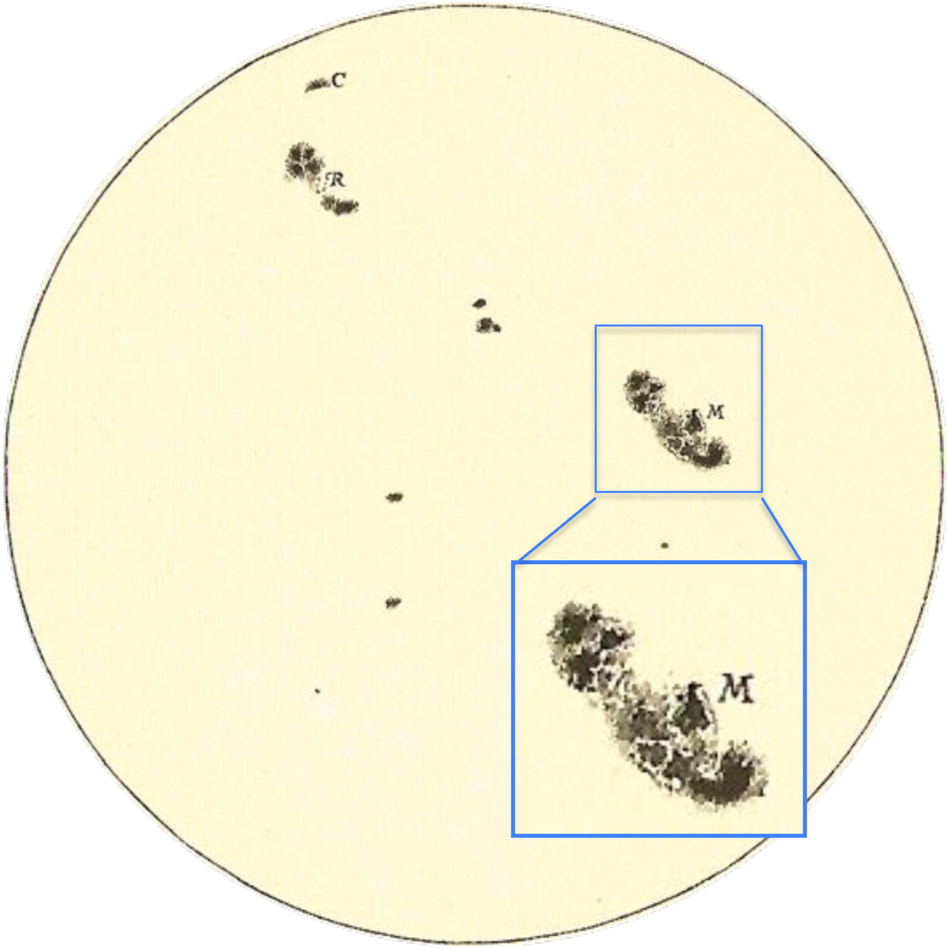
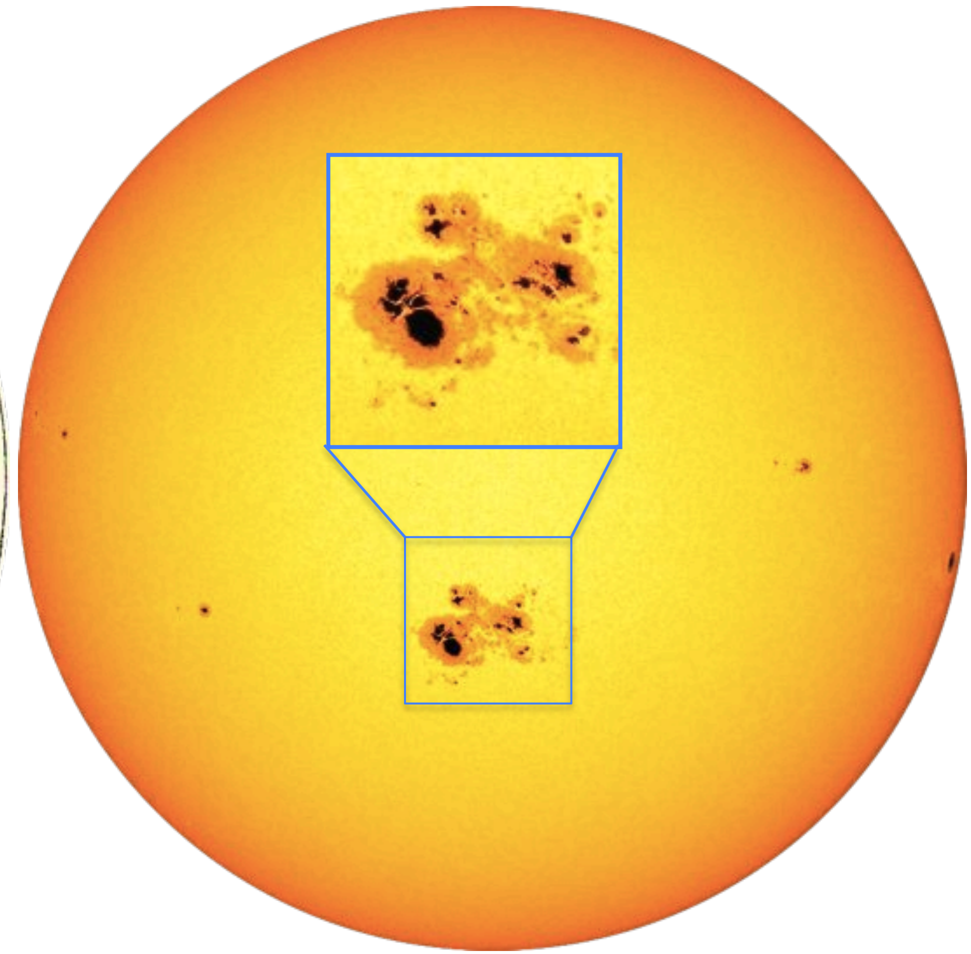
Cap. 11 – O Sol
11.3 O ciclo de atividade solar

Dr. Jorge Meléndez
AGA 0293, Astrofísica Estelar

Manchas solares

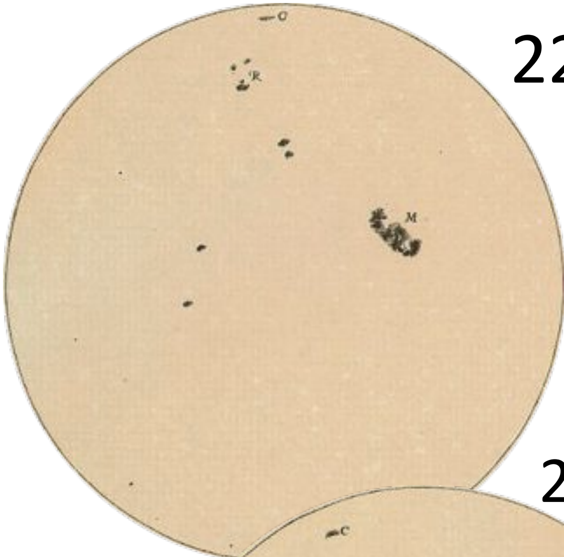


23/6/1613
Galileu Galilei

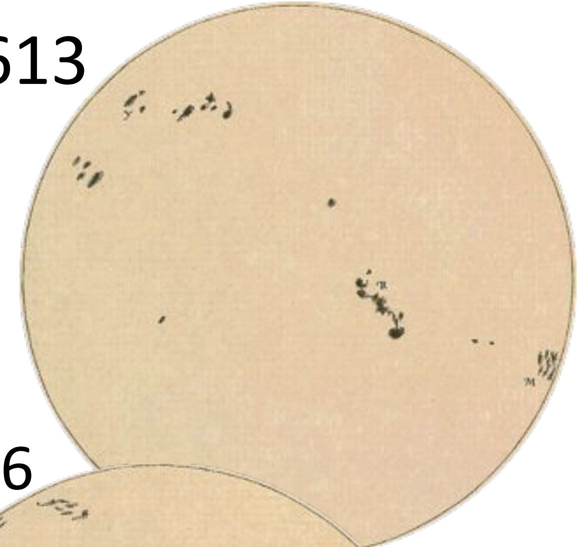


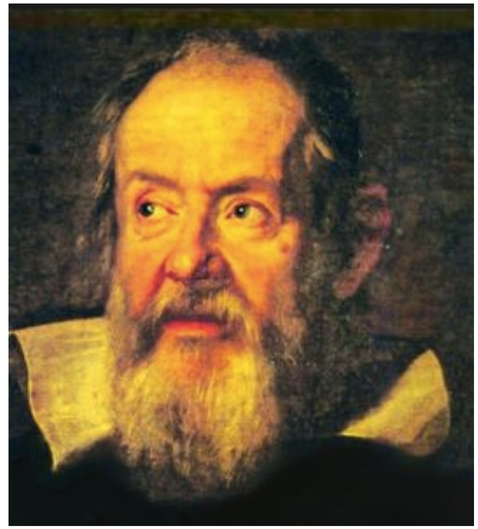
23/10/2014
NASA/SDO

22/6/1613



27/6/1613





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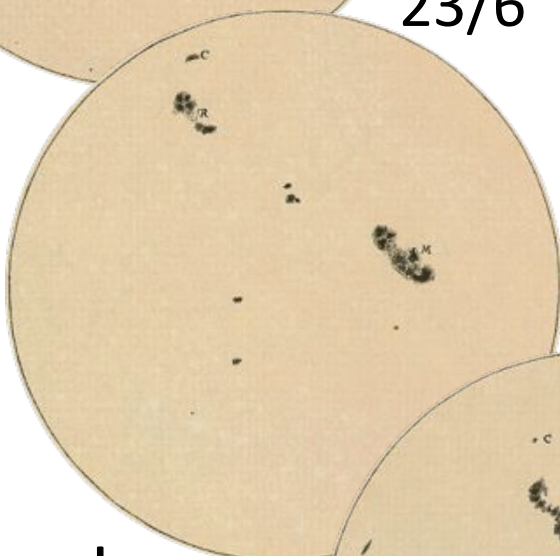

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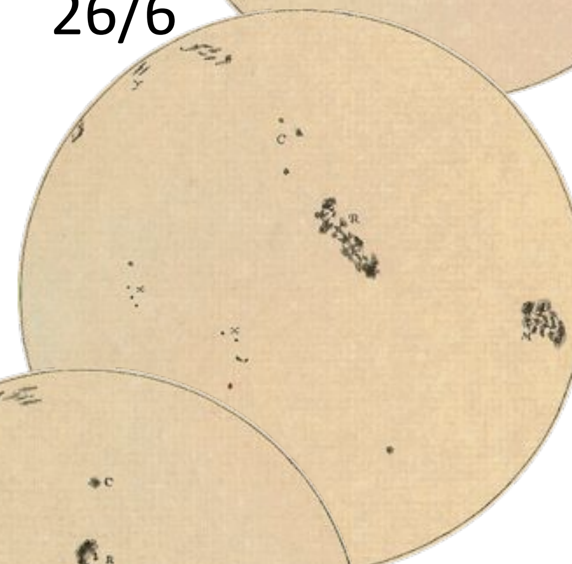

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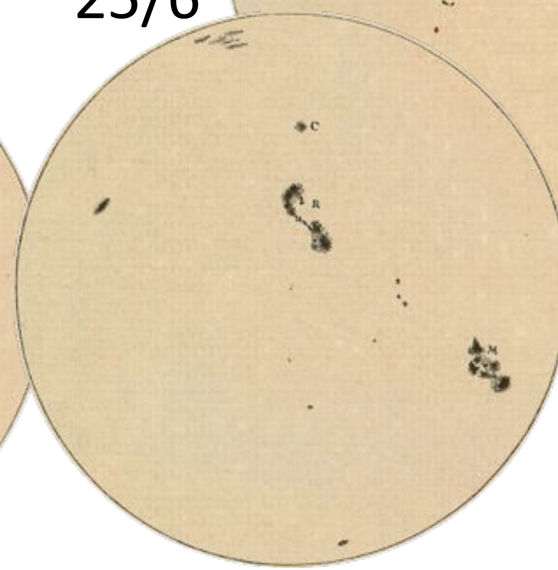
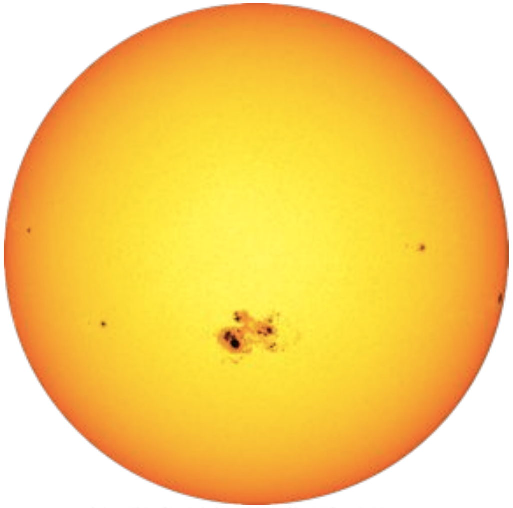
25/6

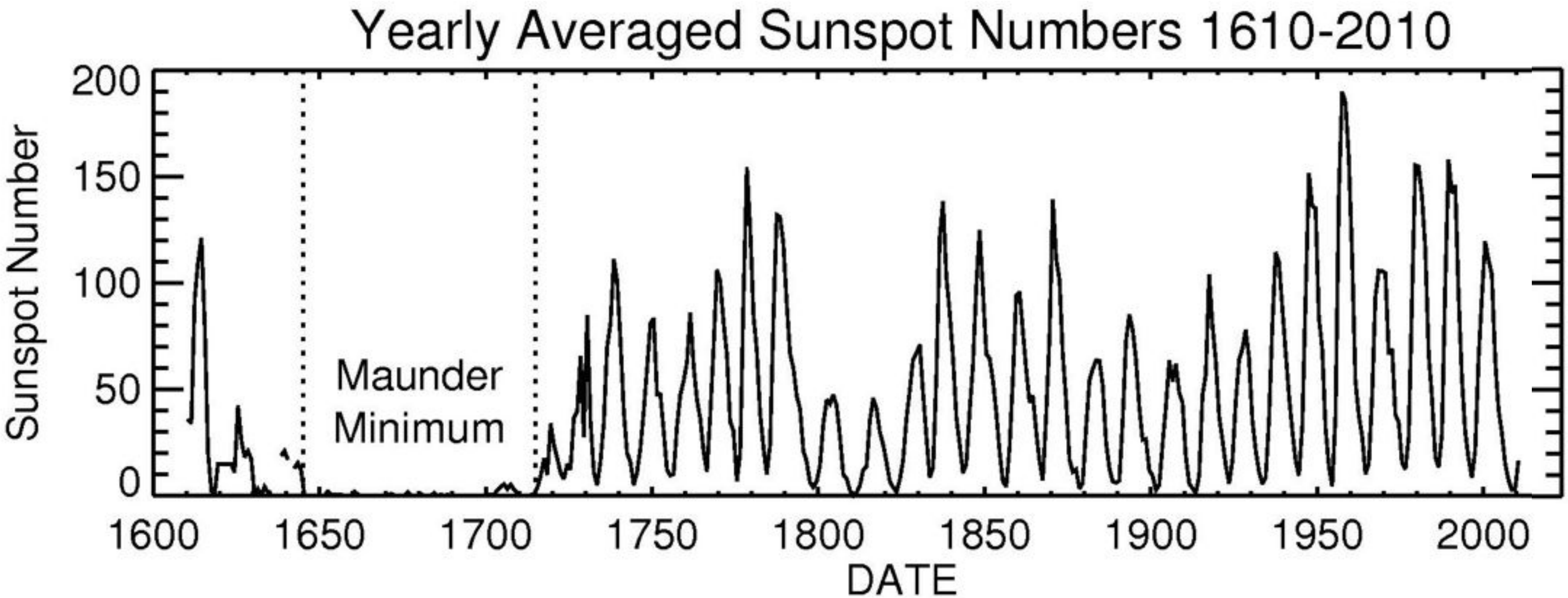


Manchas solares observadas por Galileu

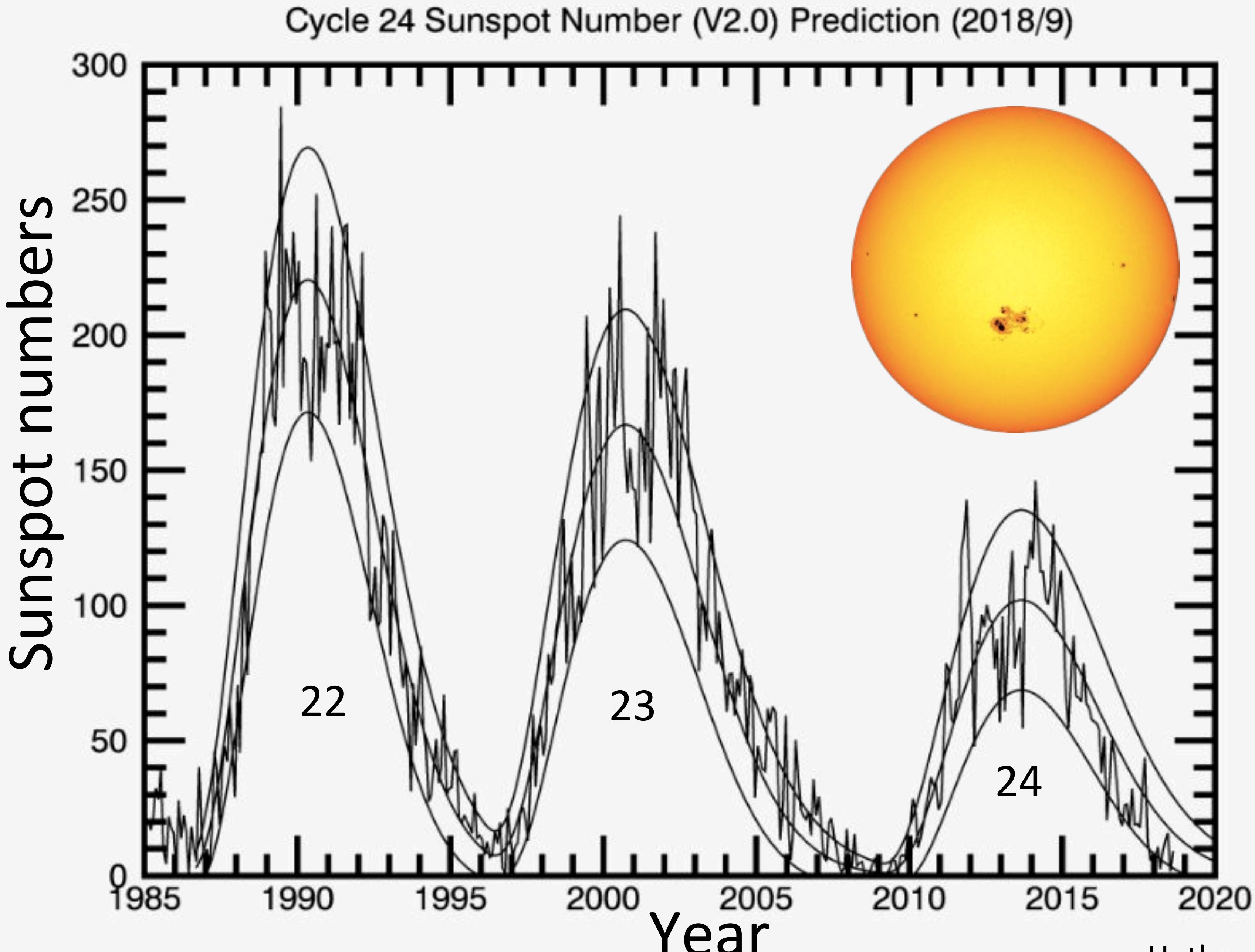
http://galileo.rice.edu/sci/observations/sunspot_drawings.html

Ciclo de manchas solares quase periódico ~ 11 anos





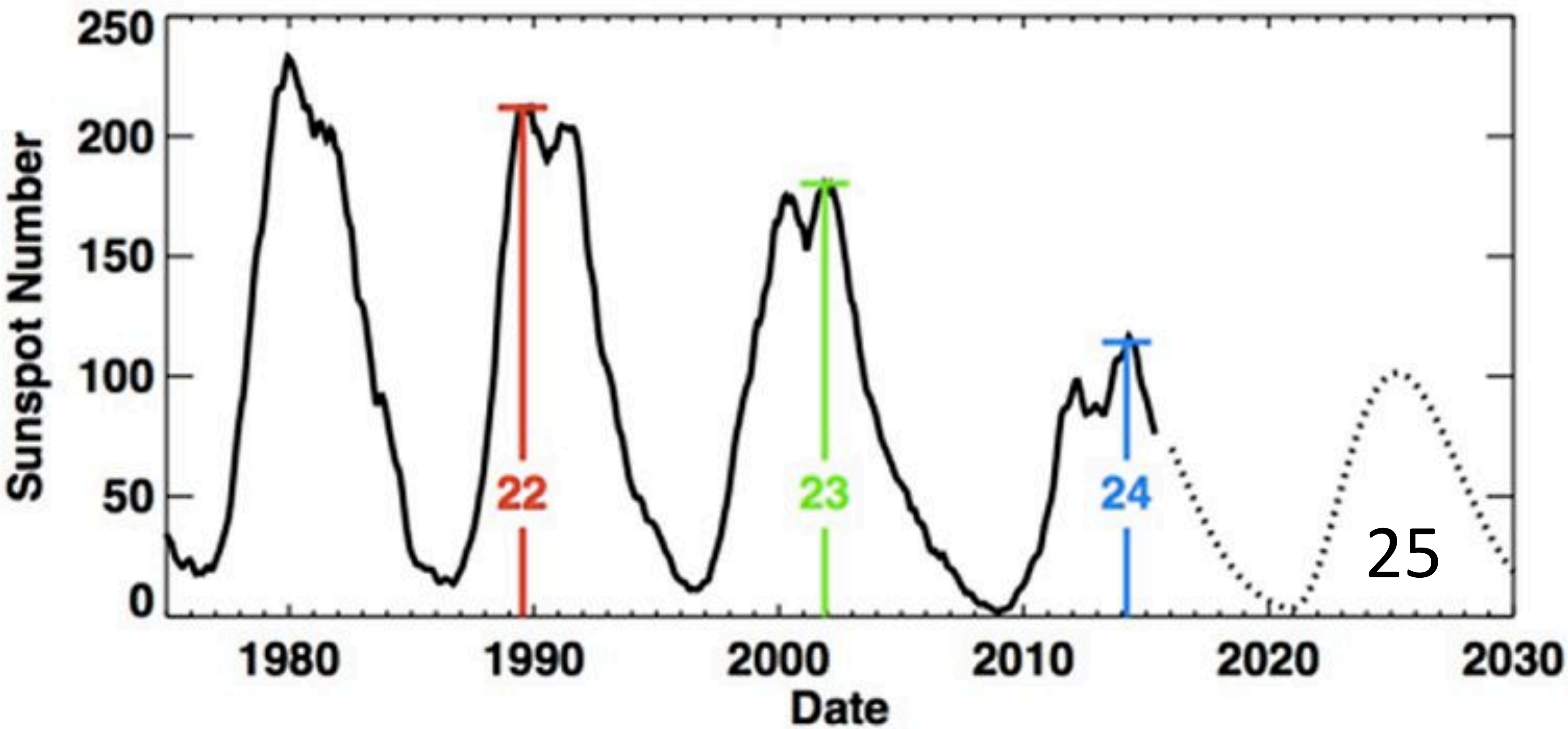
https://www.nasa.gov/mission_pages/sunearth/news/solarcycle-primer.html



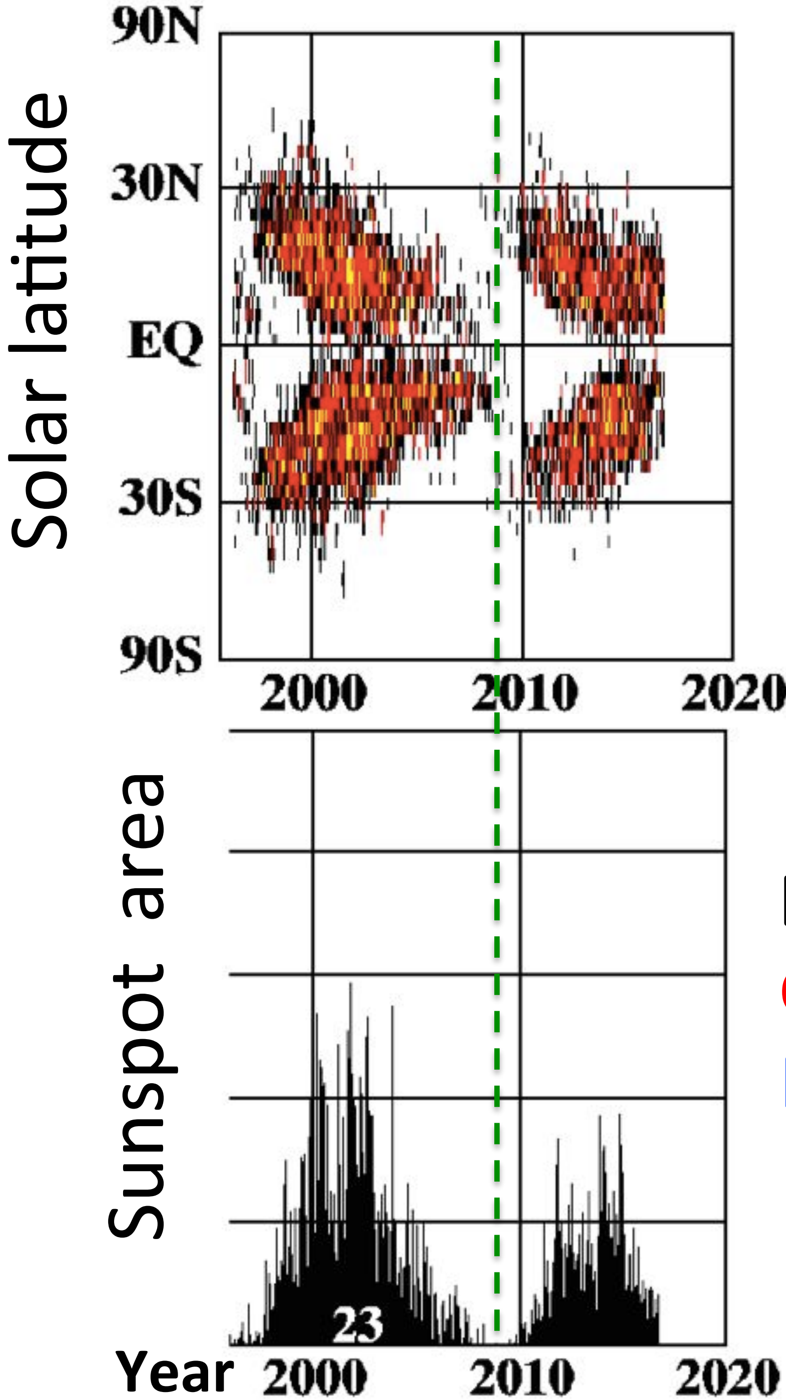
Hathaway

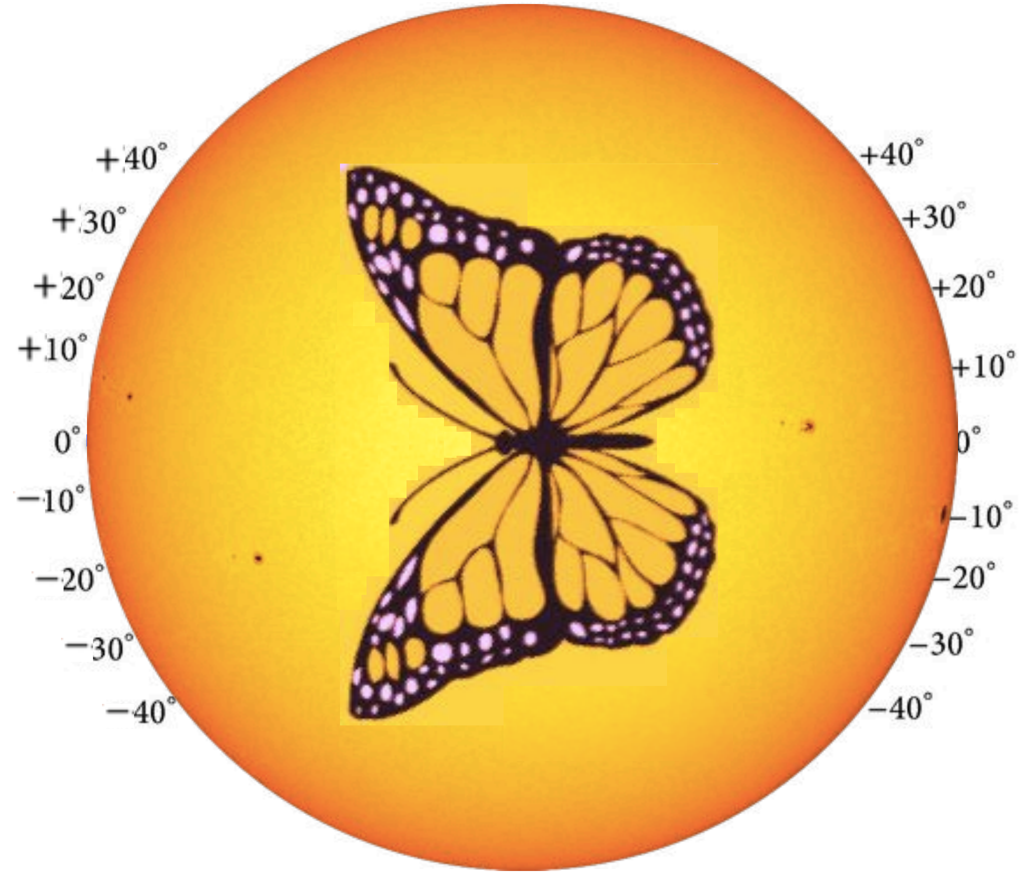
http://solarcyclescience.com/forecasts.html

Previsão do ciclo solar 25



http://solarcyclescience.com/forecasts.html





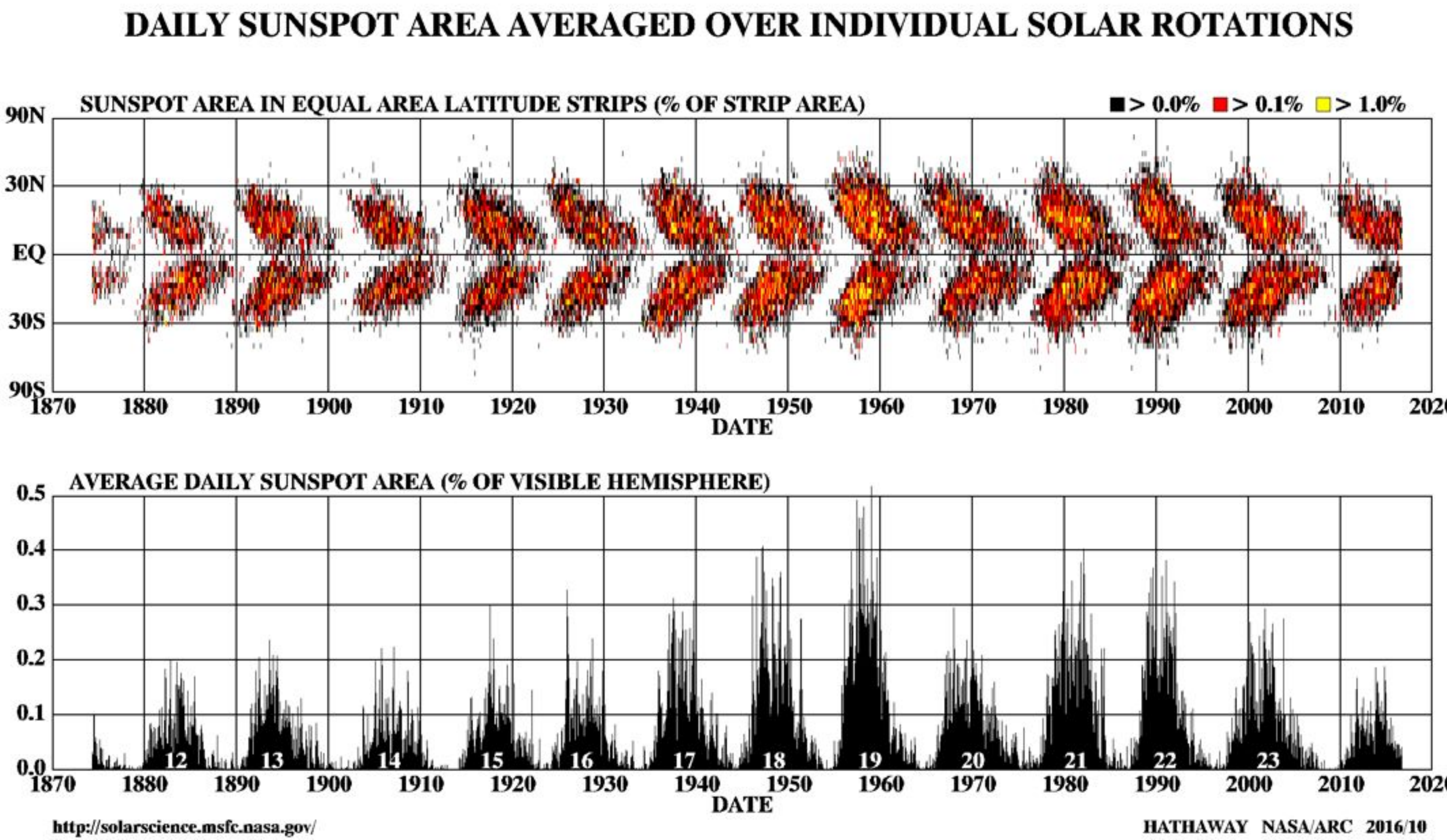
Butterfly diagram

Começa ciclo: altas latitudes (±40^0)

Fim do ciclo: perto do equador

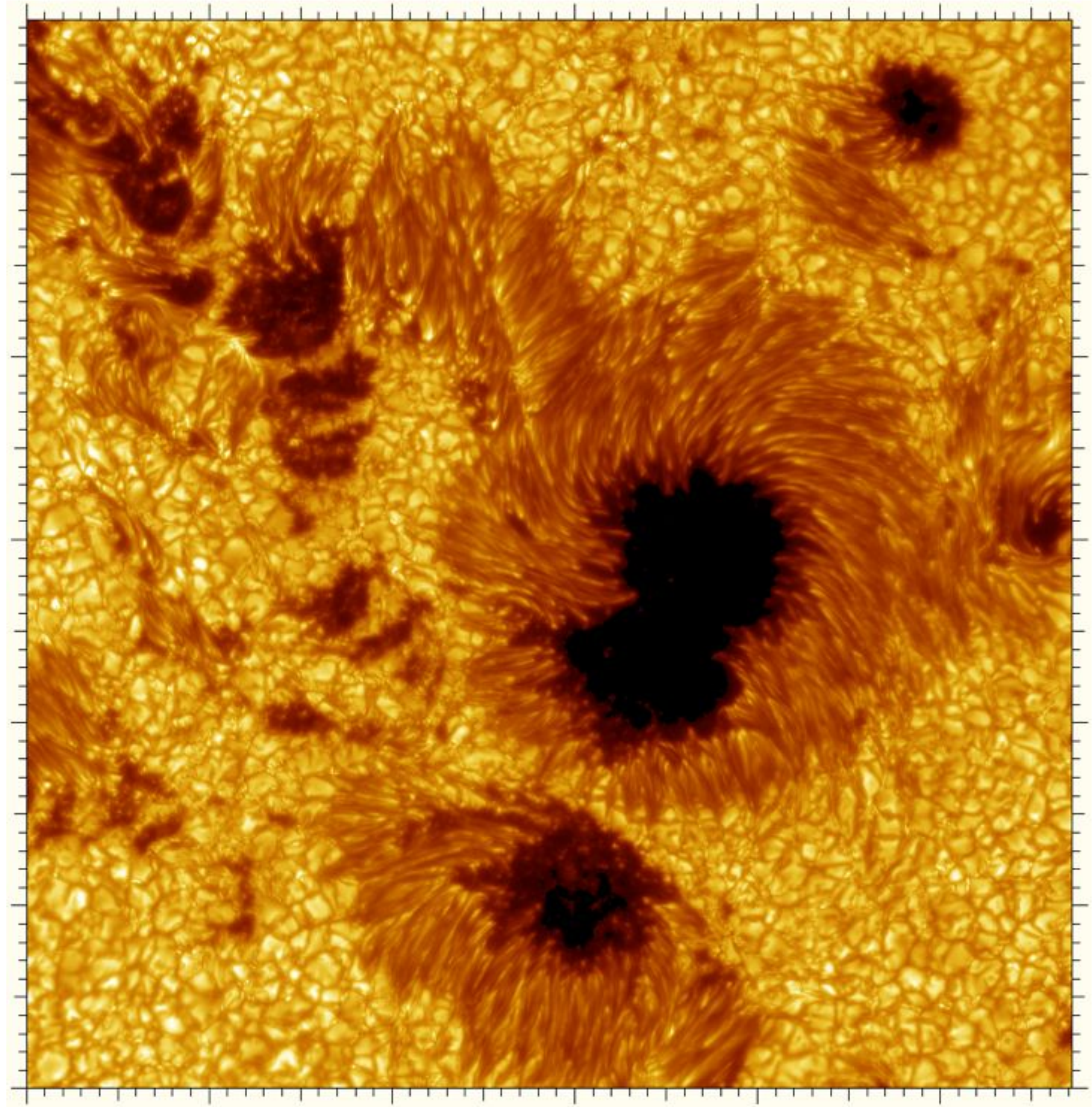
Butterfly diagram

Começo do ciclo: altas latitudes $\pm 40^0$. Fim do ciclo: perto do equador



Umbra: região mais escura.

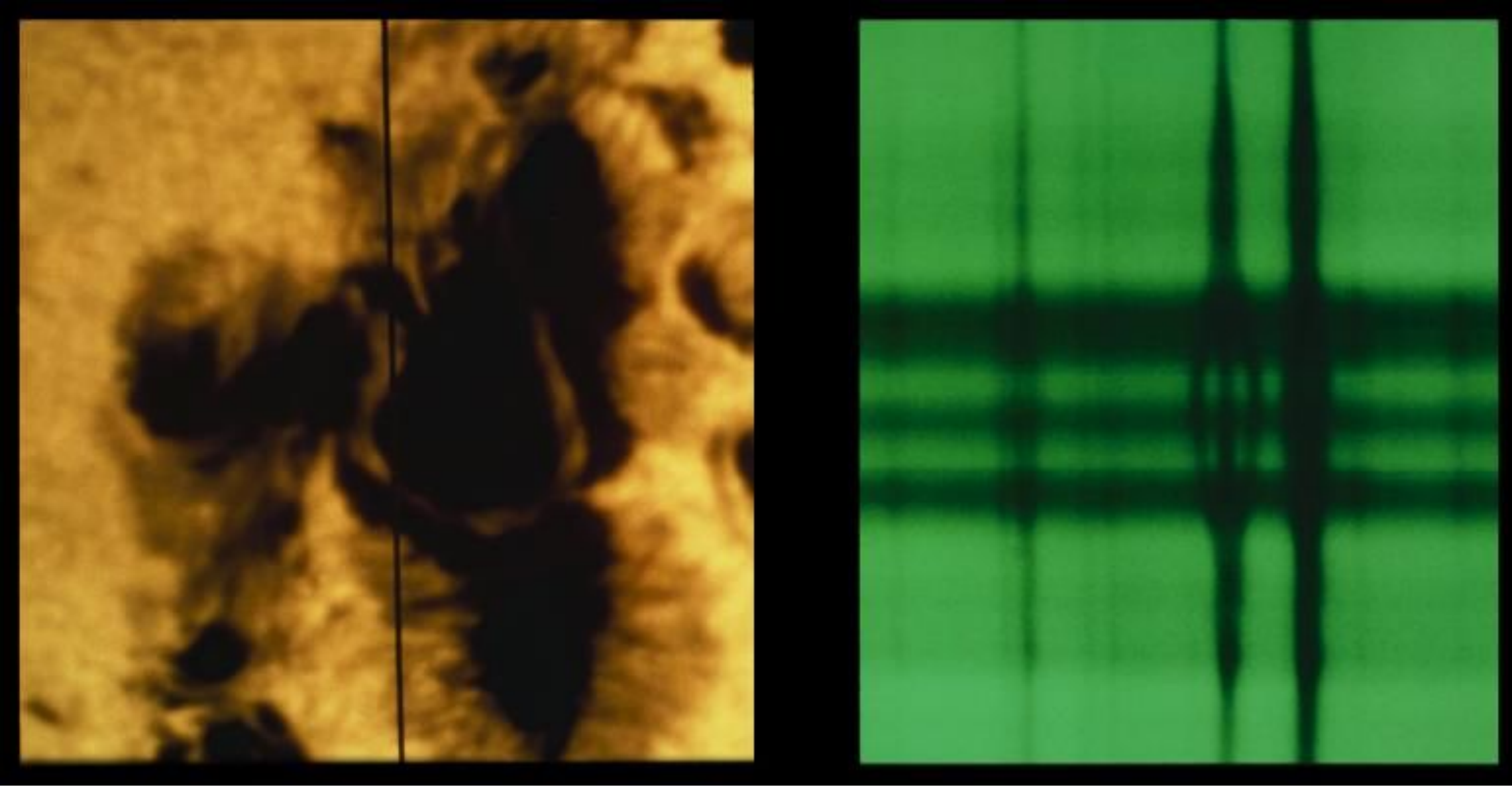
Penumbra: região um pouco mais clara e com estrutura filamentar, que sugere linhas de campos magnéticos.



Nota: além dos grânulos, é possível observar algumas fáculas (pontos brilhantes)

Sunspots observed on 15 July 2002.
The distance between 2 ticks is 1000 km

http://www.isf.astro.su.se/NatureNov2002/press_images_eng.html



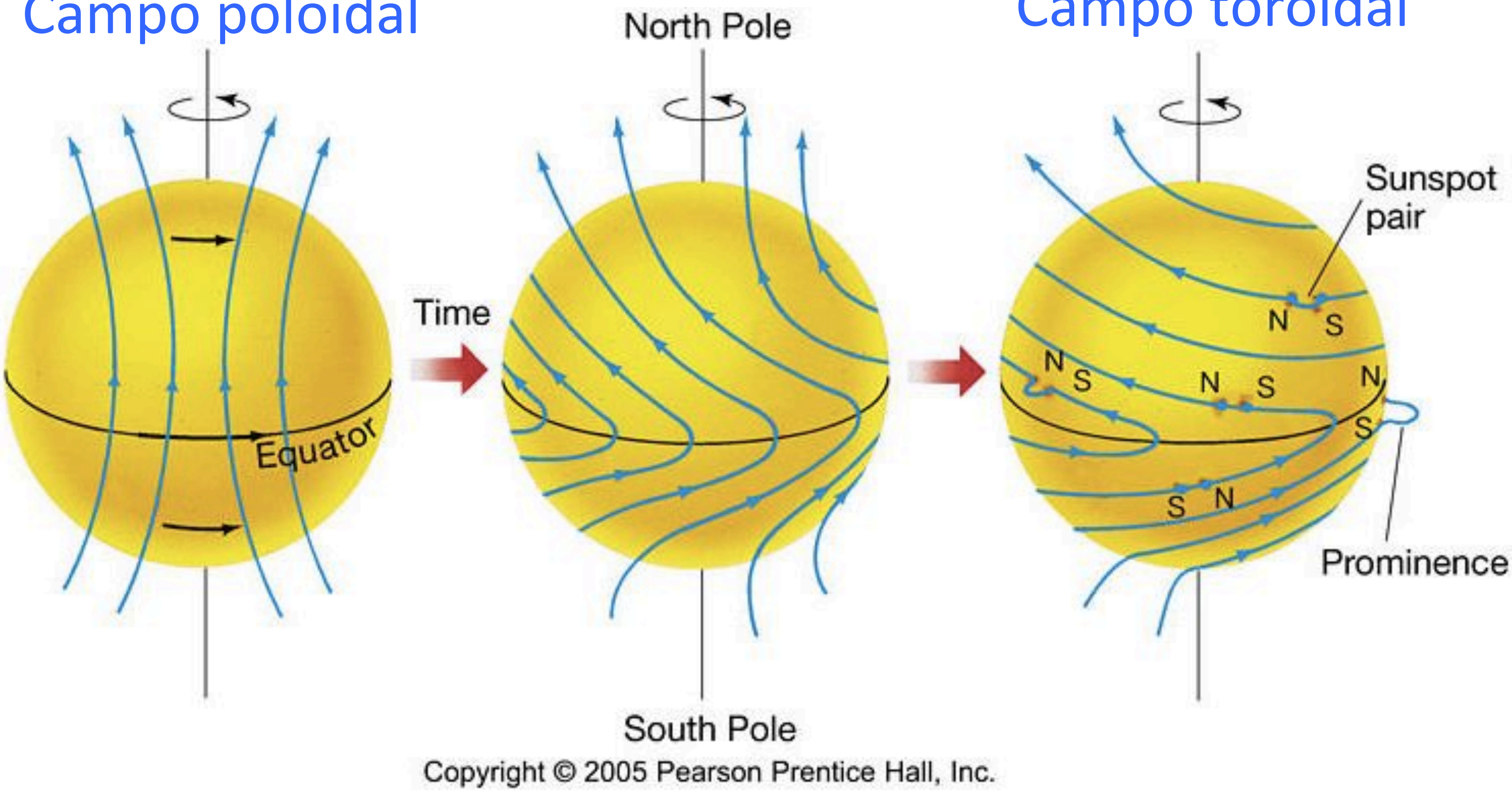
The vertical black line on the **left** indicates the location of the slit for the spectrograph which took the spectrum (**right**). The division of 1 spectral line into 3 demonstrates the Zeeman effect. The splitting of this iron line at 5250.2 Å, indicates a field strength of 4130 Gauss.

https://www.noao.edu/image_gallery/html/im0404.html

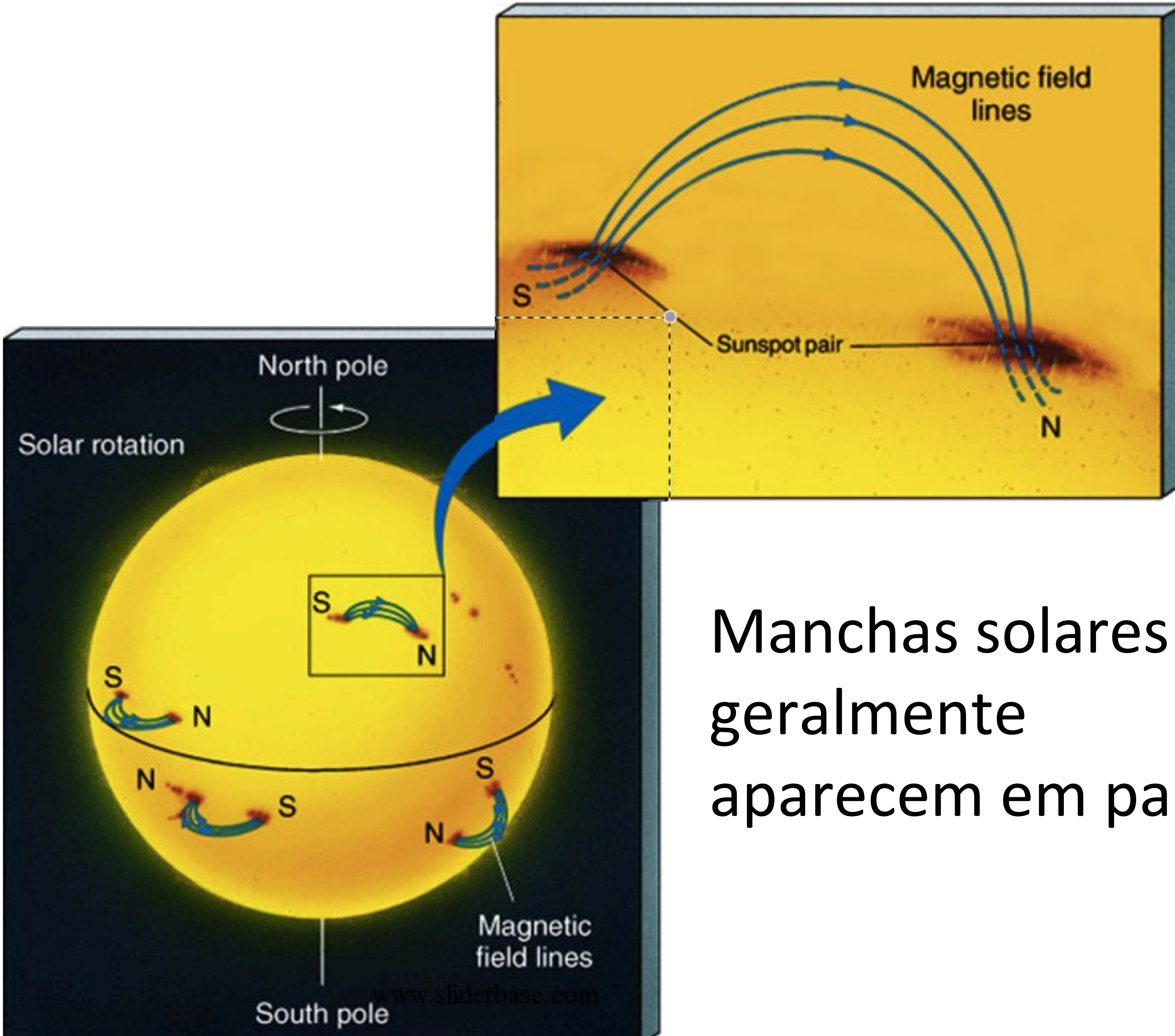
Ciclo de manchas solares

Campo poloidal

Campo toroidal

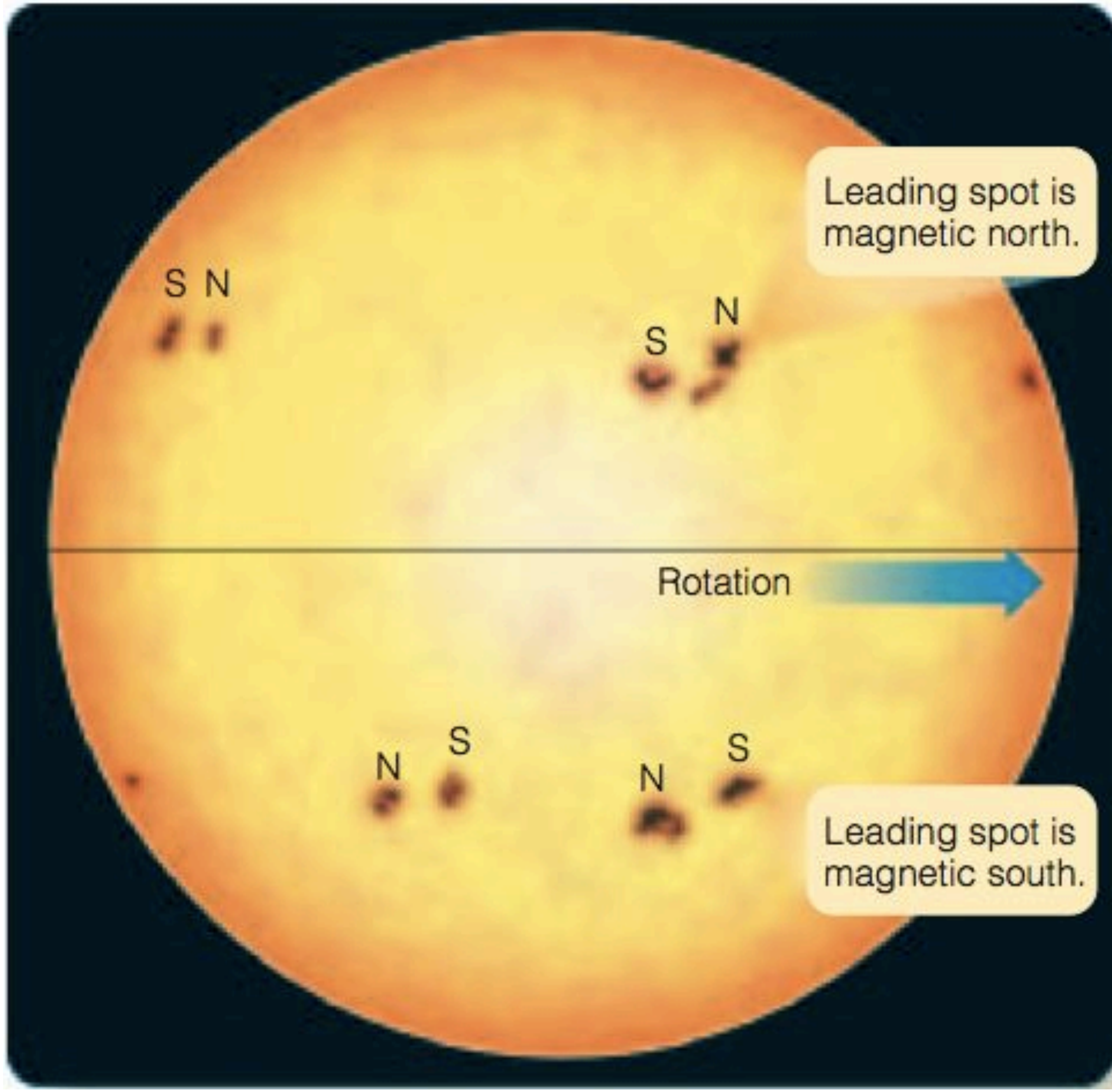


Linhas de campo magnético mais enroladas → manchas solares



Manchas solares geralmente aparecem em pares

In sunspot groups, here simplified into pairs of major spots, the leading spot and the trailing spot have opposite magnetic polarity. Spot pairs in the southern hemisphere have reversed polarity from those in the northern hemisphere.



Ciclo magnético: 22 anos

Campo poloidal é invertido a cada 11 anos, e volta após 22 anos

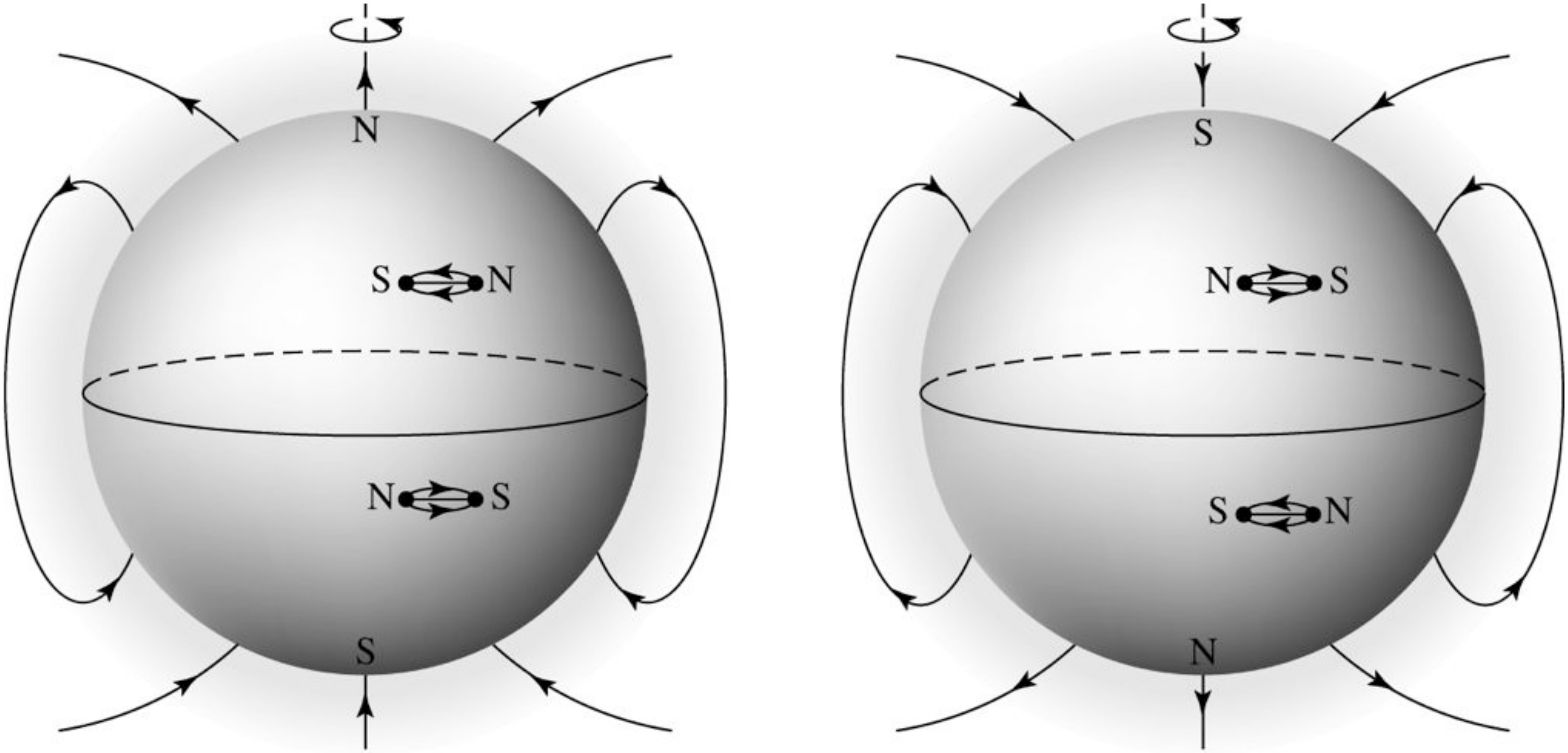
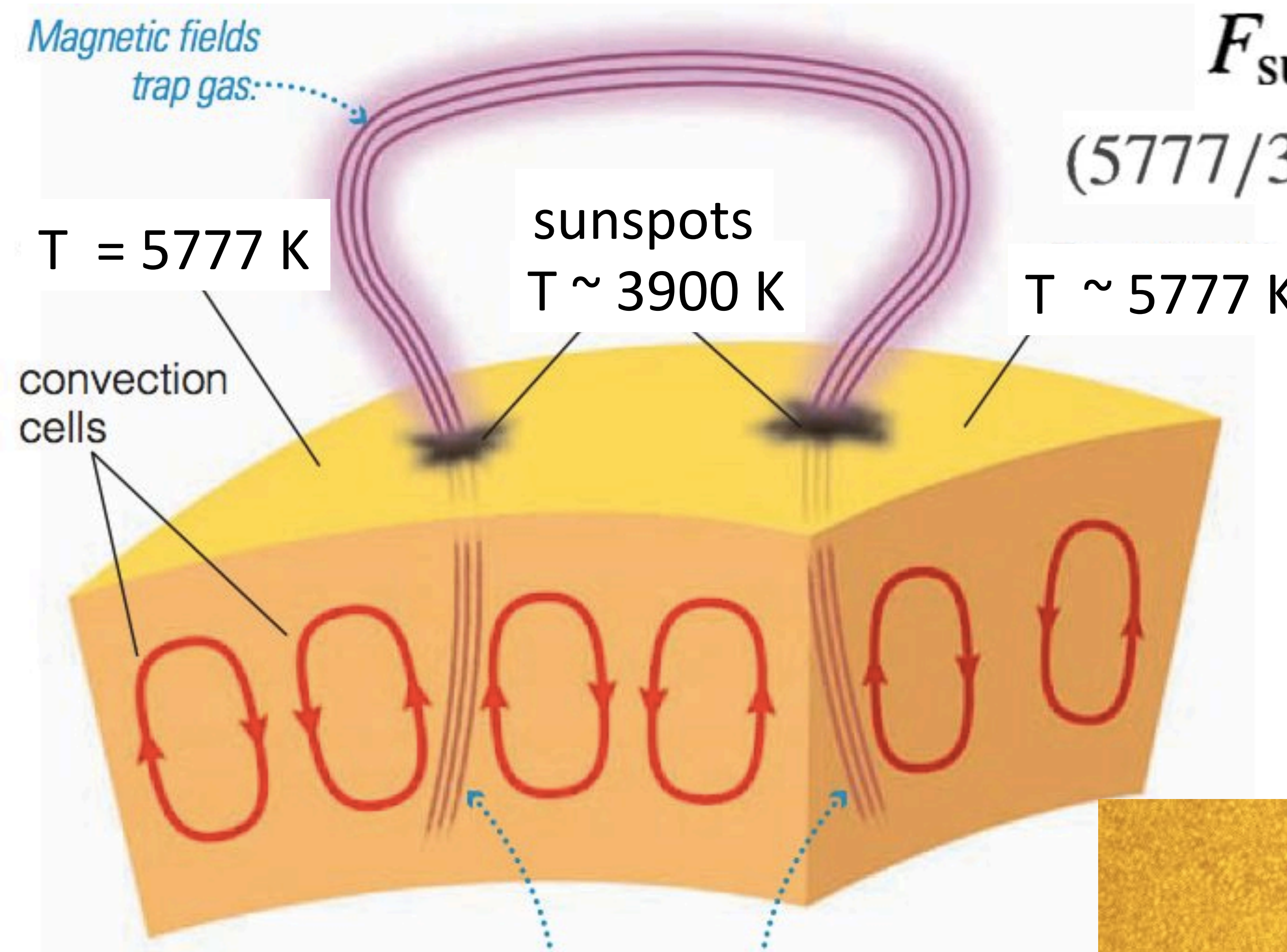
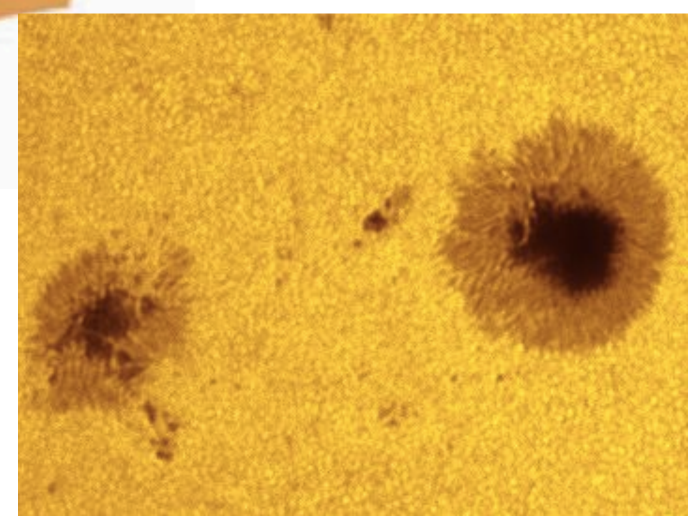


FIGURE 11.32 The global magnetic field orientation of the Sun, along with the magnetic polarity of sunspots during successive 11-year periods.

$$F_{\rm surf} = \sigma T_e^4$$

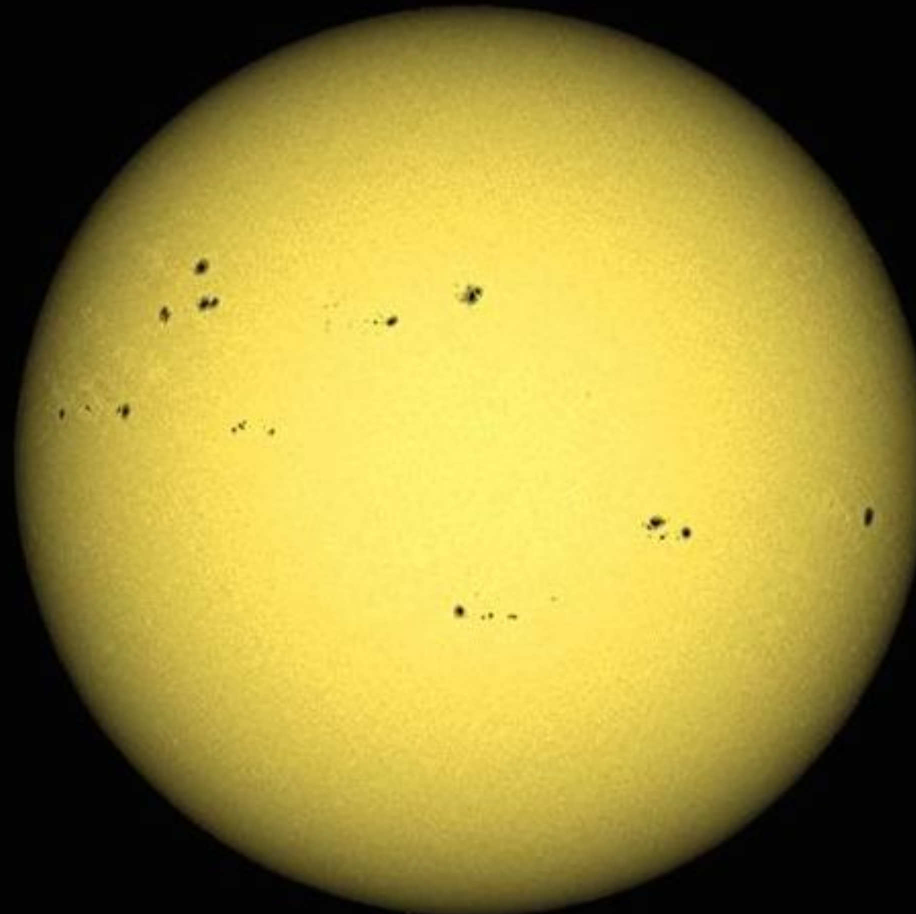
$$(5777/3900)^4 = 4.8$$





Magnetic fields of sunspots suppress convection and prevent surrounding plasma from sliding sideways into sunspot

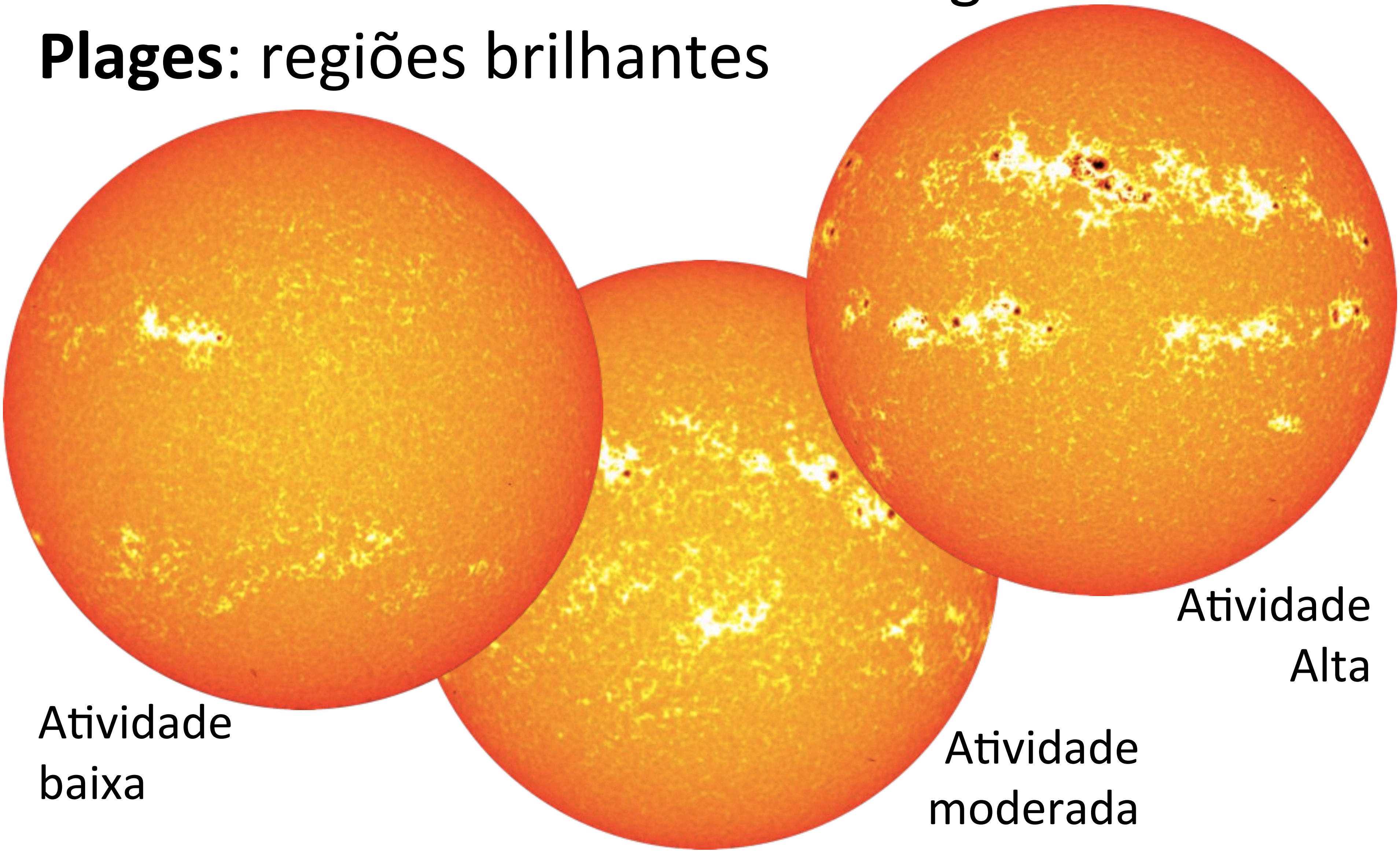
Sol no mínimo de atividade: sem manchas



Sol no máximo de atividade: maior número de manchas

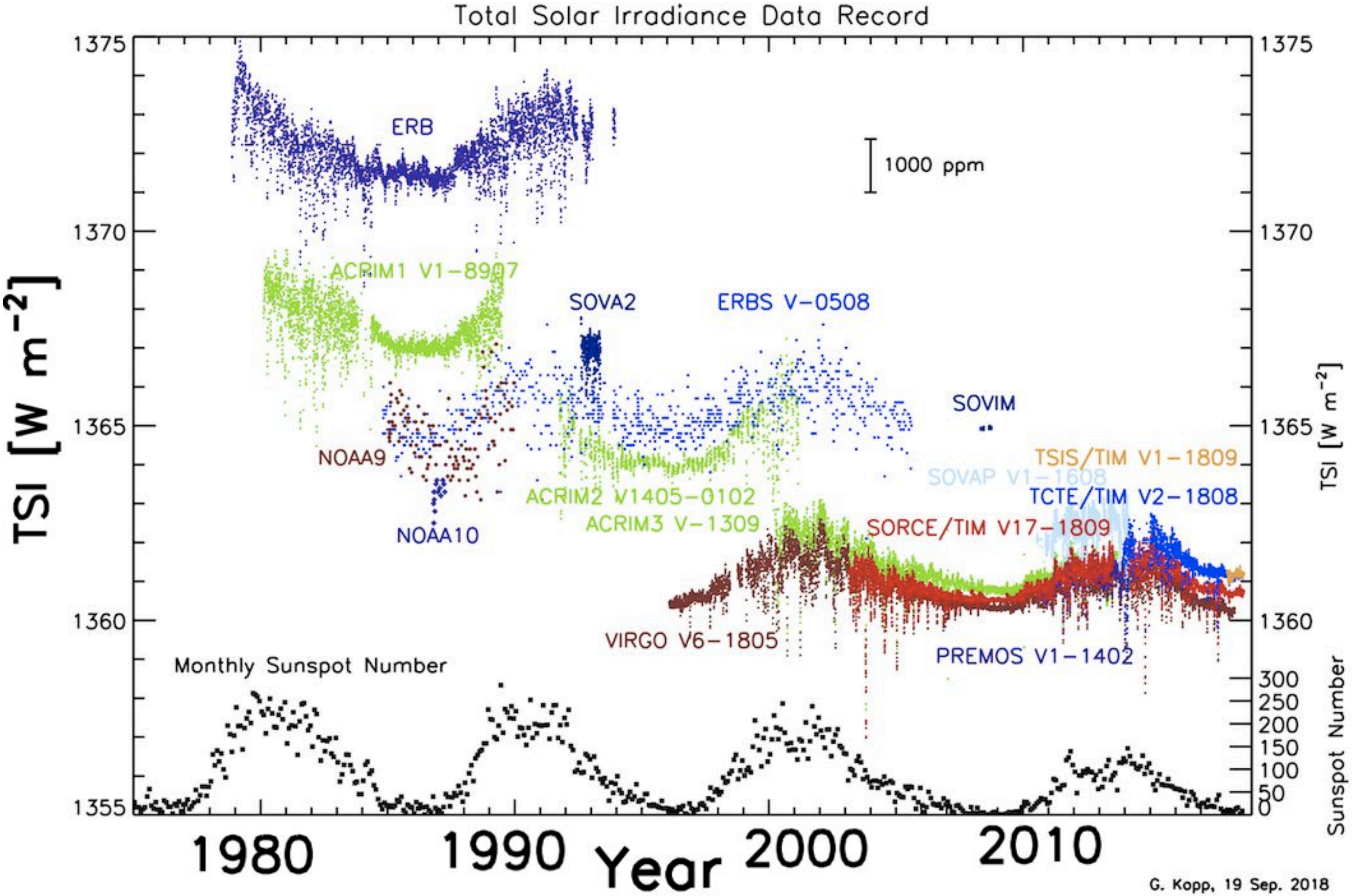
http://www.sciencemag.org/news/2011/06/end-sunspot-cycle

Sol em Hα. **Manchas solares**: regiões escuras. **Plages**: regiões brilhantes



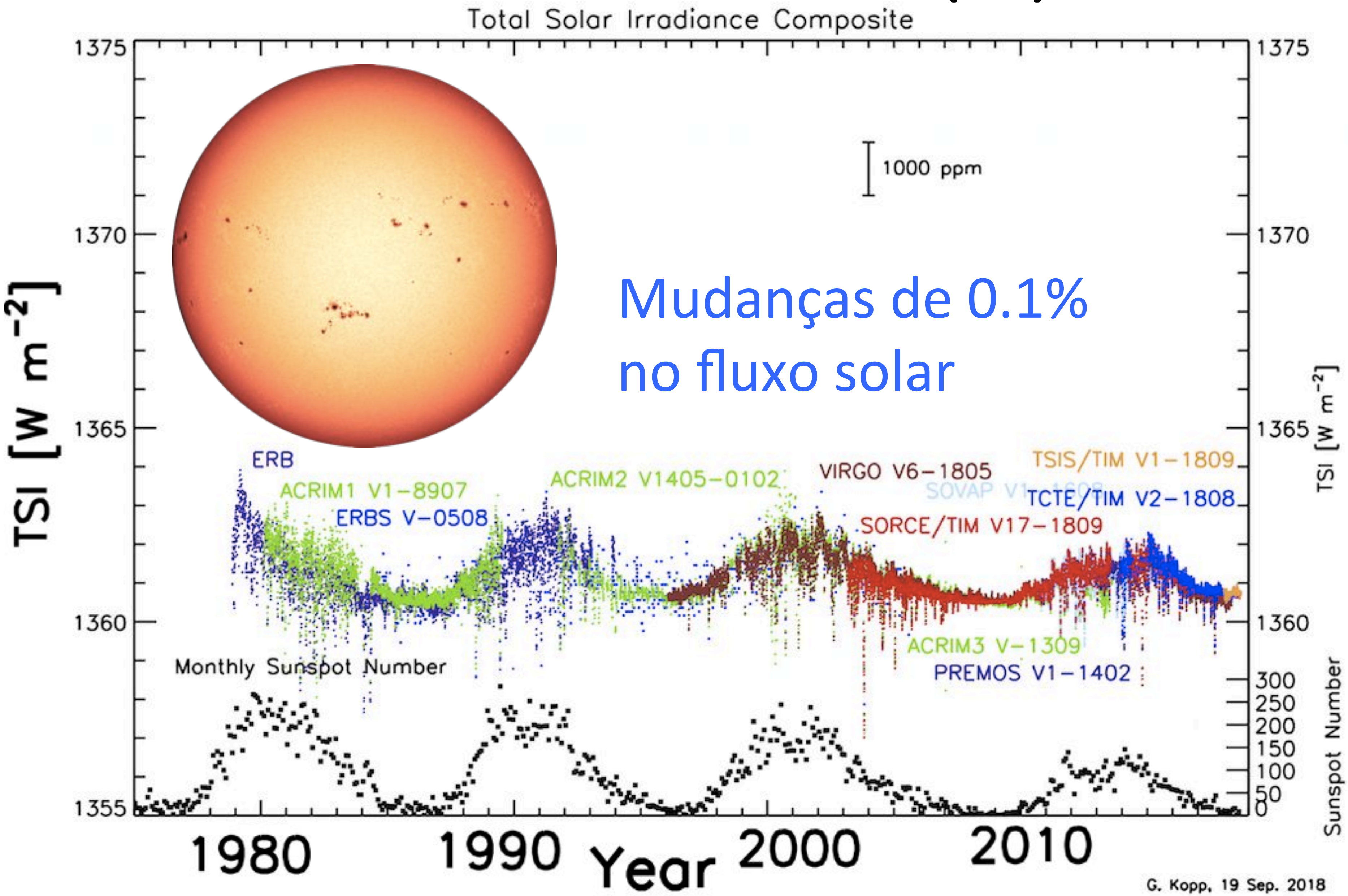
Views of the Sun showing different levels of activity. The color table has been altered to enhance faculae/plage (white regions) which are hotter than sunspots (red-black regions) and whose greater total area contribute to increasing the solar flux reaching the Earth. https://svs.gsfc.nasa.gov/2644

Irradiância Solar Total (TSI)



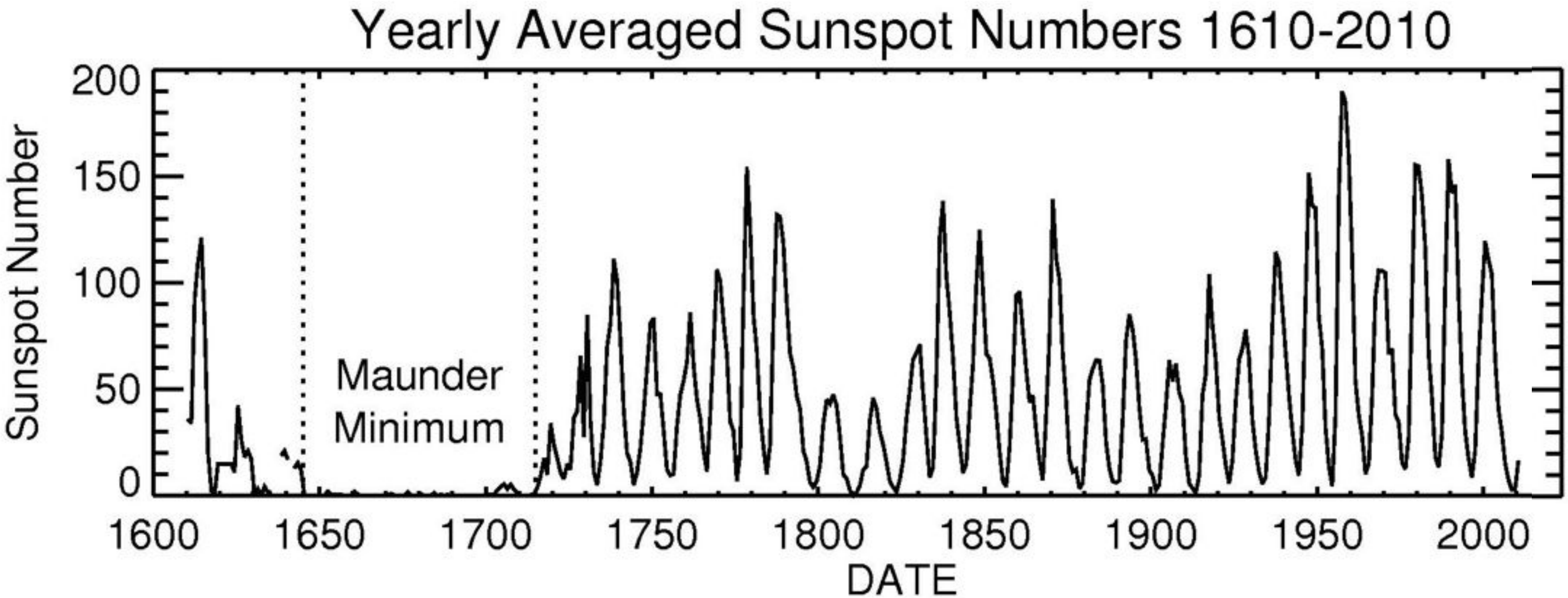
http://spot.colorado.edu/~koppg/TSI/

Irradiância Solar Total (TSI)

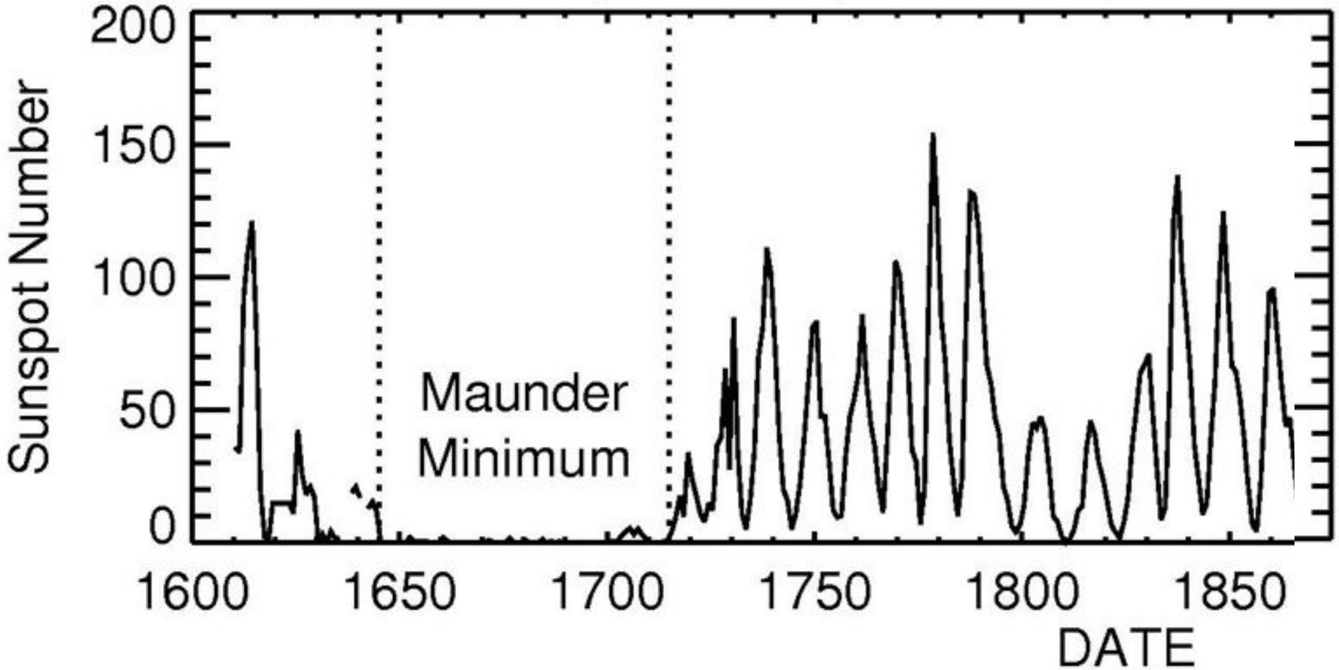


http://spot.colorado.edu/~koppg/TSI/

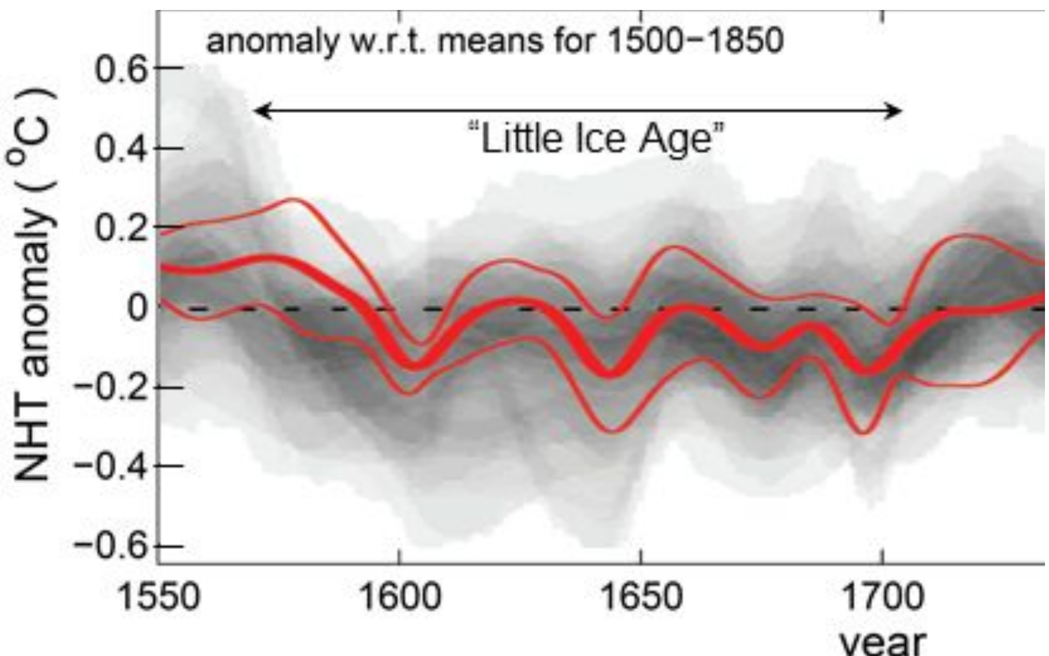
Mínimo de Maunder: entre 1645 e 1715 as manchas solares tornaram-se raras



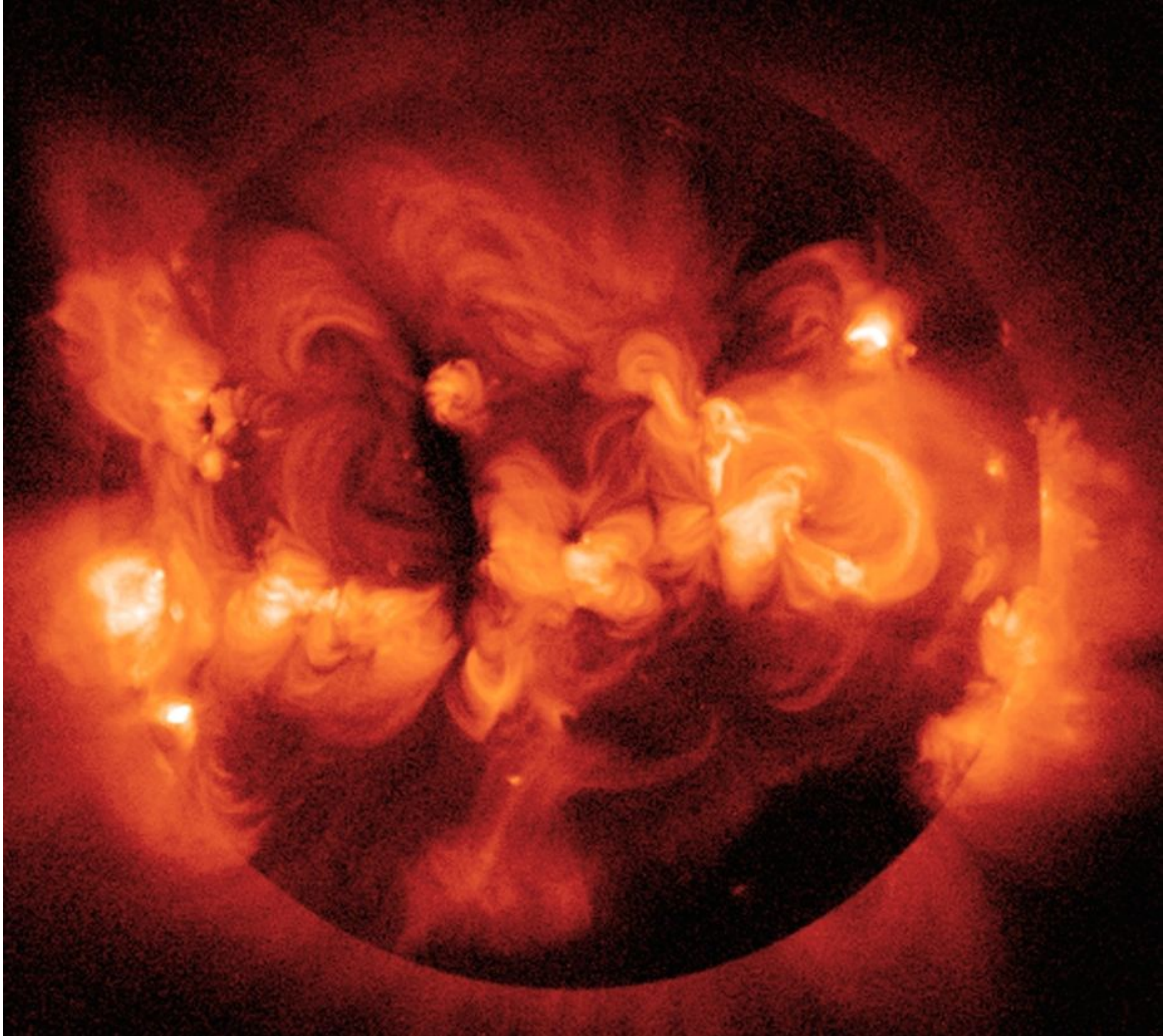
https://www.nasa.gov/mission_pages/sunearth/news/solarcycle-primer.html



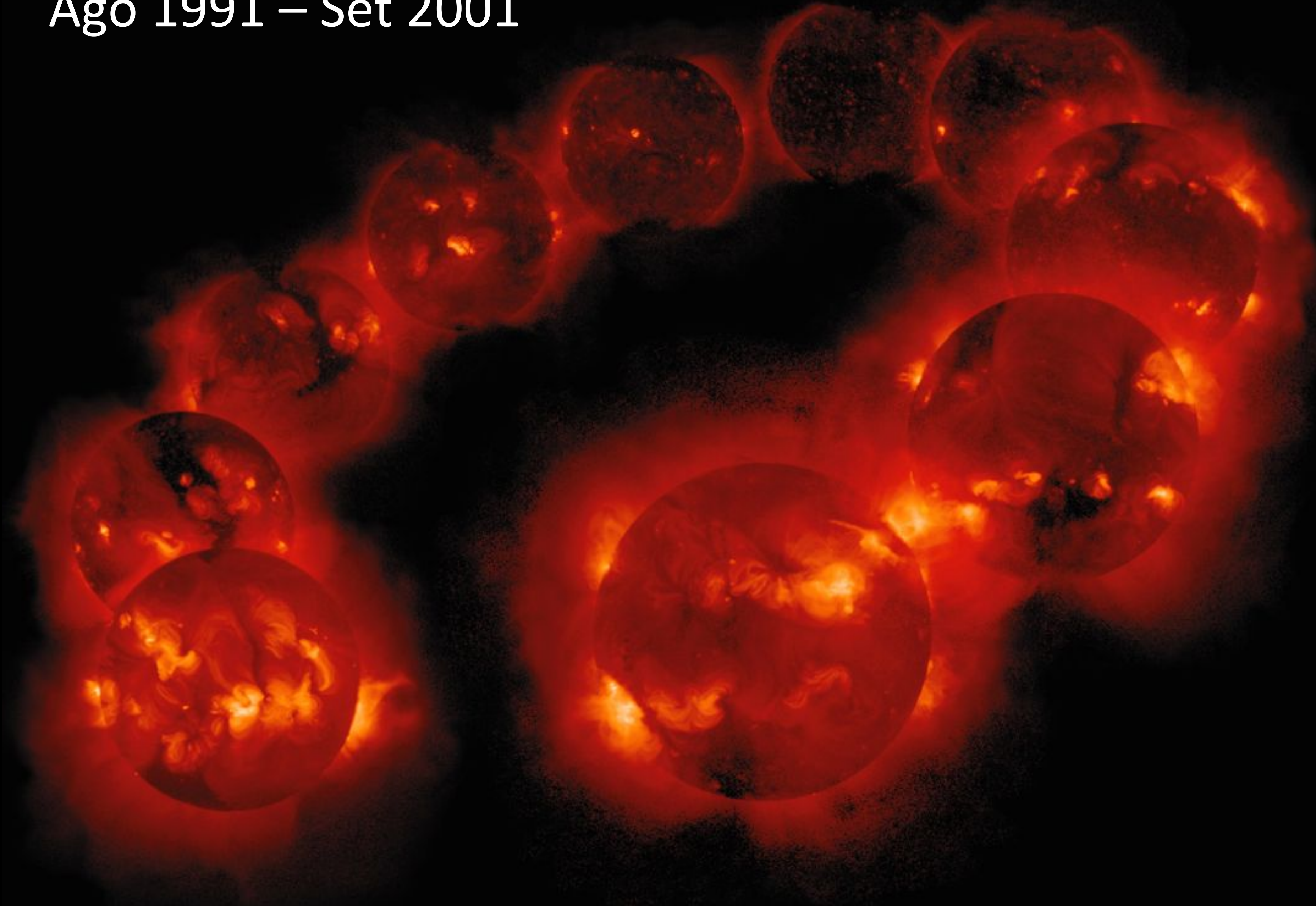
Talvez sem conexão com pequena idade de gelo



Sol em raios-X pelo Yohkoh em 1991

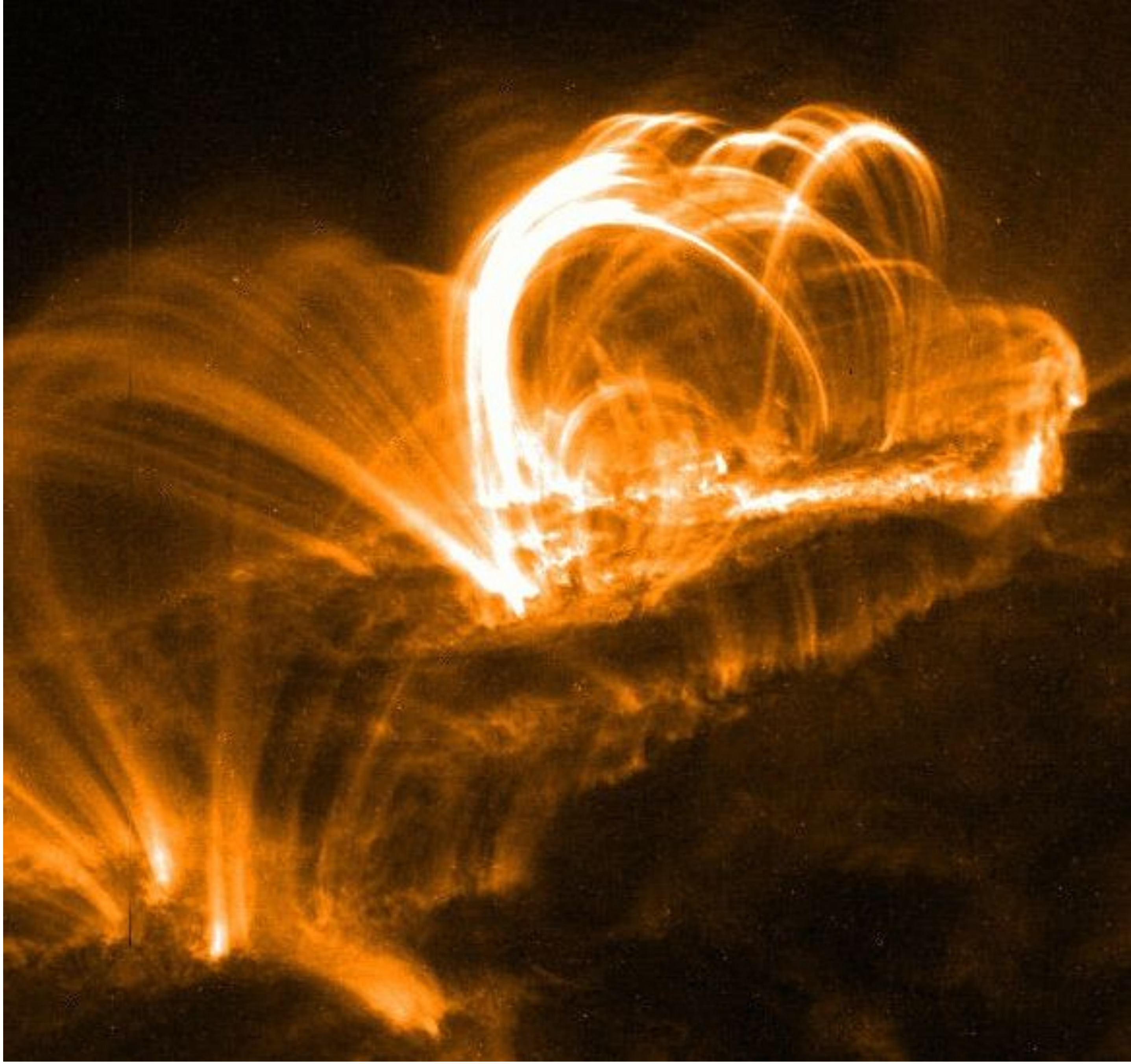


Ciclo de atividade solar em raios-X pelo Yohkoh
Ago 1991 – Set 2001



Solar flare

Image of a typical solar flare from our sun, from September 2005, captured in the X-ray waveband by NASA's TRACE satellite. Note the bright magnetic loops of matter. The twisting and reconnecting of these loops initiate the flare.



https://www.nasa.gov/mission_pages/swift/bursts/monster_flare_prt.htm

Flare solar (erupção solar)

- Energia liberada de 10^{17} - 10^{25} J entre milisegundos a horas.
- Temperatura ~ 10^{7} K

FIGURE 11.34 (a) A solar flare seen at the limb of the Sun, observed by the Yohkoh Soft X-ray Telescope, March 18, 1999, 16:40 UT. (From the Yohkoh mission of ISAS, Japan. The X-ray telescope

Também são ejetados raios cósmicos

Densidade de energia magnética:

$$u_m = \frac{B^2}{2\mu_0}$$

μ_0: constante de permeabilidade magnética do vácuo

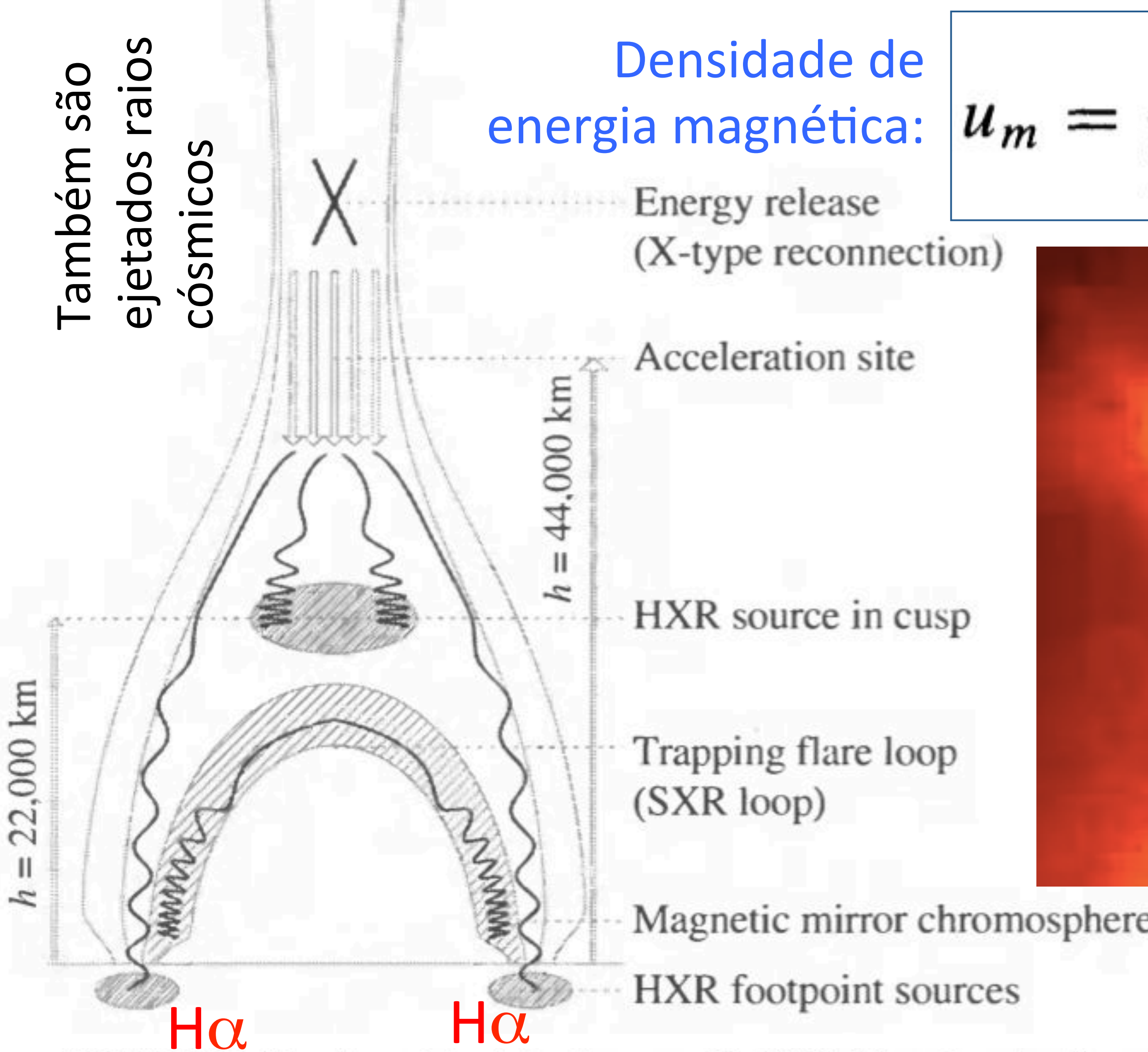


FIGURE 11.35 A model of the January 13, 1992, Masuda solar flare. Note the two hard X-ray (HXR) footpoint sources associated with Hα flare ribbons [see Fig. 11.34(b)]. Electrons are accelerated downward along the magnetic field lines until they collide with the chromosphere. The soft X-ray (SXR) loop may be compared to Fig. 11.34(a). (Figure adapted from Aschwanden, et al., *Ap. J.*, *464*, 985, 1996.)

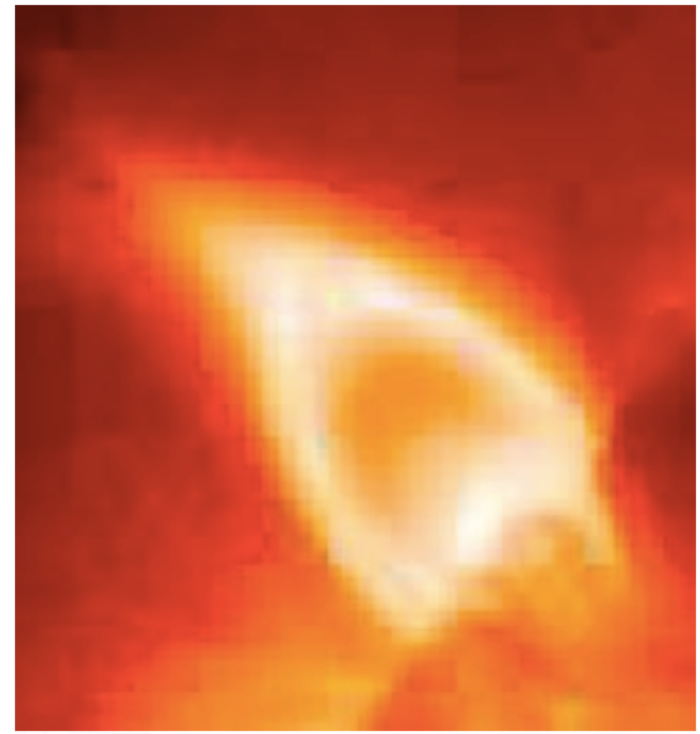


Imagem raios-X de *flare* (erupção) solar

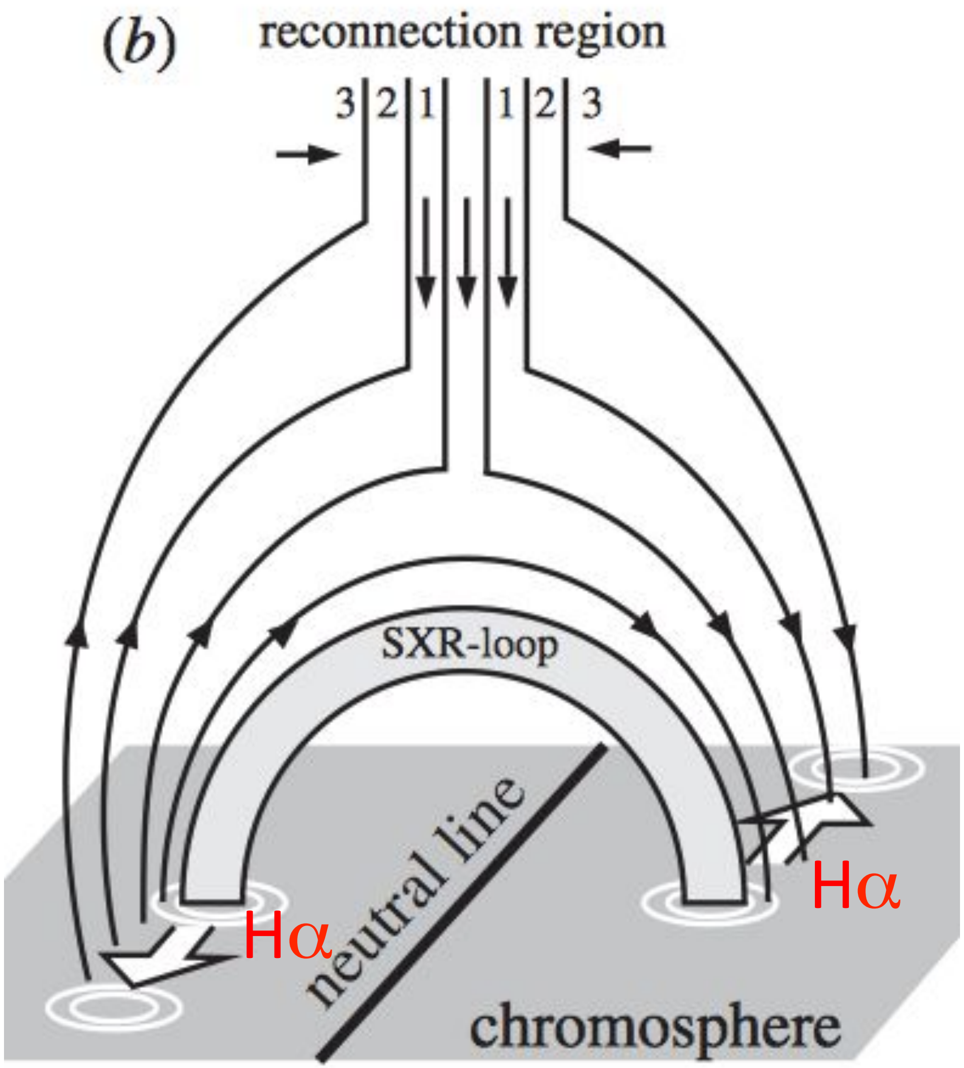
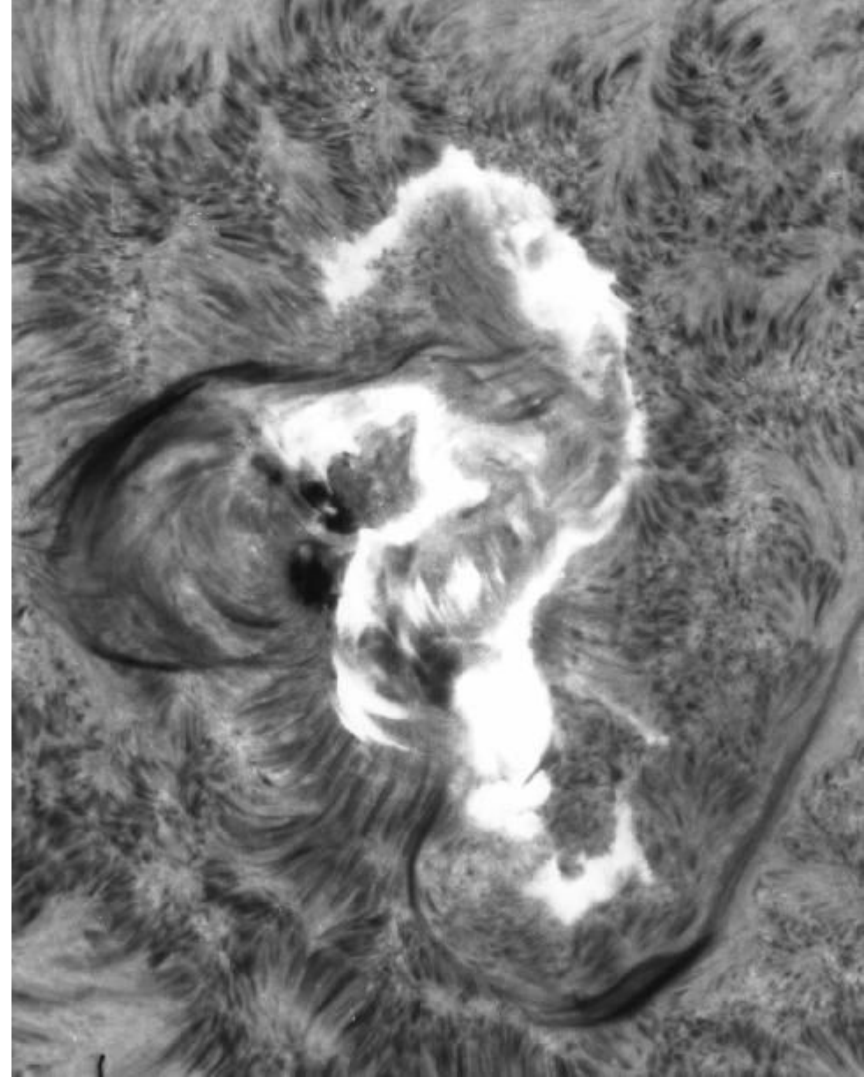
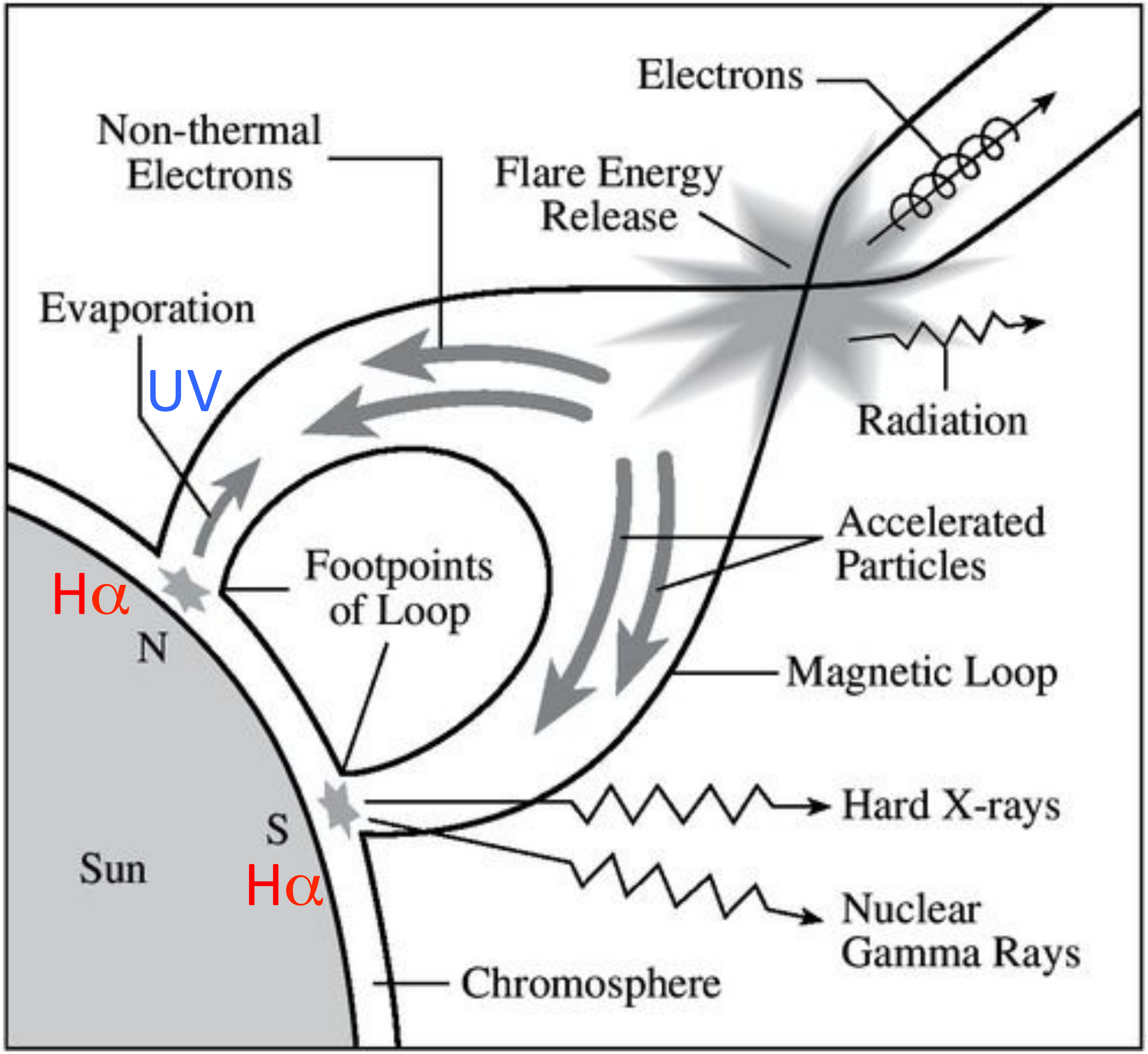


Fig. 3b, Solar flares and energetic particles
NICOLE VILMER, *Phil. Trans. R. Soc. A* (2012) **370**, 3241



The great `Seahorse Flare' of August 7th, 1972: This image in H-alpha shows the two-ribbon structure late in the event, with bright H-alpha loops connecting the ribbons.

http://www.bbso.njit.edu/images.html



Radio: synchroton

Soft X-rays: altas temperaturas

Hard X-ray: Bremsstrahlung

Gamma rays: reações nucleares

https://ase.tufts.edu/cosmos/print_images.asp?id=47

$$^{1}_{1}H + ^{16}_{8}O \rightarrow ^{12}_{6}C^{*} + ^{4}_{2}He + ^{1}_{1}H,$$

where C^{*} represents a carbon nucleus in an excited state, followed by the de-excitation reaction

$$^{12}_{6}C^{*} \rightarrow ^{12}_{6}C + \gamma,$$

with $E_\gamma = 4.438$ MeV, or

$$^{1}_{1}H + ^{20}_{10}Ne \rightarrow ^{16}_{8}O^{*} + ^{4}_{2}He + ^{1}_{1}H,$$

followed by the de-excitation reaction

$$^{16}_{8}O^{*} \rightarrow ^{16}_{8}O + \gamma,$$

with $E_\gamma = 6.129$ MeV. Other examples of reactions produced by flares on the Sun's surface include electron–positron annihilation,

$$e^{-} + e^{+} \rightarrow \gamma + \gamma$$

where $E_\gamma = 0.511$ MeV, and the production of deuterium by

$$^{1}_{1}H + n \rightarrow ^{2}_{1}H^{*} \rightarrow ^{2}_{1}H + \gamma,$$

where $E_\gamma = 2.223$ MeV.

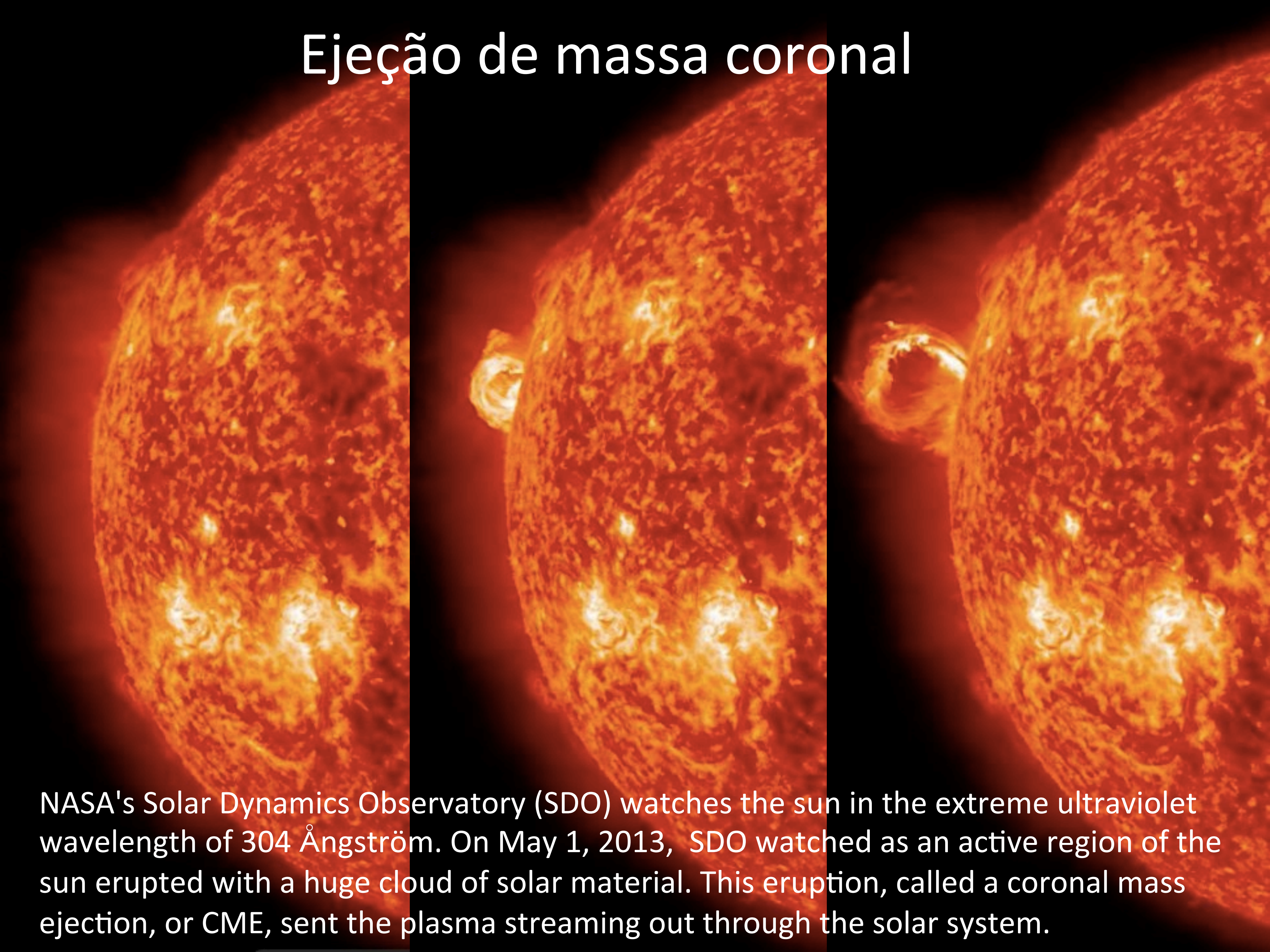
An **eruptive prominence** in extreme UV light on March 30, 2010. Credit: NASA/SDO.

A prominence (also known as a filament when viewed against the solar disk) is a large, bright feature extending outward from the Sun's surface. Prominences are anchored to the Sun's photosphere, and extend outwards into the Sun's corona. A prominence forms over timescales of ~ 1 day, and stable prominences may persist for months. The red-glowing looped material is plasma, flowing along a tangled & twisted structure of magnetic fields generated by the sun's internal dynamo. An erupting prominence occurs when such a structure becomes unstable and bursts outward, releasing the plasma.

Proeminência solar

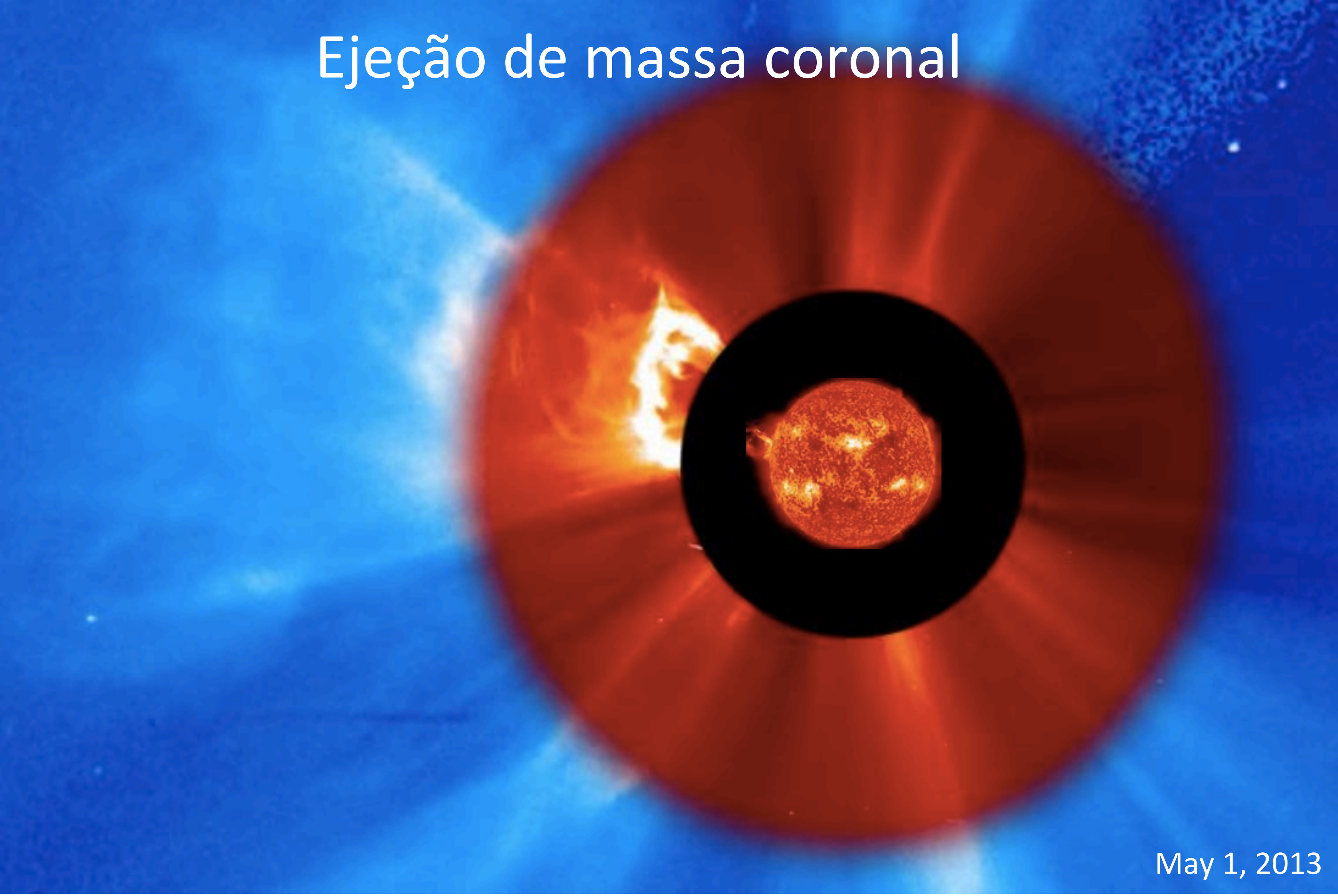
https://www.nasa.gov/content/goddard/what-is-a-solar-prominence

Ejeção de massa coronal



NASA's Solar Dynamics Observatory (SDO) watches the sun in the extreme ultraviolet wavelength of 304 Ångström. On May 1, 2013, SDO watched as an active region of the sun erupted with a huge cloud of solar material. This eruption, called a coronal mass ejection, or CME, sent the plasma streaming out through the solar system.

Ejeção de massa coronal



Besides the SDO images, the CME was also observed by SOHO using 2 coronagraphs where the bright sun is blocked by a disk so it does not overpower the fainter corona.

Ejeção de massa coronal

Máximo do ciclo de atividade: ~ 3,5 por dia

Mínimo: aprox. 1 cada 5 dias.

$5x10^{12}$ kg a $5x10^{13}$ kg

v ~ 400 km/s a 1000 km/s

Com *flares*: 40%

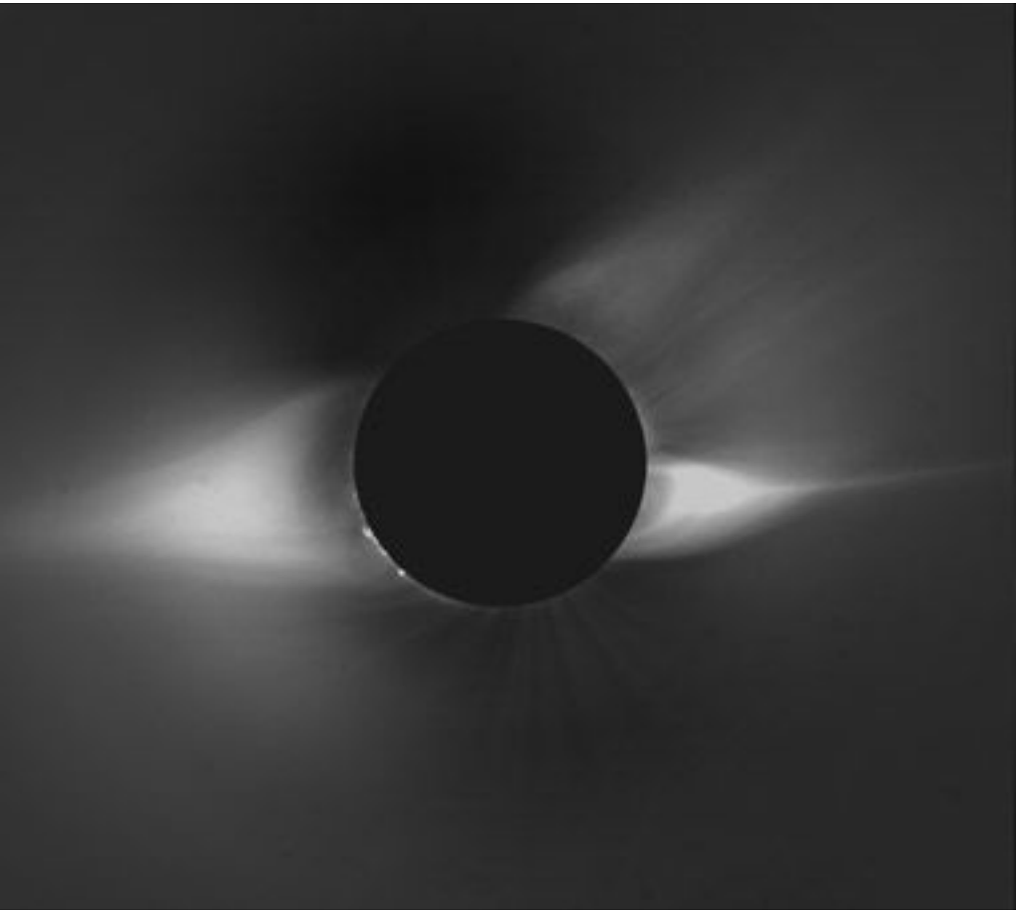
Com proeminência solar eruptiva: 70%

http://www.esa.int/Our_Activities/Space_Science/The_Sun_has_a_great_idea

Coroa solar durante eclipse

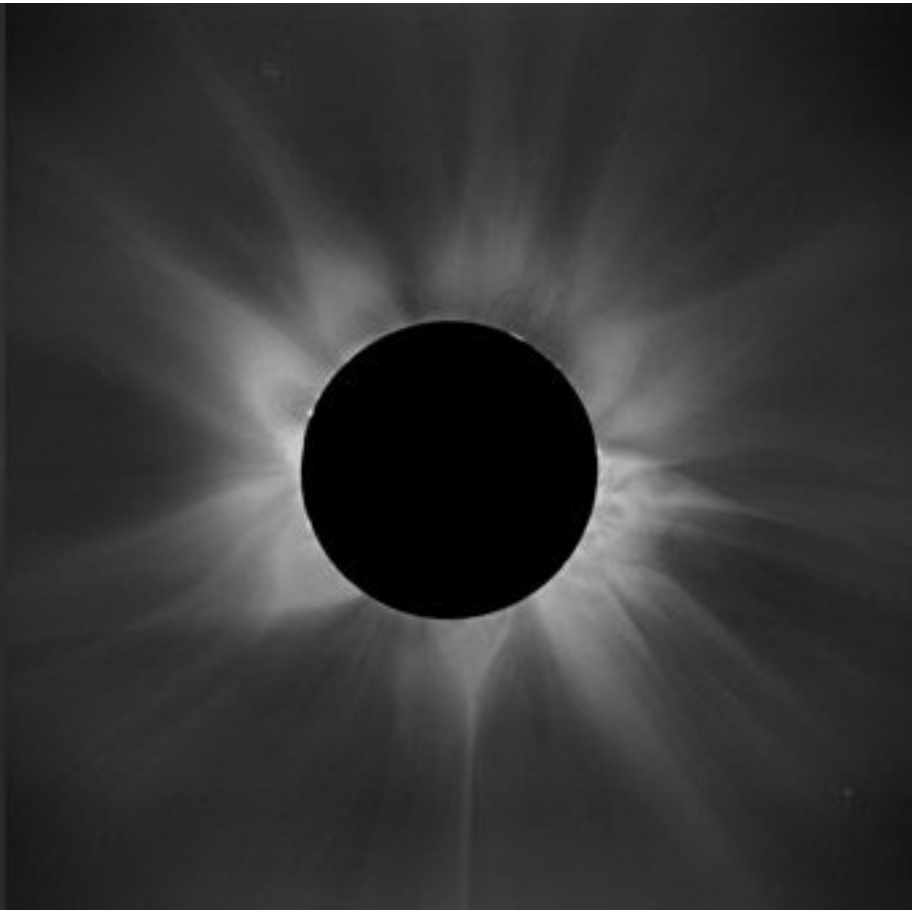
1994 (mínimo de atividade)

Mais extendida no equador, consistente com campo dipolar



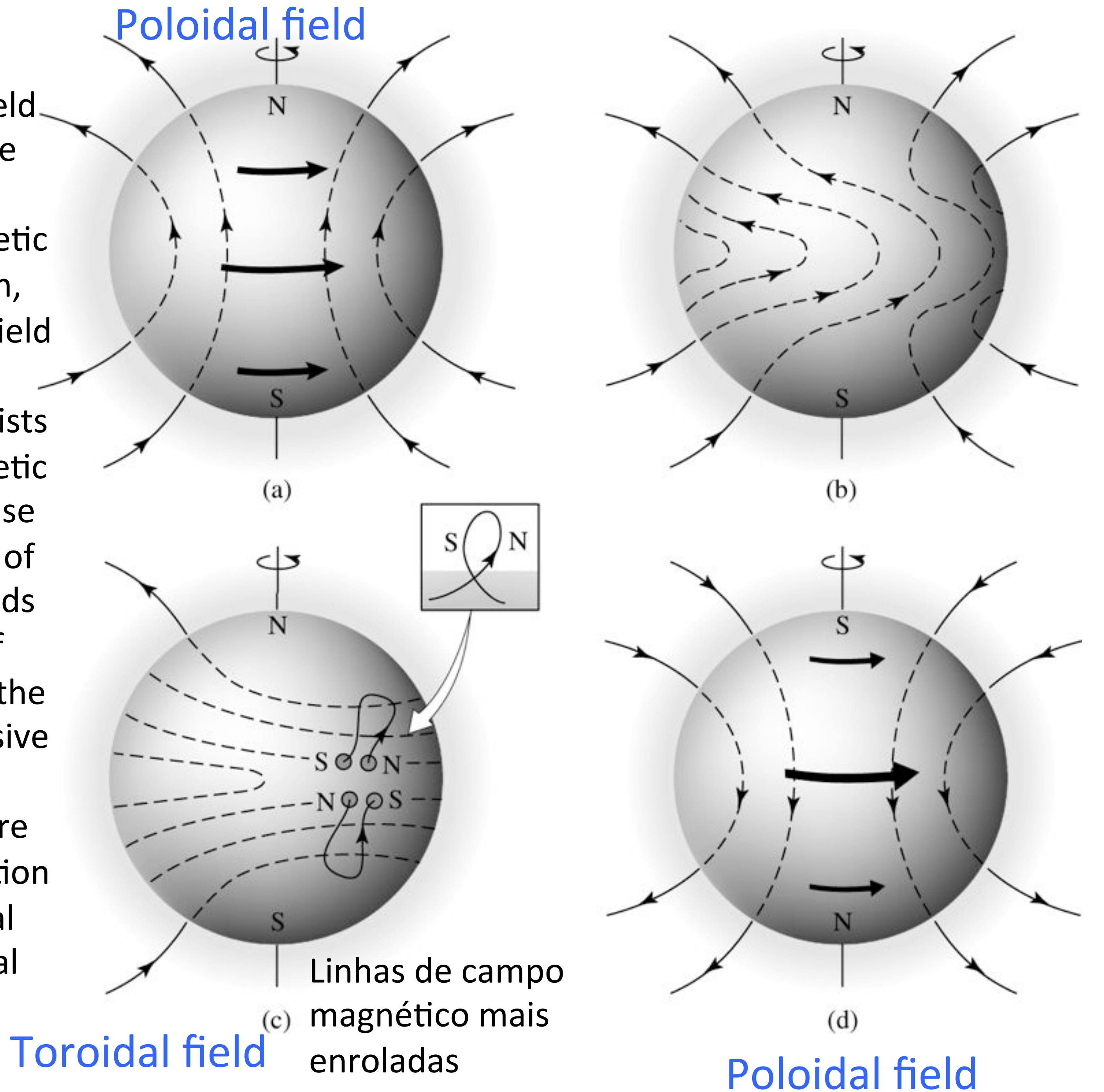
1980 (máximo de atividade)

Coroa é mais complexa

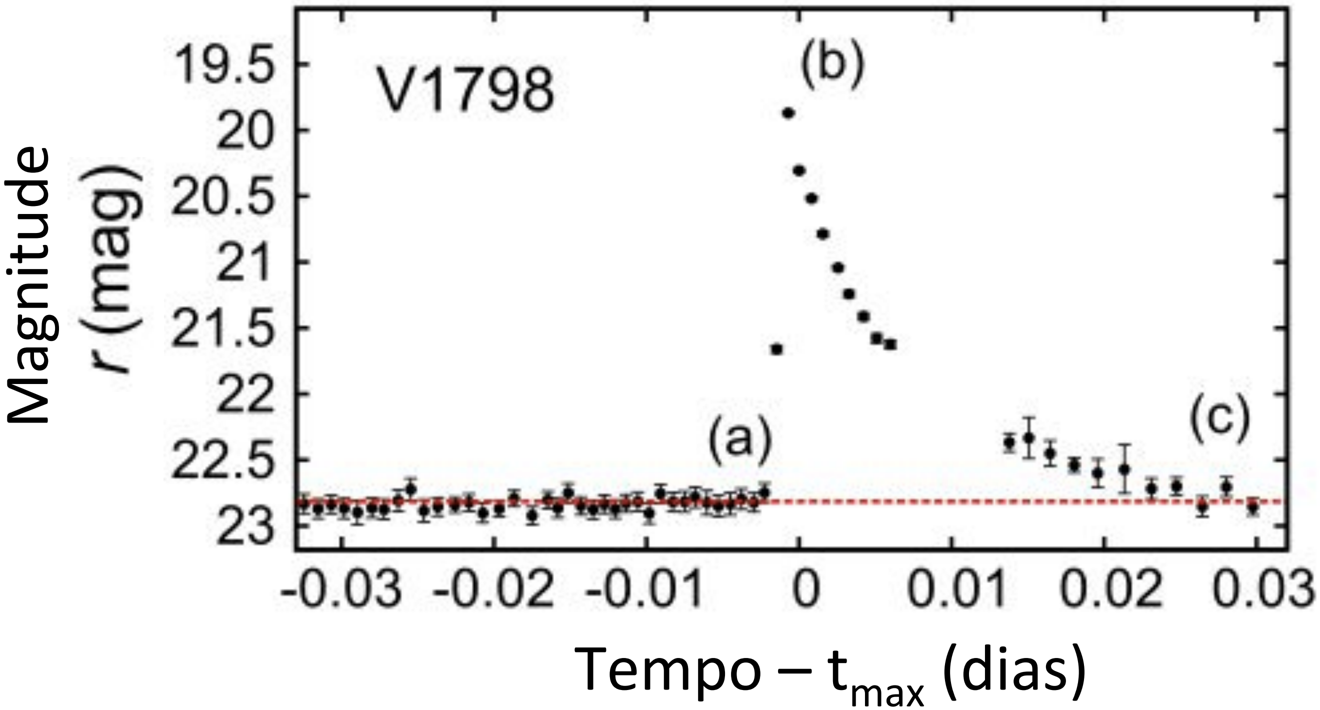


http://www.windows2universe.org/sun/images/eclipse/sun_eclipse_corona_max_vs_min_big_jpg_image.html

The magnetic dynamo model of the solar cycle. (a) The solar magnetic field is initially poloidal (simple dipole). (b) Differential rotation drags the magnetic field lines around the Sun, converting the poloidal field into a toroidal field. (c) Turbulent convection twists the field lines into magnetic ropes, causing them to rise as sunspots, the polarity of the lead spots corresponds to the original polarity of the poloidal field. (d) As the cycle progresses, successive sunspot groups migrate toward the equator where magnetic field reconnection reestablishes the poloidal field, but with the original polarity reversed.

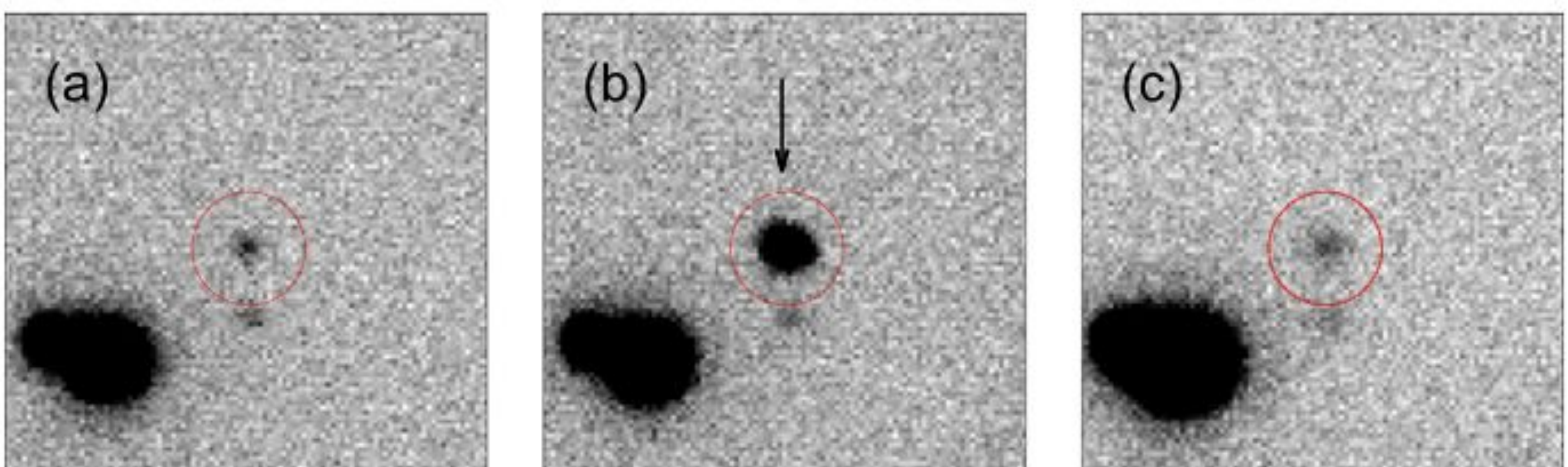


Estrelas “flare” (geralmente estrelas M)



Anã M no aglomerado aberto M37

Chang et al. 2015, ApJ 814, 35



Superflares on solar-type stars

Nature **485**, 478–481 (24 May 2012)

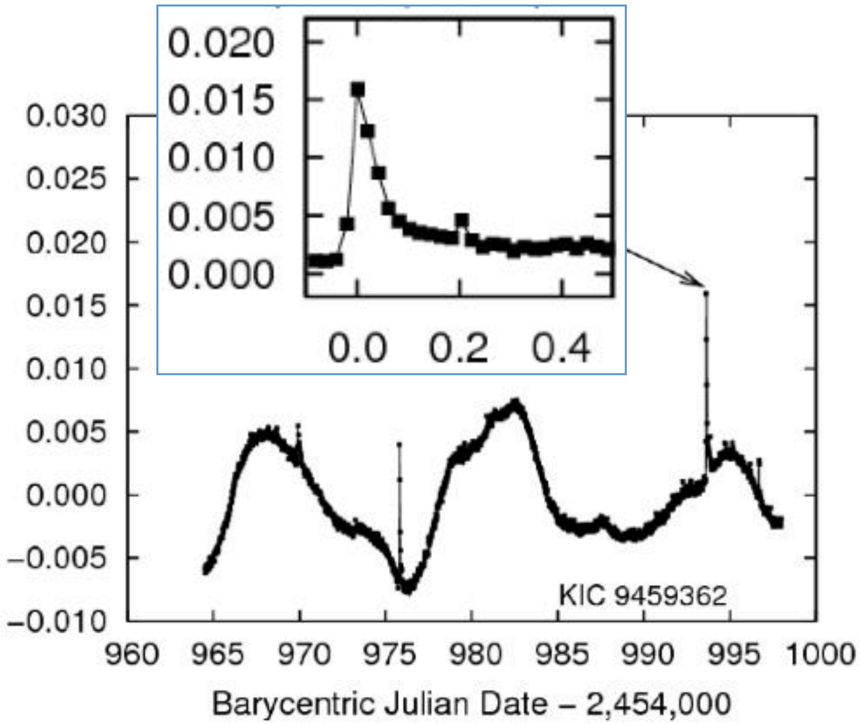
Hiroyuki Maehara, Takuya Shibayama, Shota Notsu, Yuta Notsu, Takashi Nagao, Satoshi Kusaba, Satoshi Honda, Daisaku Nogami & Kazunari Shibata

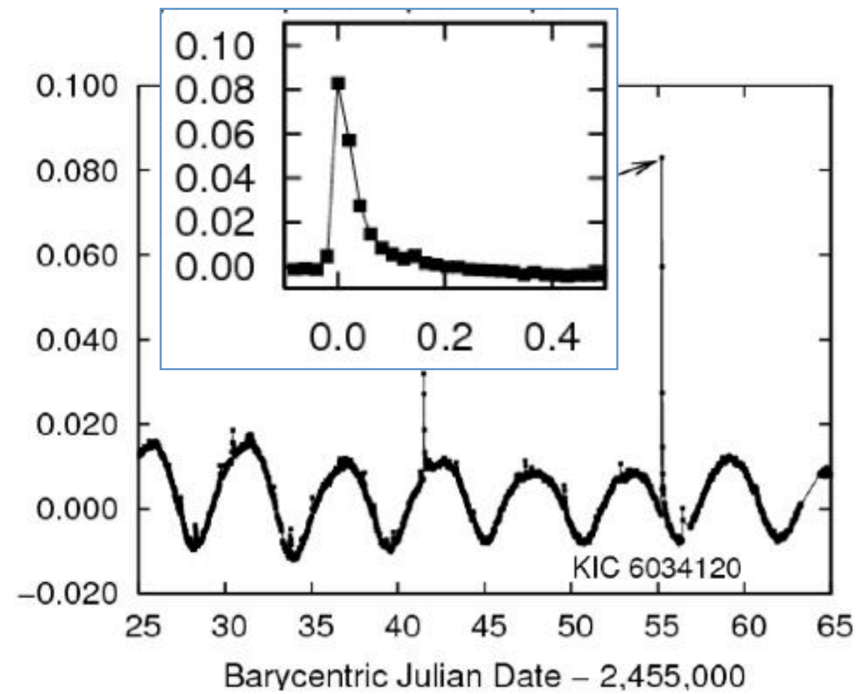
14 flares on 10 Sun-like stars (T_{eff}: 5600-6000; P>10days)

Amplitude: 0.1-10%;   Duration: ~0.1 days

Total bolometric energy of superflares: 10^{33}-10^{36} ergs

10-10,000 times larger than the largest solar flares (10^{32} ergs)





Ciclo de atividade na estrela BD+26730

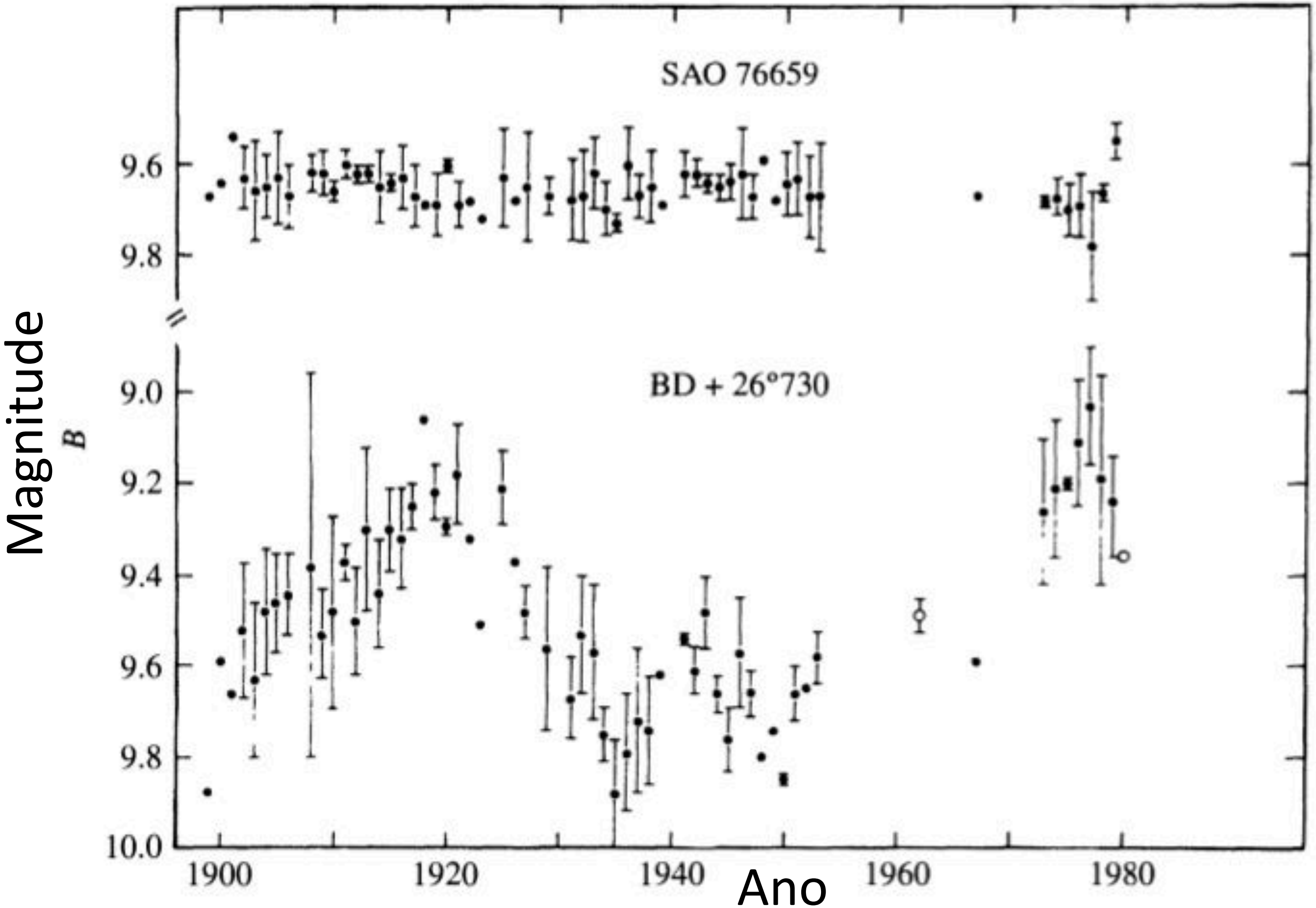
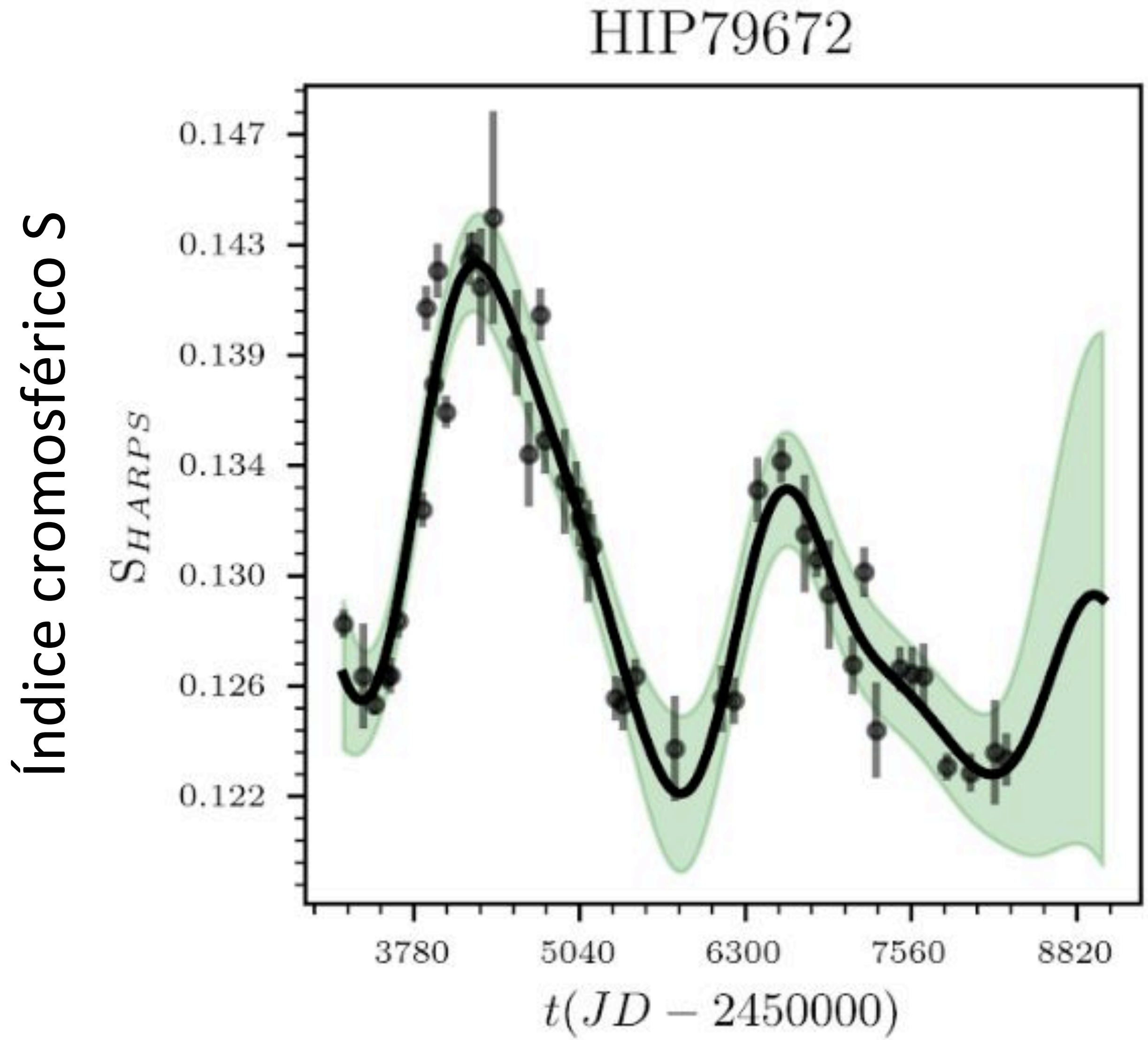
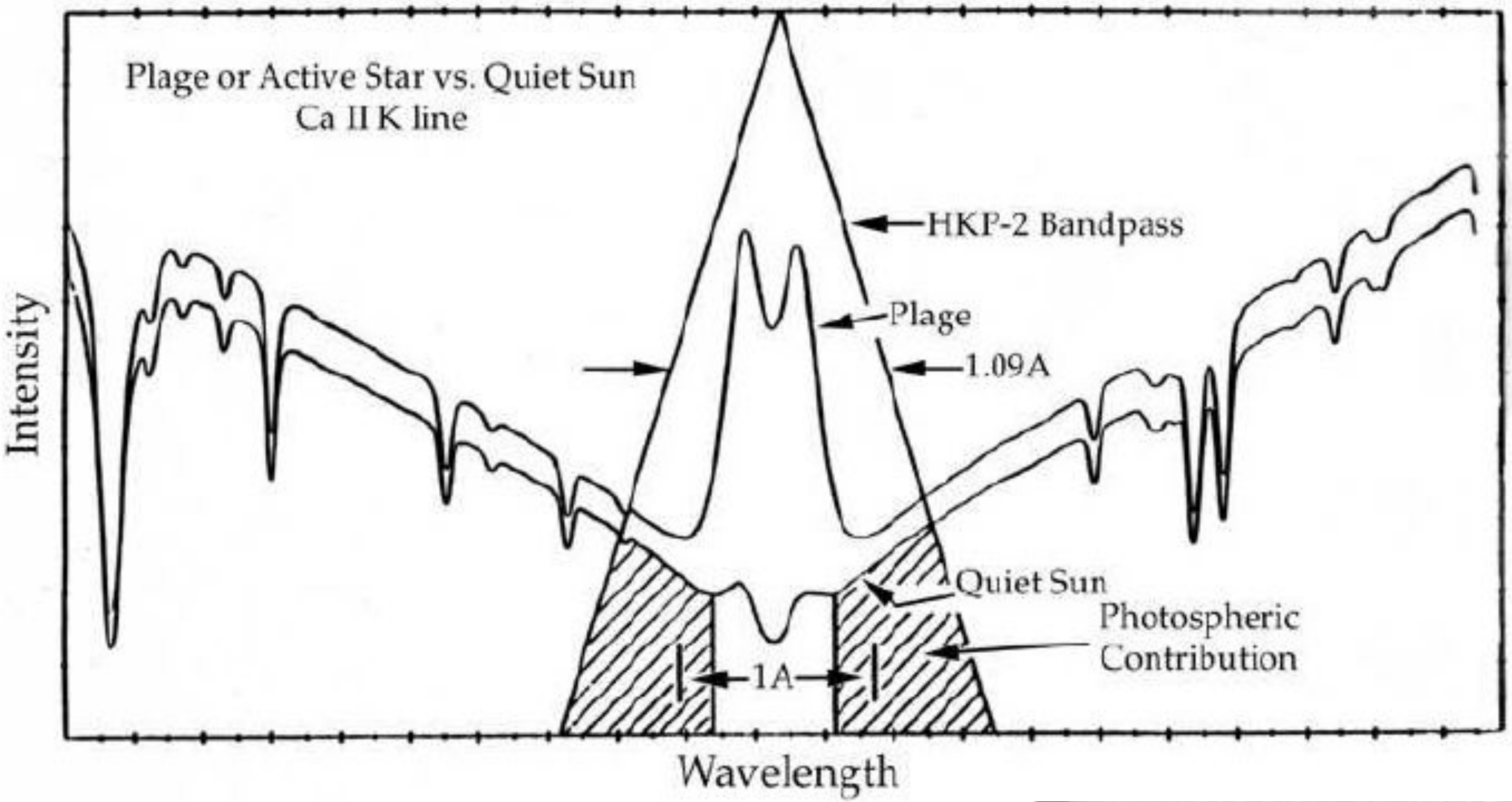


FIGURE 11.39 The light curve of BD + 26°730, a BY Dra star. SAO 76659 is a nearby reference star. (Figure from Hartmann et al., *Ap. J.*, *249*, 662, 1981.)

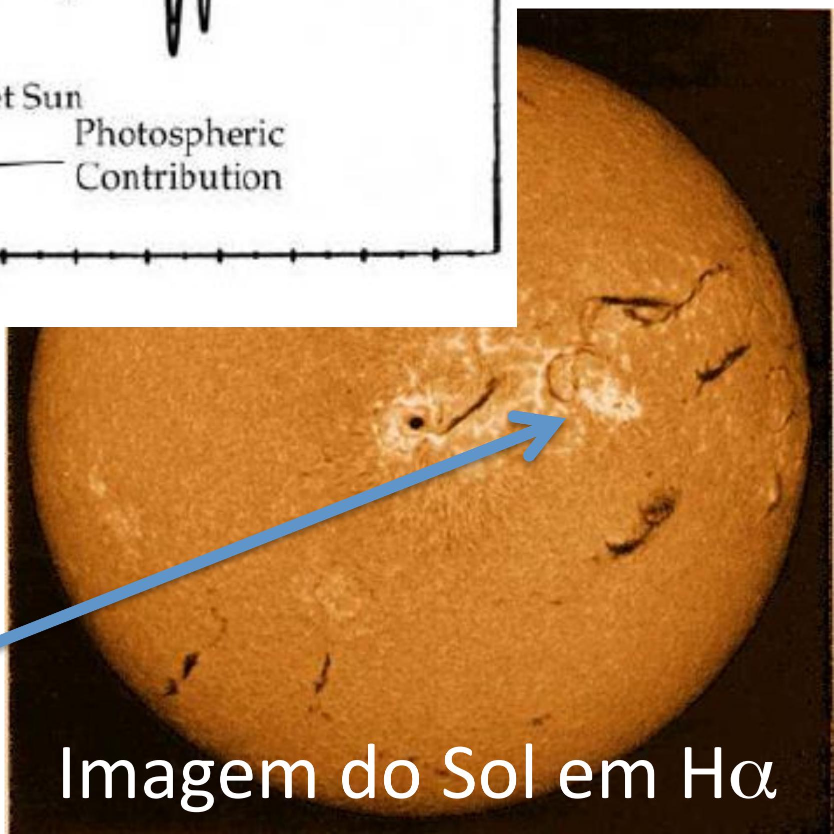
Em estrelas como o Sol (HD 146233 = HIP 79672), as variações do ciclo de atividade podem ser estudadas usando o índice cromosférico *S*



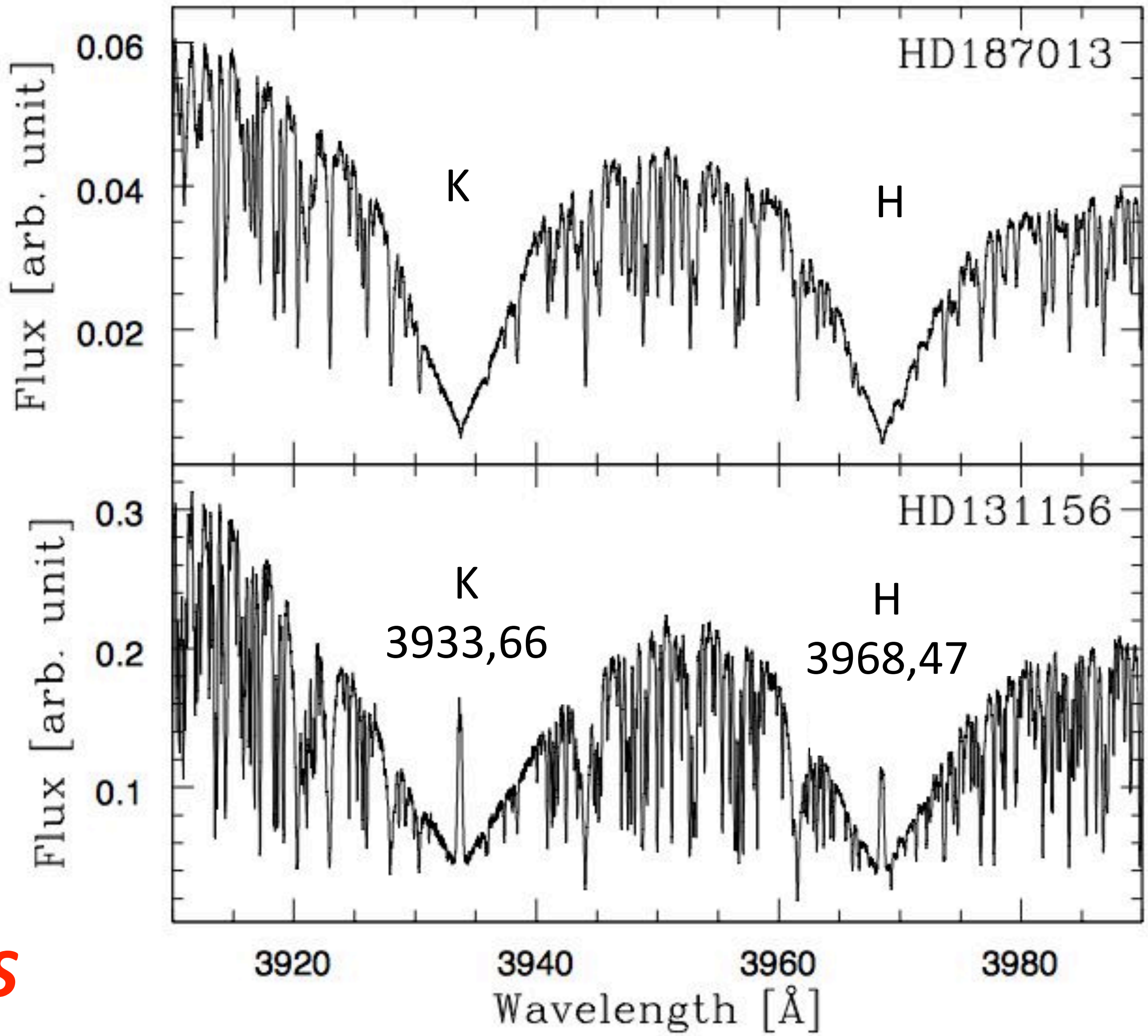
Linha de **absorção fotosférica** e **emissão cromosférica** (no *plage*) da linha K do Ca II



Plage: emissão brilhante na cromosfera



Estrelas ativas apresentam **emissão cromosférica** no centro das linhas H e K do CaII.



Medida da emissão nas linhas H e K → índice cromosférico *S*

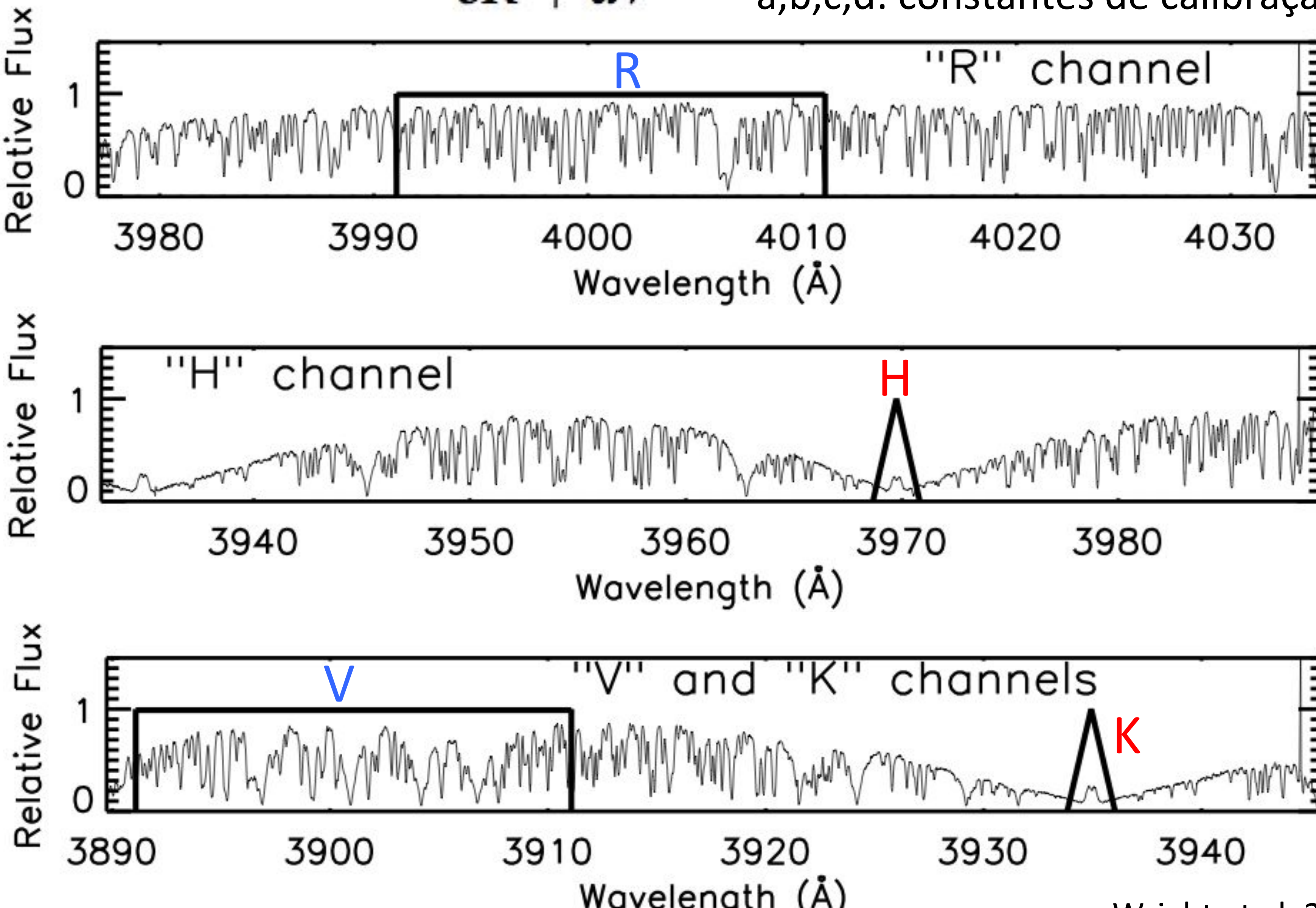
Boisse et al. 2010 A&A 523, A88

Fig. C.1. Two SOPHIE spectra of the region of the CaII H and K lines between 3900 and 4000 Å. *Bottom*: Active star. *Top*: Non active star.

Índice S:

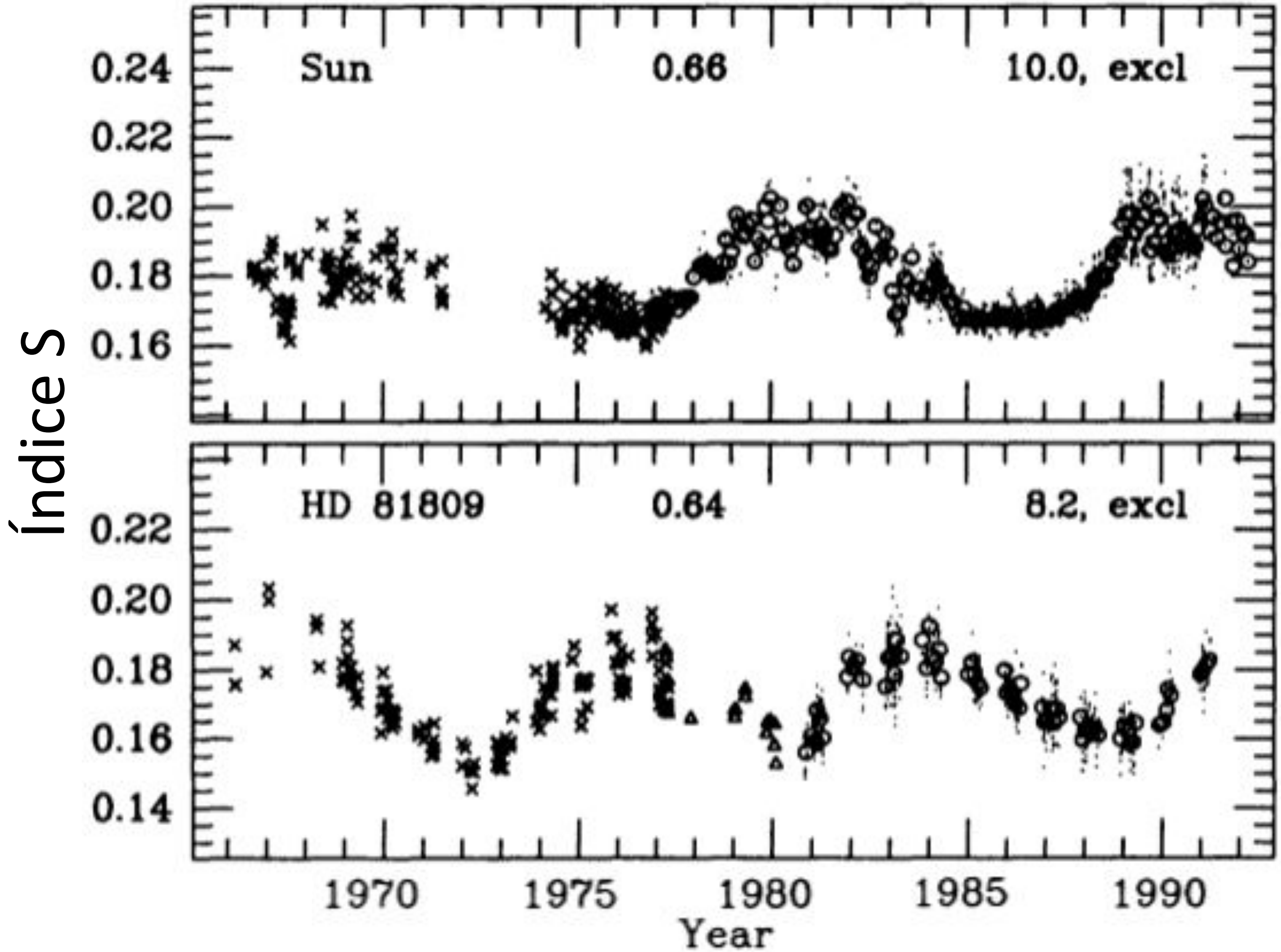
$$S = \frac{a\mathrm{H} + b\mathrm{K}}{cR + dV}$$

H, K: fluxo nas bandas das linhas
R, V: fluxo nas bandas de contínuo
a,b,c,d: constantes de calibração



Wright et al. 2004

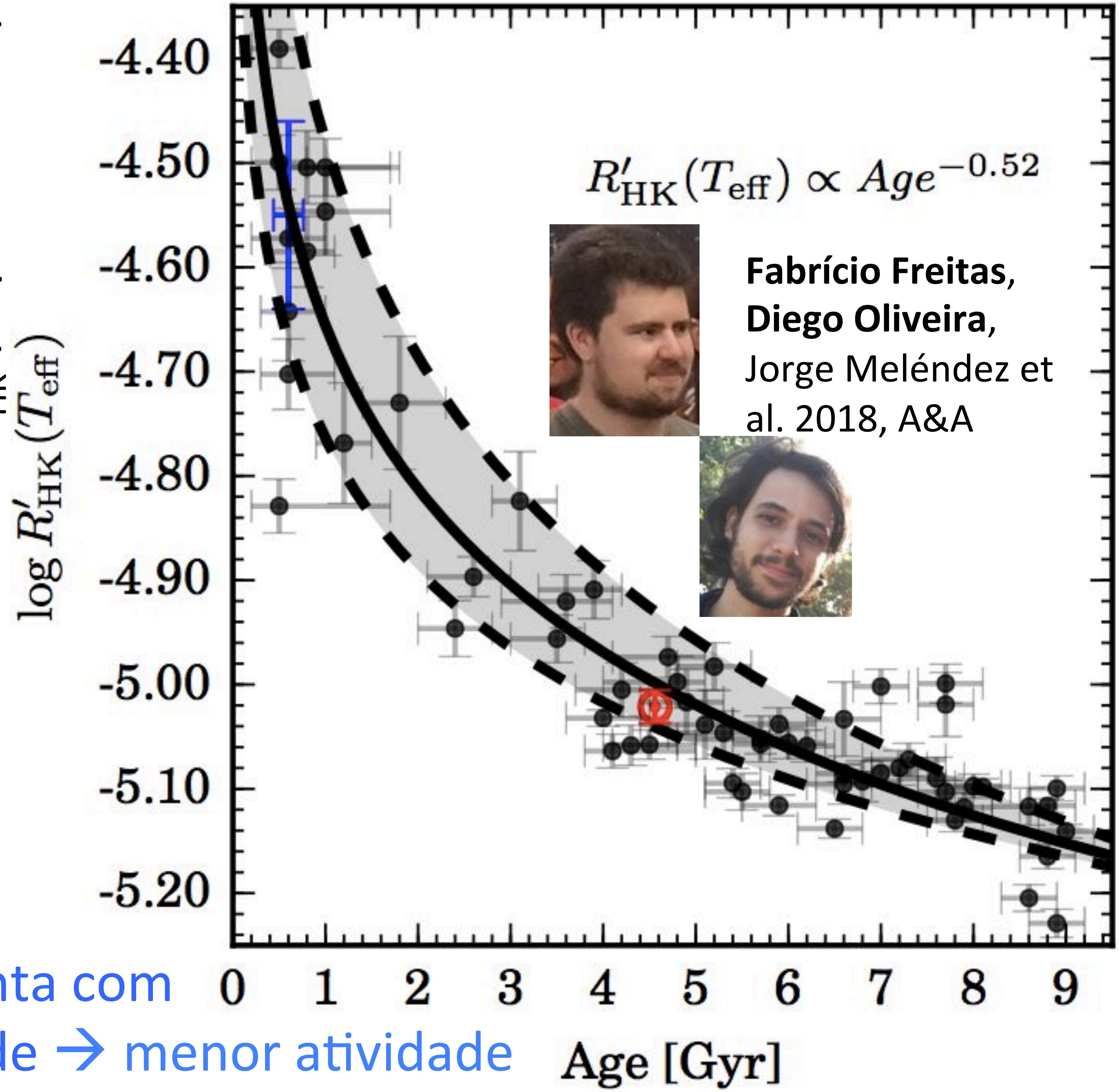
Ciclo de atividade usando o índice cromosférico *S*



Baliunas et al. 1995 ApJ 438, 269

Variações de atividade estelar em gêmeas solares na sequência principal (escala de bilhões de anos).

Índice de atividade R'_{HK} (depende do S)



Fabrício Freitas, **Diego Oliveira**, Jorge Meléndez et al. 2018, A&A

Rotação mais lenta com aumento da idade → menor atividade

No índice R'_{HK} a contribuição fotosférica é subtraida → mais sensível à atividade cromosférica

Diferentes escalas de atividade estelar (dia – anos – bilhões de anos)

- Flutuações rápidas (< 1 dia), explosões (*flares*), proeminência solar eruptiva, ejeção de massa coronal (CME)
- Ciclo de atividade estelar (~ anos), como o ciclo de 11 anos do Sol.
- Diminuição da atividade durante a sequência principal (escalas de milhões a bilhões de anos): estrelas jovens são muito ativas, estrelas velhas são mais calmas.

Provinha 10

1) Why the observed solar flux is higher at the maximum of the solar sunspot cycle

2) Explain briefly the 3 timescales of solar activity: (A) days, (B) 11 years, (C) billions of years

Extra slides

- More detailed cartoons on the evolution of the magnetic field during the magnetic activity cycle, from the paper by Sanchez et al. 2014, An. Acad. Bras. Ciênc. vol.86 no.1:

A mean-field Babcock-Leighton solar dynamo model with long-term variability

http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0001-37652014000100011

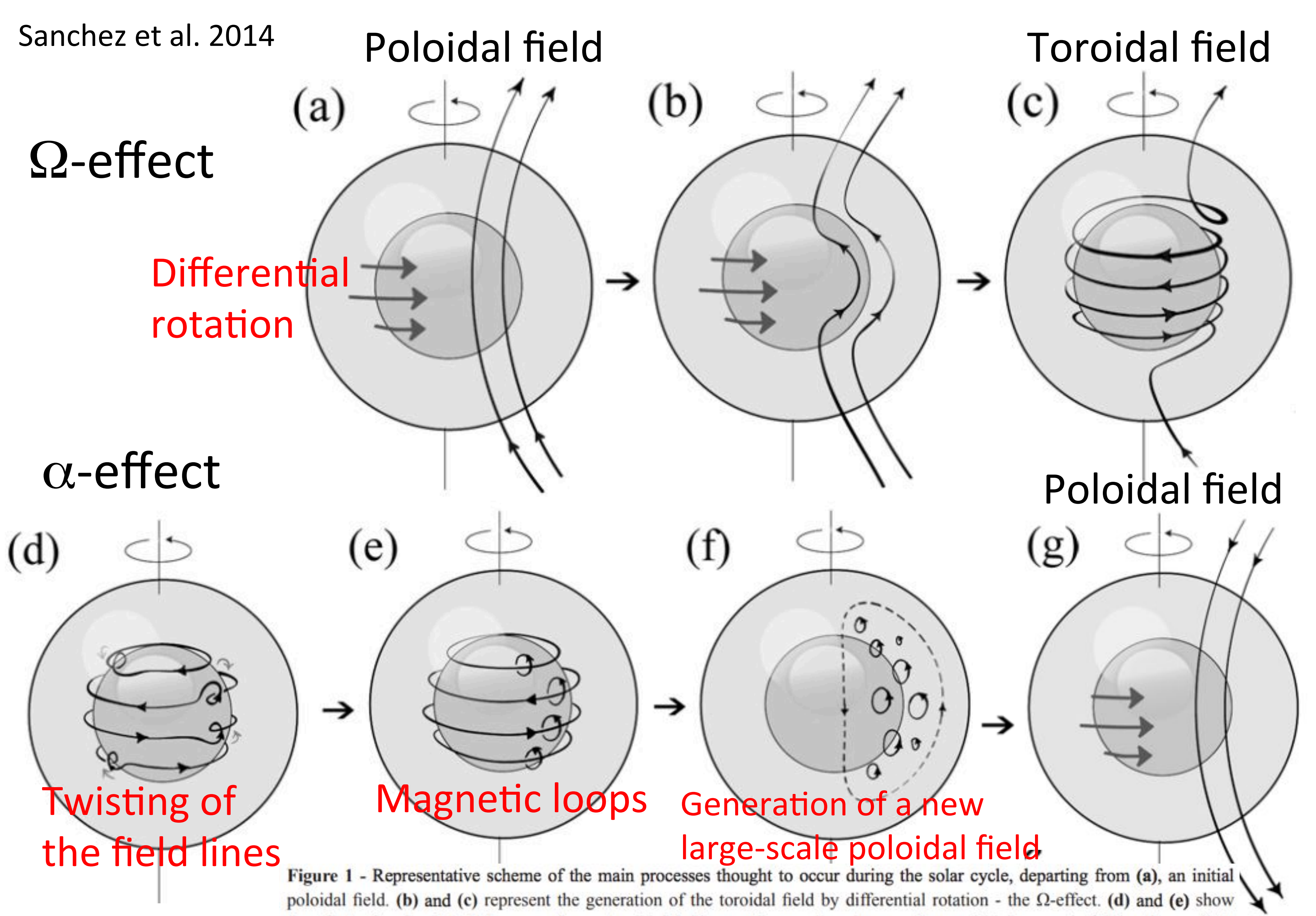
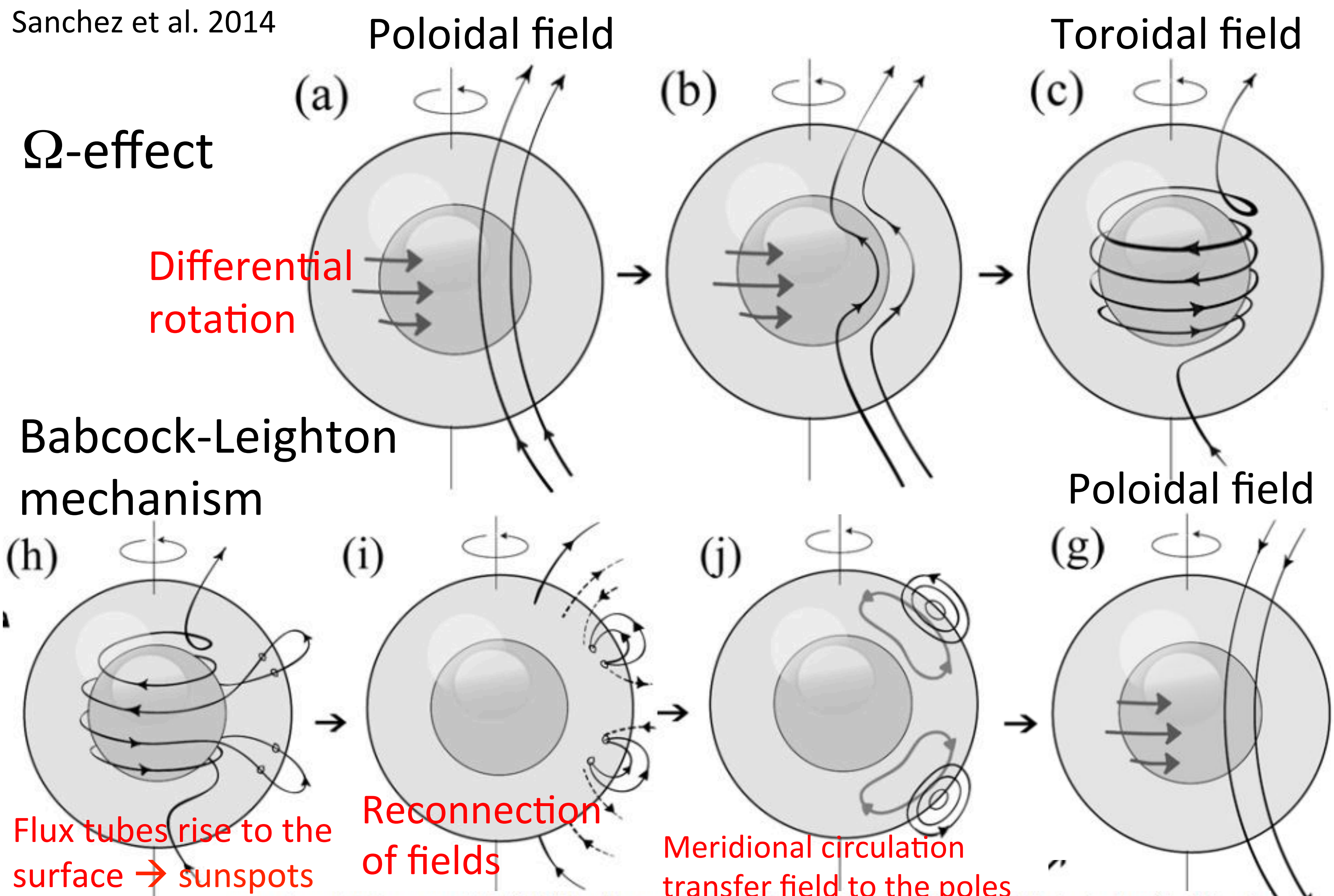


Figure 1 - Representative scheme of the main processes thought to occur during the solar cycle, departing from **(a)**, an initial poloidal field. **(b)** and **(c)** represent the generation of the toroidal field by differential rotation - the Ω-effect. **(d)** and **(e)** show the effect of cyclonic turbulence on former toroidal fields, creating small-scale secondary poloidal magnetic fields - the *α*-effect. Averaged, they result in a net electromotive force generating a new large-scale poloidal field **(f)**, closing the first half part of the magnetic cycle with a new poloidal field **(g)**, with opposite polarity than the initial one. **(h) represents the beginning of the Babcock-**



magnetic cycle with a new poloidal field **(g)**, with opposite polarity than the initial one. **(h)** represents the beginning of the Babcock-Leighton mechanism: toroidal flux tubes buoyantly rise to the surface forming sunspots, tilted bipolar regions. In **(i)**, the fields from the bipolar regions diffuse and reconnect with each other and with the polar fields. The resulting poloidal flux is advected by **meridional circulation to the poles (j)**, generating the final large-scale poloidal field in **(g)**.