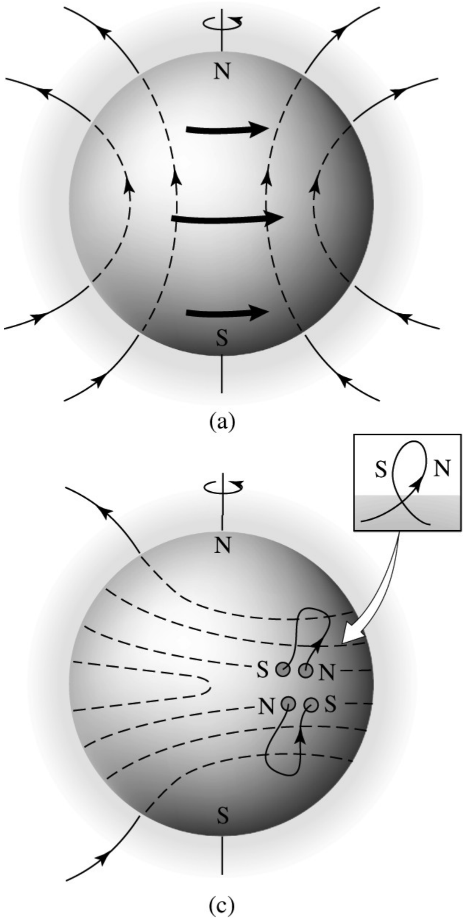
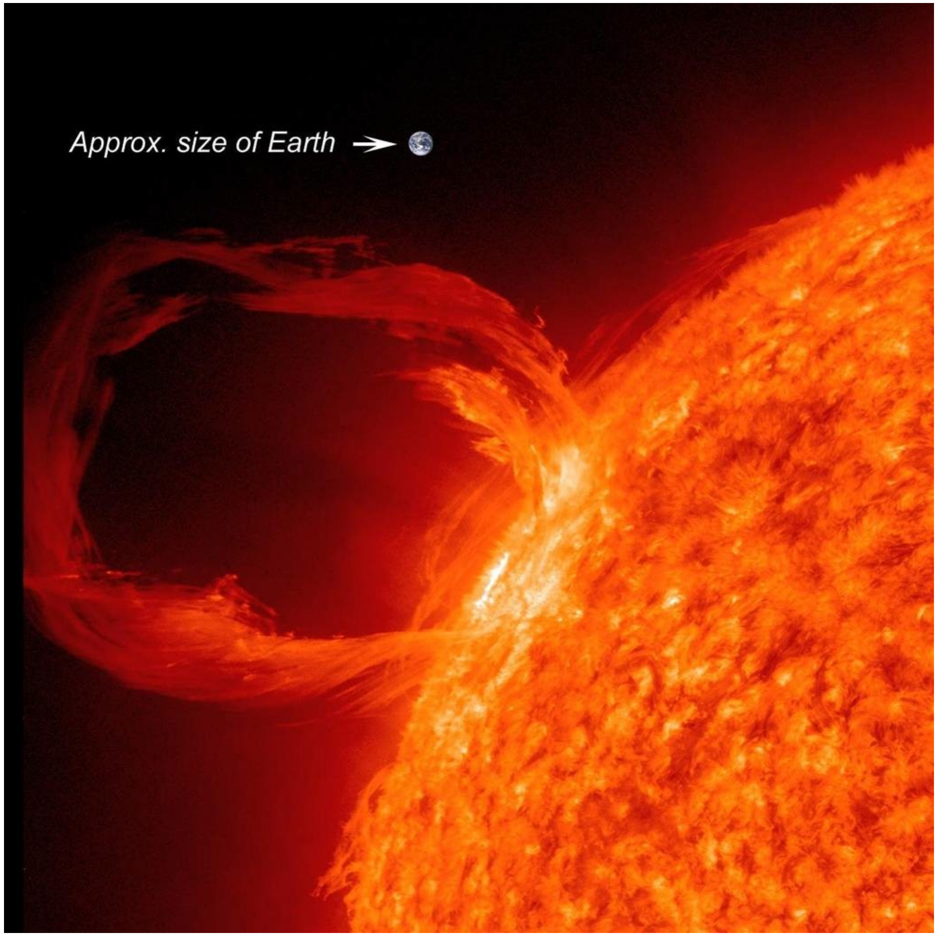
Cap. 11 – O Sol

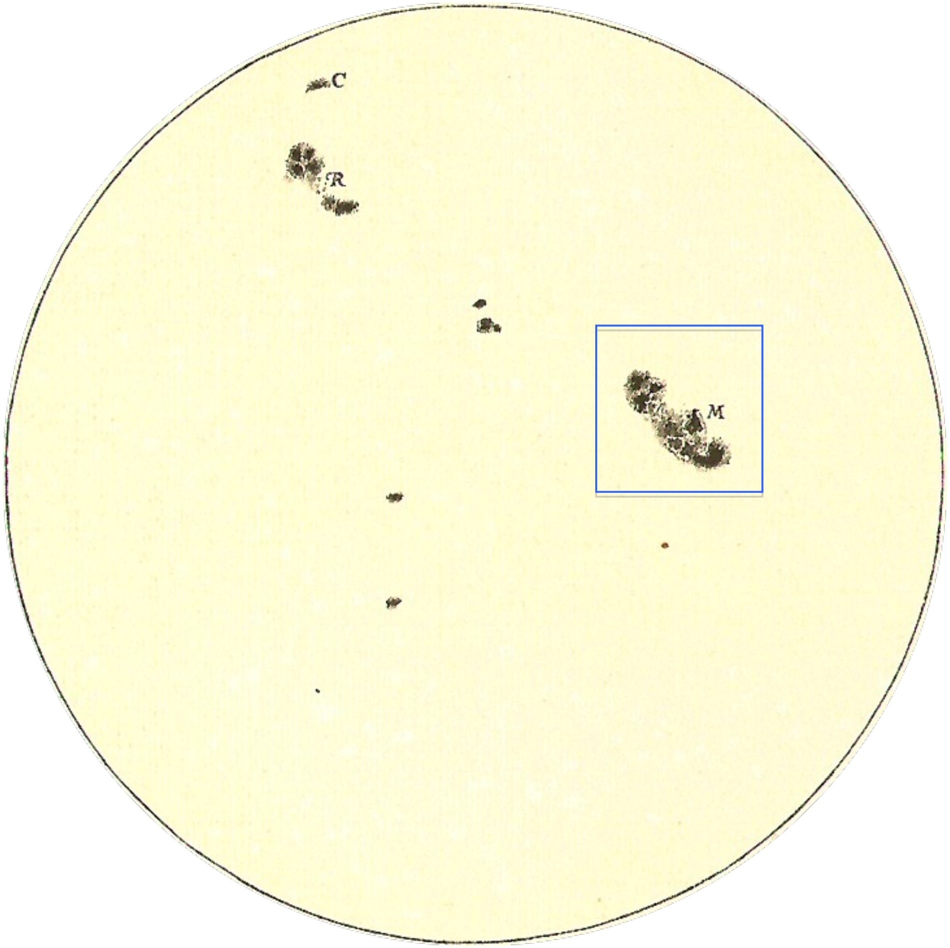
11.3 O ciclo de atividade solar

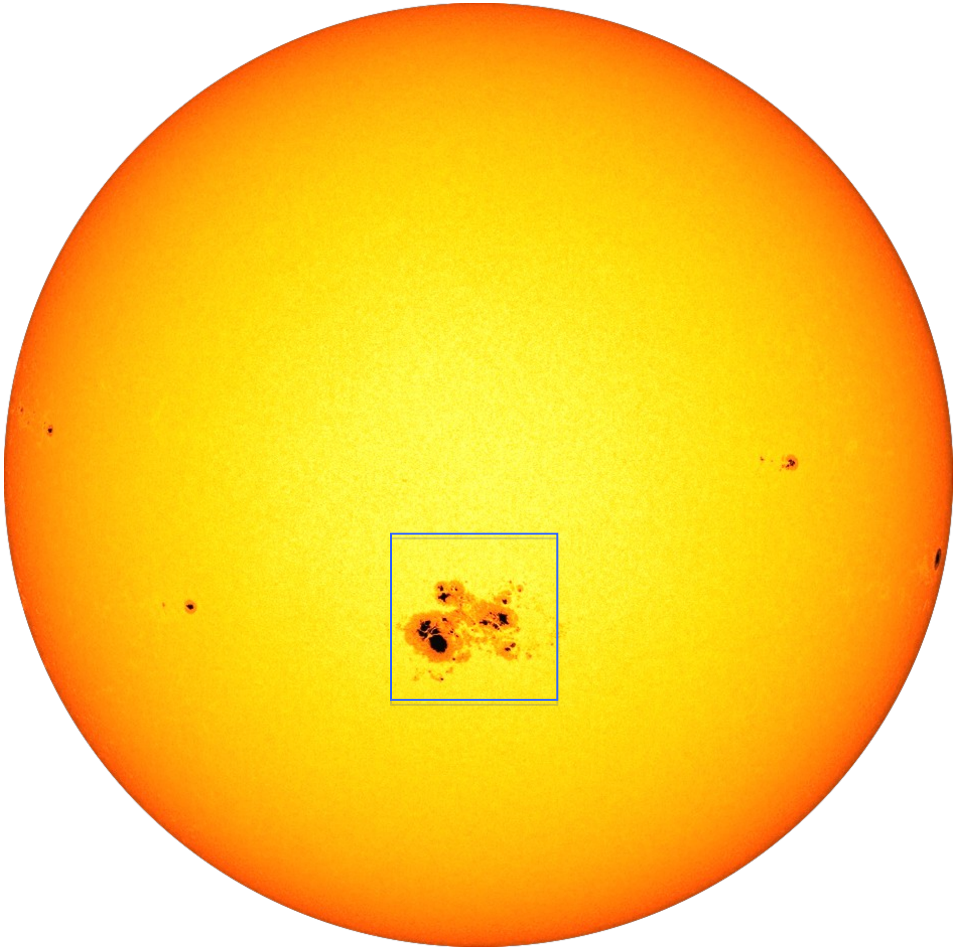




Prof. Jorge Meléndez, AGA 0293, Astrofísica Estelar, IAG-USP

Manchas solares

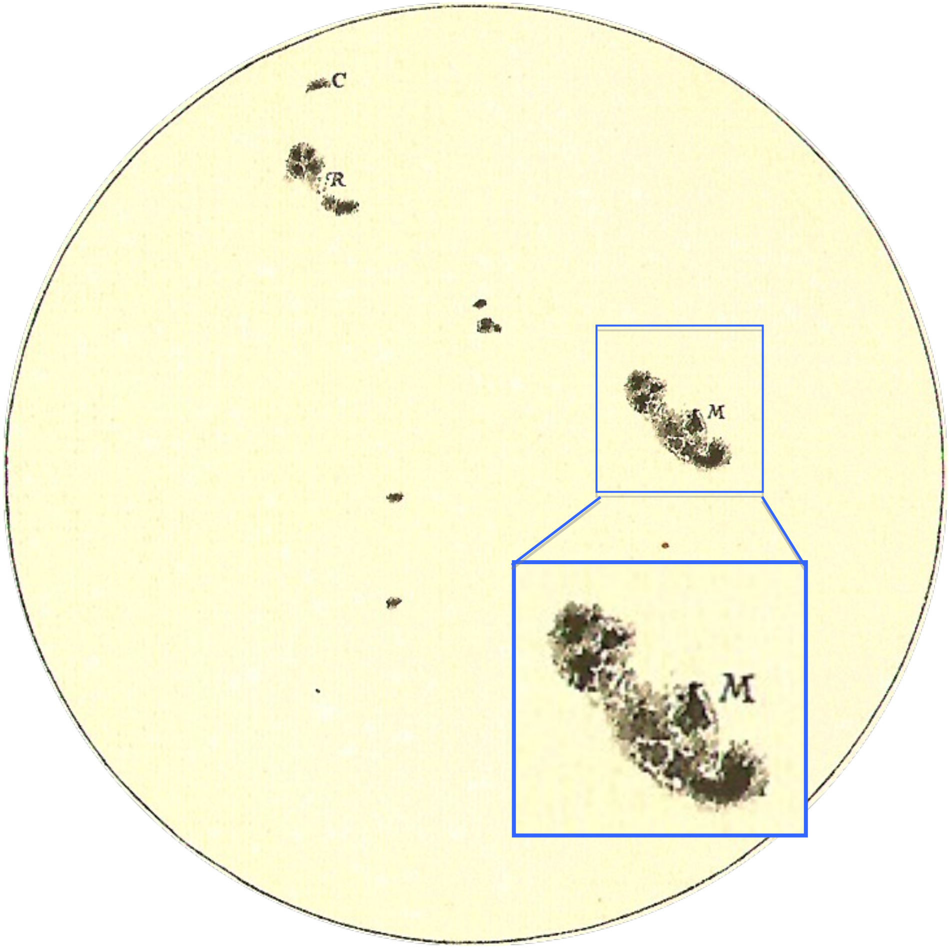


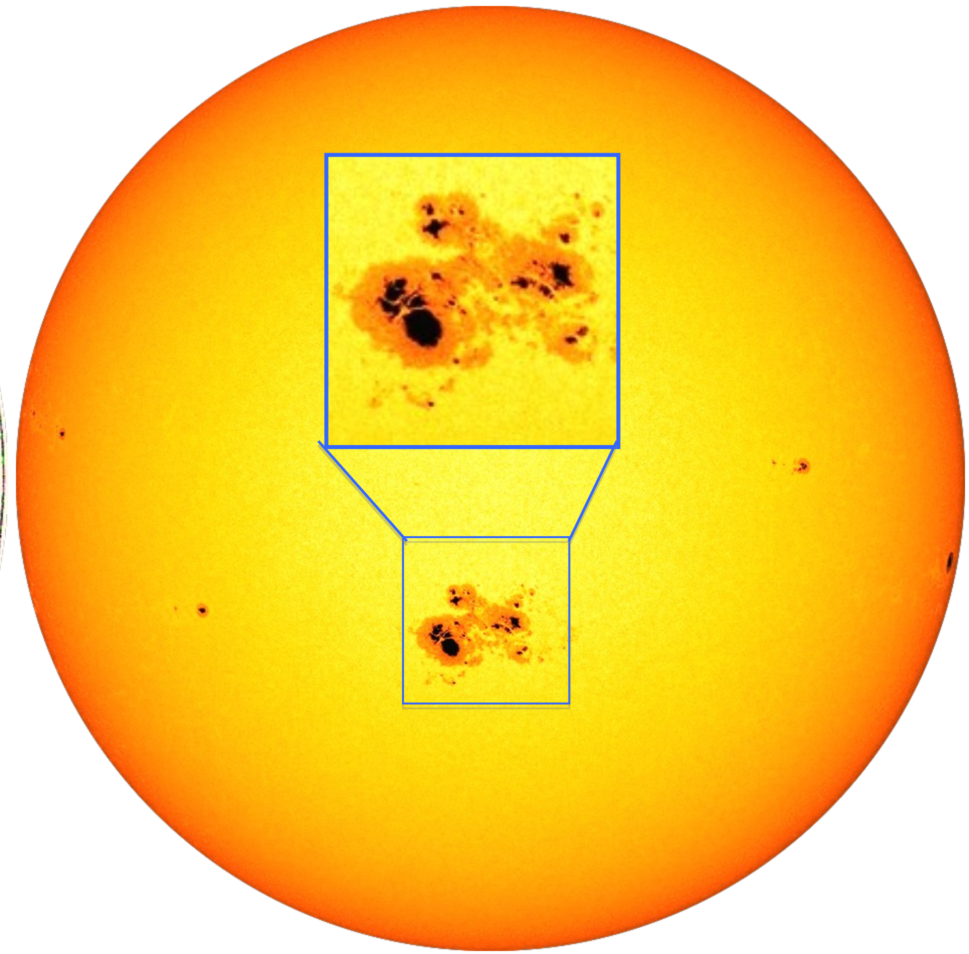


23/6/1613
Galileu Galilei

23/10/2014
NASA/SDO

Manchas solares

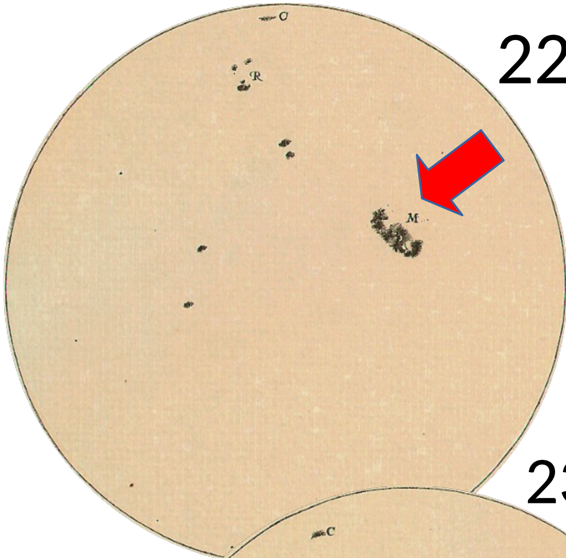




23/6/1613
Galileu Galilei

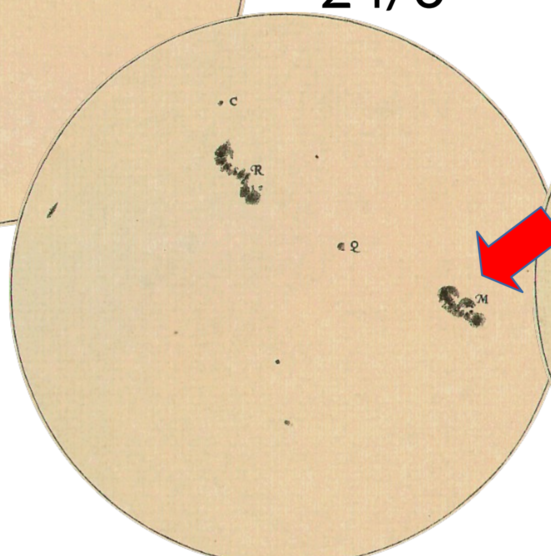
23/10/2014
NASA/SDO

22/6/1613

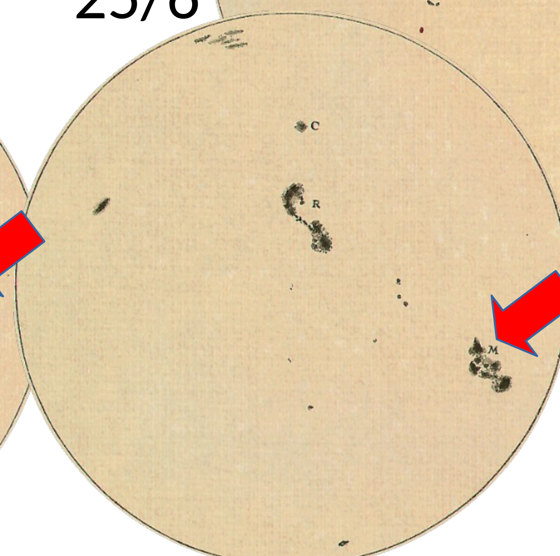


23/6

24/6

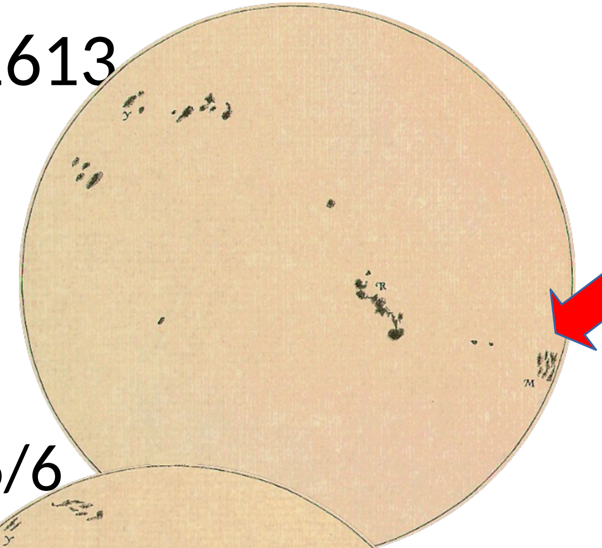


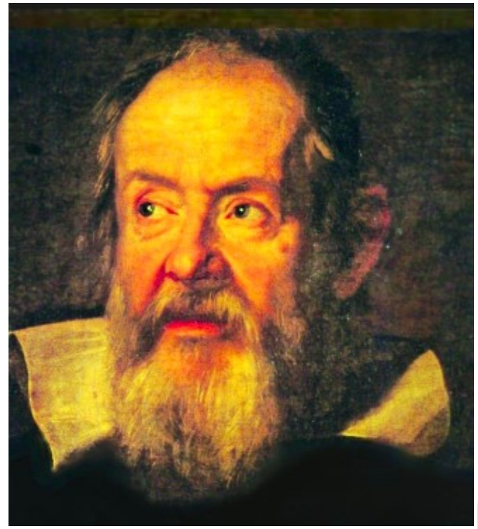
25/6



26/6

27/6/1613





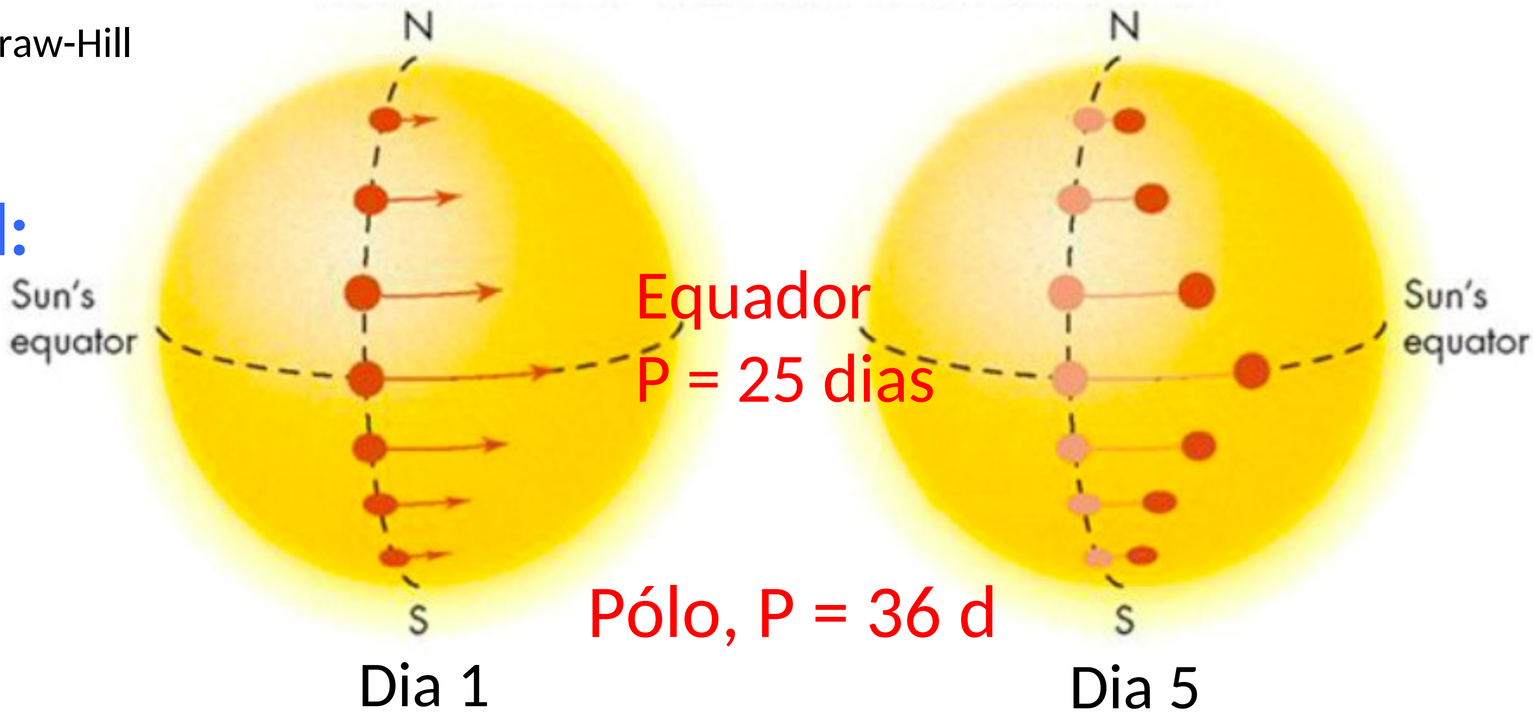
Manchas solares observadas por Galileu

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

Adatado: (c) McGraw-Hill

Rotação diferencial:

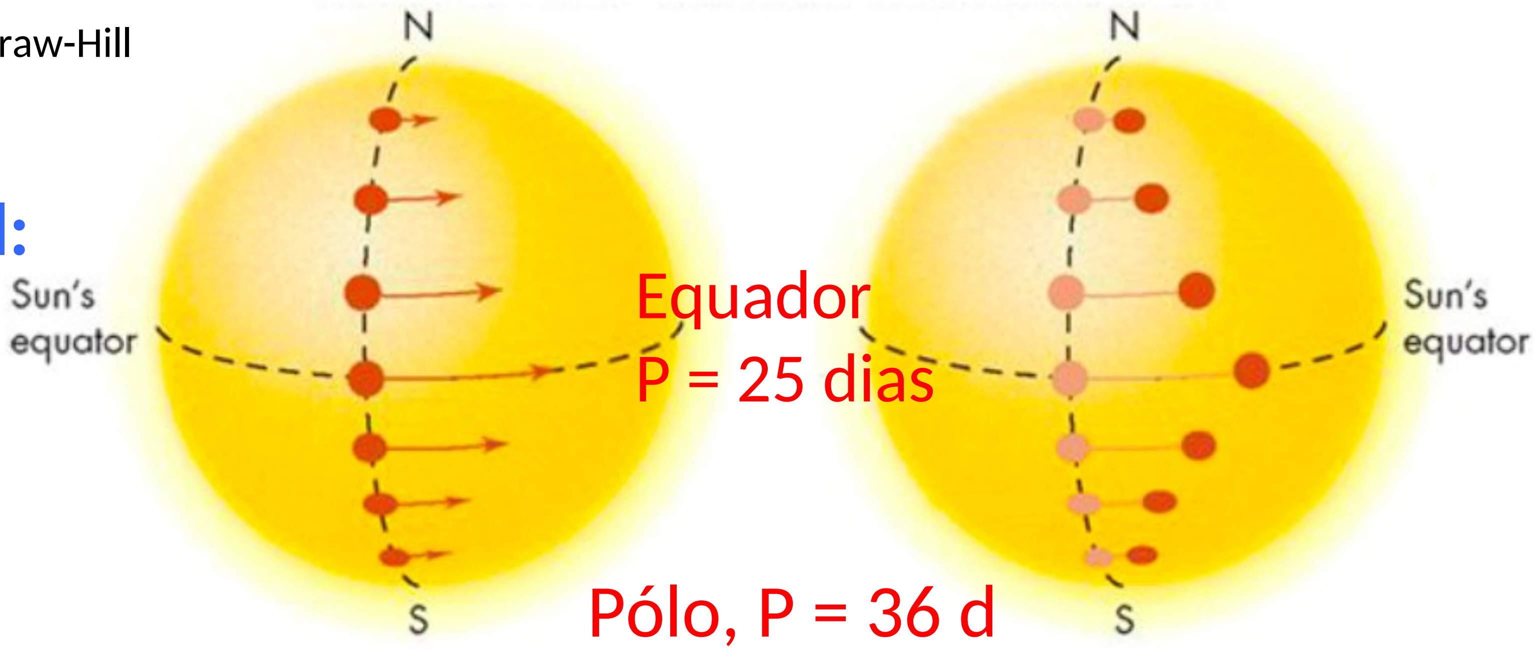
Efeito nas manchas solares



Adatado: (c) McGraw-Hill

Rotação diferencial:

Efeito nas manchas solares



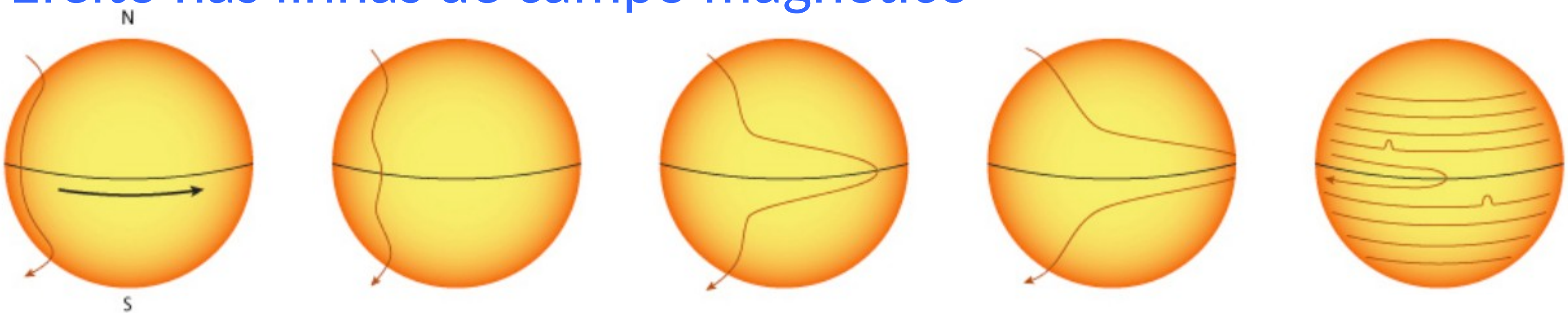
Equador
P = 25 dias

Pólo, P = 36 d

Dia 1

Dia 5

Efeito nas linhas de campo magnético



Começo

1 rotação

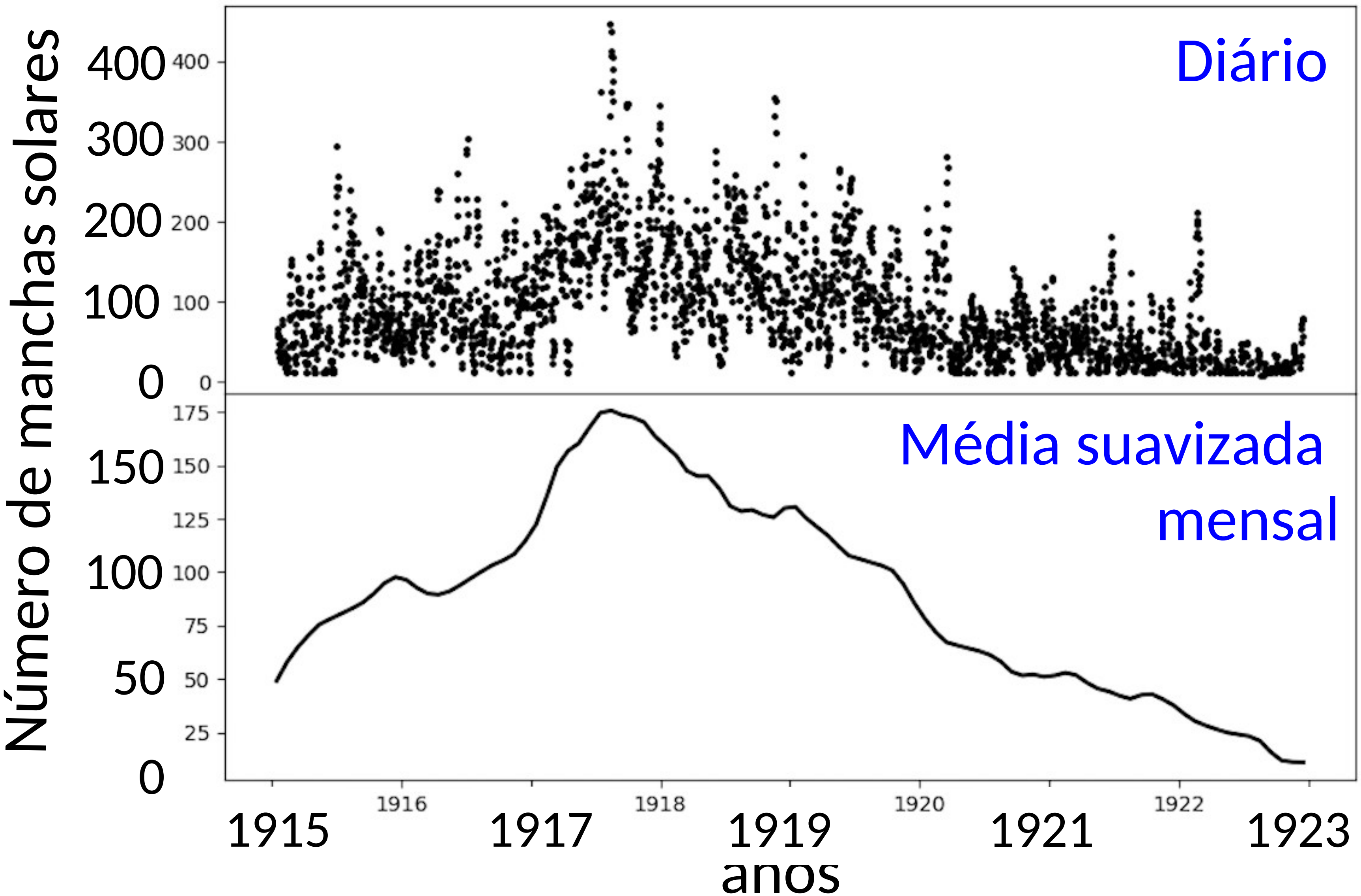
2 rotações

3 rotações

muitas rotações

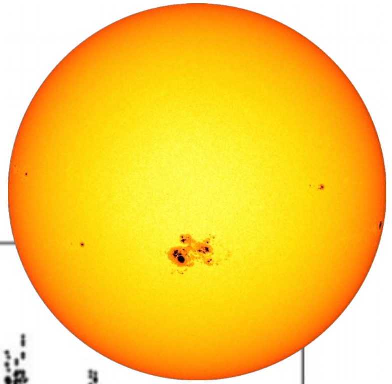
Adatado: (c) NASA/IBEX

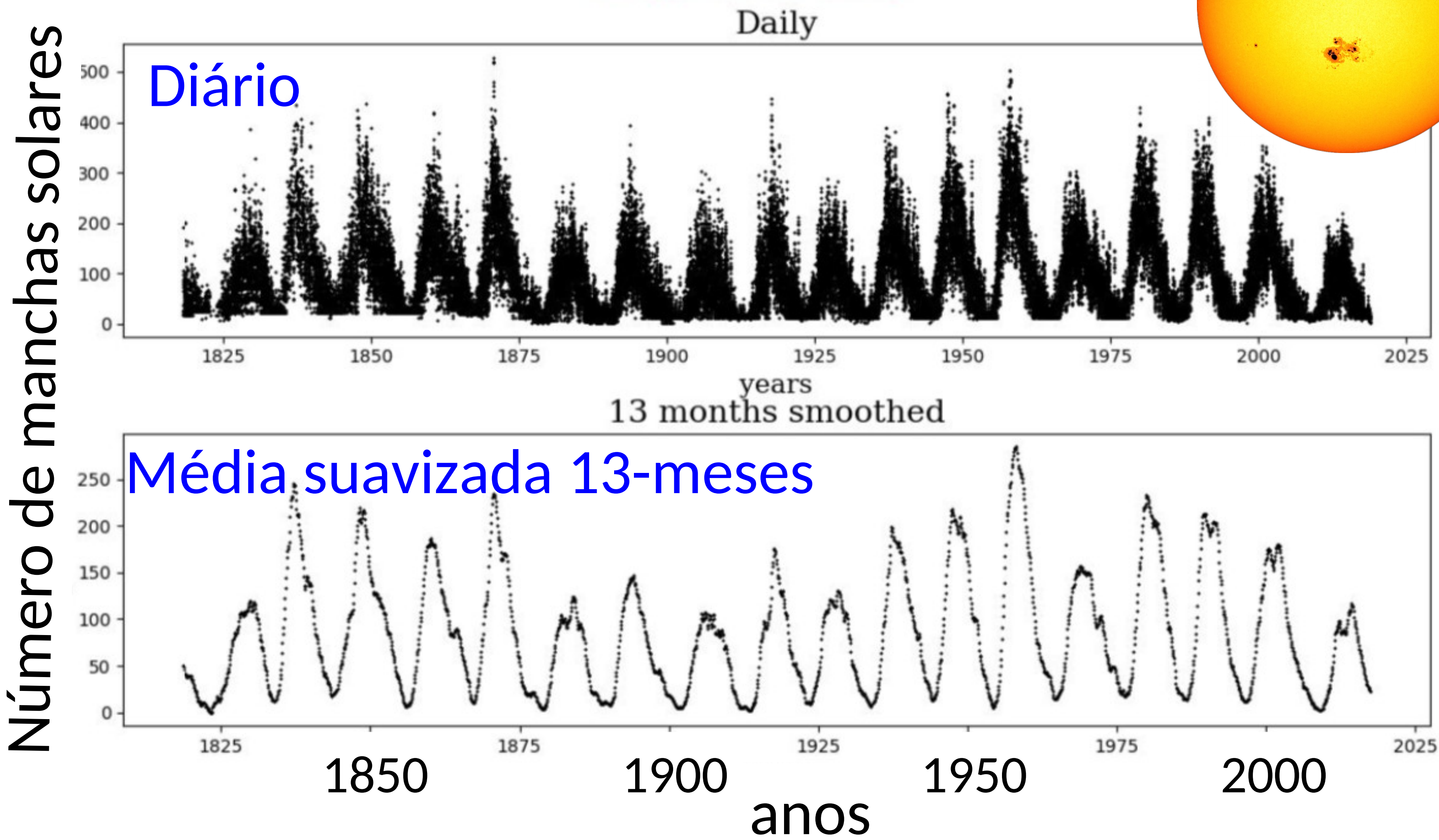
Variação do número de manchas



(c) Gabriela C. Silva, IF-USP (aluna de IC do grupo SAMPA, IAG-USP)

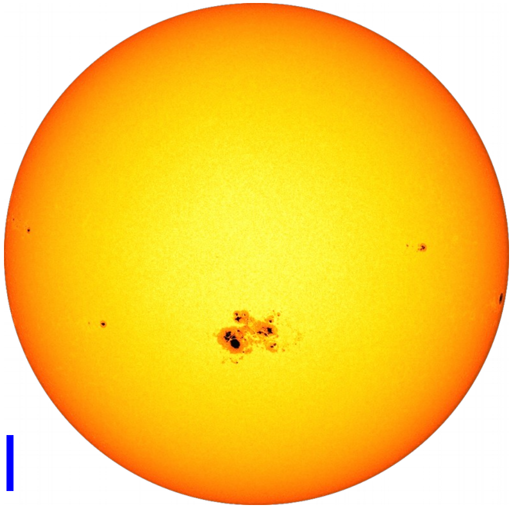
Número de manchas solares



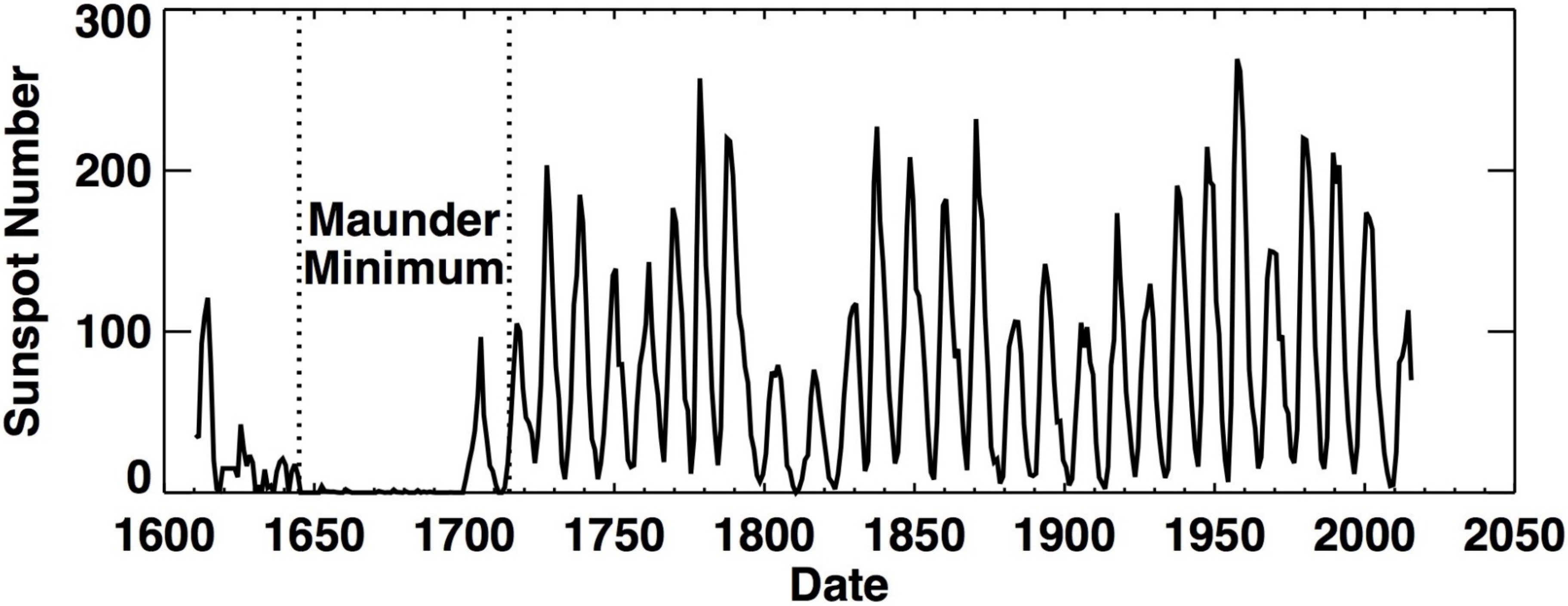


(c) Gabriela C. Silva, IF-USP (aluna de IC do grupo SAMPA, IAG-USP)

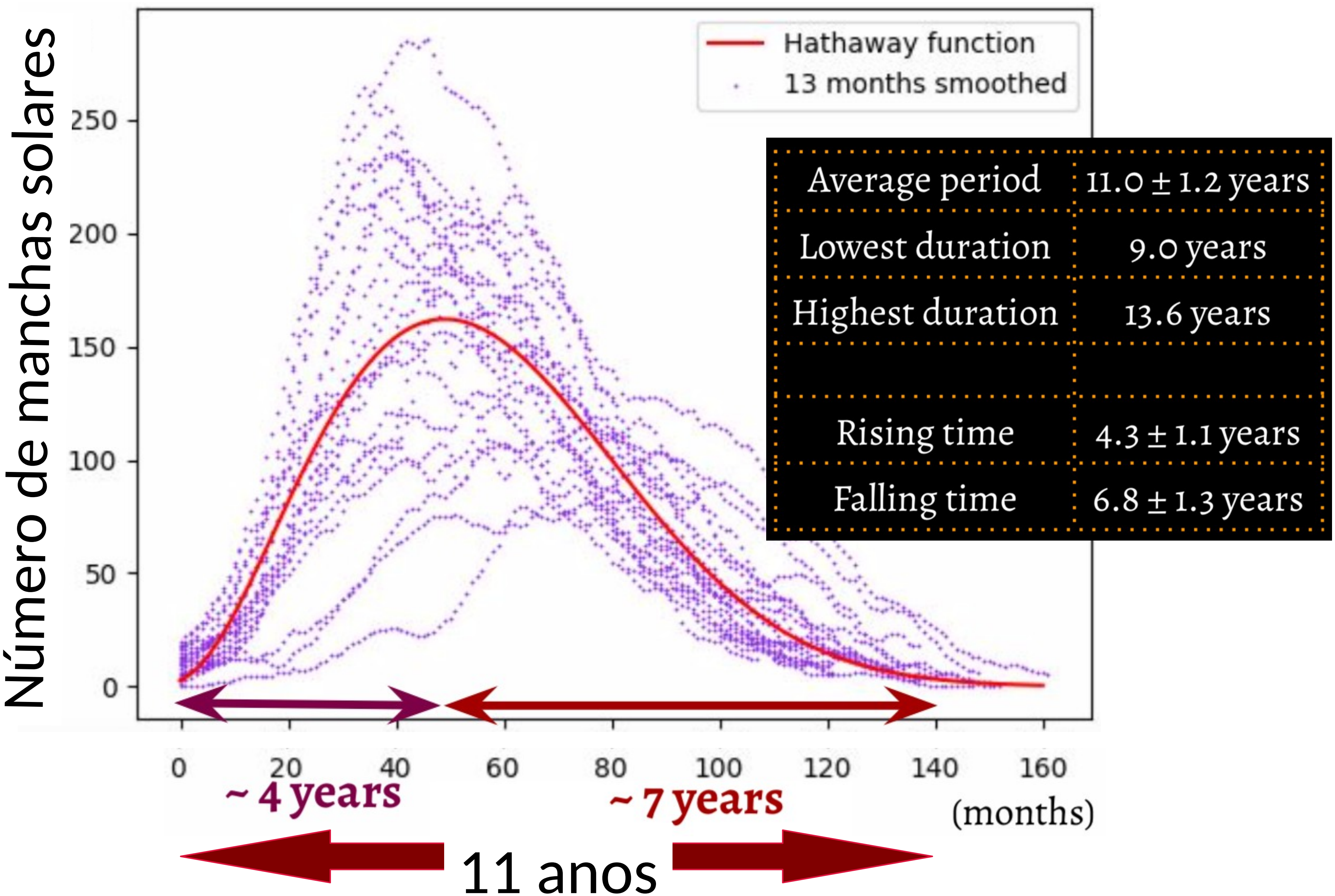
Ciclo de manchas solares quase periódico ~ 11 anos



Média anual



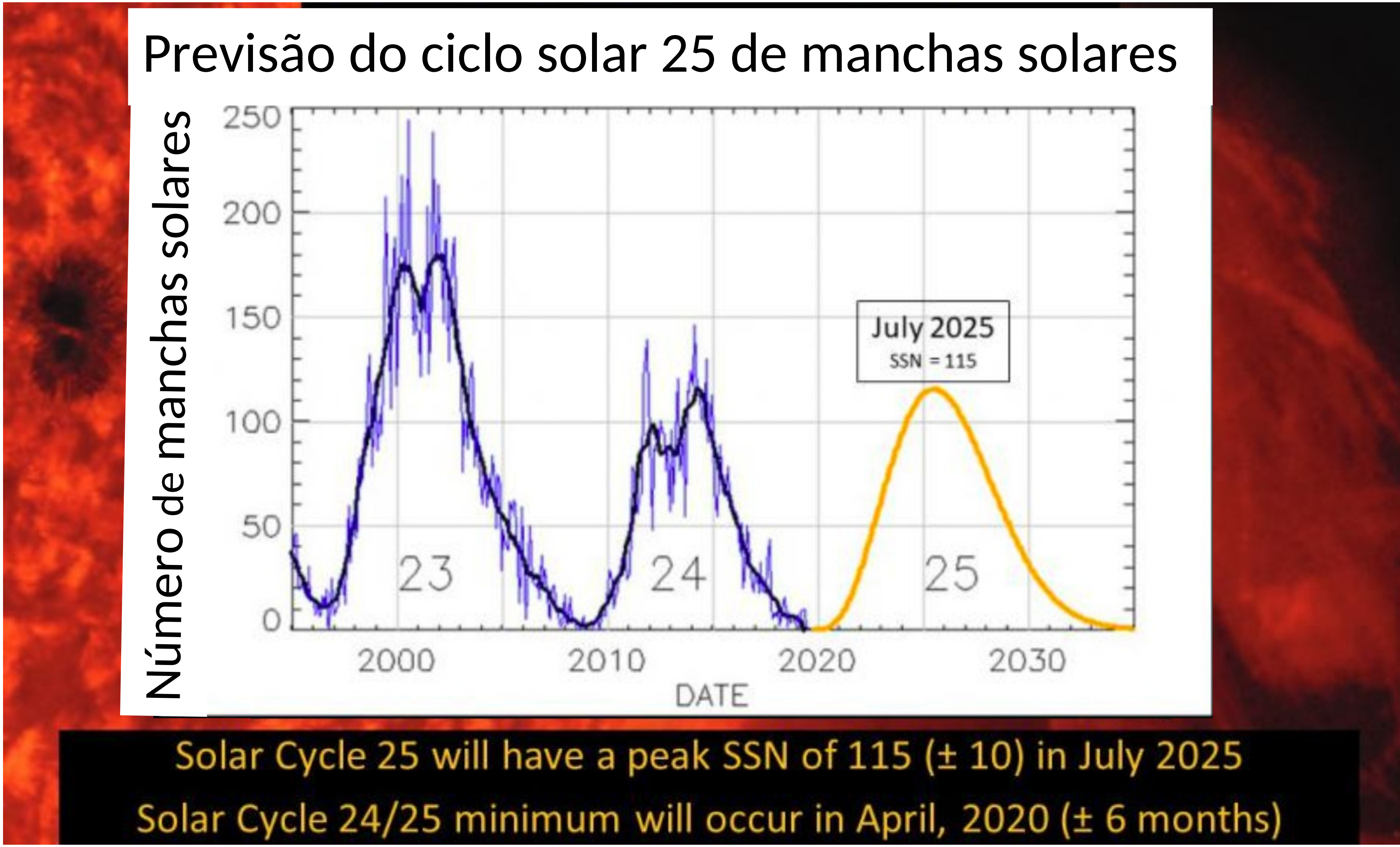
(c) David Hathaway/NASA



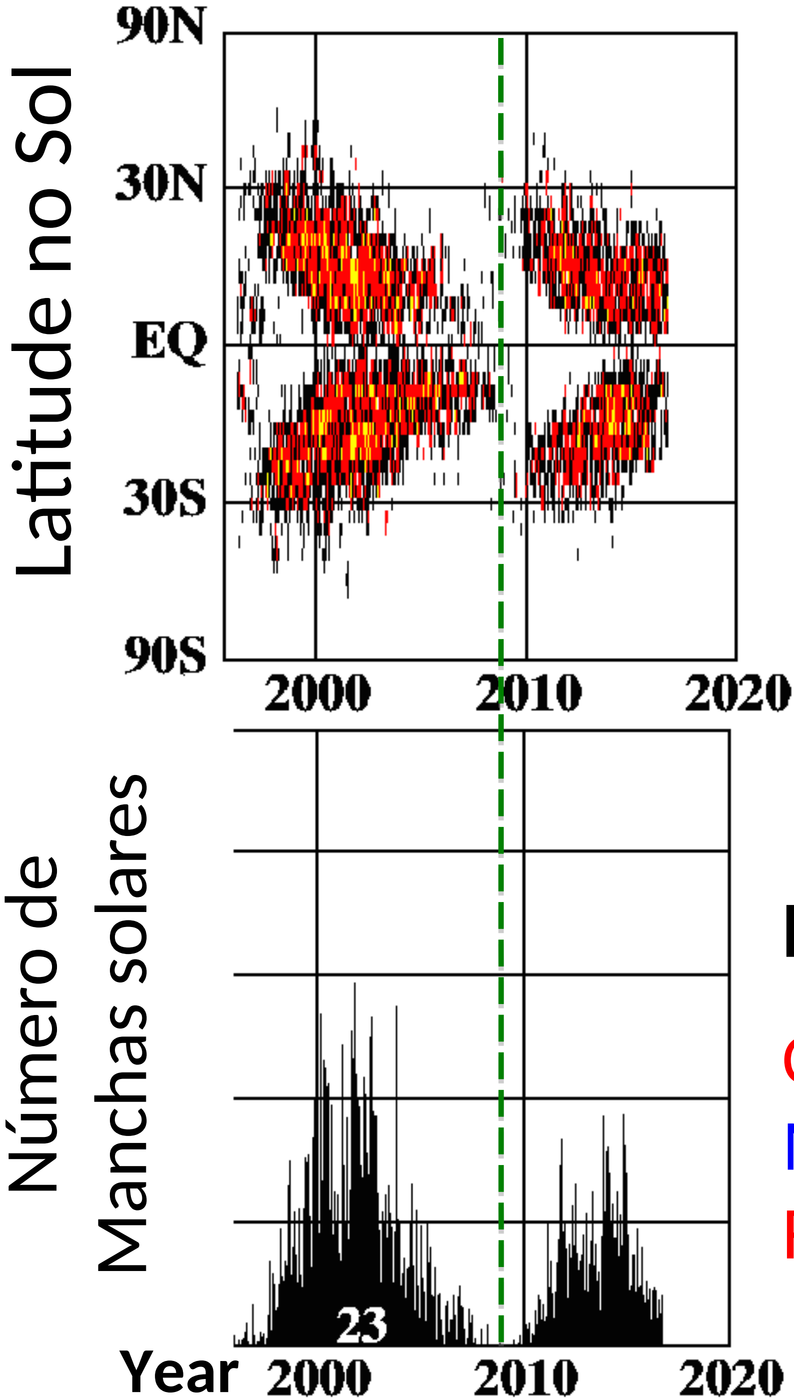
Average period	11.0 ± 1.2 years
Lowest duration	9.0 years
Highest duration	13.6 years
Rising time	4.3 ± 1.1 years
Falling time	6.8 ± 1.3 years

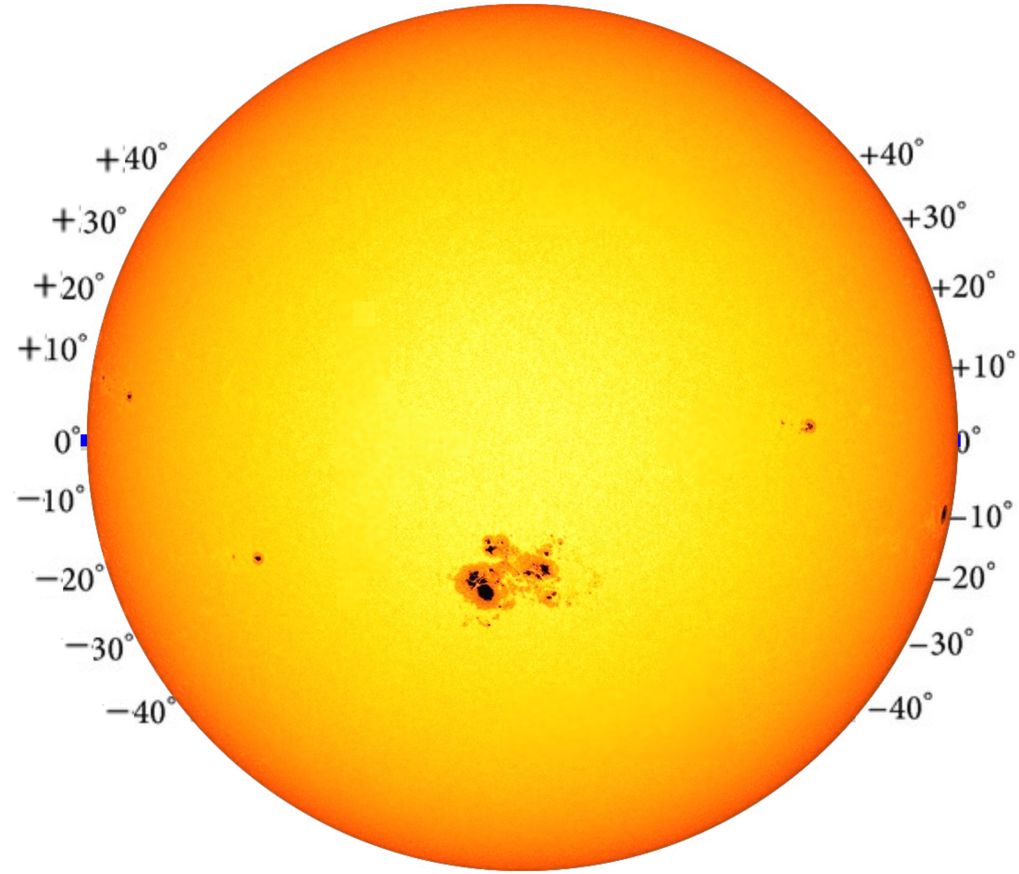
(c) Gabriela C. Silva, IF-USP (aluna de IC do grupo SAMPA, IAG-USP)

Previsão do ciclo solar 25:
início em 12/2019, máximo 7/2025



https://www.swpc.noaa.gov/news/solar-cycle-25-forecast-update



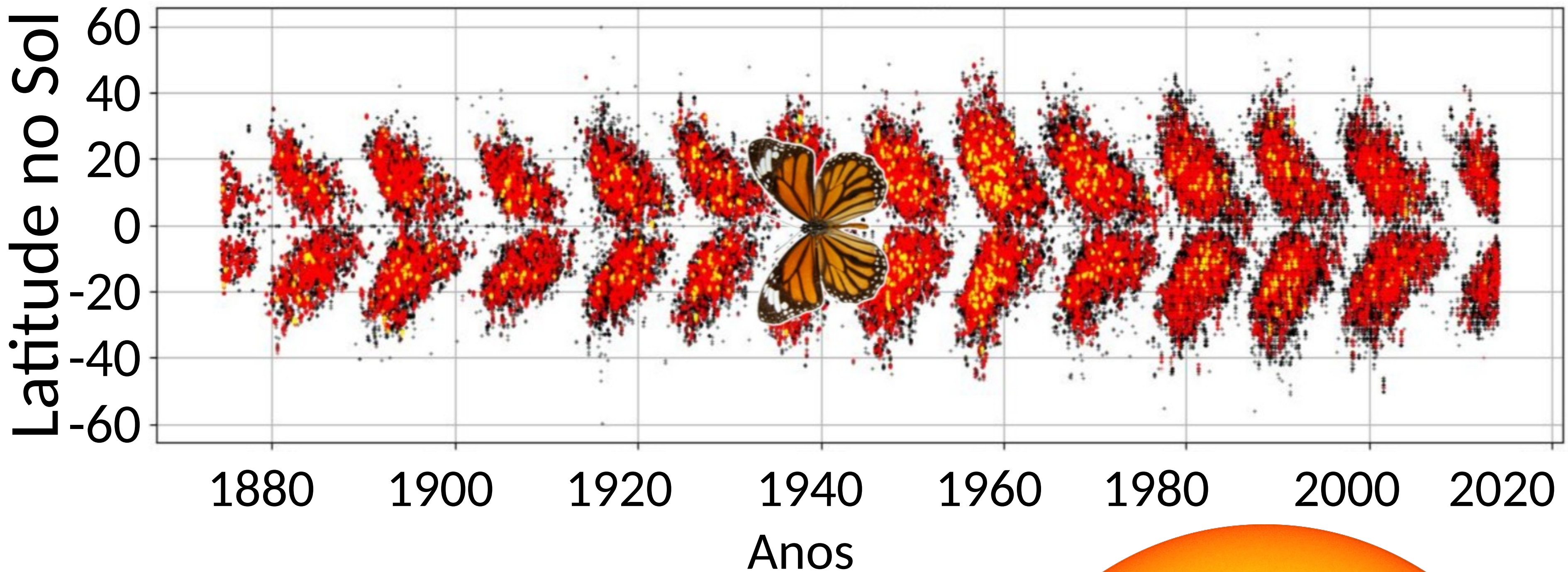


Posição das manchas solares:

Começo ciclo: altas latitudes (±40^0)

Máximo: latitudes intermediárias

Fim do ciclo: perto do equador



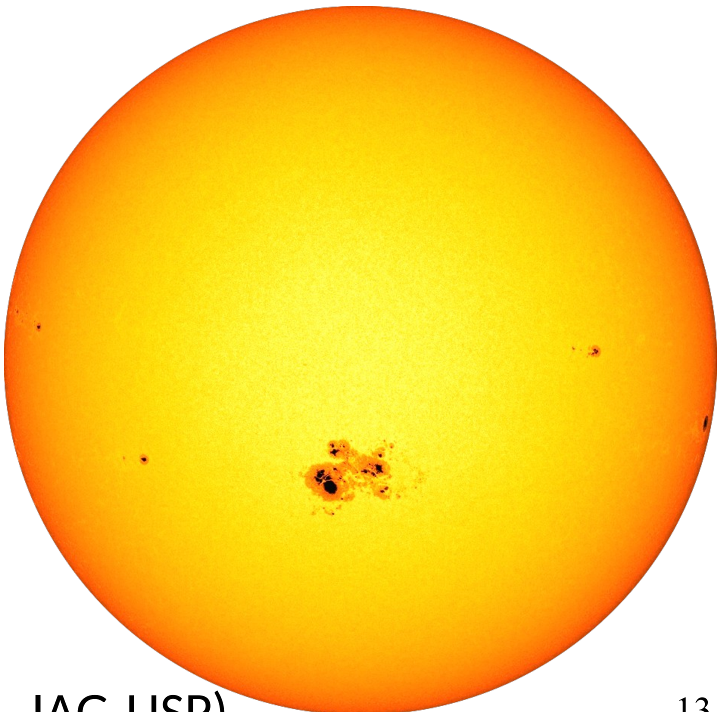
Butterfly diagram

Diagrama da borboleta

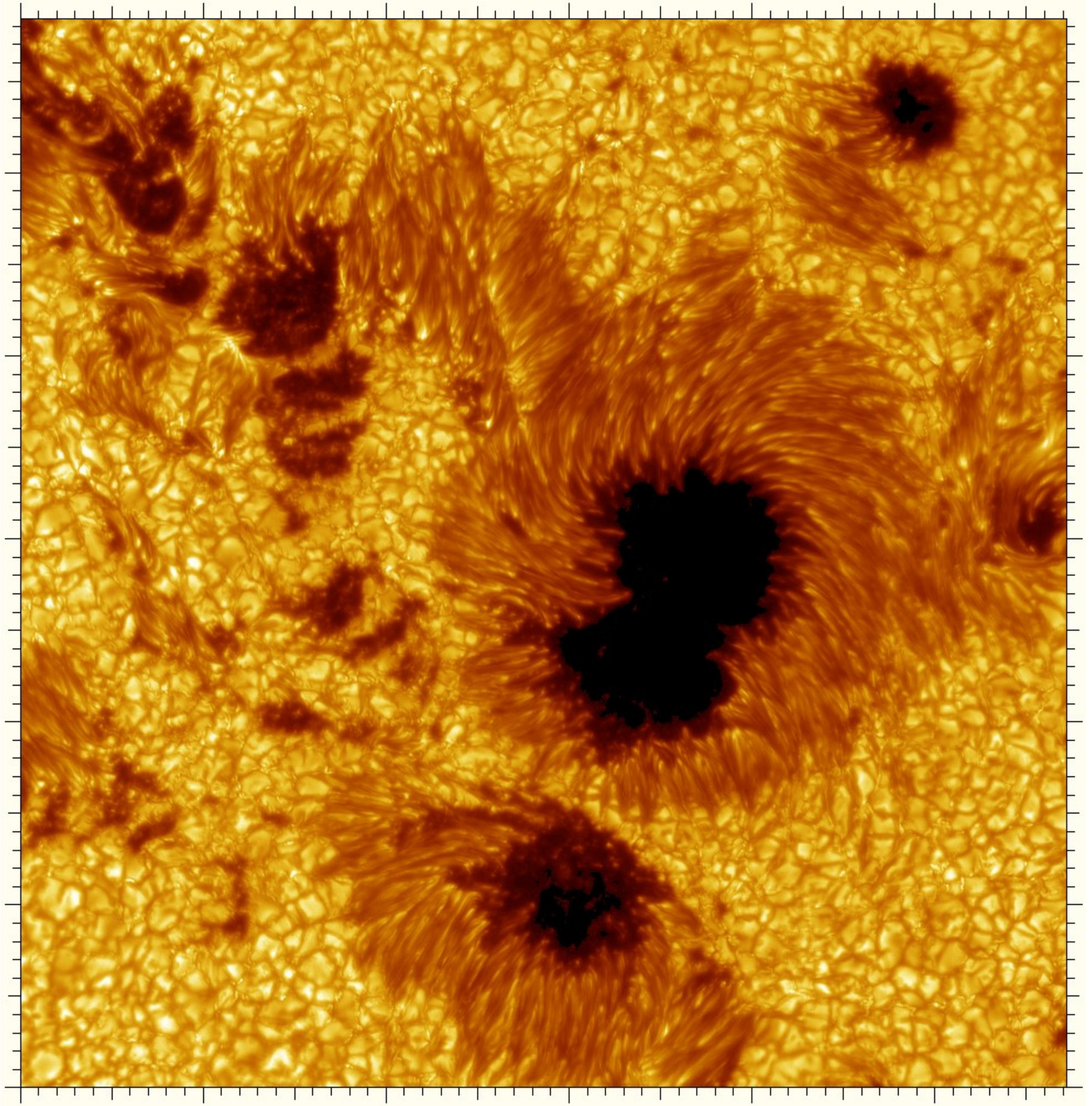
Começo ciclo: altas latitudes (±40^0)

Máximo: latitudes intermediárias

Fim do ciclo: perto do equador



(c) Gabriela Silva, IF-USP (aluna de IC do grupo SAMPA, IAG-USP)



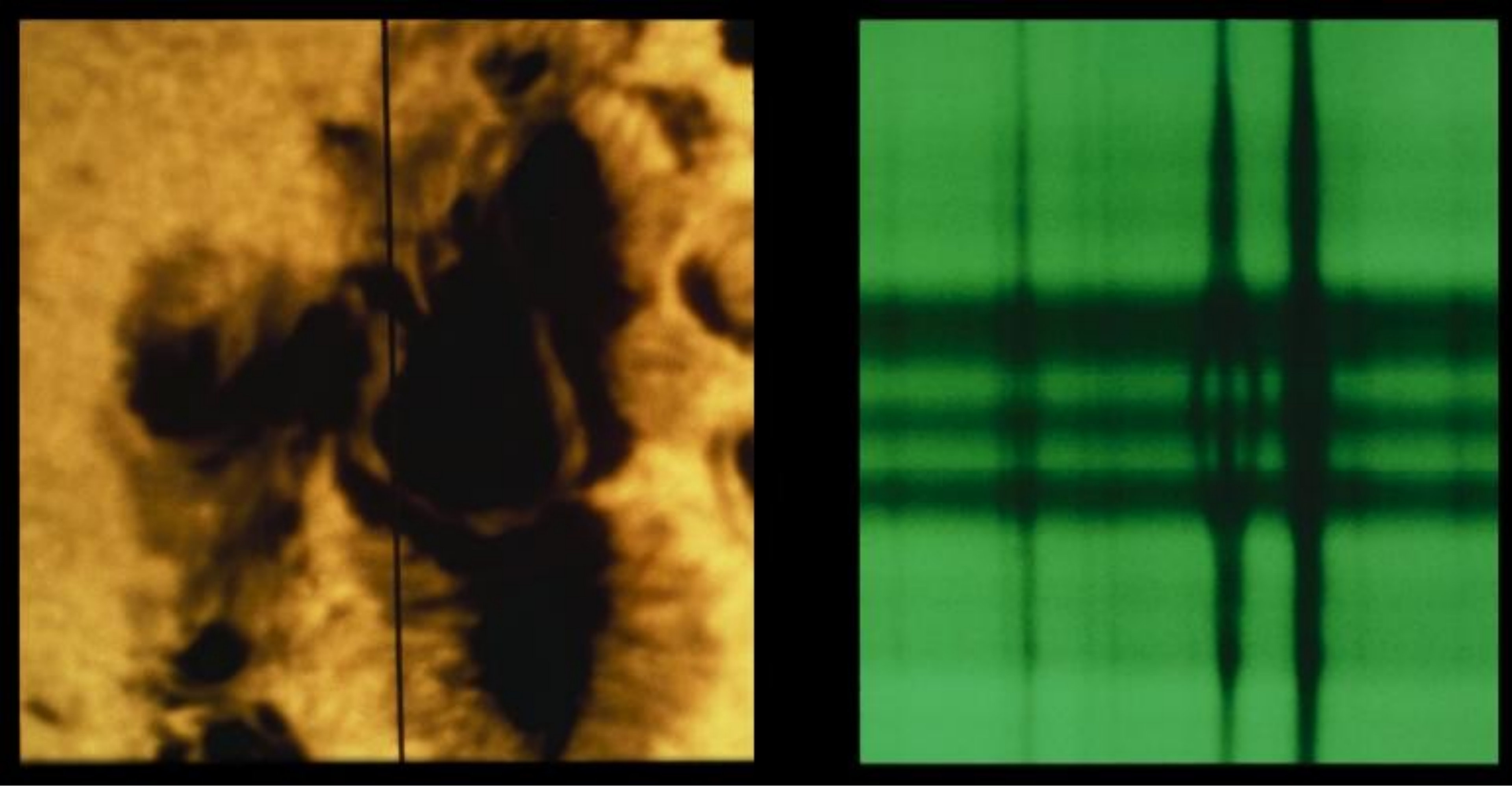
Umbra: região mais escura.

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

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

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

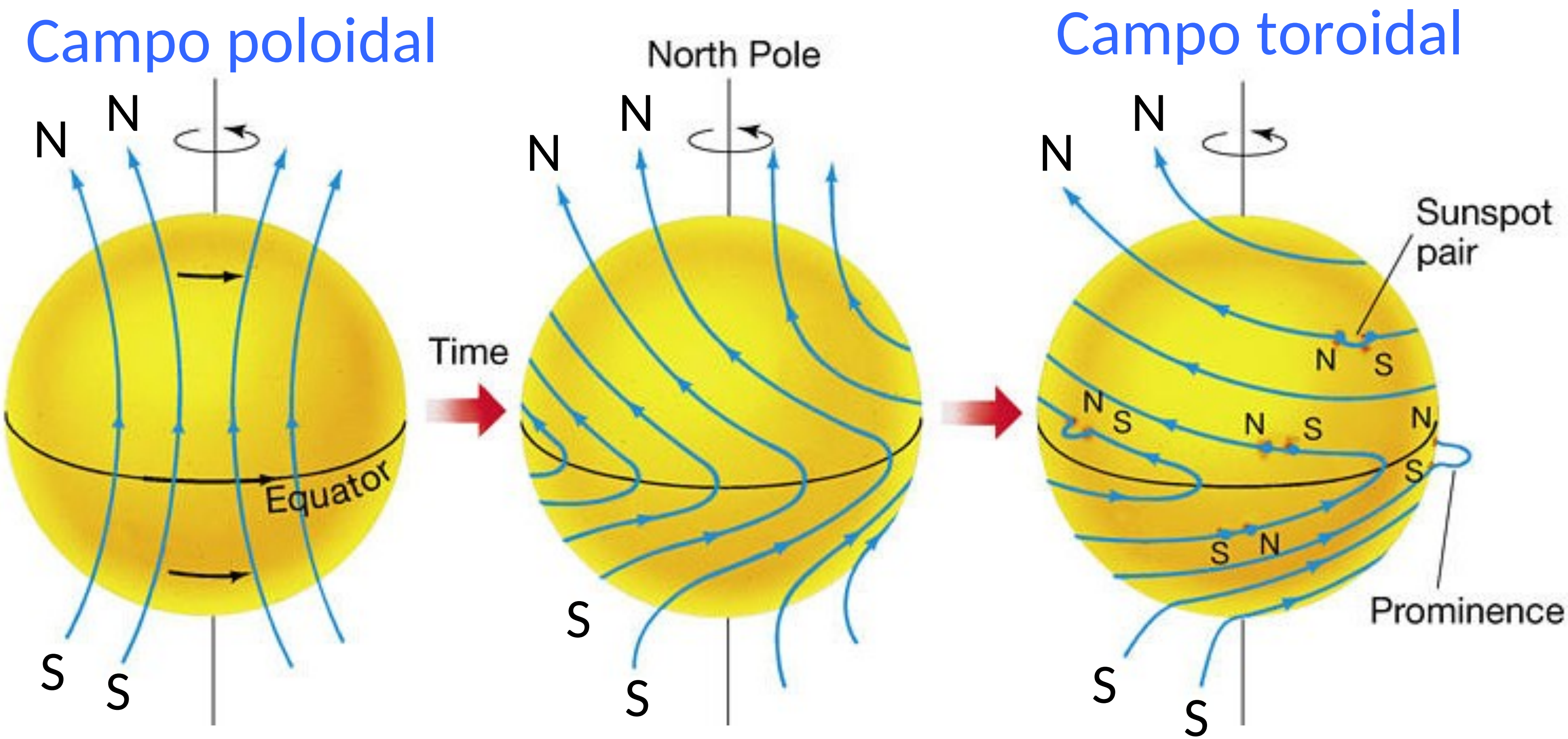
Sunspots observed on 15 July 2002.
The distance between 2 ticks is 1000 km



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.

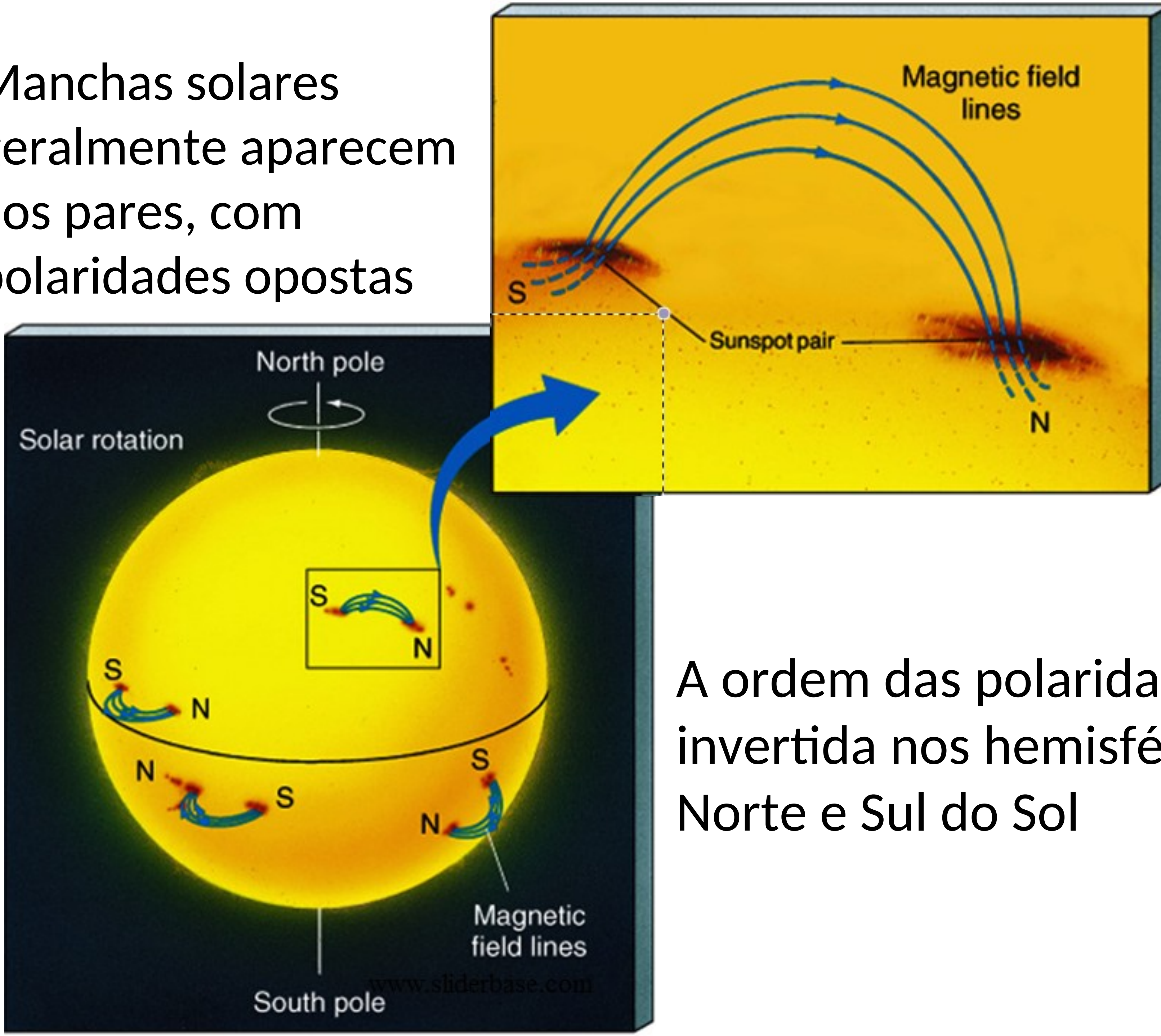
https://www.noao.edu/image_gallery/html/im0404.html

Ciclo de manchas solares



Rotação diferencial → linhas de campo magnético mais enroladas → manchas solares

Manchas solares geralmente aparecem aos pares, com polaridades opostas



A ordem das polaridades é invertida nos hemisférios Norte e Sul do Sol

Ciclo magnético: 22 anos

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

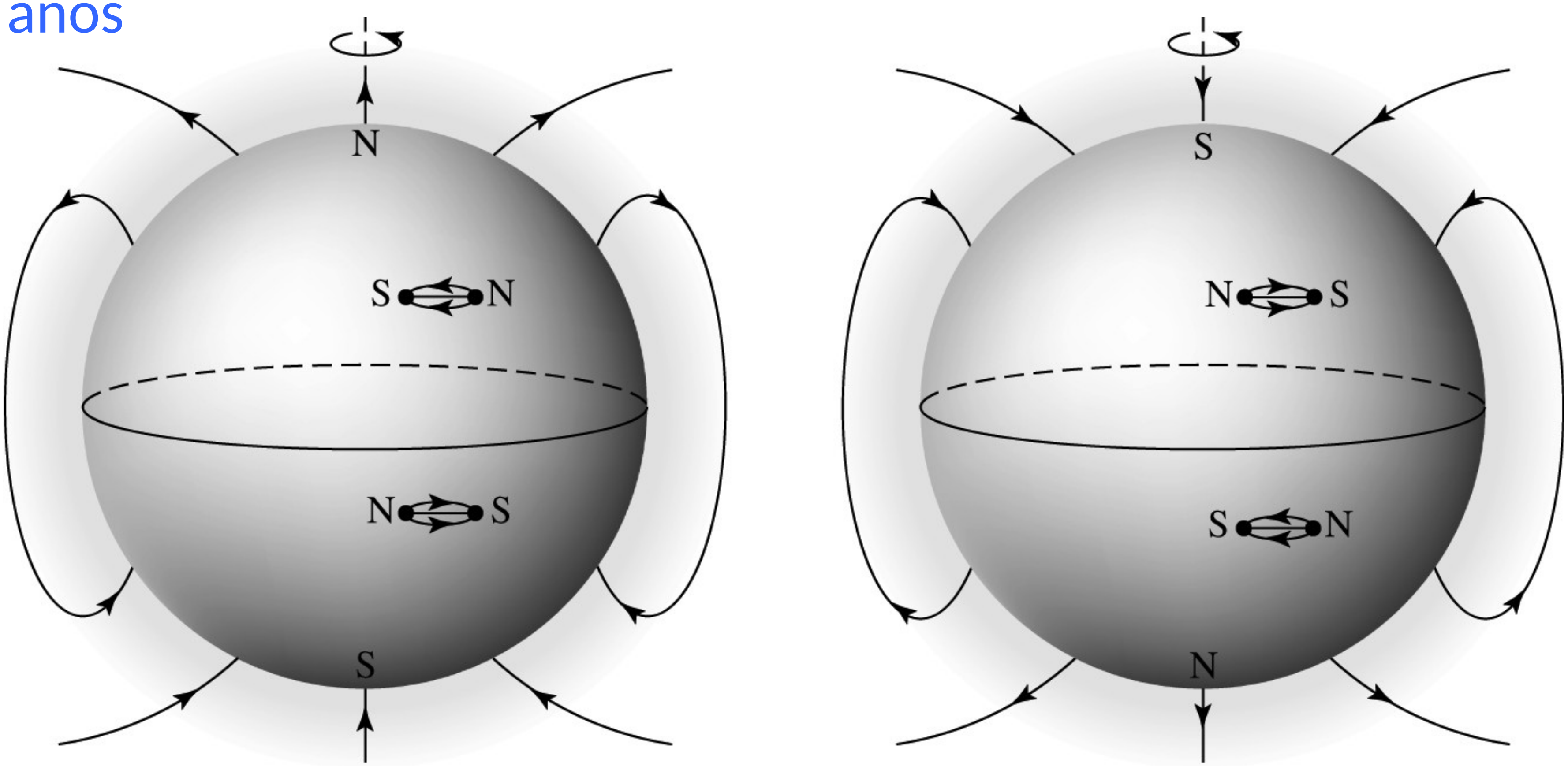
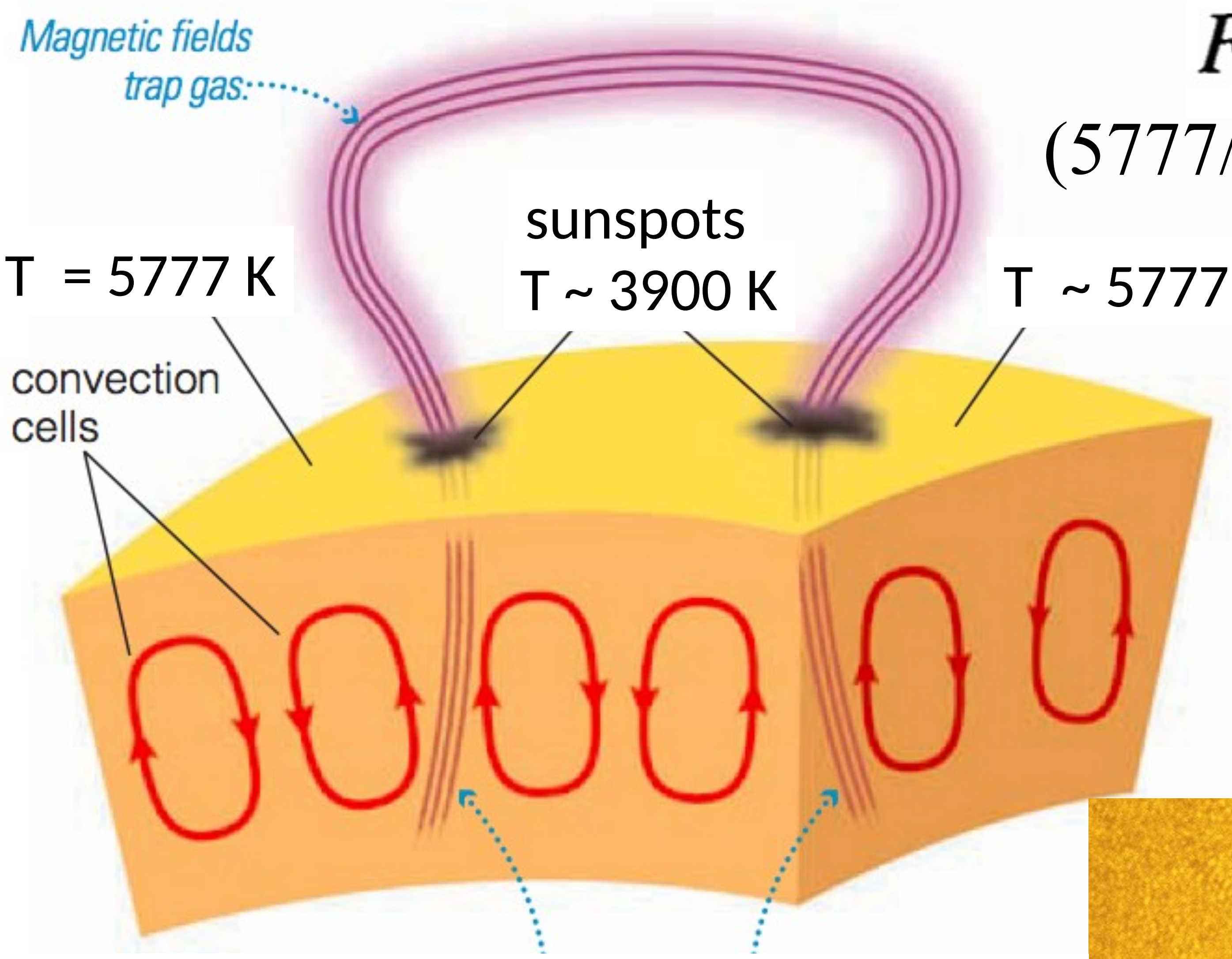


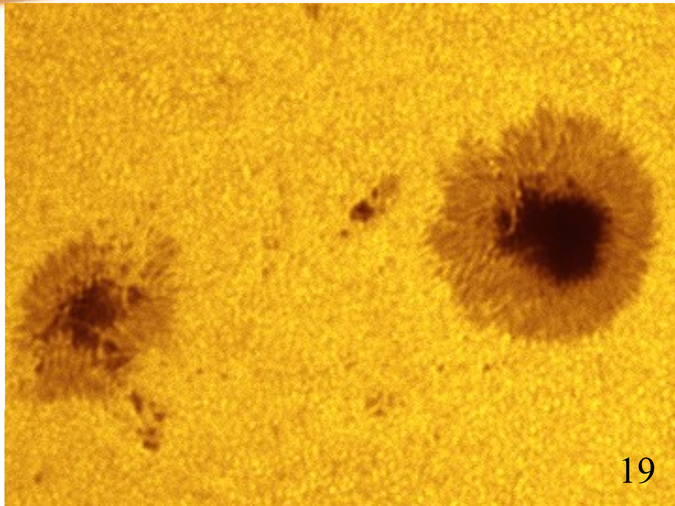
FIGURE 11.32 The global magnetic field orientation of the Sun, along with the magnetic polarity of sunspots during successive 11-year periods.

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

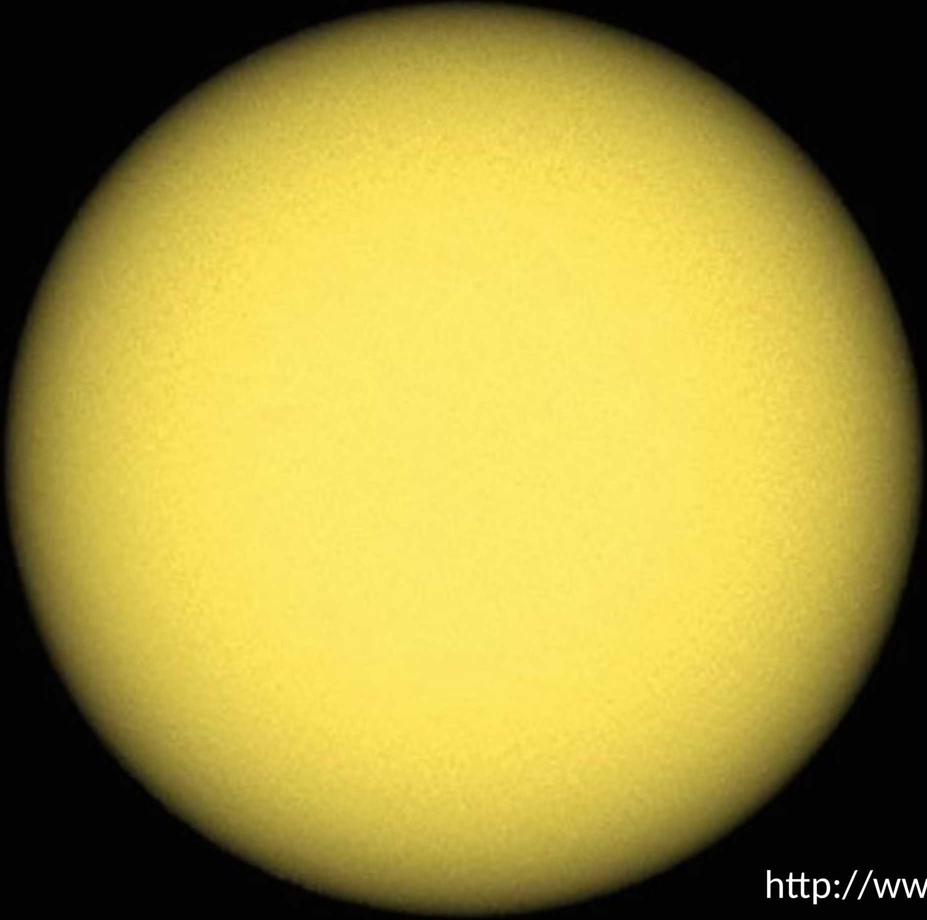
$$(5777/3900)^4 = 4{,}8$$

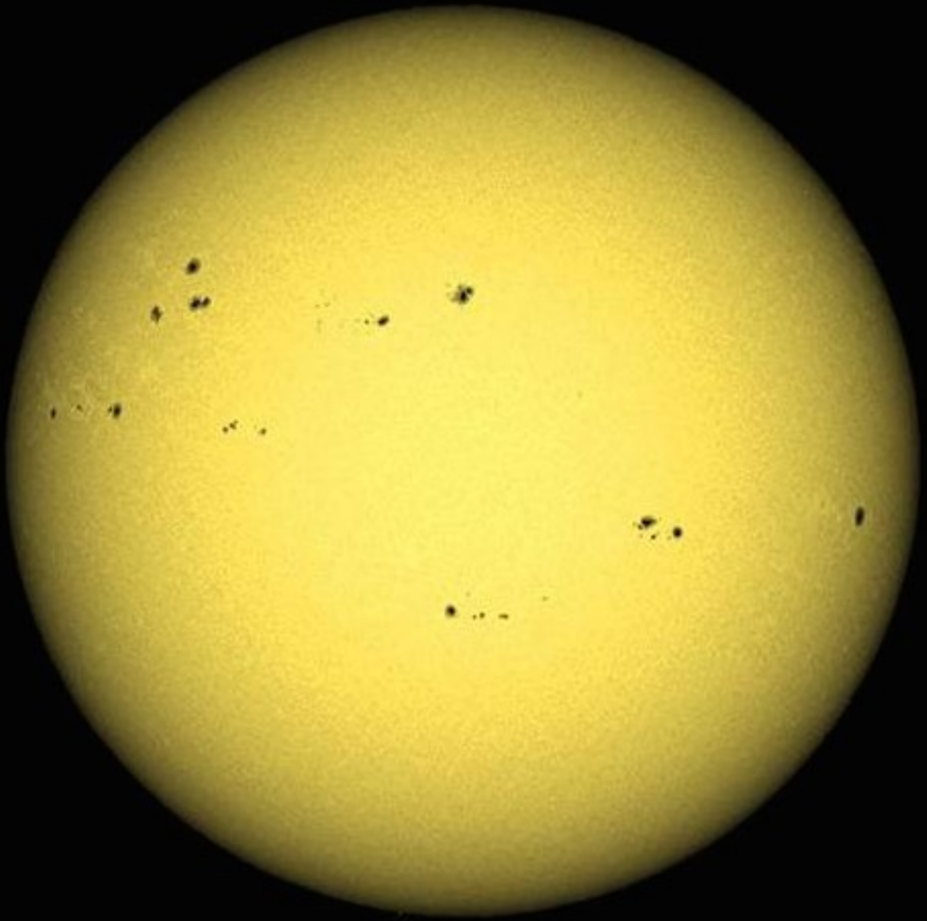


Magnetic fields of sunspots suppress convection and prevent surrounding plasma from sliding sideways into sunspot



Sol no mínimo de atividade: sem manchas





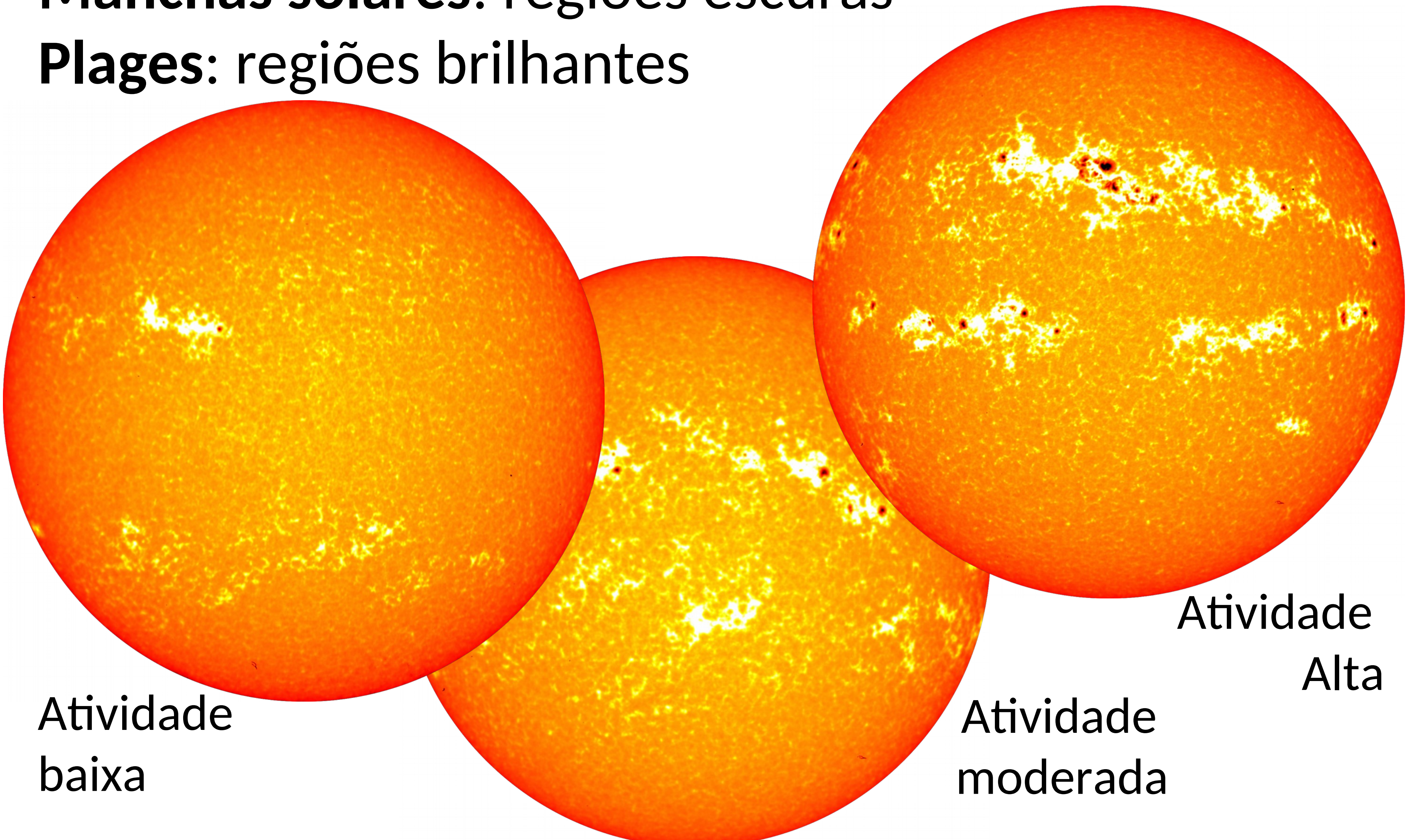
Sol no máximo de atividade: maior número de manchas

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

Manchas solares: regiões escuras

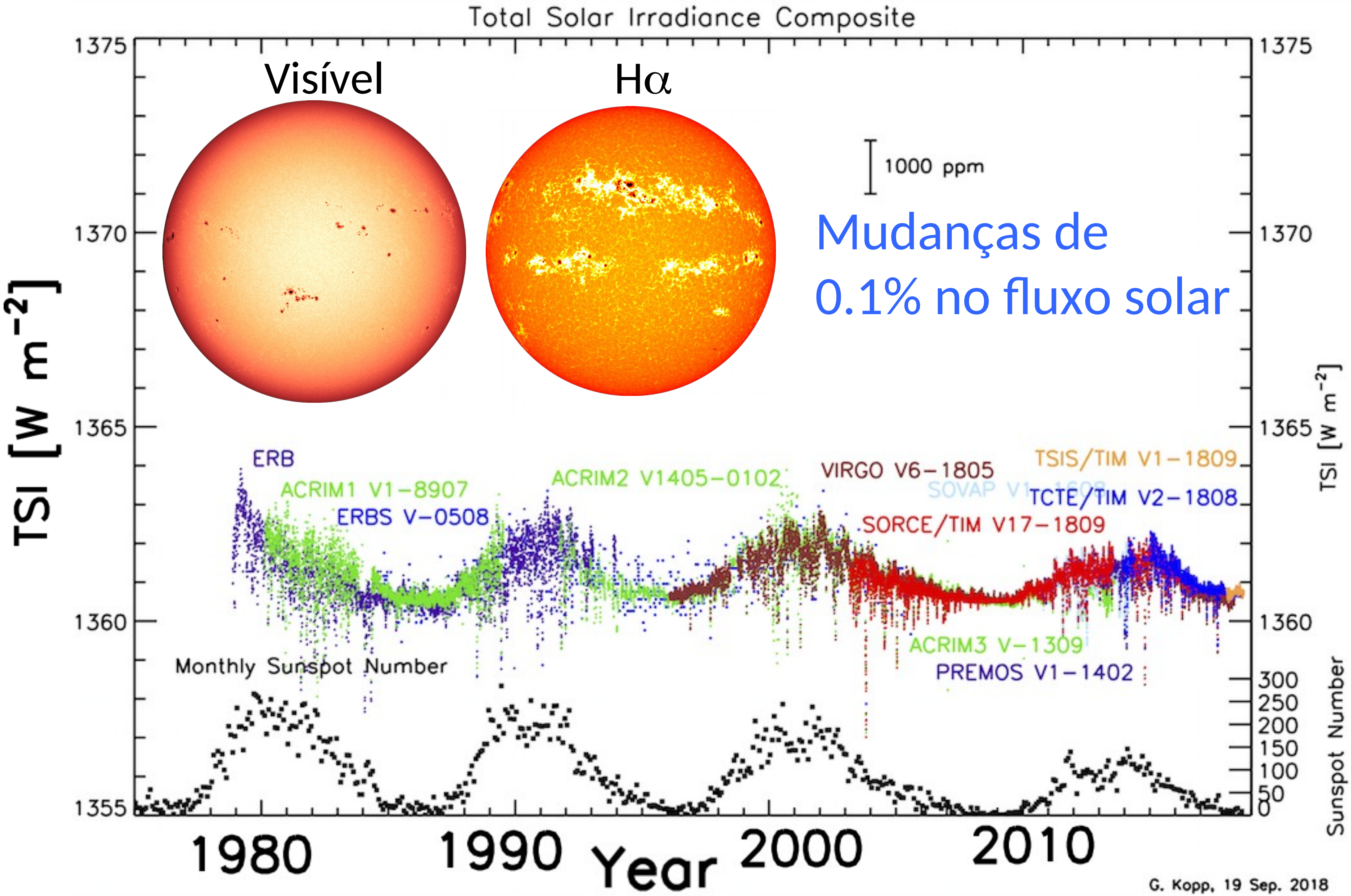
Plages: regiões brilhantes

Sol em Hα



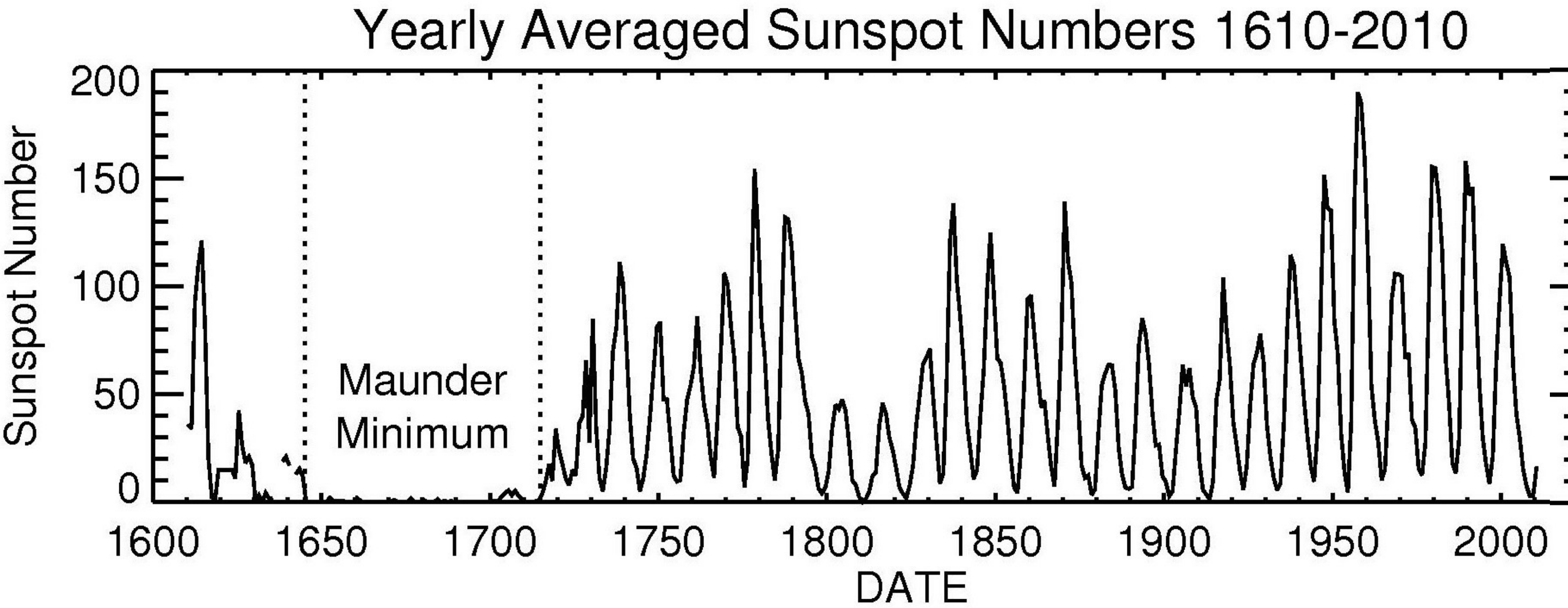
Views of the Sun showing different levels of activity. The color table has been altered to enhance faculae/plage (white regions) which are hotter than sunspots (red-black regions) and whose greater total area contribute to increasing the solar flux reaching the Earth. https://svs.gsfc.nasa.gov/2644

Irradiância Solar Total (TSI)

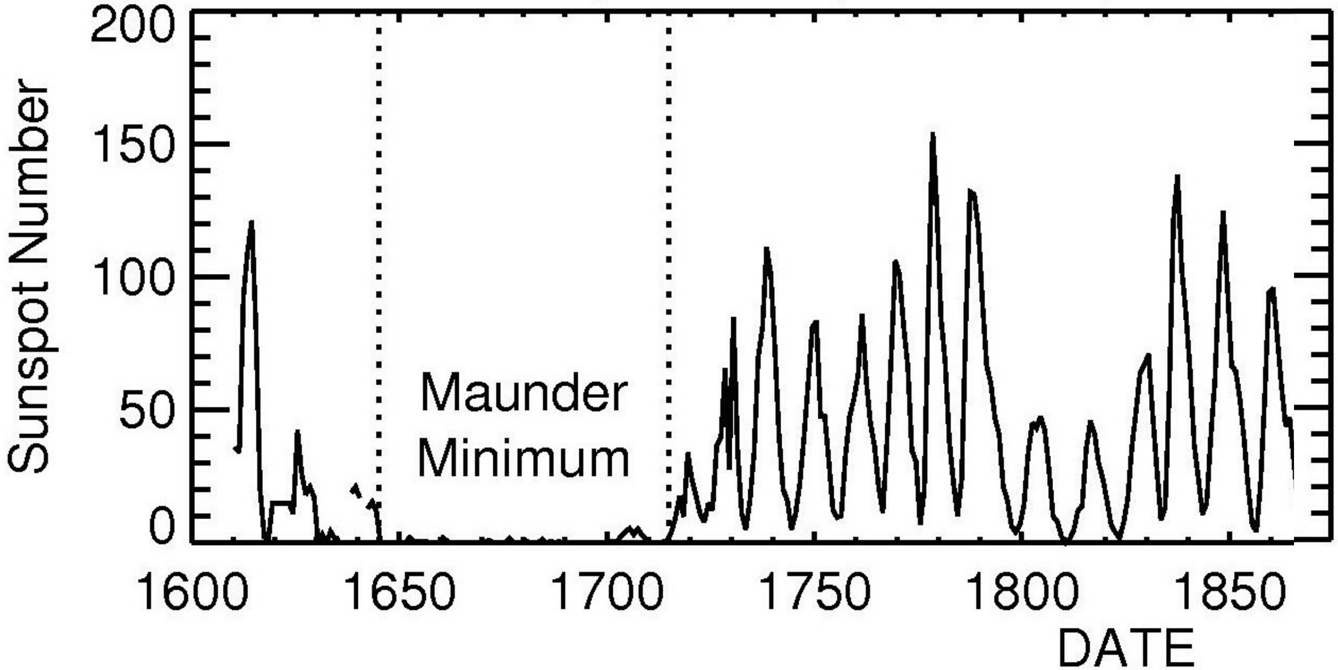


http://spot.colorado.edu/~koppg/TSI/

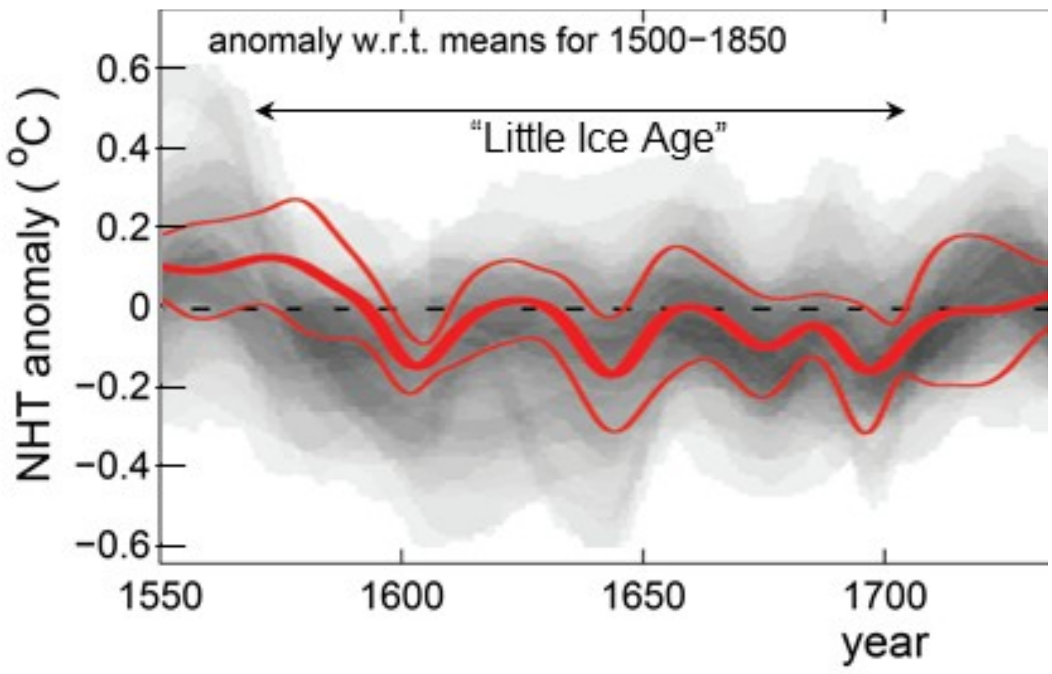
Mínimo de Maunder: entre 1645 e 1715 as manchas solares tornaram-se raras



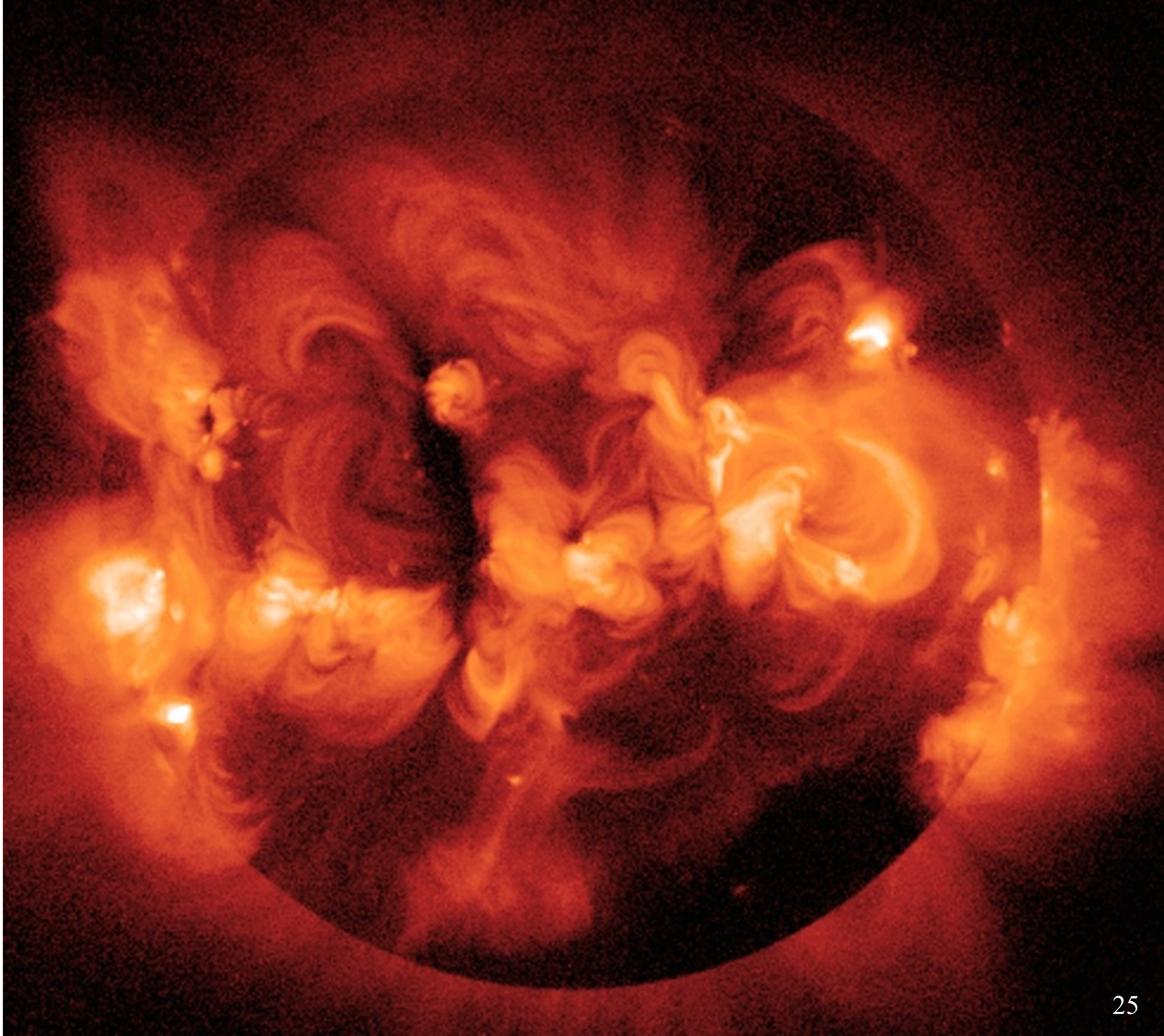
https://www.nasa.gov/mission_pages/sunearth/news/solarcycle-primer.html



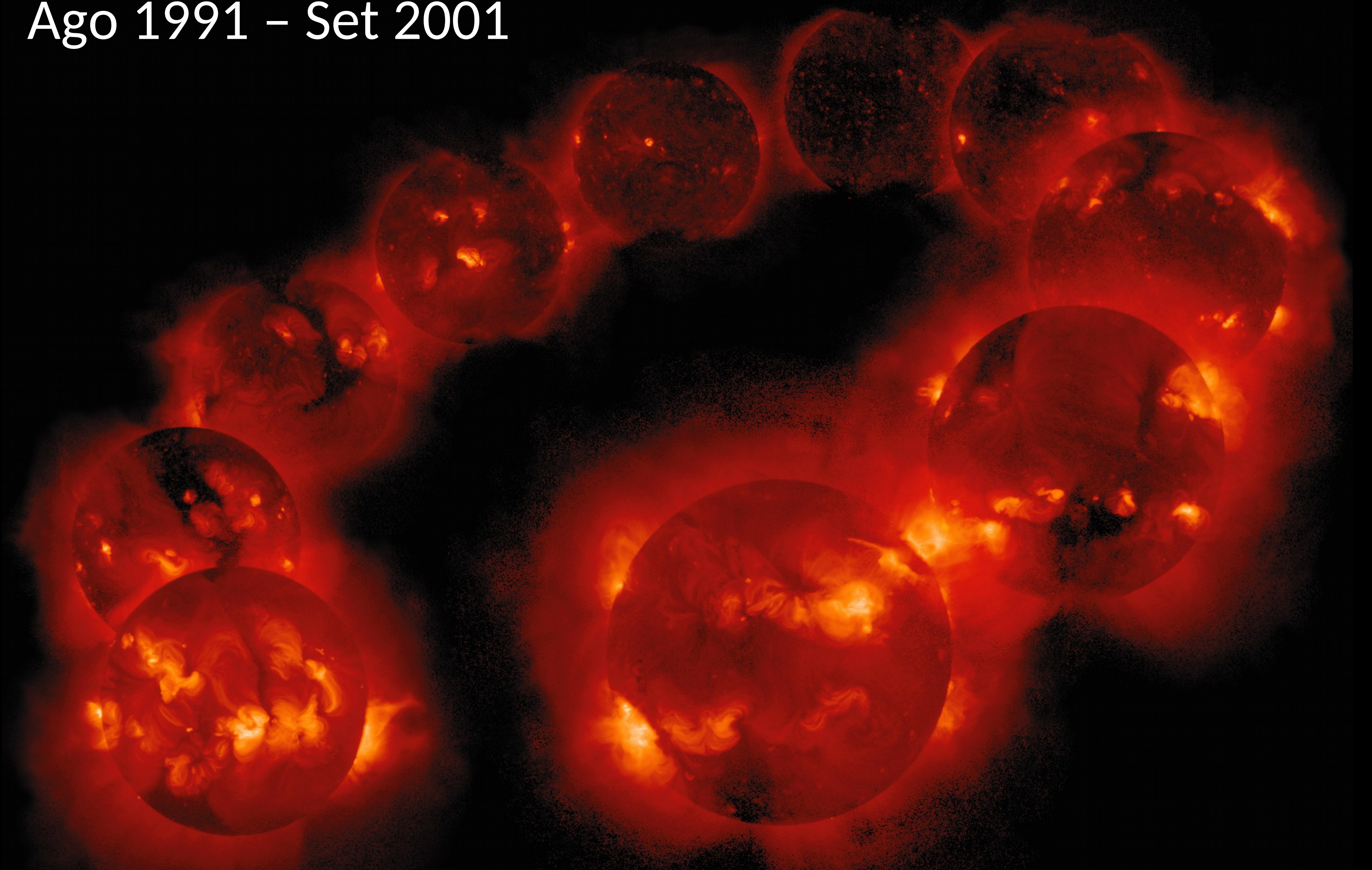
Talvez sem conexão com pequena idade de gelo



Sol em raios-X pelo Yohkoh em 1991



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



~ máximo do ciclo 22 ao máximo do ciclo 23

Flare solar (erupção solar)

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

podem alcançar

uma altura de

~ 100 000 km

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

No flare, também são ejetados raios cósmicos

Densidade de energia magnética:

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

μ_0: constante de permeabilidade magnética do vácuo

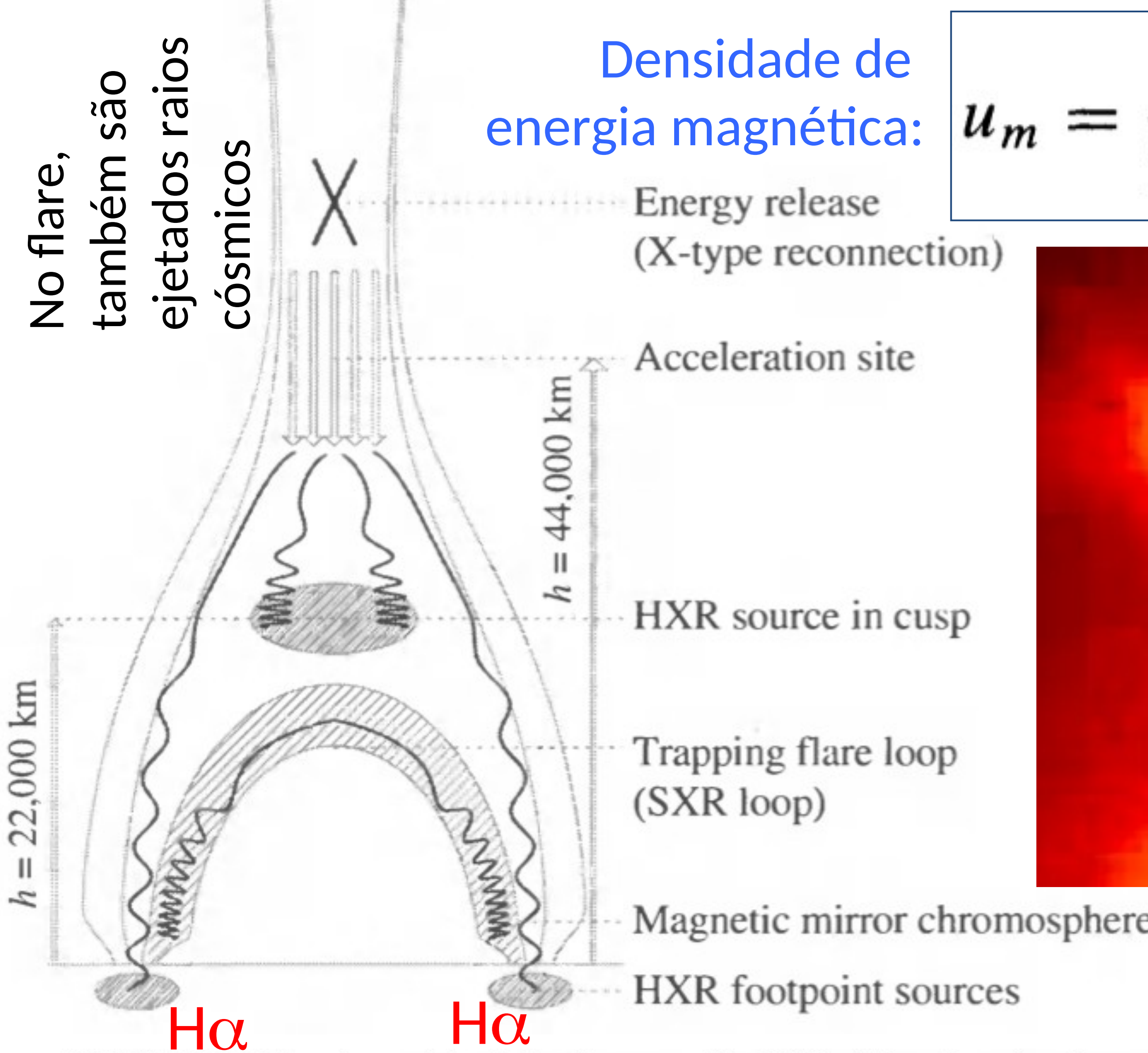


Imagem raios-X de *flare* (erupção) solar

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.)

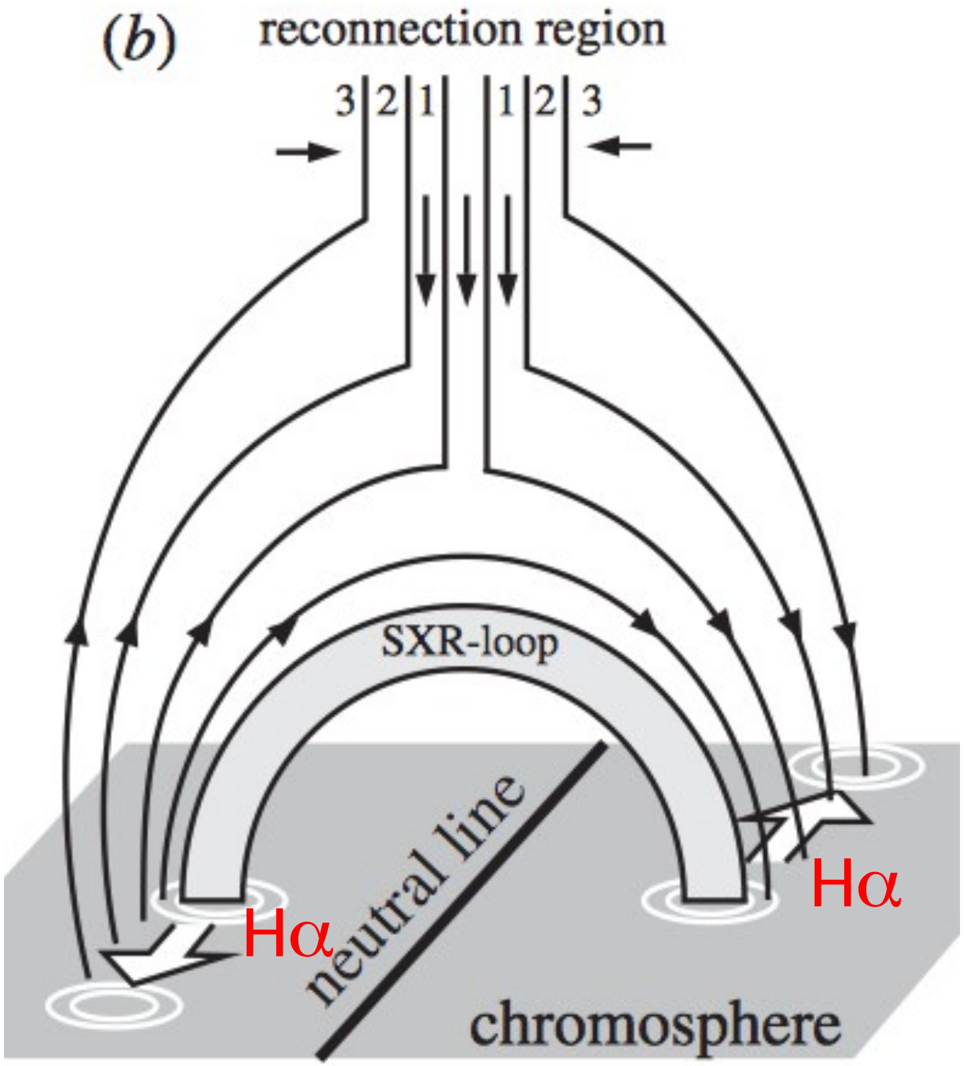
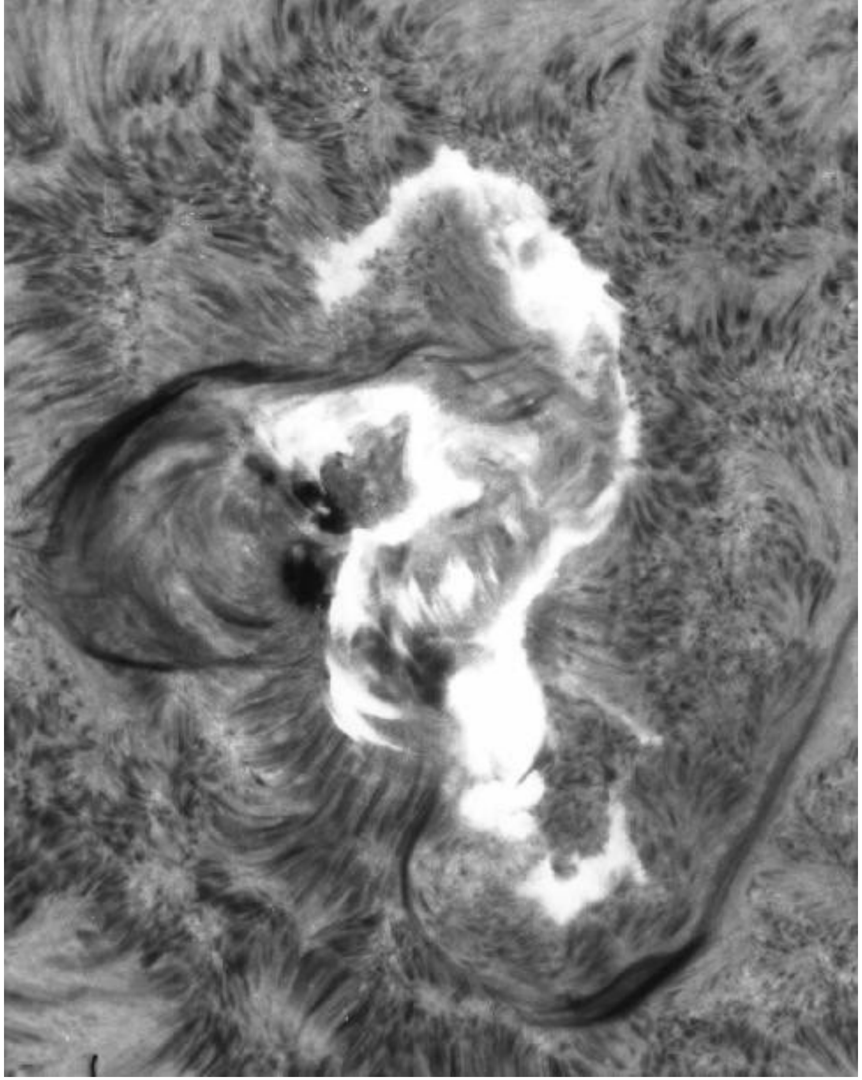
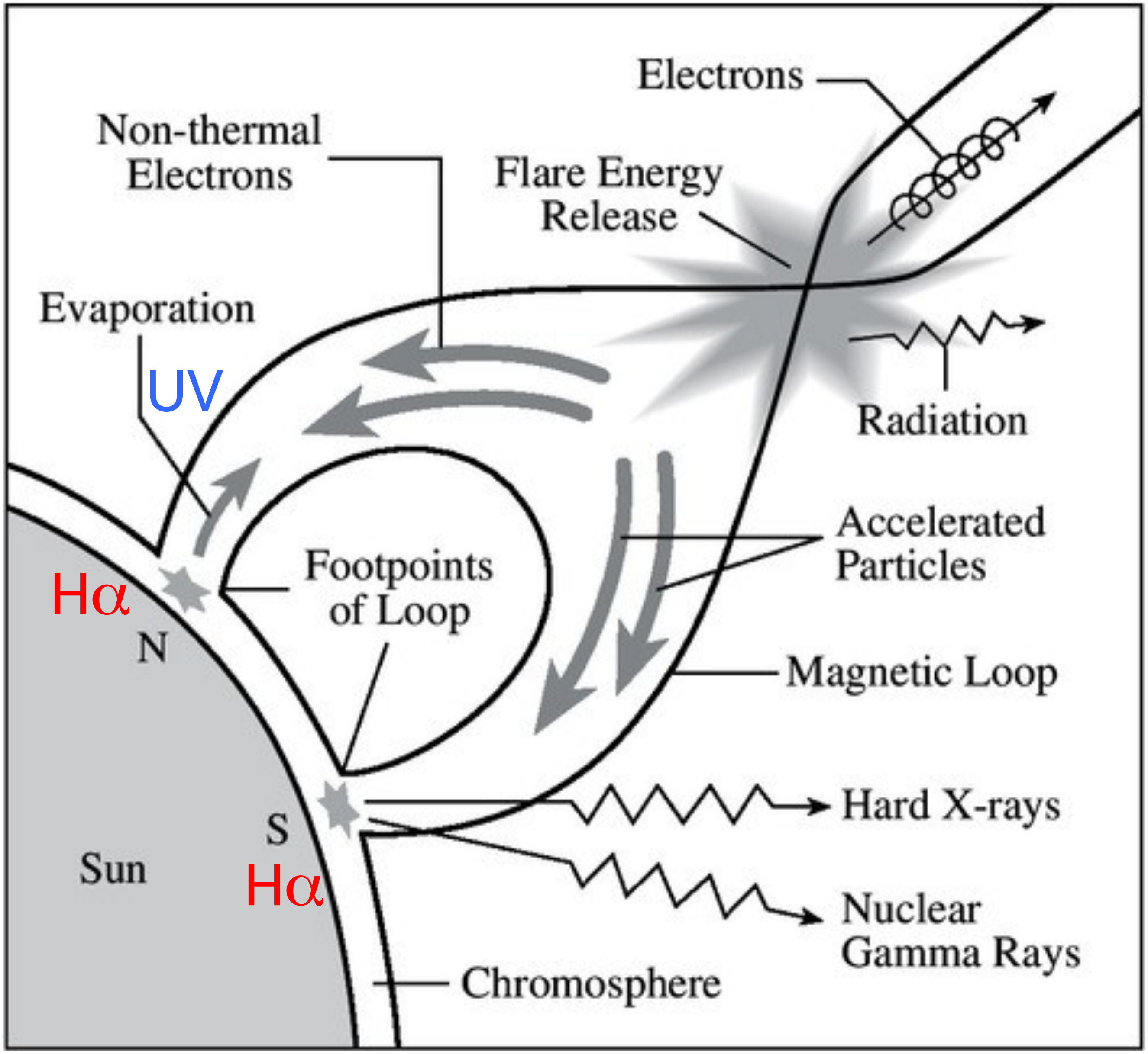


Fig. 3b, Solar flares and energetic particles NICOLE VILMER, *Phil. Trans. R. Soc. A* (2012) **370**, 3241



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

Hα: recombinação do H (p+ e-)

Soft X-rays: altas temperaturas

Hard X-ray: Bremsstrahlung

Gamma rays: reações nucleares

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

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

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

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

with $E_\gamma = 4.438$ MeV, or

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

followed by the de-excitation reaction

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

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

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

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

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

where $E_\gamma = 2.223$ MeV.

Proeminência solar quiescente

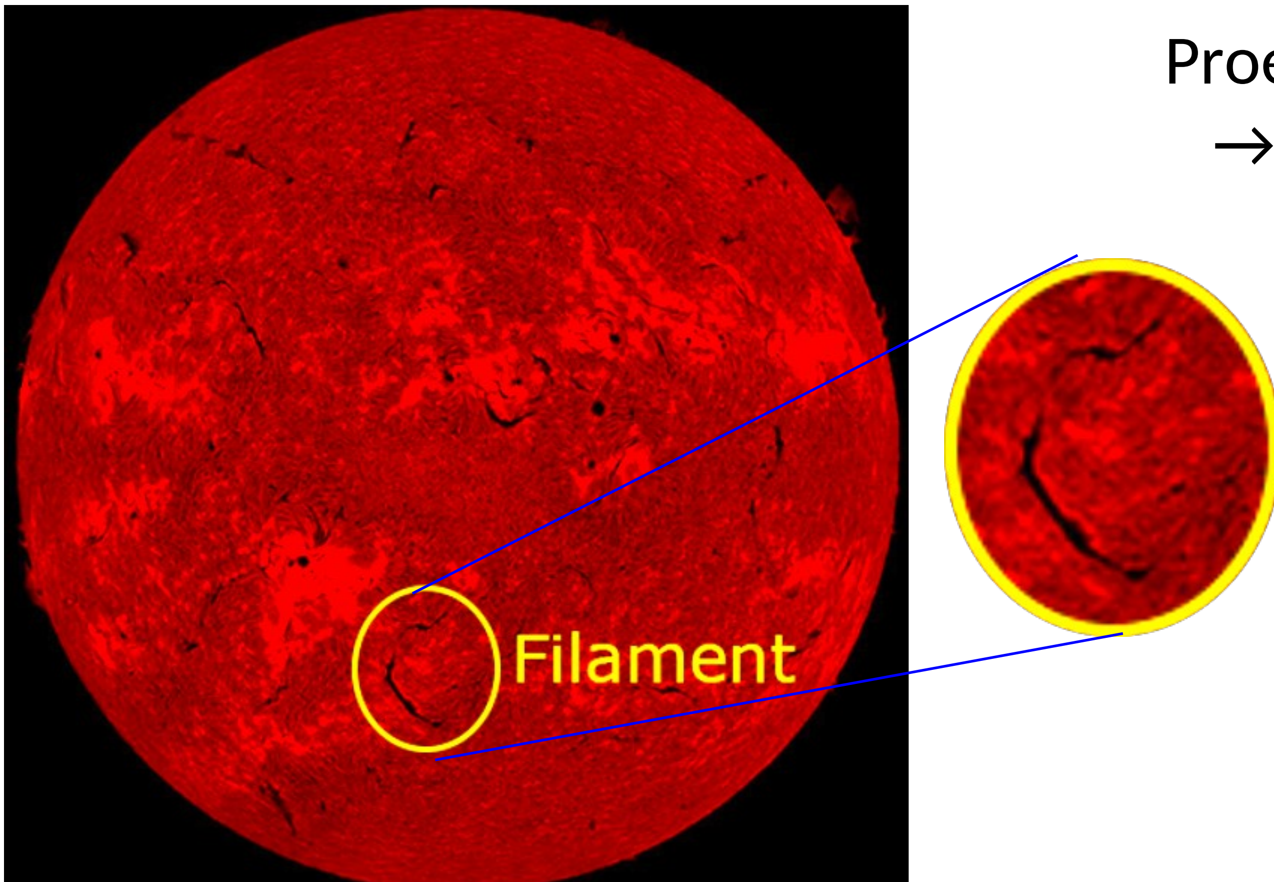
Estruturas de gás ionizado que se estendem até a coroa e podem durar semanas. Perto do limbo são brilhantes em Hα

Fig. 11.36. A quiescent hedgerow prominence. (c) Big Bear Solar Observatory

18/6/2017
(c) Eukasz Sujka

Filamentos solares: são proeminências vistas no disco solar. Os filamentos aparecem escuros pois a temperatura do proeminência é menor à do disco solar visto em Hα

Proeminência no disco → filamento escuro



(c) Big Bear Solar Observatory, 7/2000

Proeminência no limbo → estrutura brilhante

(c) Eukasz Sujka, 18/6/2017

Uma proeminência solar eruptiva pode existir por apenas algumas horas, ejetando gás do Sol.

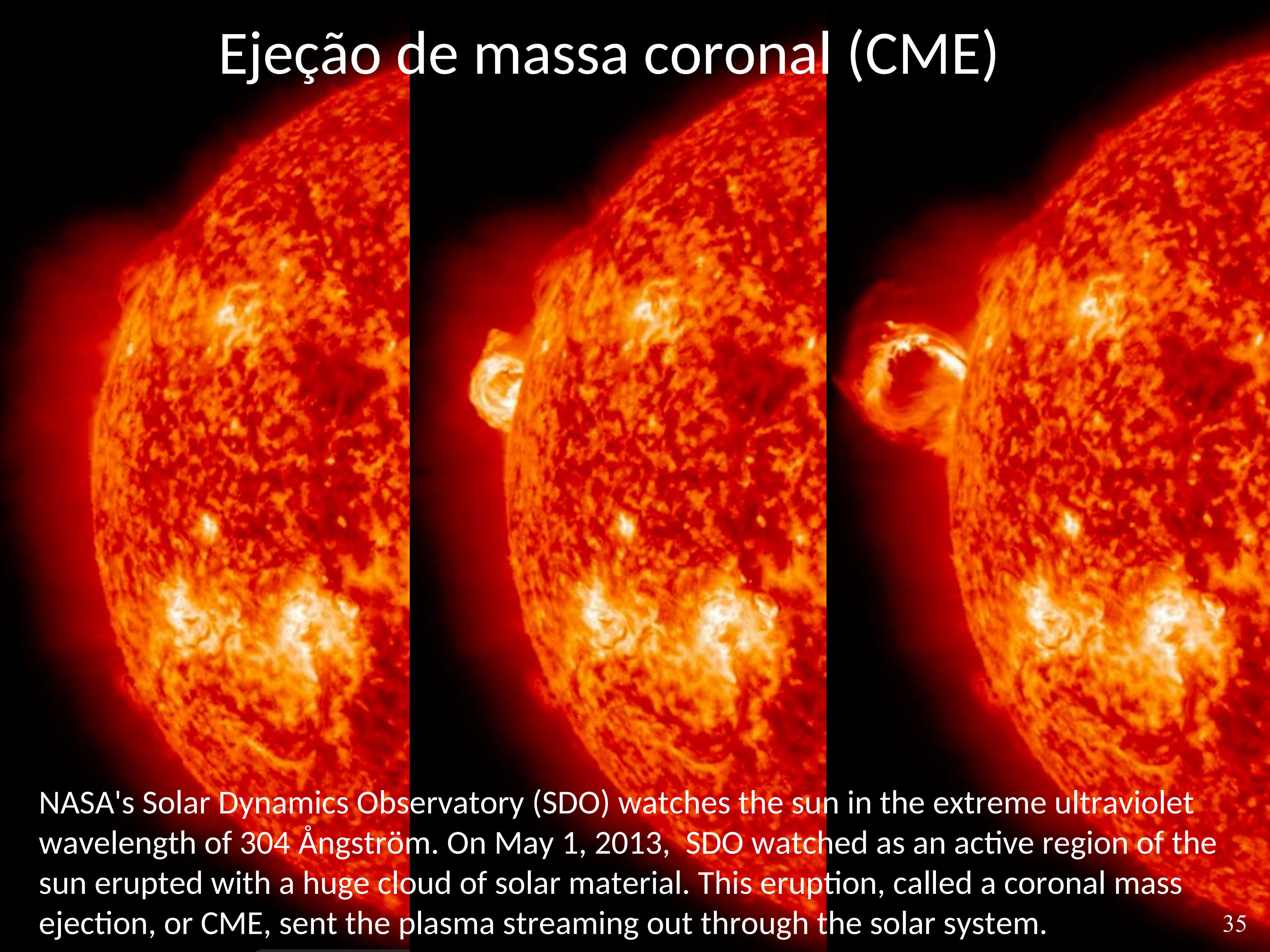
Elas podem se desenvolver a partir de proeminências quiescentes.

Gigantesca proeminência solar eruptiva

An **eruptive prominence** in extreme UV light on 30/3/2010. © NASA/SDO

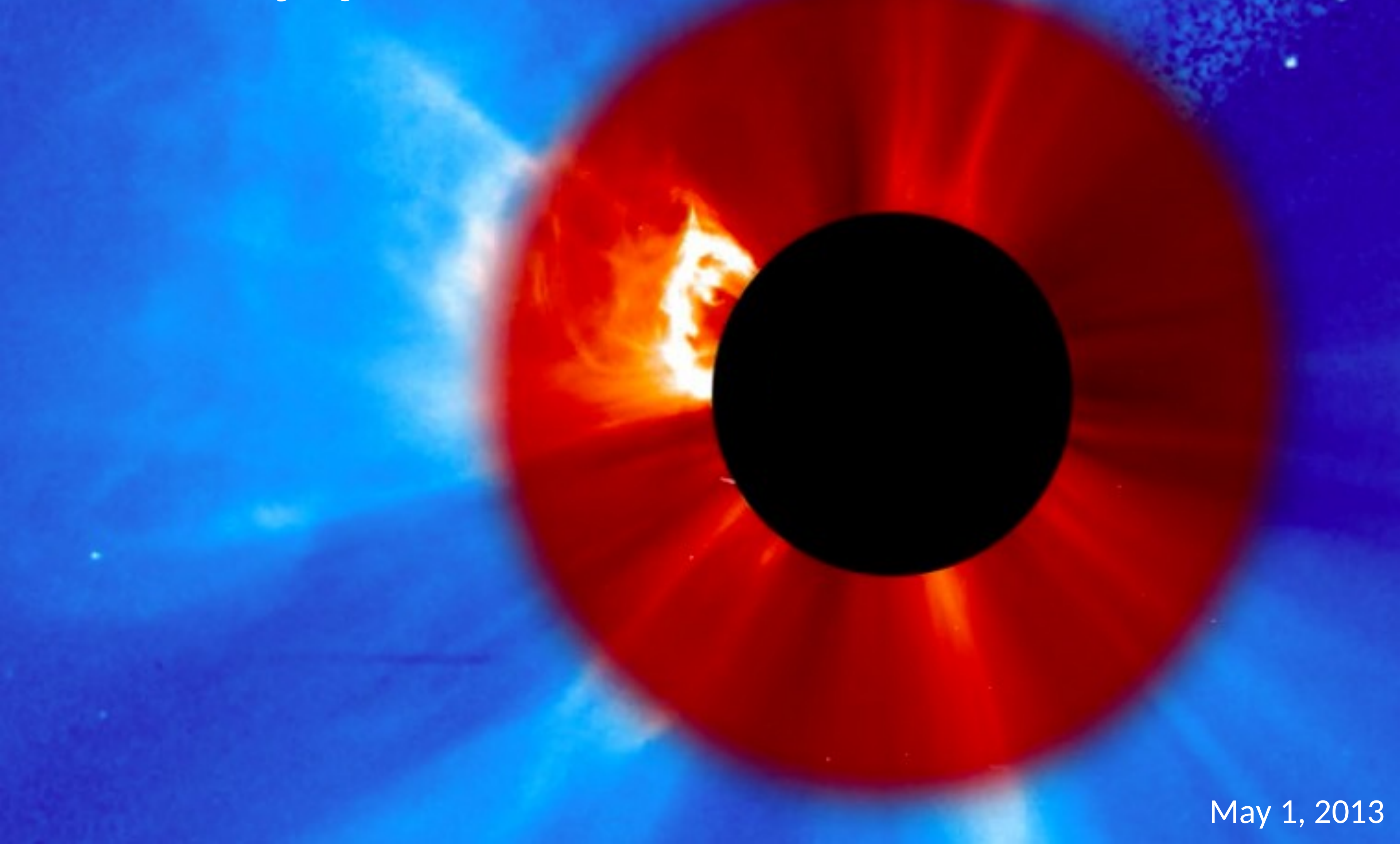
https://www.nasa.gov/content/goddard/what-is-a-solar-prominence

Ejeção de massa coronal (CME)



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 (CME)

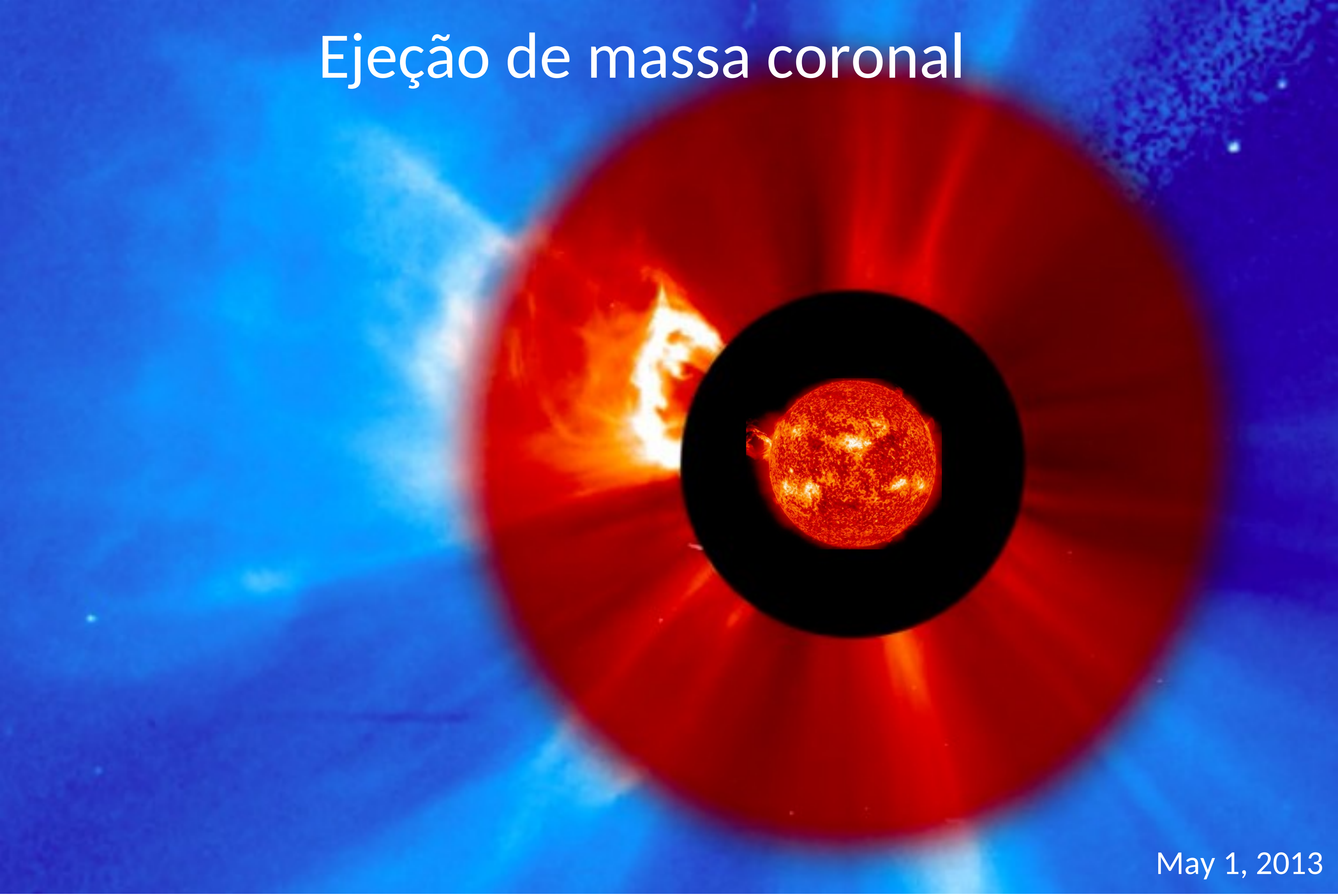


Besides the SDO images, the CME was also observed by SOHO using 2 coronagraphs where the bright sun is blocked by a disk so it does not overpower the fainter corona.

Ejeção de massa coronal (CME)

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



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.

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%

Ejeção de massa coronal (CME)

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

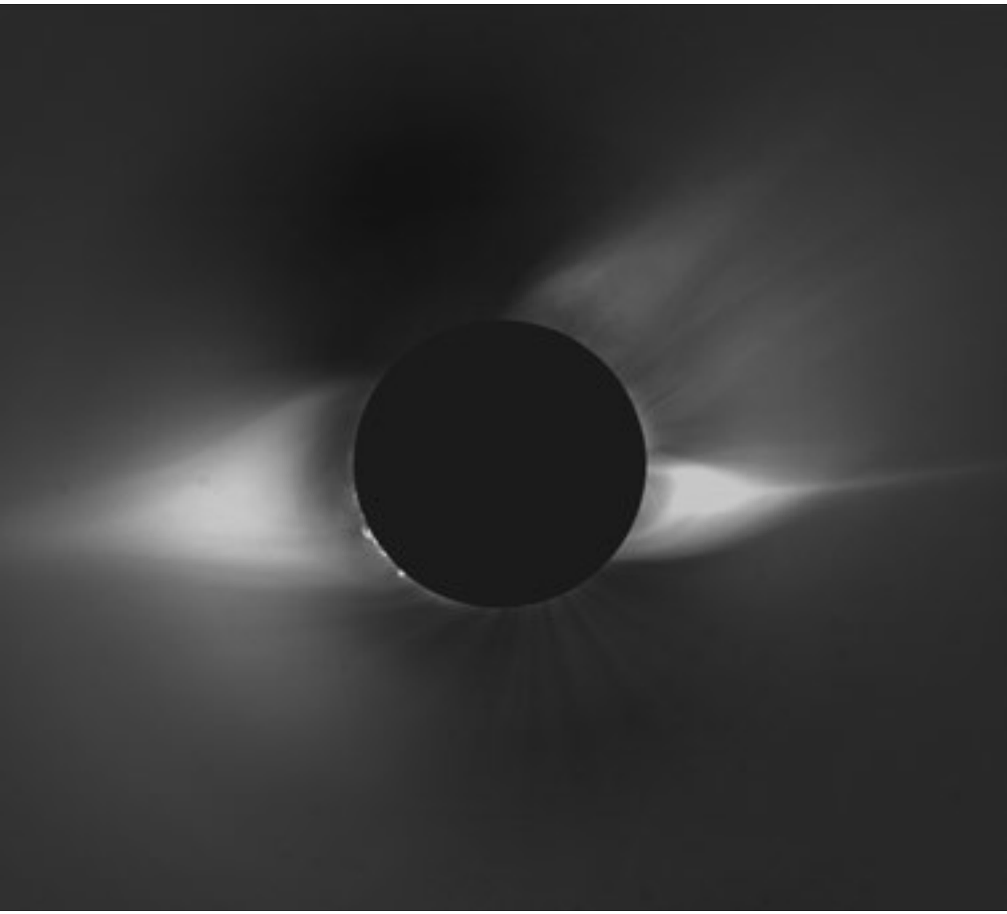
Coroa solar durante eclipse

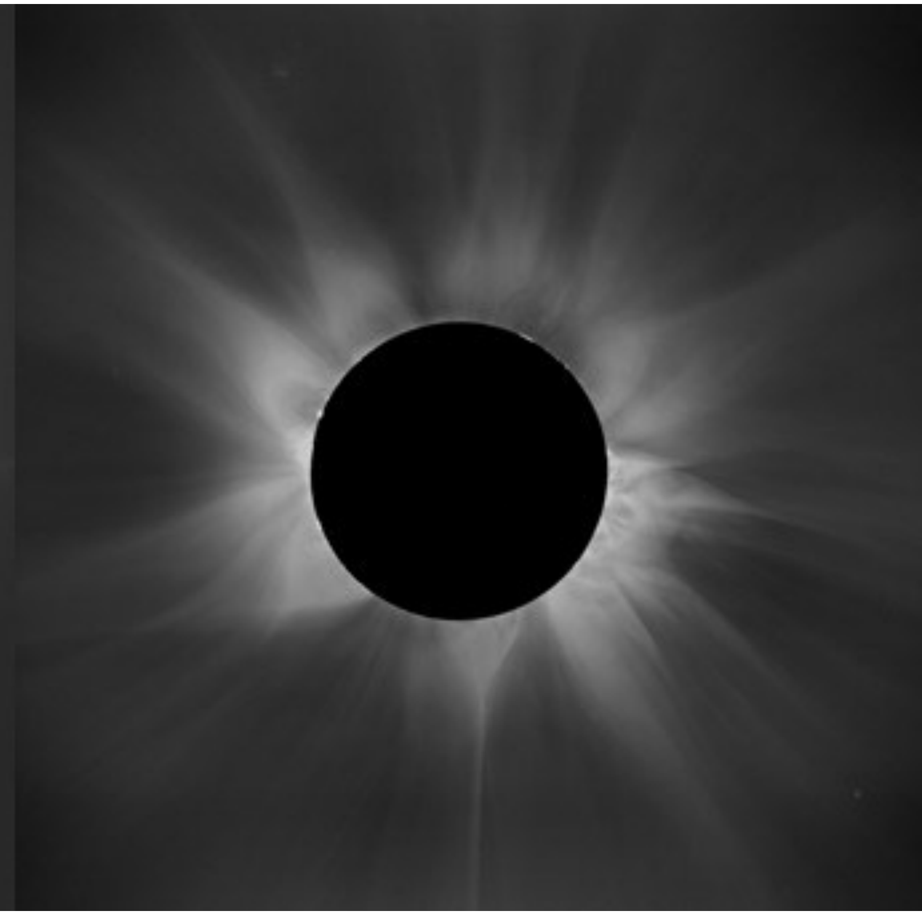
1994 (mínimo de atividade)

Mais estendida no equador, consistente com campo dipolar

1980 (máximo de atividade)

Coroa é mais complexa

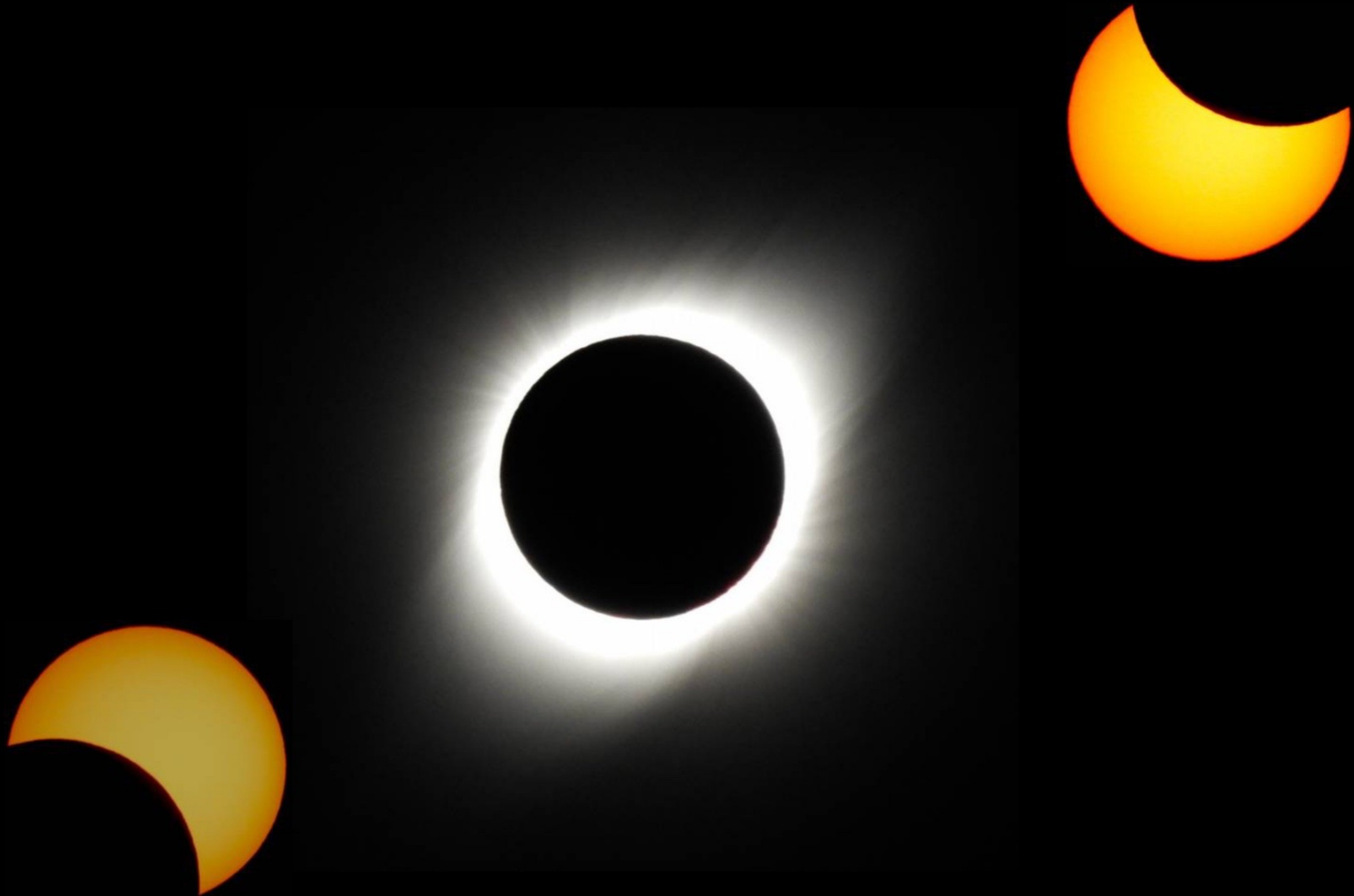




http://www.windows2universe.org/sun/images/eclipse/sun_eclipse_corona_max_vs_min_big_jpg_image.html

Eclipse solar, 2/jul/2019, Chile

(c) Jorge Meléndez



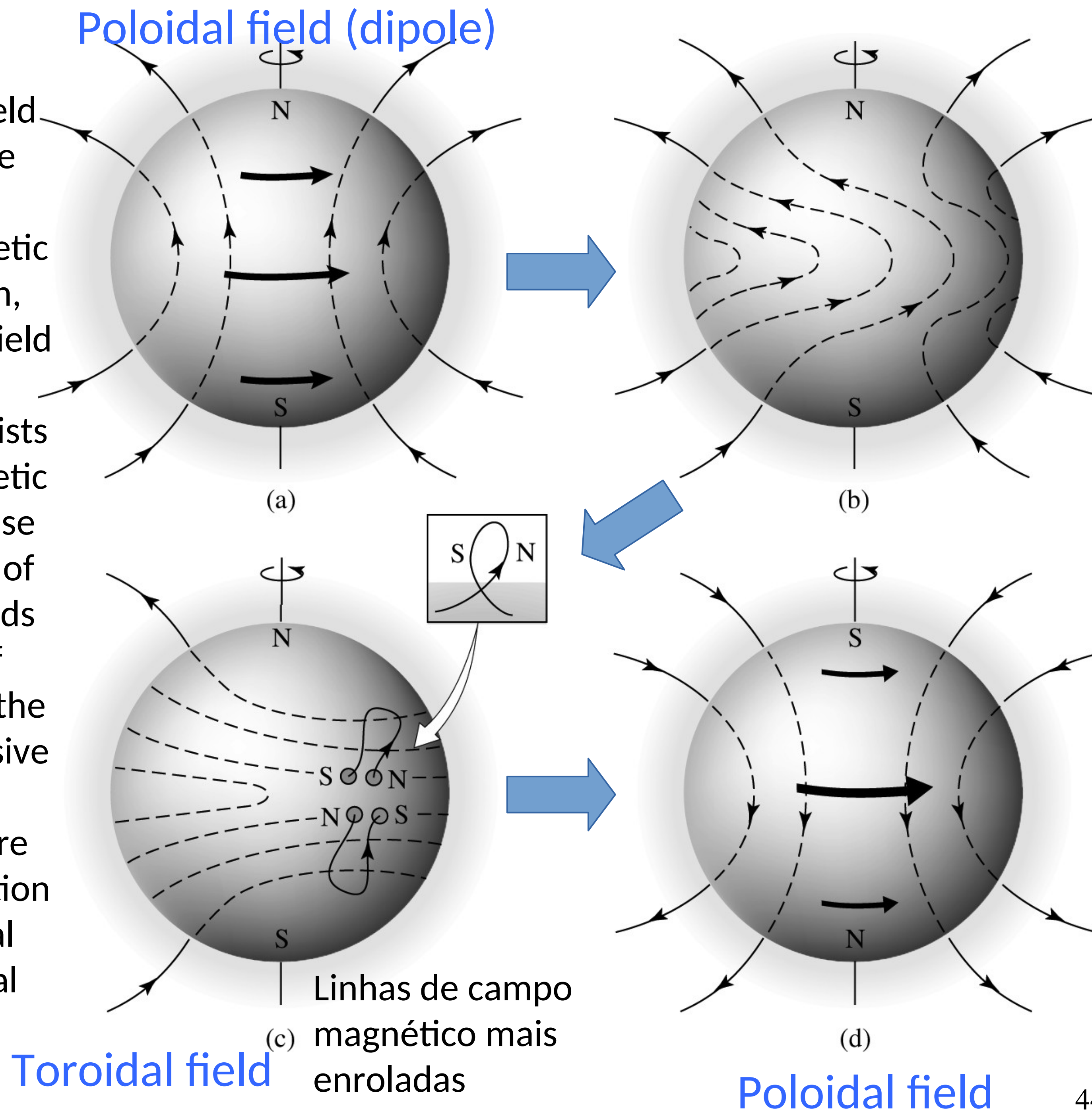
Near maximum of the solar cycle

Near minimum of the solar cycle

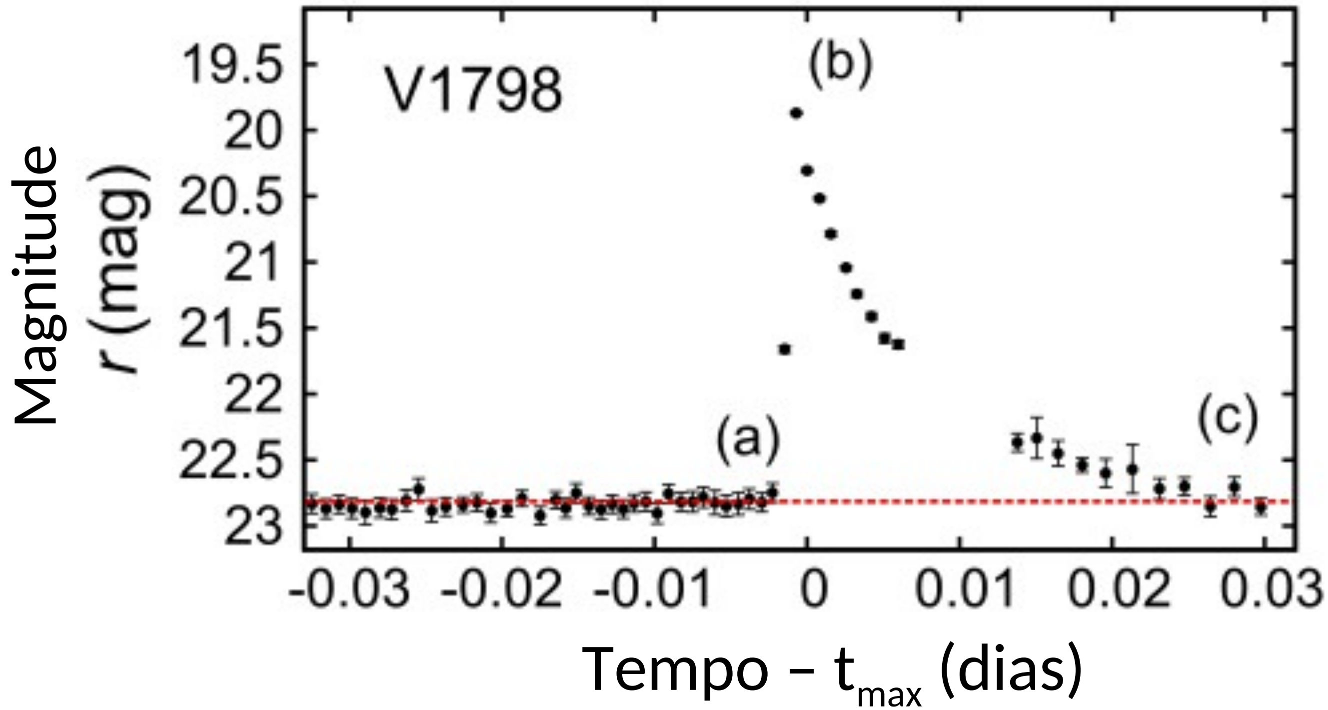
Lambaréné, Gabon, 3. 11. 2013
© Constantinos Emmanoulidis

Marshall Islands, 22.7.2009
© Miloslav Druckmuller

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.

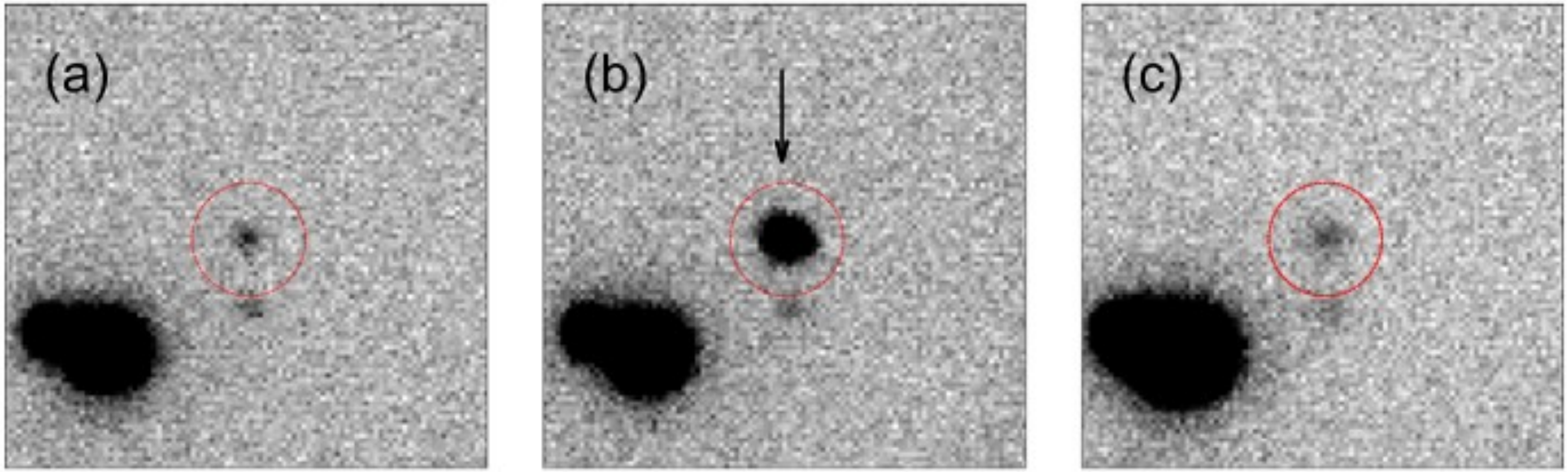


Estrelas “flare” (geralmente estrelas M)



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)

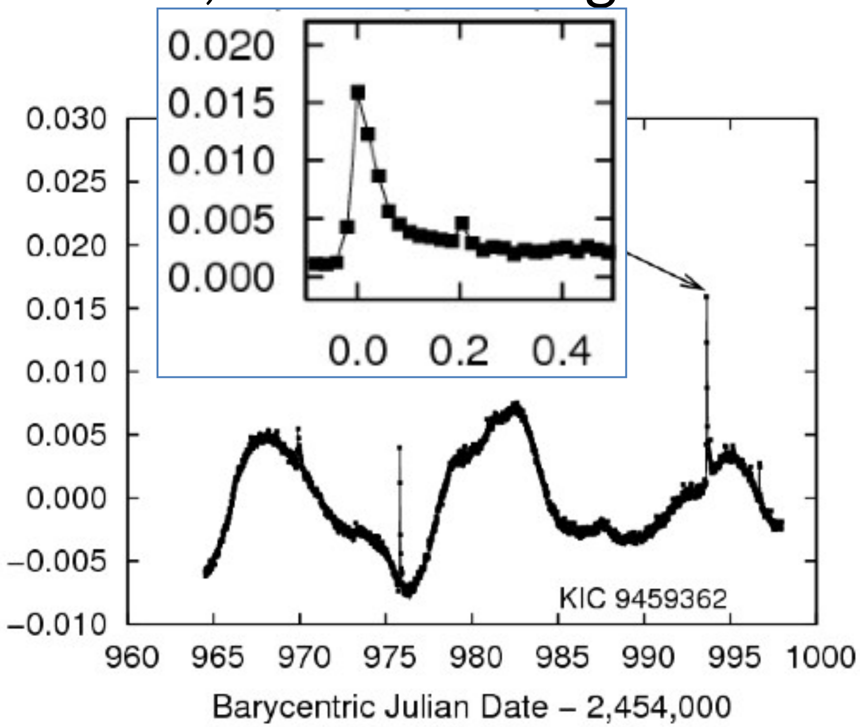
Hiroyuki Maehara, Takuya Shibayama, Shota Notsu, Yuta Notsu, Takashi Nagao, Satoshi Kusaba, Satoshi Honda, Daisaku Nogami & Kazunari Shibata

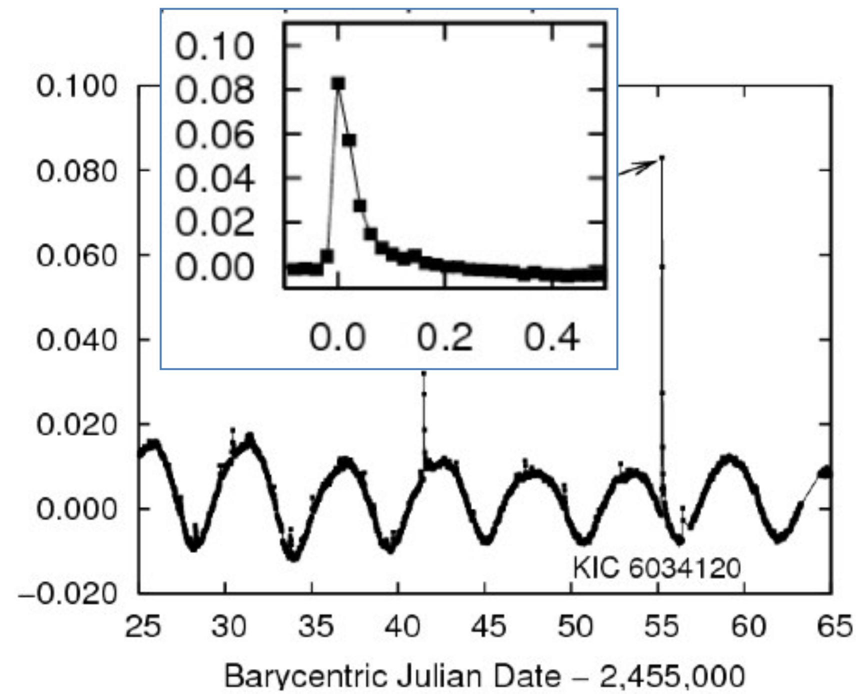
14 flares on 10 Sun-like stars (T_{eff}: 5600-6000; P>10days)

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 da estrela BD+26730

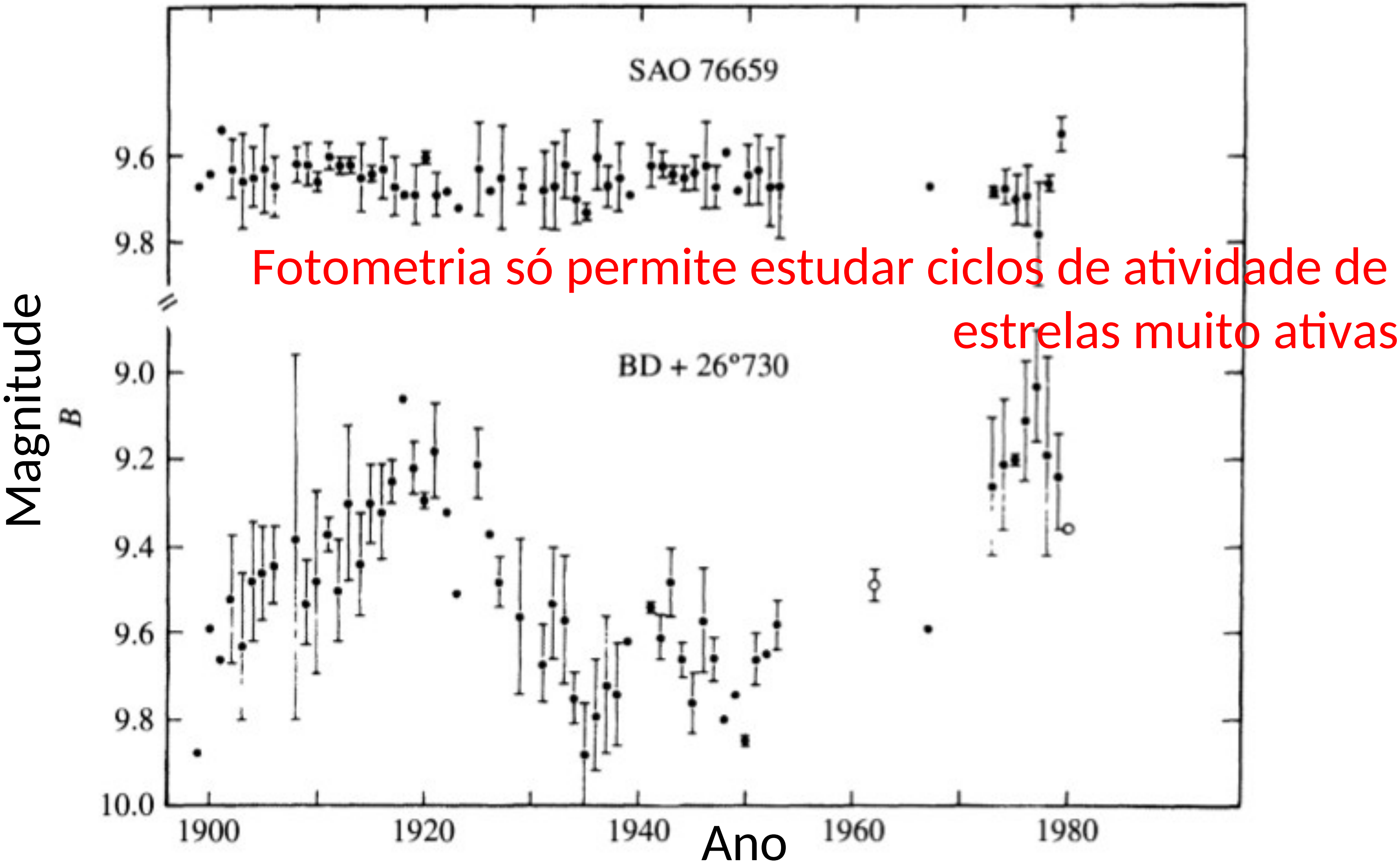
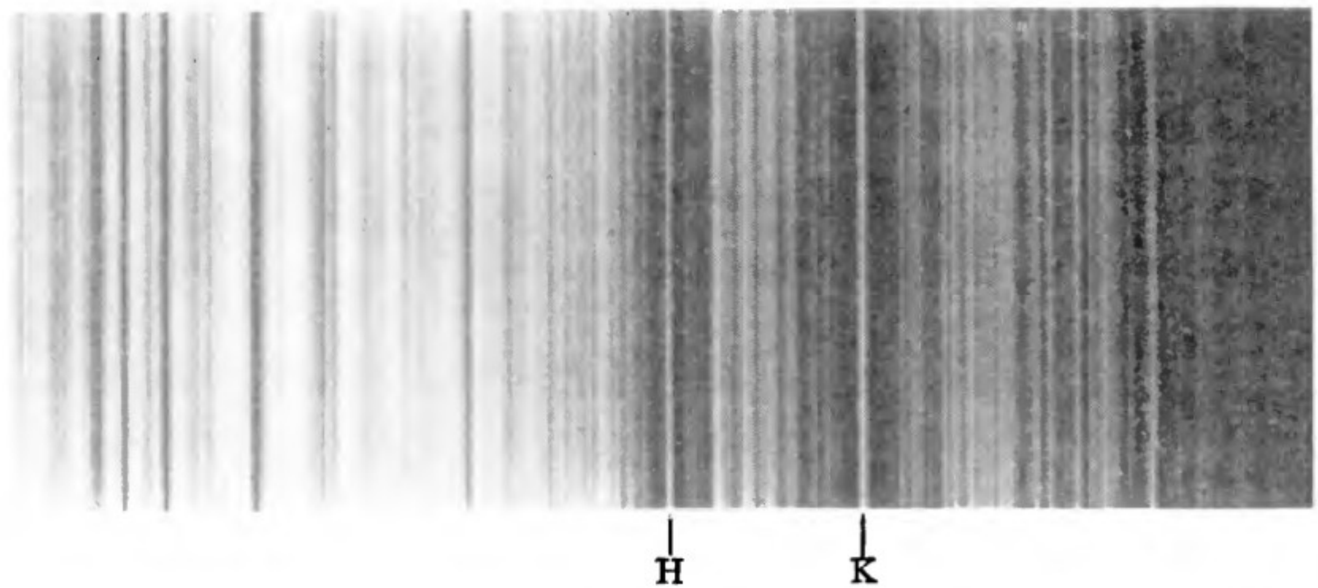


FIGURE 11.39 The light curve of BD + 26°730, a BY Dra star. SAO 76659 is a nearby reference star. (Figure from Hartmann et al., *Ap. J.*, *249*, 662, 1981.)

Linhas de emissão H e K (Ca II)

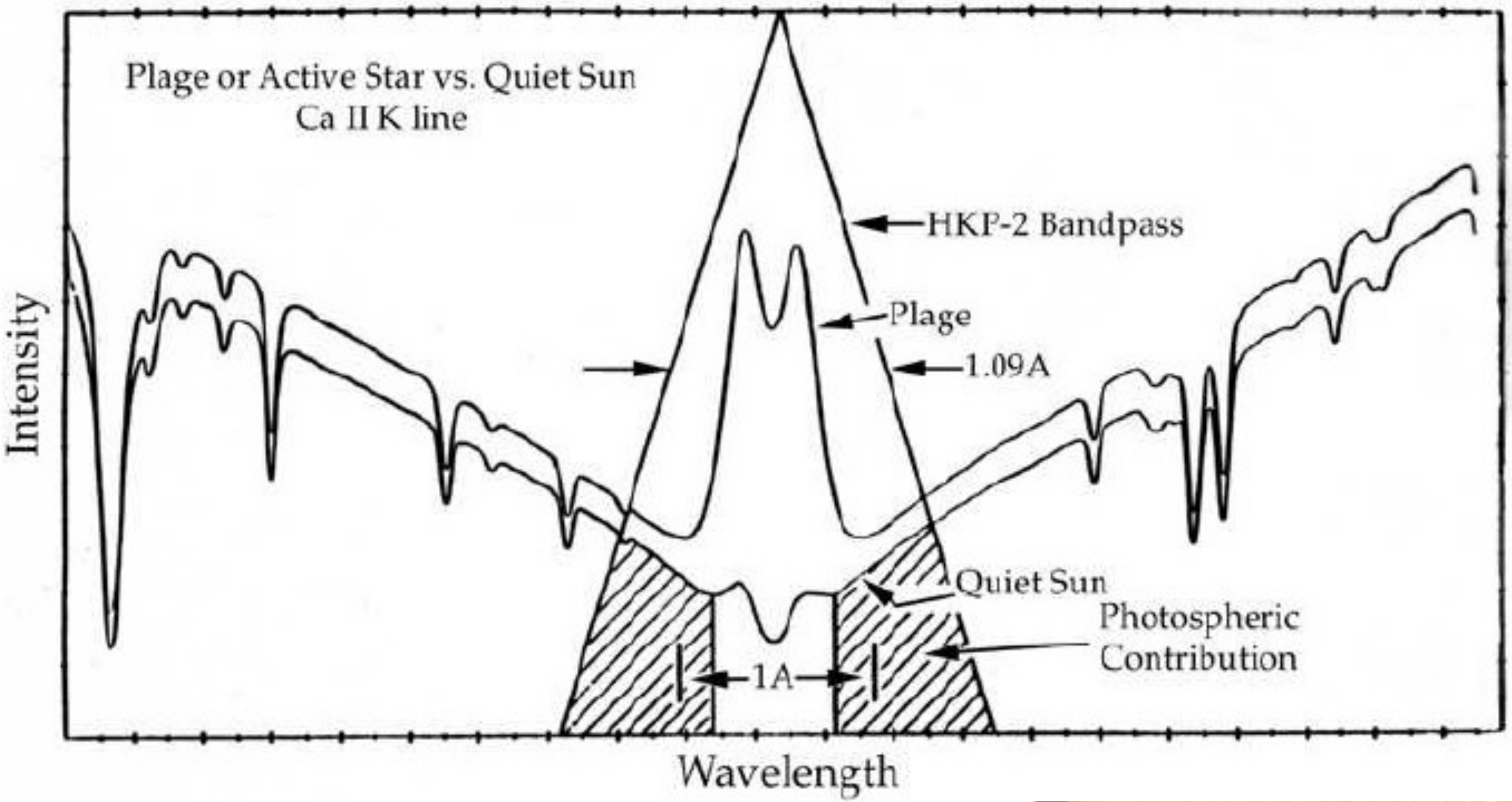


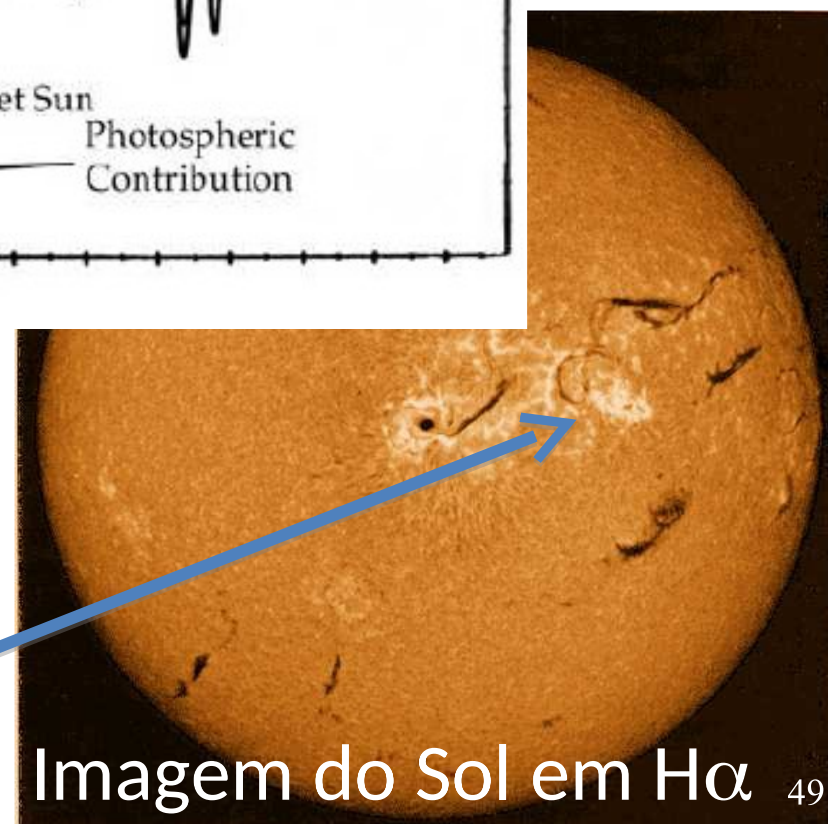
Spectrum of σ *Geminorum* taken with the Zeiss triplet and U.V. objective-prism, 1913, March 9. Enlarged and broadened about 12 times.

Two problems arise in this connection. It remains to be shown whether the emission lines of the star have a possible variation in intensity analogous to the sun-spot period. It is known

Eberhard,G.; Schwarzschild, K. 1913, ApJ, 38, 292

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





Plage: emissão brilhante na cromosfera

Imagem do Sol em Hα

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

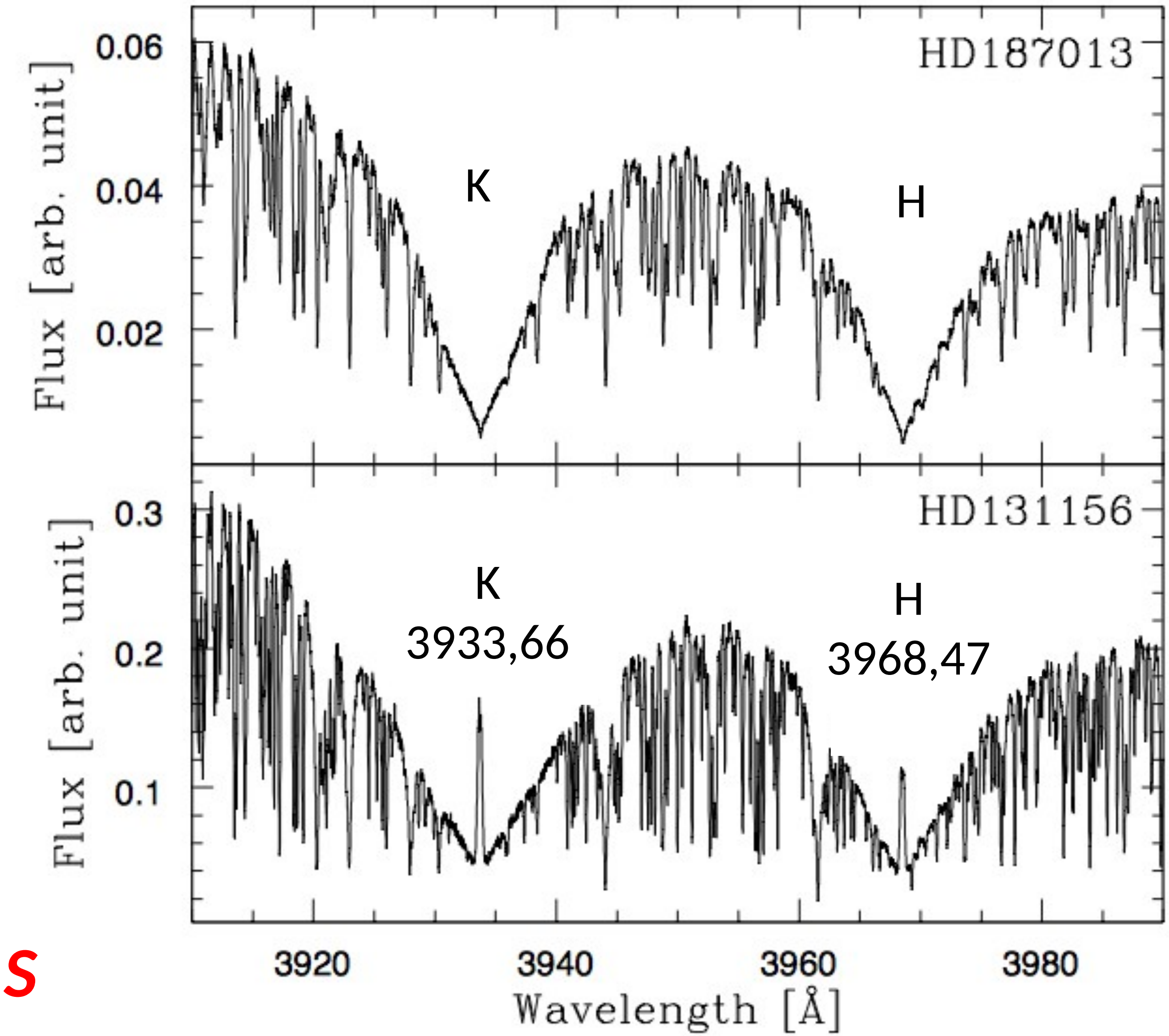


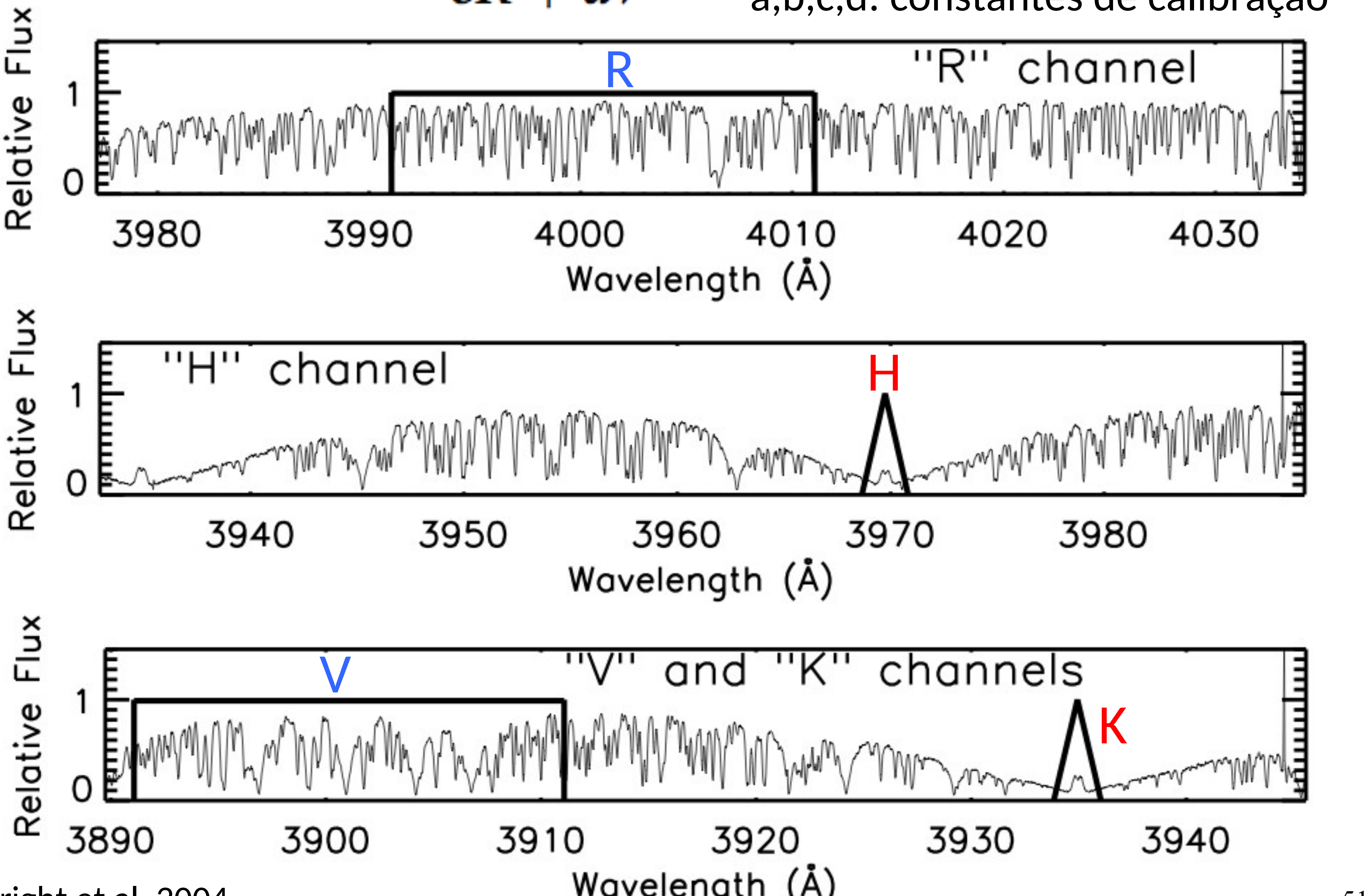
Fig. C.1. Two SOPHIE spectra of the region of the CaII H and K lines between 3900 and 4000 Å. *Bottom*: Active star. *Top*: Non active star.

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

Boisse et al. 2010 A&A 523, A88

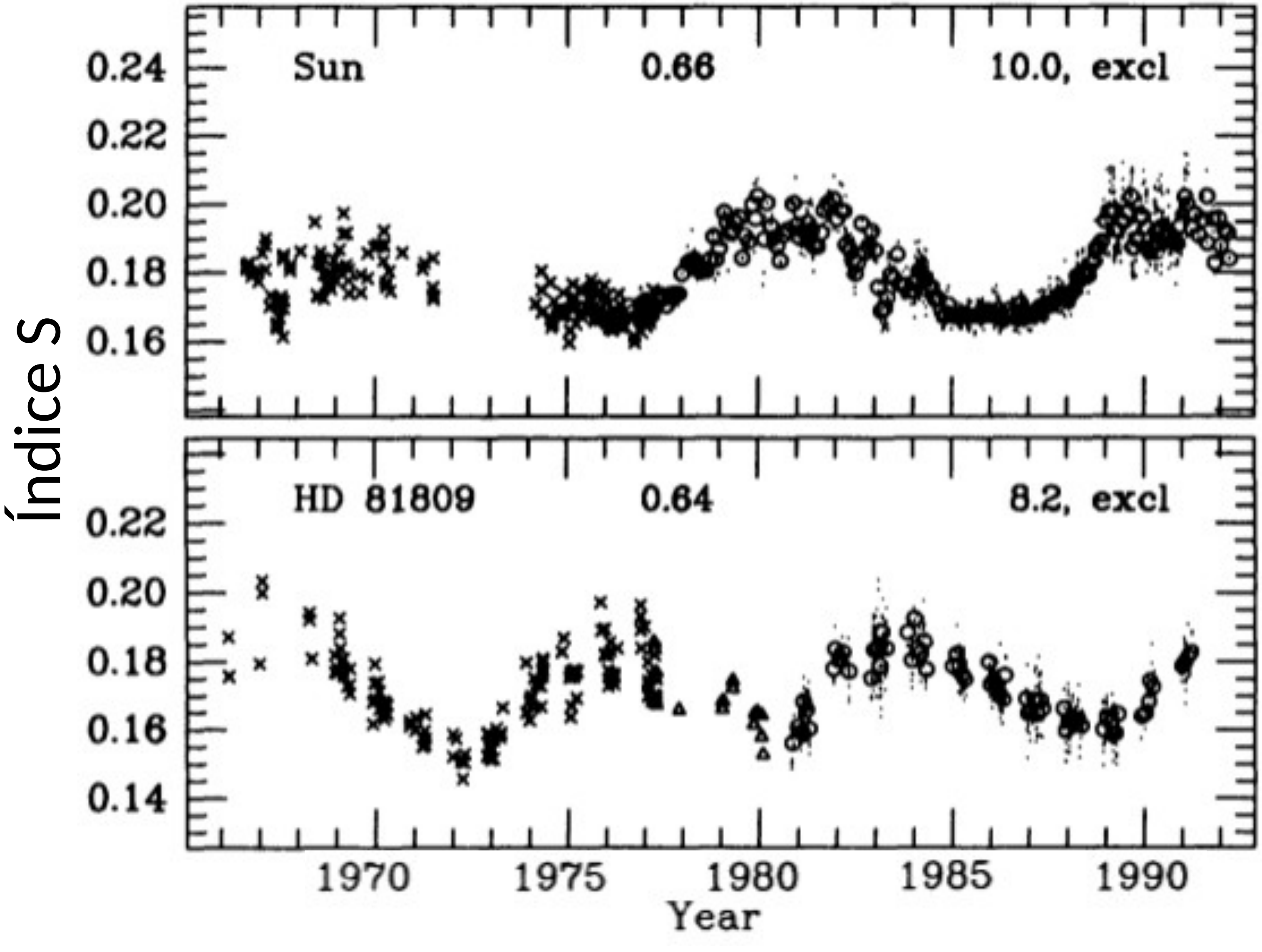
Índice S: $S = \frac{aH + bK}{cR + dV}$

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

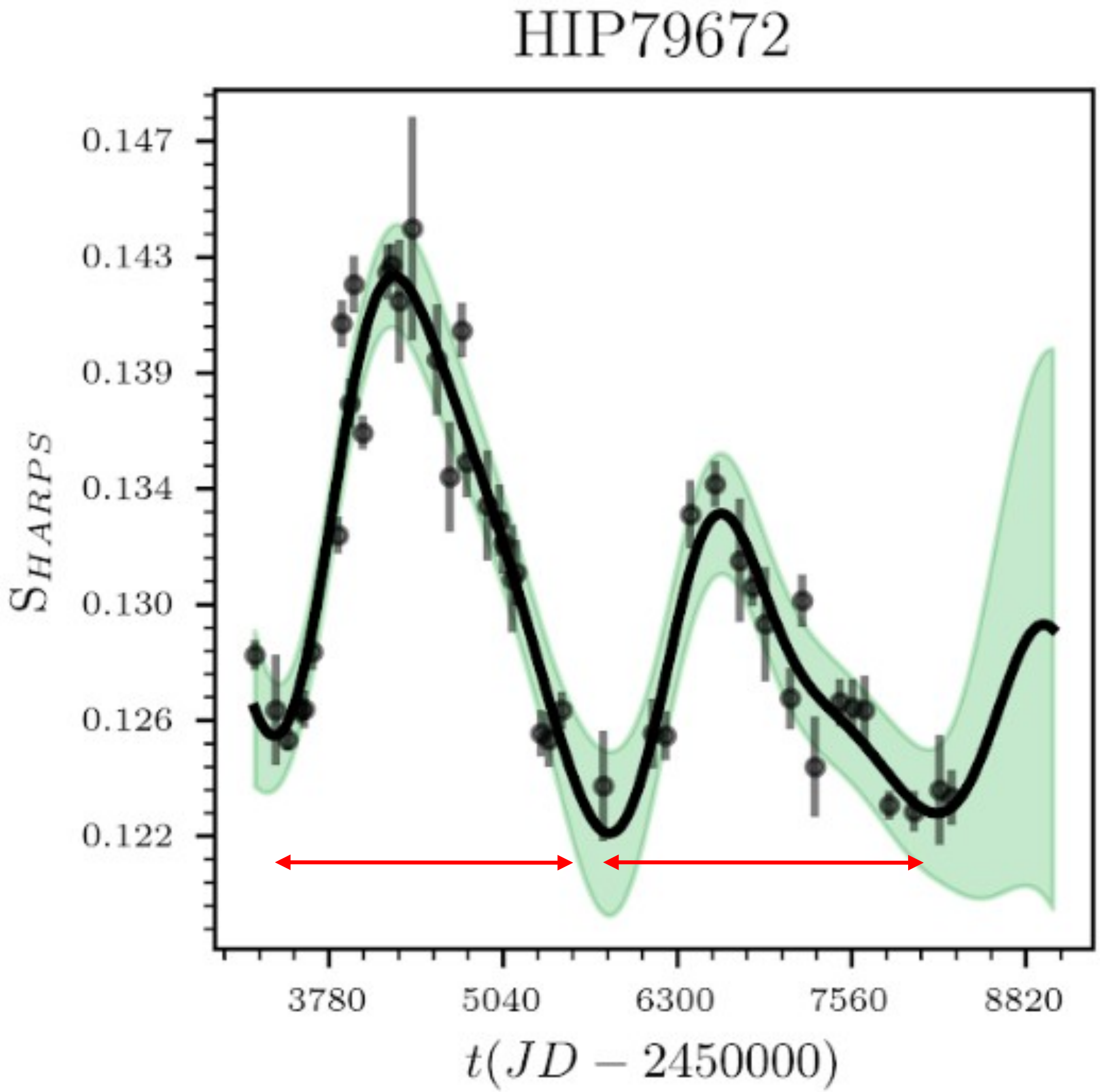
Ciclo de atividade usando o índice cromosférico *S*



Baliunas et al. 1995 ApJ 438, 269

Em estrelas como o Sol (18 Sco = HIP 79672), as variações do ciclo de atividade podem ser estudadas usando o índice cromosférico *S*

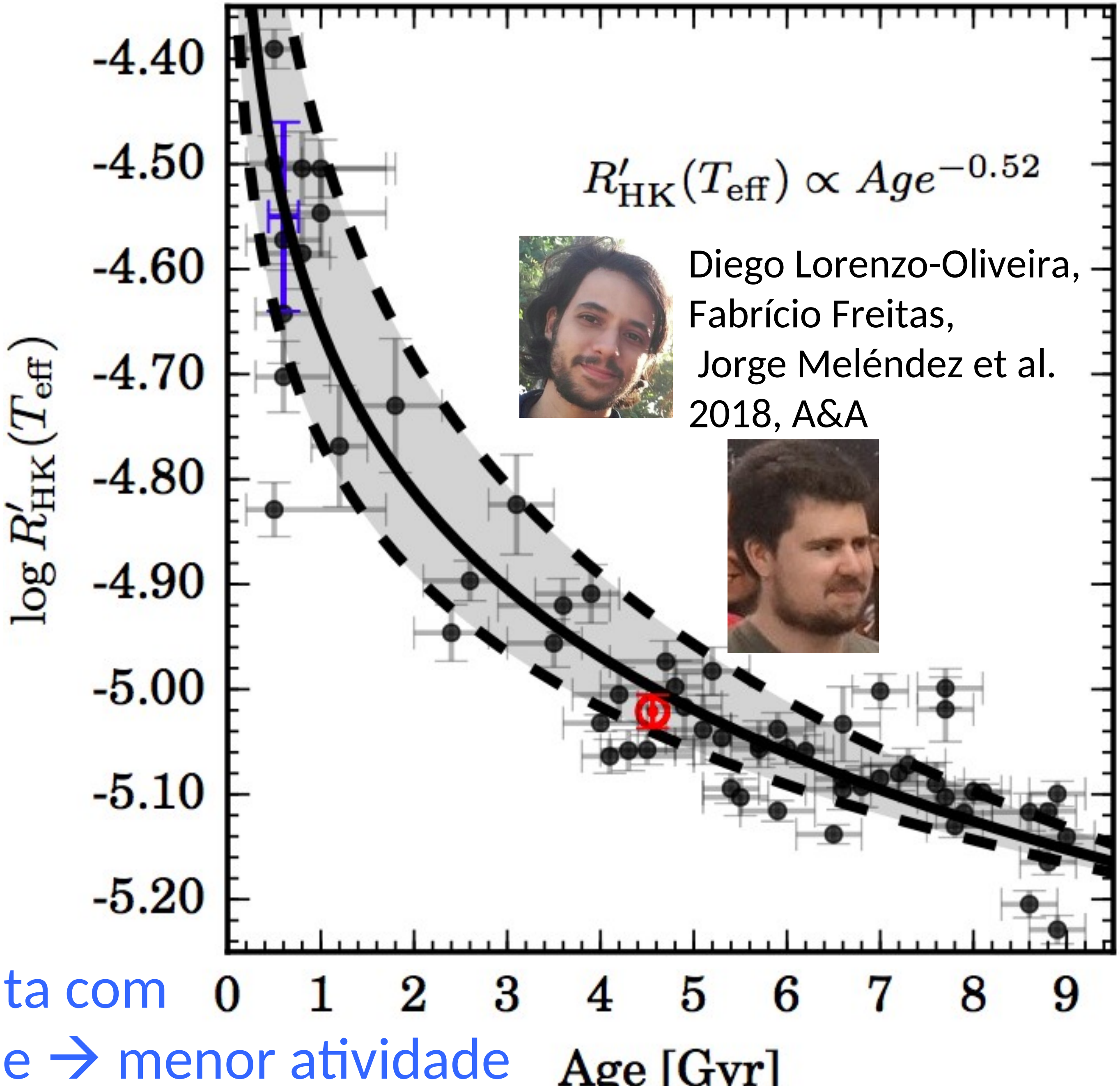
Índice cromosférico S, usando as linhas H e K



Diego Lorenzo-Oliveira (em preparação)

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

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



Diego Lorenzo-Oliveira, Fabrício Freitas, 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.