The solar-stellar complement: what we cannot readily learn from the (present) Sun about its activity

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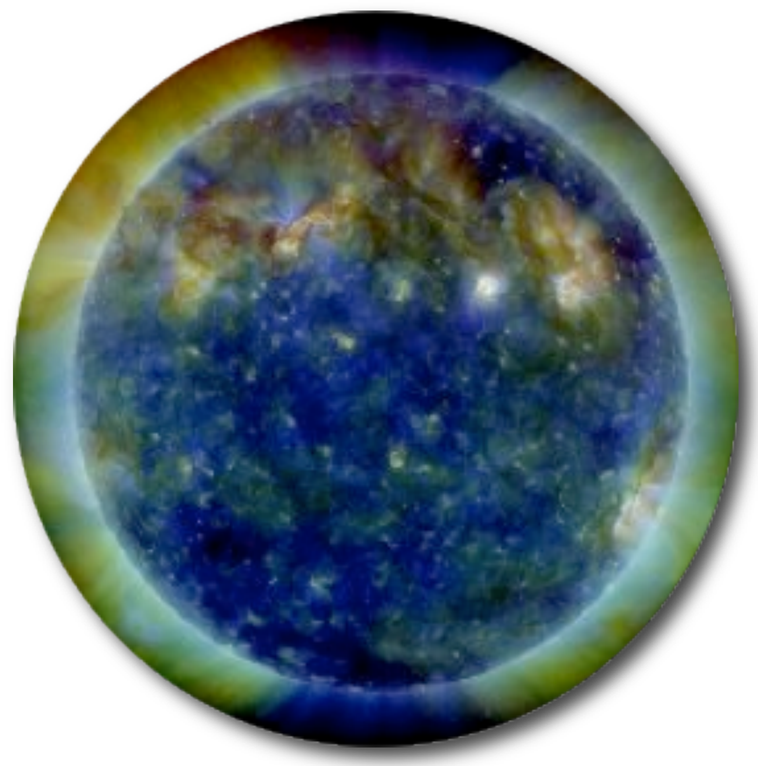
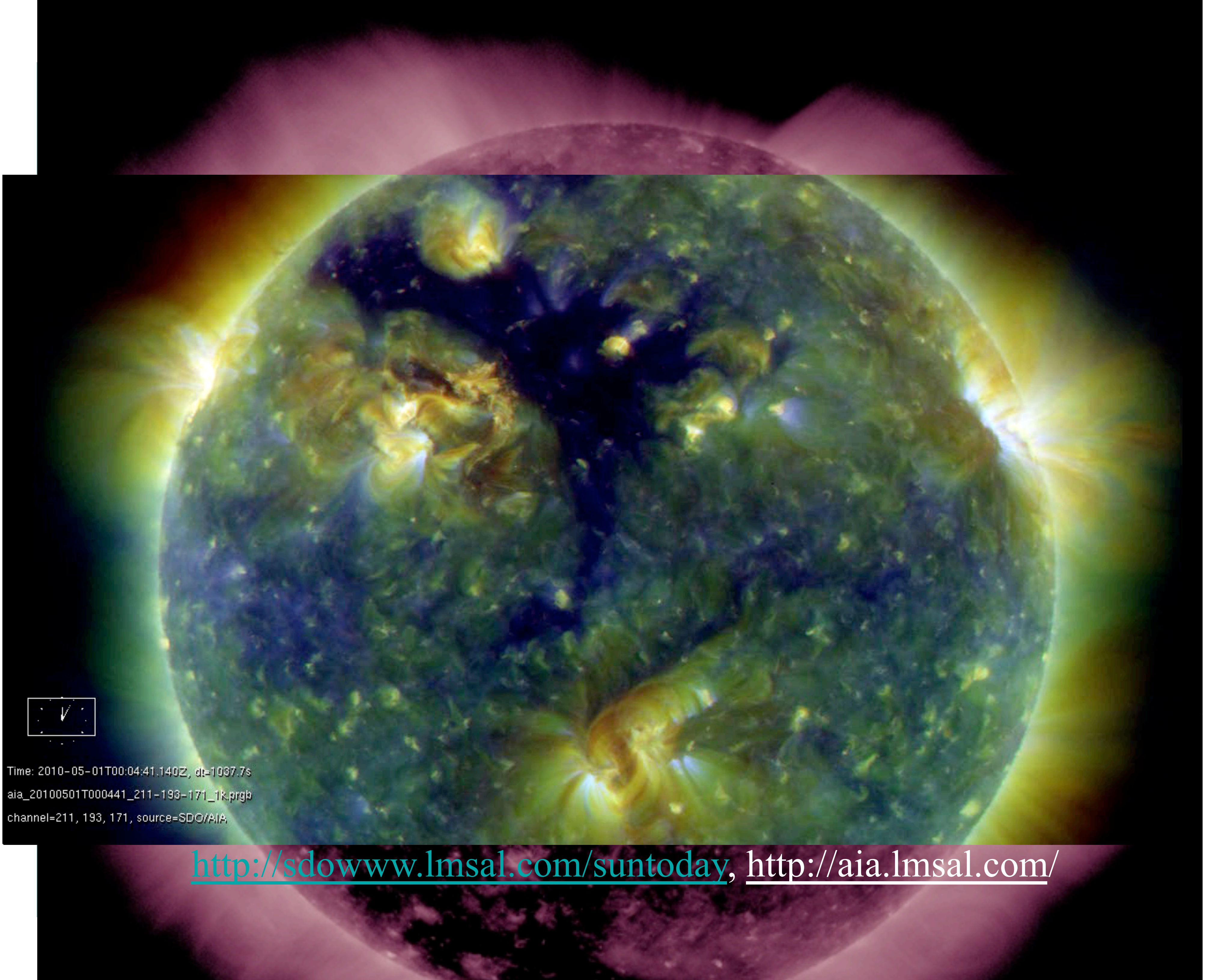
AGCI - June 2010, Aspen, Colorado





http://sdowww.lmsal.com/suntoday, http://aia.lmsal.com/

Solar-heliospheric variability

- Many coupled processes - some couplings known, few understood, all subject to cyclic variation, many (all?) to cycle-to-cycle variations, most non-linear.

spots/faculae

magnetic bipole spectrum

dipole orientations (axial dipole moments)

latitude distribution (butterfly diagram)

large-scale flows (meridional poleward advection, differential rotation)

eruptions/flares

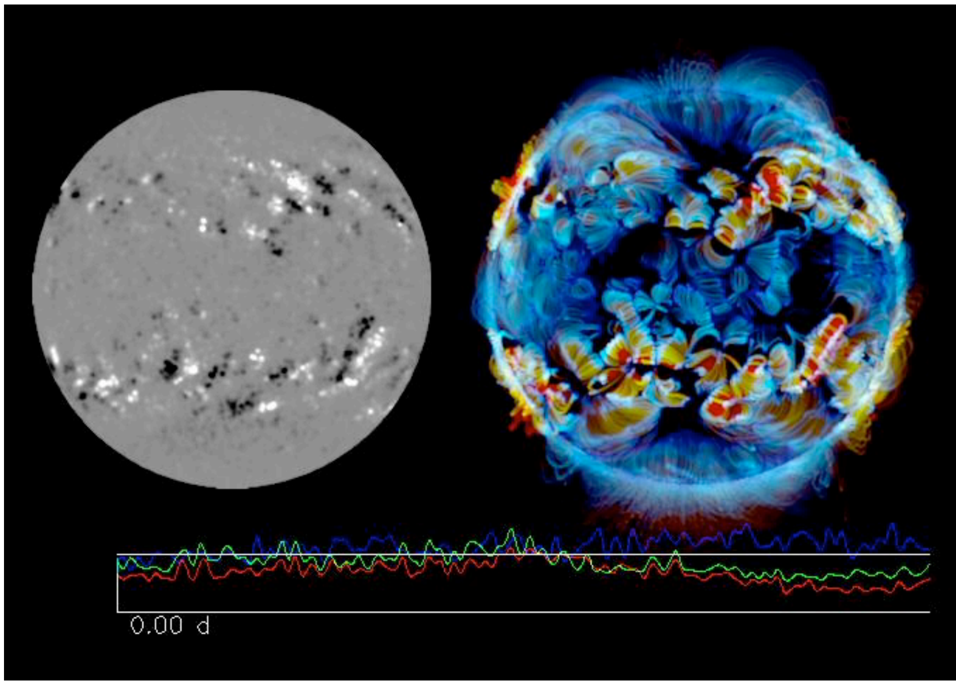
spectral irradiance

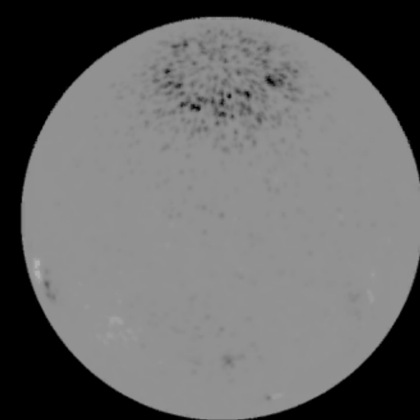
heliospheric wind

heliospheric energetic particles

galactic cosmic rays

A global view of solar activity





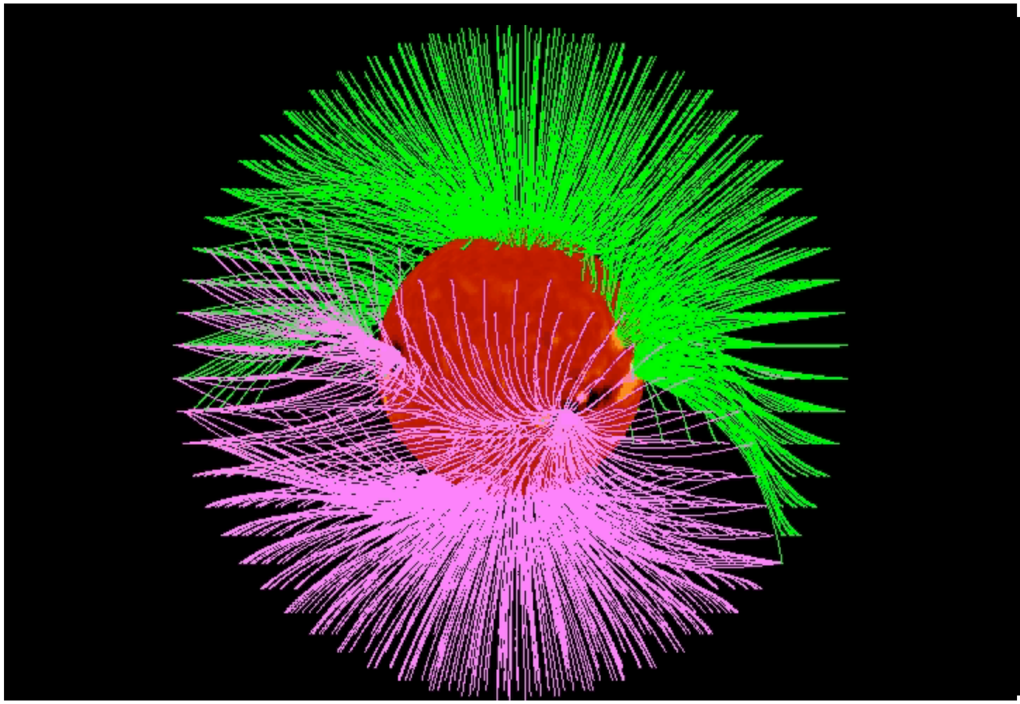
Heliospheric/polar-cap flux: O(4 10^{22} Mx) = flux in one large sunspot, or ~0.01% of ephemeral regions!

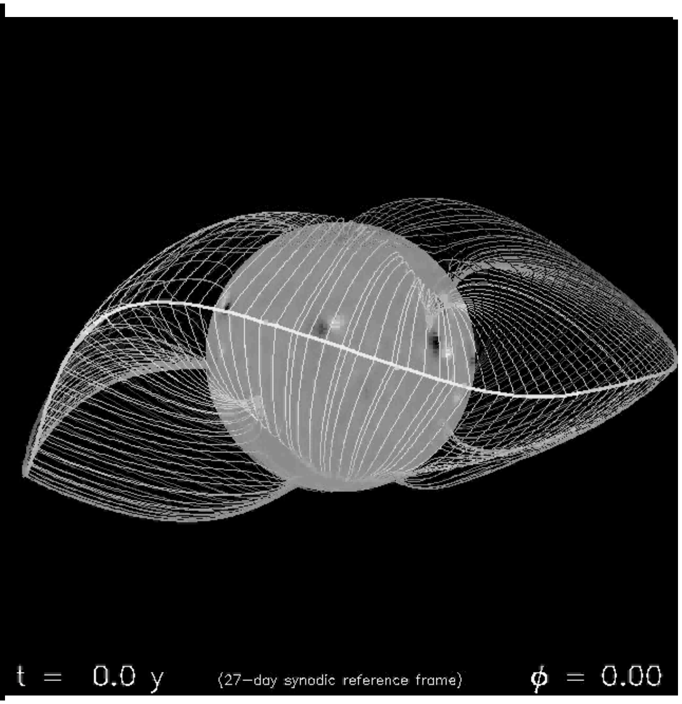
Surface magnetism and 1, 1.5, 2 MK simulated quiescent corona, from corotating perspective.

Surface magnetism from out-of-ecliptic corotating perspective.

A global view of solar activity

- Heliospheric magnetic field ‘known’ in quiescence, subject to substantial uncertainties because of limited surface coverage, effects of electrical curents, waves, ...





Surface magnetism and coupling into the heliosphere, from co-rotating perspective.

‘Helmet streamer belt’, from co-rotating perspective.

Bipolar-region emergence spectrum

- Continuous spectrum from AR to small scales, with a spectrum in which neither extreme can be ignored.
- Cycle variation weak for ephemeral regions
- Depends on flux imbalance for ephemeral regions
- Properties for granulation-scale convection: TBD

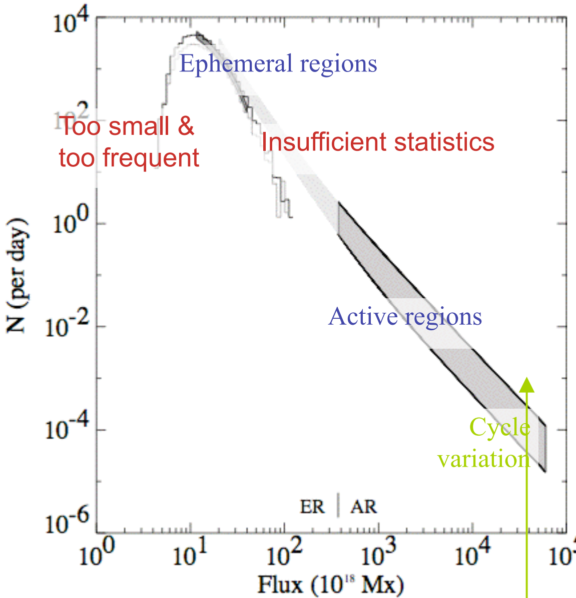


FIG. 11.—Composite distribution function of bipoles emerging on the Sun per day, per flux interval of 10^{18} Mx. The distribution for active regions (defined as regions larger than 2.5 deg^2) taken from the literature varies by about a factor of 8 through a typical cycle; the extremes of that variation bound the dark shaded area on the right. The much smaller variation for the smallest ephemeral regions—studied here, and shown by the darkest shading—is likely weakly in antiphase with the sunspot cycle; full histograms are shown for 1997 October (*black*) and 2000 August (*gray*). The turnover below 10^{18} Mx likely reflects the detection threshold of MDI. The lightly shaded area between the smallest ephemeral regions and the active regions is an approximation that still awaits confirmation (see § 5).

Hagenaar et al. (2003)
http://adsabs.harvard.edu/abs/2003ApJ...584.1107H

Active region flux spectrum is a power law with slope close to -2; hence, flux integral does not converge (very fast): is there a cutoff at largest scales [and at smallest]?

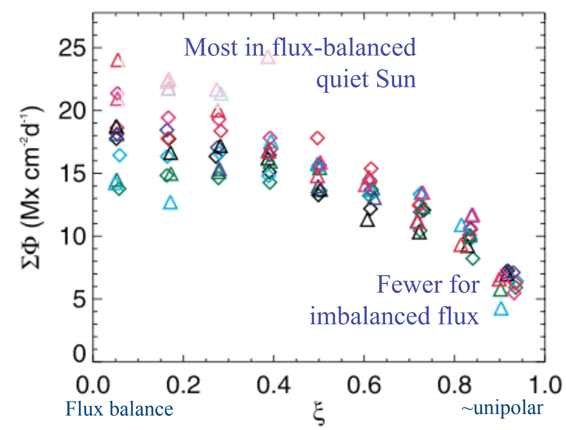
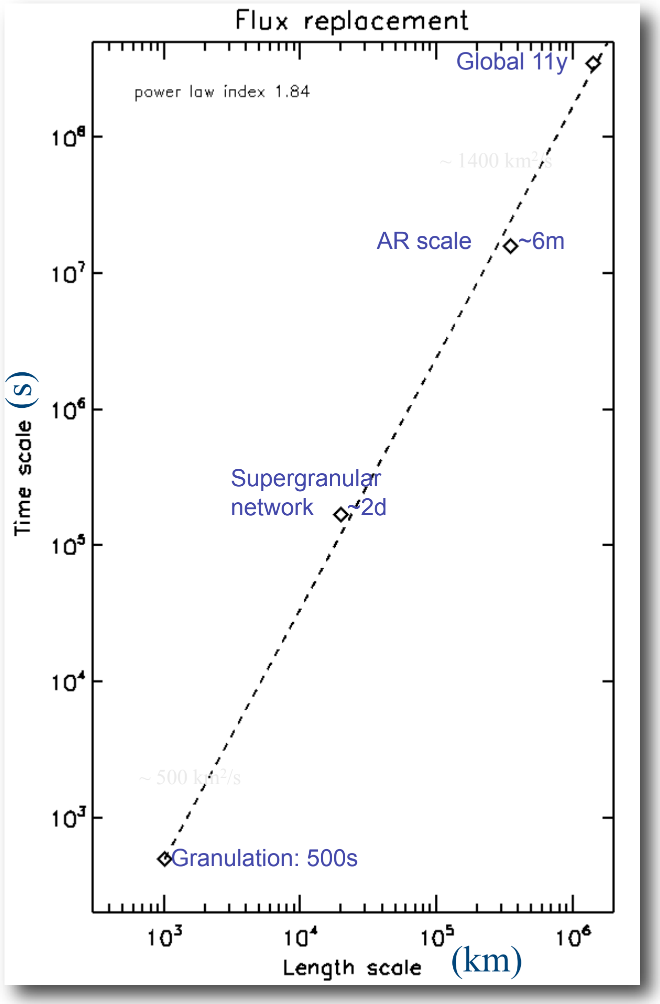


FIG. 5.—*Top*: Emergence frequency N_{er} of ephemeral regions, per unit surface, per day, as a function of the flux imbalance ξ in a region. *Bottom*: Total absolute flux $\sum \Phi$ emerging in those regions. Diamonds represent quiet Sun outside coronal holes and triangles represent quiet Sun inside coronal holes. The squares and triangles do not show a difference. Colors represent different data sets. *Black*: 2000; *green*: 2001; *light blue*: 2002; *dark blue*: 2003; *pink*: 2004; *red*: 2005.

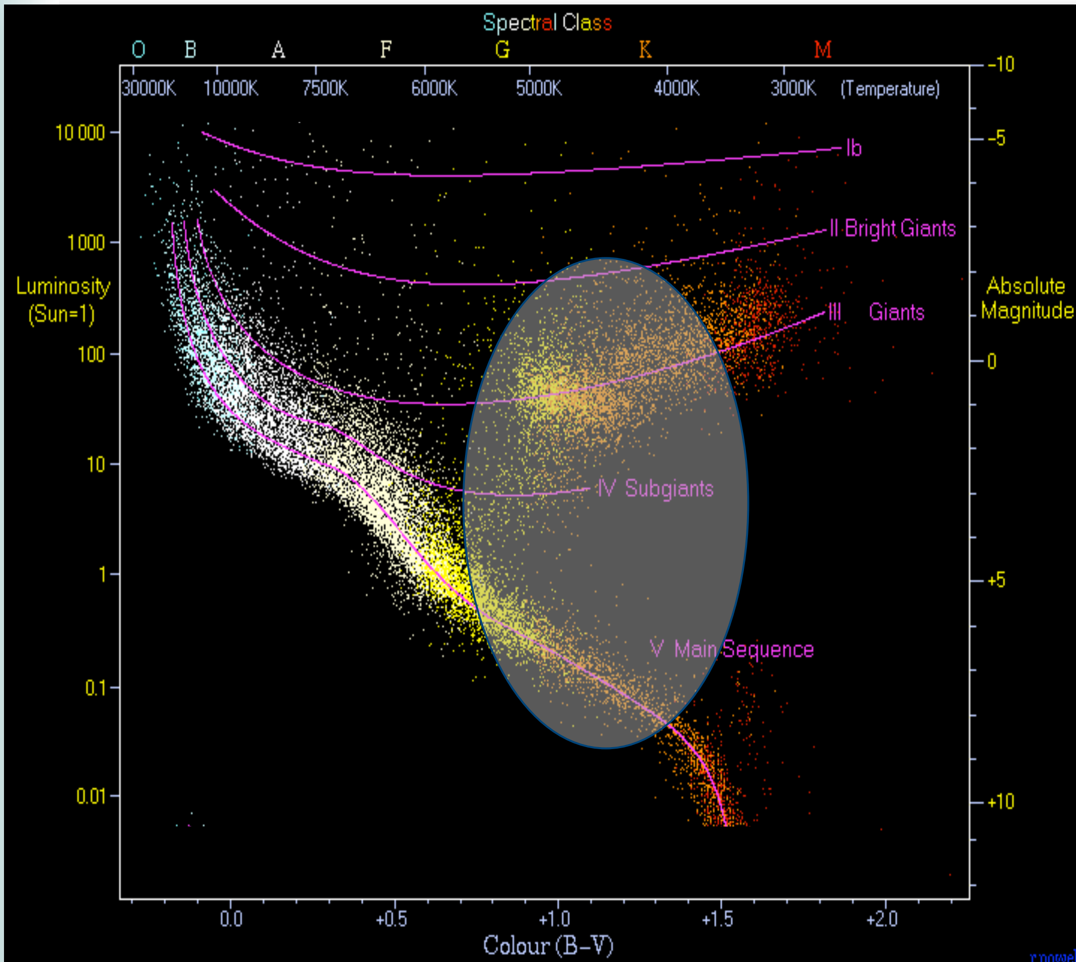
Hagenaar et al. (2008)
http://adsabs.harvard.edu/abs/2008ApJ...678..541H

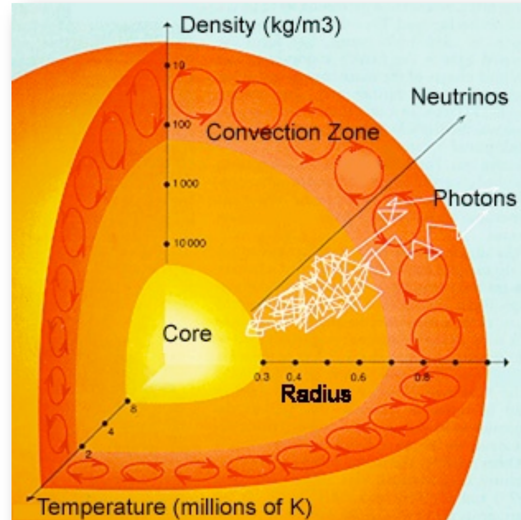
Field replacement & reconfiguration

- Flux replacement time scale decreases with decreasing length scale.
- Field reconnection time scales are (~10x?) shorter than that (e.g., http://adsabs.harvard.edu/abs/2004ApJ...612L..81C).



Solar-like stellar activity

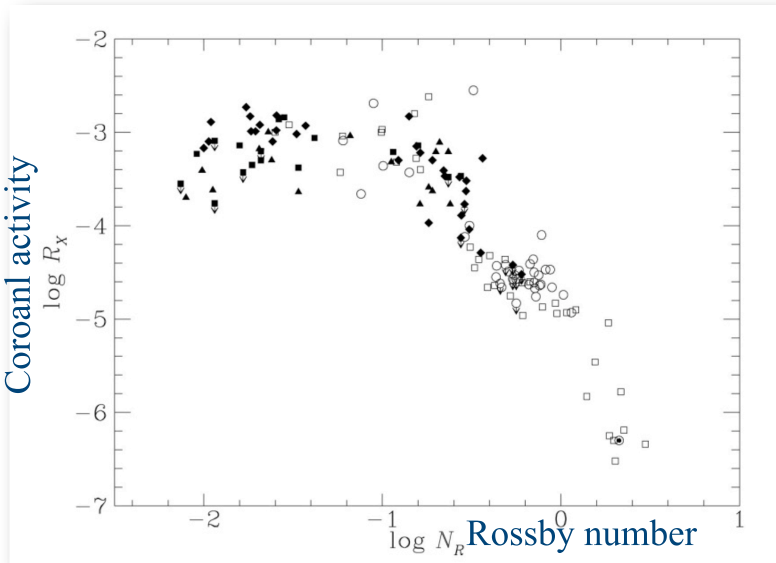


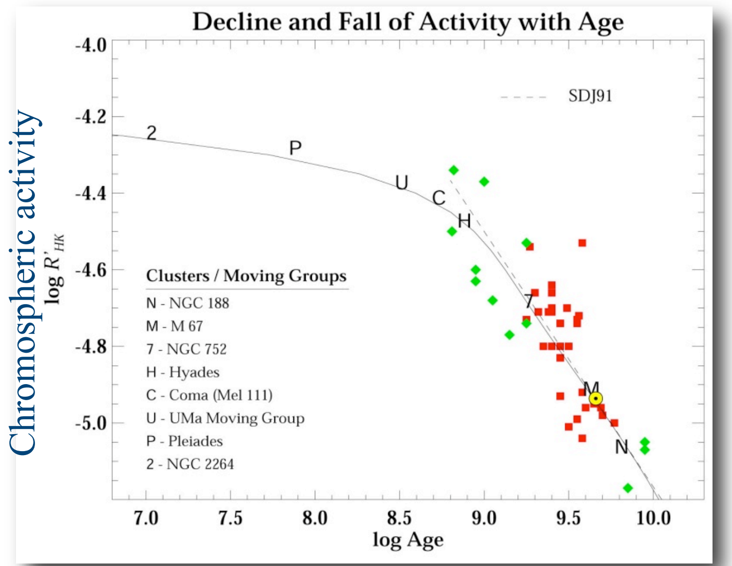


All rotating stars with convective envelopes exhibit atmospheric magnetic activity.

Activity, rotation, age

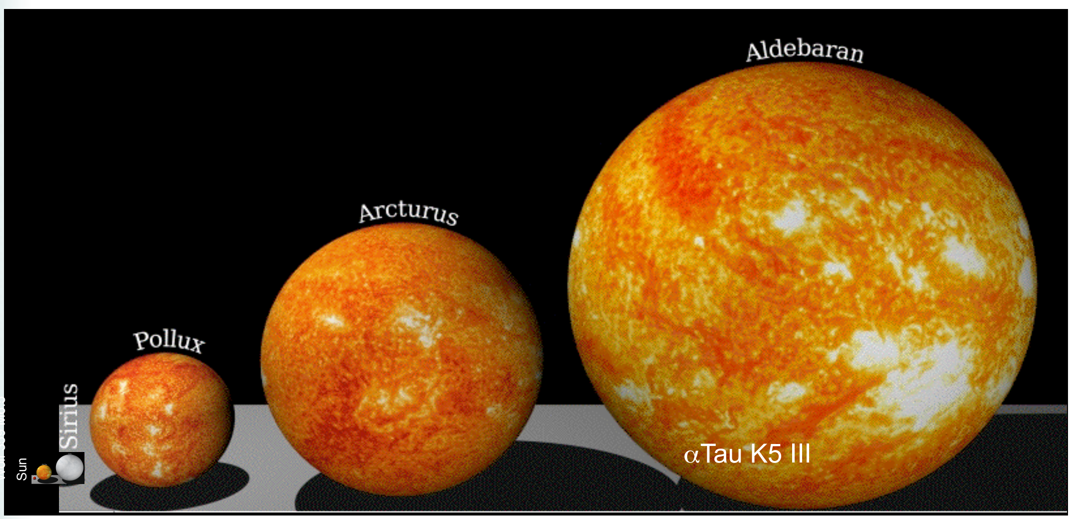
- Activity decreases with decreasing rotation and increasing age.
- Note “saturation” and “supersaturation” for short rotation periods.

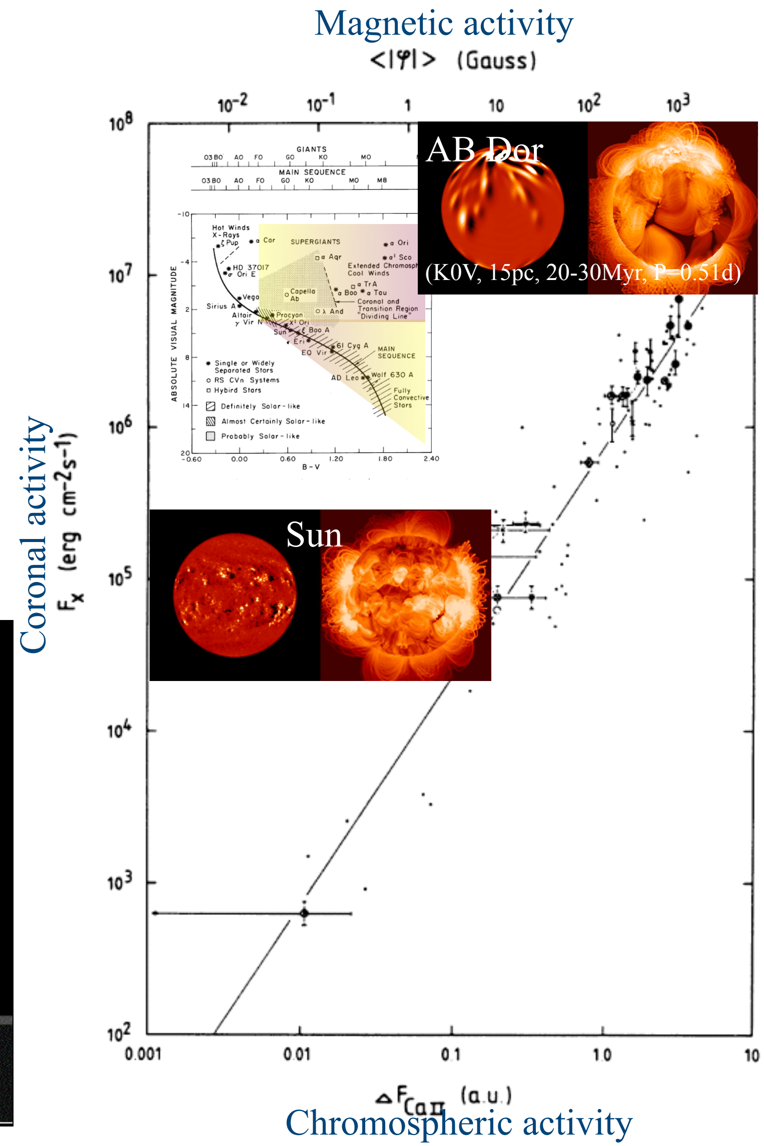




Magnetic energy conversion in stellar atmospheres

- 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, …?

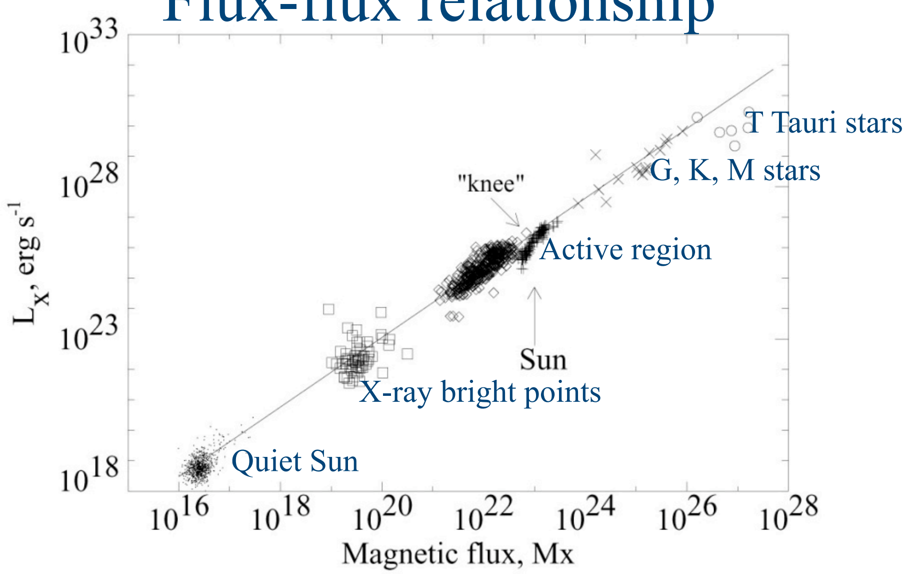




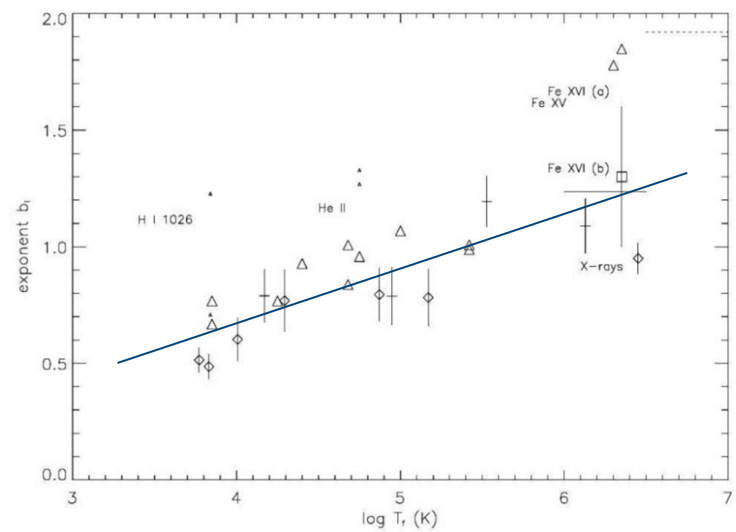
“Flux-flux relationships”

- 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.

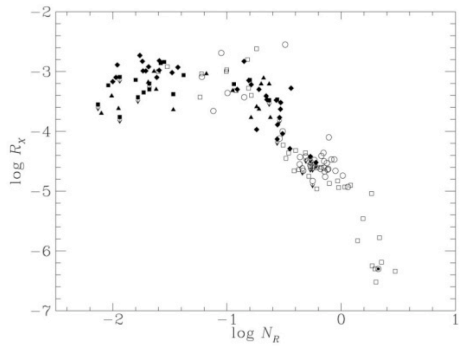
“Flux-flux relationship”

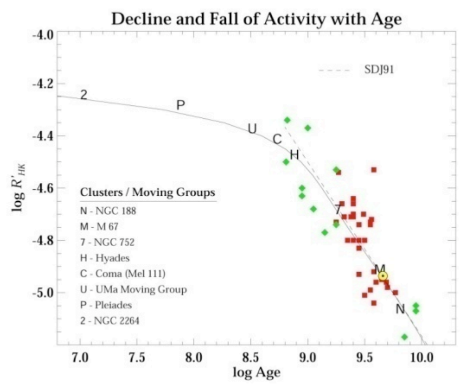


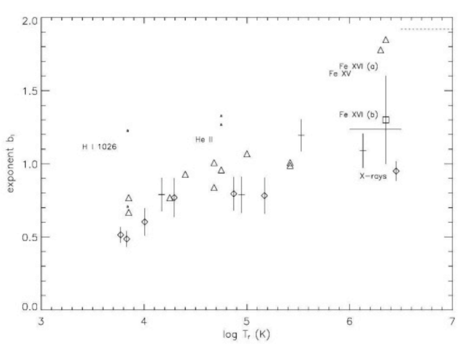
Power-law indices

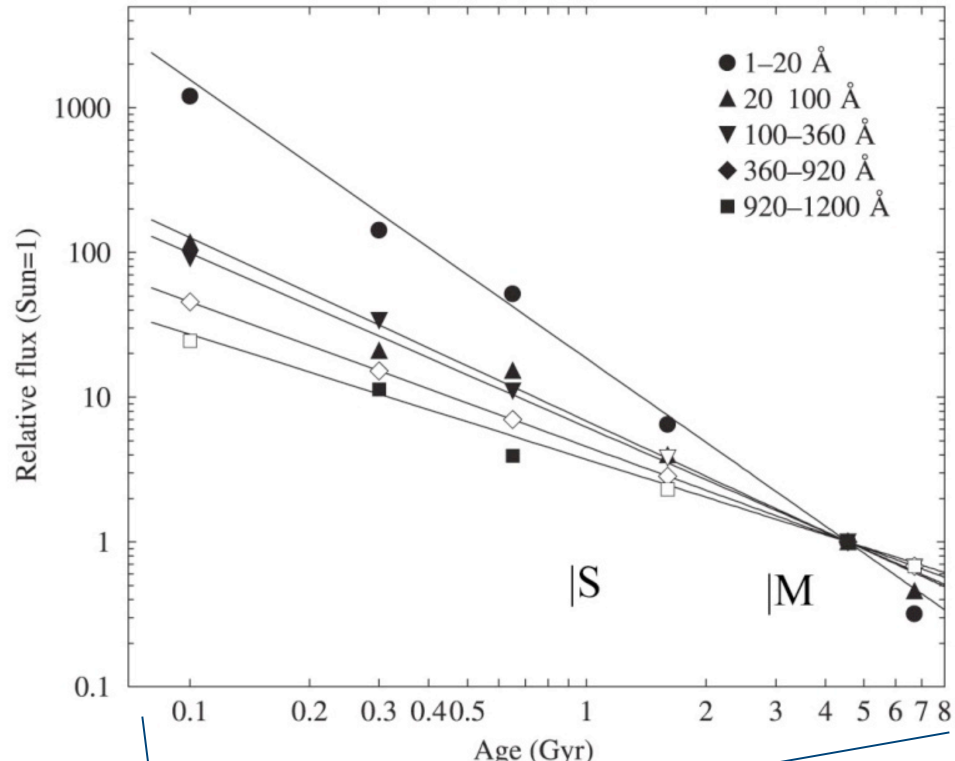


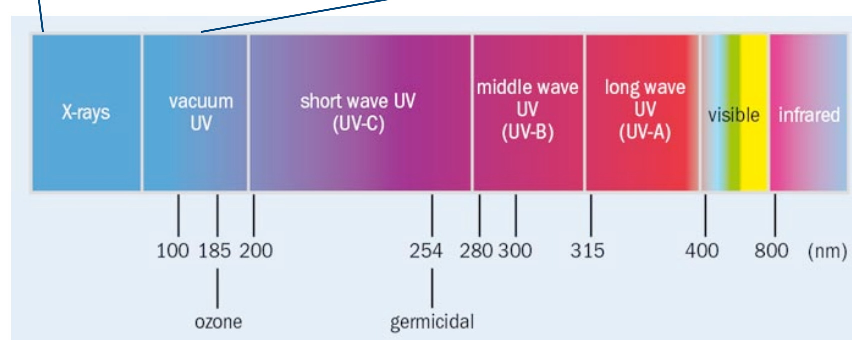
Radiative losses of the Sun in time







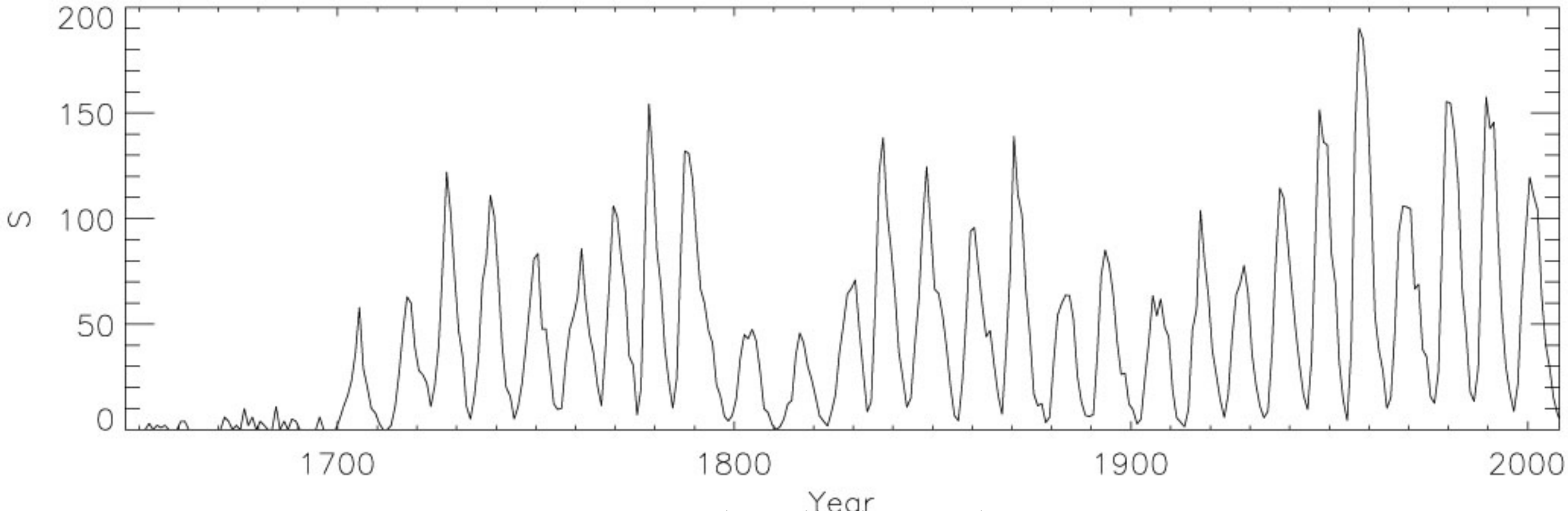




Sunspot records

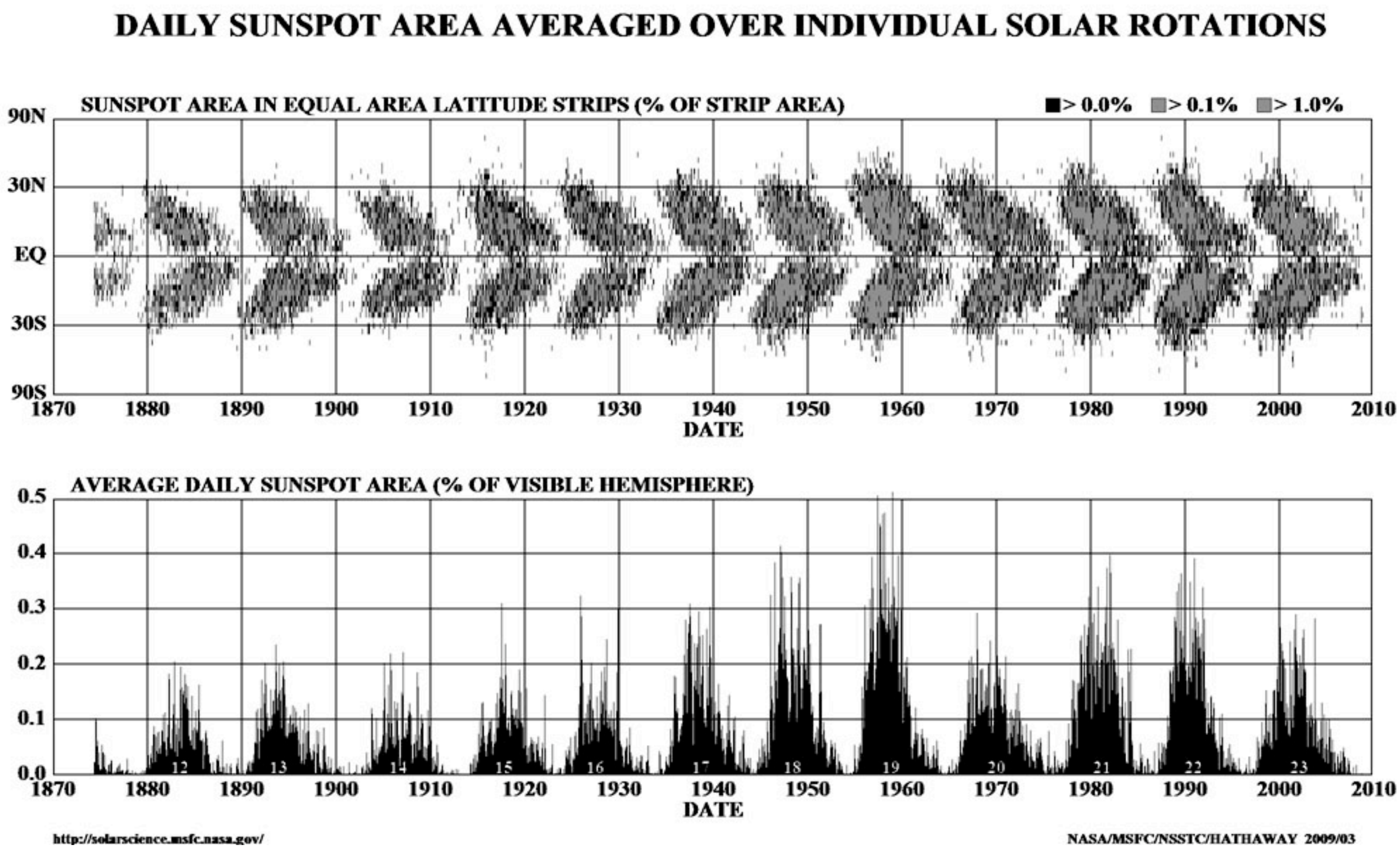
- Sunspot cycles vary in strength, duration, shape, overlap, …

Historical sunspot records; yearly smoothed sunspot number

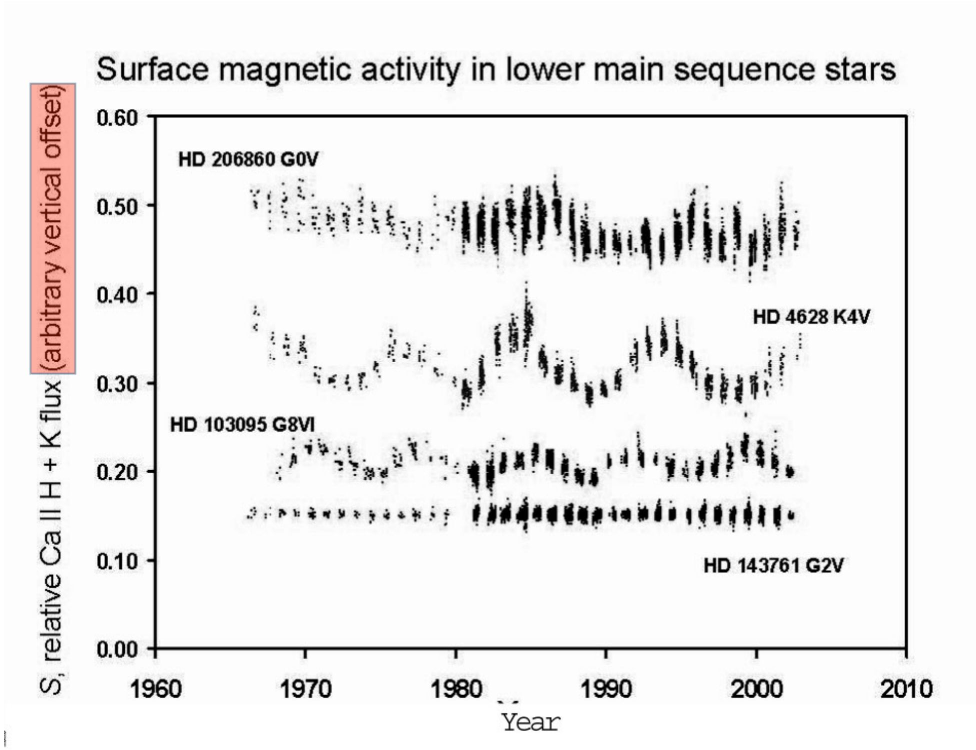


e.g, http://sidc.oma.be

Sunspot cycle

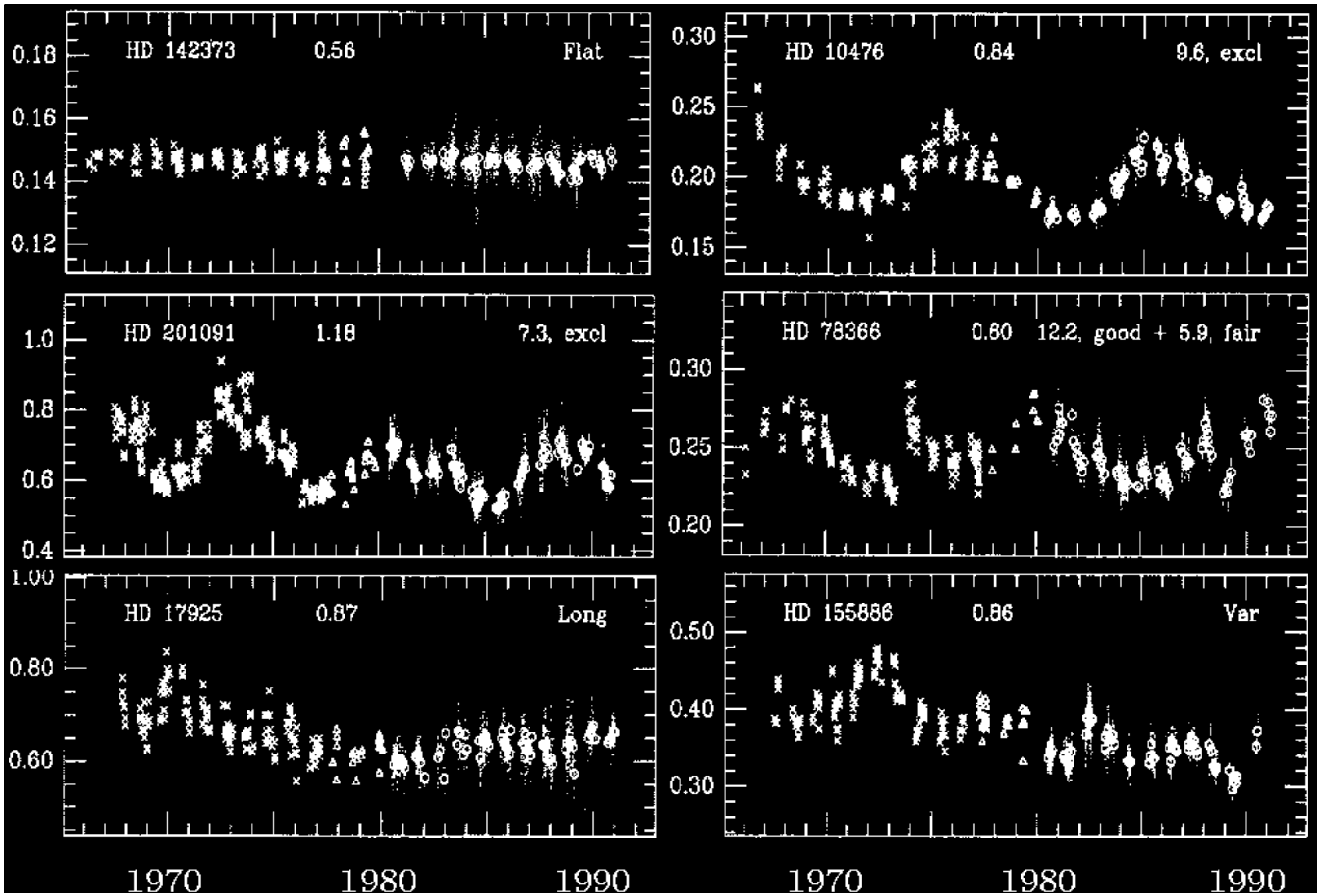


“Sun in time”

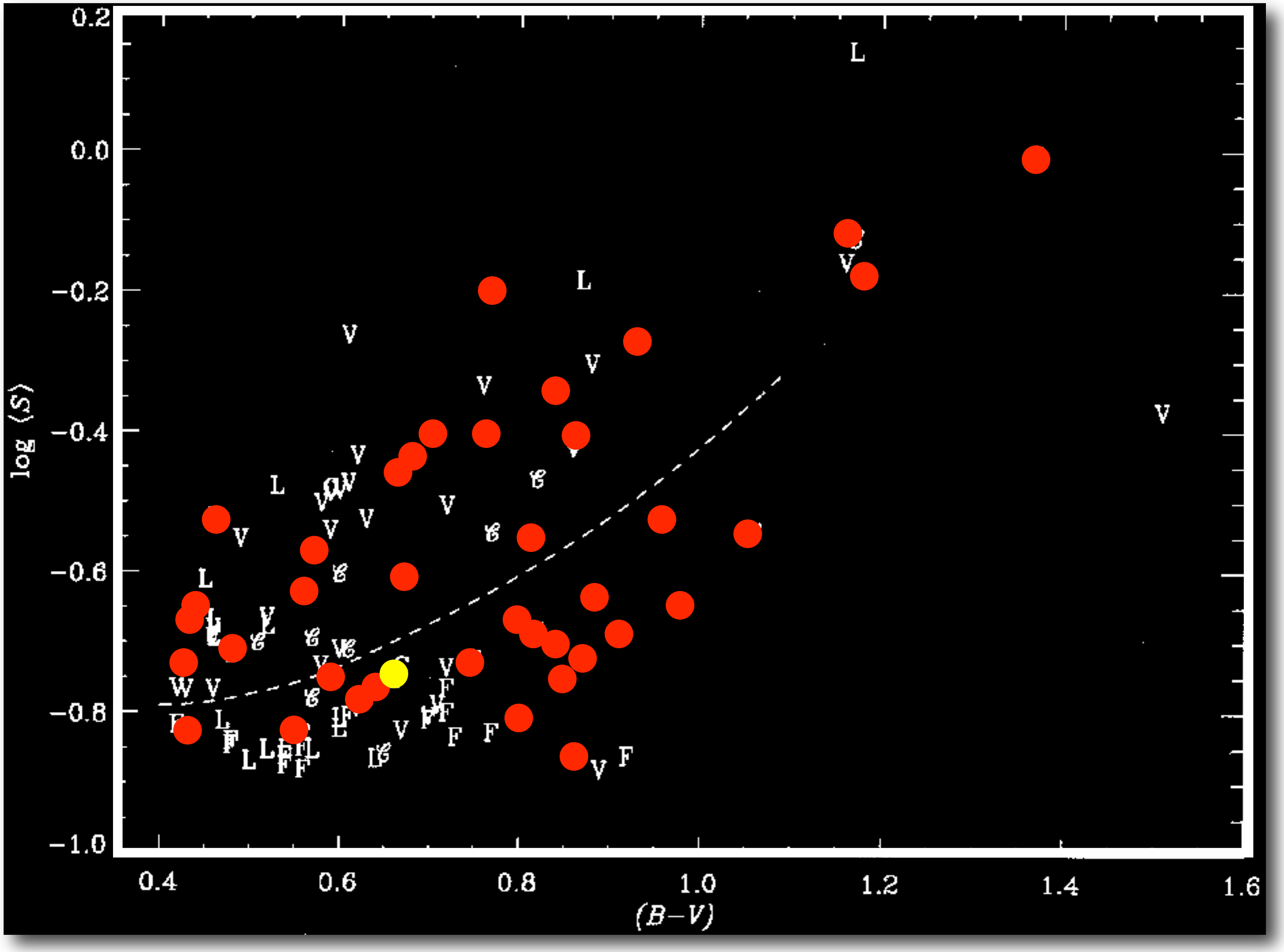


- Top: HD 206860; P=4.7d - a counterpart of the sun approximately 2 billion years ago.
- Lower curves: three Sun-like stars – HD 4628 (P=38d), HD 103095 (P=31d, or P=60d, age ~10 Gy) and HD 143761 (P=21 d). HD 143761 may be in a state like the Sun’s Maunder minimum.

Examples of stellar activity "cycles"

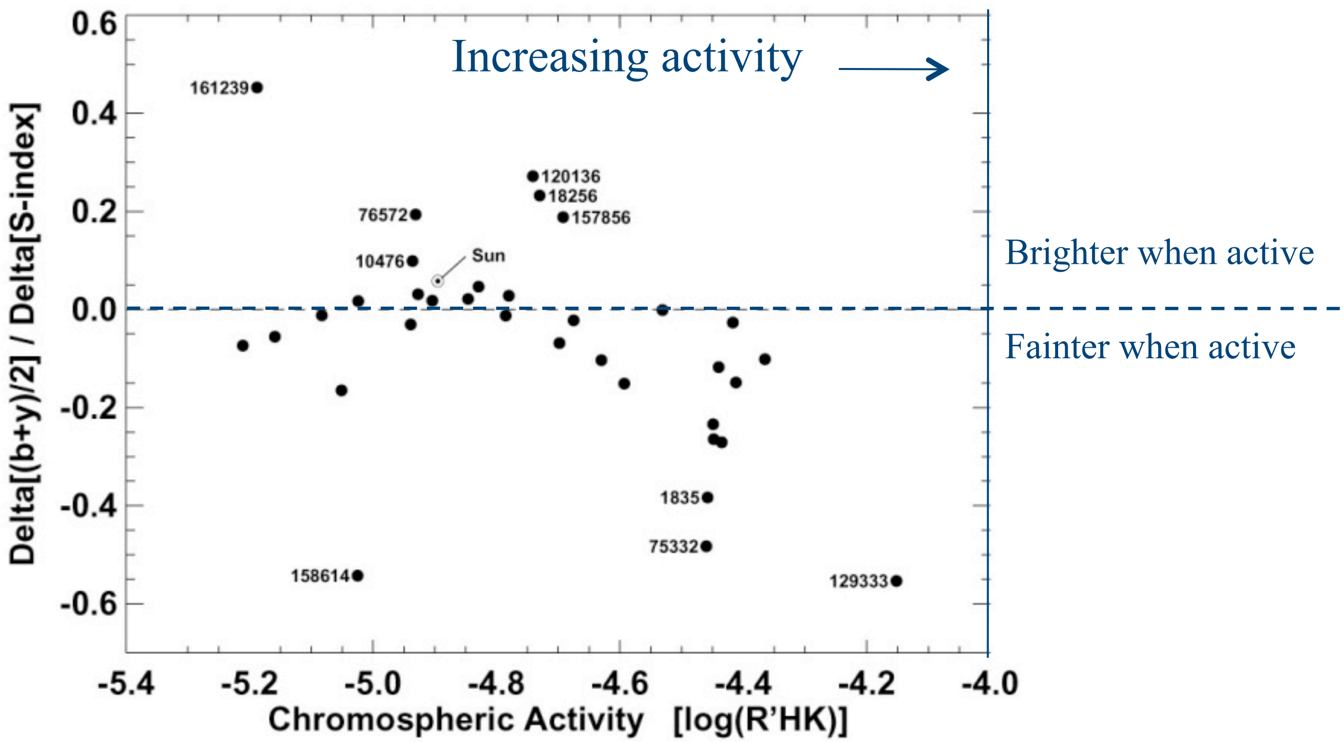


Stellar activity "cycles": common but not dominant

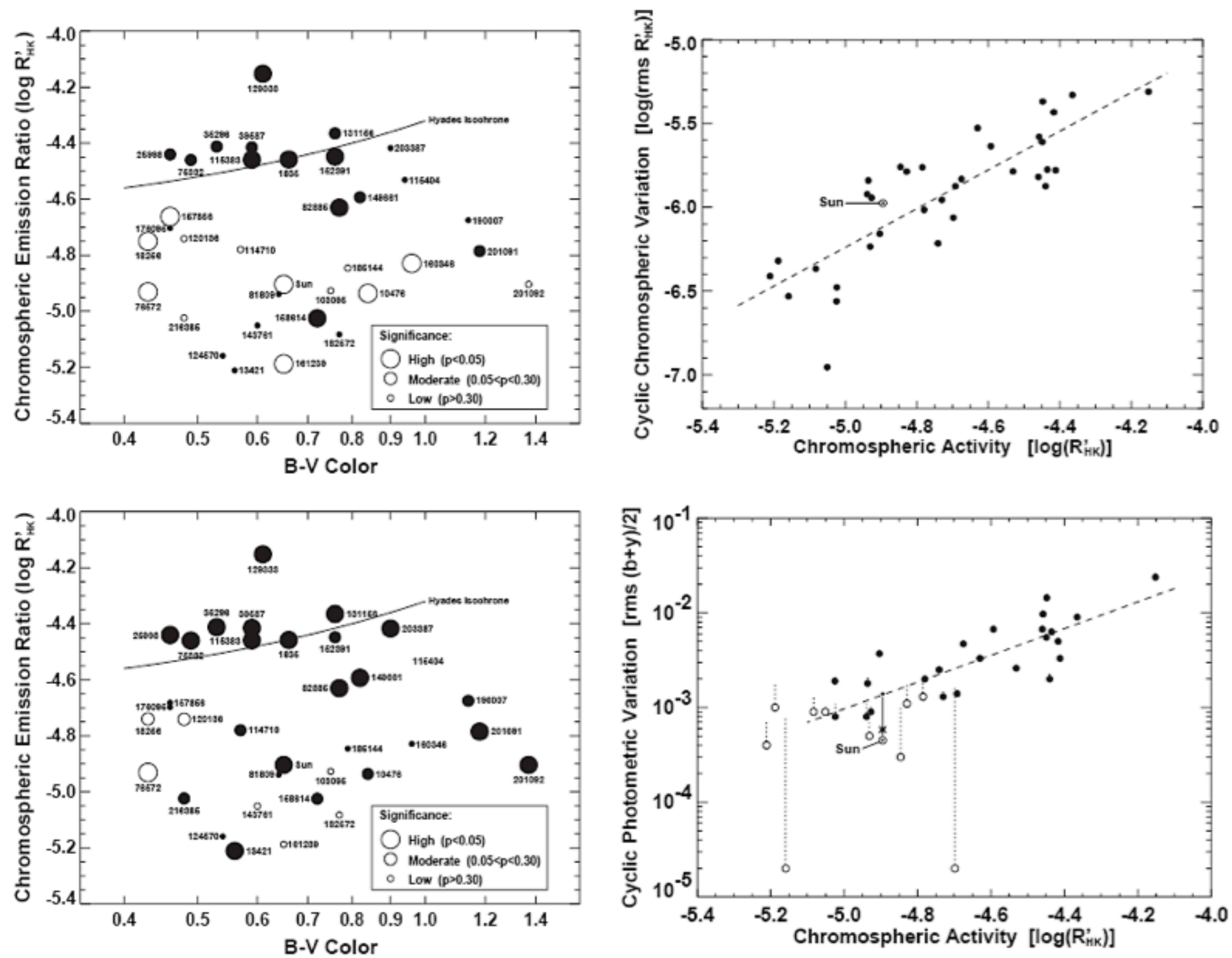


Radiance variations at visible wavelengths.

- Increasing activity: "blocking" by starspots outweighs facular brightening

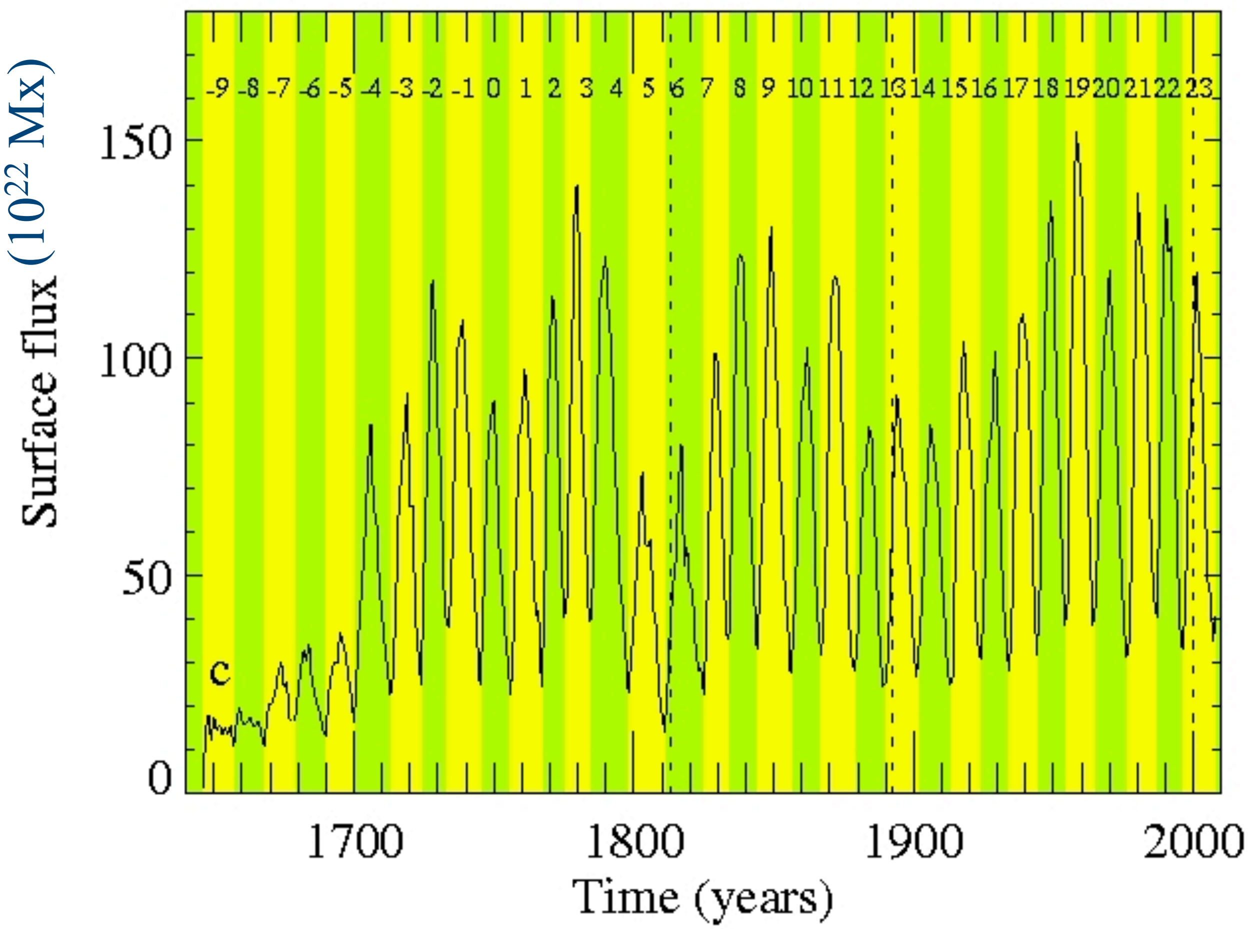


Activity vs. 'brightness'



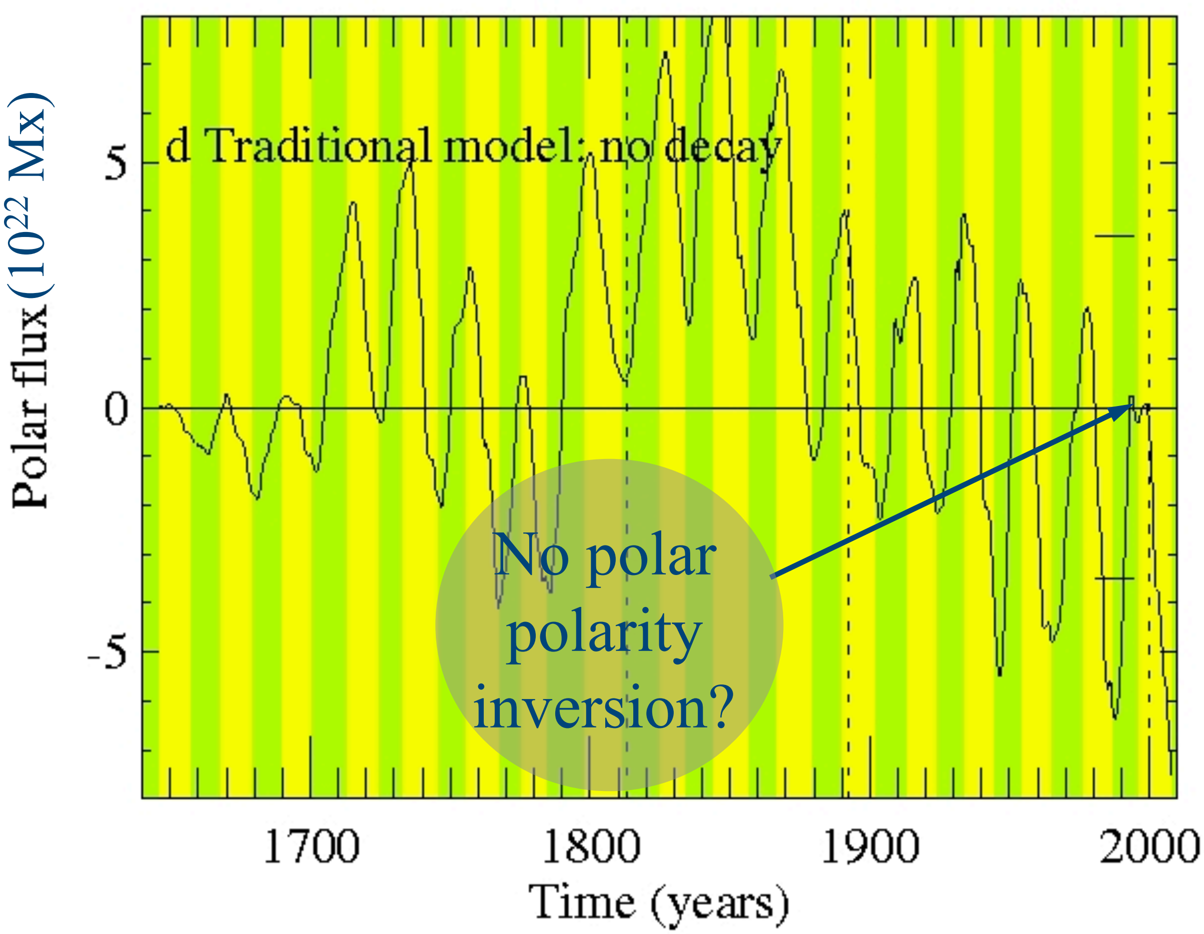
- Top: long-term correlations. Bottom: short-term correlations.
- Filled symbols: anti-correlation of activity and brightness
- Open symbols: positive correlation of activity and brightness

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



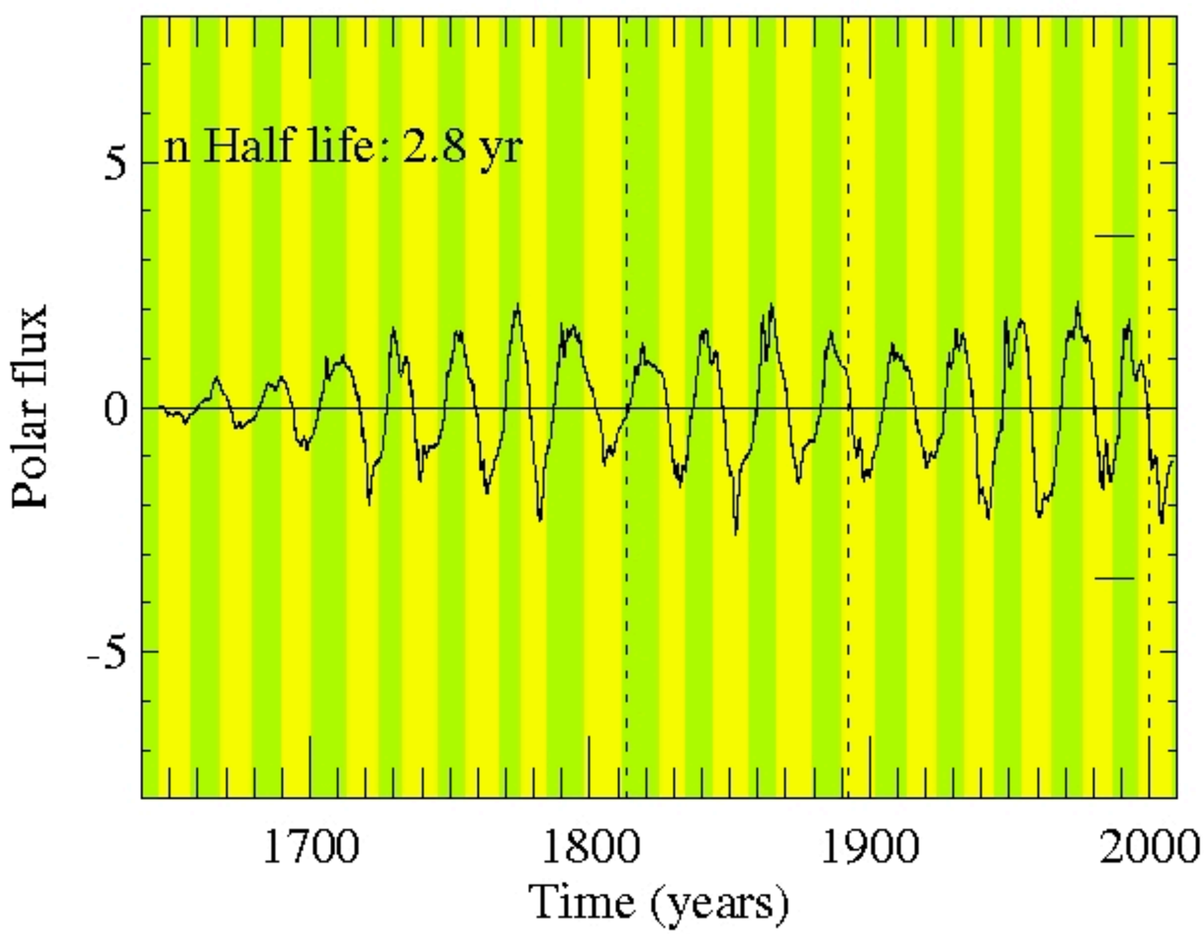
Total flux on the Sun: cycle-to-cycle modulation

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



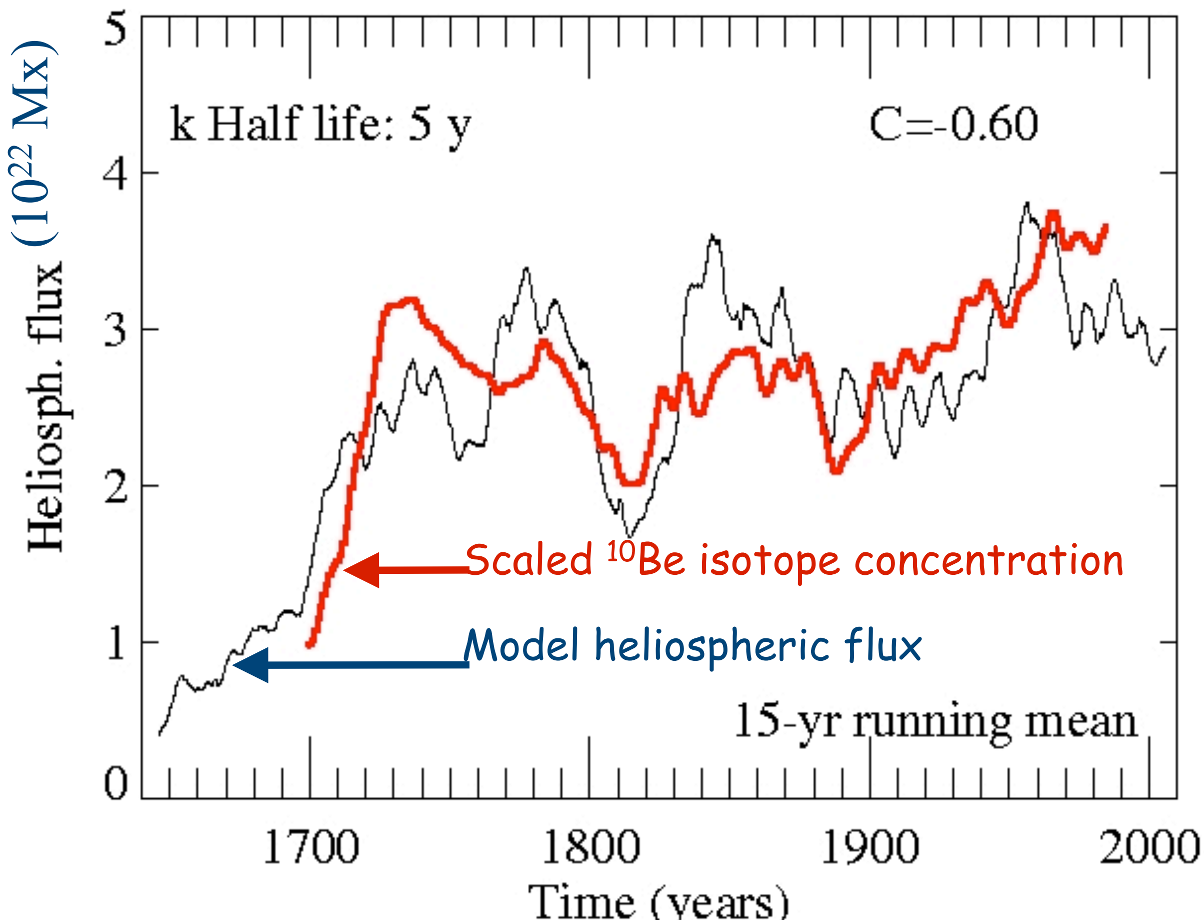
Polar-cap flux key driver of heliospheric field

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



Heliospheric field responds to weak effects

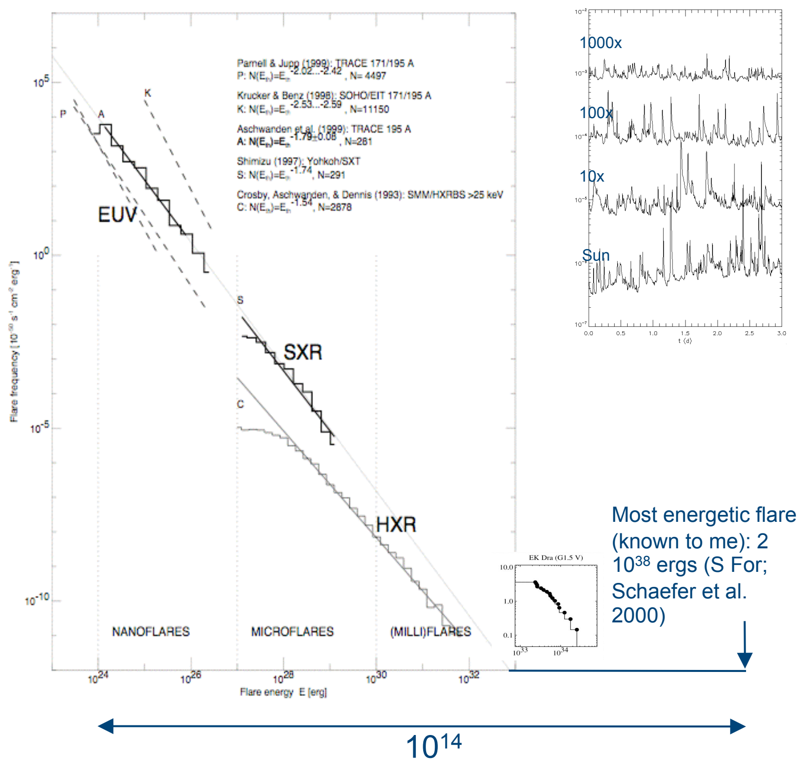
With polar-cap behavior 'regularized'*, the heliospheric and cosmic-ray fluxes are roughly *anti*-correlated:



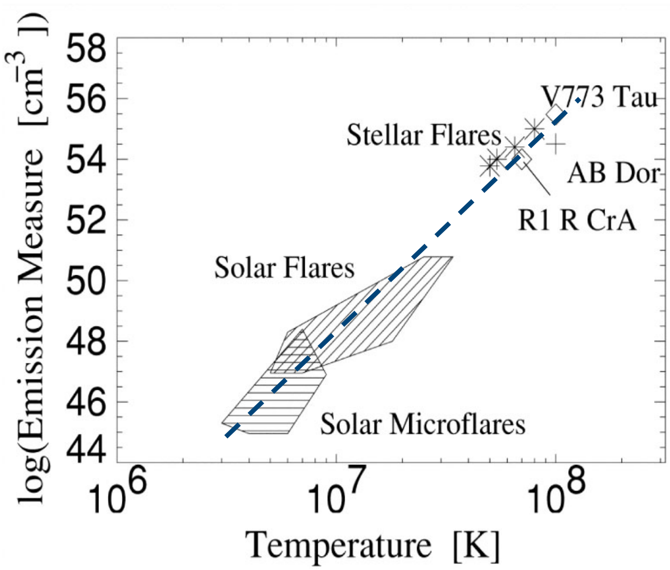
* For example by introducing 3D flux transport (Schrijver & DeRosa, Baumann et al.), by modulating advection (Wang et al., Schrijver et al.), or AR tilt angles (Dasi-Espuig et al. 2010)

Solar and stellar flares

- Power-law spectra and self-similarity in solar-stellar flares.



Flare energy spectrum is a power law with slope close to -2; hence, flux integral does not converge (very fast): is there a cutoff at largest scales [and at smallest]?



Evaluating the probability of huge flares

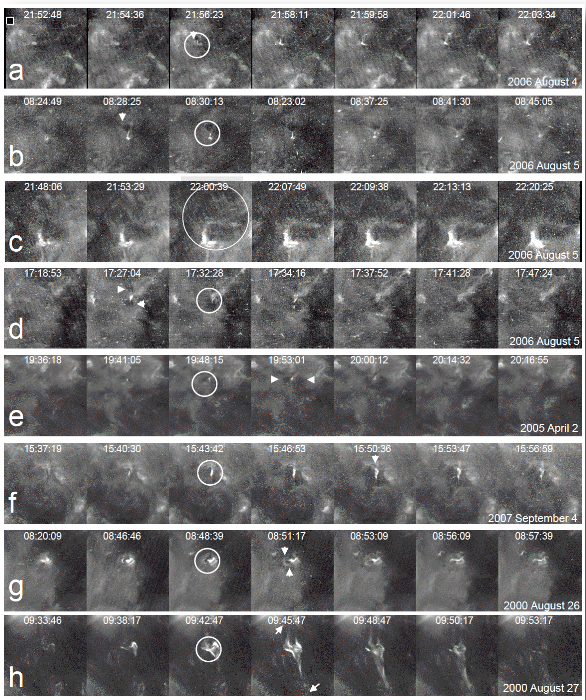
- Using the characteristic power-law spectrum for stellar flares in Audard et al. (2000), assuming there is no cutoff of the flare spectrum.
- N.B. L_X(Sun) = 3 10^{27} ergs/s; X1-class flare ~ 10^{32} ergs

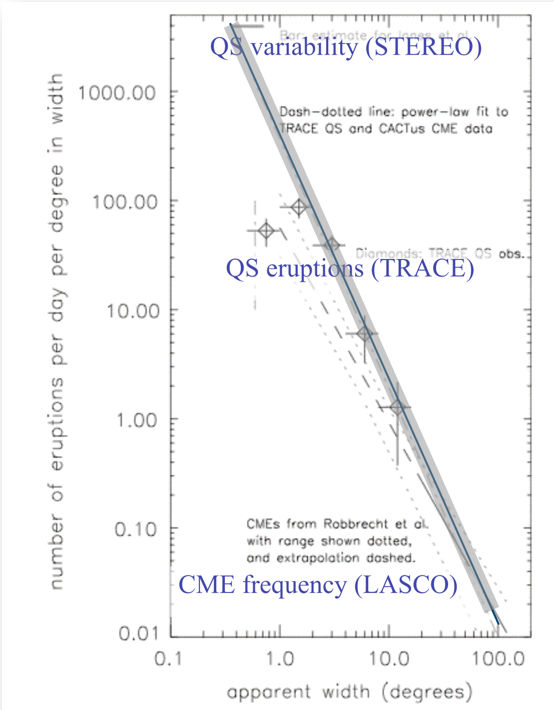
Likely interval between flares of given total energy or larger

Flare energy:	**>10^{32} ergs**	**>10^{34} ergs**	**>10^{36} ergs**	**>10^{38} ergs**
Sun at max.	4d	1y	100y	10000y
EK Draconis	8min	5d	50d	15y
	X1	X20	X40	X60

Quiet-Sun - Active-Sun eruptions

- Quiet-Sun coronal field erupts with power-law scaling, as for active regions





Schrijver (2010)
http://adsabs.harvard.edu/abs/2010ApJ...710.1418S

Spectrum of ‘flux-rope’ eruptions is a power law with slope close to -2: is there a cutoff at largest scales [in energy/momentum]?

“Known links” from Sun to near-Earth

- Given a magnetic activity level, knowledge and understanding of spectral irradiance improving rapidly (empirically)
- Very-long term (*O*(1 Gyr)) evolution of solar activity

‘Missing links’ from Sun to near-Earth

- Solar-cycle forecasts (there is NO validated dynamo model)
- Knowledge of heliospheric magnetic field during unusual states of activity (including Maunder minimum, recent extended minimum)
- Knowledge of active-region flux, flare, and eruption distribution function during extreme states of activity

Four focus areas of solar-heliospheric physics in the Sun-climate arena

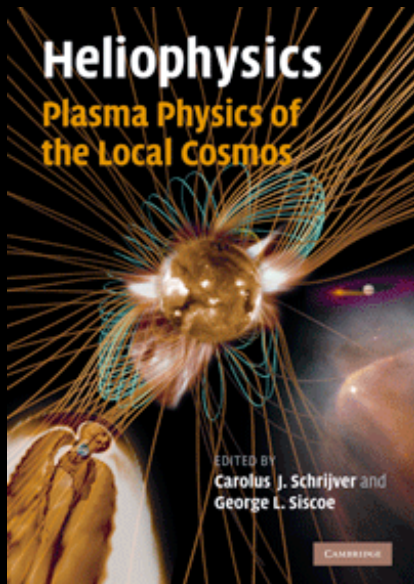
- Long-term variability: weeks to billions of years
  - Dynamo: magnetic variability from smallest to largest
    - Magnetic field transport: from generation to surface 'cancellation'
    - Heliospheric magnetic field
- Short-term variation: up to weeks
  - Atmospheric heating
  - Impulsive/explosive phenomena
  - Coupling of evolving magnetic field into the heliosphere
    - Solar-wind acceleration
    - Heliospheric plasma/field evolution
    - Heliospheric shocks and particle acceleration

The 'meta-astrophysical' perspective on science policy

- Identify the critical questions in cross-disciplinary evaluation:
  - Include ecology/climate physics/geospace physics/heliospheric science/solar physics/stellar astrophysics/(exo-)planetary physics in
    - strategic plans like the NRC's decadal surveys
    - mission definition teams
    - interagency coordination

- Observe/investigate from a systems perspective:
  - Utilize and optimize the Heliophysics Great Observatory
  - Remove artificial boundaries set by funding agencies in, e.g., strategic planning, mission definition teams, proposal reviews, time-allocation panels, ...
  - Develop 'virtual topical journals' to move away from discipline-specific journals.

- Teach the ecology of our home in space: heliophysics & ecology:
  - Develop resources
  - Teach at undergraduate and graduate level
  - Public outreach, inter-disciplinary lectures, ...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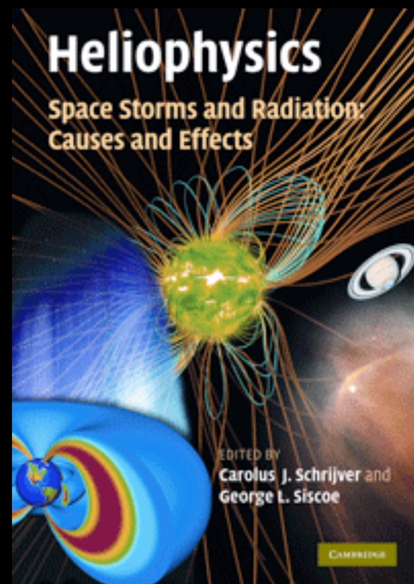
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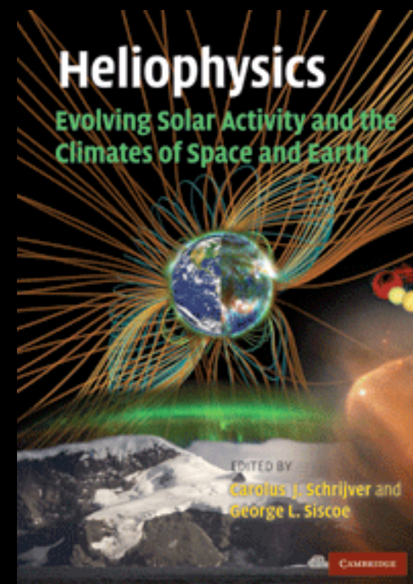
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Main lessons:

- From long-term stellar observations (<- Jeff Hall):
  - There is no dynamo model yet that can tell us ab initio how active a star will be, how it will vary in time, what the statistics of emerging bipolar regions or eruptive/explosive processes will be. Need: stellar observations for guidance and validation of advanced modeling.
  - Whereas the Sun is in a characteristic dynamo state of the solar/stellar ensemble, stellar observations show a range of patterns that the Sun has not shown in the instrumental era. Cycle-property characterization and cycle forecasting need stellar guidance. Need: continuation and (pan-chromatic) expansion of observational base.
- From solar and stellar ensemble studies:
  - Sun and stars exhibit many scale-invariant (power-law) properties that appear insensitive to stellar fundamental properties (mass, age, composition, ...). Need: learn to exploit these relationships (and their - as yet - hidden correlation) in order to extrapolate to historical and future Sun, and to characterize variability (and extreme events) of solar and space climate.
  - Many solar/heliospheric records remain hidden in Earth's deposits of ice and sediments with information that is needed by solar/heliospheric physicists and climate physicists for long-term trend characterization. Need: trans-disciplinary studies to exploit that information in iterative analyses with, at least, biologists/chemists, geomagnetic physicists, heliospheric physicists, solar physicists.