar absorption

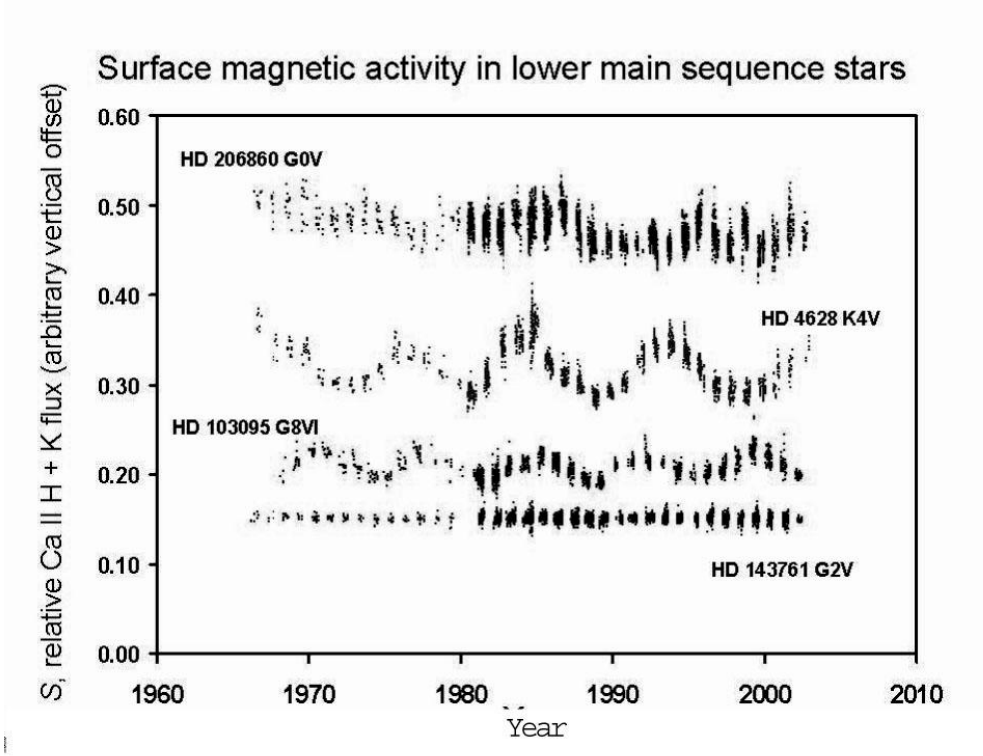
Model stellar profile

Asterospheric absorption



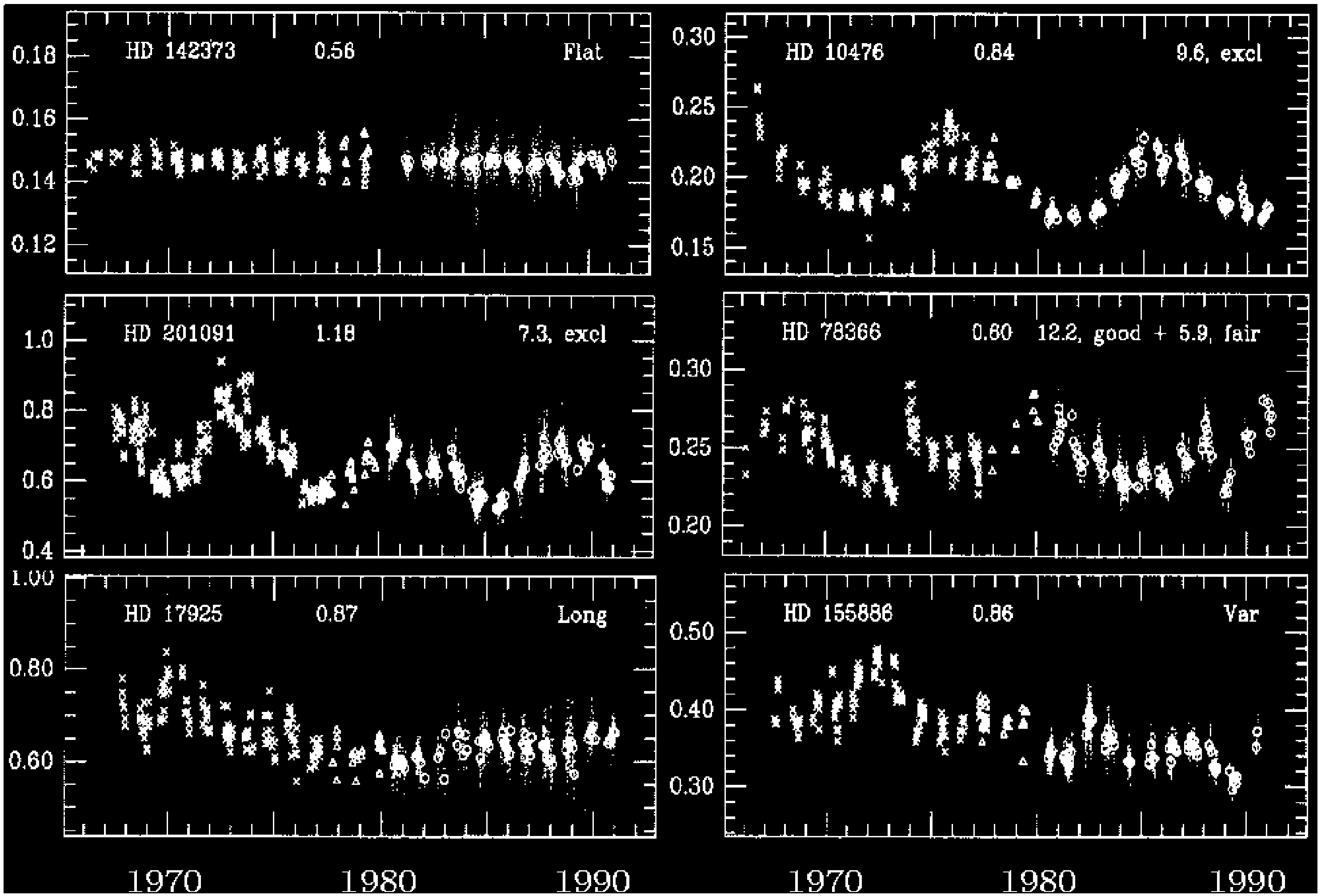


"Sun in time"

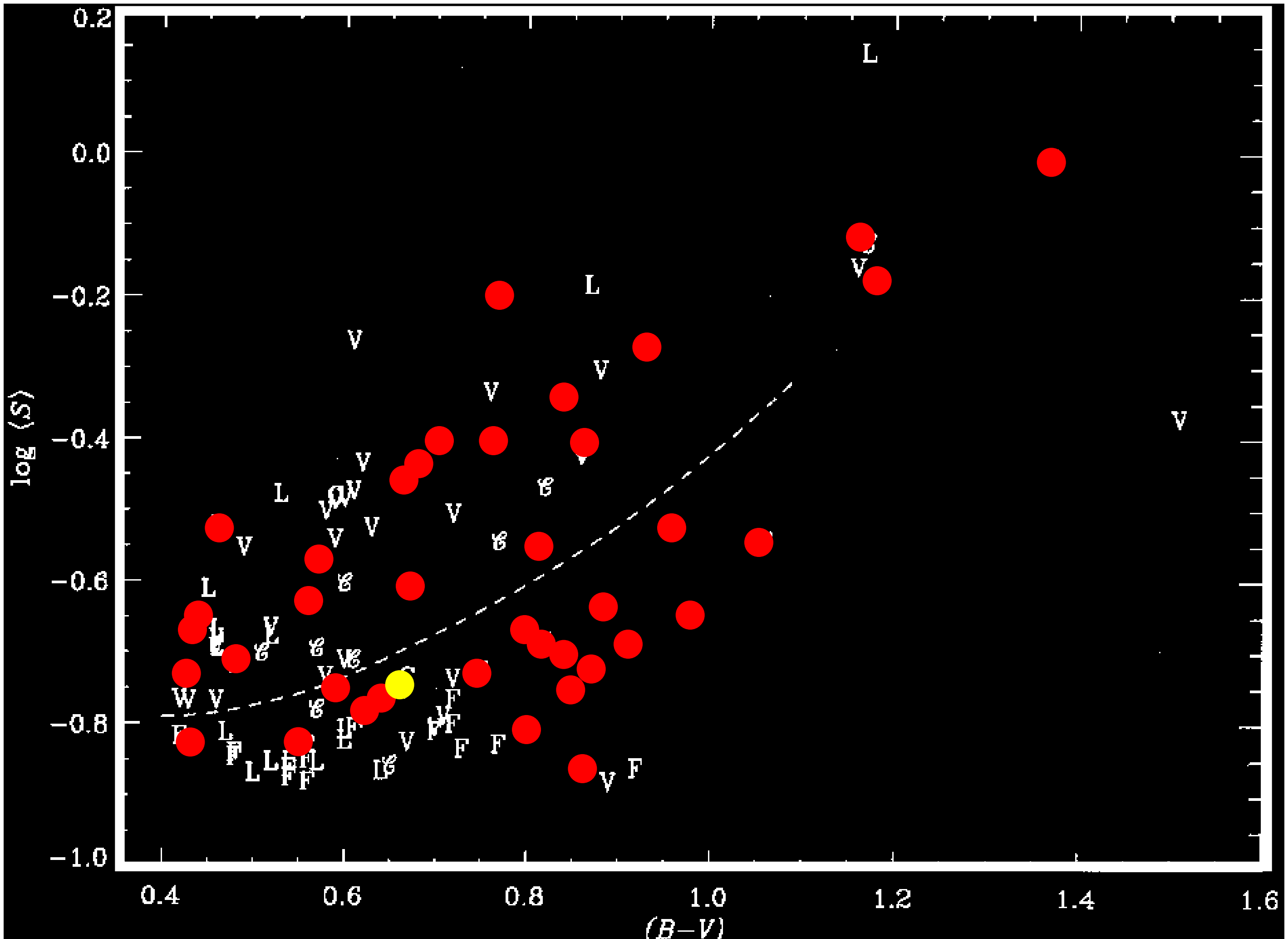


- Top: HD 206860; P=4.7d - a counterpart of the sun approximately 2 billion years ago.
- Lower curves: three Sun-like stars – HD 4628 (P=38d), HD 103095 (P=31d, or P=60d, age ~10 Gy) and HD 143761 (P=21 d). HD 143761 may be in a state like the Sun's Maunder minimum.

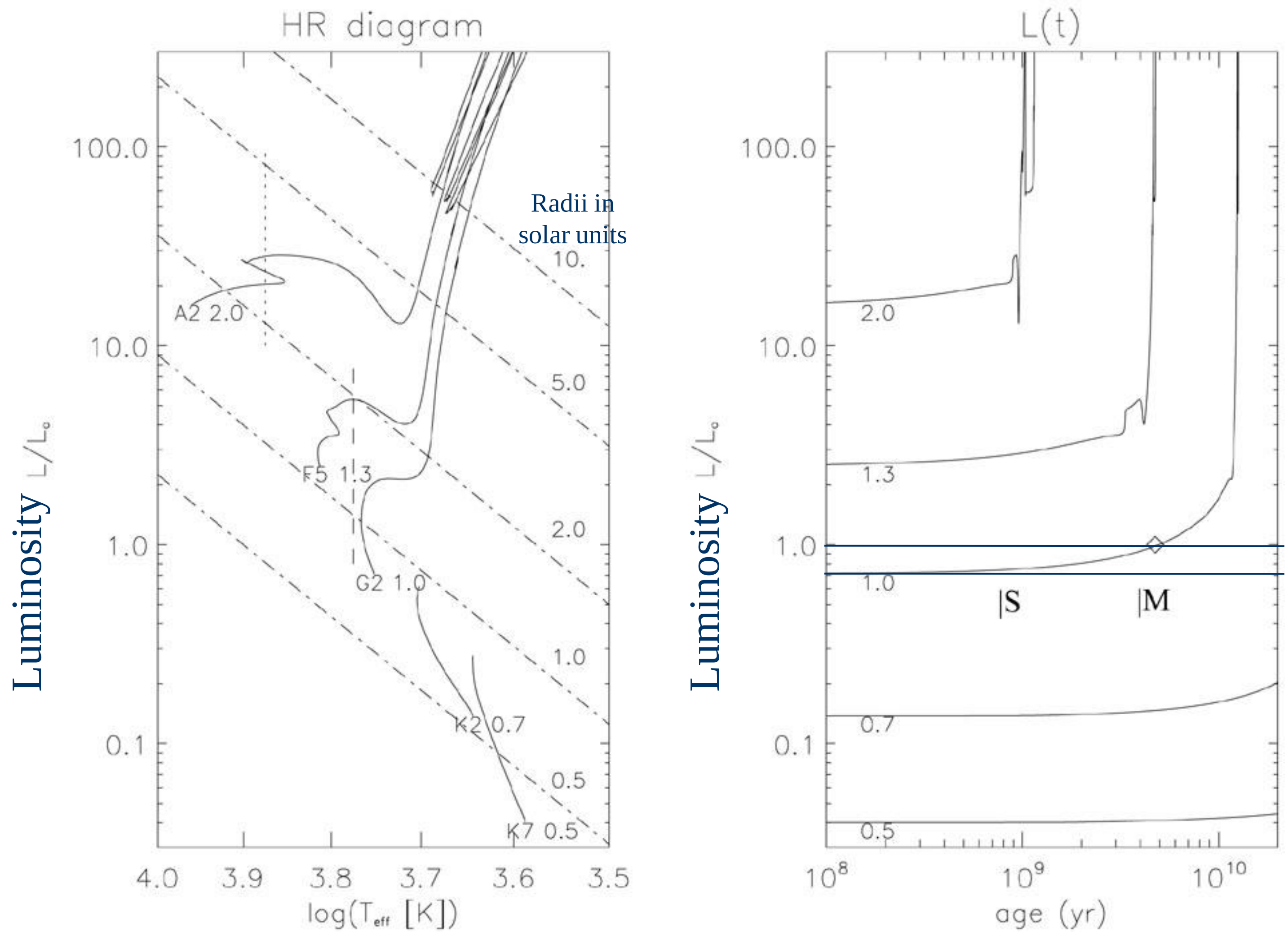
Examples of stellar activity "cycles"



Stellar activity "cycles": common but not dominant

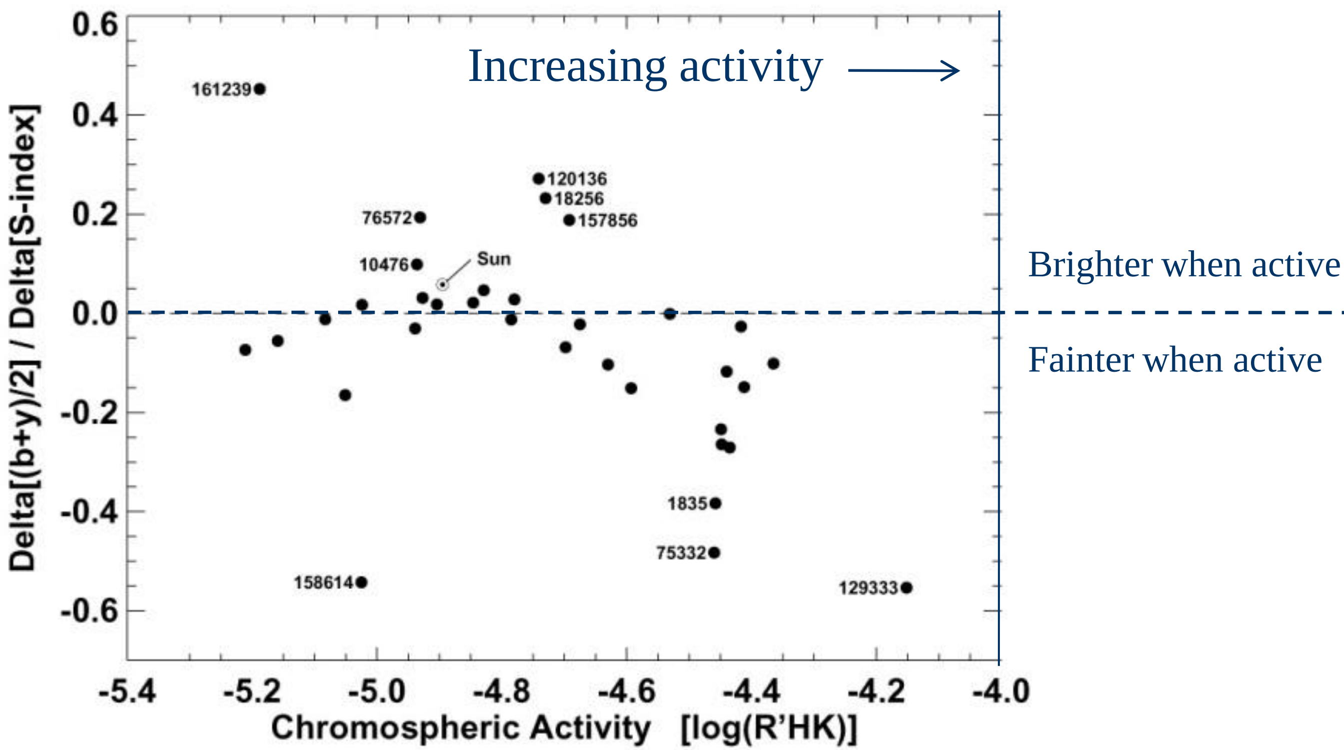


Stellar evolution and luminosity/radiance



Radiance variations at visible wavelengths.

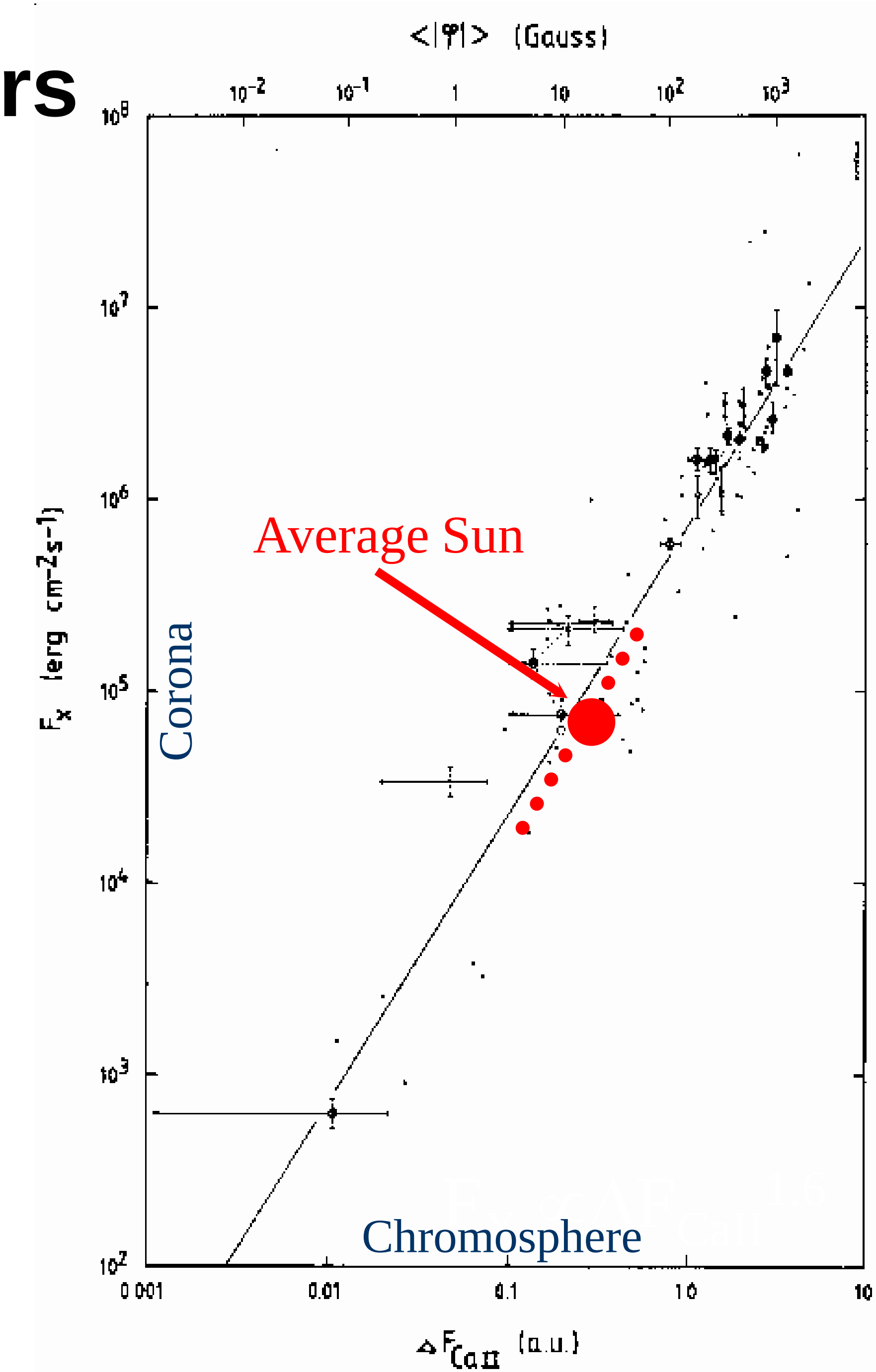
- Increasing activity: “blocking” by starspots outweighs facular brightening



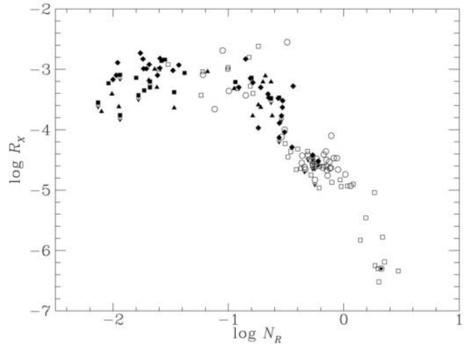
The Sun among the Stars

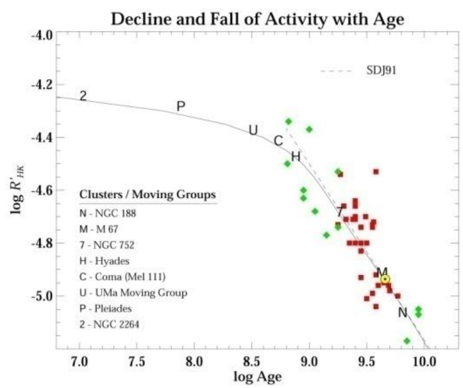
- Flux-flux relationships are power laws over a factor 100,000 in soft X-rays
- The average Sun lies on those relationships, and moves along them through the cycle

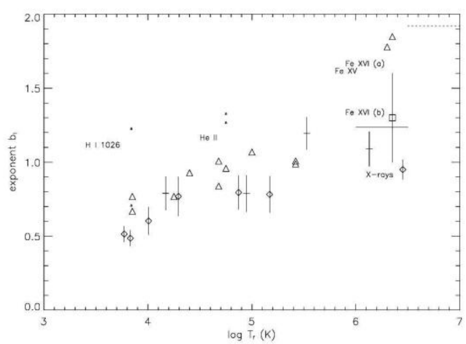
: Energy distribution in stellar outer atmospheres is largely independent of stellar properties

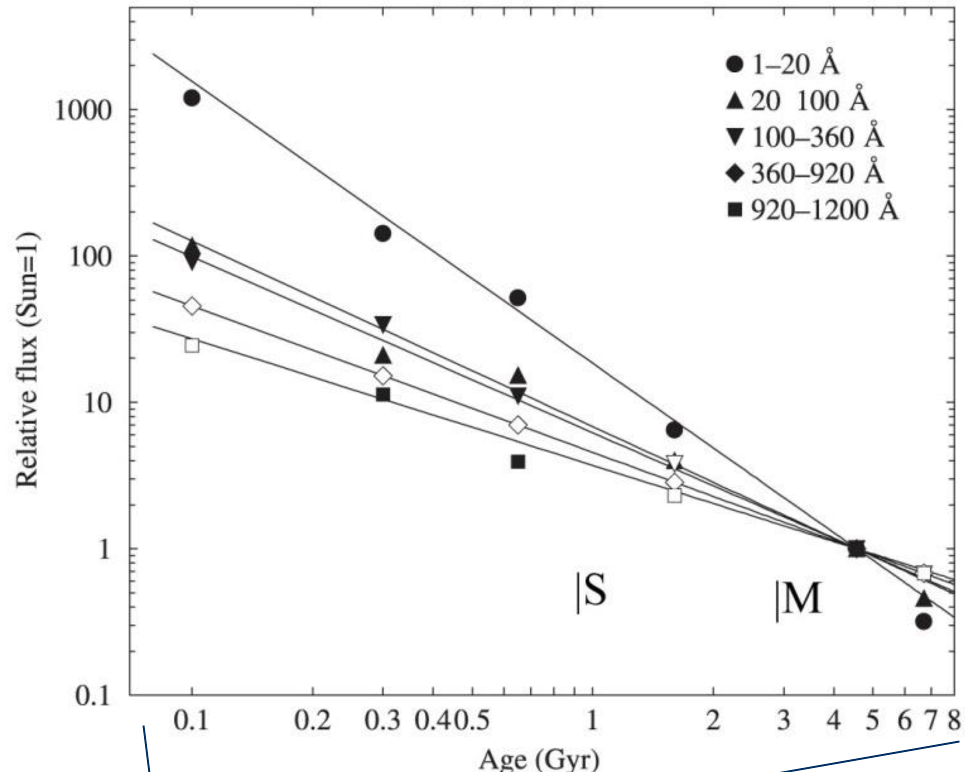


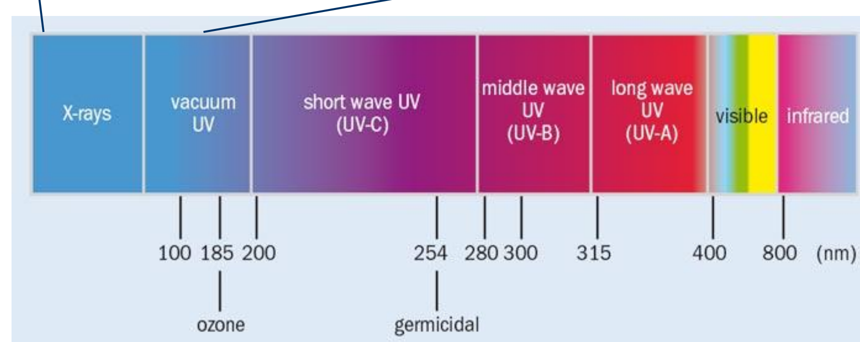
Radiative losses of the Sun in time





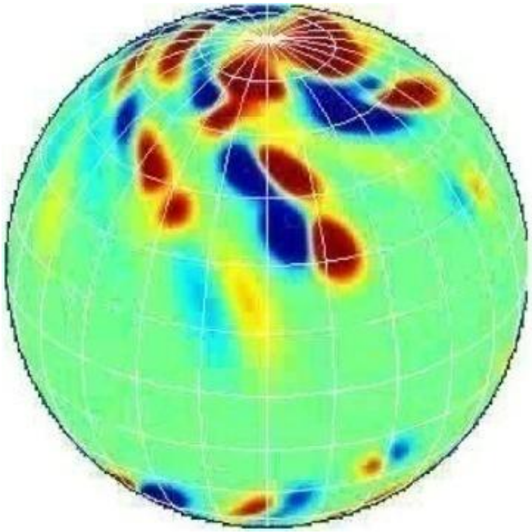




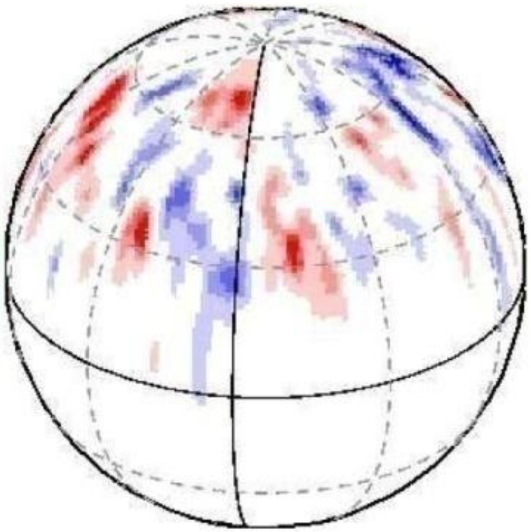


Spots and flux emergence

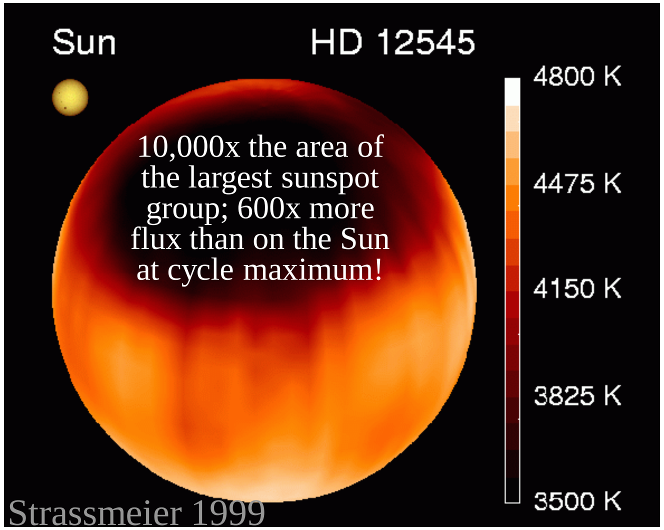
- Starspots: common high-latitude or polar spots in active stars, including “young Sun”



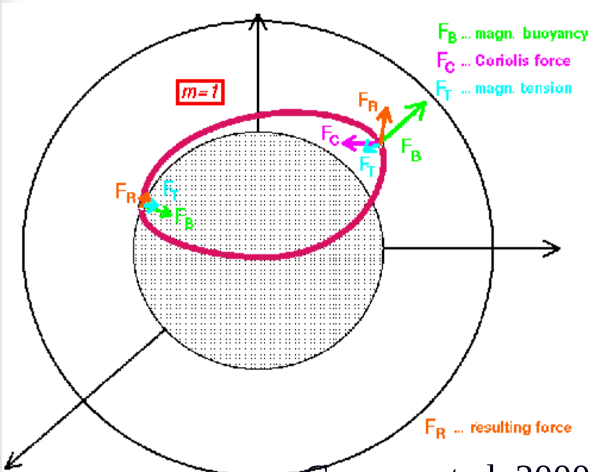
Flux-transport simulation with large latitudinal range and strong meridional flow



AB Doradus (P=0.51d)
K0V, 15pc, 20-30Myr

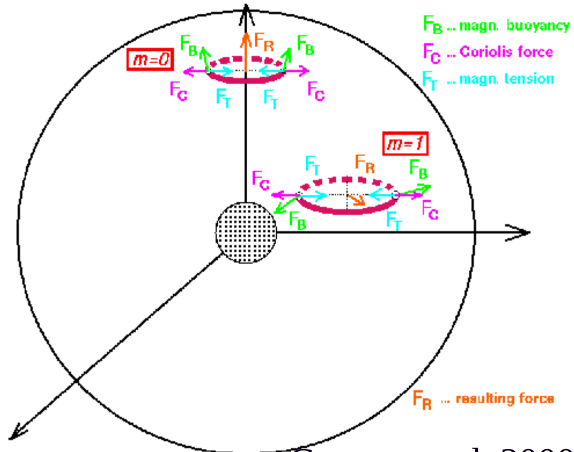


Spot formation on active stars



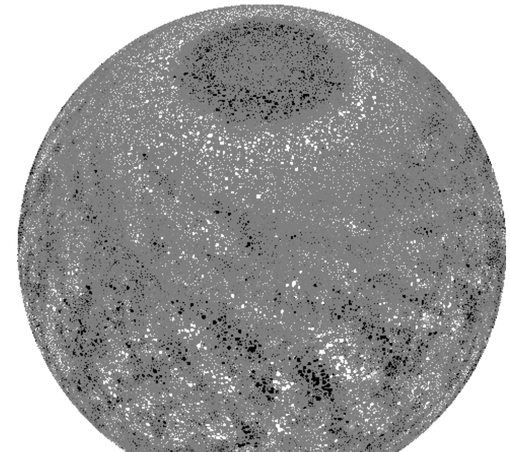
Granzer et al. 2000

Deflection of rising flux



Granzer et al. 2000

Tension of field around small core



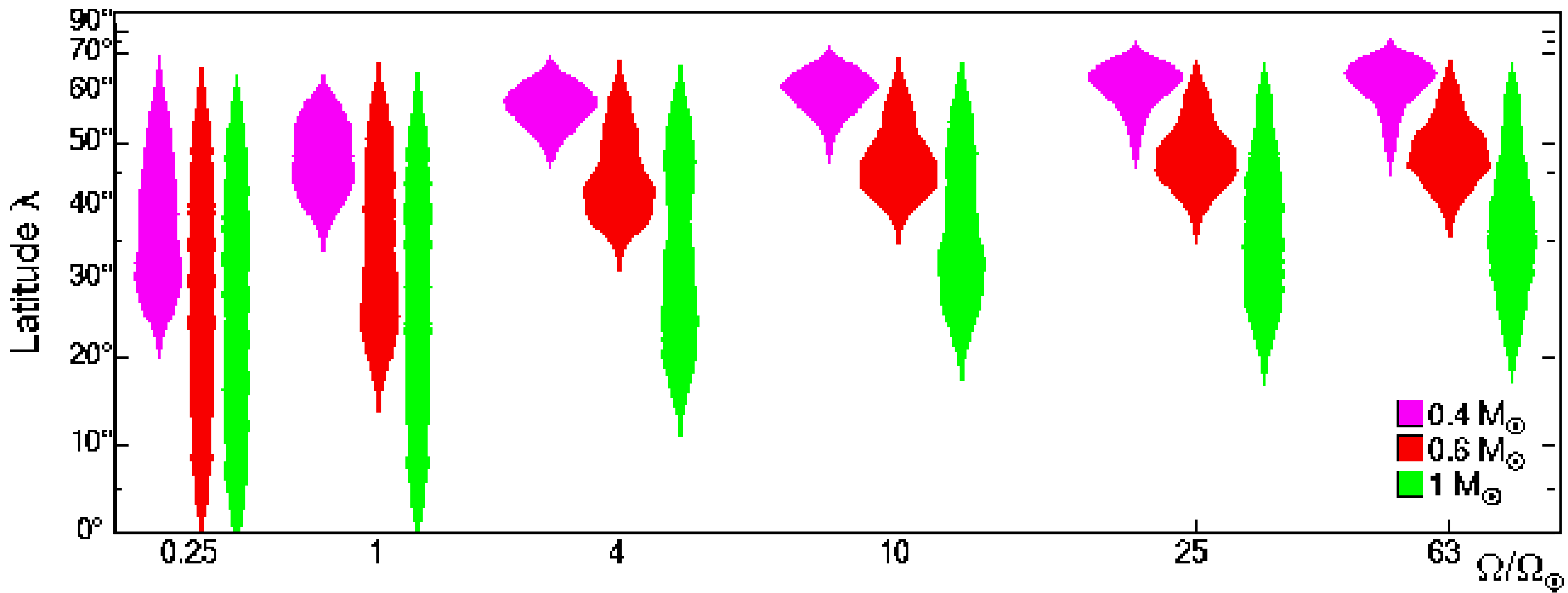
Schrijver & Title 2001

Advection in meridional flow

- In a rapidly rotating sun-like star, the Coriolis force may deflect rising flux to "high" latitudes.
- In a rapidly-rotating cooler star, magnetic tension may cause the entire loop to rise, sometimes to high latitudes.
- For solar emergence and transport properties, high activity leads to persistent flux reservoirs in the polar caps, and likely spots or spot/pore clusters.

Models of flux emergence

- Simulated flux emergence for stars

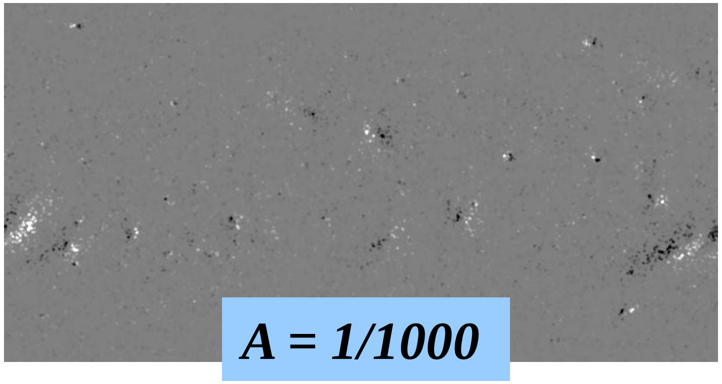


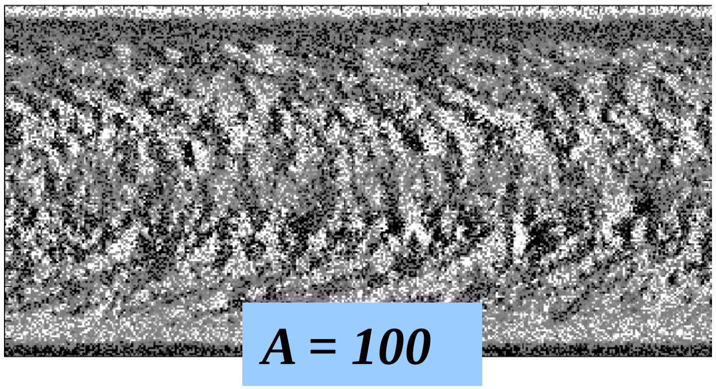
Increasing rotation ⟶

Simulating magnetic activity of other stars

Hypothesis:

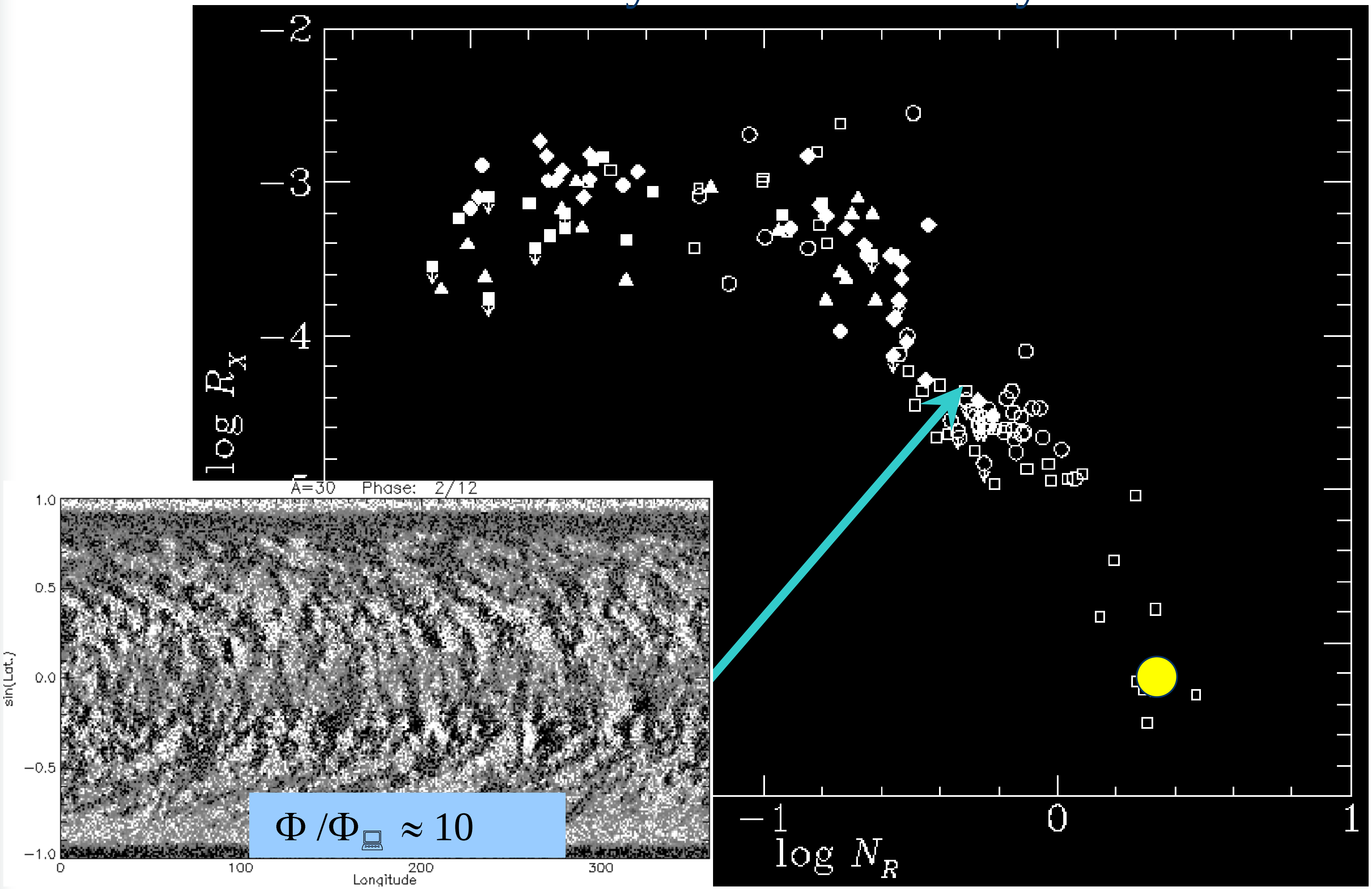
Stellar dynamos are like that of the Sun, *except for the frequency of active-region emergence*





Activity, rotation, and saturation

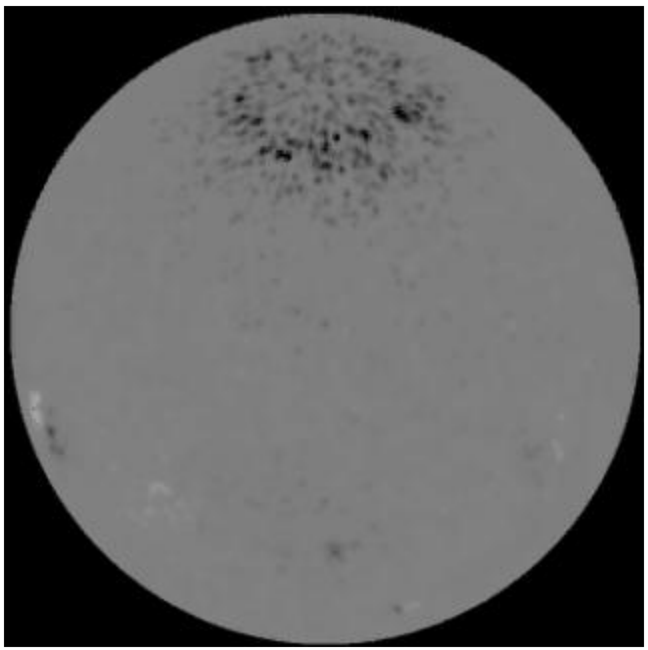
A star at 30x solar rate of flux injection is of merely moderate activity:



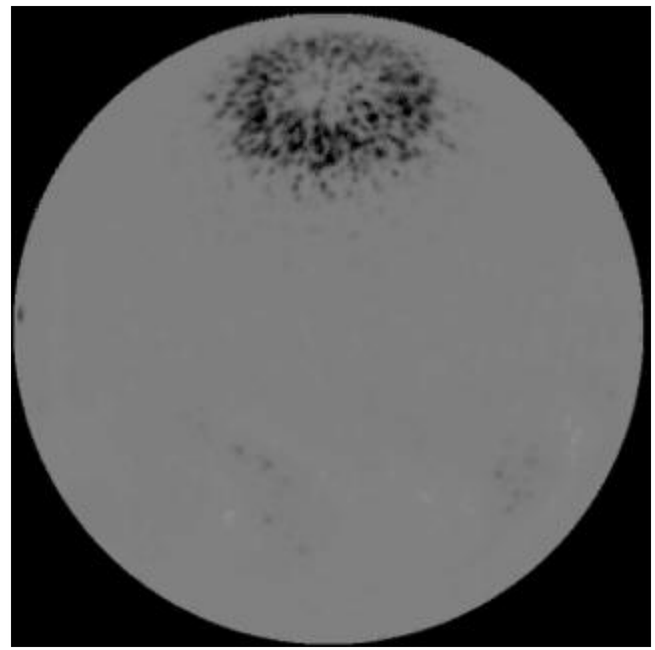
Simulations of activity

Simulated “Sun” from 40°N:

Active star (30x higher rate of flux injection), from 40°N:



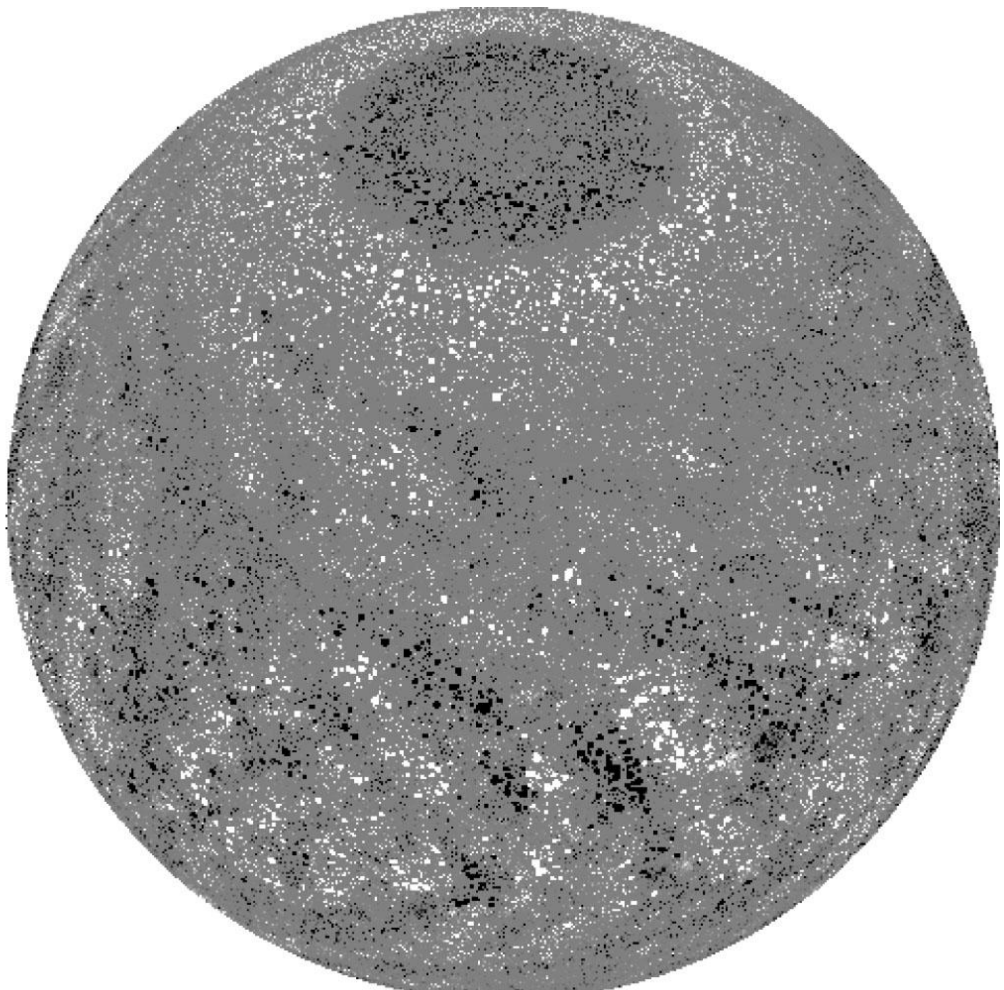
Present Sun



Young Sun at ~500 Myr?

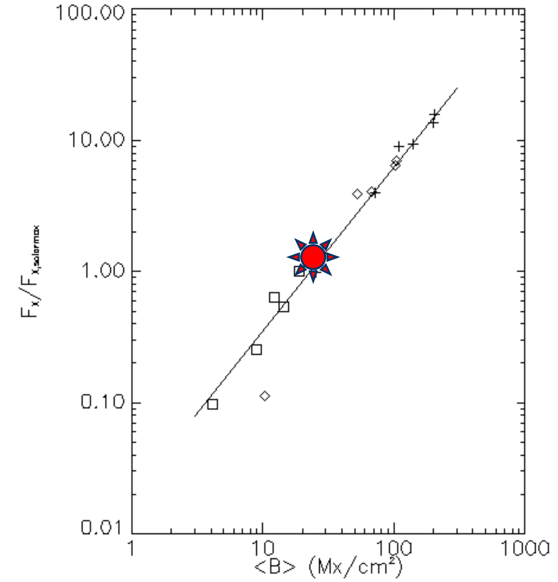
A young Sun?

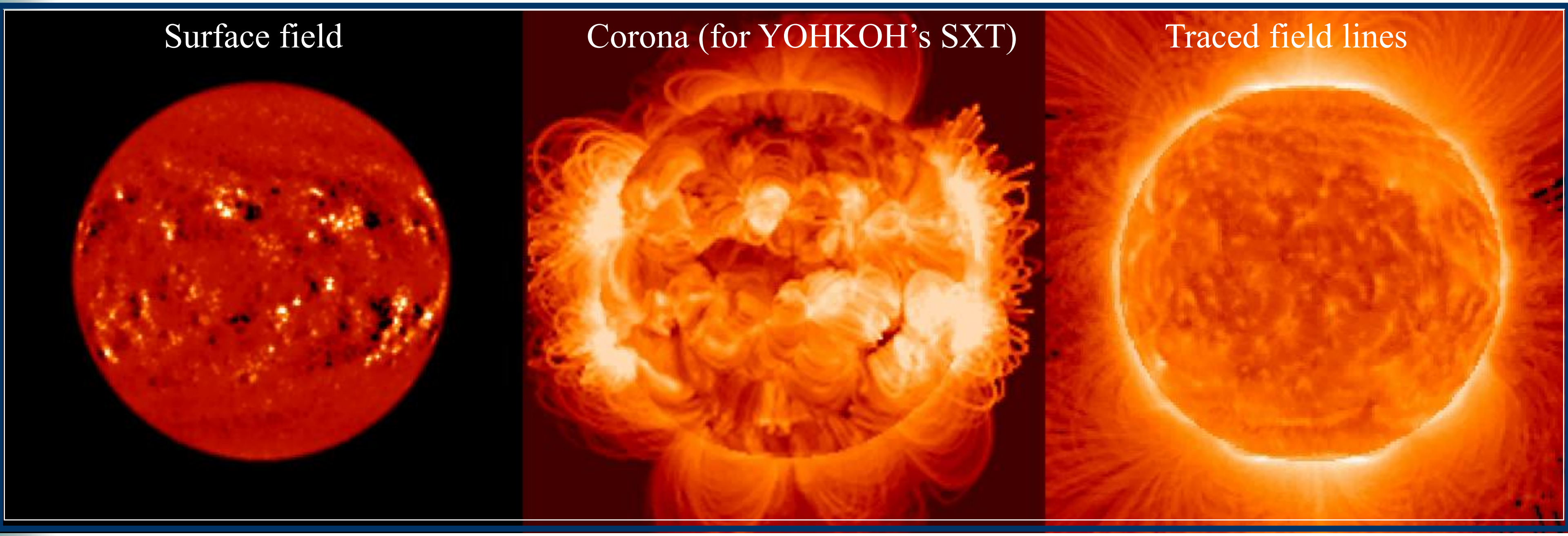
- Simulation result assuming only increased flux emergence rates:



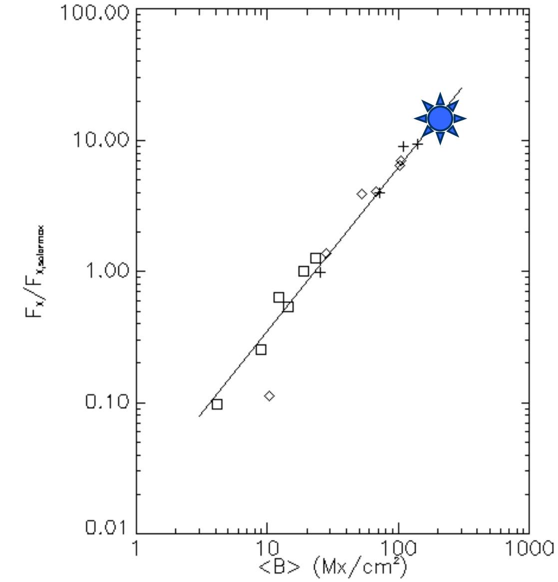
Sun-like star

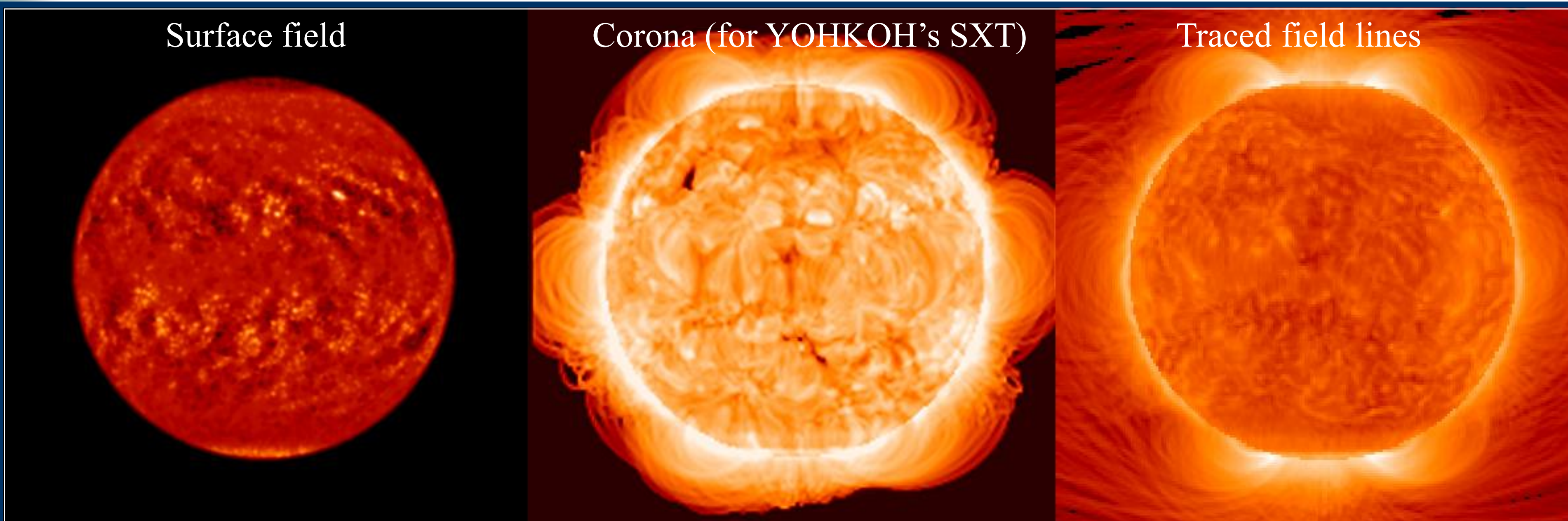
Cycle maximum





30x solar emergence rate

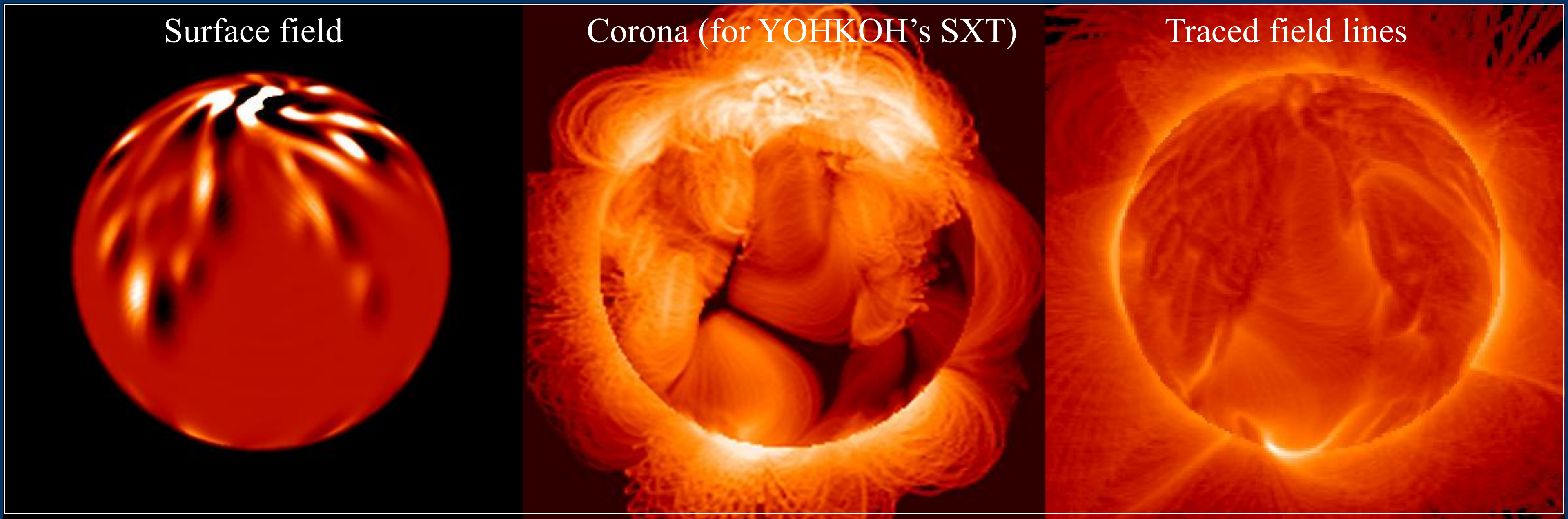




AB Dor – like star

Simulated magnetic field on a star like AB Dor (K0V, 15pc, 20-30Myr, P=0.51d), just prior to “cycle maximum”

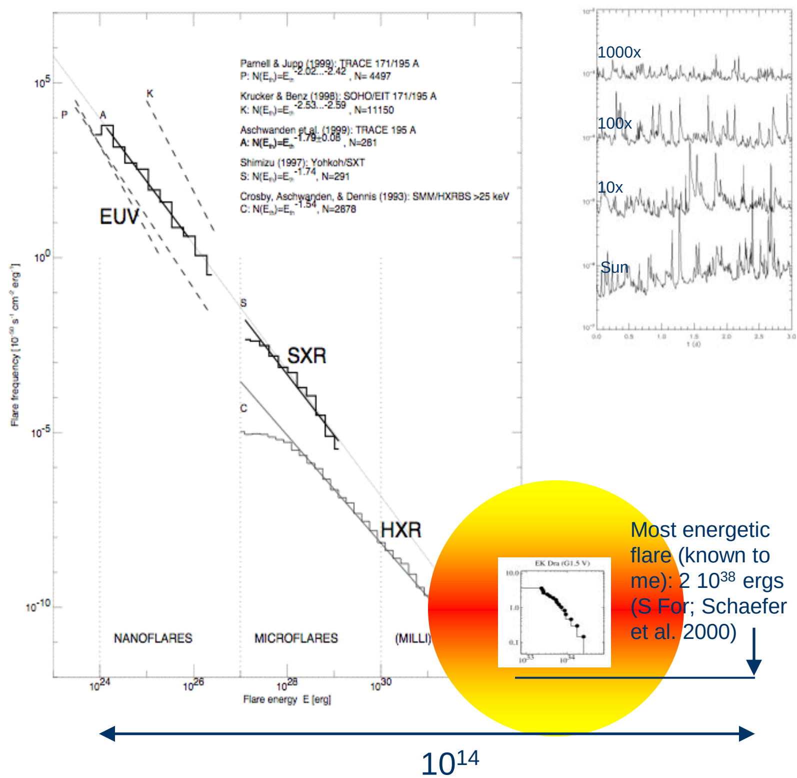
by MacKay, Jardine, Collier Cameron, Donati, Hussain (2004)

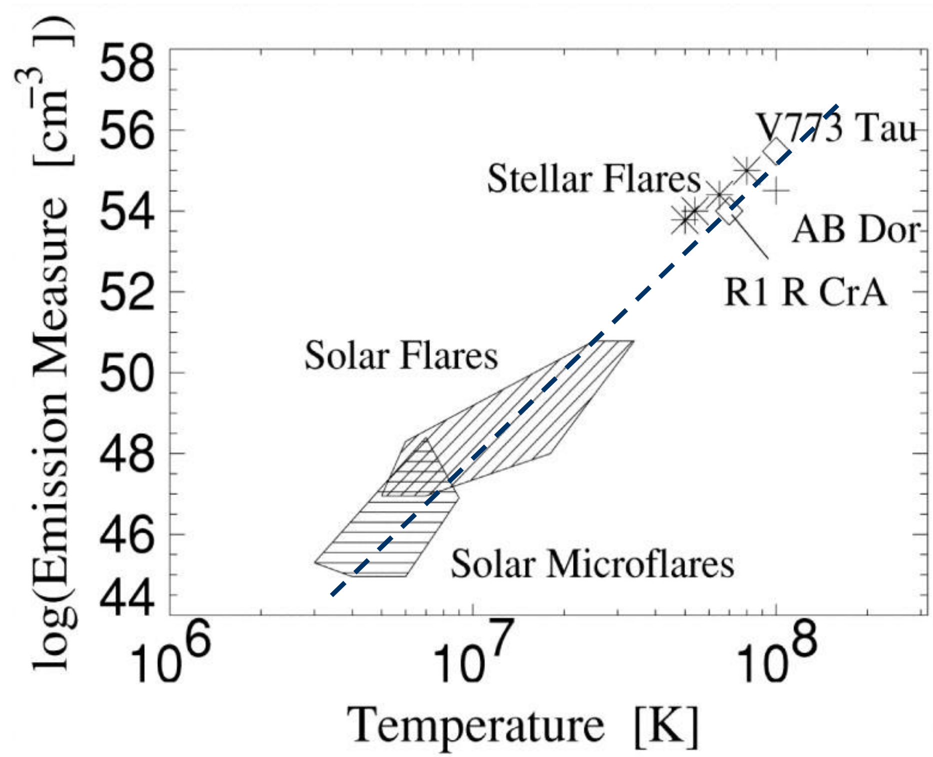


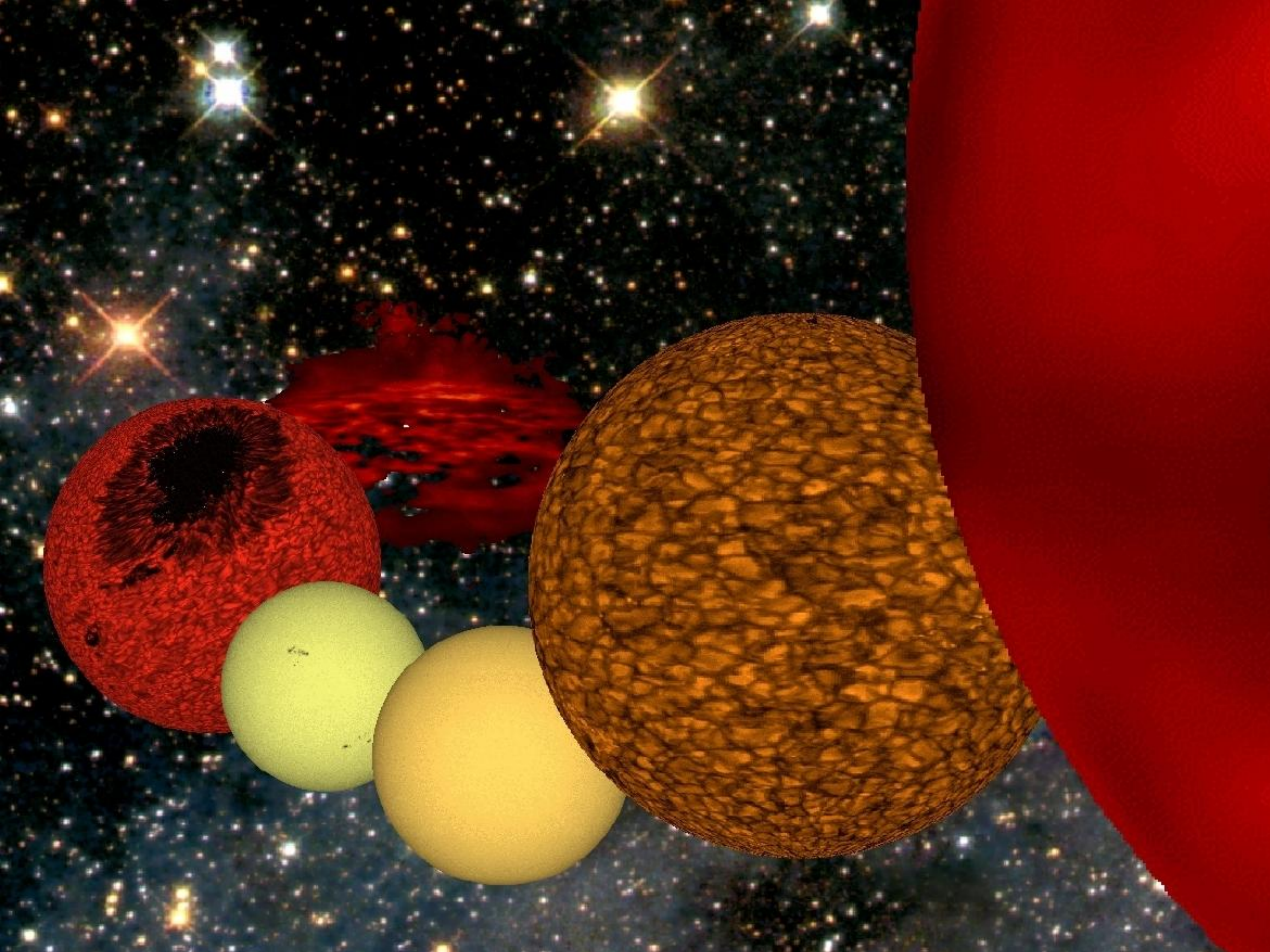
Solar and stellar flares

- Power-law spectra and self-similarity.

Solar and stellar flares:





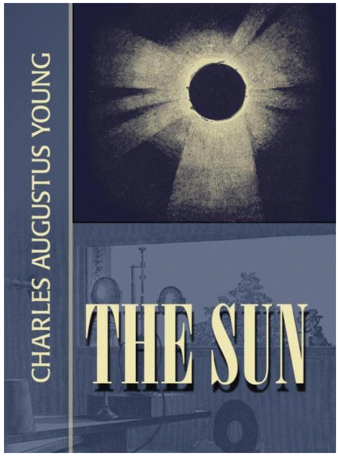


In perspective:□

"At present it would seem that the most important and fundamental problems of solar physics which are now pressing for solution are these:

- first, a satisfactory explanation of the peculiar law of rotation of the sun's surface;
- second, an explanation of the periodicity of the spots;
- third, a determination of the variations in the amount of the solar radiation at different times and different points upon its surface;
- fourth, a satisfactory explanation of the relations of the gases and other matters above the photosphere to the sun itself -- the problem of the corona and the prominences; and
- *fifth, the discovery of [the source of the Sun's energy]."*

Charles□□A. Young, 1892, "The Sun", p. 343,□□
Kegan, Paul, Trench, Truebner, & Co., London



Discussion topics

- 27d recurrence pattern in medium-level geomagnetic activity
- Hysteresis in solar bipole and heliospheric field
- Planetary magnetospheres and stellar coronae
- Probability of huge flares and CMEs
- Syzygies and sunspot cycles

Recurrence in terrestrial-magnetic activity

- http://www-ssc.igpp.ucla.edu/spa/papers/cme/

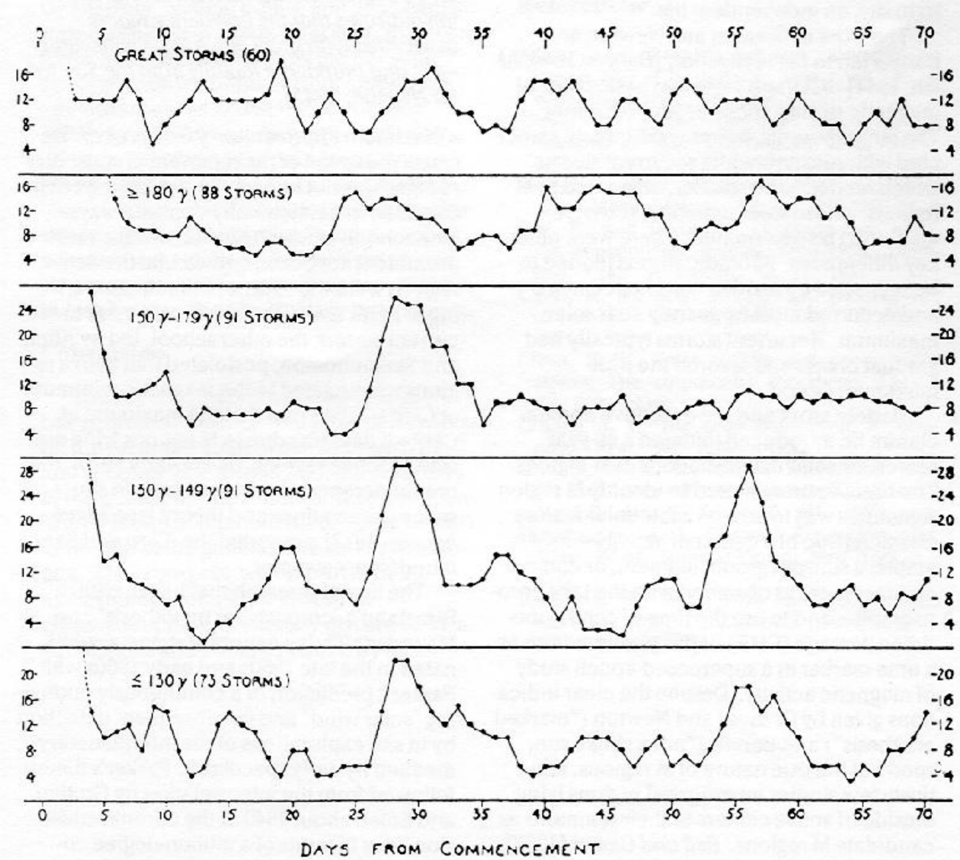
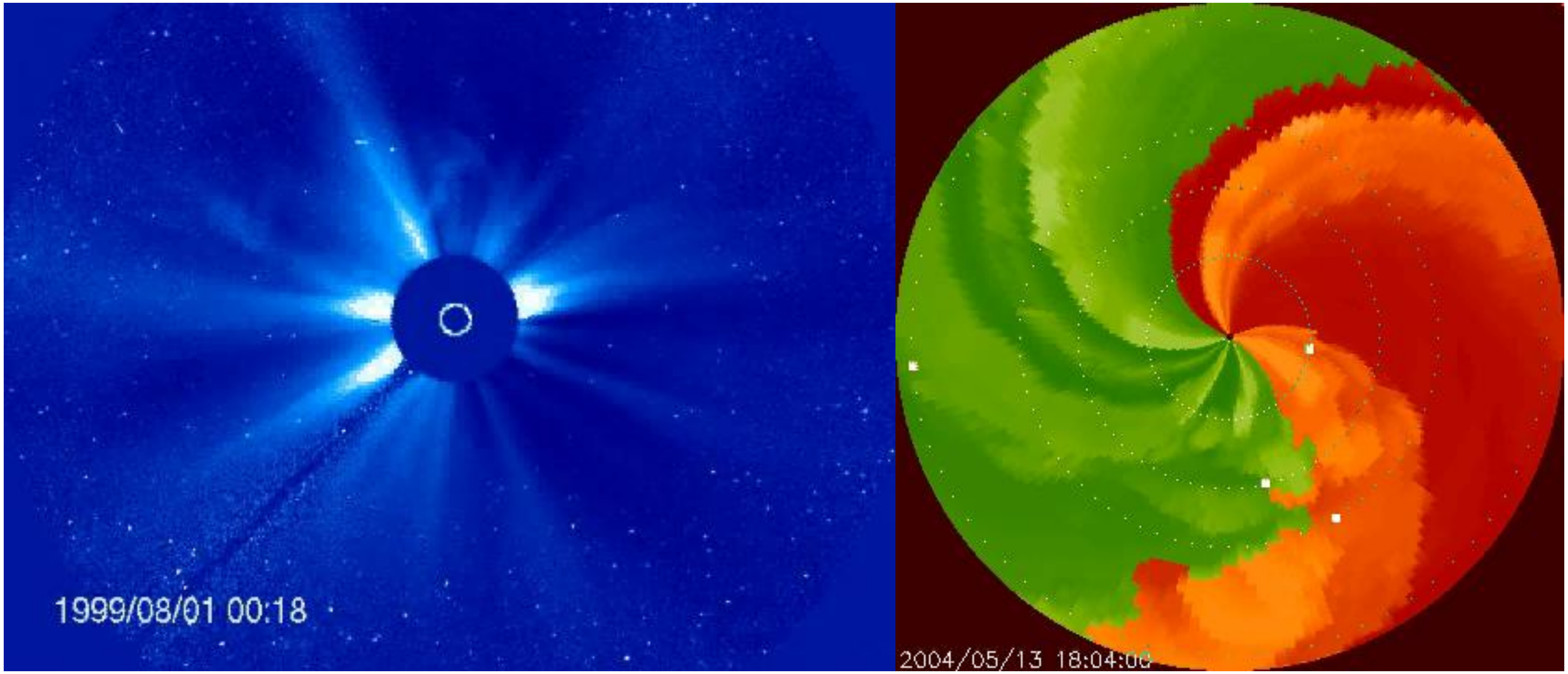
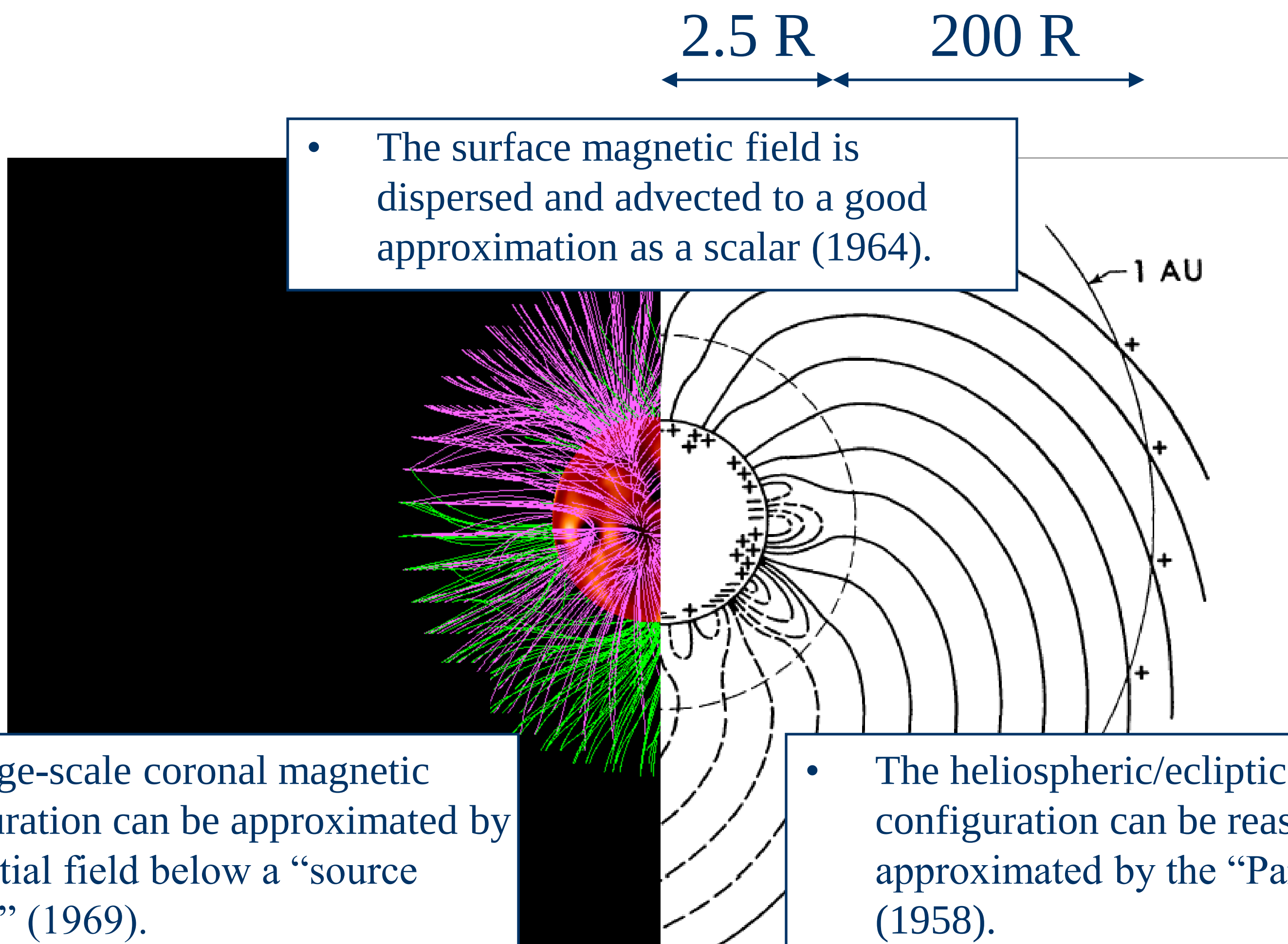


Fig. 1. Figure from Greaves and Newton *[1929] showing that the 27-day recurrence property of magnetic storms is mainly a property of the smaller events. The y axis in this superposed epoch analysis gives the percentage of cases in which magnetic storms of any size were observed on given days following storms of the indicated sizes.*

The extended stellar atmosphere



An ideal world: solar/heliospheric model



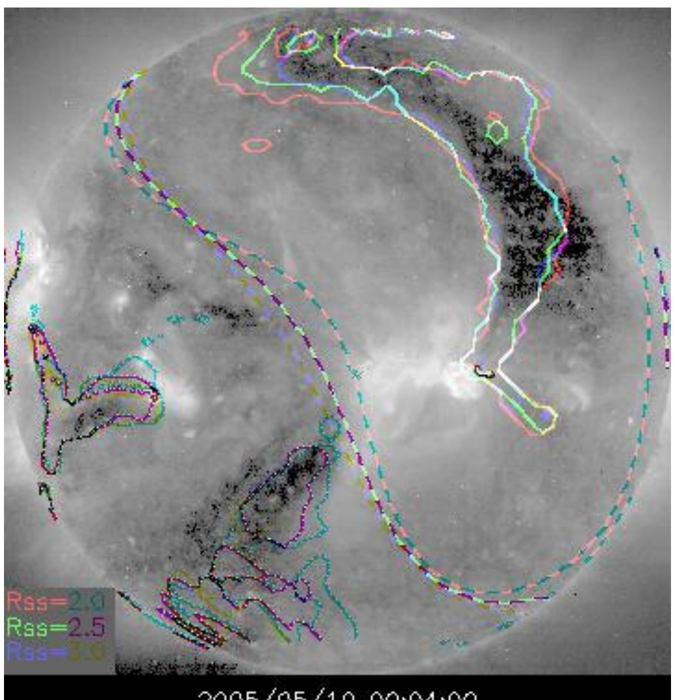
- The surface magnetic field is dispersed and advected to a good approximation as a scalar (1964).

- The large-scale coronal magnetic configuration can be approximated by a potential field below a “source surface” (1969).

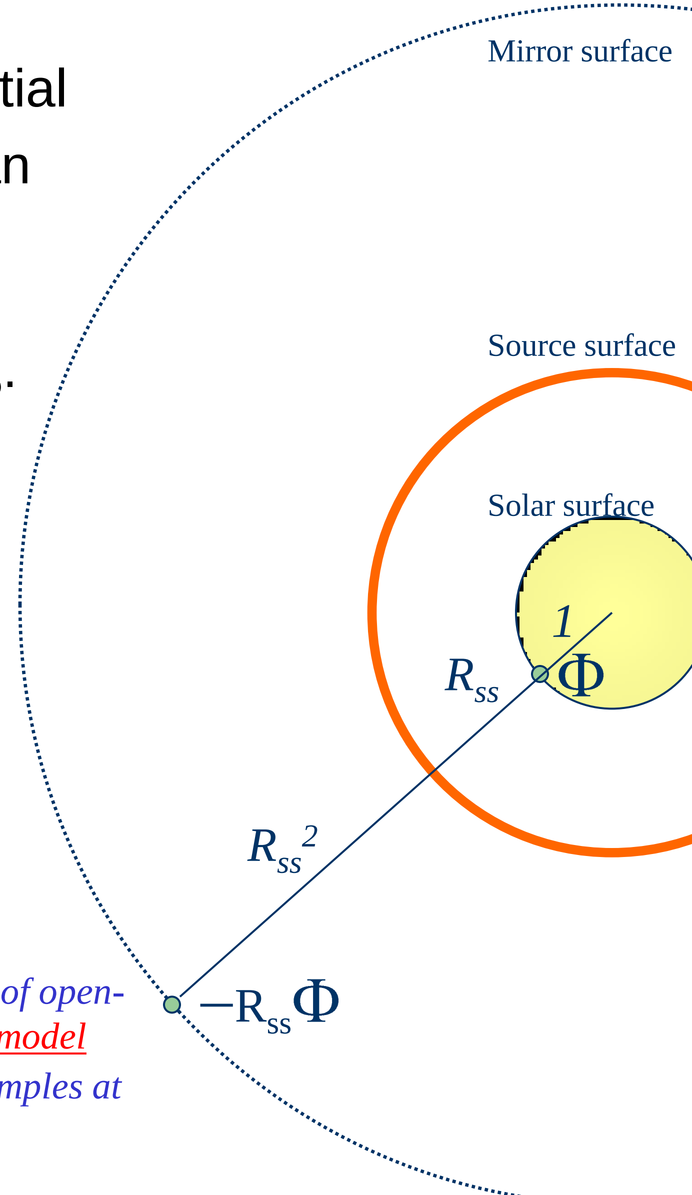
- The heliospheric/ecliptic magnetic configuration can be reasonably approximated by the “Parker spiral” (1958).

PFSS model and coronal holes

- The large-scale coronal field is mostly potential
- It can be approximated remarkably well by an *electrostatic model:*
  - charge distribution on the solar photosphere
  - within a perfectly conducting sphere of ~5 $R_\odot$.



SOHO/EIT 284Å with overlay of open-field boundaries from a PFSS model for different R_{ss} (see other examples at www.lmsal.com/forecast).



Simulation of the solar cycle

Visualizing the evolution of the solar wind source domains, as seen in a ‘corotating’ frame, over 1-1.5 magnetic cycles:

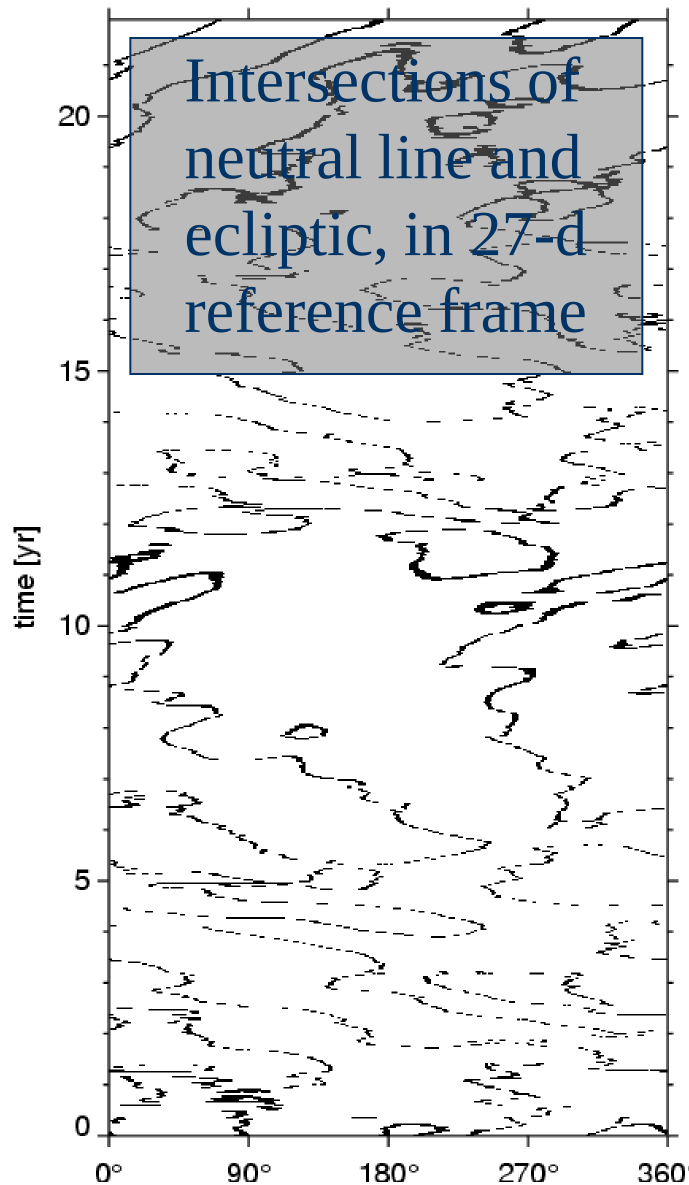
Surface view	Surface grid	Source-surf. grid
Equatorial	Equatorial	Equatorial
40 North	40 North	40 North
90 North	90 North	90 North

Streamer belt still:
From ‘Earth’:

Streamer belt envelope (27-d syn. Bartels frame):

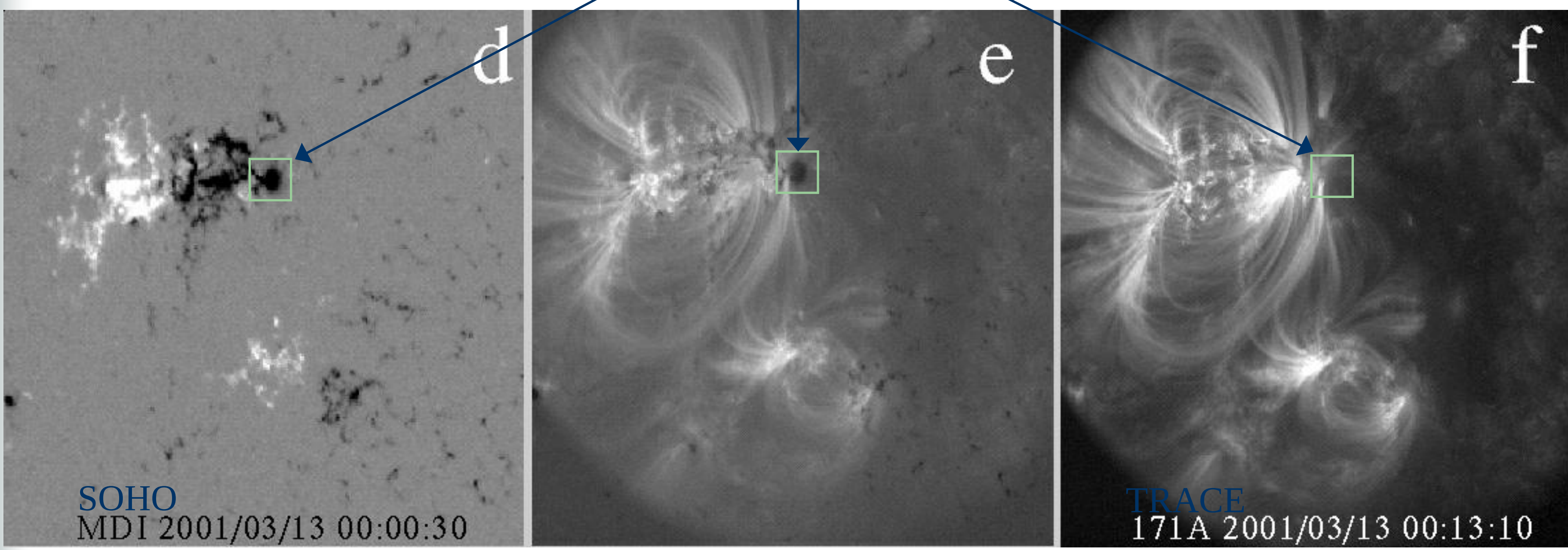
The “current sheet” for a model Sun

- The neutral line drifts around a 27-d synodic rate, as observed.
- Model:
  - One neutral line 90% of the time.
  - One additional polarity island: 10% of the time
  - Only ~30 islands throughout a full magnetic cycle.
  - Islands commonly pinch off from, and re-merge with, the neutral line.
  - Very few islands form at cusp: *the quiescent corona rarely blows bubbles.*



At solar maximum, 30-50% of the interplanetary magnetic field connects directly to active regions (incl. sunspots)

Model: field open to the heliosphere



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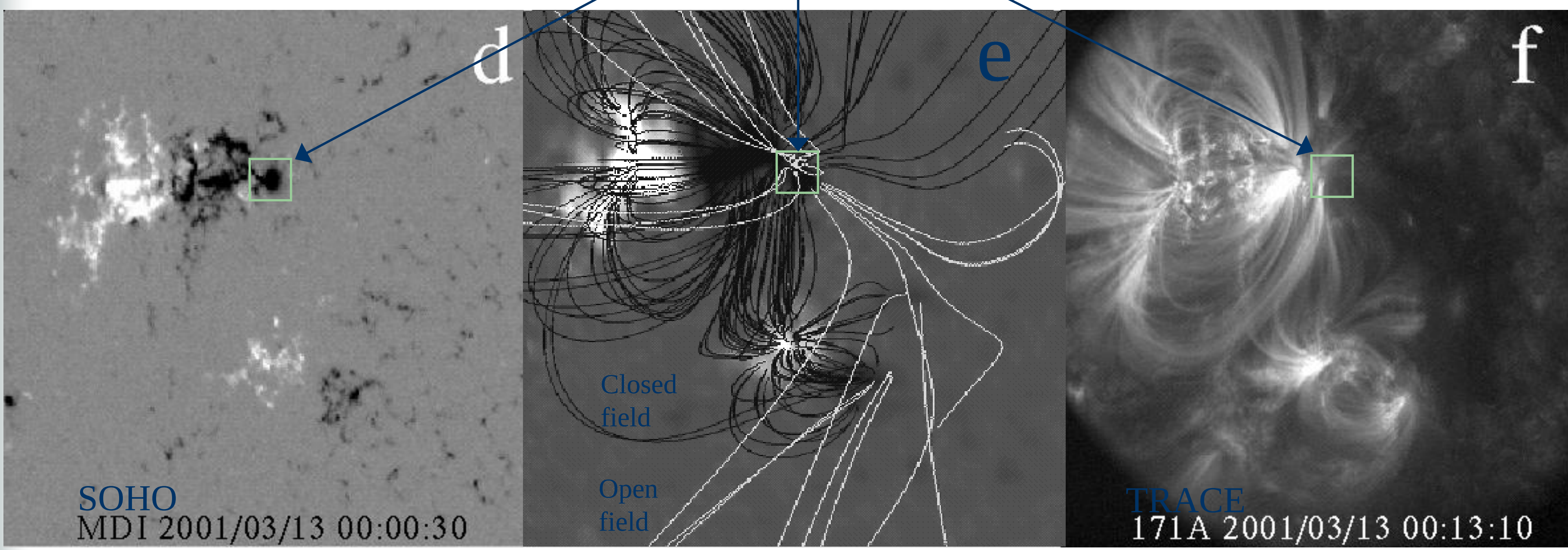
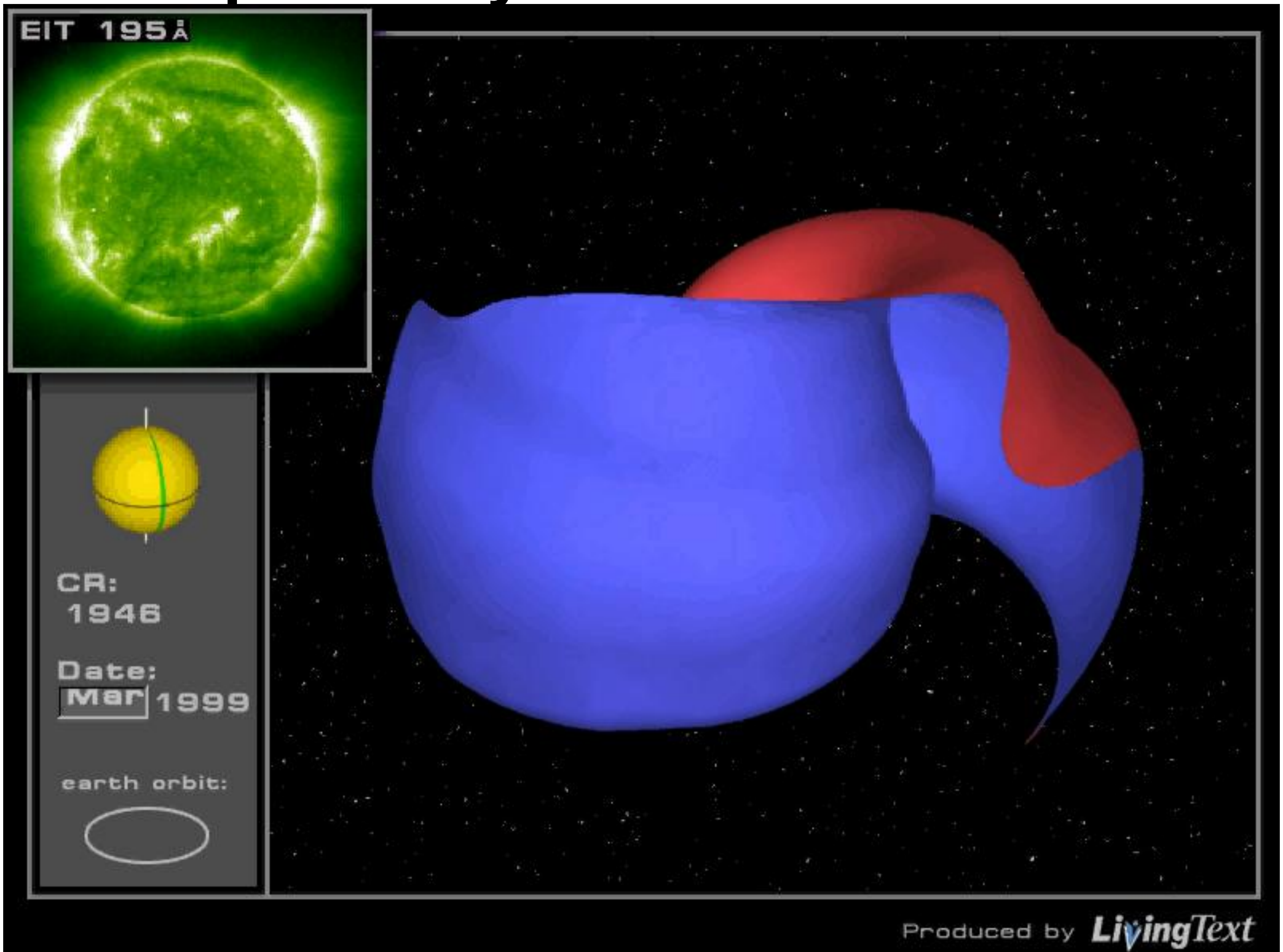
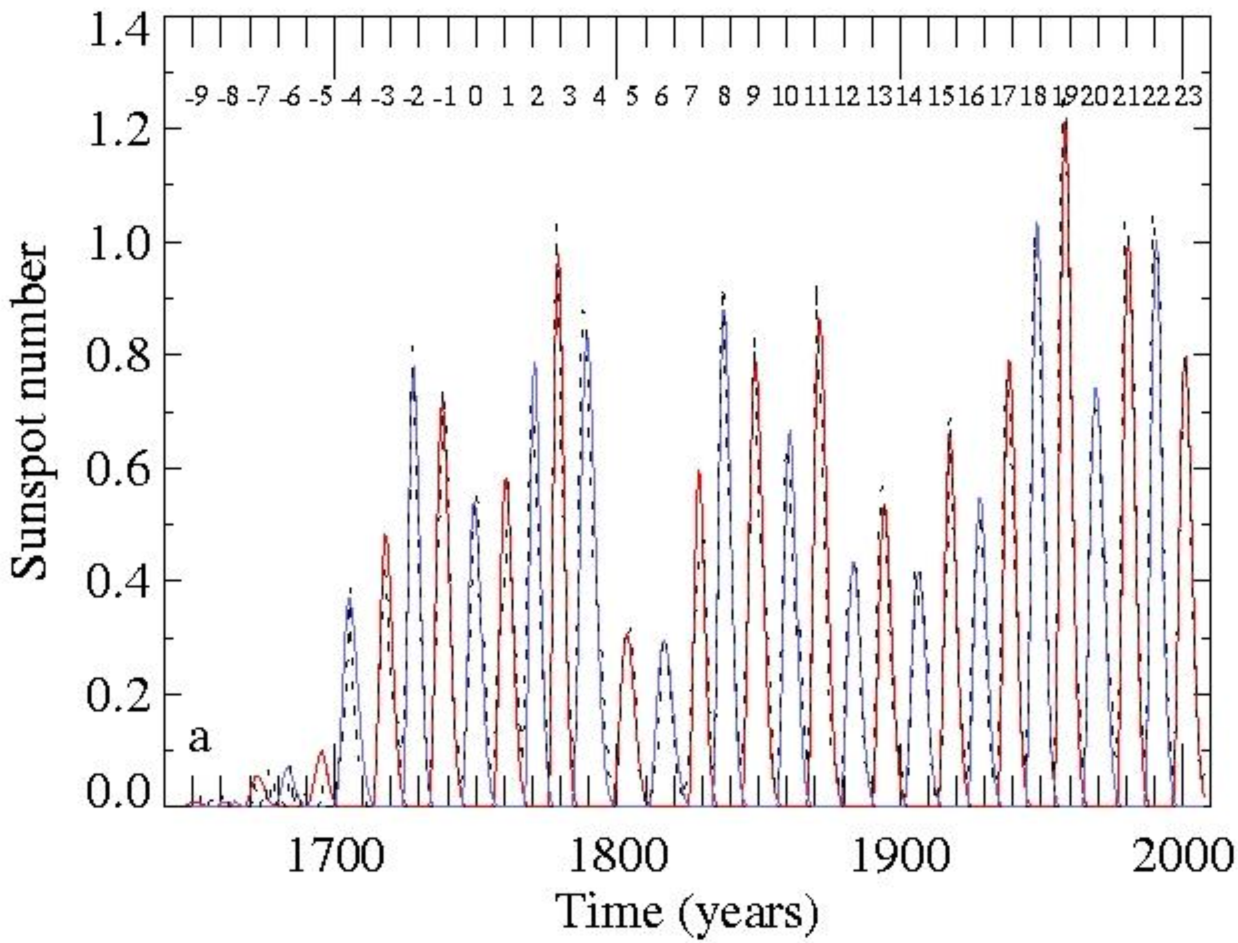


Heliospheric hysteresis



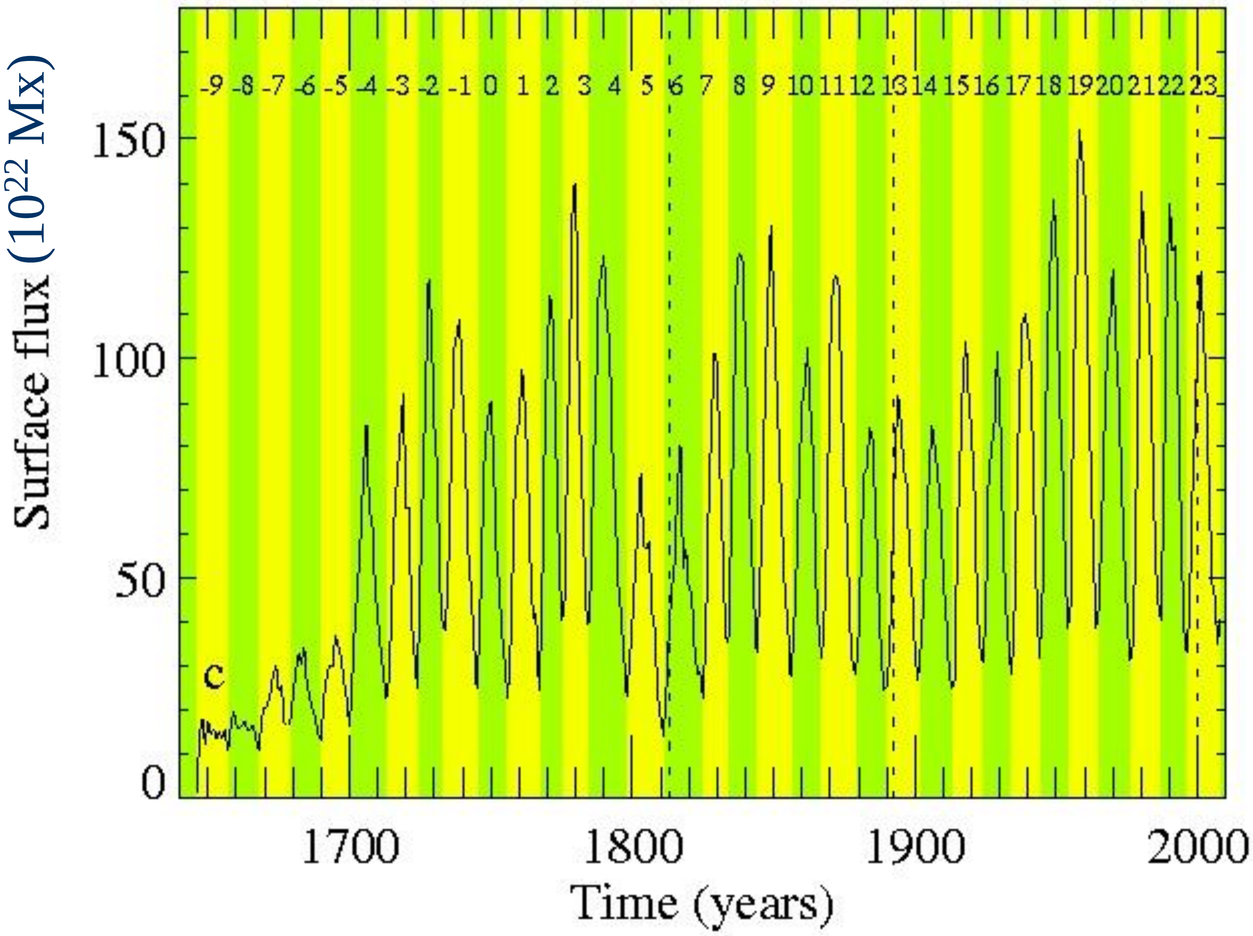
Sunspot cycles: history and approximation

Successive cycles often differ strongly:



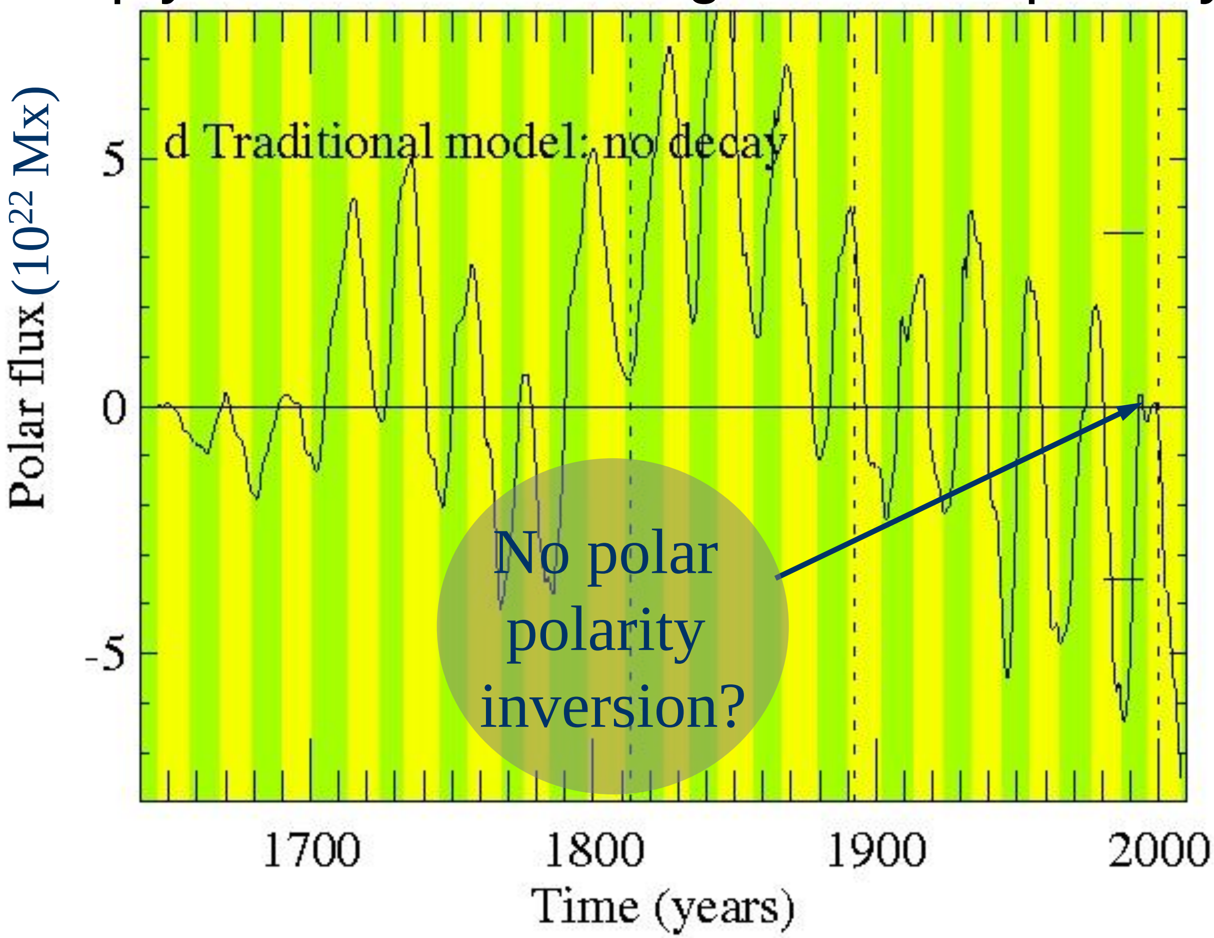
Total flux on the Sun: cycle-to-cycle modulation

Consequently the total flux on the Sun is modulated:



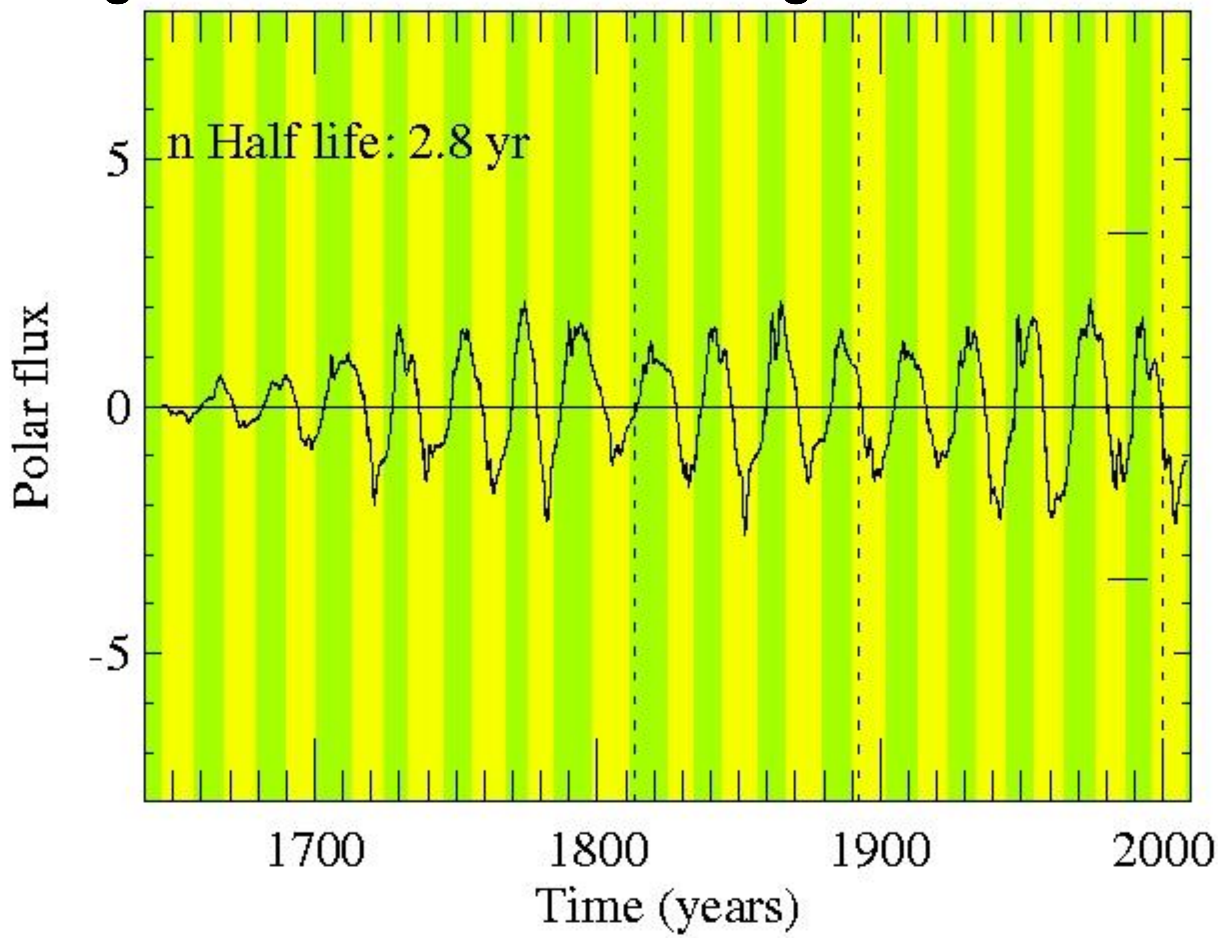
Polar-cap (>60°) absolute flux

And the polar-cap field "capacitor" does not simply alternate in strength or even polarity:



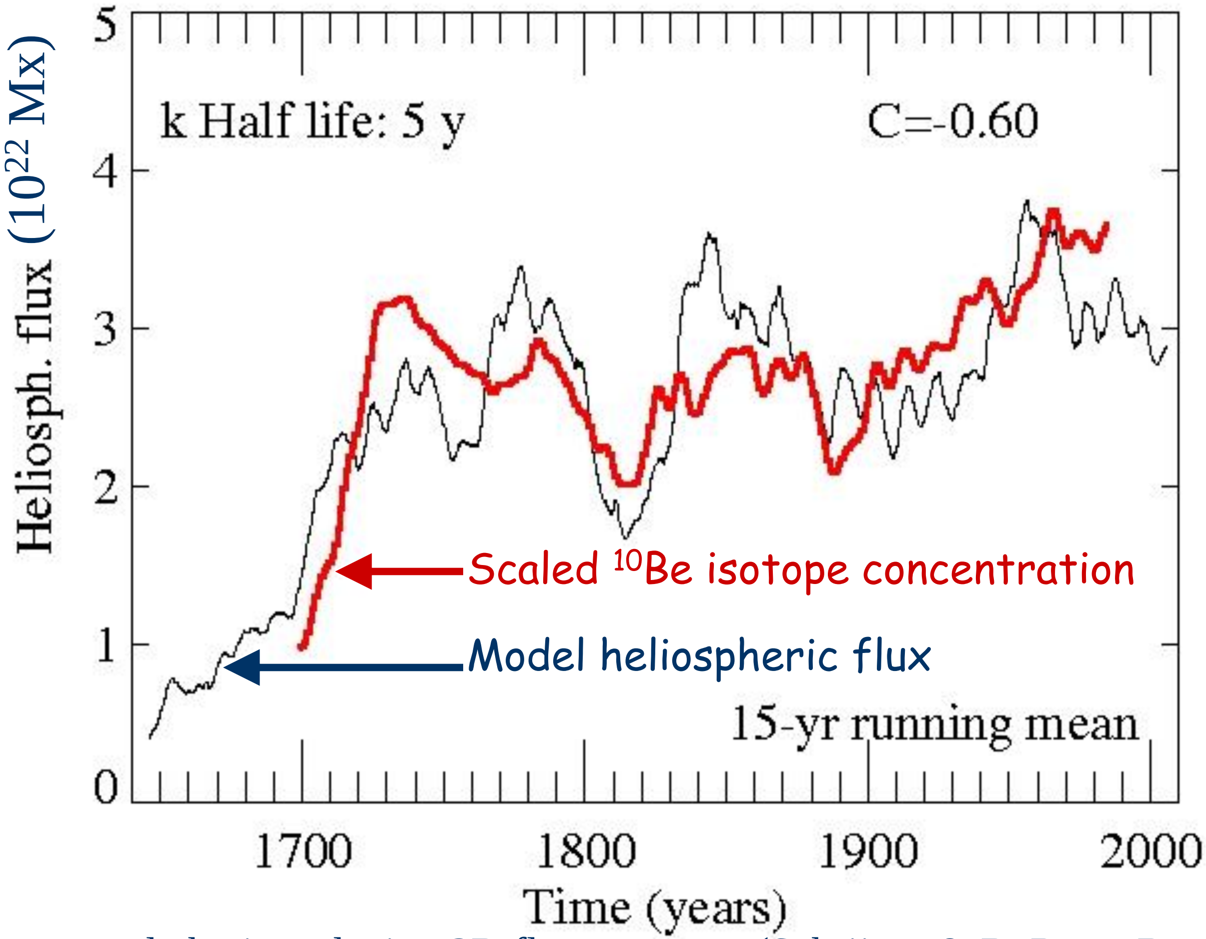
What if flux “decayed” by, e.g., 3D transport?

The polar-cap flux behavior signals something is missing from our understanding:



What if flux transport were modified?

With polar-cap behavior 'regularized'*, the heliospheric and cosmic-ray fluxes are roughly *anti*-correlated:



* For example by introducing 3D flux transport (Schrijver & DeRosa, Baumann et al.) or by modulating flux transport (Wang et al., Schrijver et al.).

Planetary magnetospheres & stellar coronae

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ON A TRANSITION FROM SOLAR-LIKE CORONAE TO ROTATION-DOMINATED JOVIAN-LIKE MAGNETOSPHERES IN ULTRACOOL MAIN-SEQUENCE STARS

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Received 2009 April 27; accepted 2009 May 8; published 2009 June 24

ABSTRACT

For main-sequence stars beyond spectral type M5, the characteristics of magnetic activity common to warmer solar-like stars change into the brown-dwarf domain: the surface magnetic field becomes more dipolar and the evolution of the field patterns slows, the photospheric plasma is increasingly neutral and decoupled from the magnetic field, chromospheric and coronal emissions weaken markedly, and the efficiency of rotational braking rapidly decreases. Yet, radio emission persists, and has been argued to be dominated by electron–cyclotron maser emission instead of the gyrosynchrotron emission from warmer stars. These properties may signal a transition in the stellar extended atmosphere. Stars warmer than about M5 have a solar-like corona and wind-sustained heliosphere in which the atmospheric activity is powered by convective motions that move the magnetic field. Stars cooler than early-L, in contrast, may have a Jovian-like rotation-dominated magnetosphere powered by the star's rotation in a scaled-up analog of the magnetospheres of Jupiter and Saturn. A dimensional scaling relationship for rotation-dominated magnetospheres by Fan et al. is consistent with this hypothesis.

Key words: planets and satellites: general – stars: late-type – stars: low-mass, brown dwarfs – stars: magnetic fields

Evaluate the probability of huge flares

- Use the characteristic power-law spectrum for stellar flares in Audard et al. to fill out the table below. Assume there is no cutoff of the flare spectrum.
- N.B. L_X(Sun) = $10^{27.5}$ ergs; X-class flare ~ 10^{32} ergs
- Discuss the potential consequences of such large flares/CMEs on magnetosphere/ITM/troposphere.

Likely interval between flares of given total energy or larger

Flare energy:	>10^{32} ergs	>10^{34} ergs	>10^{36} ergs	>10^{38} ergs
Sun today				
EK Draconis				

THE ASTROPHYSICAL JOURNAL, 541:396–409, 2000 September 20

EXTREME-ULTRAVIOLET FLARE ACTIVITY IN LATE-TYPE STARS

MARC AUDARD,[1,2] MANUEL GÜDEL,[1,2] JEREMY J. DRAKE,[3] AND VINAY L. KASHYAP[3]
Received 2000 March 7; accepted 2000 May 2

ABSTRACT

Extreme Ultraviolet Explorer Deep Survey observations of cool stars (spectral type F to M) have been used to investigate the distribution of coronal flare rates in energy and its relation to activity indicators and rotation parameters. Cumulative and differential flare rate distributions were constructed and fitted with different methods. Power laws are found to approximately describe the distributions. A trend toward flatter distributions for later type stars is suggested in our sample. Assuming that the power laws continue below the detection limit, we have estimated that the superposition of flares with radiated energies of about 10^{29}–10^{31} ergs could explain the observed radiative power loss of these coronae, while the detected flares are contributing only ≈10%. Although the power-law index is not correlated with rotation parameters (rotation period, projected rotational velocity, Rossby number) and only marginally with the X-ray luminosity, the flare occurrence rate is correlated with all of them. The occurrence rate of flares with energies larger than 10^{32} ergs is found to be proportional to the average total stellar X-ray luminosity. Thus, energetic flares occur more often in X-ray bright stars than in X-ray faint stars. The normalized occurrence rate of flares with energies larger than 10^{32} ergs increases with increasing L_X/L_{bol} and stays constant for saturated stars. A similar saturation is found below a critical Rossby number. The findings are discussed in terms of simple statistical flare models in an attempt to explain the previously observed trend for higher average coronal temperatures in more active stars. It is concluded that flares can contribute a significant amount of energy to coronal heating in active stars.

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Likely interval between flares of given total energy or larger

Flare energy:	**>10^{32} ergs**	**>10^{34} ergs**	**>10^{36} ergs**	**>10^{38} ergs**
Sun today	4d	1y	100y	10000y
EK Draconis	8min	5d	50d	15y

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Syzygies and cycles

- Critique ("referee") the manuscript: evaluate arguments in favor and against the proposed hypothesis:

Impact Generated Shockwaves are Proposed for the Origin of Sunspots to Explain the Detected Planetary Correlations with Solar Activity

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Abstract Correlations between solar activity and the heliocentric longitudes of Jupiter, Neptune and Uranus at the time of the syzygies of Jupiter and Saturn are detected. In order to explain these correlations it is suggested that the resonance of the outer planets destabilizes the orbit of Kuiper Belt Objects and generates a cyclical impact frequency on the Sun. The vaporization of the object initiates a shock way disrupting the upwelling of the plasma resulting in a sunspot formation. The proposed model is able to explain the length of the cycle, the latitude distribution of the sunspots and the extremely long term stability of the cycles. Calculating the positions of the Jovian planets at syzygies of Jupiter and Saturn allows the long term prediction of the solar activity.