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

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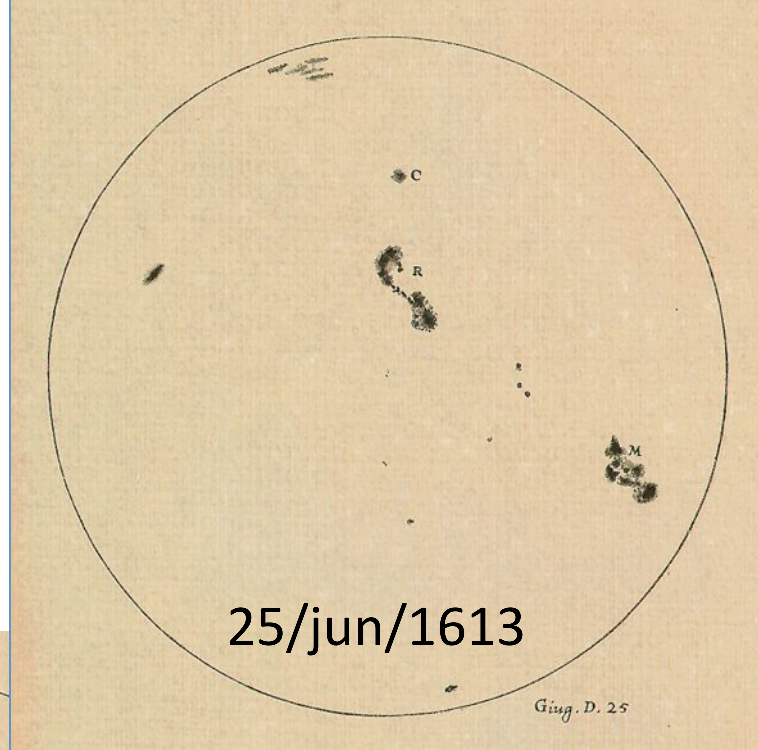
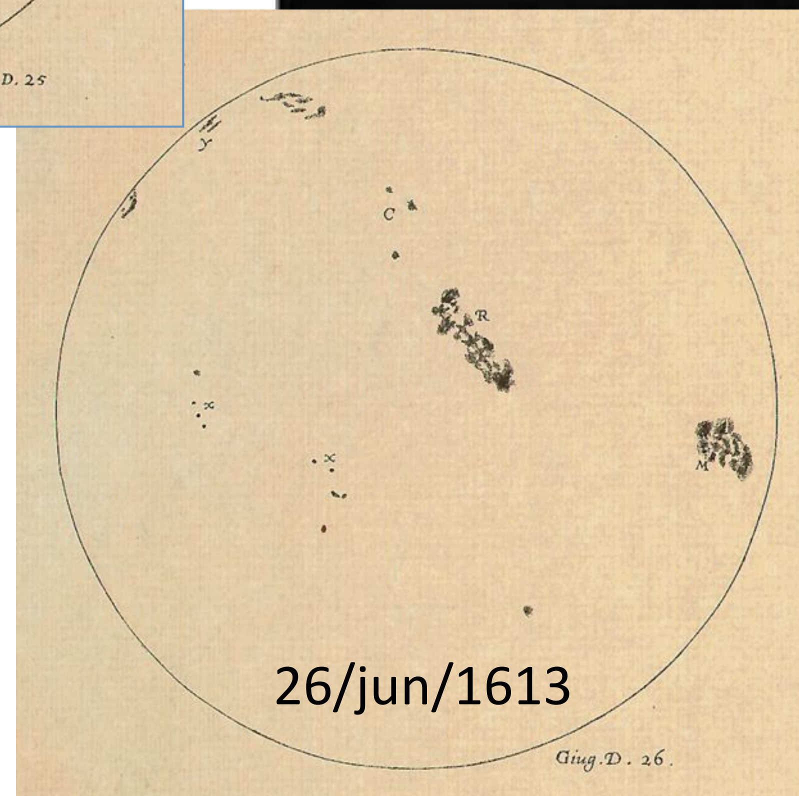
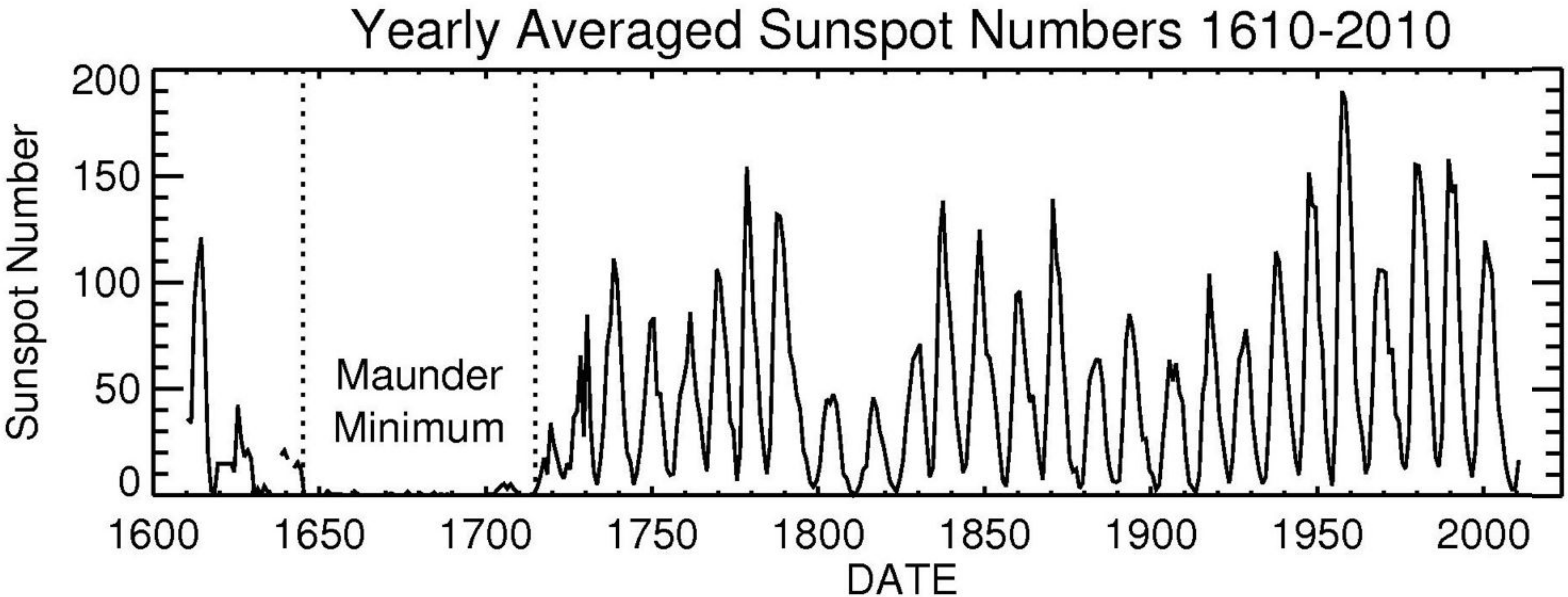
Manchas solares observadas por Galileu em 1613



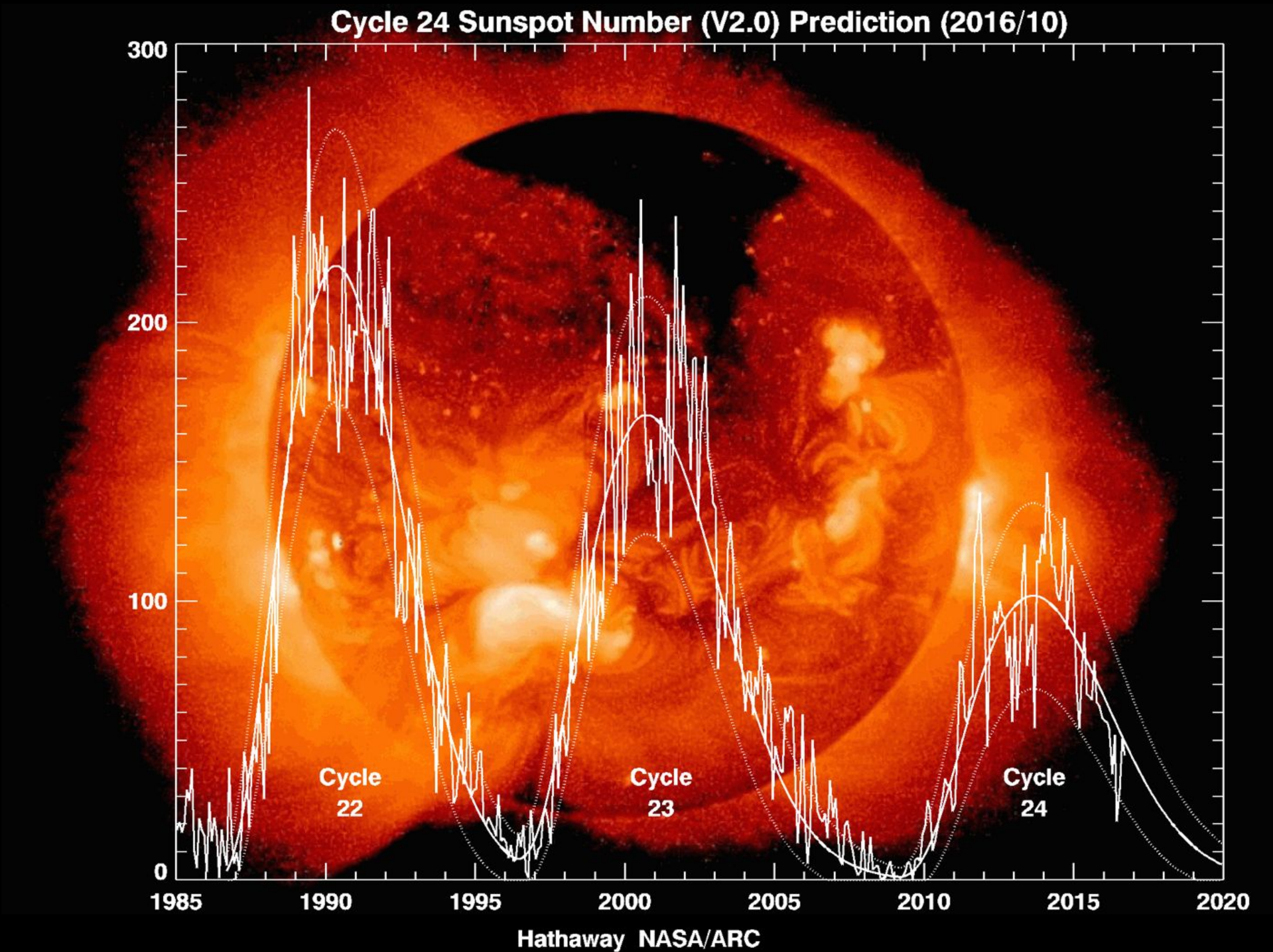


http://galileo.rice.edu/sci/observations/sunspot_drawings.html

Ciclo de manchas de ~ 11 anos



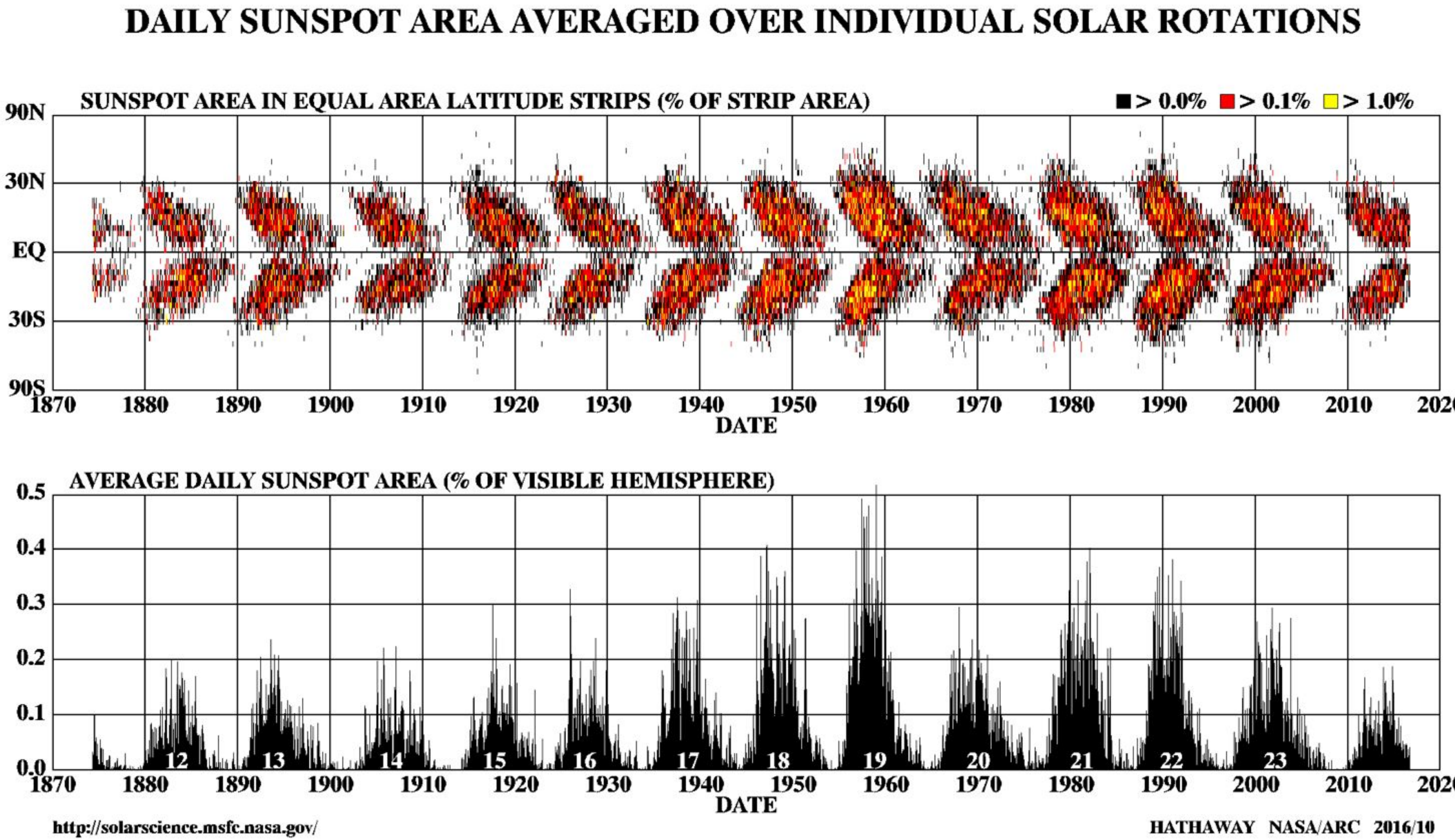
https://www.nasa.gov/mission_pages/sunearth/news/solarcycle-primer.html



https://solarscience.msfc.nasa.gov/predict.shtml

Butterfly diagram

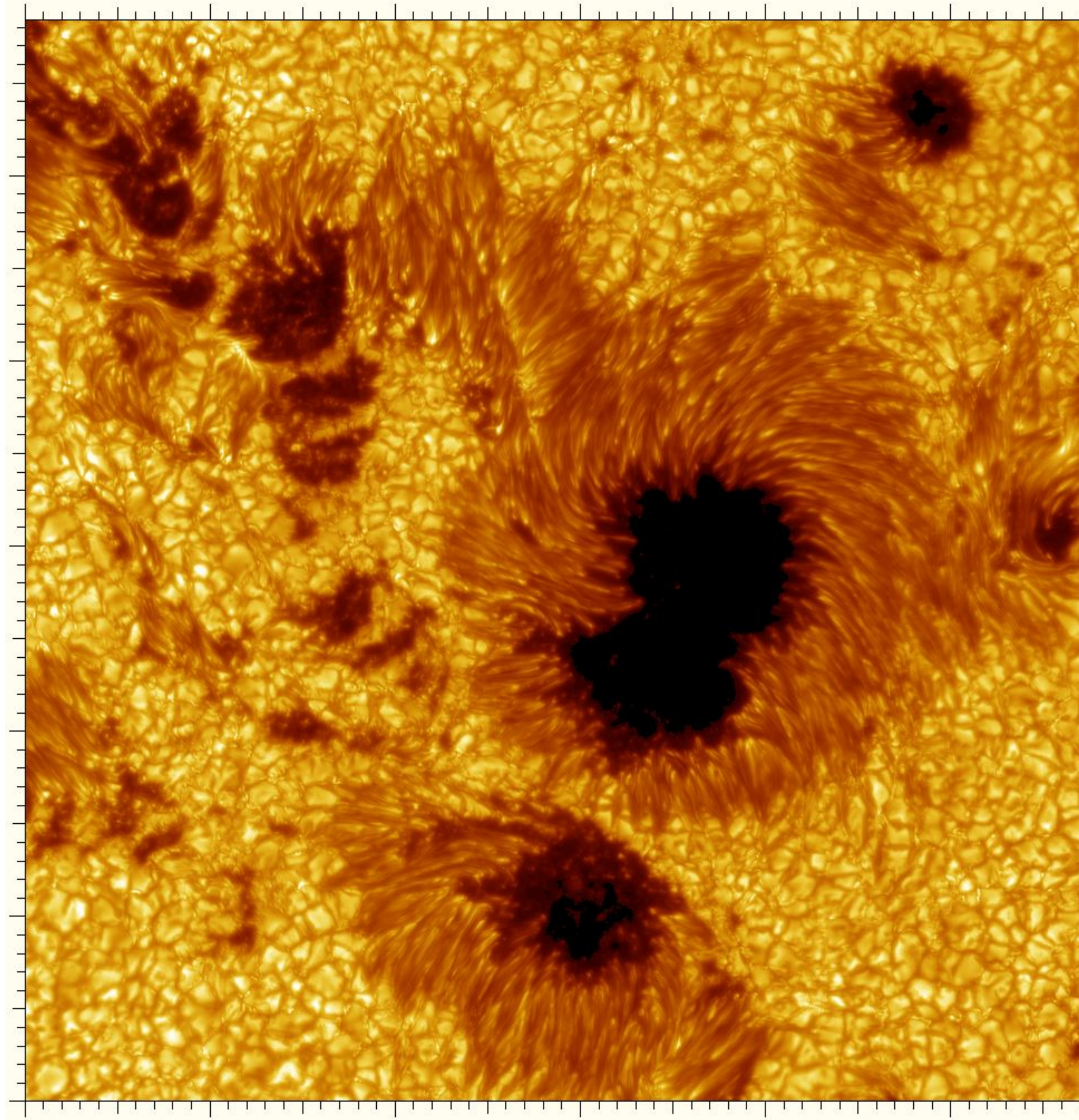
Começo do ciclo: altas latitudes ±40^0. Fim do ciclo: perto do equador



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

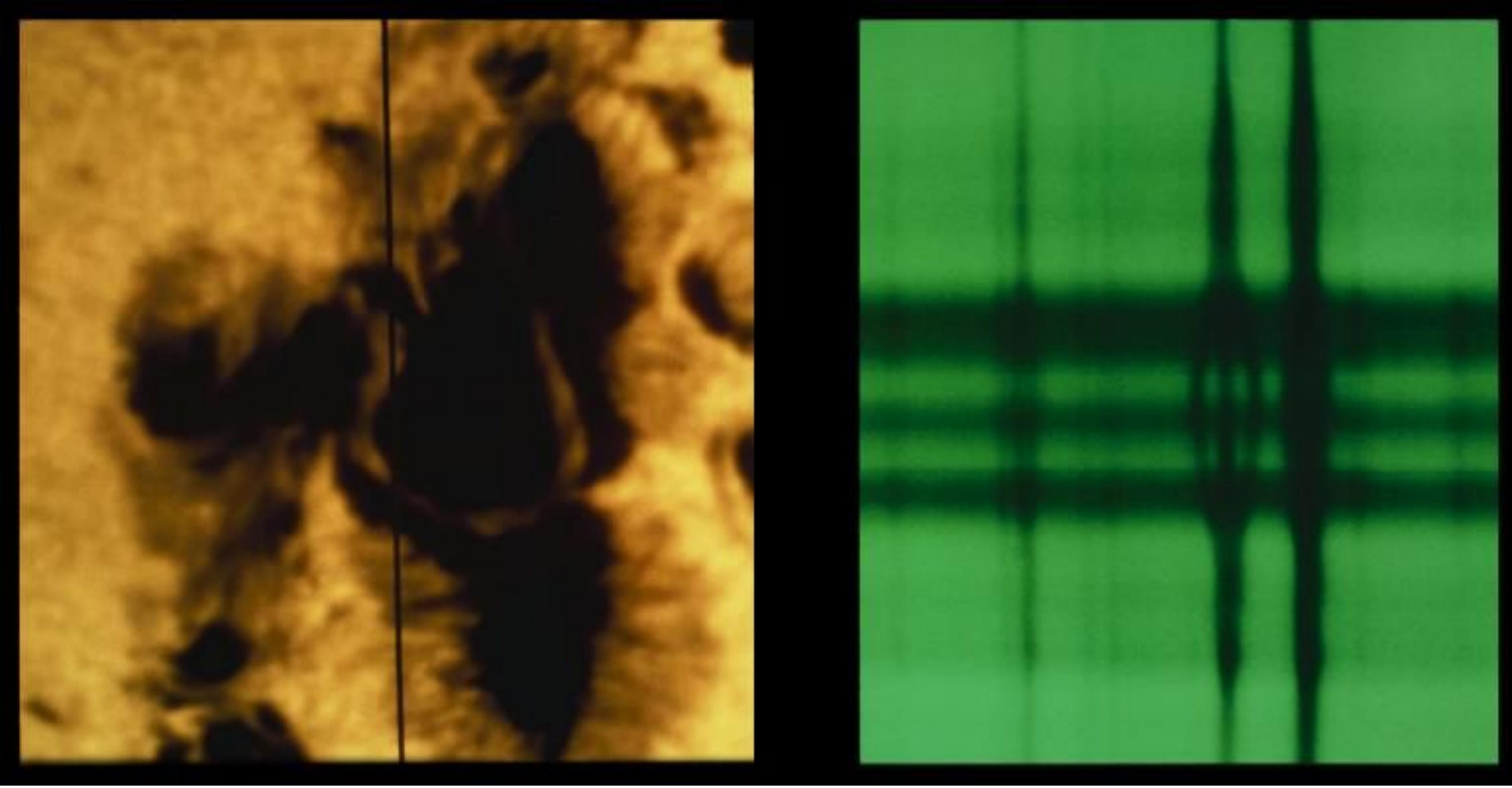
Umbra: região mais escura.

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



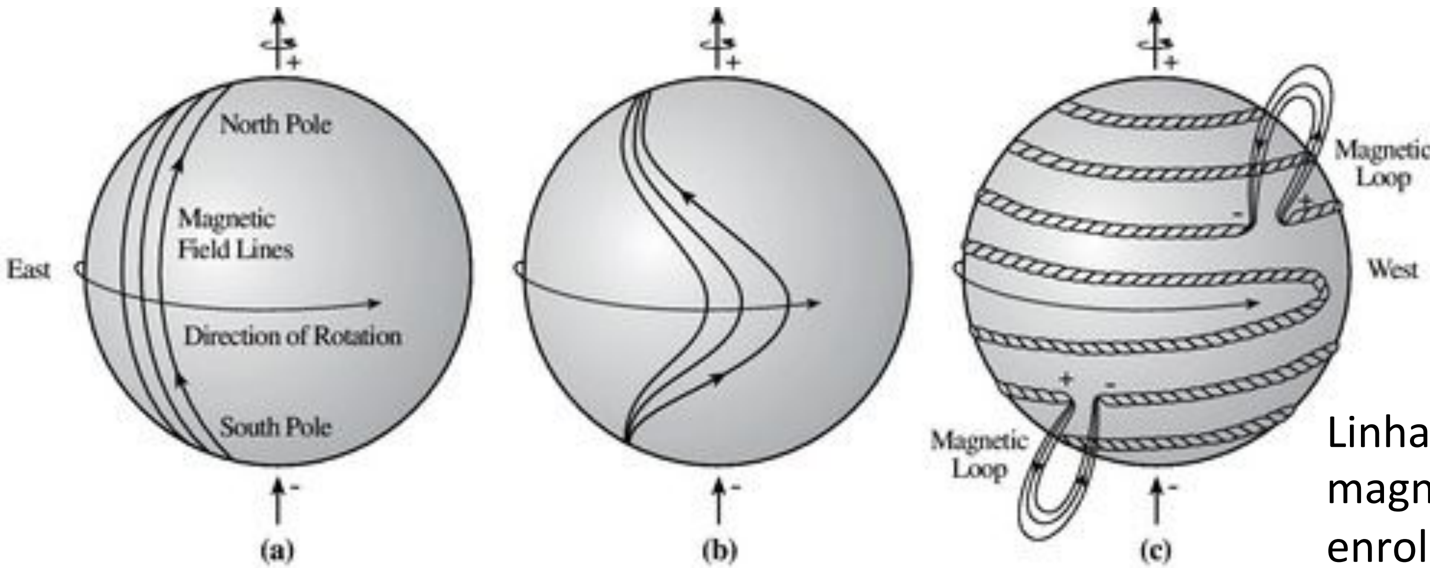
Nota: além dos grânulos, é possível observar algumas fáculas (pontos brilhantes)

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

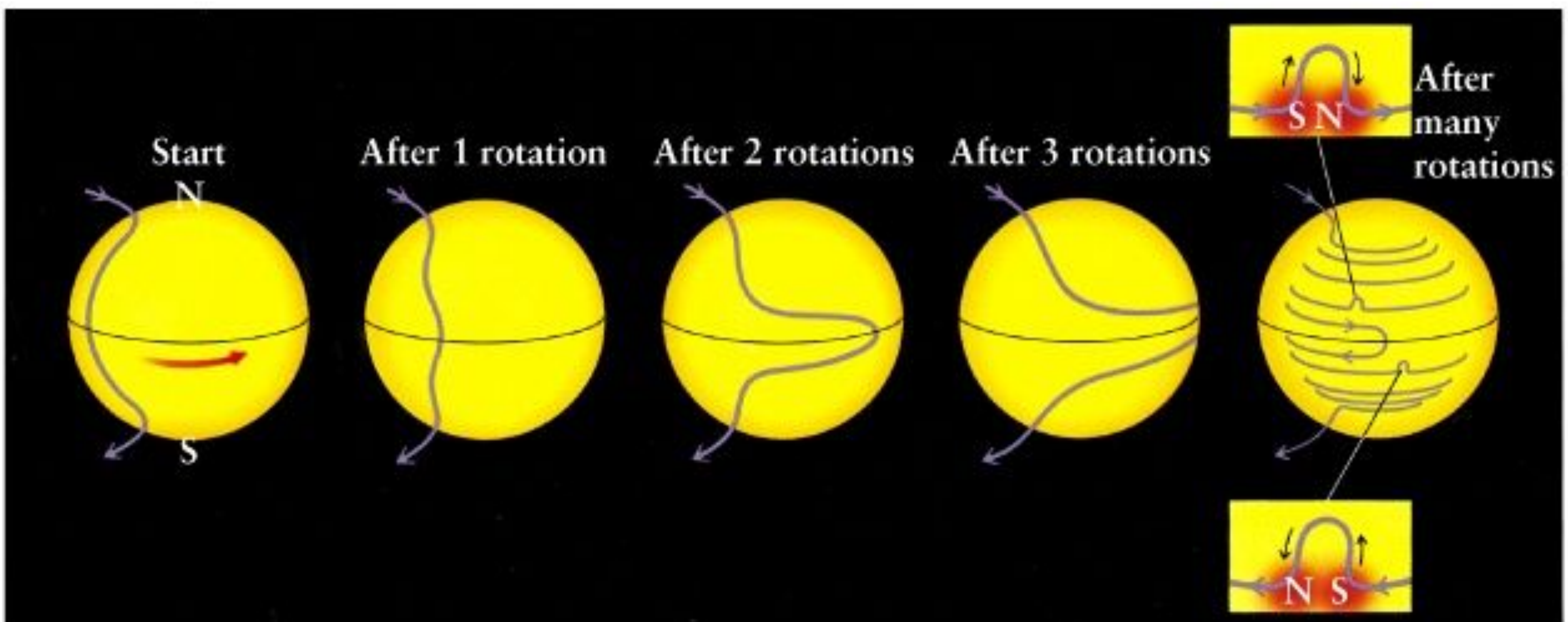


The vertical black line on the **left** indicates the location of the slit for the spectrograph which took the spectrum (**right**). The division of 1 spectral line into 3 demonstrates the Zeeman effect. The splitting of this iron line at 5250.2 Å, indicates a field strength of 4130 Gauss.

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

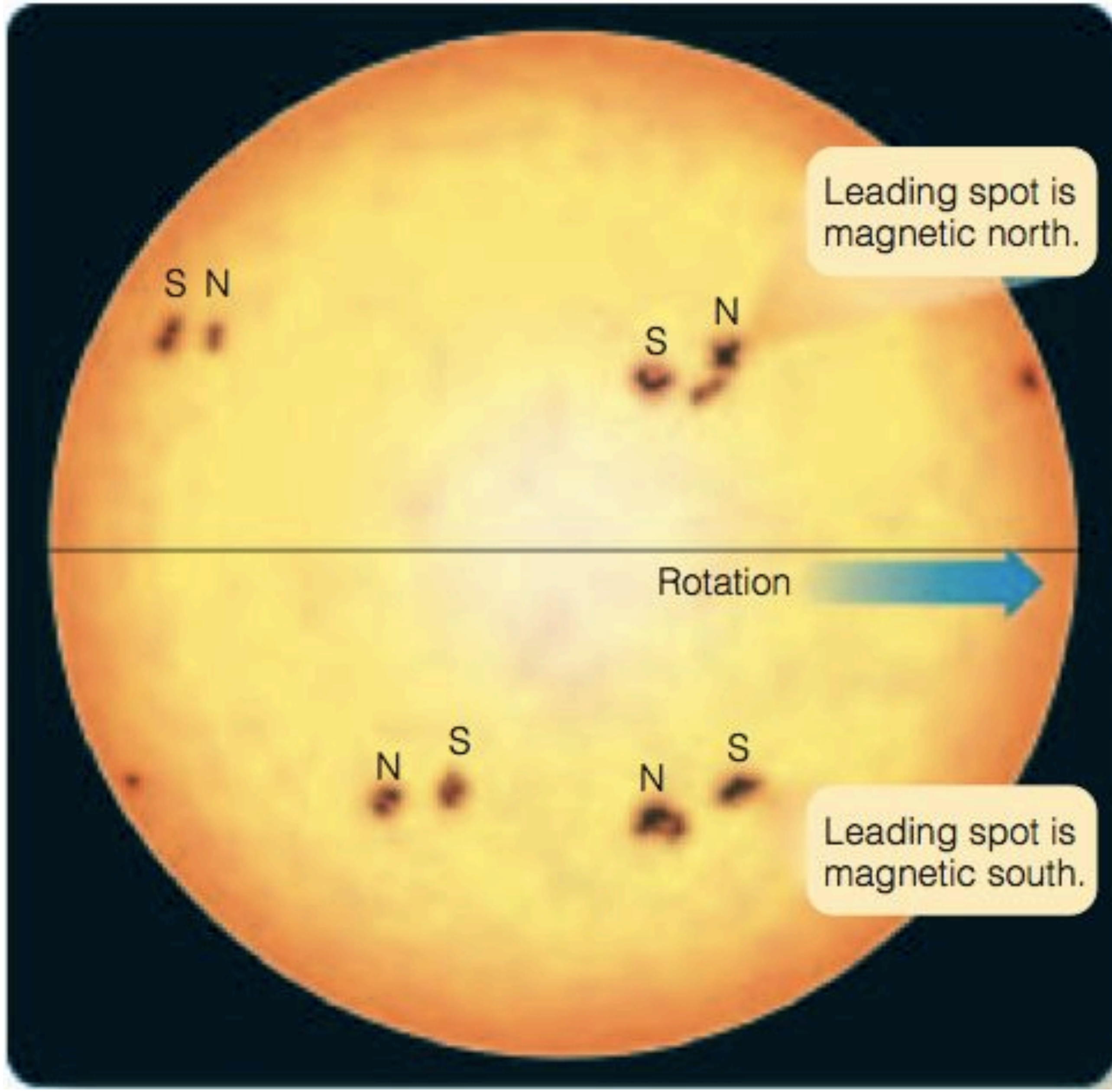


Linhas de campo magnético mais enroladas



http://www.math.nus.edu.sg/aslaksen/gem-projects/hm/0203-1-02-sunspots/sscyc.html

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

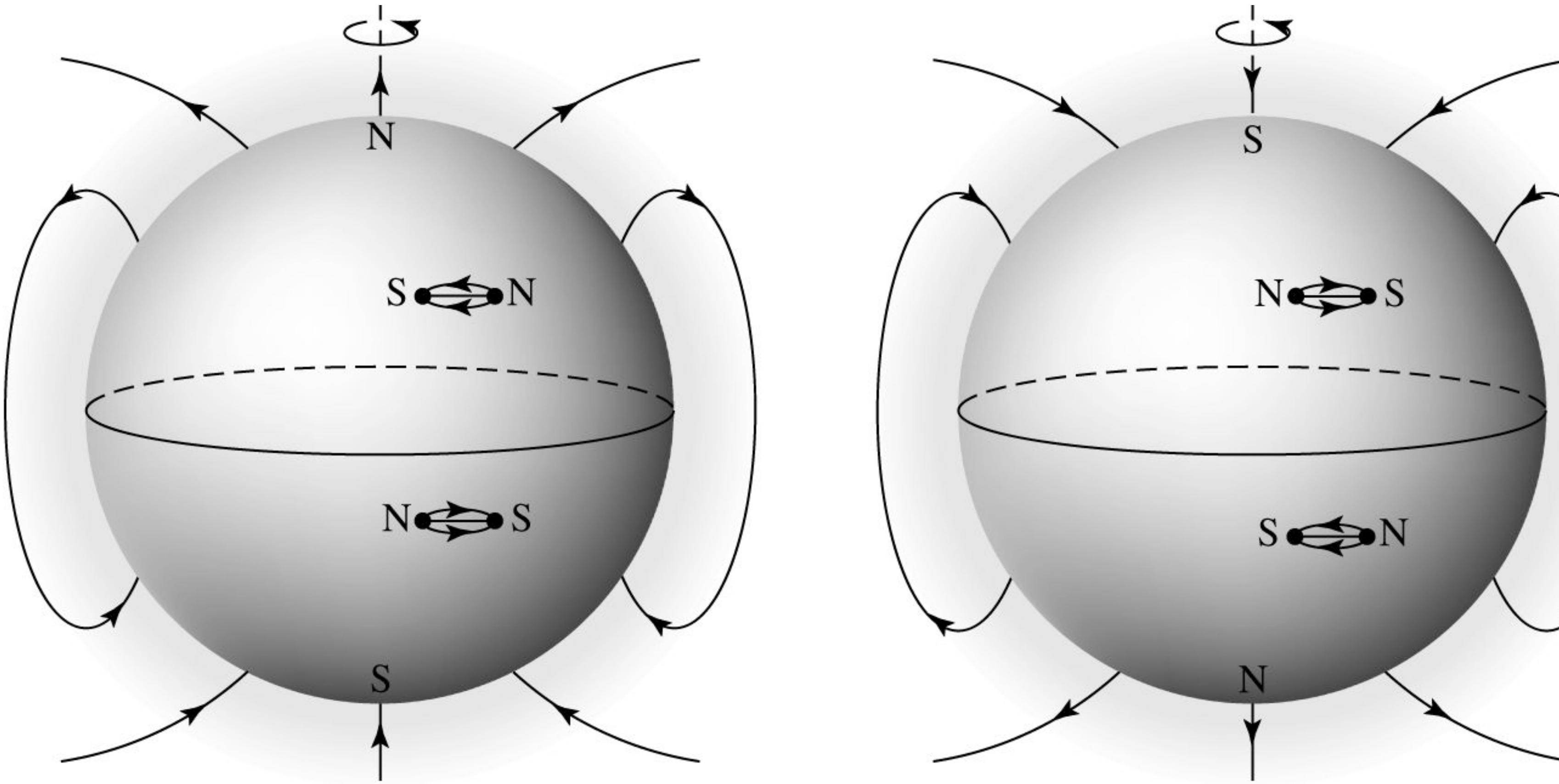
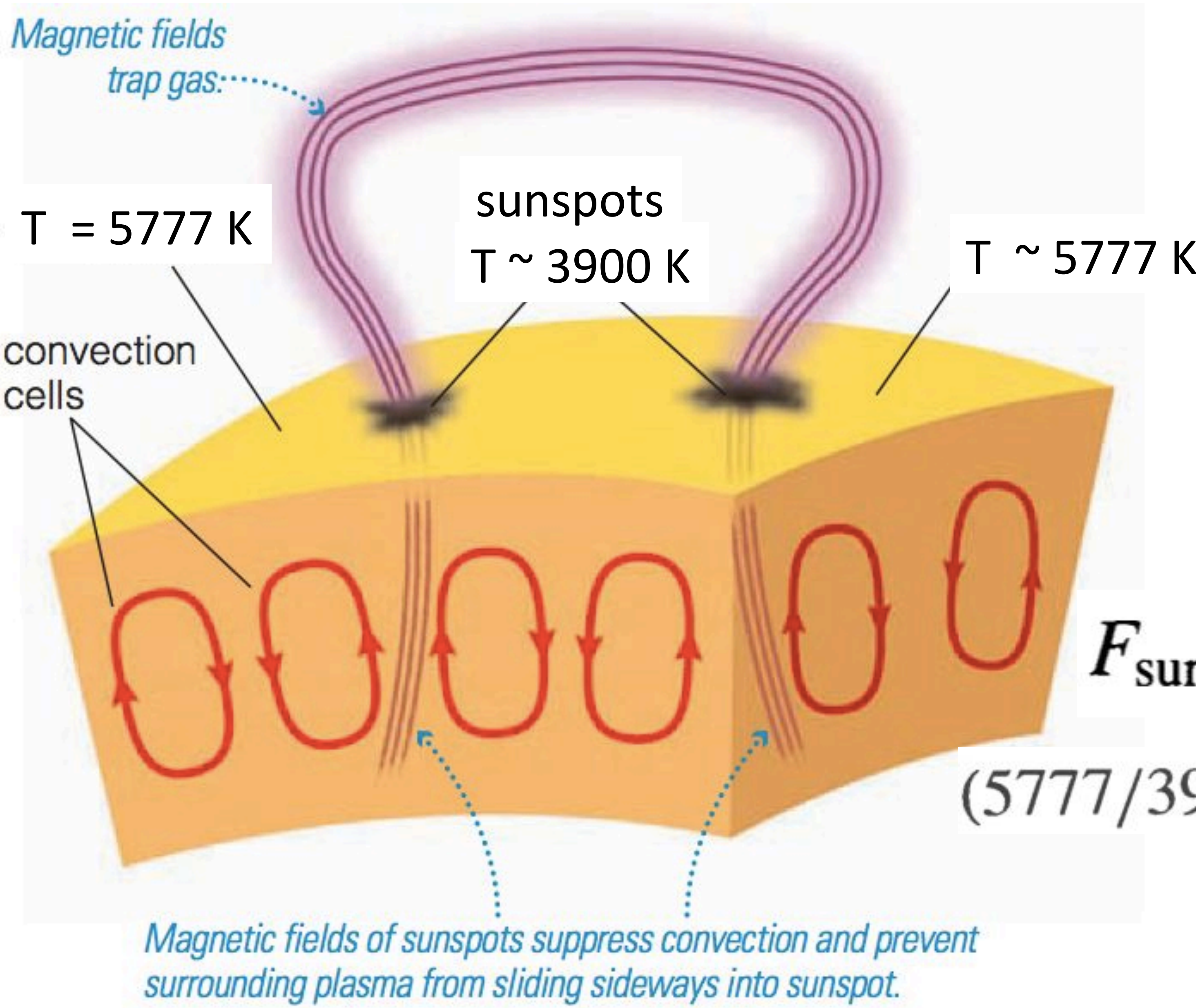


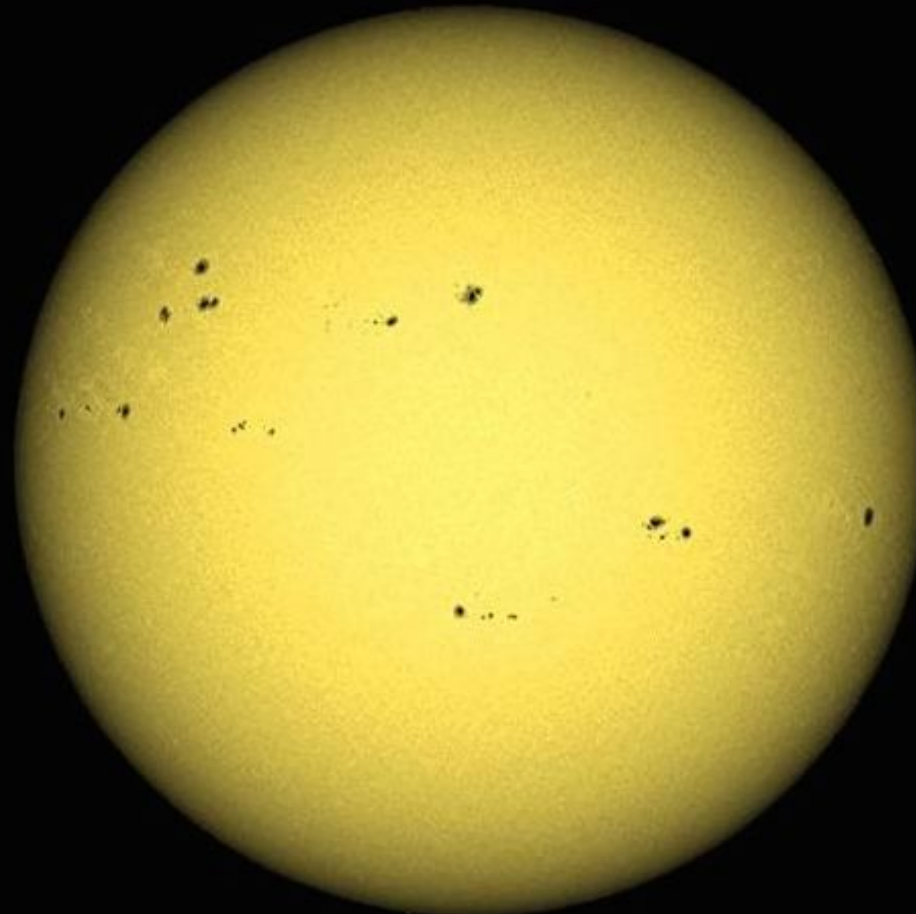
FIGURE 11.32 The global magnetic field orientation of the Sun, along with the magnetic polarity of sunspots during successive 11-year periods.



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

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

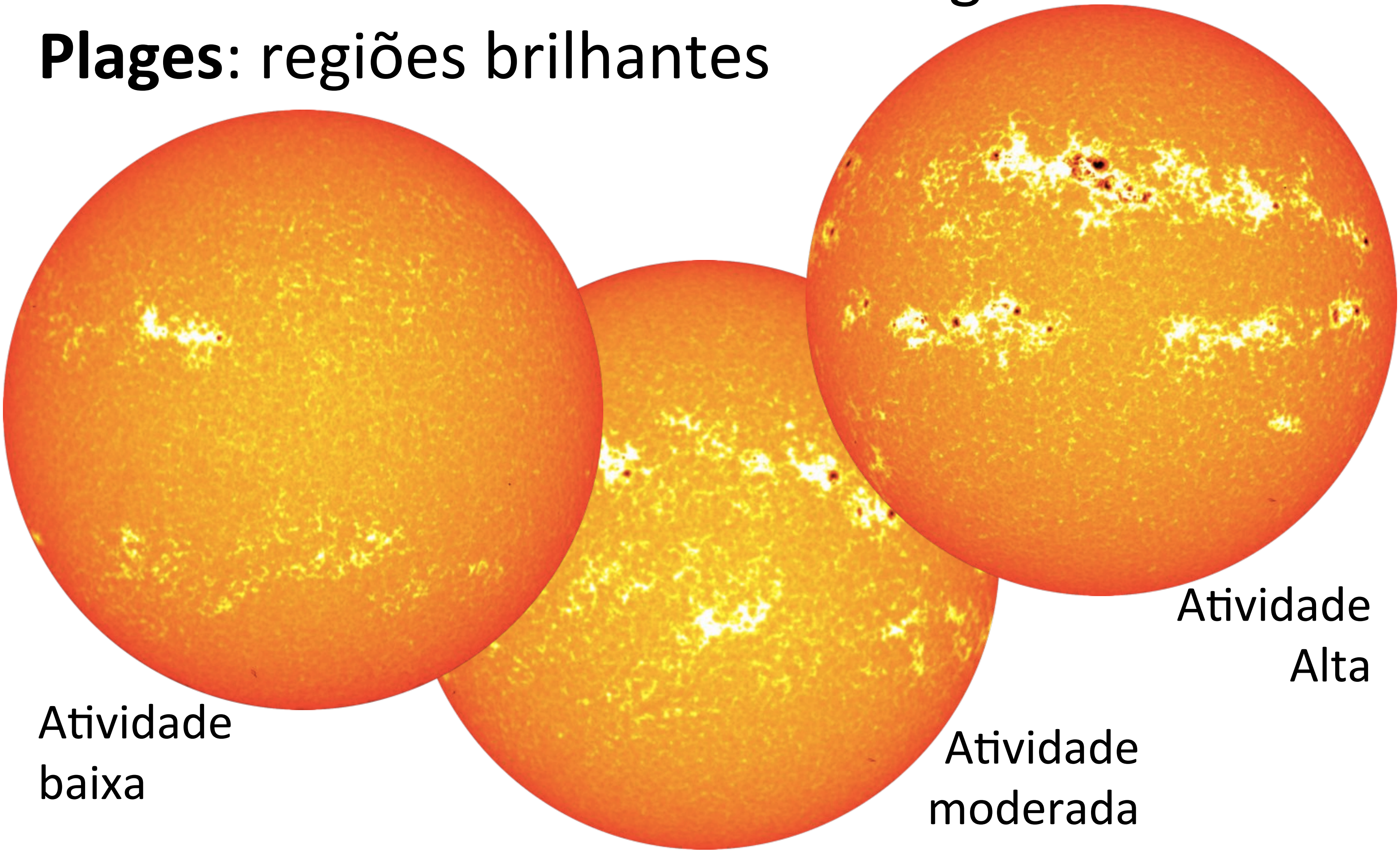
Sol no mínimo de atividade: sem manchas



Sol no máximo de atividade: maior número de manchas

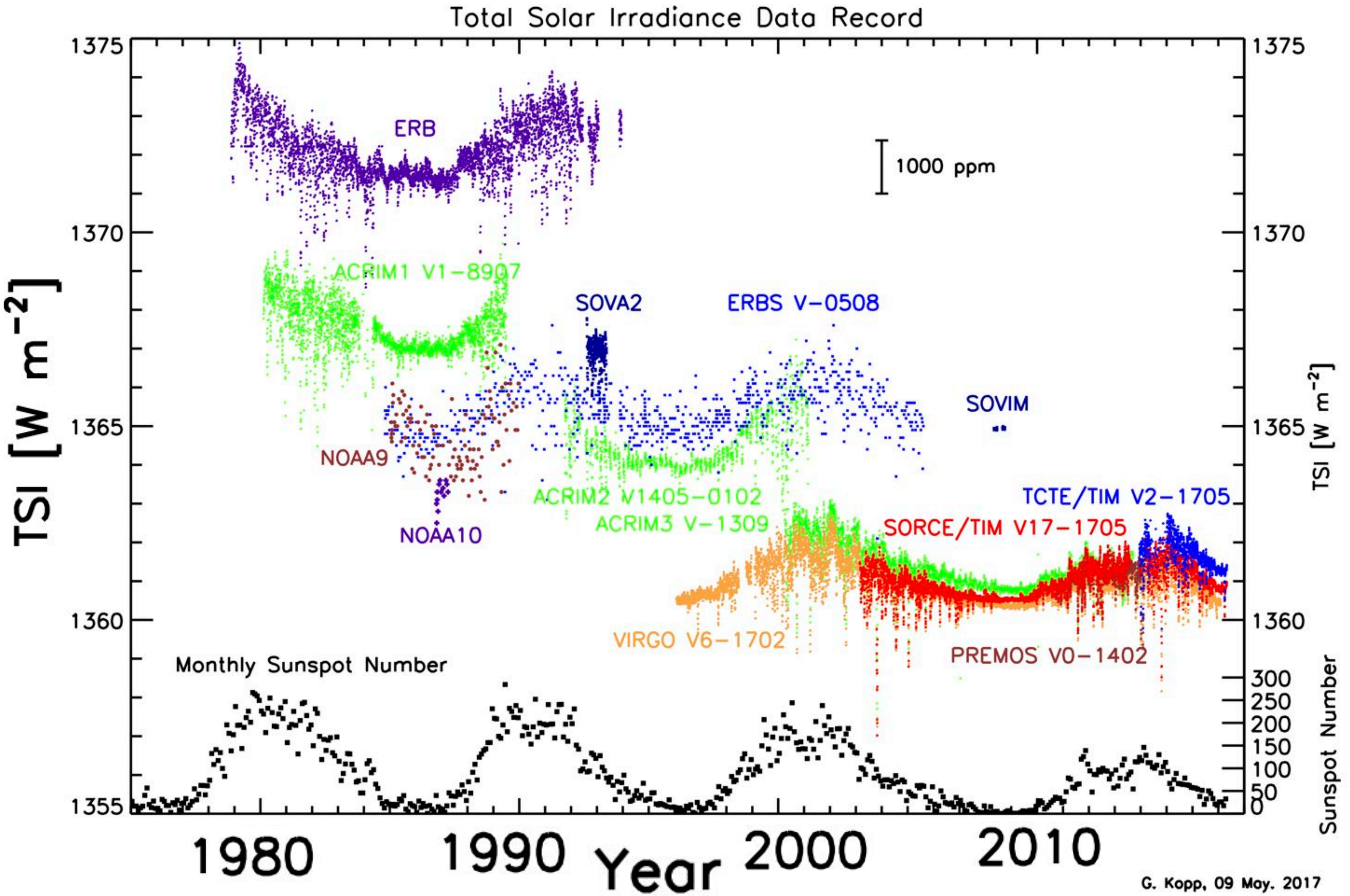
http://www.sciencemag.org/news/2011/06/end-sunspot-cycle

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



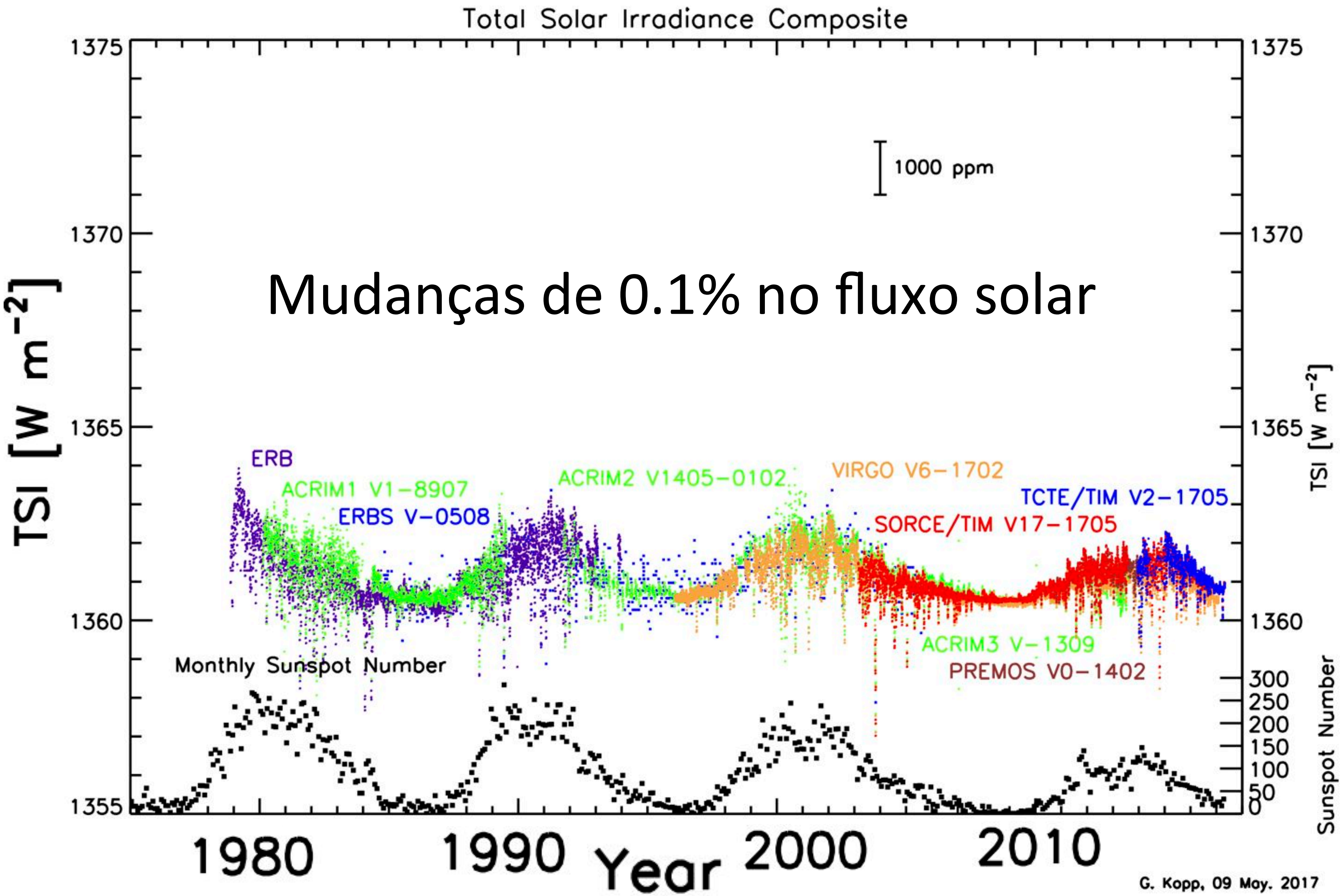
Views of the Sun showing different levels of activity. The color table has been altered to enhance faculae/plage (white regions) which are hotter than sunspots (red-black regions) and whose greater total area contribute to increasing the solar flux reaching the Earth. https://svs.gsfc.nasa.gov/2644

Irradiância Solar Total (TSI)



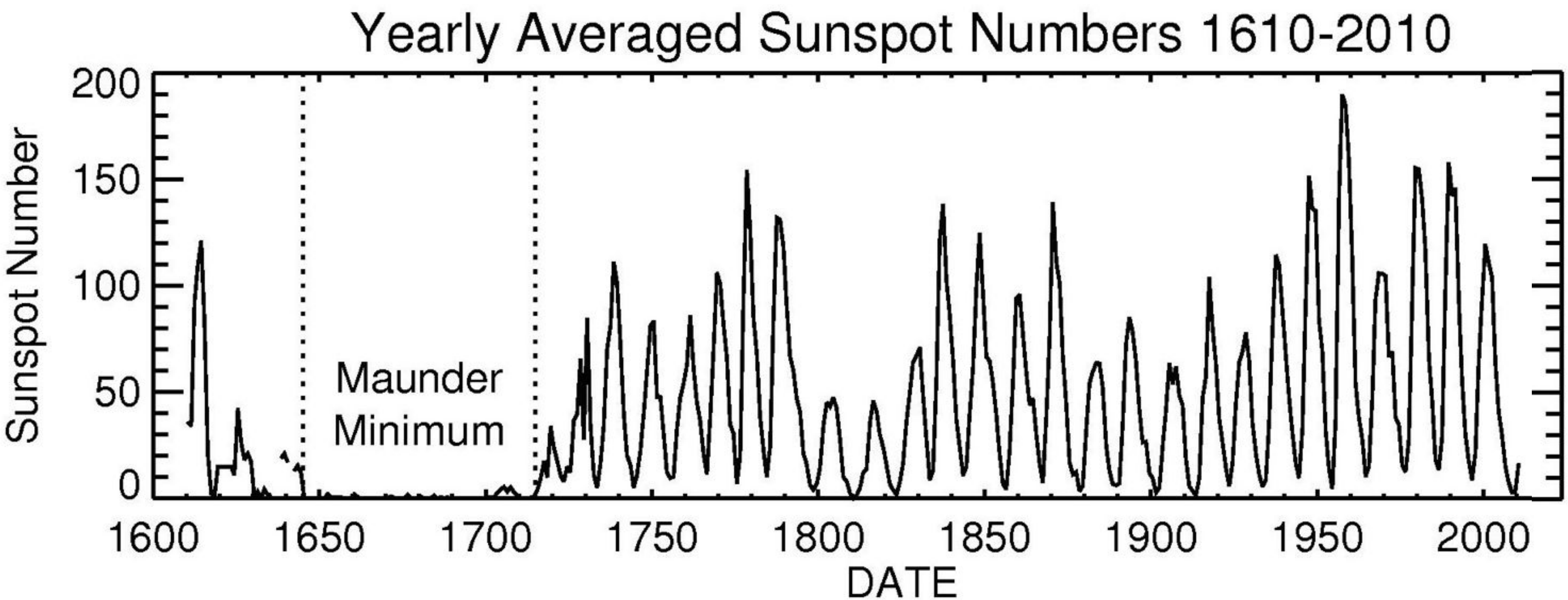
http://spot.colorado.edu/~koppg/TSI/

Irradiância Solar Total (TSI)

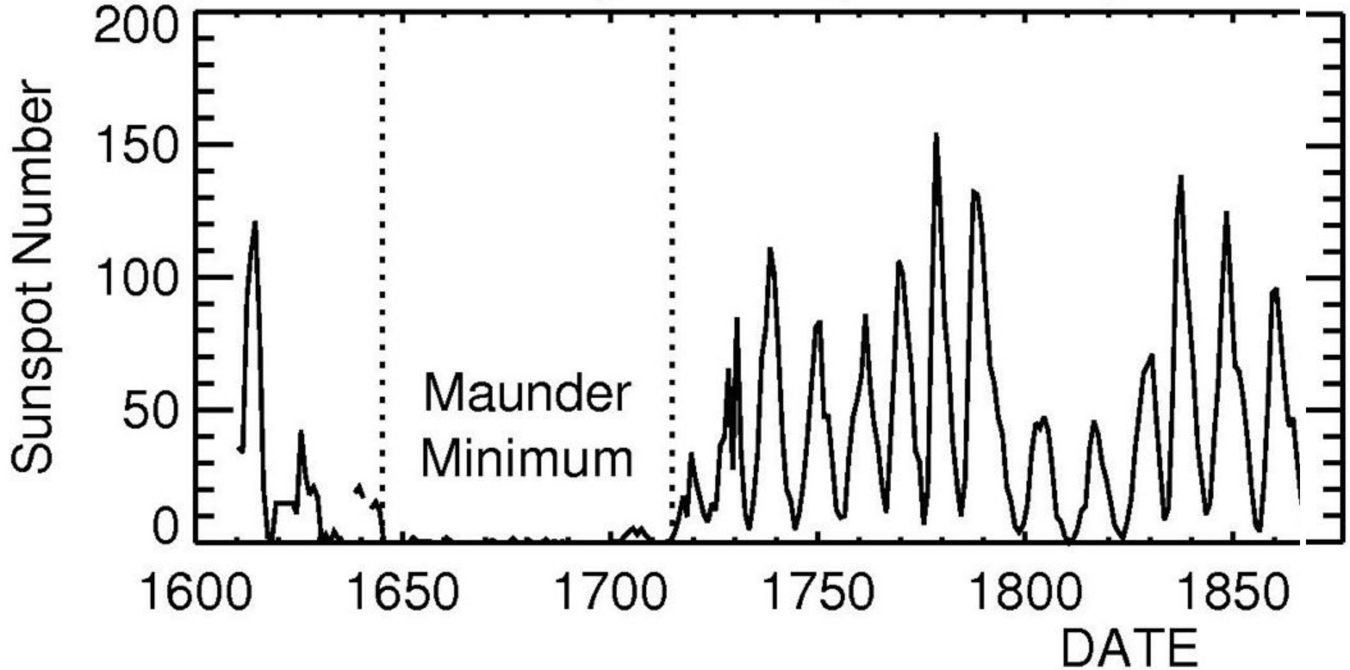


http://spot.colorado.edu/~koppg/TSI/

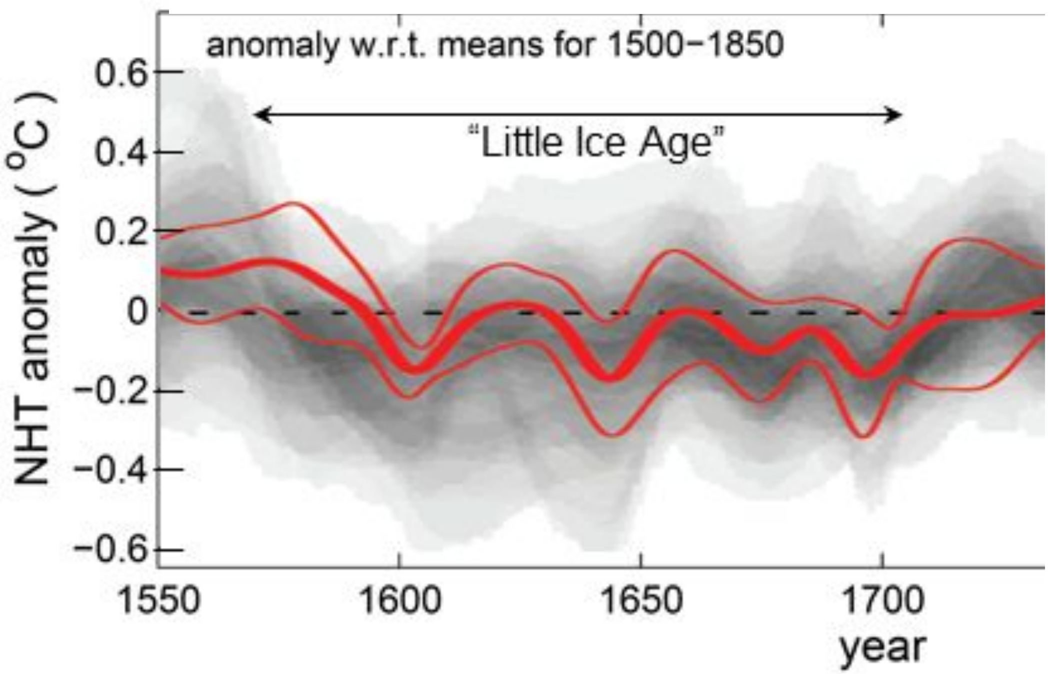
Mínimo de Maunder: entre 1645 e 1715 as manchas solares tornaram-se raras

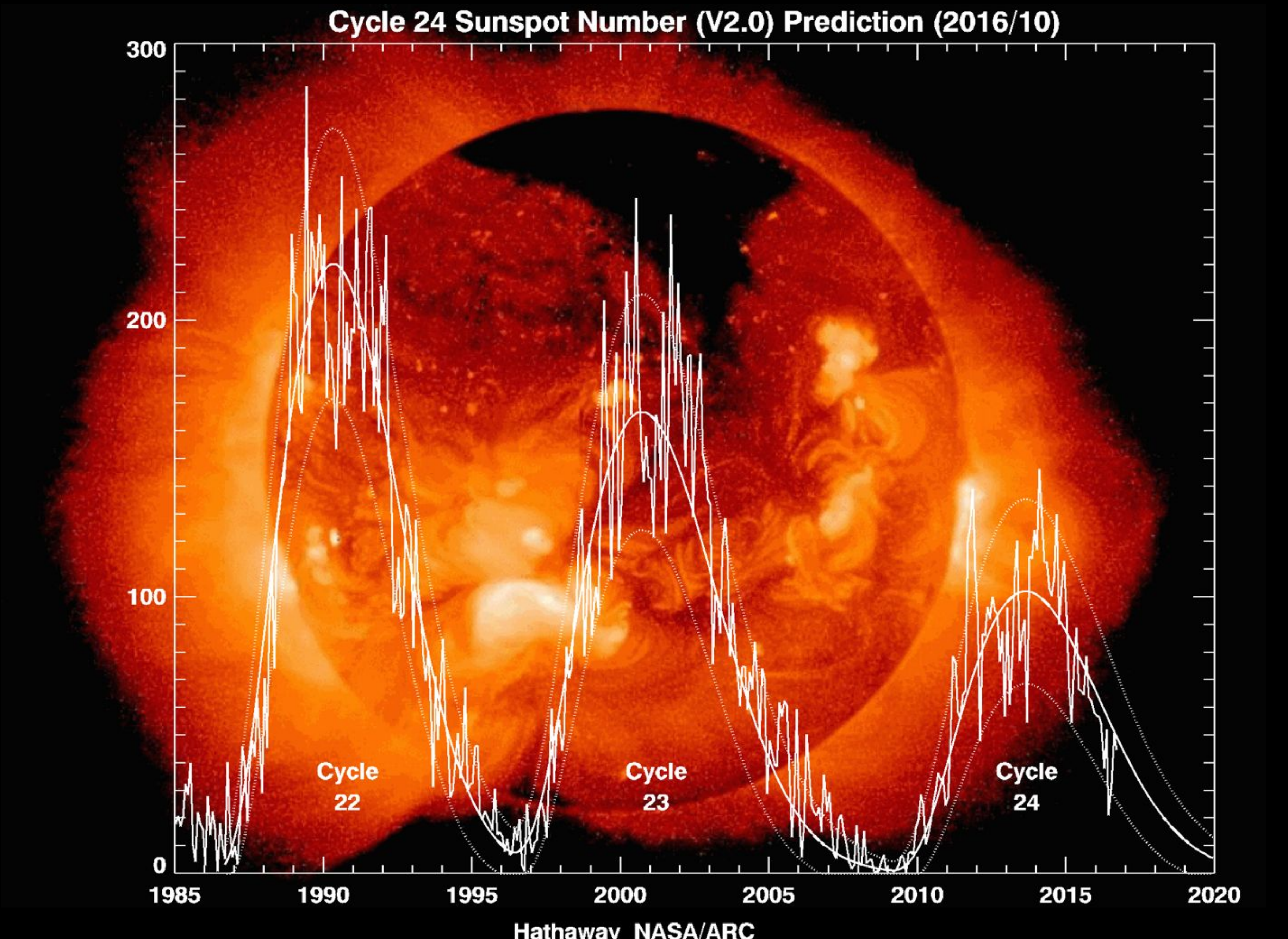


https://www.nasa.gov/mission_pages/sunearth/news/solarcycle-primer.html



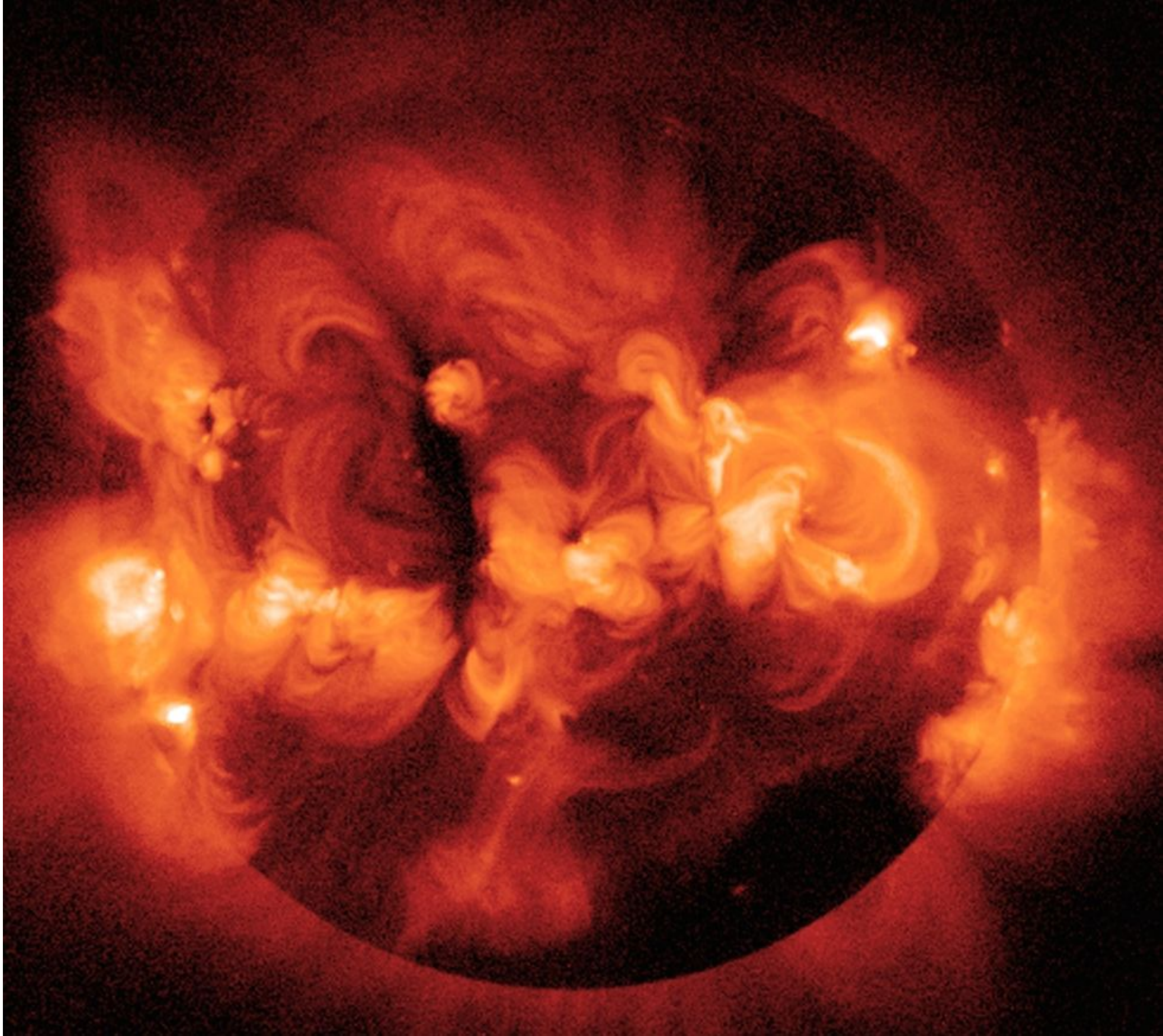
Talvez sem conexão com pequena idade de gelo



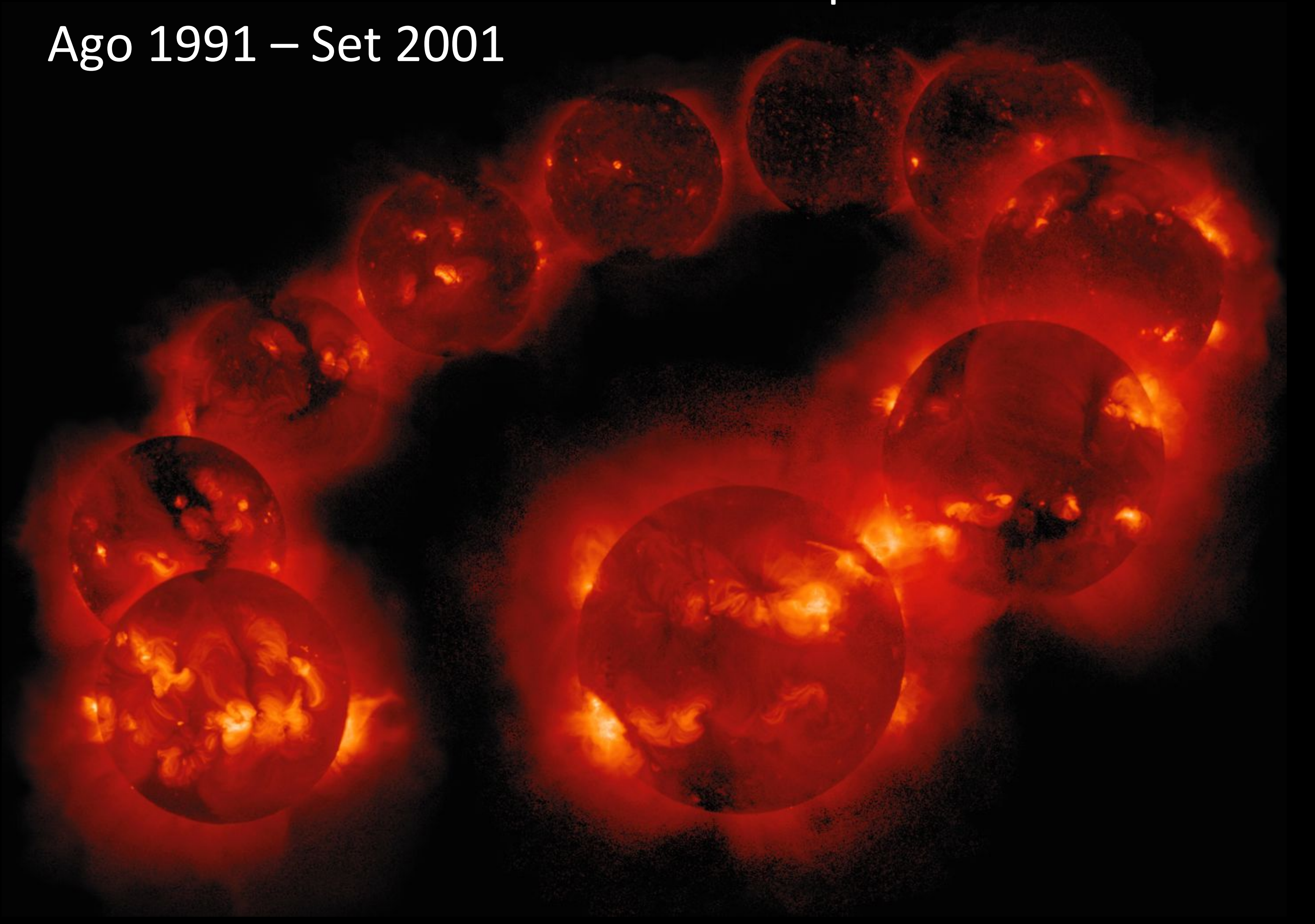


https://solarscience.msfc.nasa.gov/predict.shtml

Sol em raios-X pelo Yohkoh em 1991

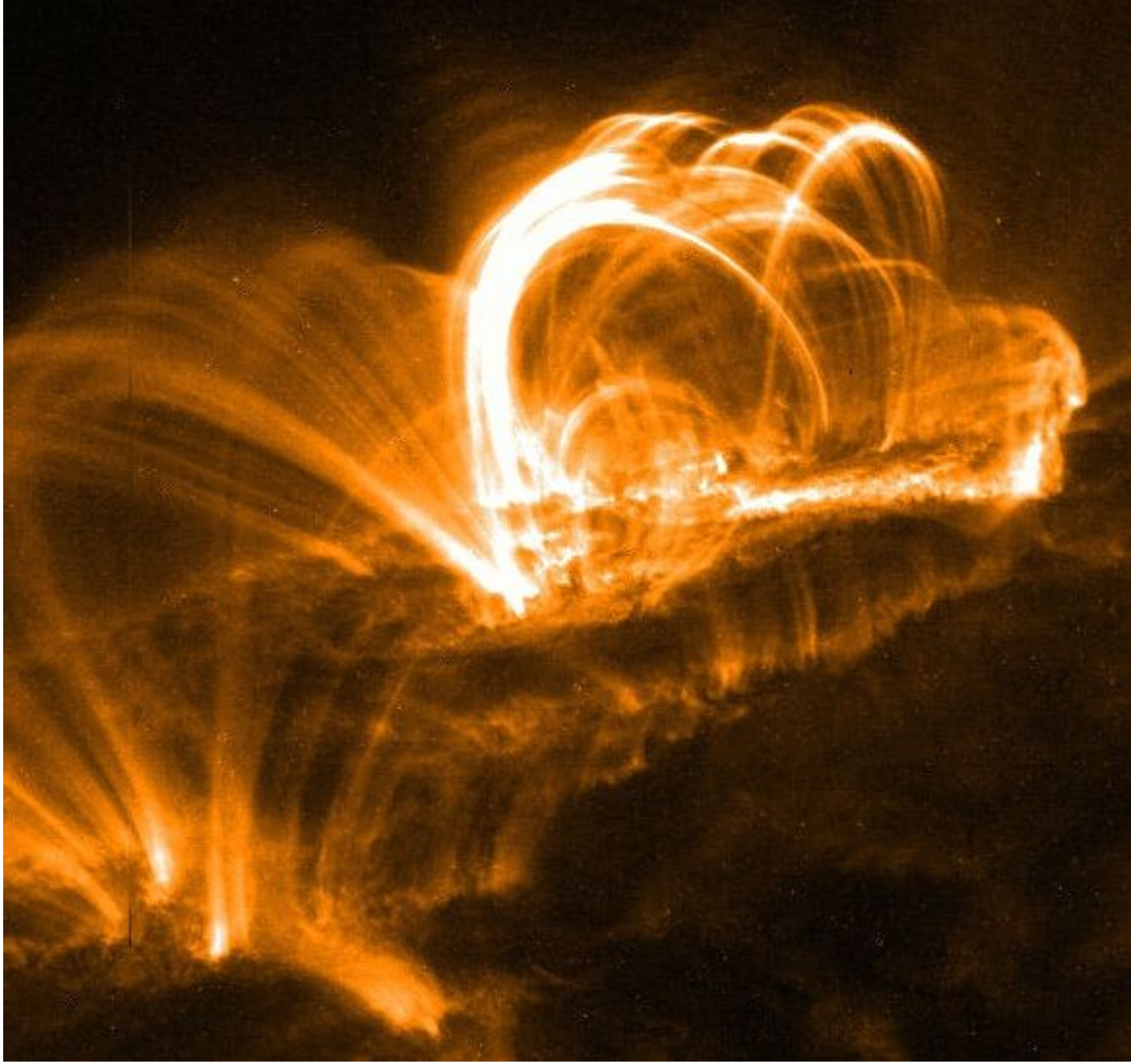


Ciclo de atividade solar em raios-X pelo Yohkoh
Ago 1991 – Set 2001



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.



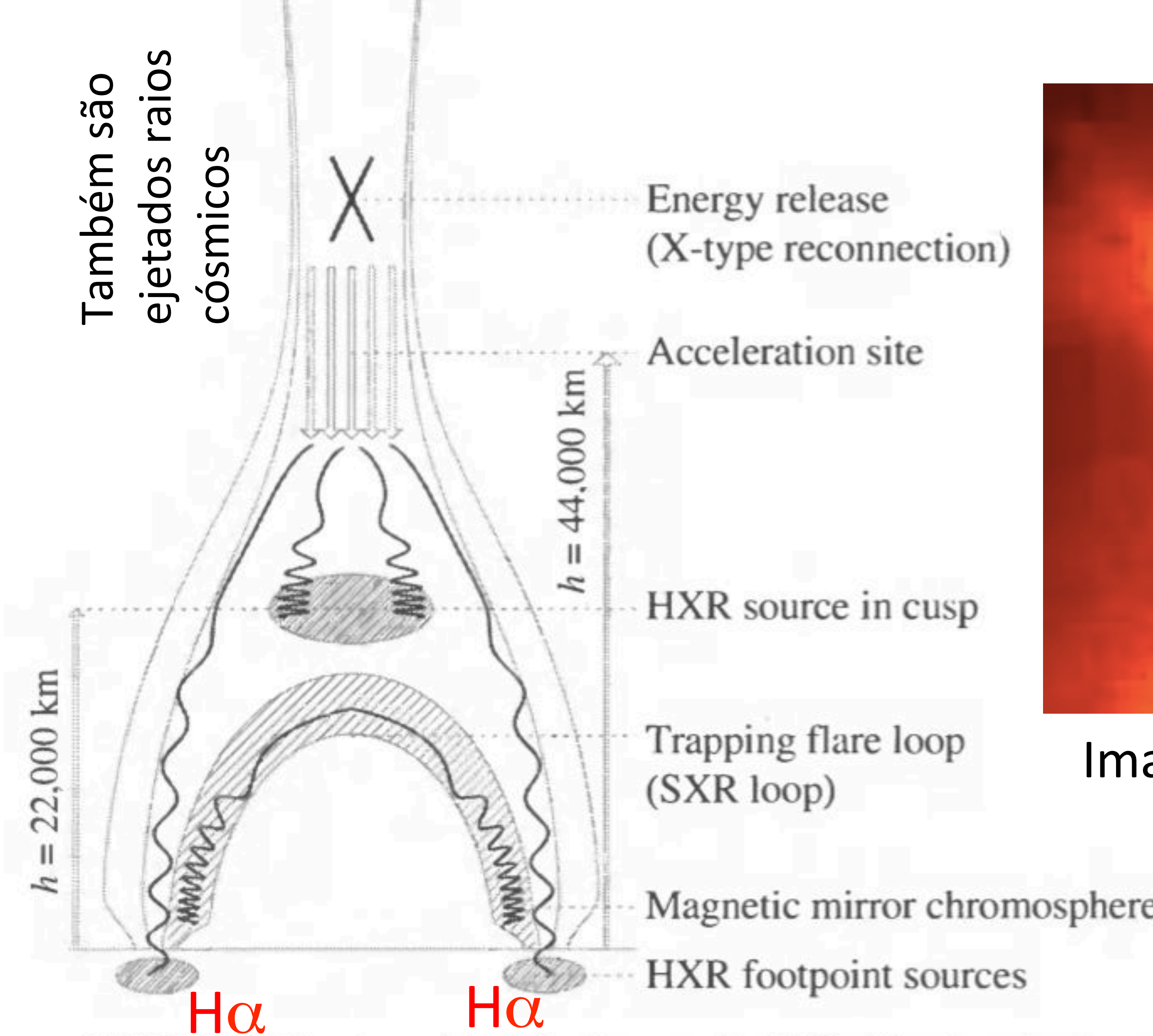
https://www.nasa.gov/mission_pages/swift/bursts/monster_flare_prt.htm

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



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

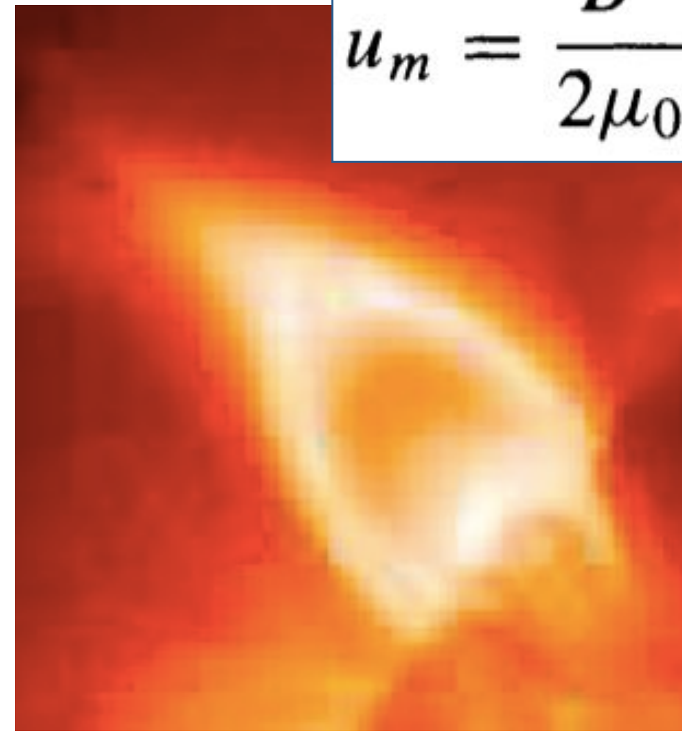


Imagem raios-X de *flare* (erupção) solar

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.)

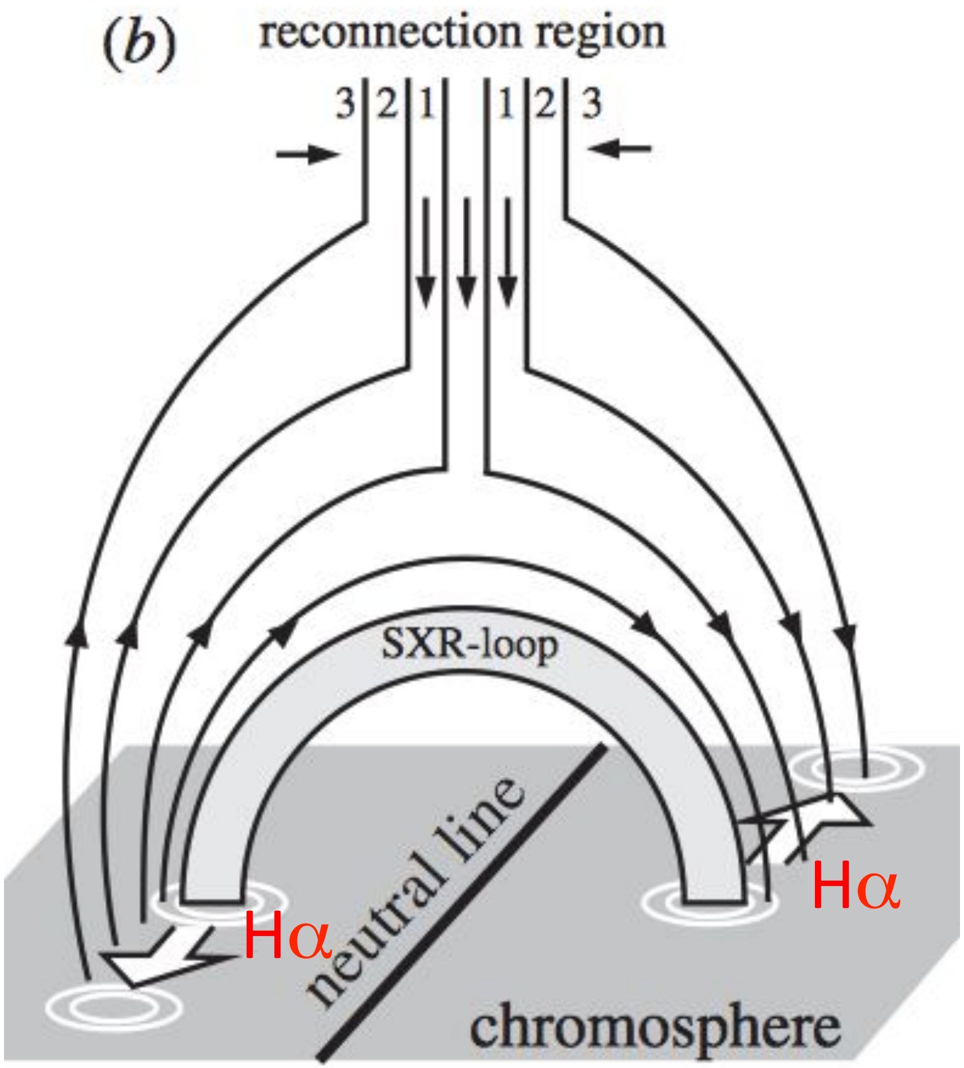
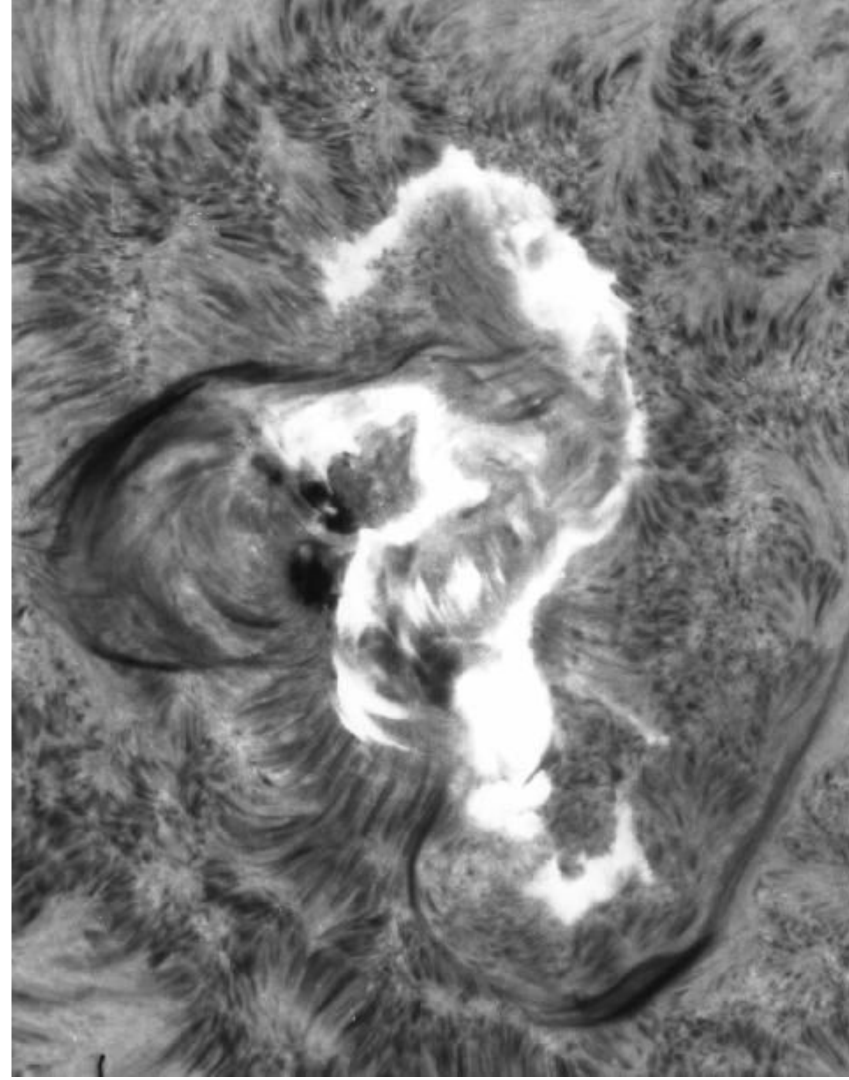
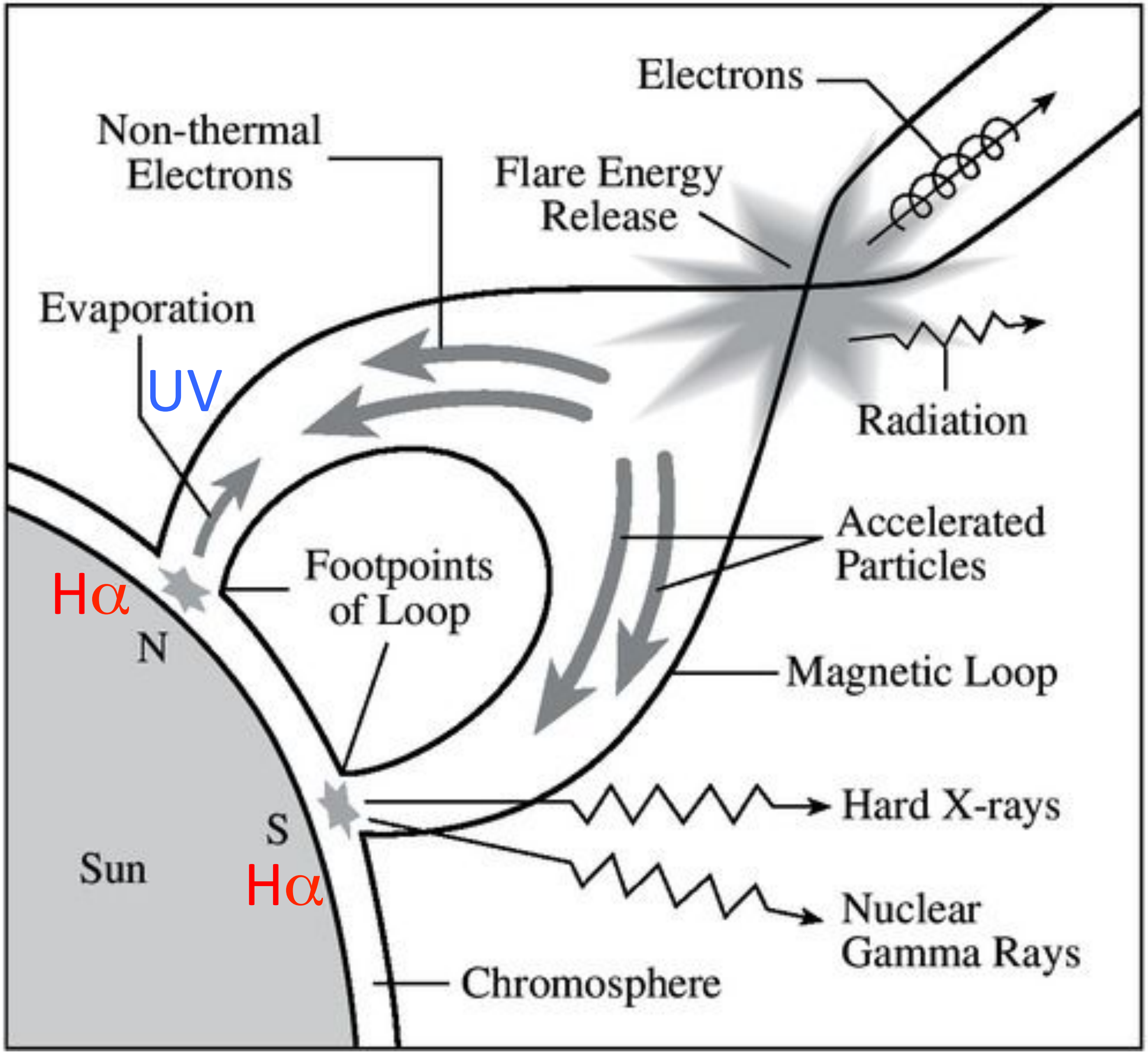


Fig. 3b, Solar flares and energetic particles NICOLE VILMER, *Phil. Trans. R. Soc. A* (2012) **370**, 3241



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

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

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

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

with $E_\gamma = 4.438$ MeV, or

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

followed by the de-excitation reaction

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

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

$$ e^- + e^+ \to \gamma + \gamma $$

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

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

where $E_\gamma = 2.223$ MeV.

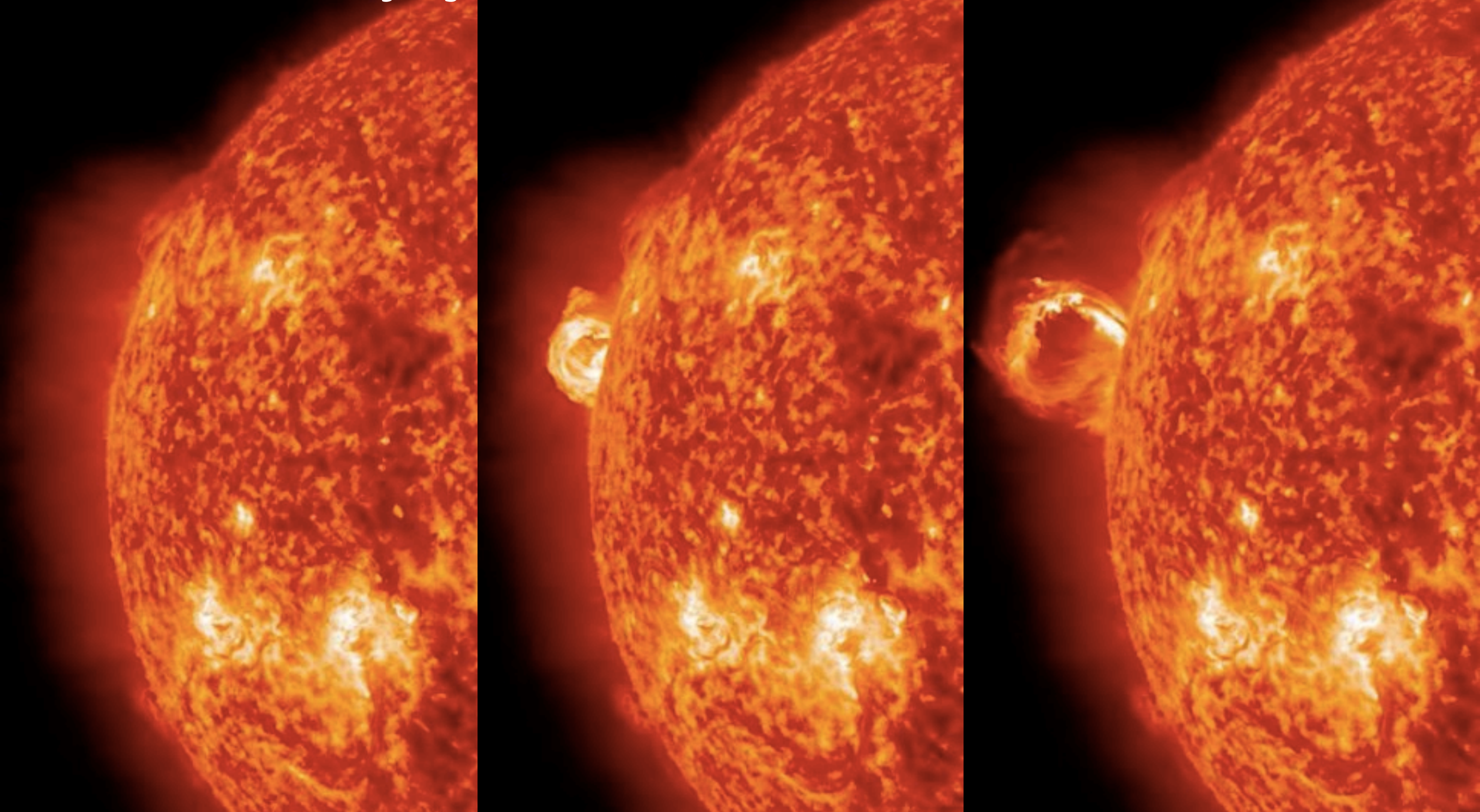
Proeminência solar

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.

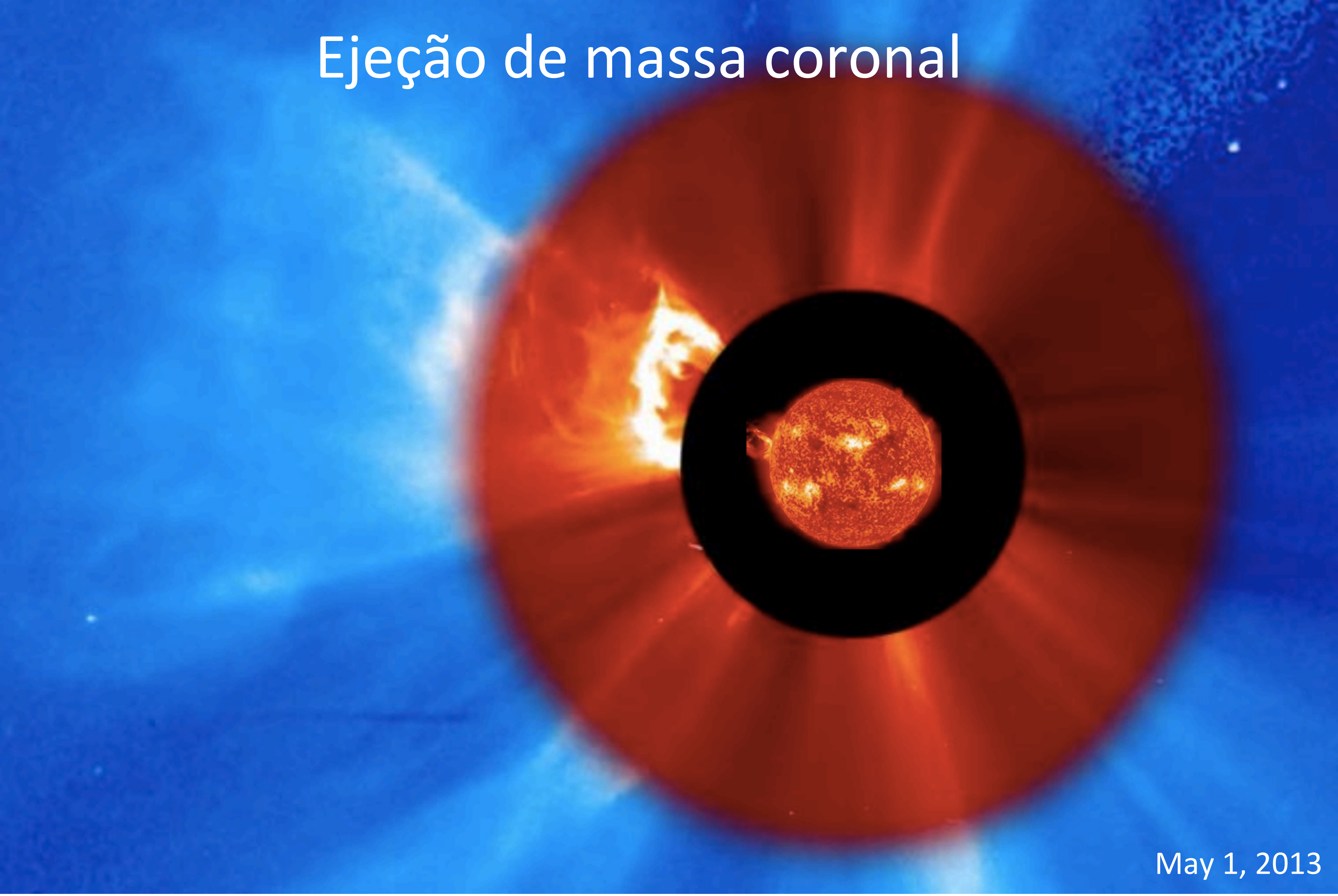
https://www.nasa.gov/content/goddard/what-is-a-solar-prominence

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.

5×10^{12} kg a 5×10^{13} kg

v ~ 400 km/s a 1000 km/s

Com *flares*: 40%

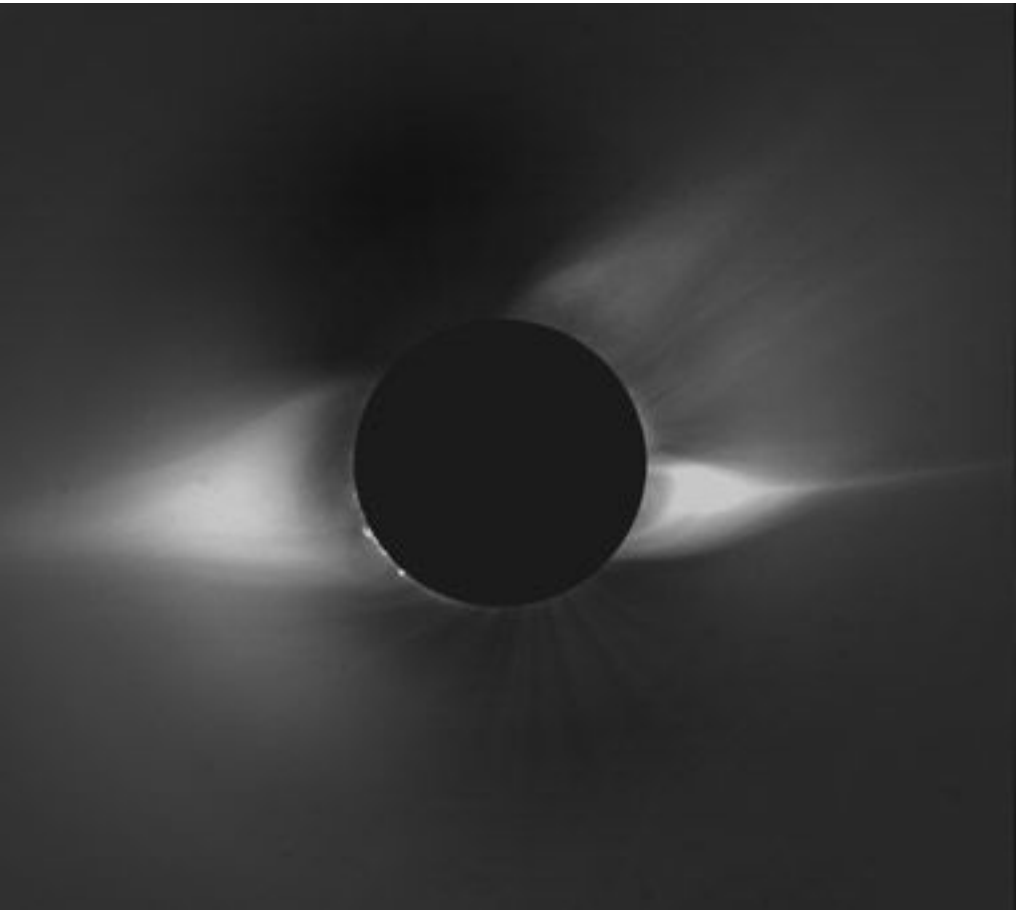
Com proeminência solar eruptiva: 70%

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

Coroa solar durante eclipse

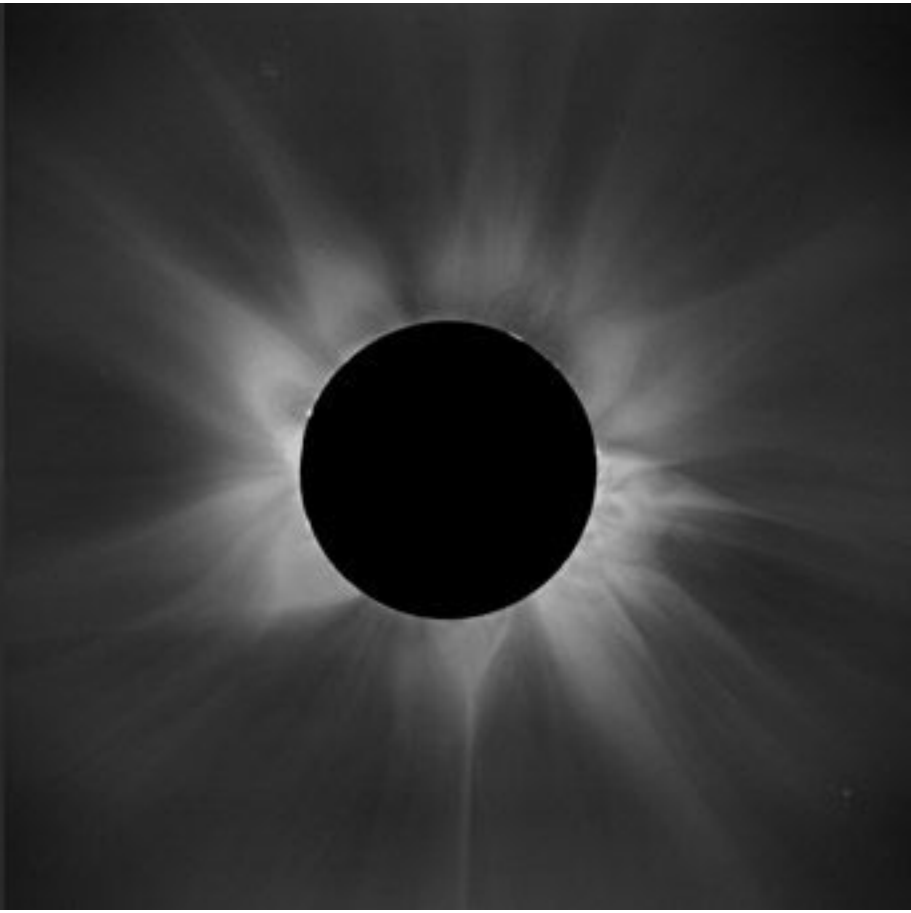
1994 (mínimo de atividade)

Mais extendida no equador, consistente com campo dipolar



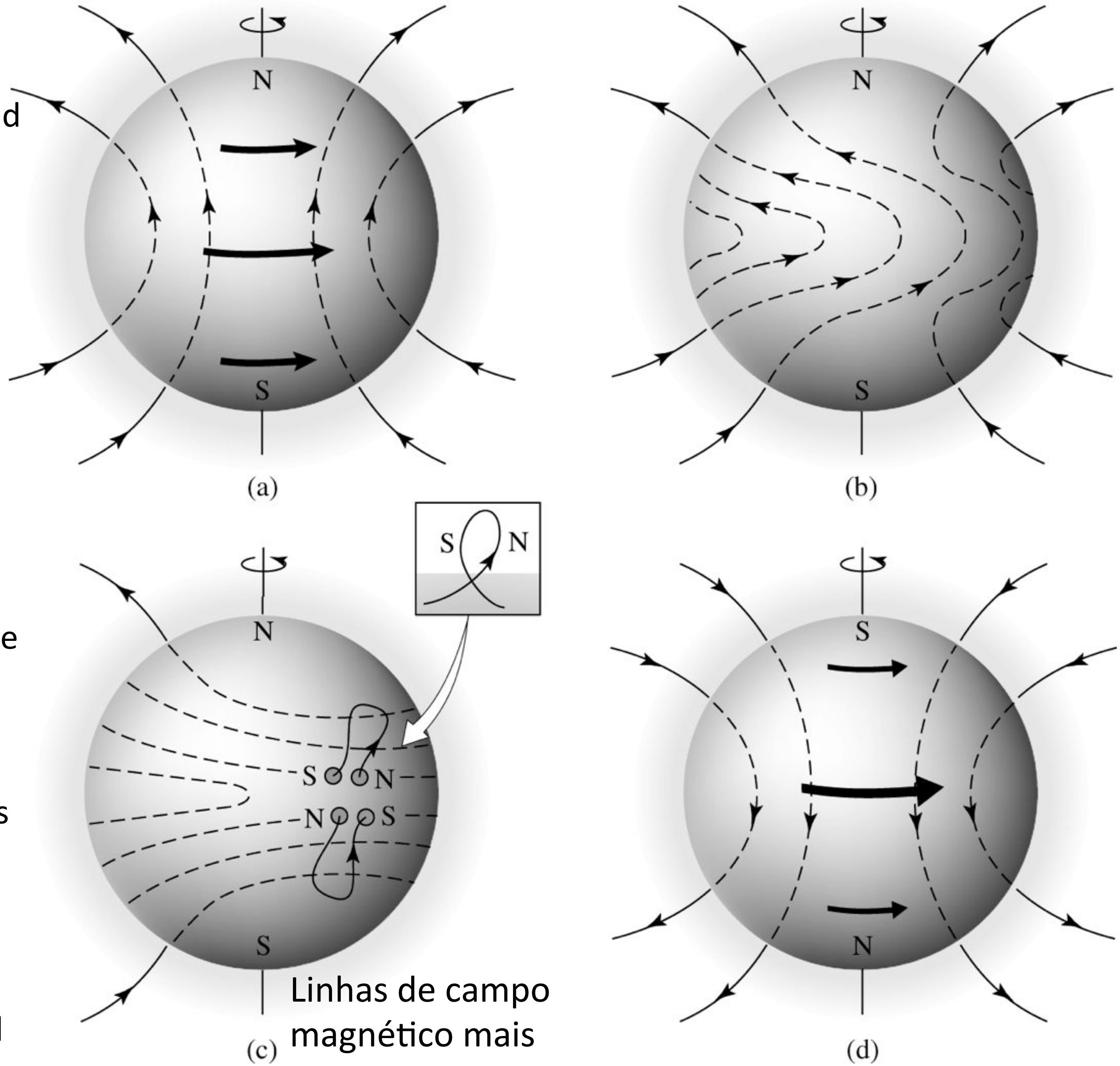
1980 (máximo de atividade)

Coroa é mais complexa

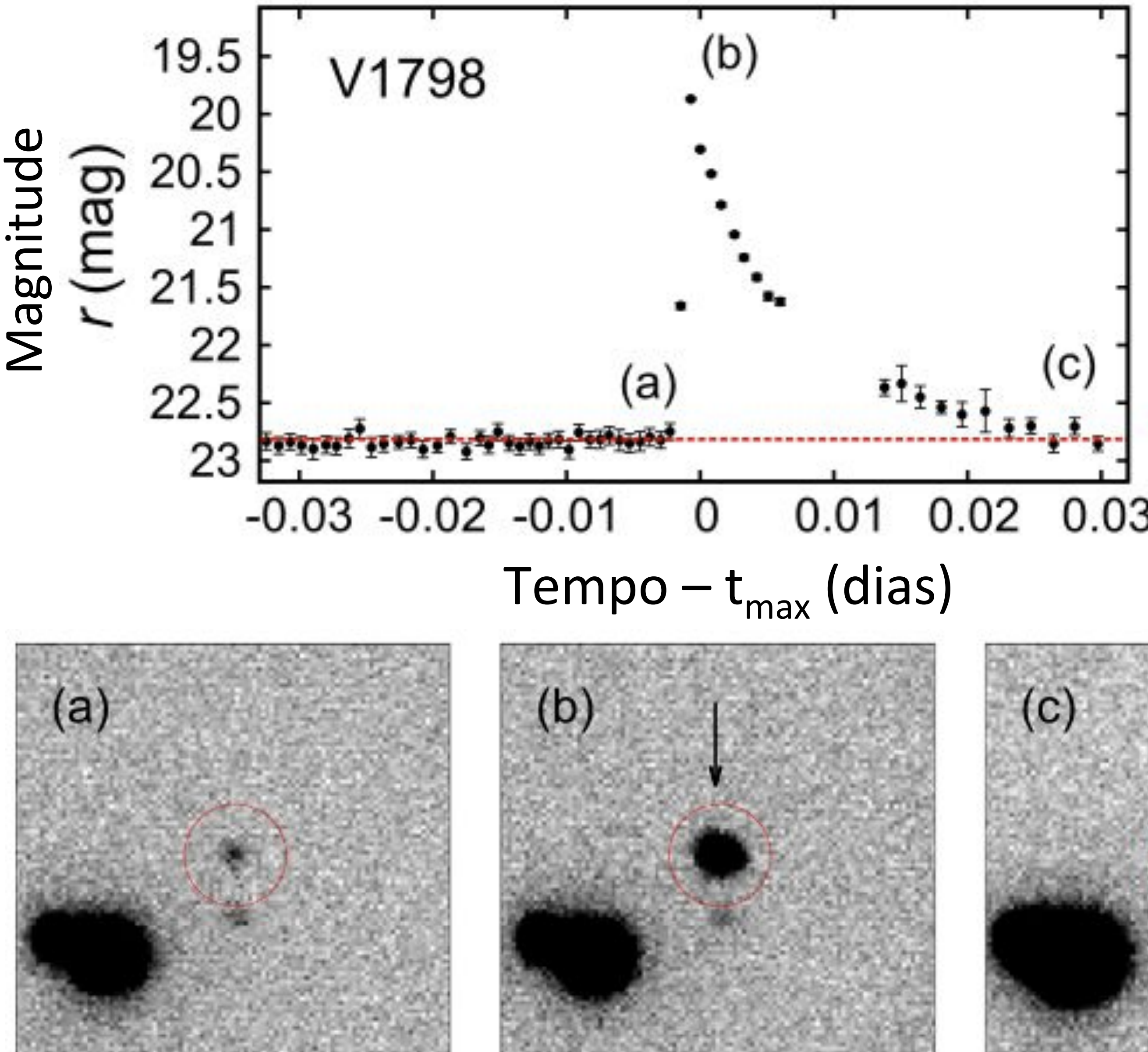


http://www.windows2universe.org/sun/images/eclipse/sun_eclipse_corona_max_vs_min_big_jpg_image.html

The magnetic dynamo model of the solar cycle. (a) The solar magnetic field is initially poloidal. (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 corresponding 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

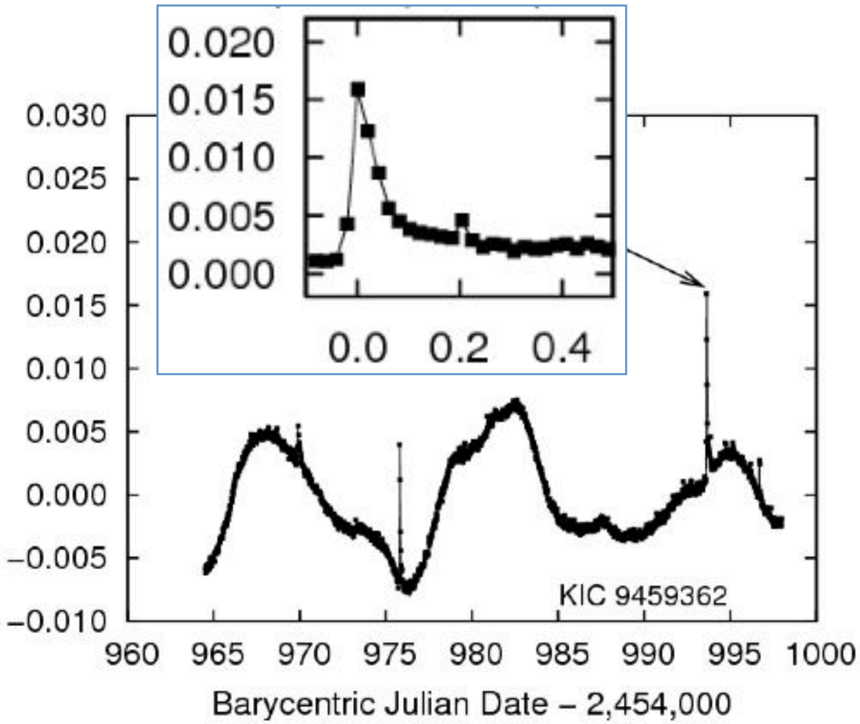
Chang et al. 2015, ApJ 814, 35

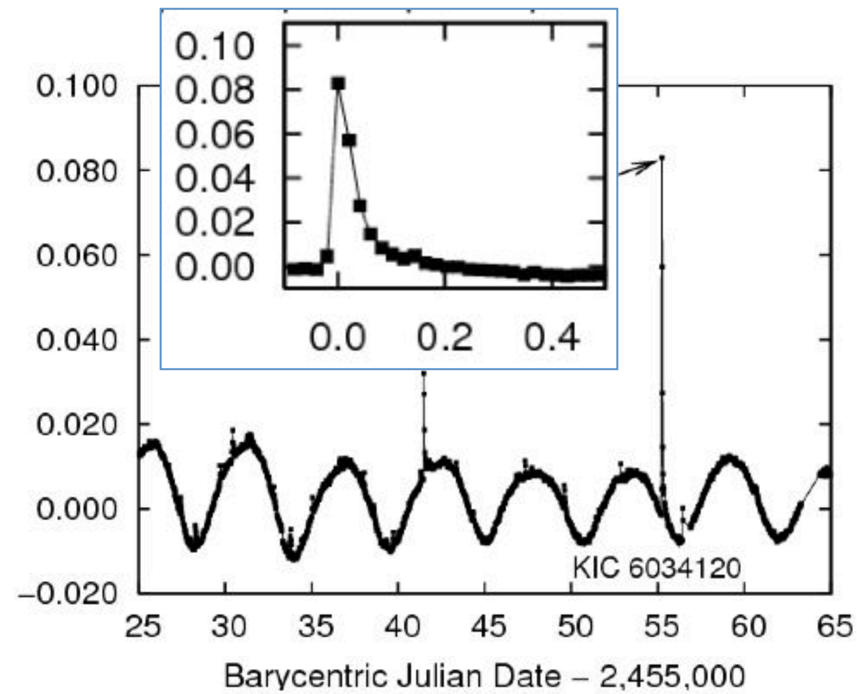
Superflares on solar-type stars

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

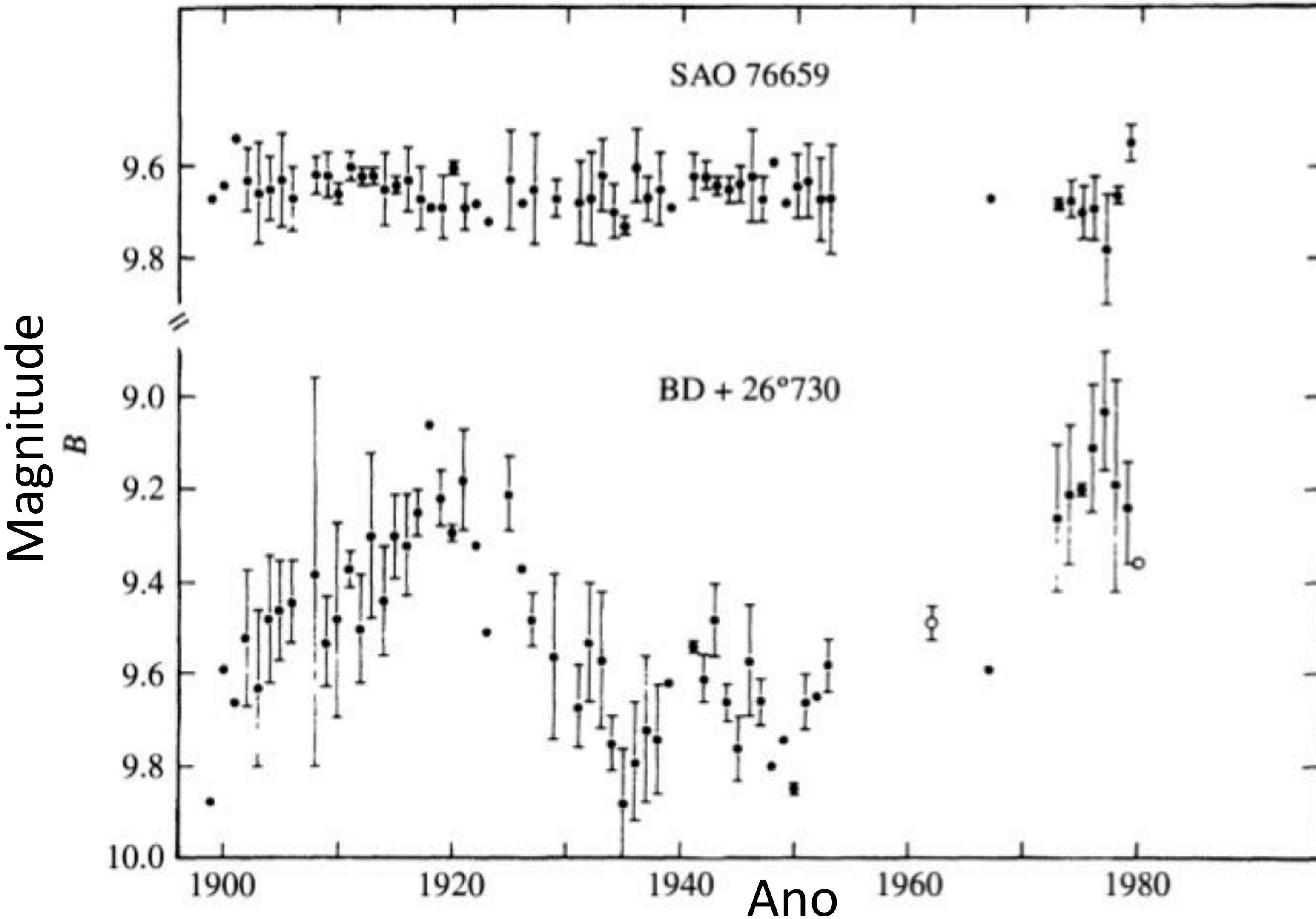


FIGURE 11.39 The light curve of BD + 26°730, a BY Dra star. SAO 76659 is a nearby reference star. (Figure from Hartmann et al., *Ap. J.*, *249*, 662, 1981.)

Em estrelas como o Sol (HD 146233), as variações em fluxo (magnitude) durante o ciclo de atividade são muito pequenas, porem podemos usar o índice cromosférico *S* para estudar o ciclo de atividade.

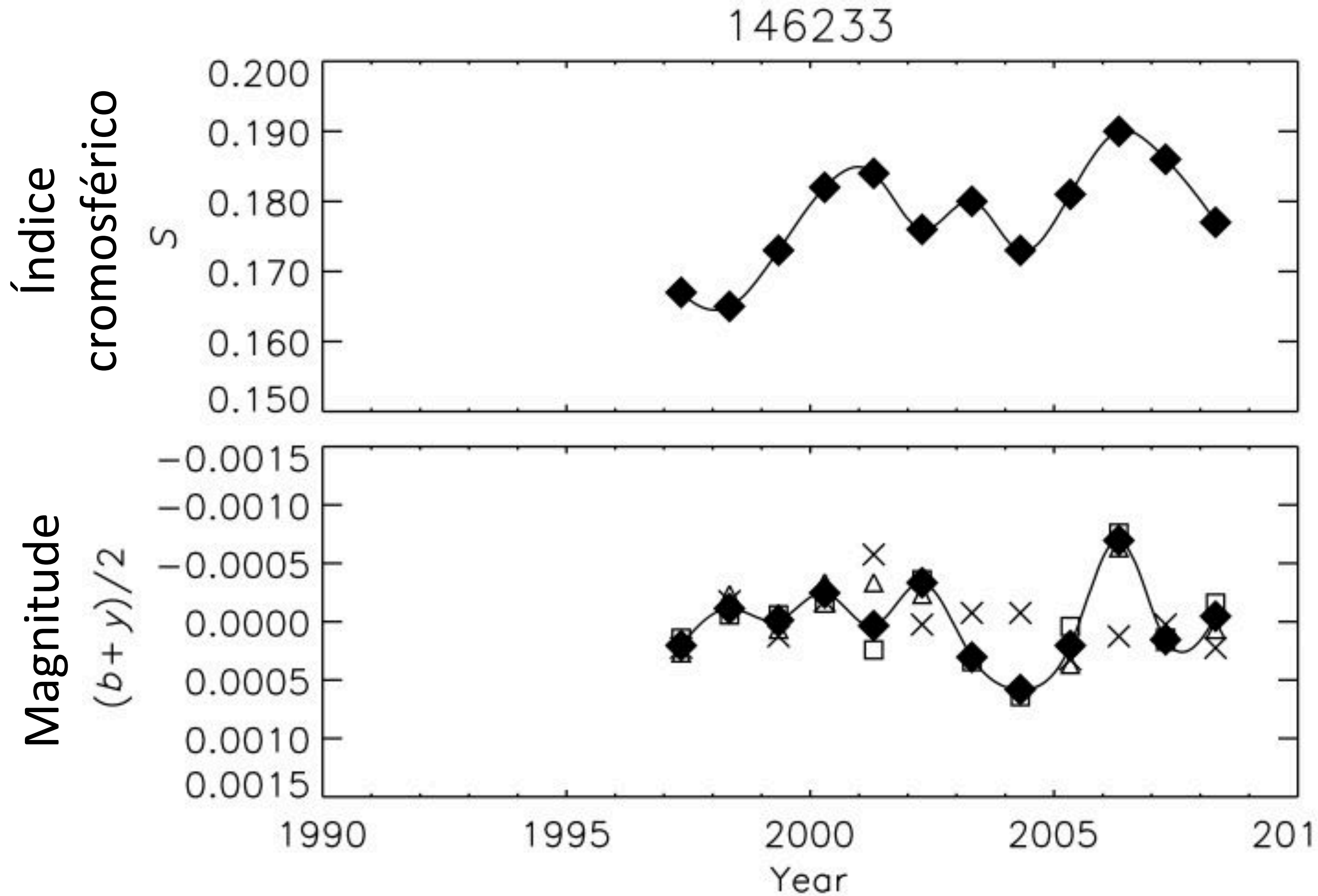
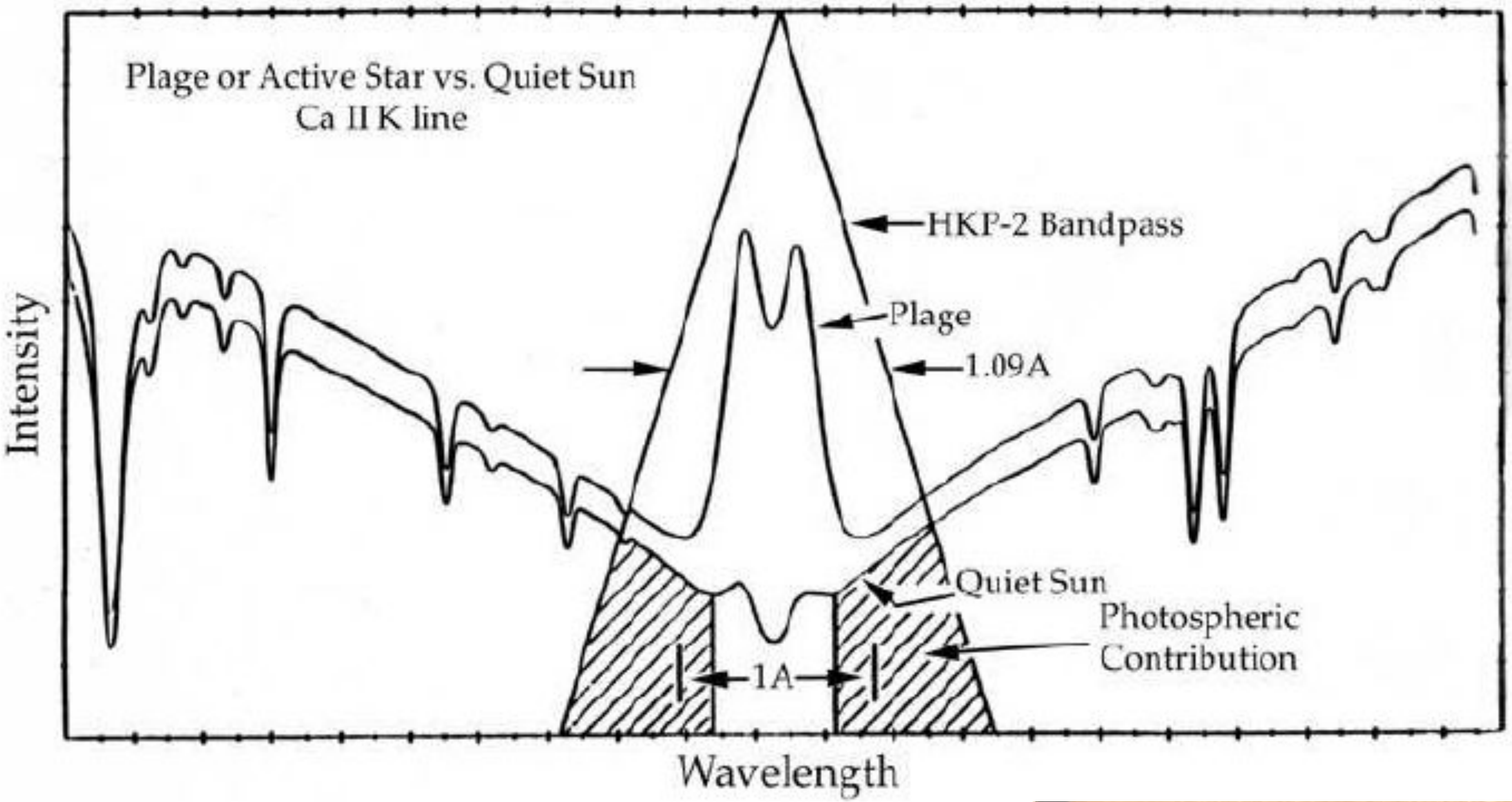
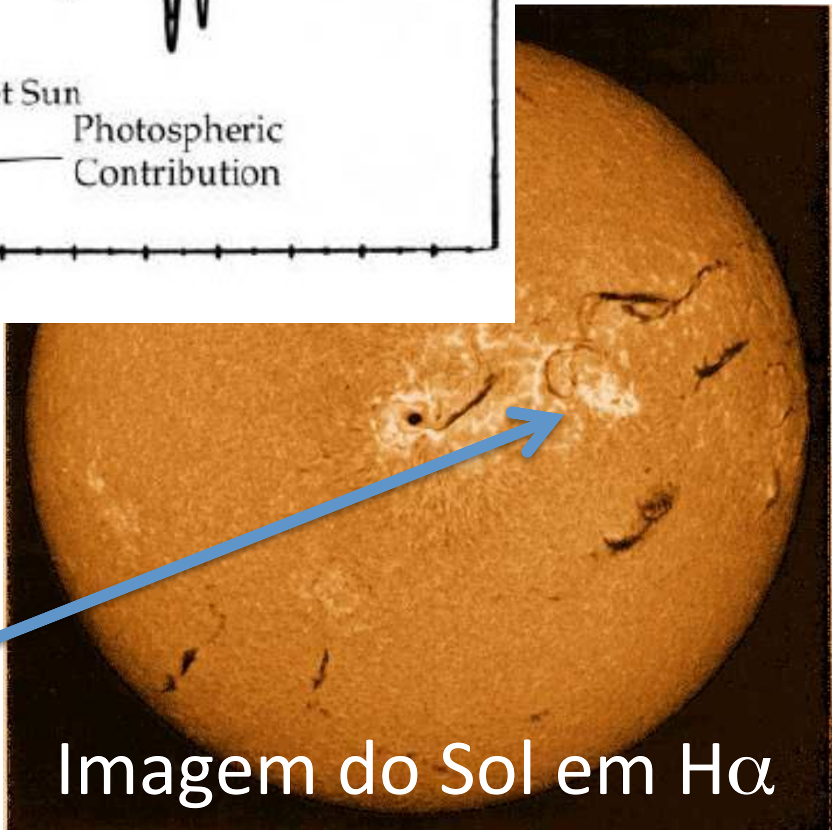


Figure 4. Time series for HD 146233 (18 Sco).

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***

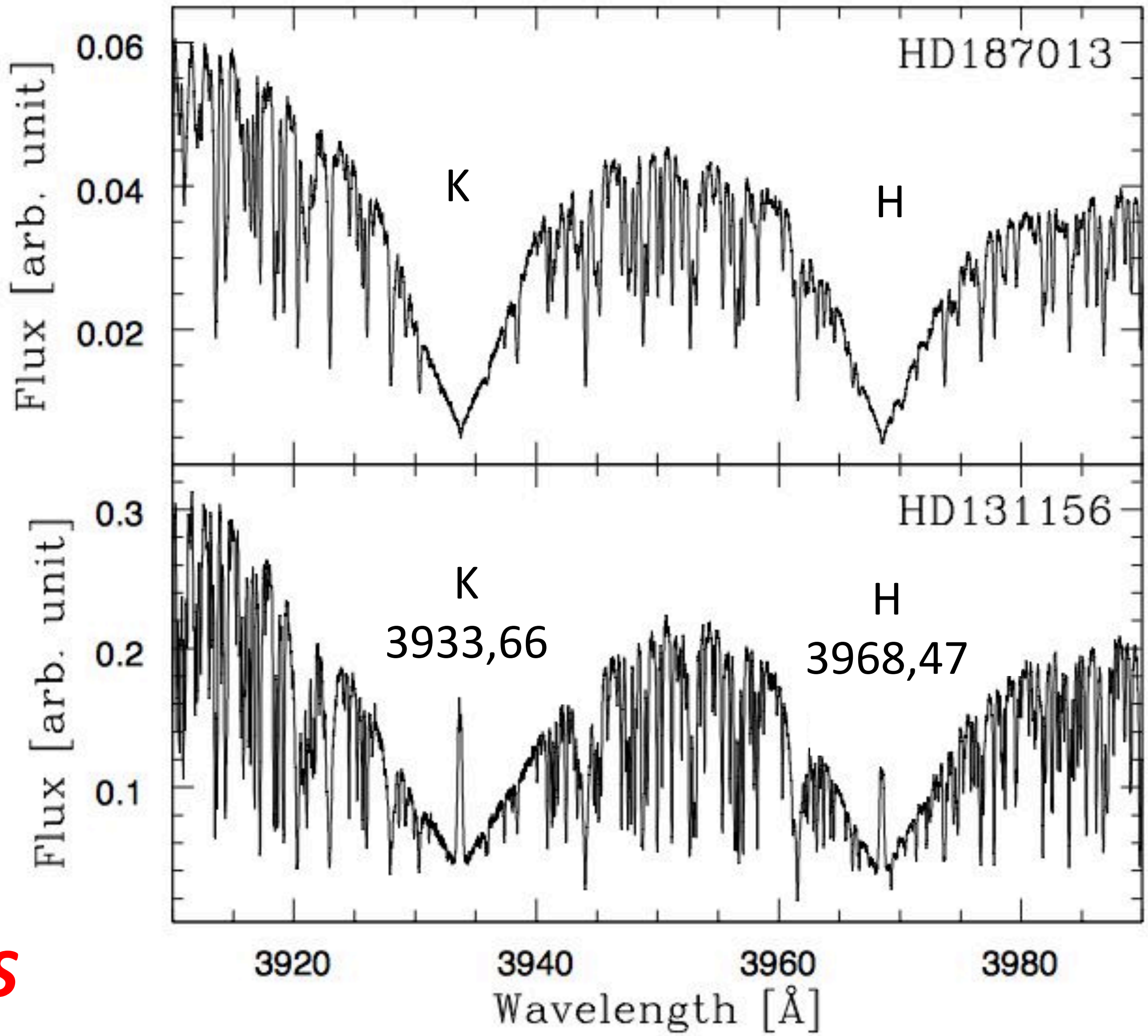


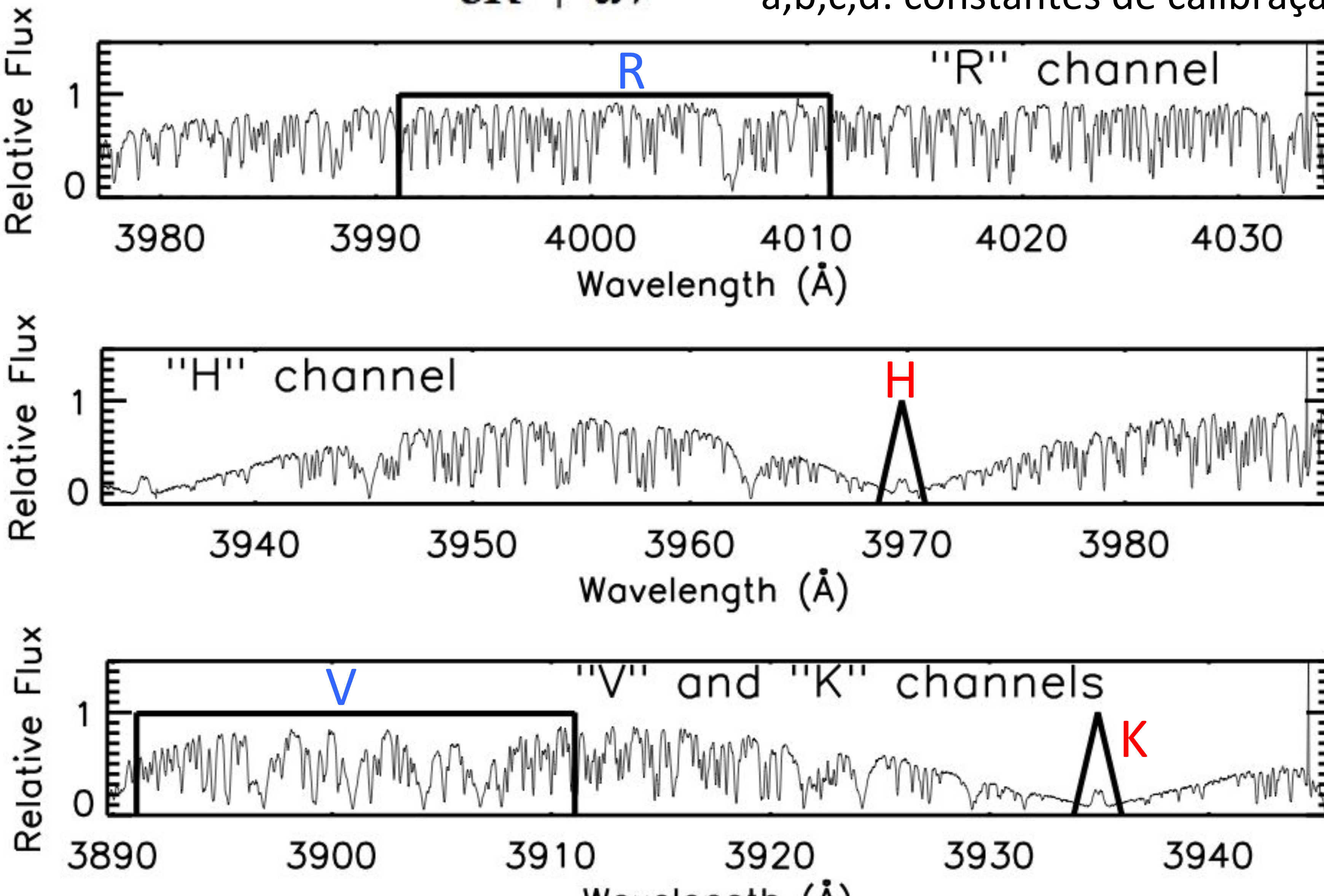
Fig. C.1. Two SOPHIE spectra of the region of the CaII H and K lines between 3900 and 4000 Å. *Bottom*: Active star. *Top*: Non active star.

Boisse et al. 2010 A&A 523, A88

Índice S:

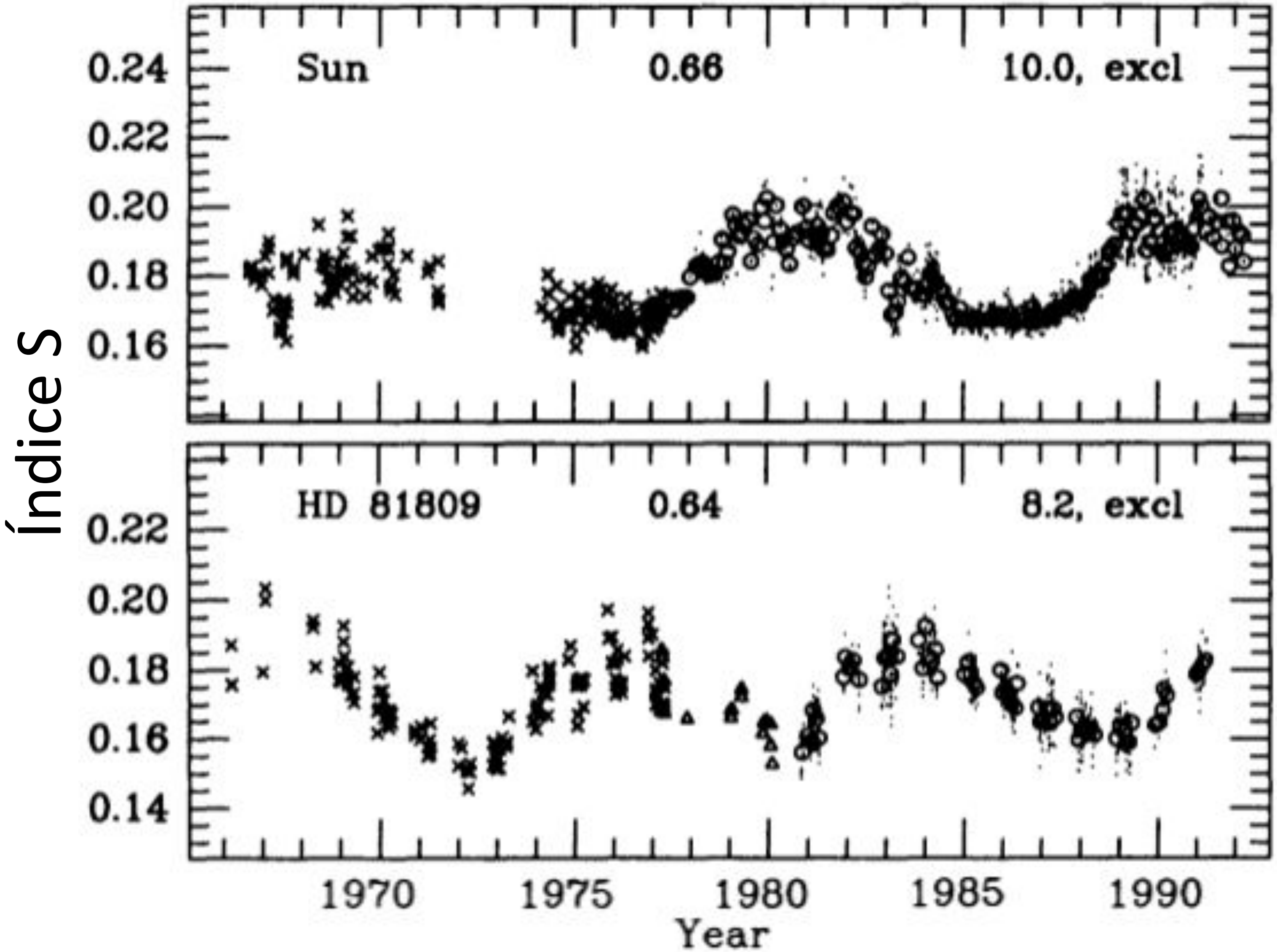
$$S = \frac{a\mathrm{H} + b\mathrm{K}}{cR + dV}$$

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

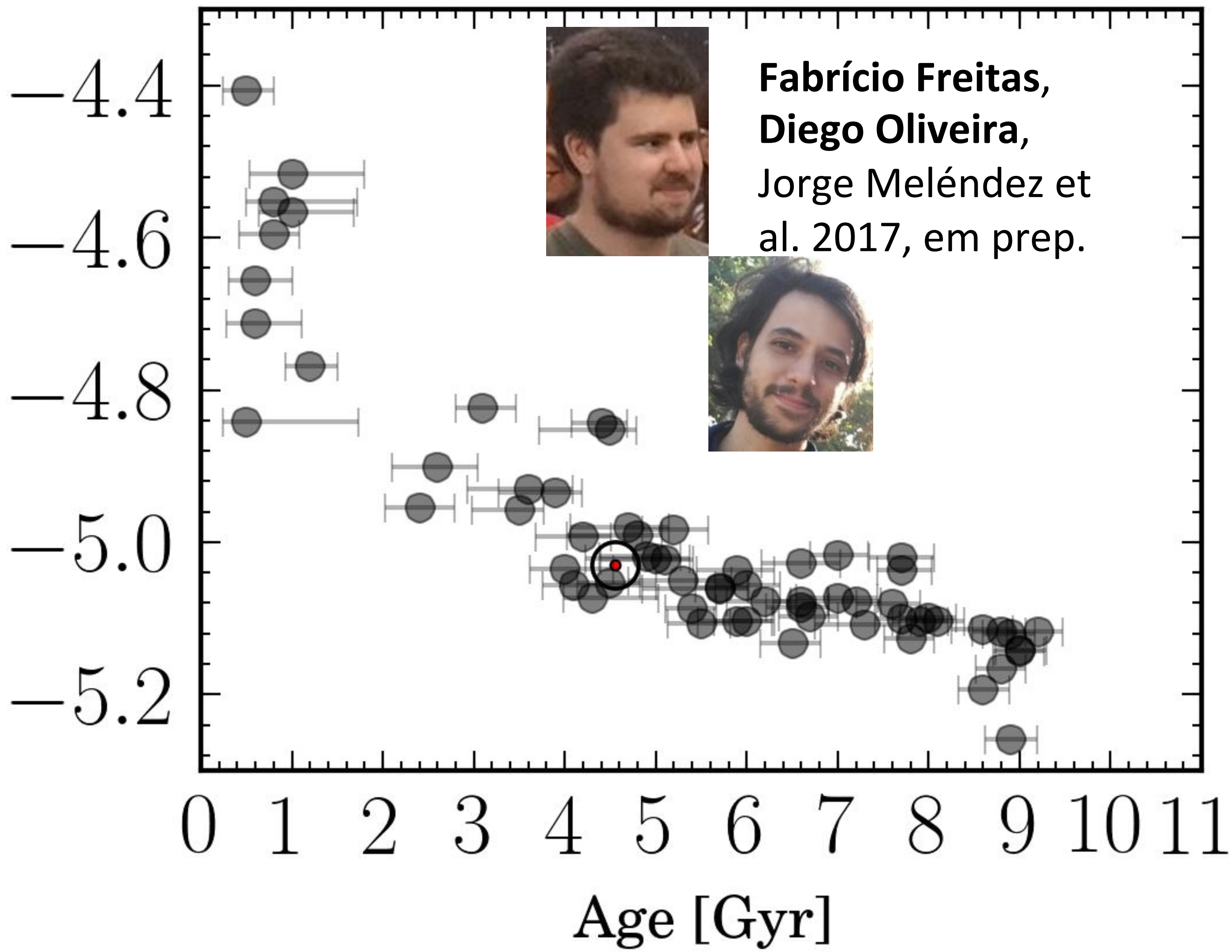
Ciclo de atividade usando o índice cromosférico *S*



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 cromosférica
R'_{HK} (depende do *S*)



Fabrício Freitas, Diego Oliveira, Jorge Meléndez et al. 2017, em prep.

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), *flares*, proeminência solar eruptiva, ejeção de massa coronal.
- 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.