Cap. 11 – O Sol
11.1 O interior solar
11.2 A atmosfera solar

Dr. Jorge Meléndez

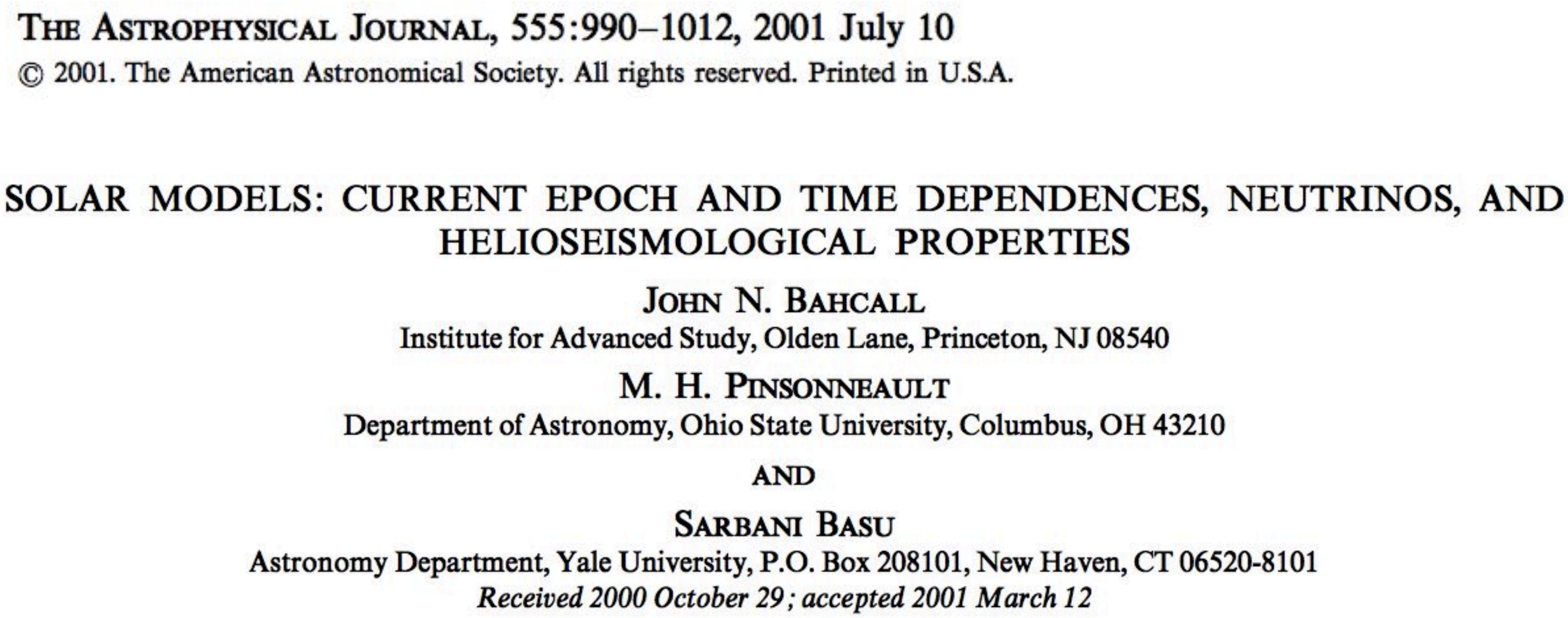
AGA 0293, Astrofísica Estelar

11.1 O interior solar

Estrela mais importante. Devido à sua proximidade conhecemos em detalhe:

- Composição química
- Temperatura
- Luminosidade
- Raio
- Rotação; Campos magnéticos; Frequências de oscilação; Fluxo de neutrinos

No livro-texto, são apresentados resultados de um modelo “padrão” do Sol, por **Bahcall, Pinsonneault & Basu 2001, ApJ, 555, 990**



THE ASTROPHYSICAL JOURNAL, 555:990–1012, 2001 July 10

SOLAR MODELS: CURRENT EPOCH AND TIME DEPENDENCES, NEUTRINOS, AND HELIOSEISMOLOGICAL PROPERTIES

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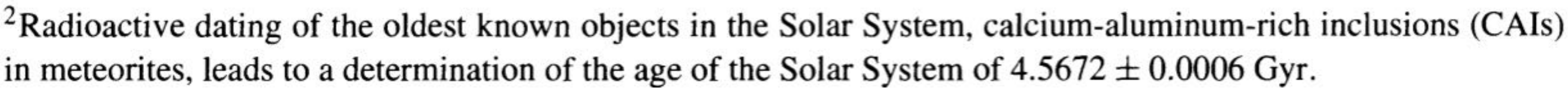
Received 2000 October 29; accepted 2001 March 12

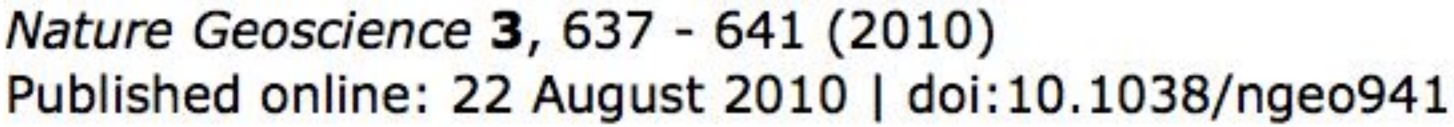
Idade do Sol: 4,57 bilhões de anos

Livro-Texto: 4,5672 Gyr



[2] Radioactive dating of the oldest known objects in the Solar System, calcium-aluminum-rich inclusions (CAIs) in meteorites, leads to a determination of the age of the Solar System of 4.5672 ± 0.0006 Gyr.

Artigo mais recente em Nature Geoscience: 4,5682 Gyr



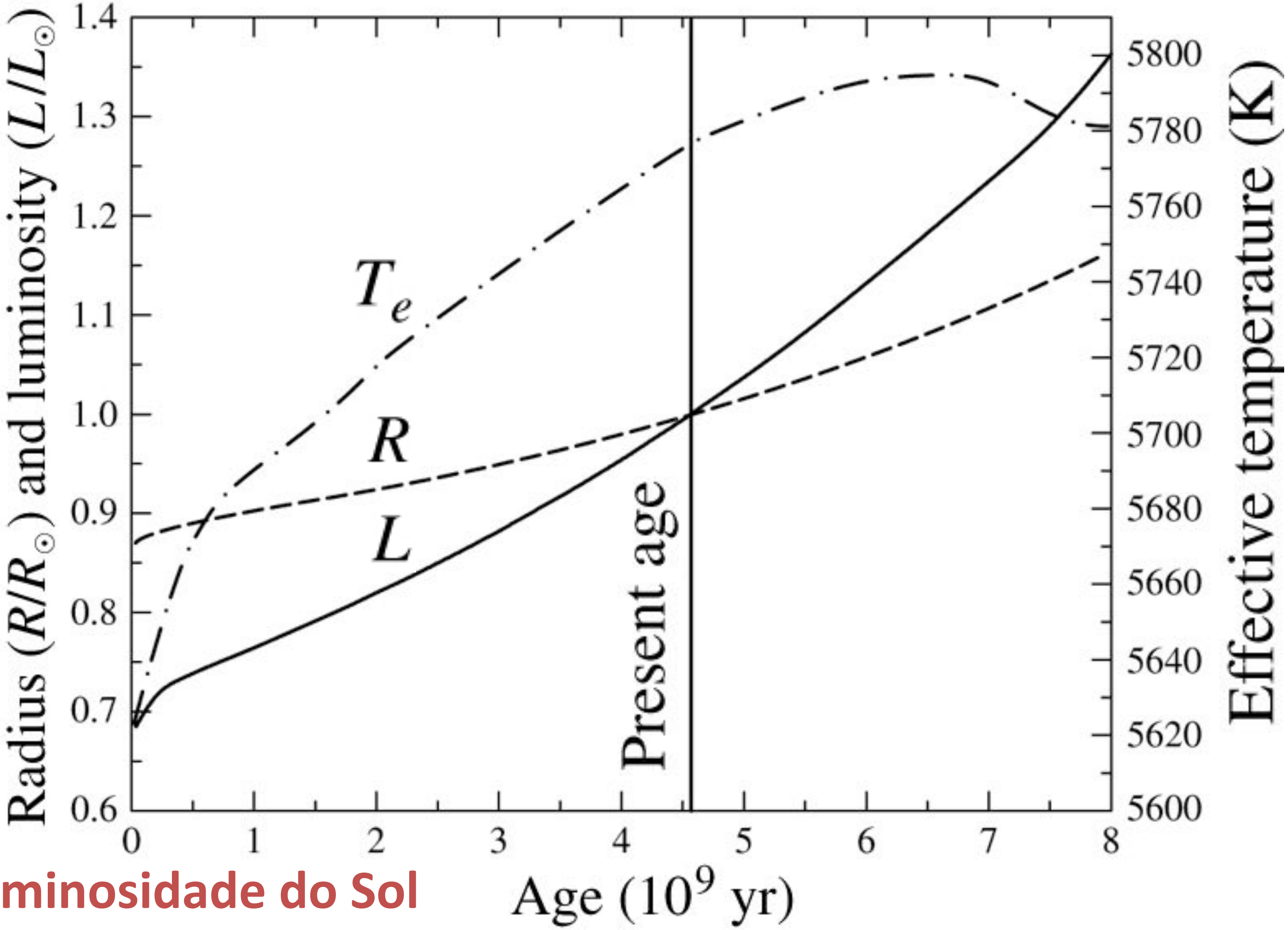
Nature Geoscience **3**, 637 - 641 (2010)
Published online: 22 August 2010 | doi:10.1038/ngeo941

Audrey Bouvier[1] & Meenakshi Wadhwa[1]

The age of the Solar System redefined by the oldest Pb–Pb age of a meteoritic inclusion

Chondrite meteorite with calcium–aluminium-rich inclusions seen as white specks. From the collection of the American Museum of Natural History.

História evolucionária do Sol

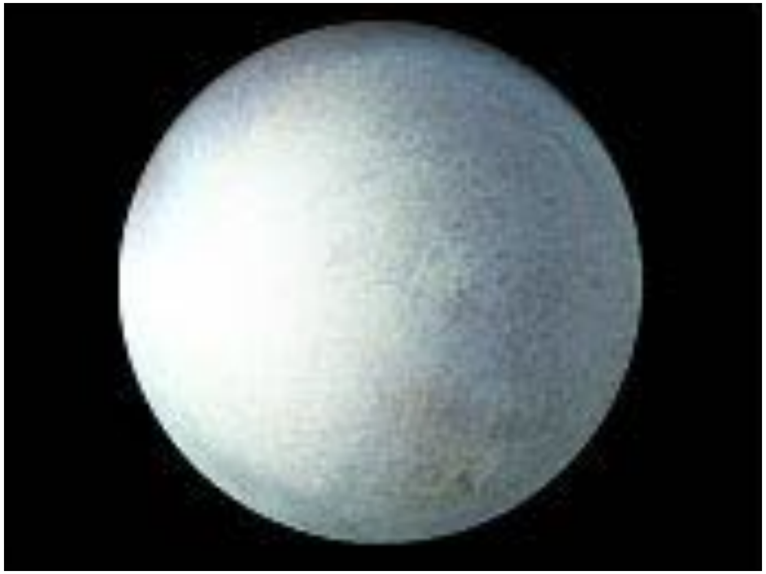


Luminosidade do Sol jovem ~ 75% da atual !

Faint young Sun paradox

Paradoxo do jovem Sol fraco

O problema do jovem Sol fraco é a contradição aparente entre observações de água líquida no início da história da Terra, e a predição de que o brilho do Sol na época era de apenas 75% em relação ao presente, insuficiente para manter água no estado líquido



SNOWBALL: a Terra nos seus primordios?

JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, VOL. 118, 1–18, doi:10.1002/jgrd.50808, 2013

Exploring the faint young Sun problem and the possible climates of the Archean Earth with a 3-D GCM

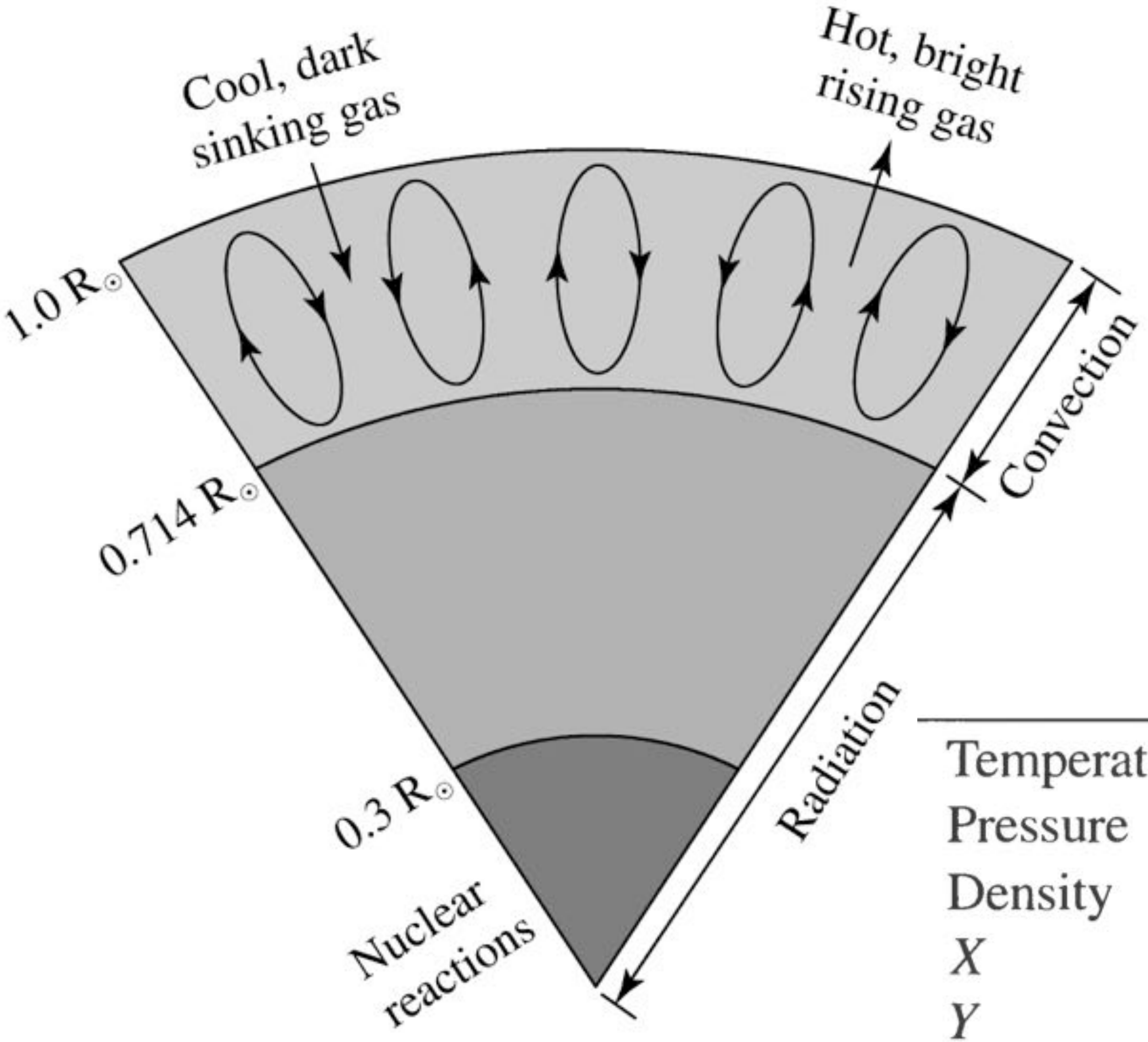
B. Charnay,[1] F. Forget,[1] R. Wordsworth,[2] J. Leconte,[1] E. Millour,[1]
F. Codron,[1] and A. Spiga[1]

[9] Methane has been suggested as an important complement to CO_2 to warm the early Earth [*Kiehl and Dickinson*, 1987]. It can absorb thermal radiation at 7–8 μm, thus at the edge of the atmospheric window (8–12 μm), where CO_2 cannot. It can therefore produce an efficient warming. In an anoxic atmosphere, the lifetime of methane is 1000 times higher than today [*Zahnle*, 1986; *Kasting and Howard*, 2006]. During the Archean, methane would have been released by methanogenic bacteria through the reaction:

$$CO_2 + 4H_2 \Rightarrow CH_4 + 2H_2O \qquad (1)$$

where H_2 comes from hydrothermal sources and volcanoes, or from the primitive atmosphere [*Tian et al.*, 2005].

A estrutura interior do Sol **hoje**



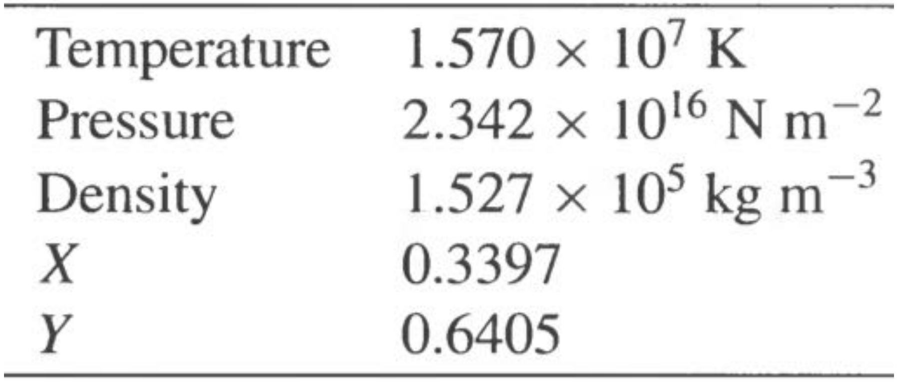
Condições no centro do Sol:

X = 0.34 (X_i=0.71)

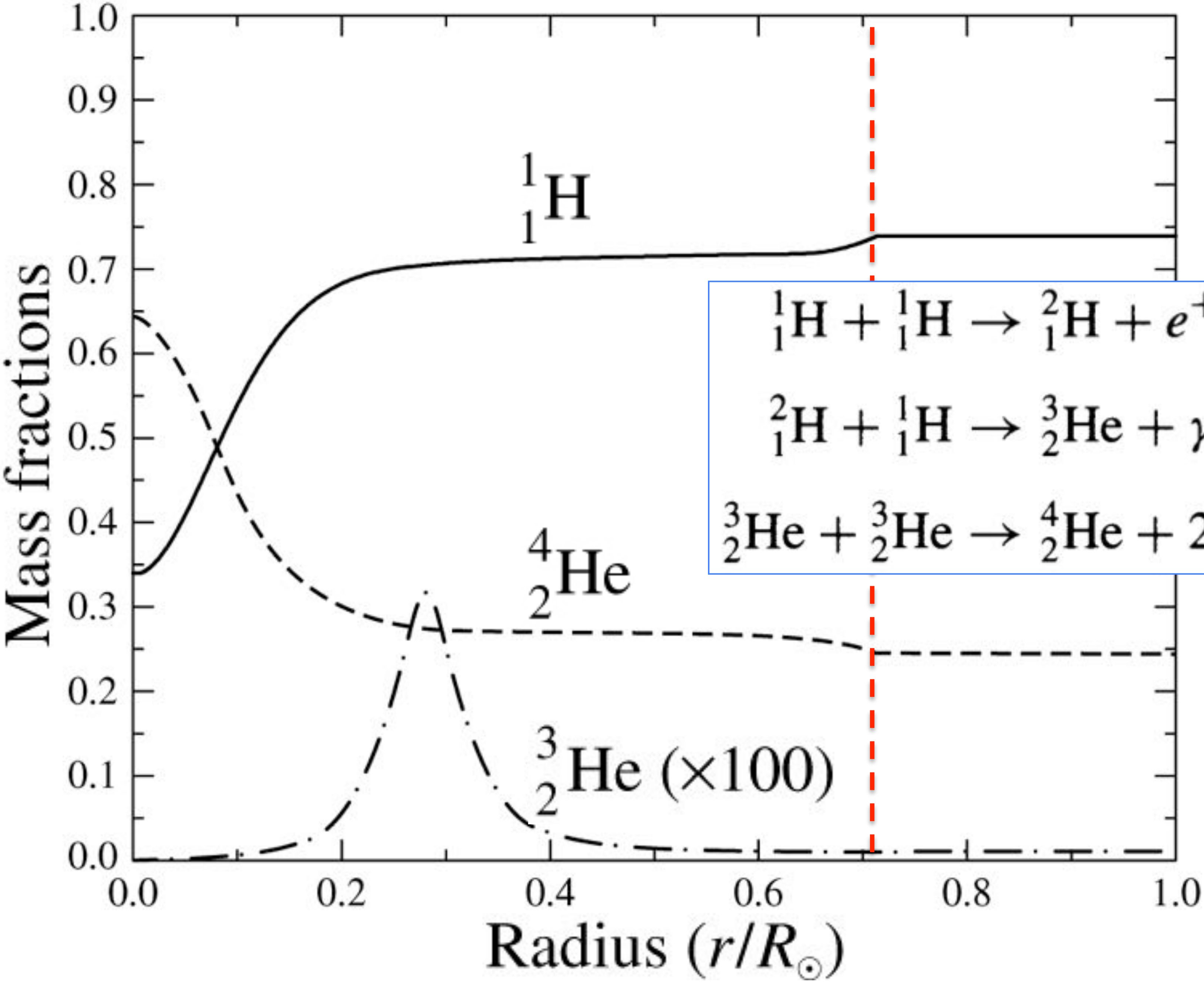
Y = 0.64 (Y_i=0.27)

T = 1,57 10^6K

P = 2,34 10^{16} Nm^{-2}



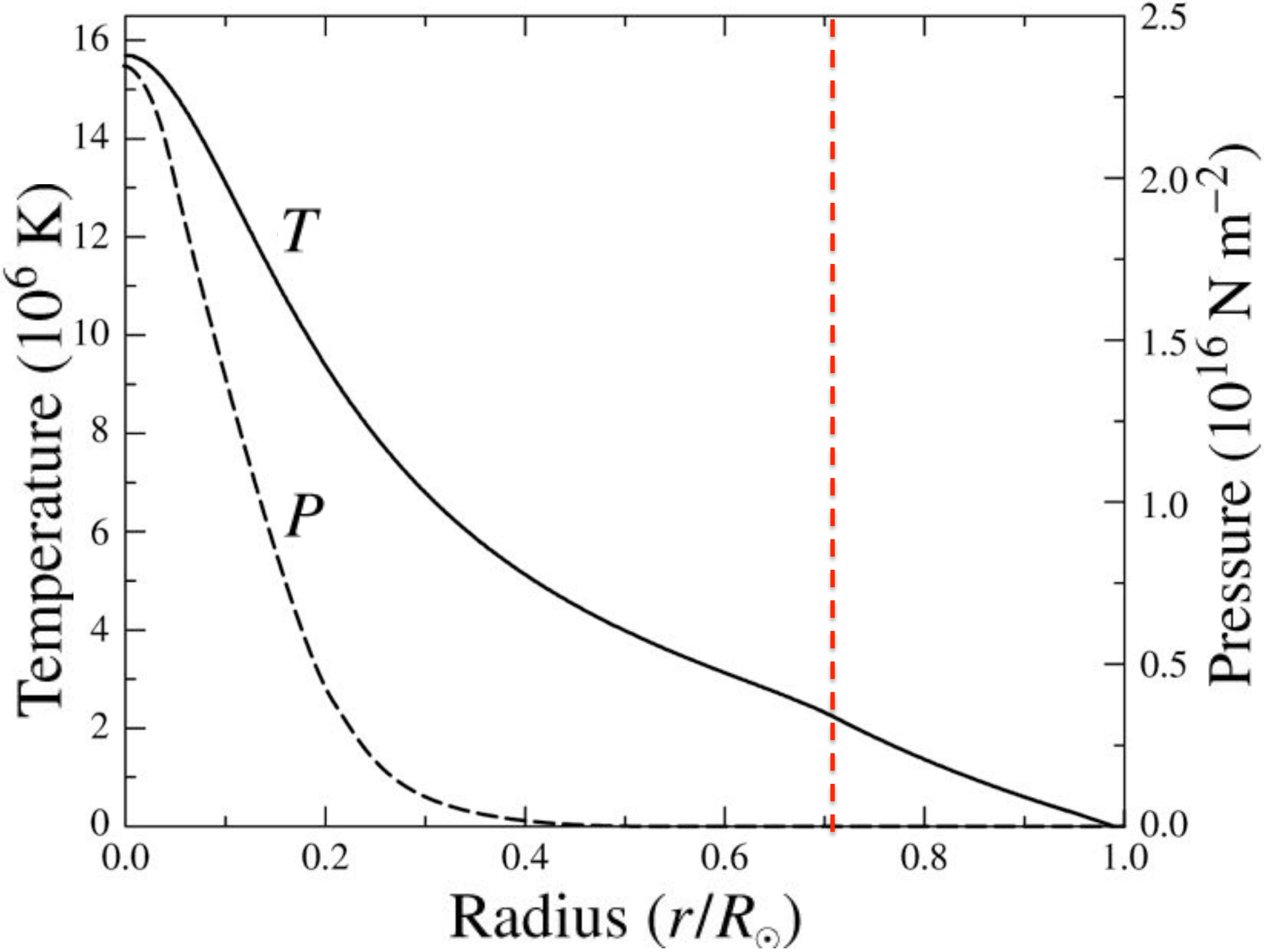
Temperature	1.570×10^7 K
Pressure	2.342×10^{16} N m^{-2}
Density	1.527×10^5 kg m^{-3}
X	0.3397
Y	0.6405

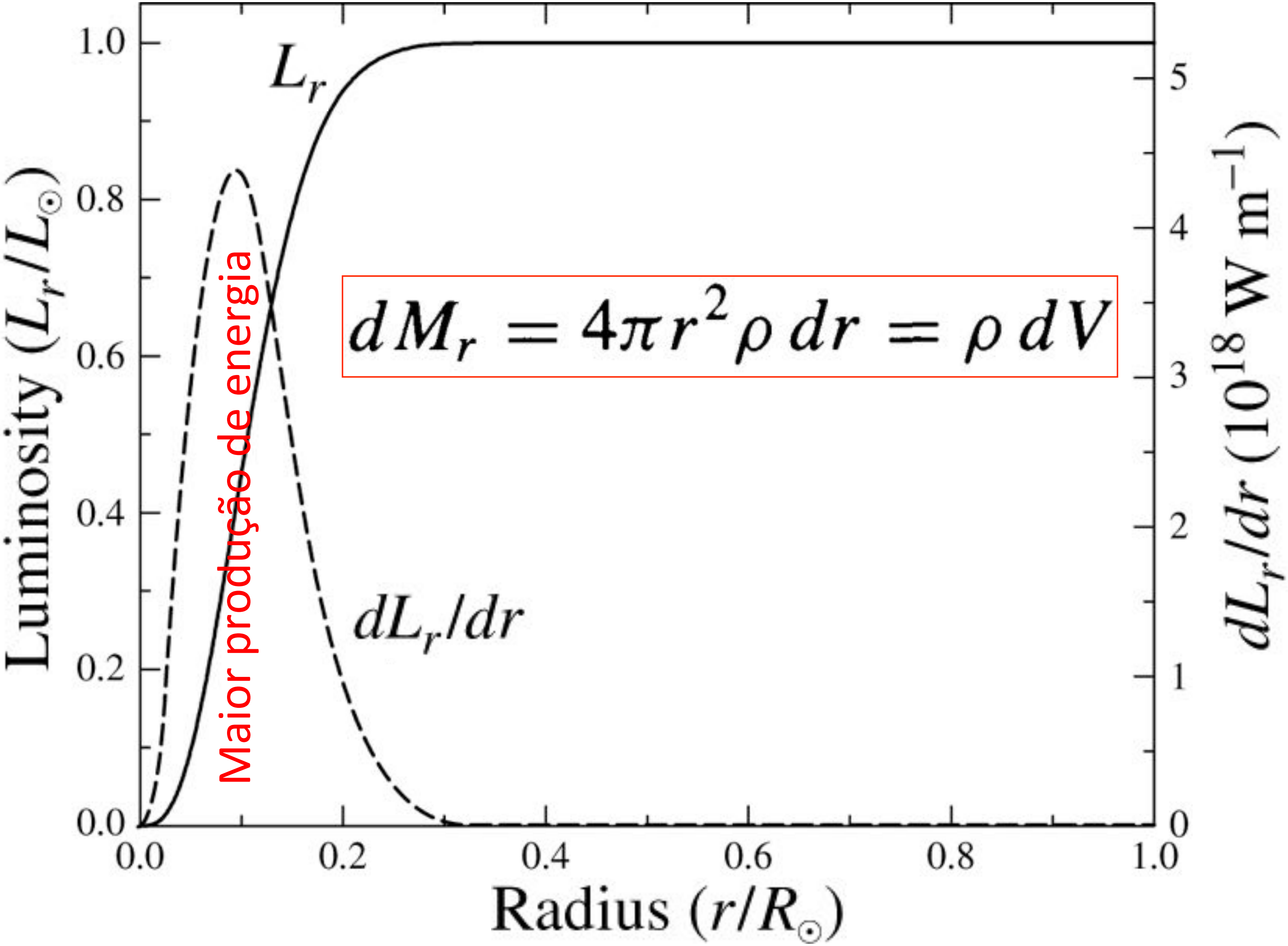


$$^1_1H + ^1_1H \rightarrow ^2_1H + e^+ + \nu_e$$

$$^2_1H + ^1_1H \rightarrow ^3_2He + \gamma$$

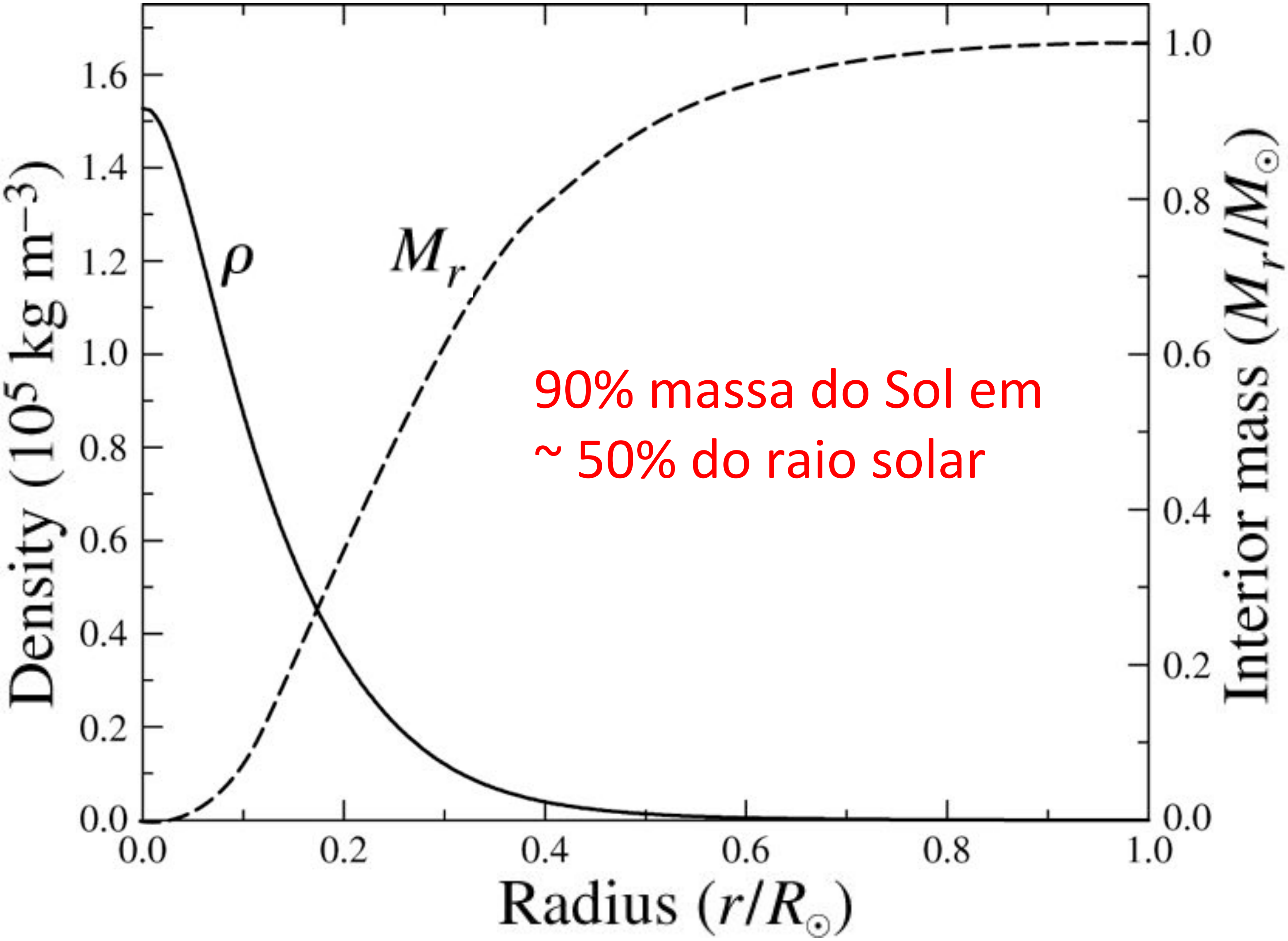
$$^3_2He + ^3_2He \rightarrow ^4_2He + 2\ ^1_1H.$$


Temperature (10^6 K)
16
14
12
10
8
6
4
2
0
Pressure (10^{16} N m^{-2})
2.5
2.0
1.5
1.0
0.5
0.0
T
P
0.0
0.2
0.4
0.6
0.8
1.0
Radius ($r/R_\odot$)

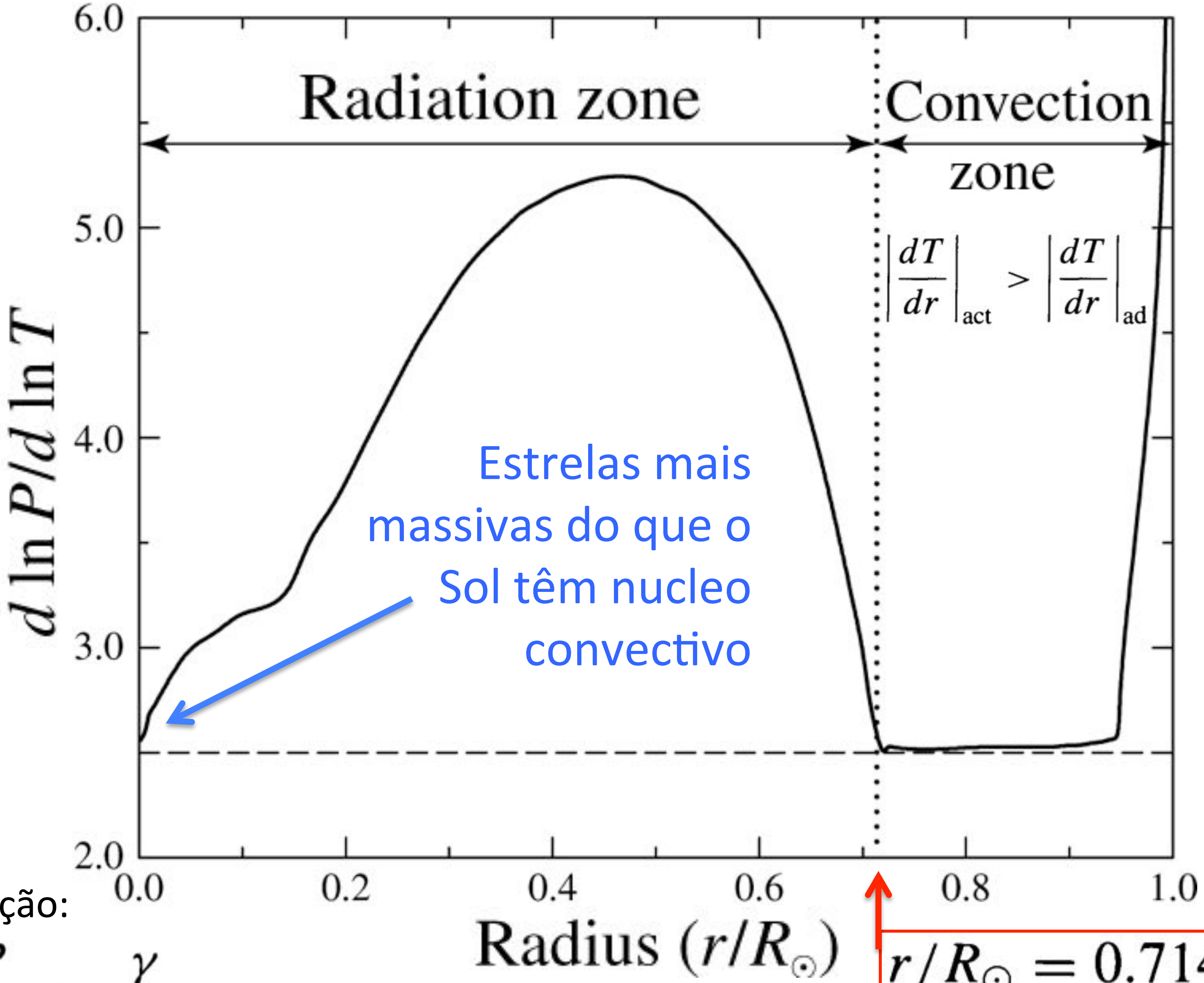


Maior produção de energia

$$\boxed{dM_r = 4\pi r^2 \rho \, dr = \rho \, dV}$$



90% massa do Sol em
~ 50% do raio solar



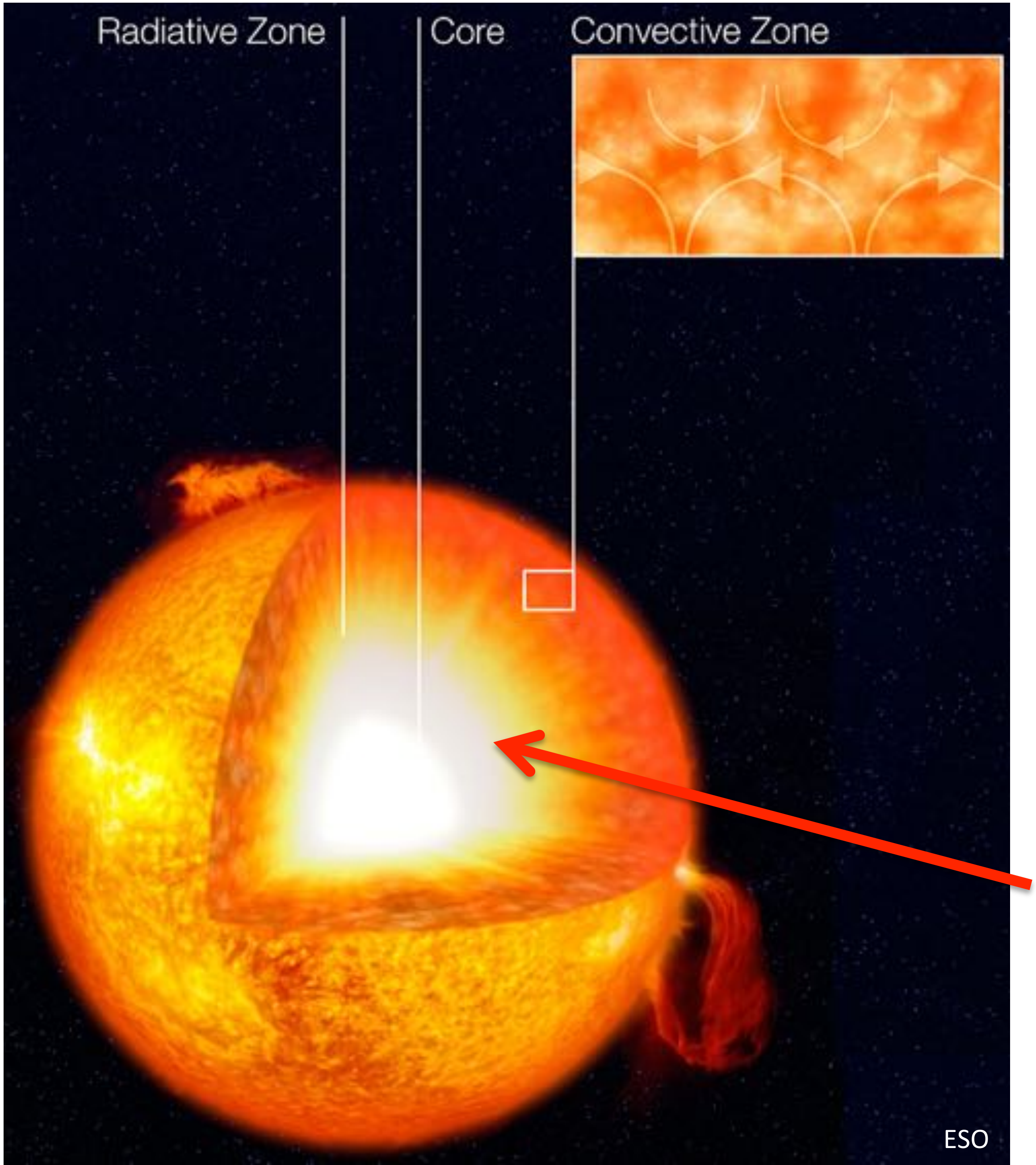
Estrelas mais massivas do que o Sol têm nucleo convectivo

$r/R_\odot = 0.714$

Convecção:

$$\frac{d \ln P}{d \ln T} < \frac{\gamma}{\gamma - 1}$$ = 2,5 in a monoatomic gas

O Problema do lítio solar



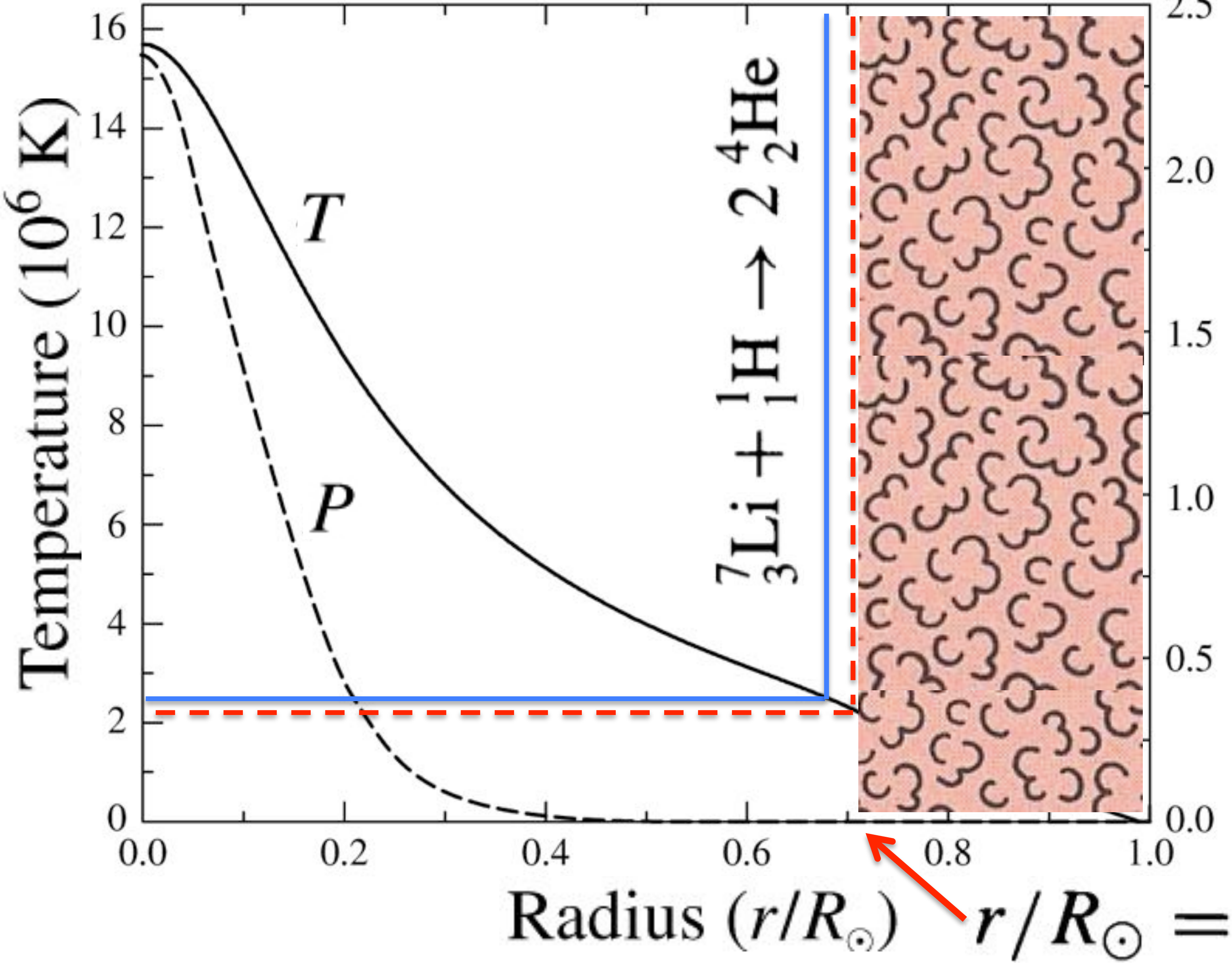
ESO

www.kgs.ku.edu/

A abundância de lítio observada no Sol é 160 vezes menor à de meteoritos.

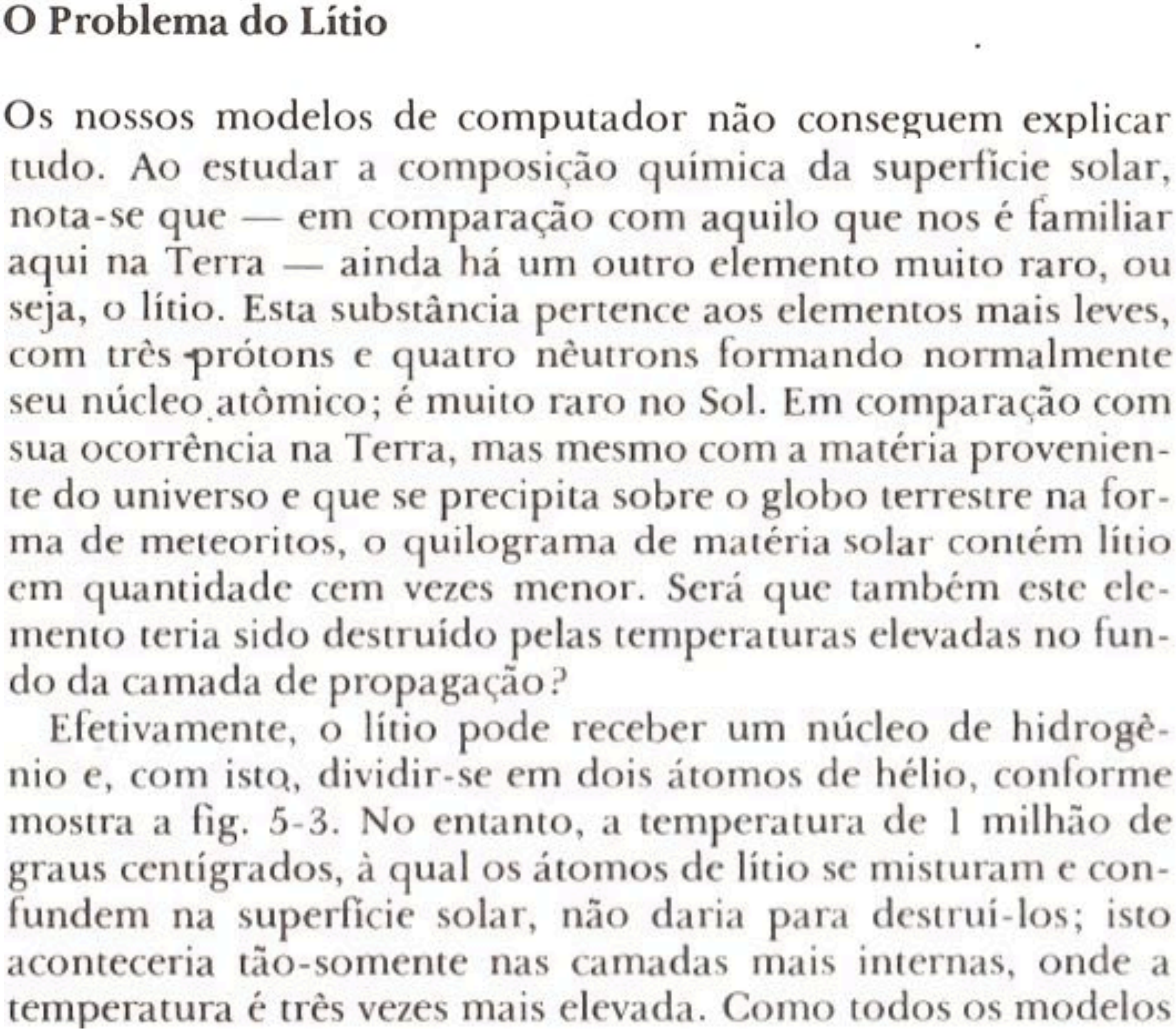
Li queima a $T=2.5\times10^6$ *K,* ***sob*** *a zona convectiva → não seria observada a destruição do lítio!*

Queima do lítio solar a T = 2,5x10^{6}K



$r/R_\odot = 0.714$

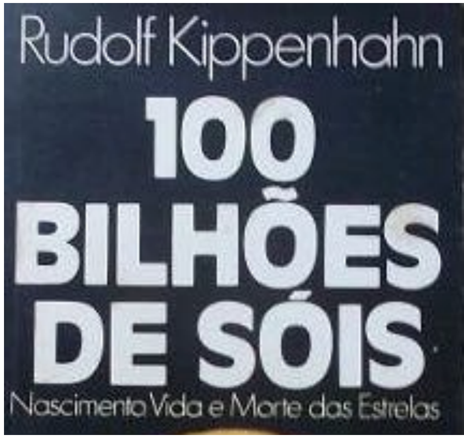
Mistério de mais de 60 anos!



O Problema do Lítio

Os nossos modelos de computador não conseguem explicar tudo. Ao estudar a composição química da superfície solar, nota-se que — em comparação com aquilo que nos é familiar aqui na Terra — ainda há um outro elemento muito raro, ou seja, o lítio. Esta substância pertence aos elementos mais leves, com três prótons e quatro nêutrons formando normalmente seu núcleo atômico; é muito raro no Sol. Em comparação com sua ocorrência na Terra, mas mesmo com a matéria proveniente do universo e que se precipita sobre o globo terrestre na forma de meteoritos, o quilograma de matéria solar contém lítio em quantidade cem vezes menor. Será que também este elemento teria sido destruído pelas temperaturas elevadas no fundo da camada de propagação?

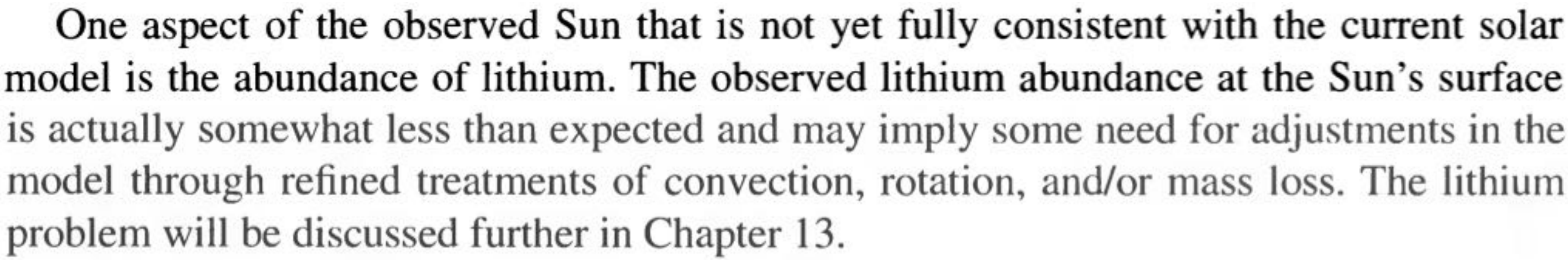
Efetivamente, o lítio pode receber um núcleo de hidrogênio e, com isto, dividir-se em dois átomos de hélio, conforme mostra a fig. 5-3. No entanto, a temperatura de 1 milhão de graus centígrados, à qual os átomos de lítio se misturam e confundem na superfície solar, não daria para destruí-los; isto aconteceria tão-somente nas camadas mais internas, onde a temperatura é três vezes mais elevada. Como todos os modelos



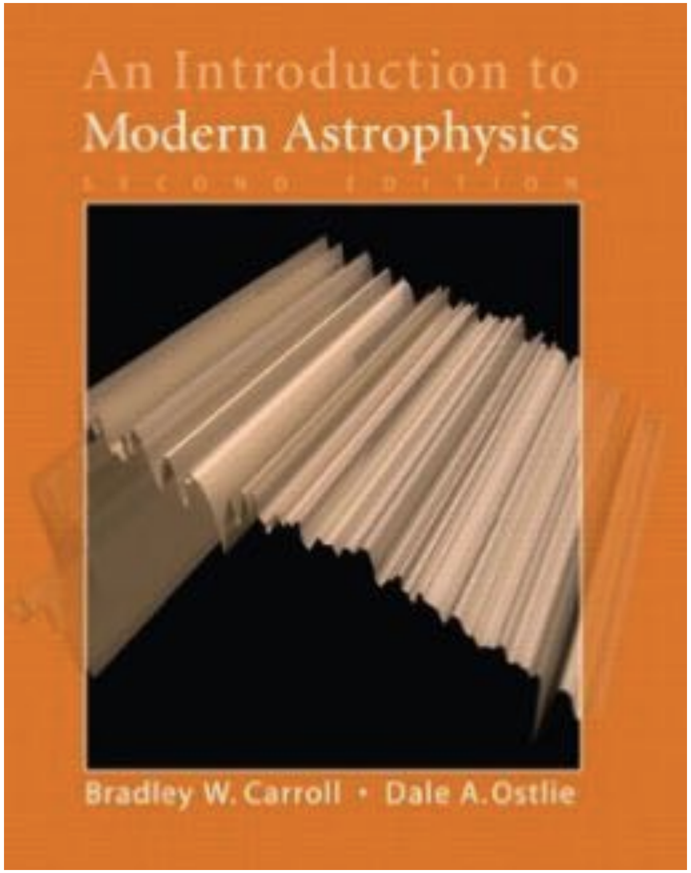
Rudolf Kippenhahn
100 BILHÕES DE SÓIS
Nascimento Vida e Morte das Estrelas

1981
> 35 anos

Mistério de mais de 60 anos!



One aspect of the observed Sun that is not yet fully consistent with the current solar model is the abundance of lithium. The observed lithium abundance at the Sun's surface is actually somewhat less than expected and may imply some need for adjustments in the model through refined treatments of convection, rotation, and/or mass loss. The lithium problem will be discussed further in Chapter 13.



An Introduction to Modern Astrophysics, 2nd Edition, by Bradley W. Carroll, Dale A. Ostlie

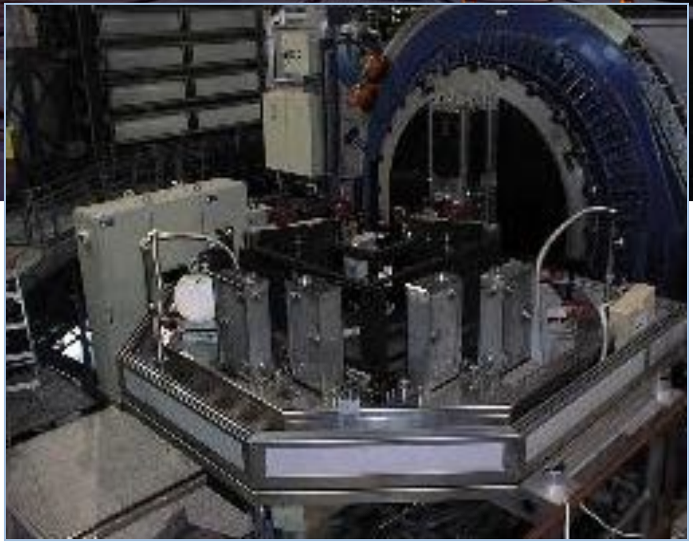
2007

Resolvendo o mistério do lítio usando gêmeas solares de diferentes idades

Telescópio VLT (8 metros) + UVES

R = 110 000, S/N ~ 500 - 1000 perto da linha de Li

Very Large Telescope, 8 meters (Paranal)

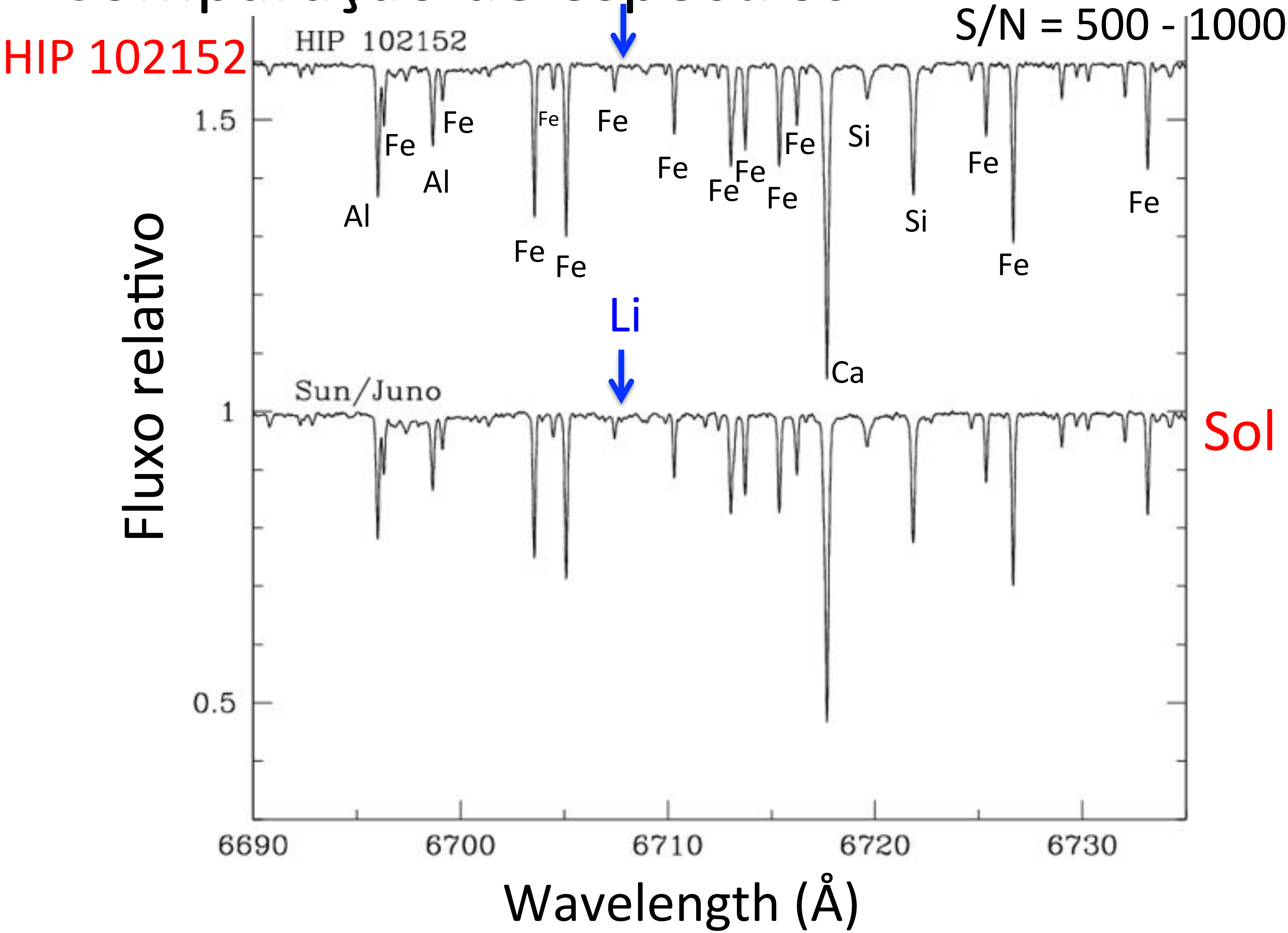


Espectrógrafo
UVES

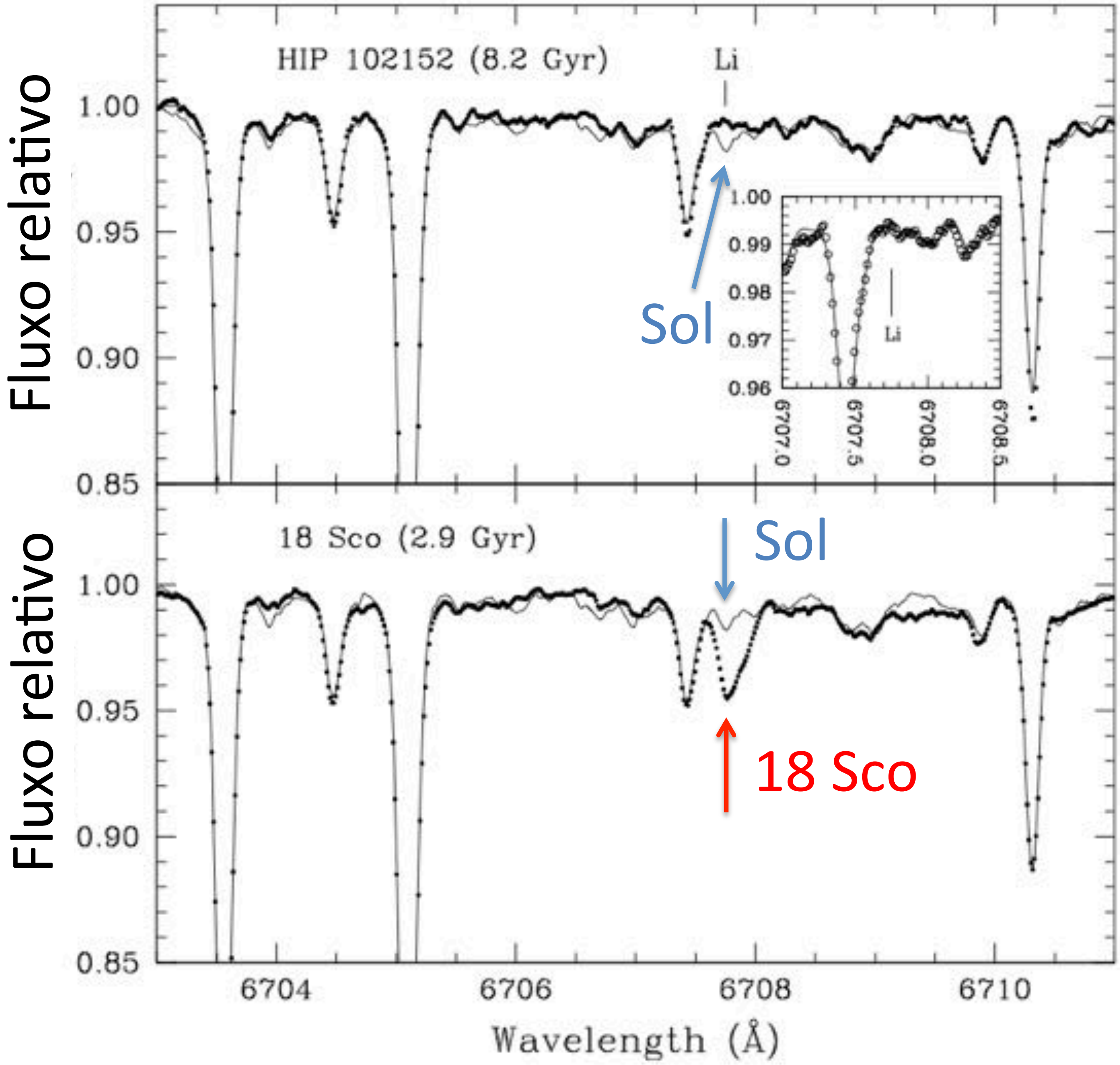
Comparação de espectros

R = 110 000

S/N = 500 - 1000

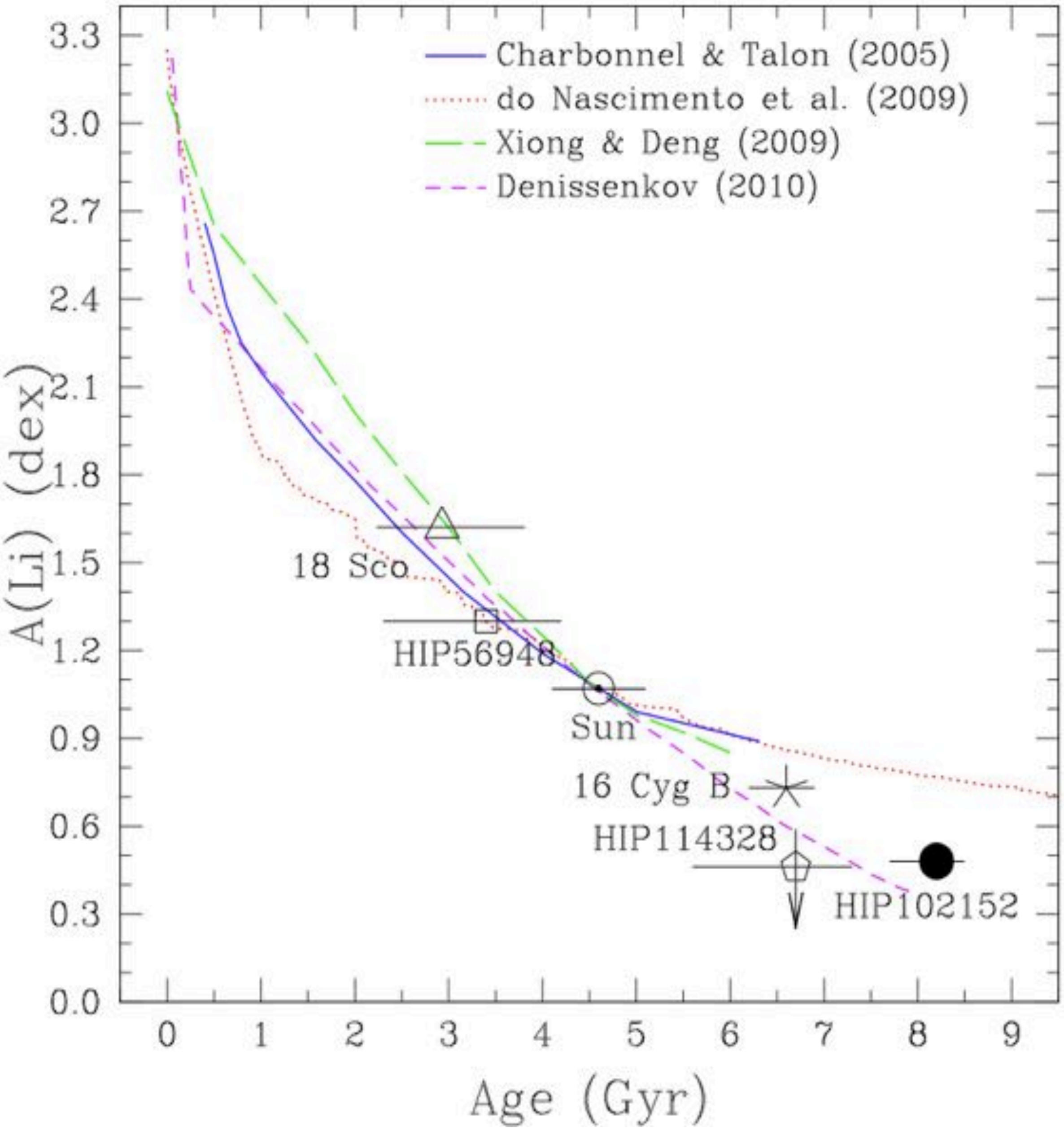


HIGH PRECISION ABUNDANCES OF THE OLD SOLAR TWIN HIP 102152: INSIGHTS ON Li DEPLETION FROM THE OLDEST SUN*



Monroe, Meléndez, Ramírez et al. 2013, ApJ, 774, L32

HIP 114328 and HIP102152: gêmeas solares velhas



Monroe et al. 2013

Meléndez et al. 2014

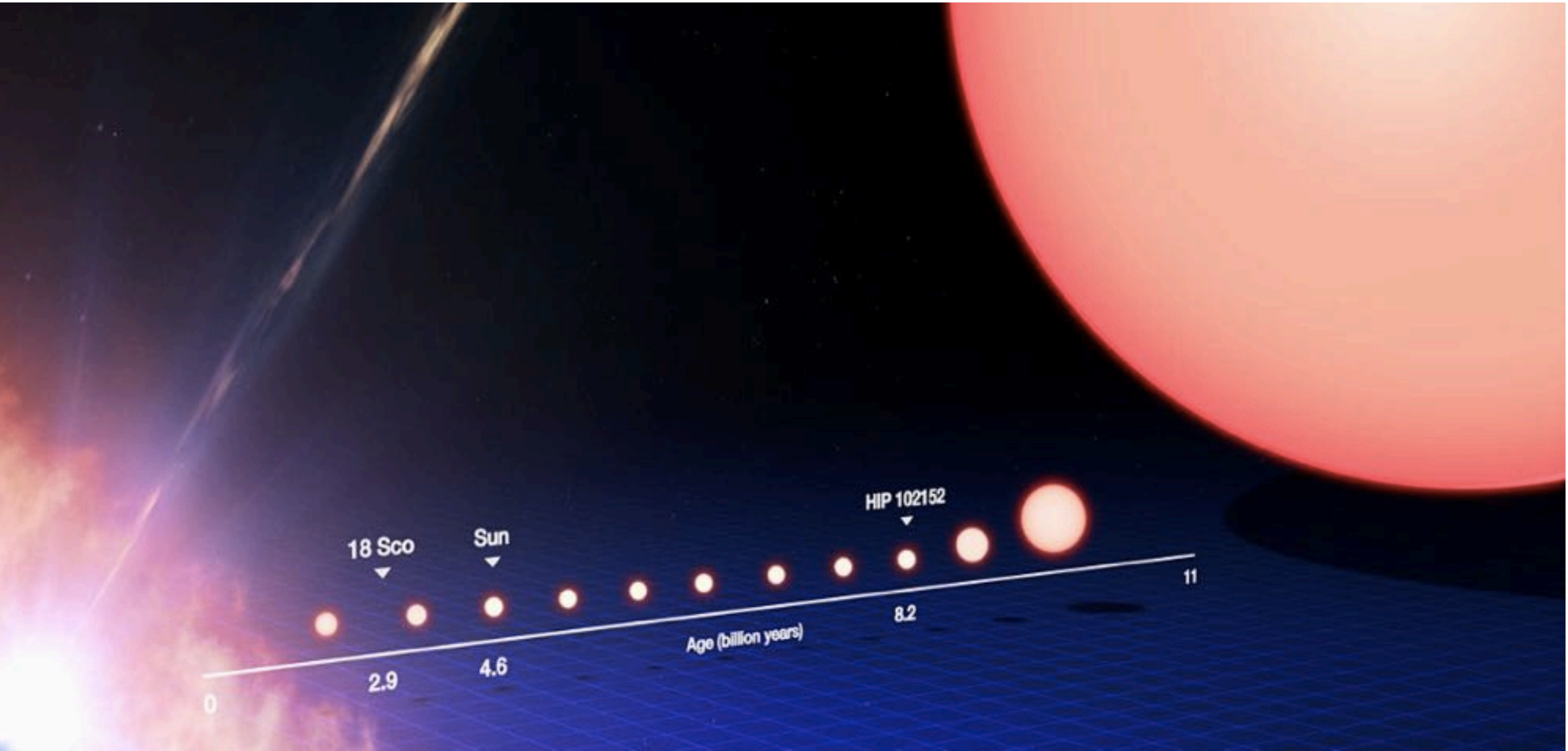
eso1337pt-br — Nota de imprensa científica

Identificada a estrela gêmea do Sol mais velha conhecida até hoje

O VLT do ESO fornece novas pistas que ajudam a solucionar o mistério do lítio

28 de Agosto de 2013

European
Southern
Observatory



Press release mais coletiva de imprensa, IAG/USP, 28/8/2013, 10h30m

Globo

http://g1.globo.com/ciencia-e-saude/noticia/2013/08/equipe-da-usp-ajuda-descobrir-mais-velha-estrela-gemea-do-sol.html

28/08/2013 10h29 - Atualizado em 29/08/2013 11h18

Equipe da USP ajuda a descobrir mais velha estrela 'gêmea' do Sol

HIP 102152 tem 8,2 bilhões de anos e fica a 250 anos-luz da Terra.
Estudo foi feito em parceria com o Observatório Europeu do Sul (ESO).

Luna D'Alama
Do G1, em São Paulo

Imagem: ESO/Divulgação

Imagem: Meléndez/Wikipédia

http://www.skyandtelescope.com/news/Sun-Loses-Lithium-with-Age-221836221.html

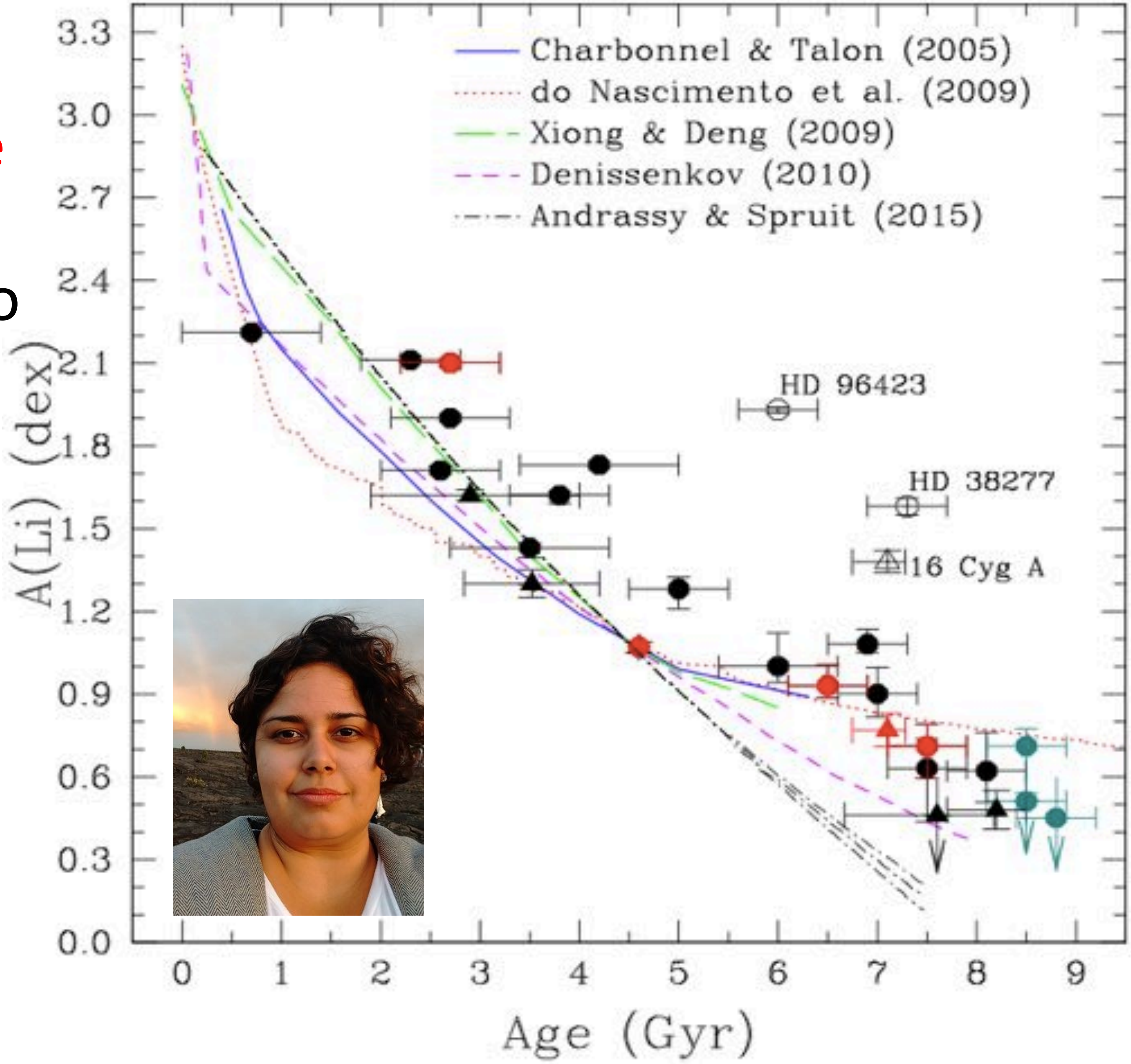
Sun Loses Lithium with Age

Observations of two solar twins — one old and one young — confirm that the Sun has probably destroyed its lithium over time.

I've blogged repeatedly here about the universe's missing lithium. But lithium is also a troublemaker in the solar system. Based on primitive meteorites that record the makeup of the nebula from which the solar system formed, the Sun seems to have destroyed more than 99% of its initial lithium.

Questões ainda em aberto sobre o lítio:

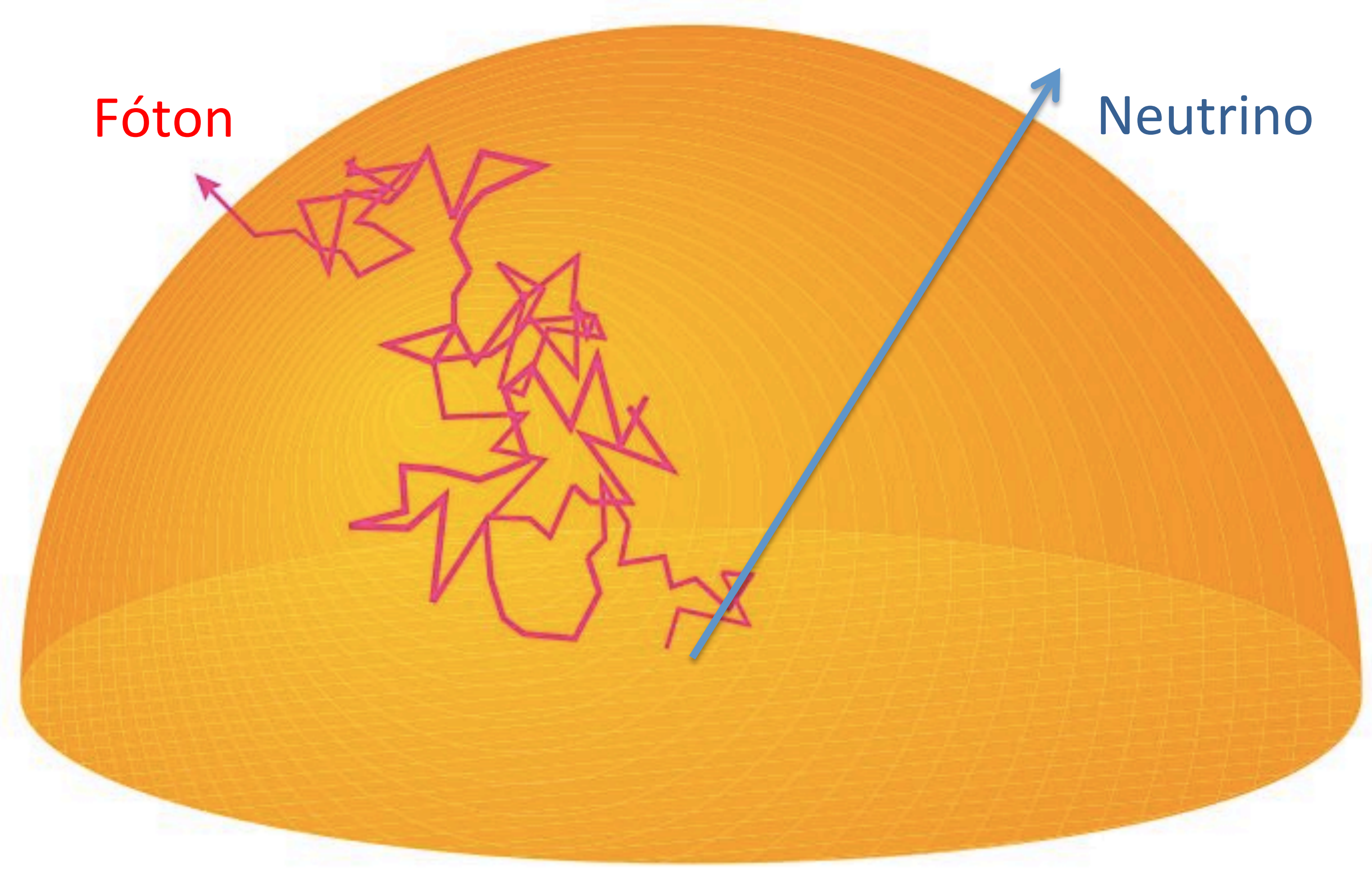
- Qual o modelo para alcançar regiões sob a camada convectiva?
- Estrelas da sequência principal ricas em lítio: **planetas?**



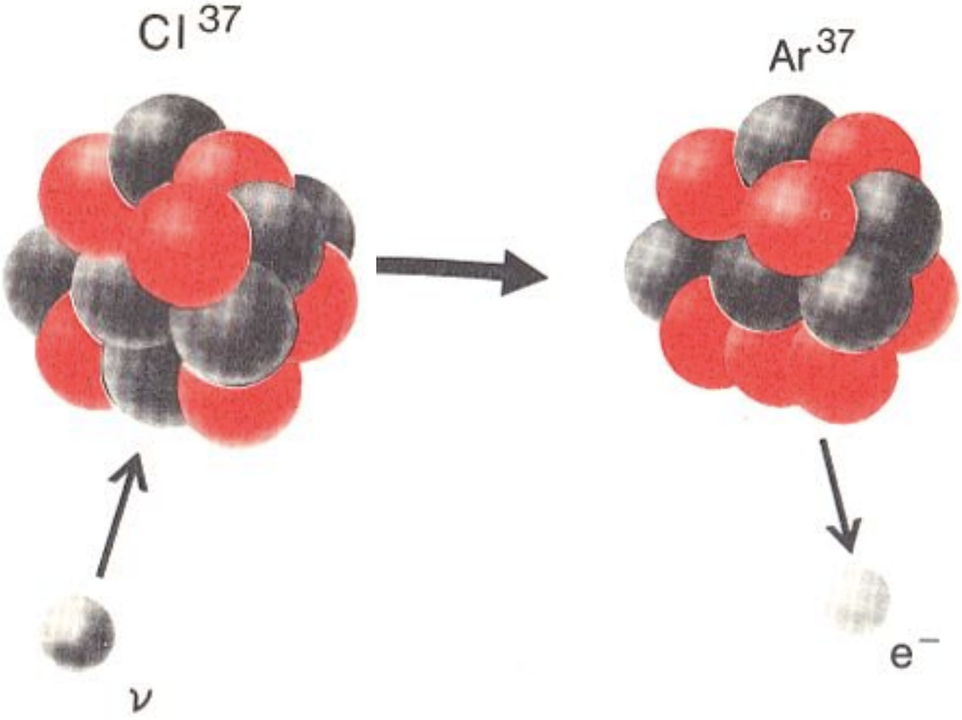
Marília Carlos, Poul Nissen & Jorge Meléndez (2016, A&A 587, A100)

O Problema do neutrino solar

São detectados menos neutrinos do que os preditos pelo modelo padrão do Sol



$$^{37}_{17}\mathrm{Cl} + \nu_e \rightleftharpoons {}^{37}_{18}\mathrm{Ar} + e^-$$



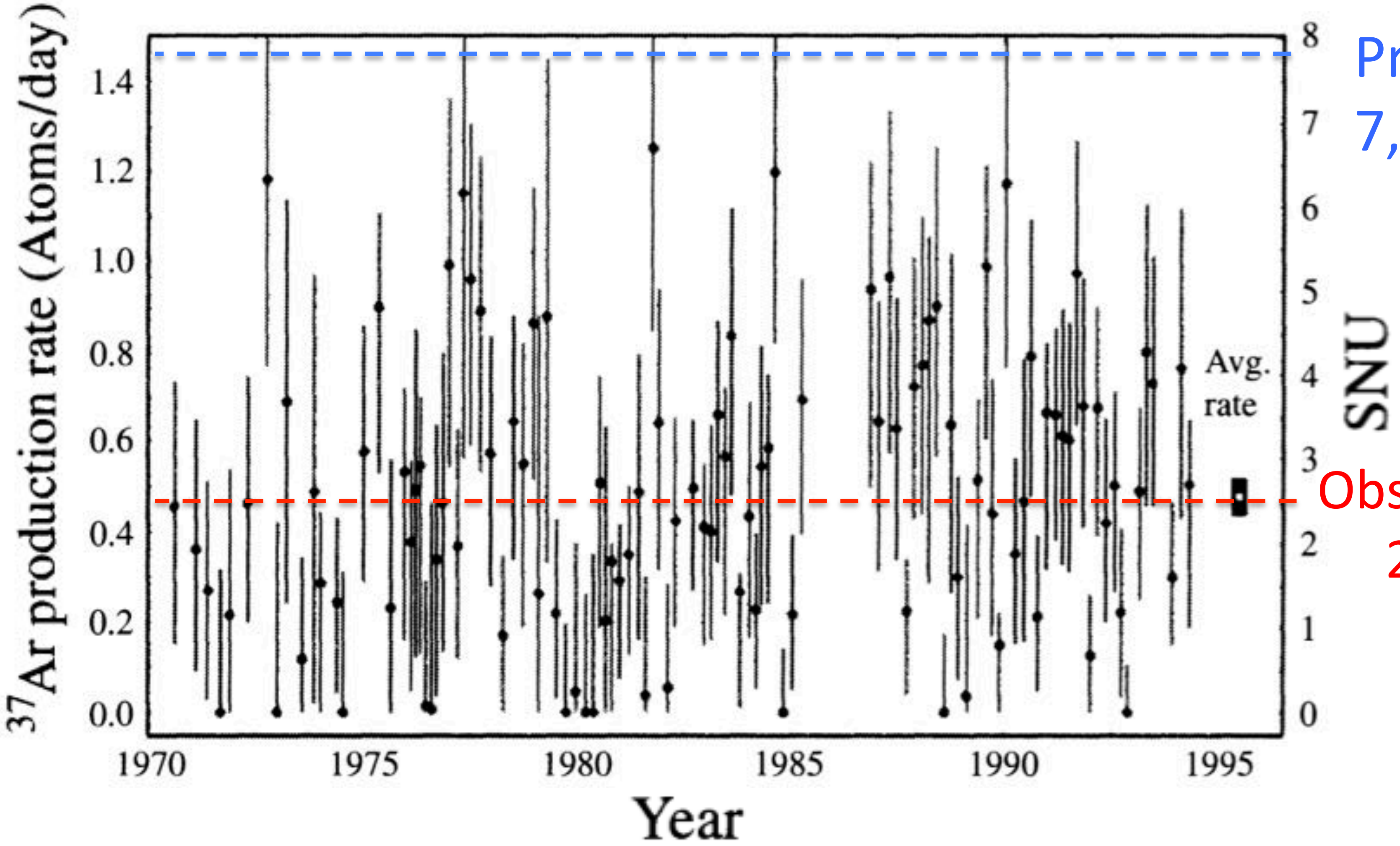
Os neutrinos que interagem com o Cl-37 são de alta energia, originados na reação rara da cadeia pp-III:

$$^{8}_{5}\mathrm{B} \rightarrow {}^{8}_{4}\mathrm{Be} + e^+ + \nu_e$$

Fig. 5.5. Um neutrino é capaz de transformar um átomo de cloro em um átomo de argônio, liberando um elétron durante o processo

Raymond Davis's solar neutrino detector

FIGURE 11.8 Raymond Davis's solar neutrino detector. The tank was located 1478 m (4850 ft) below ground in the Homestake Gold Mine in Lead, South Dakota, and was filled with 615,000 kg of C_2Cl_4 in a volume of 377,000 liters (100,000 gallons). (Courtesy of Brookhaven National Laboratory.)

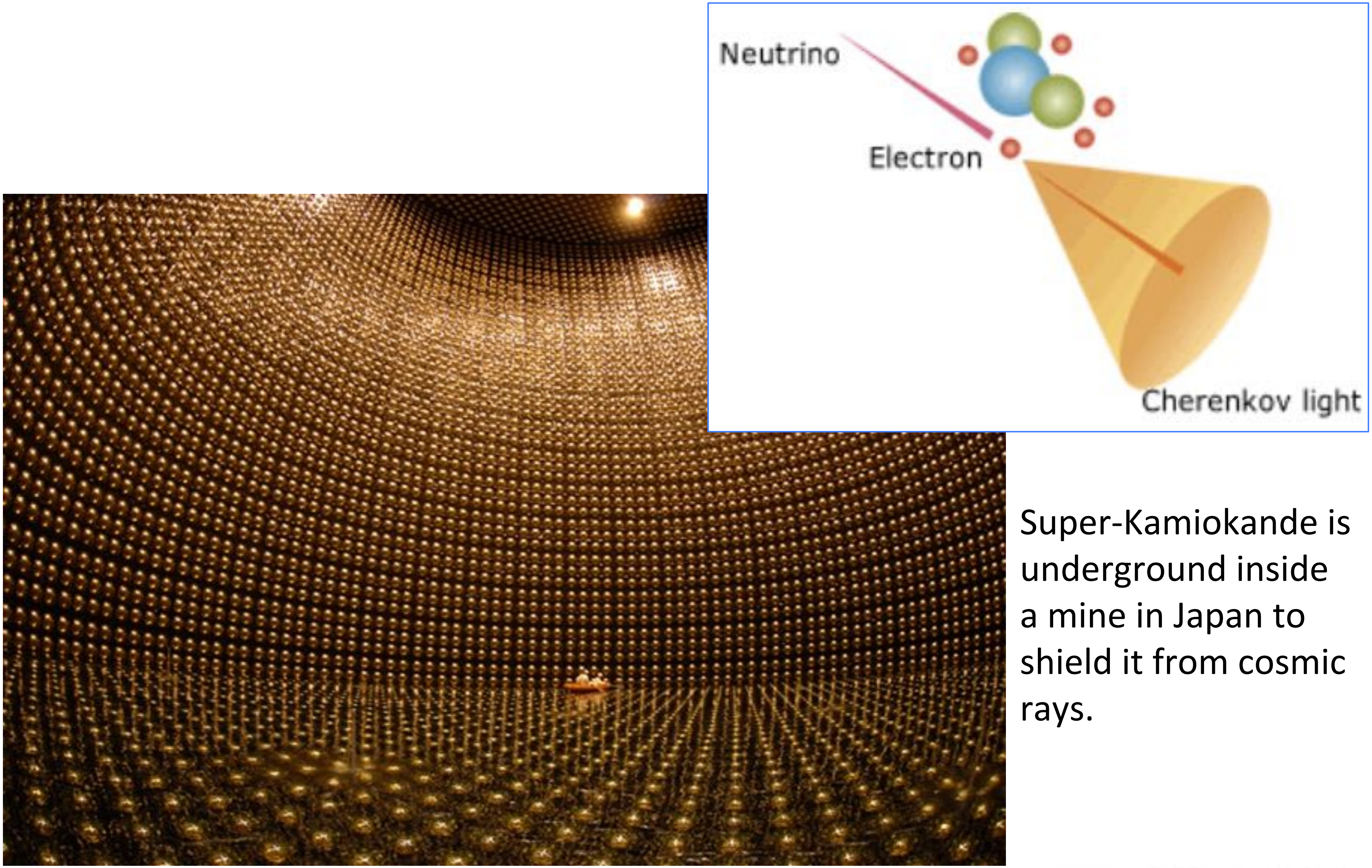


Previsto:
7,9 SNU

Observado
2,5 SNU

FIGURE 11.9 Results of the Davis solar neutrino experiment from 1970 to 1994. The uncertainties in the experimental data are shown by vertical error bars associated with each run. The predicted solar neutrino capture rate for the $^{37}_{17}$Cl detector was 7.9 SNU based on solar models without neutrino oscillations. (Figure adapted from Cleveland, et al., *Ap. J.*, *496*, 505, 1998.)

1 SNU = 10^{-36} reações por átomo alvo por segundo



Super-Kamiokande is underground inside a mine in Japan to shield it from cosmic rays.

FIGURE 11.10 Super-Kamiokande neutrino observatory in Japan contains 4.5×10^7 kg (50,000 tons) of pure water. As neutrinos pass through the water, they scatter electrons at speeds greater than the speed of light through water. The pale blue Cerenkov light that is produced is detected by the 11,200 inwardly-directed photomultiplier tubes, signaling the presence of the passing neutrino.

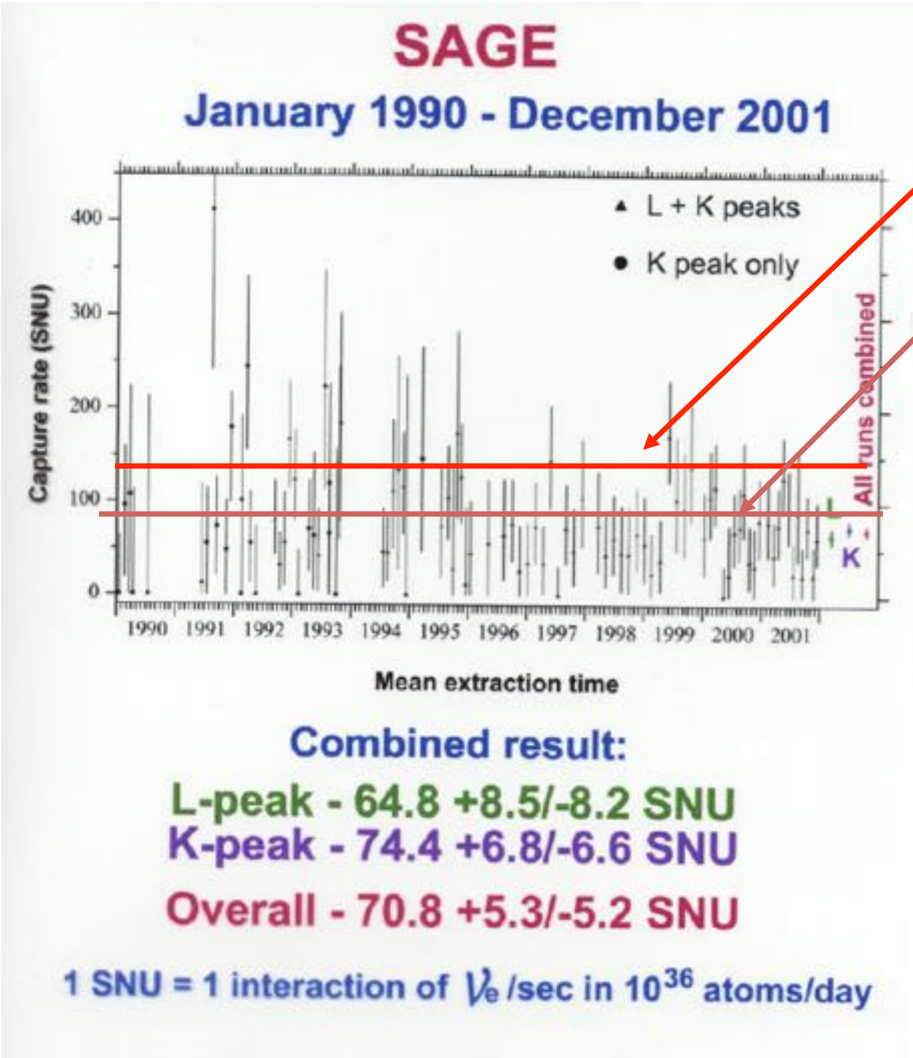
Gallium experiments $\nu_e + {}^{71}_{31}\mathrm{Ga} \rightarrow {}^{71}_{32}\mathrm{Ge} + e^-$

Similar experiments to chlorine but with gallium:

- Lower threshold (0.233 MeV) so sensitive to the lower end of the pp chain
- Further evidence of missing solar neutrinos (55% of expectation)

Expectation: 129+-8 SNU

Observed: 70.8+-6 SNU



SAGE

January 1990 - December 2001

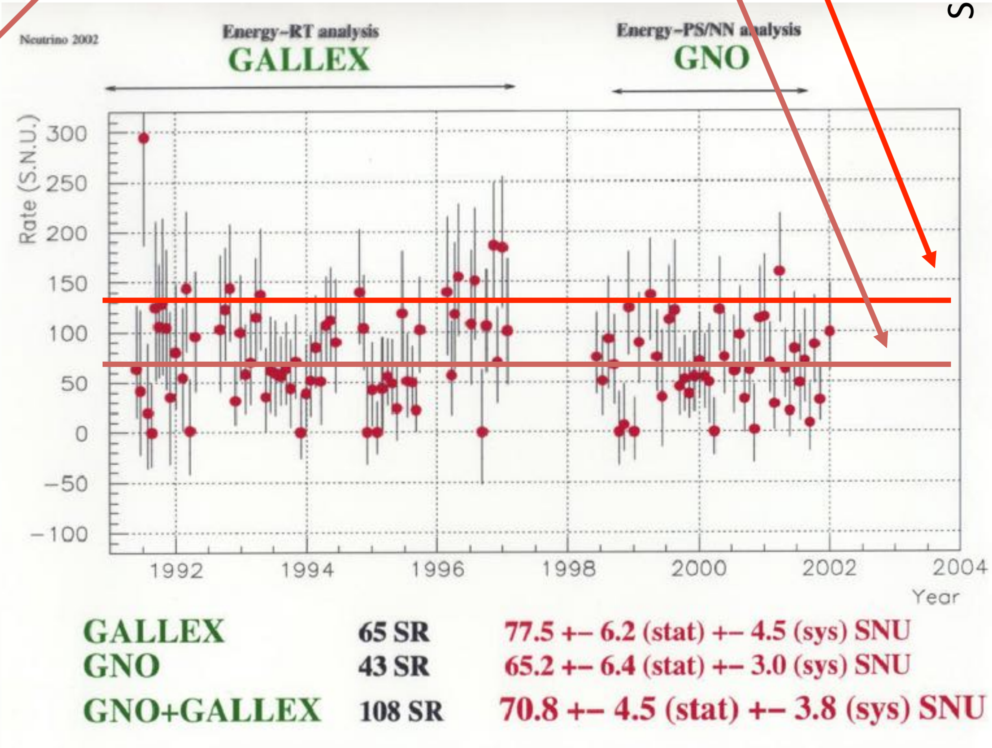
Combined result:

L-peak - 64.8 +8.5/-8.2 SNU

K-peak - 74.4 +6.8/-6.6 SNU

Overall - 70.8 +5.3/-5.2 SNU

1 SNU = 1 interaction of ν_e /sec in 10^{36} atoms/day



GALLEX	65 SR	77.5 +– 6.2 (stat) +– 4.5 (sys) SNU
GNO	43 SR	65.2 +– 6.4 (stat) +– 3.0 (sys) SNU
GNO+GALLEX	108 SR	70.8 +– 4.5 (stat) +– 3.8 (sys) SNU

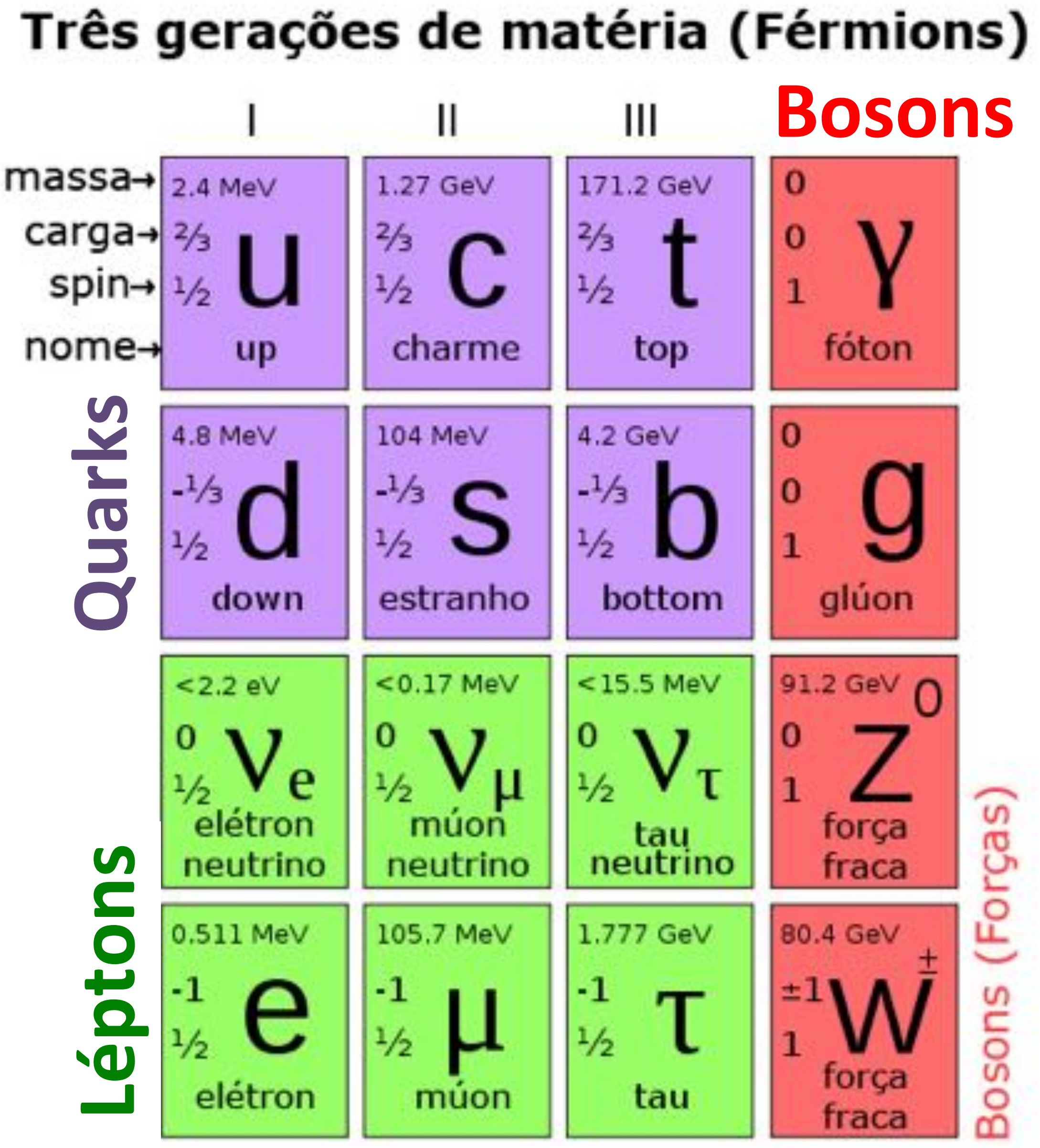
Slide: Dr Paul Soler, University of Glasgow

Solução ao problema do neutrino solar

Se os neutrinos têm massa, eles podem oscilar entre diferentes tipos de neutrinos, por exemplo:

$$\nu_{\mu} \rightarrow \nu_{\tau}$$

→ o neutrino não é necessariamente detectado



Três gerações de matéria (Férmions)

		I	II	III	Bosons
Quarks	massa→ carga→ spin→ nome→	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charme	171.2 GeV ⅔ ½ t top	0 0 1 γ fóton
		4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s estranho	4.2 GeV -⅓ ½ b bottom	0 0 1 g glúon
Léptons		<2.2 eV 0 ½ ν_e elétron neutrino	<0.17 MeV 0 ½ ν_μ múon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 força fraca
		0.511 MeV -1 ½ e elétron	105.7 MeV -1 ½ μ múon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ força fraca

Bosons (Forças)

Nobel Prize in Physics 2002

Raymond Davis Jr.
Prize share: 1/4

Masatoshi Koshiba
Prize share: 1/4

Riccardo Giacconi
Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to **Raymond Davis Jr.** and **Masatoshi Koshiba** *"for pioneering contributions to astrophysics, in particular for the* ***detection of cosmic neutrinos****"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

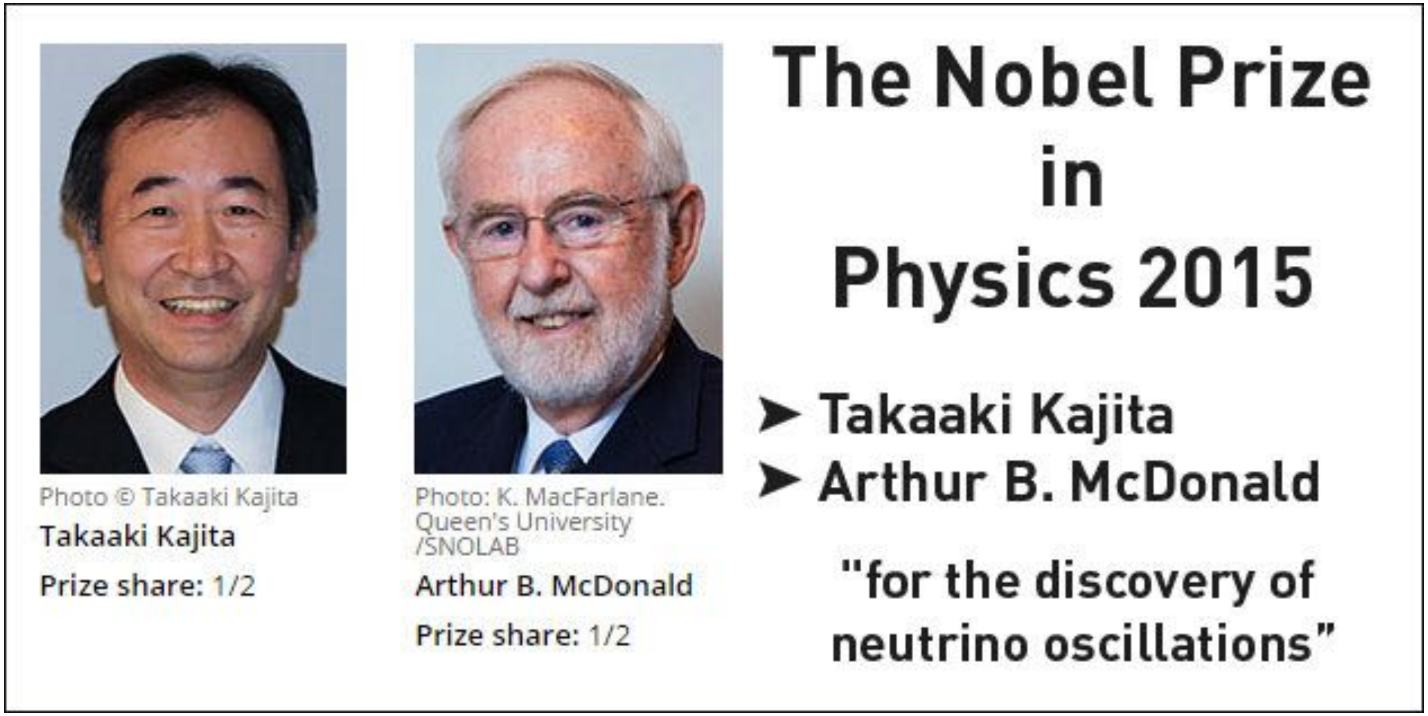
Takaaki Kajita

Super-Kamiokande Collaboration. &

Arthur B. McDonald

Sudbury Neutrino Observatory Collaboration.

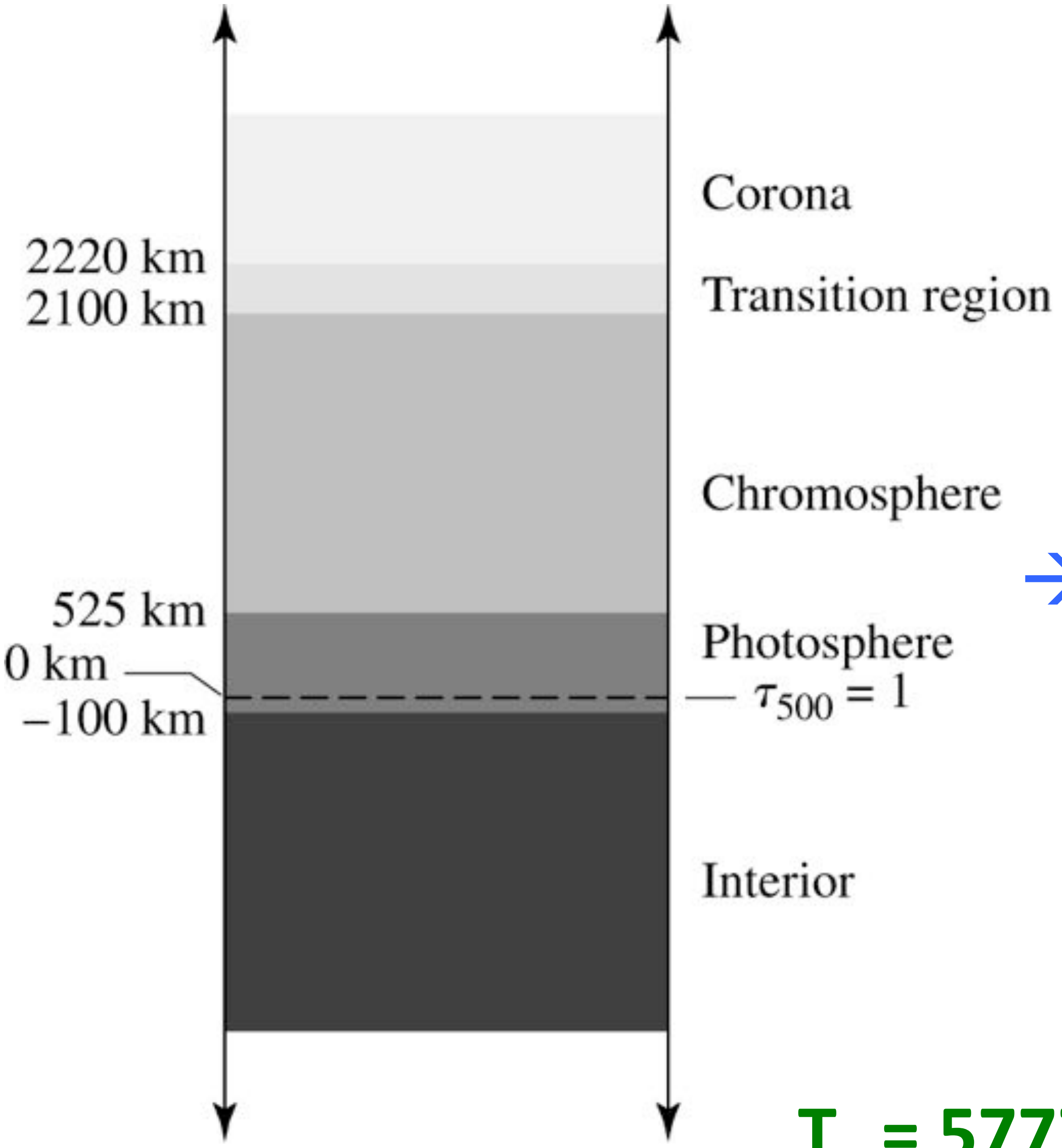
“for the discovery of neutrino oscillations, which shows that neutrinos have mass”



11.2 A atmosfera solar

Disco solar aparece bem definido pela rápida mudança da profundidade óptica. A atmosfera muda de opaca para transparente em apenas 600 km (0,09% do raio solar)

A fotosfera



Qual a base?

100 km sob a camada $\tau_{500nm} = 1$.

→ $\tau \sim 24$ e $T \sim 9400$ K.

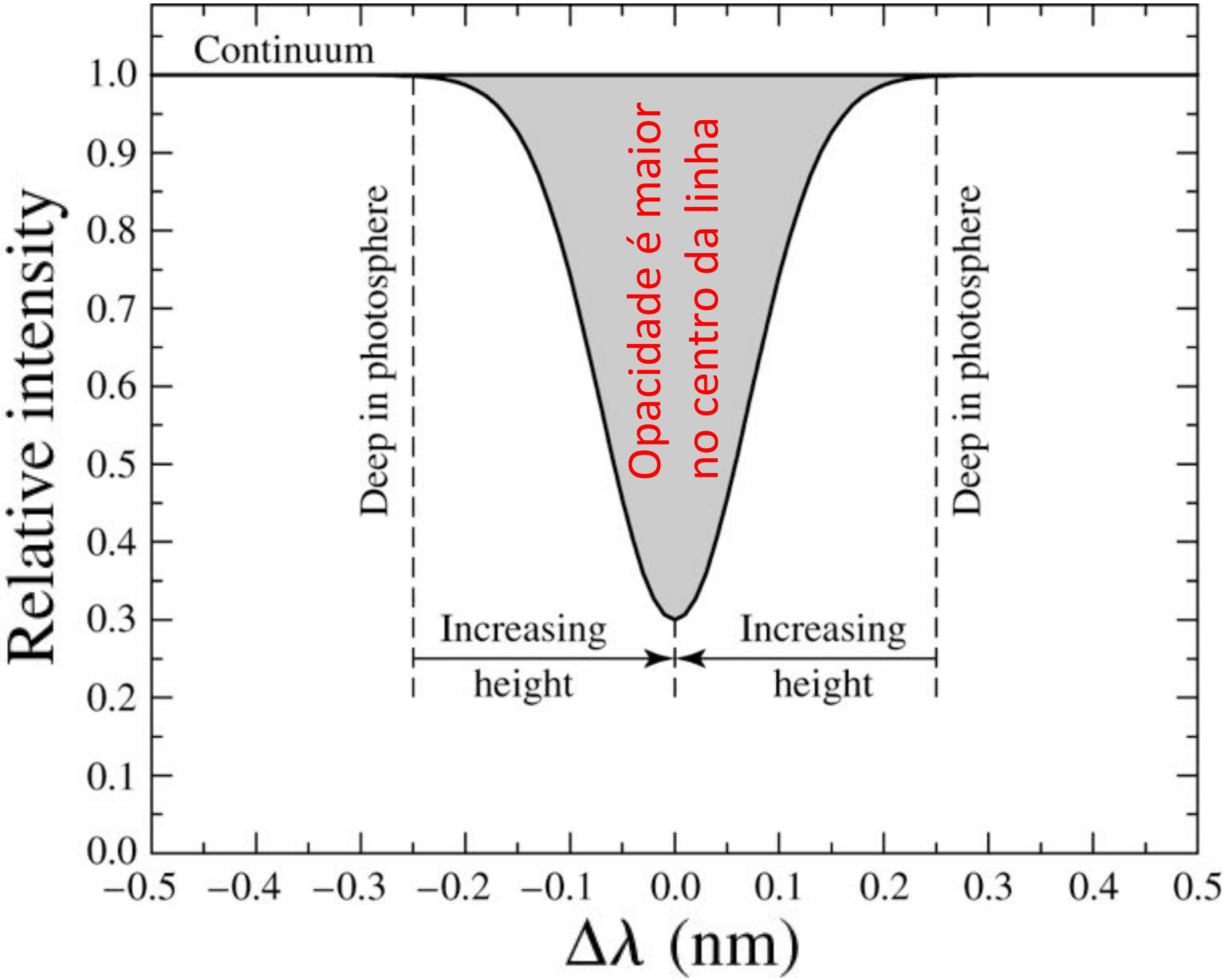
Qual o topo?

525 km acima de $\tau_{500nm} = 1$,

→ $T \sim 4400$ K

$T_e = 5777$ K em $\tau \sim 2/3$

Formação das linhas de absorção na fotosfera



Opacidade é maior no centro da linha

Granulação

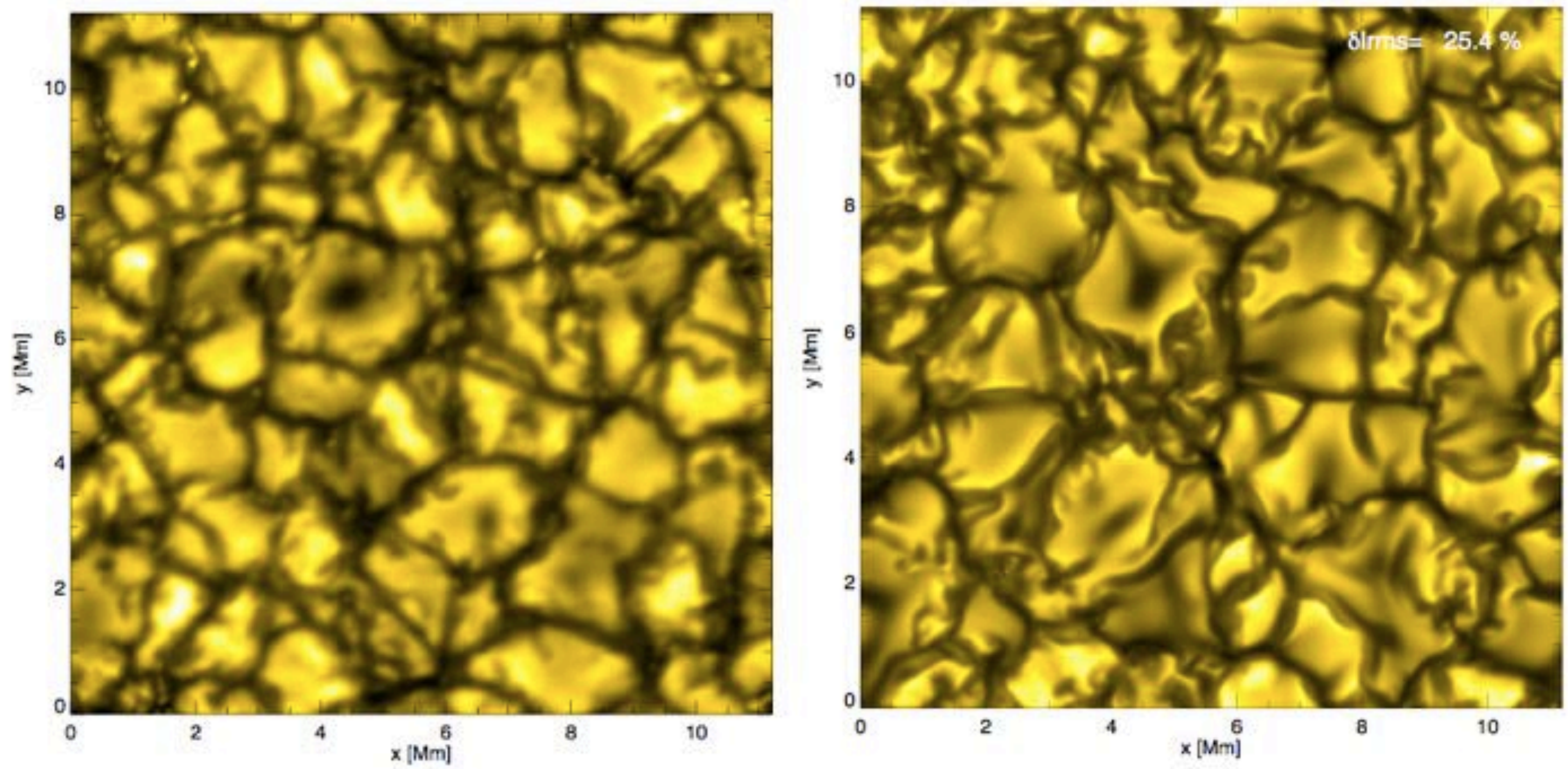


Figure 1: **Left:** Quiet solar granulation as observed with the 1m Swedish Solar Telescope (courtesy Mats Carlsson 2004). **Right:** High-resolution CO^{5}BOLD simulation of solar surface convection. Both images show the emergent continuum intensity (using identical scaling) at λ 4364 Å in a field measuring $15'' \times 15''$ (11×11 Mm).

The Solar Photospheric Nitrogen Abundance.
Determination with 3D and 1D model atmospheres.

E.Maiorca[A], *E.Caffau*[B], *P.Bonifacio*[C,B,D], *M.Busso*[A,H], *R.Faraggiana*[E], *M.Steffen*[F], *H.-G.Ludwig*[C,B], *I.Kamp*[G]

Dynamics of the solar granulation. VII. A nonlinear approach.

Nesis et al. 2001, A&A, 373, 307

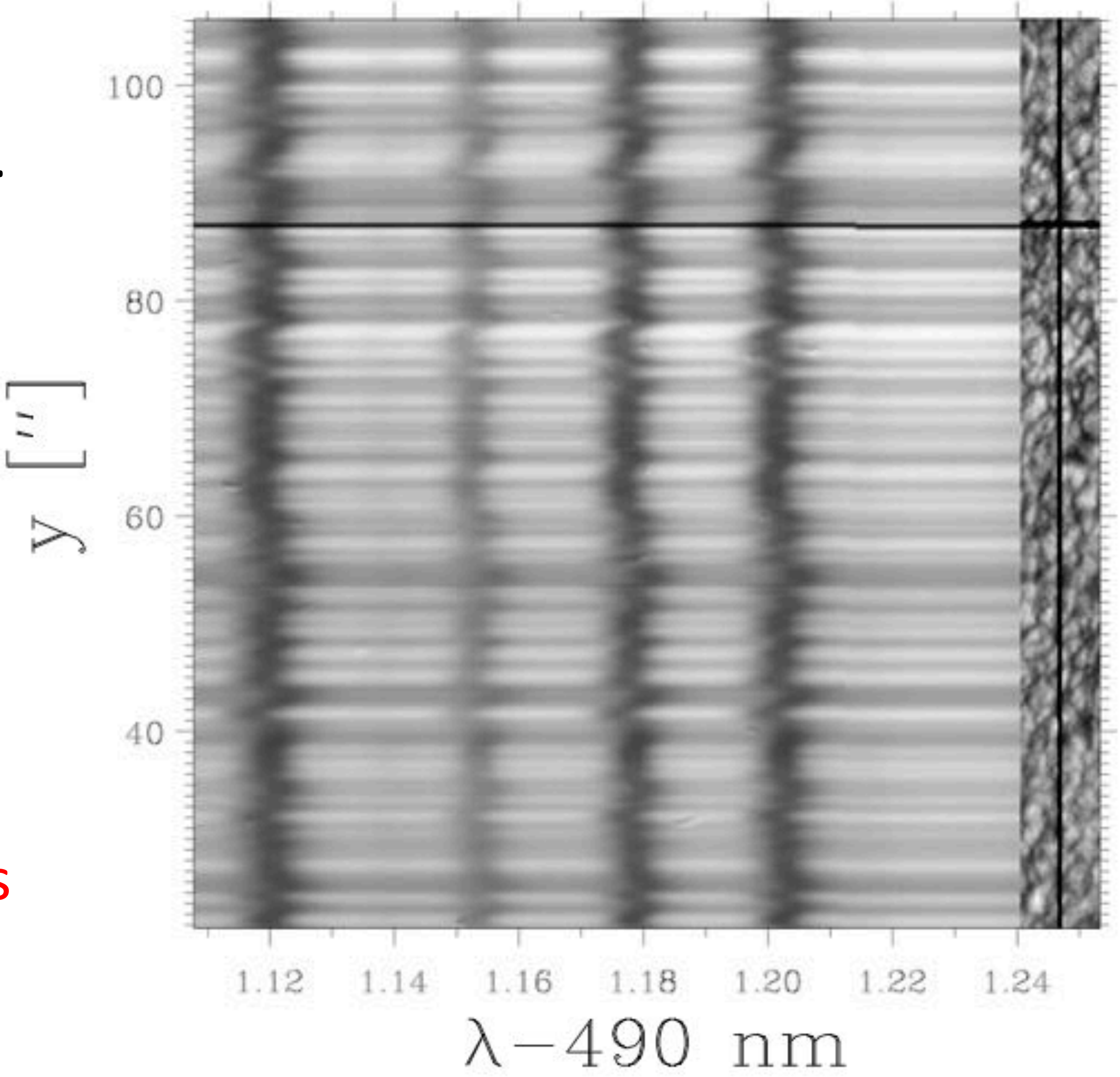


Fig. 1. Part of our best spectrogram 99S4.Sp66, in the wavelength region λλ: 491.11–491.24 nm with the corresponding slit-jaw white light picture attached at the right border. The dark line parallel to the x-axis, at 87 arcsec on the y-axis, is due to a calibration hair across the spectrograph slit. The dark line parallel to the y-axis corresponds to the spectrograph slit.

Livro-texto:
Radial velocities
~ 0,4 km/s

Nesis et al. 2001, A&A, 373, 307

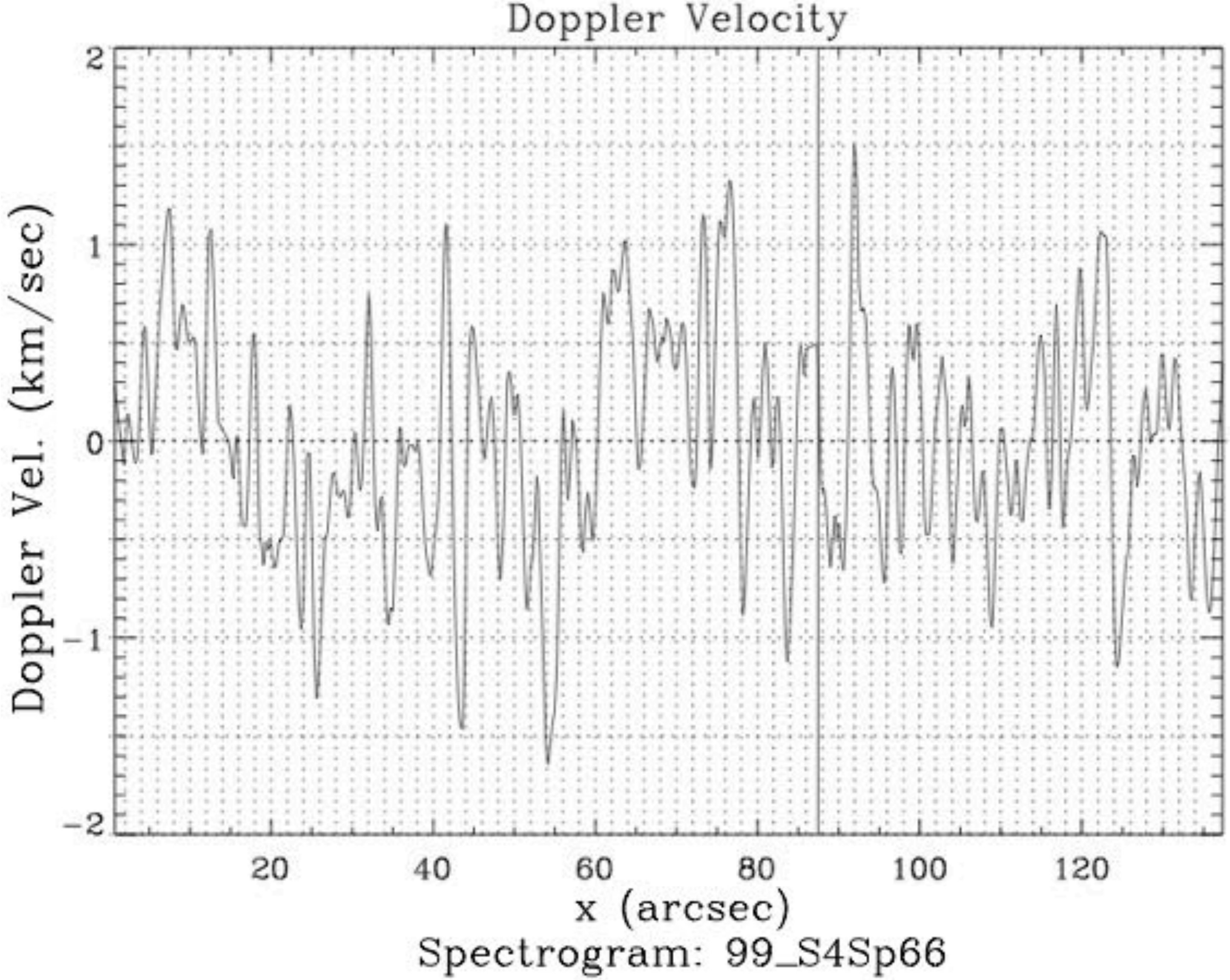
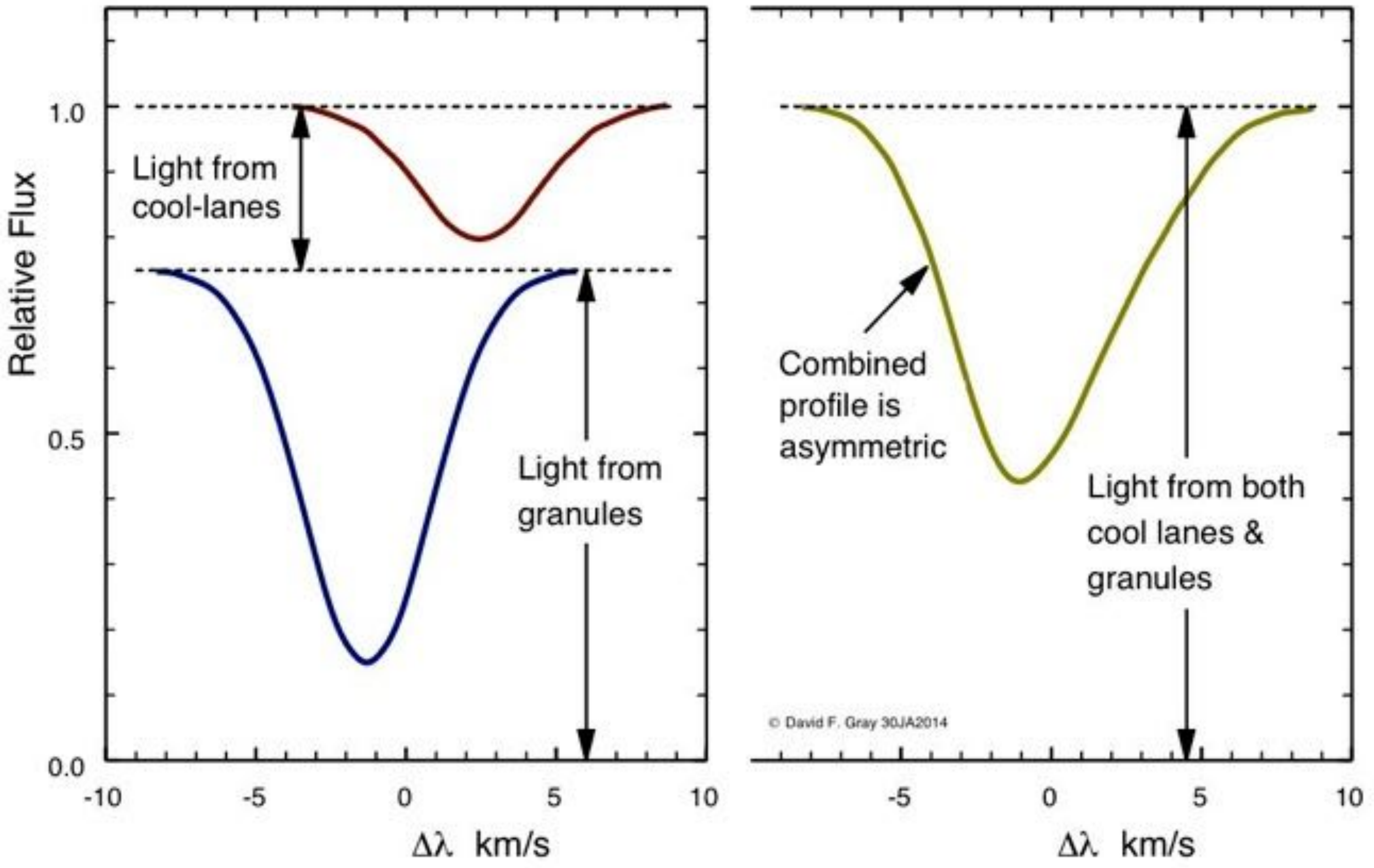


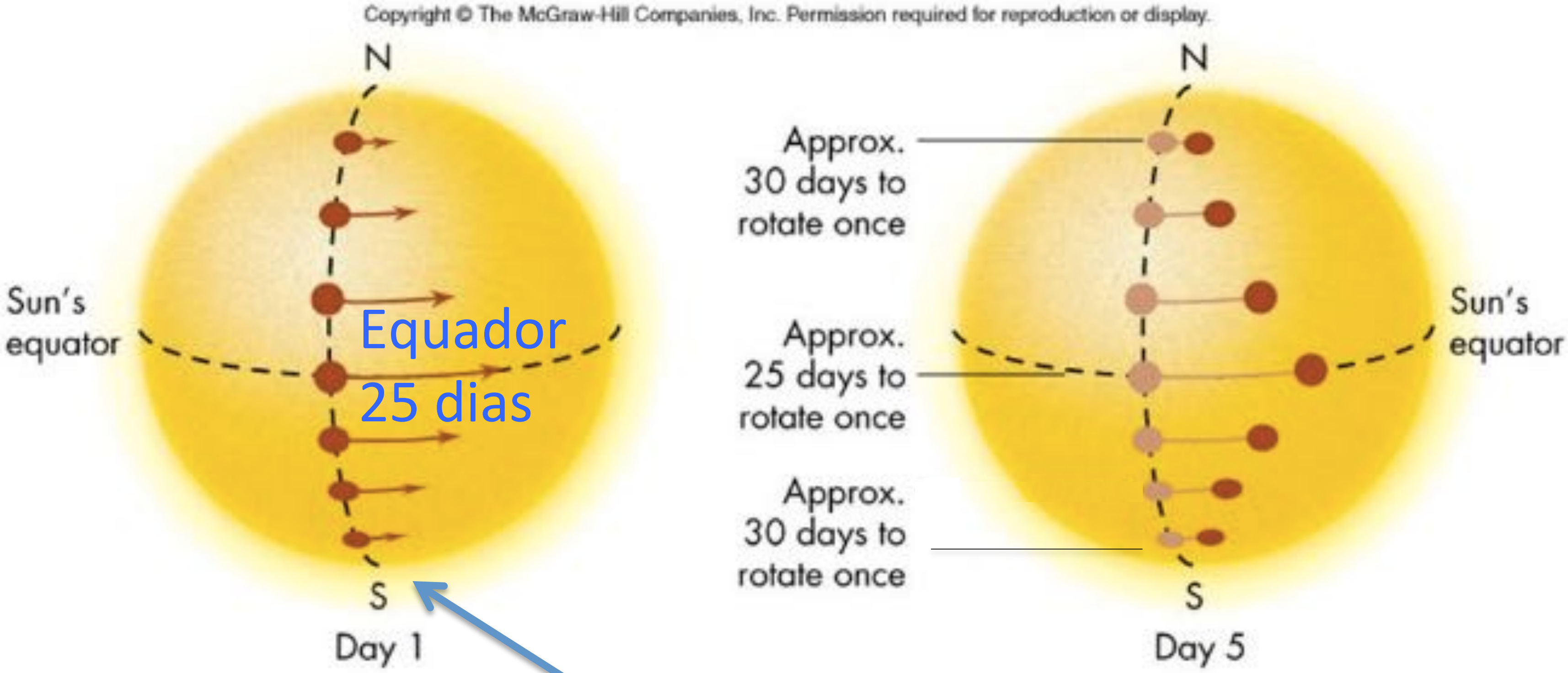
Fig. 2. Granular Doppler velocity variations vconv along the spectrograph slit derived from the line wiggles of the Ni ab- sorption line (cf. λ491.24 on the ordinate in Fig. 1). Abscissa: relative position on the solar surface (in arcsec). Ordinate: velocity variations in kms−1.



Em estrelas não observamos variações de grânulos individuais mas o efeito médio: **perfil assimétrico**

http://astro.uwo.ca/~dfgray/Granulation.html

Rotação diferencial



Equador 25 dias

Pólo: 36 dias

A rotação solar também varia com o raio.

A rotação converge sob a camada convectiva, na região chamada de tacoclina

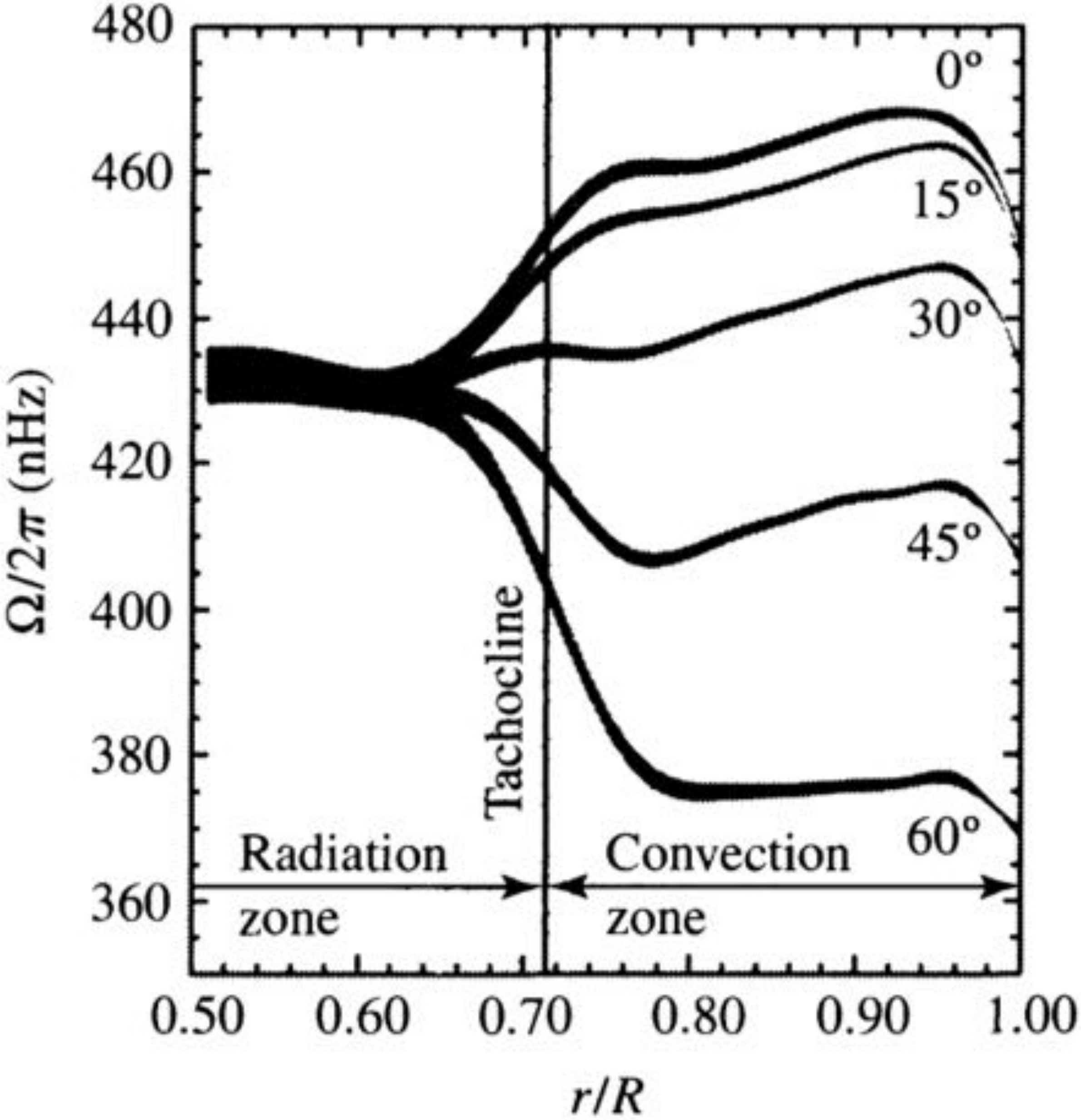
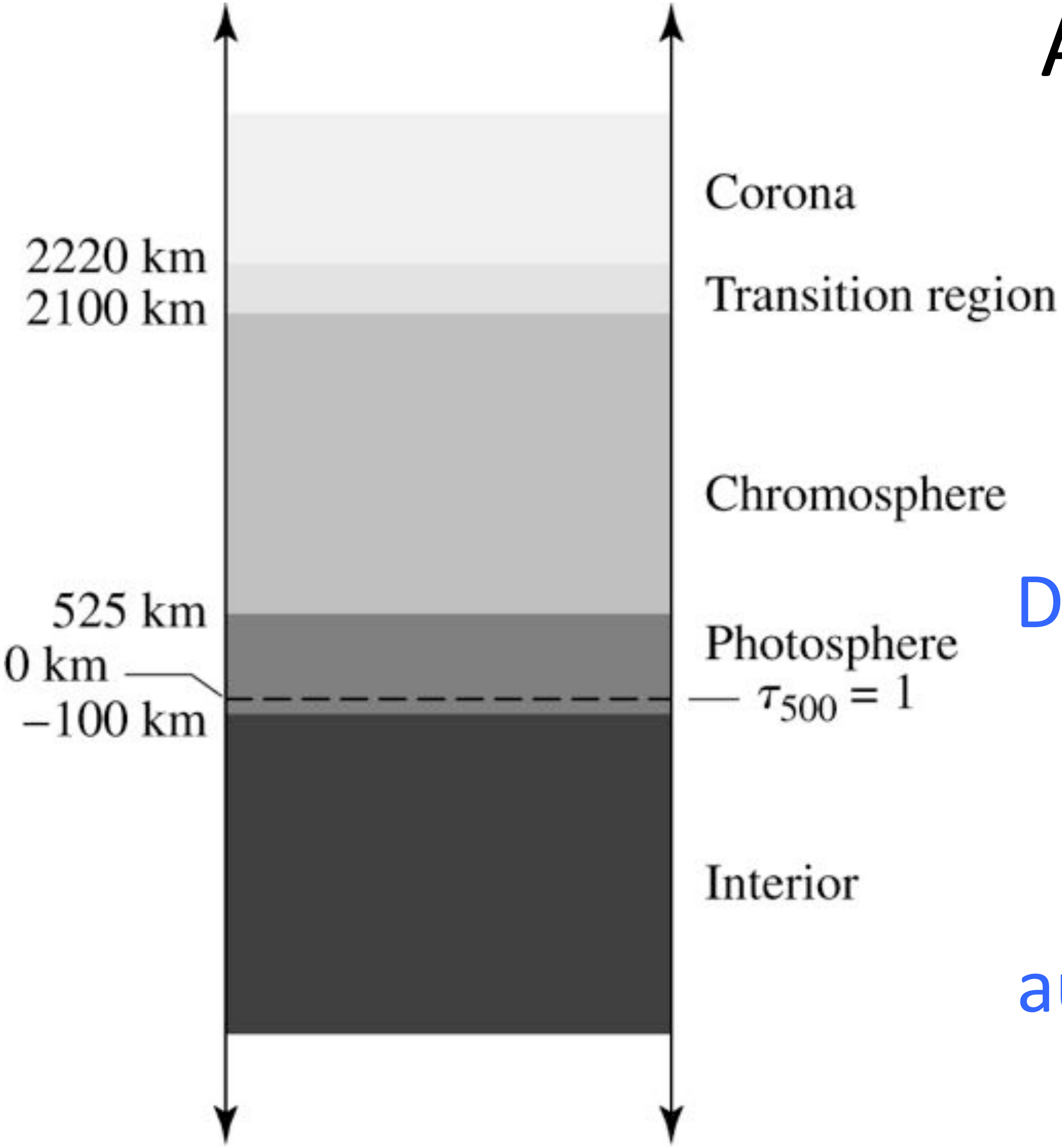


FIGURE 11.16 The rotation period of the Sun varies with latitude and depth. Ω, the angular frequency, has units of radians per second. (Adapted from a figure courtesy of NSF's National Solar Observatory.)

A cromosfera

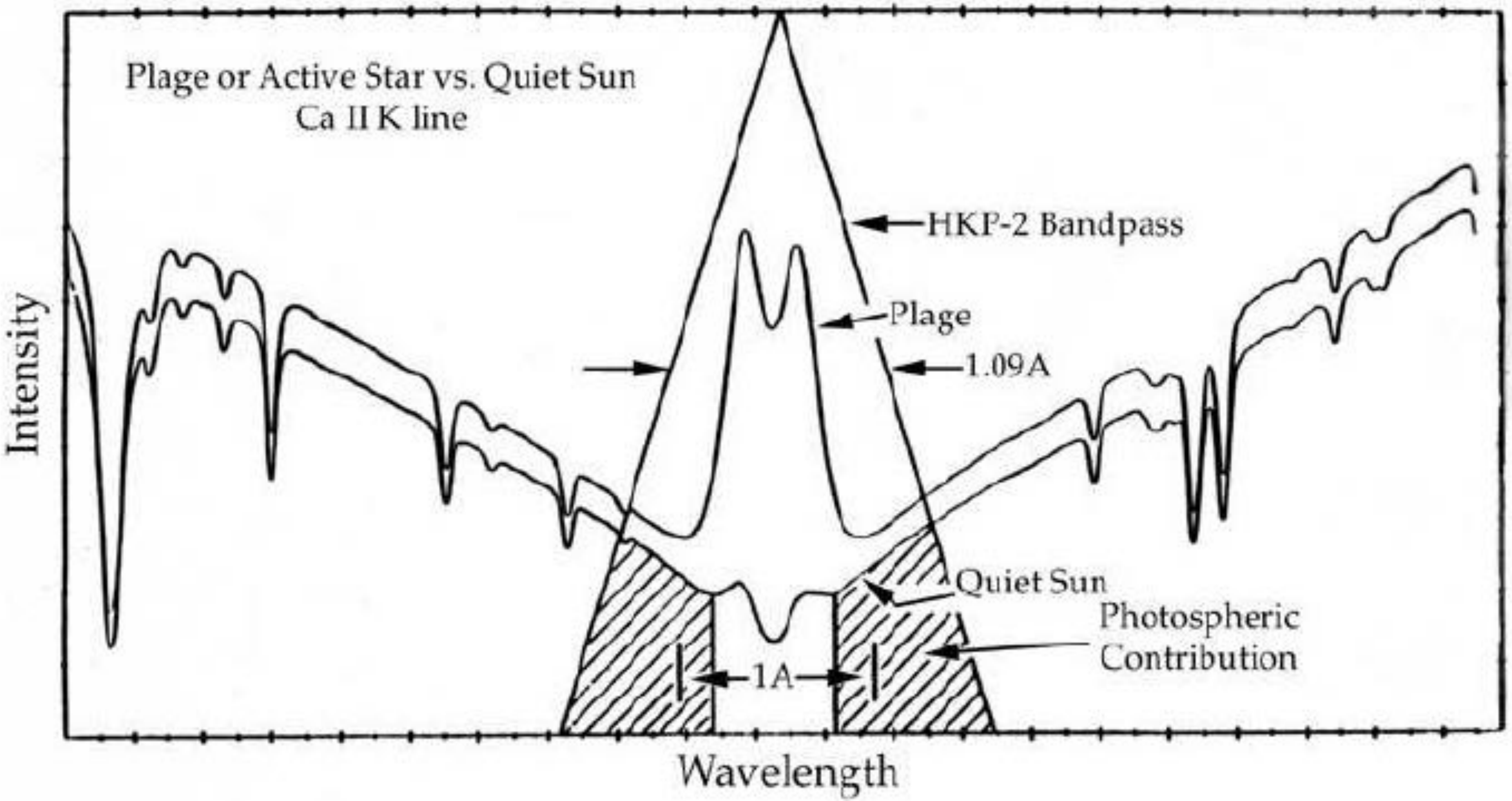


Intensidade apenas 10^{-4} da fotosfera

Densidade cai em 10^4

Temperatura aumenta de 4400 a 10 000 K

Linha de absorção (fotosfera) e emissão (plage) da linha K do Ca II



Plage: emissão brilhante na cromosfera

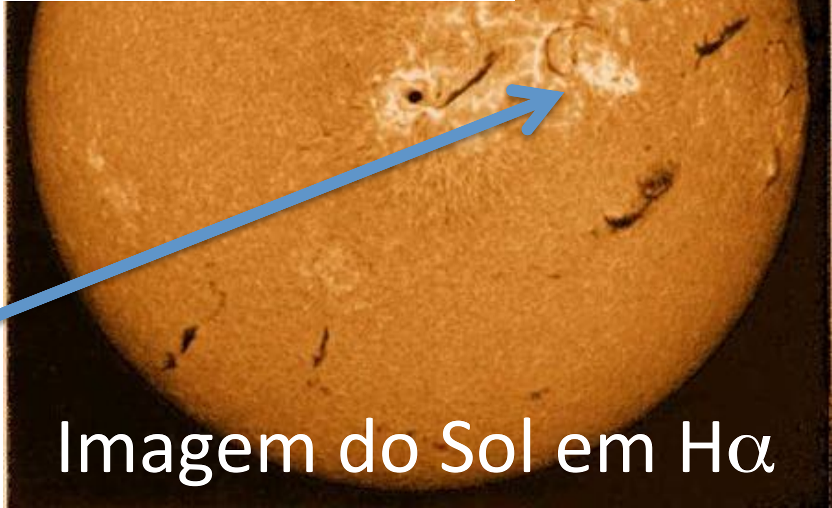
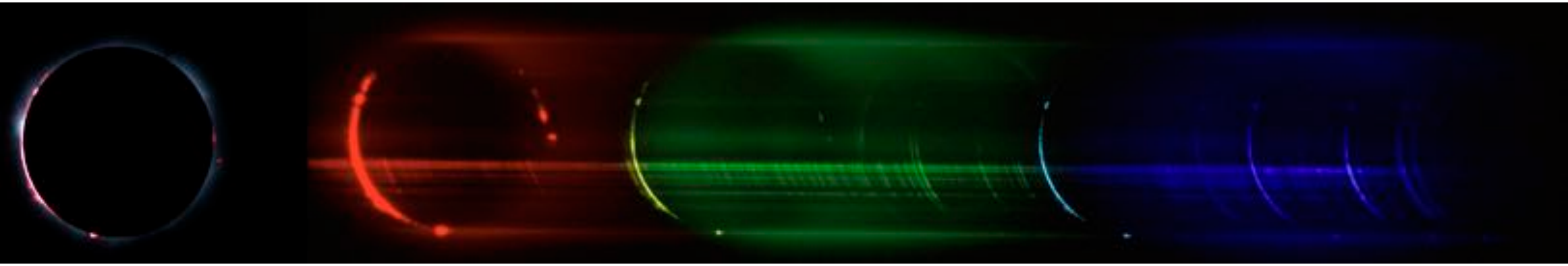
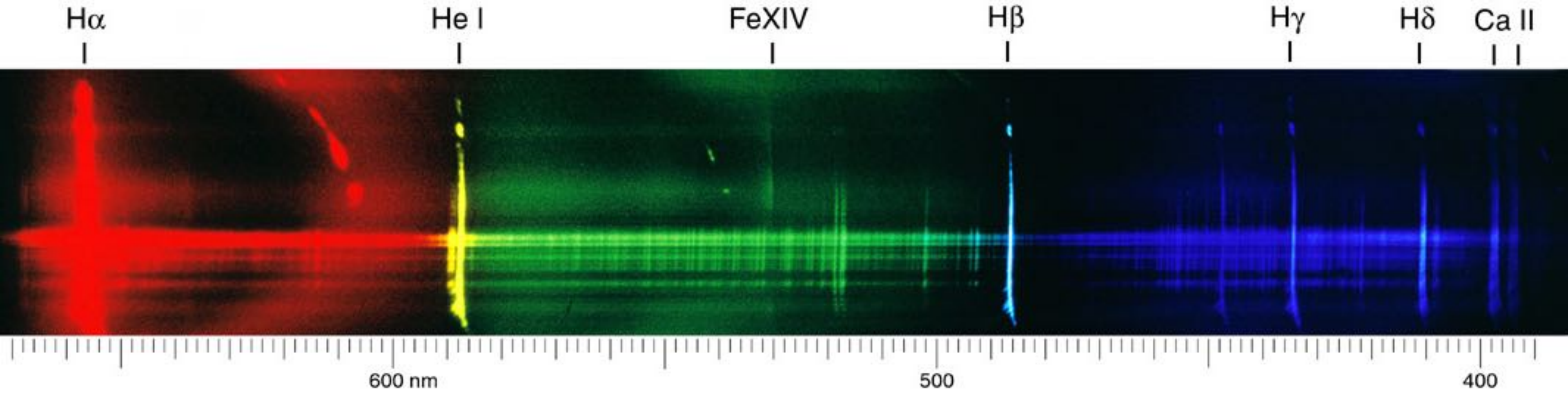


Imagem do Sol em Hα

Espectro da cromosfera durante eclipse de 1999 na Hungria

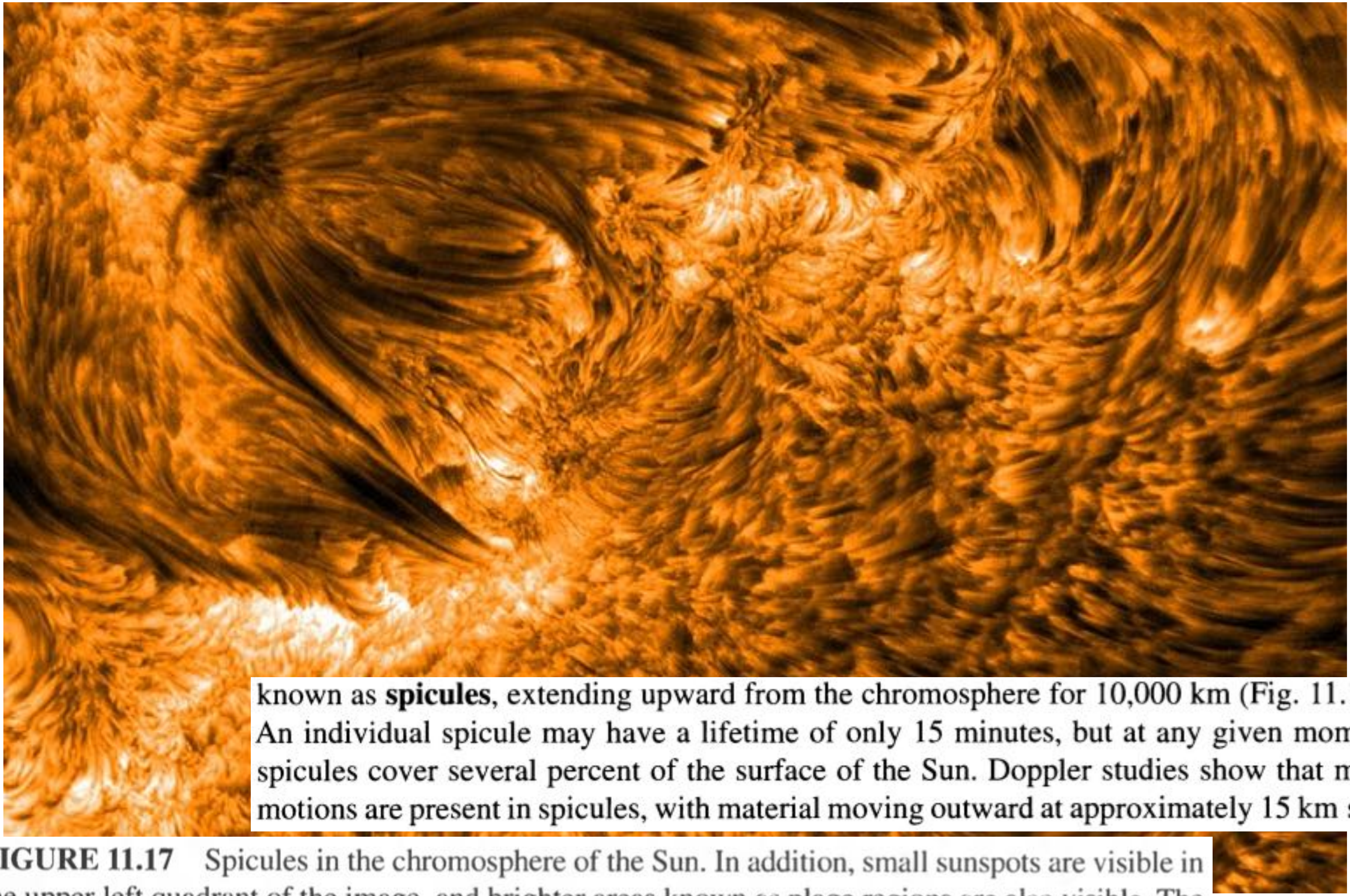
É chamado espectro *flash* pois as linhas de emissão aparecem por apenas alguns segundos





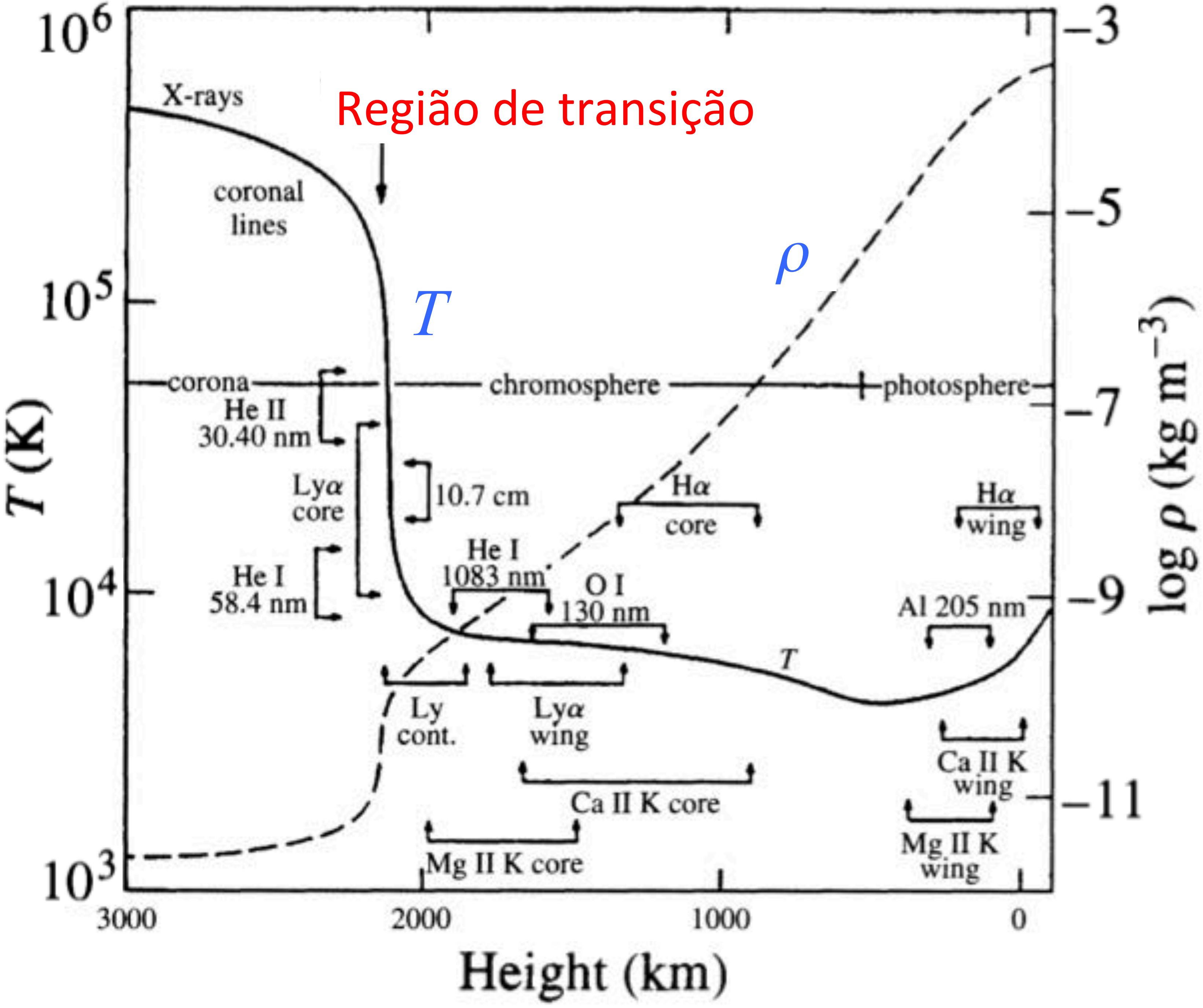
http://www.eurastro.de/webpages/MRSPECT.HTM

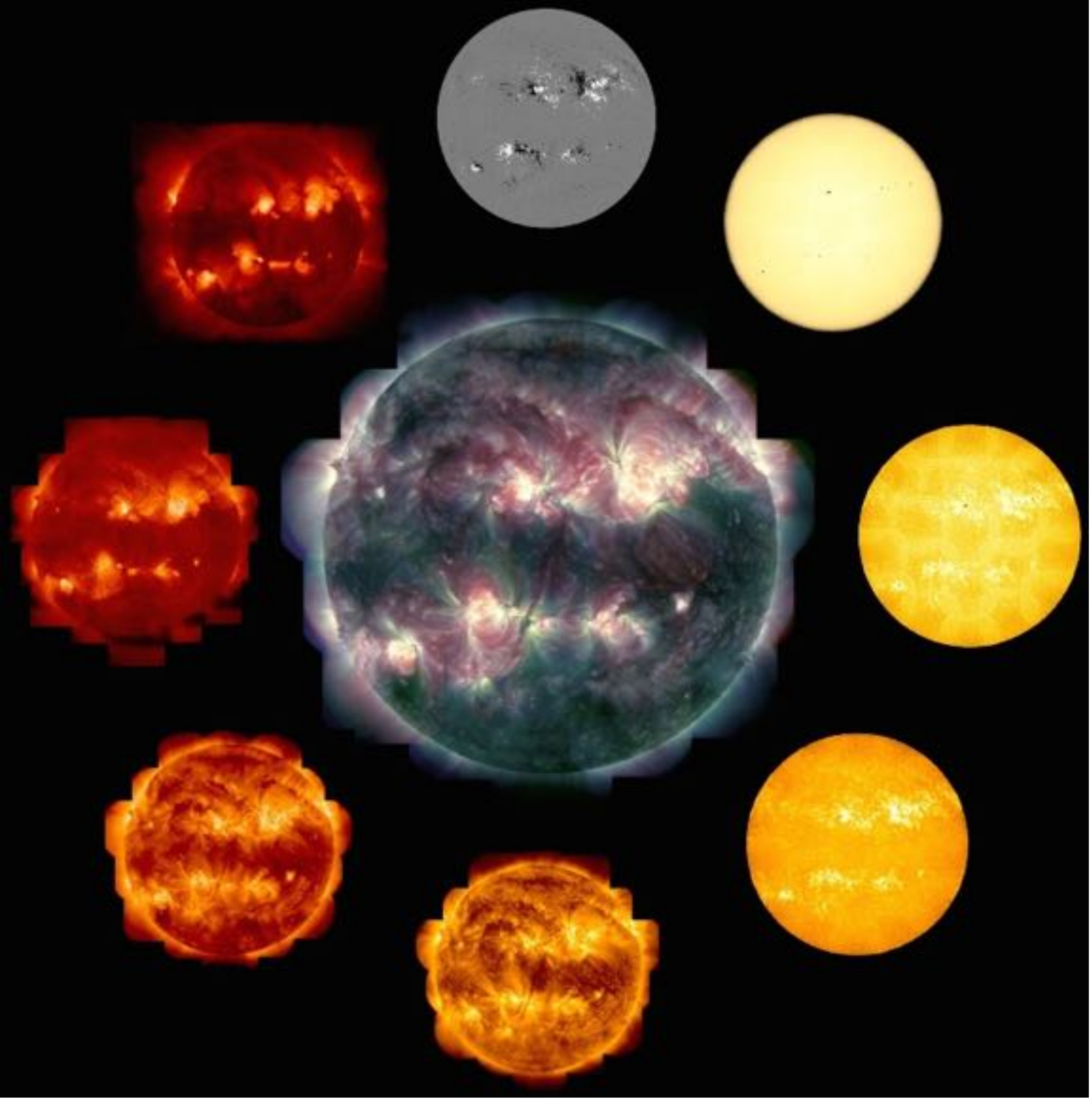
Solar active region 10380, in June 2004. Spicules (solar flux tubes) are visible, particularly evident as a carpet of dark tubes on the right. (c) Royal Swedish Academy of Sciences



known as **spicules**, extending upward from the chromosphere for 10,000 km (Fig. 11.17). An individual spicule may have a lifetime of only 15 minutes, but at any given moment spicules cover several percent of the surface of the Sun. Doppler studies show that mass motions are present in spicules, with material moving outward at approximately 15 km s^{-1}.

FIGURE 11.17 Spicules in the chromosphere of the Sun. In addition, small sunspots are visible in the upper left quadrant of the image, and brighter areas known as plage regions are also visible. The observations were made using the Hα emission line. Features as small as 130 km are evident in this image. (Courtesy of the Royal Swedish Academy of Sciences.)

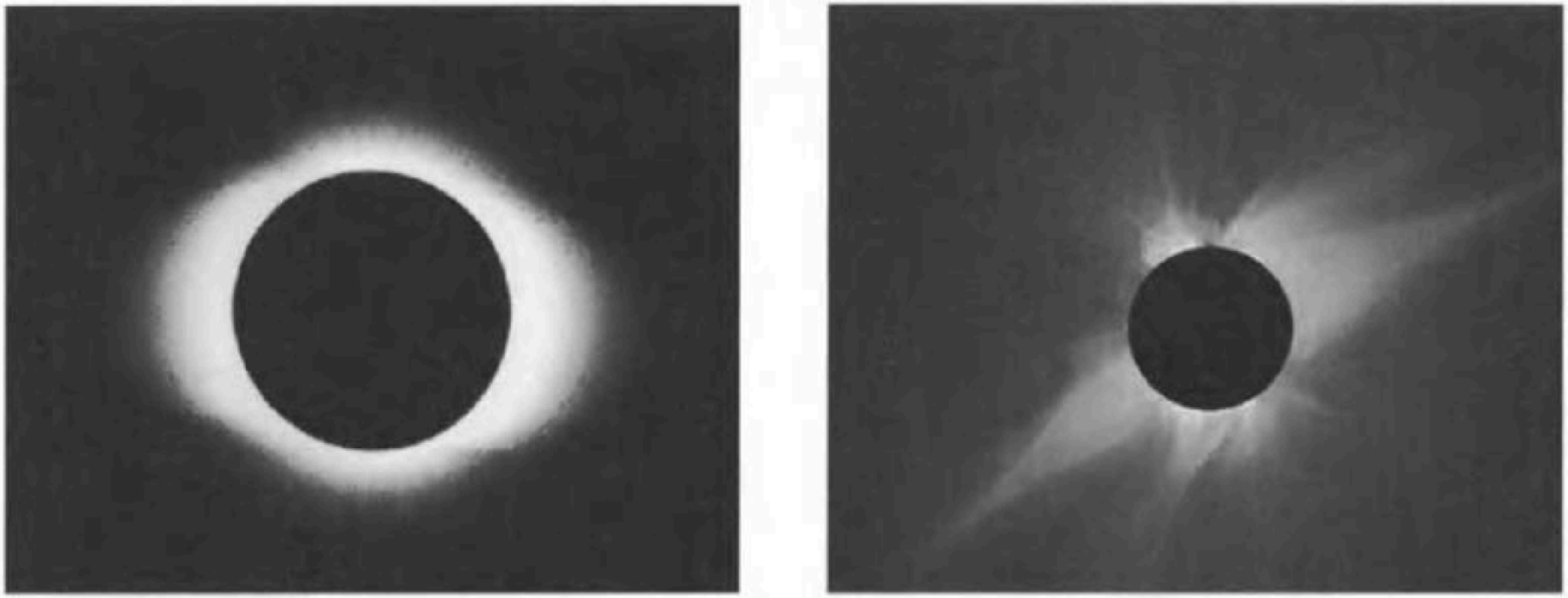

Região de transição
T
ρ
X-rays
coronal lines
corona
chromosphere
photosphere
He II 30.40 nm
Lyα core
10.7 cm
He I 58.4 nm
He I 1083 nm
O I 130 nm
Hα core
Hα wing
Al 205 nm
T
Ly cont.
Lyα wing
Ca II K core
Ca II K wing
Mg II K core
Mg II K wing
10^6
10^5
10^4
10^3
T (K)
−3
−5
−7
−9
−11
log ρ (kg m^{-3})
3000
2000
1000
0
Height (km)



Looking through the solar atmosphere. The central image is a 3-color composite of the solar corona, with the NASA Transition Region & Coronal Explorer. This mosaic is made up of 3 exposures; the green, blue, and red color tables in this ``true color'' image represent the 171Å (1 MK), 195Å (1.5 MK), and 284Å (2 MK) channels. The surrounding images are, clockwise starting from the top: SOHO/MDI magnetic map, white light, TRACE 1700A continuum,TRACE Lyman alpha, TRACE 171Å, TRACE 195Å, TRACE 284Å, YOHKOH/SXT X-ray image.

http://www.lmsal.com/TRACE/POD/TRACEpodarchive4.html

Coroa solar



(a) (b)

FIGURE 11.20 (a) The quiet solar corona seen during a total solar eclipse in 1954. The shape of the corona is elongated along the Sun's equator. (Courtesy of J. D. R. Bahng and K. L. Hallam.) (b) The active corona tends to have a very complex structure. This image of the July 11, 1991, eclipse is a composite of five photographs that was processed electronically. (Courtesy of S. Albers.)

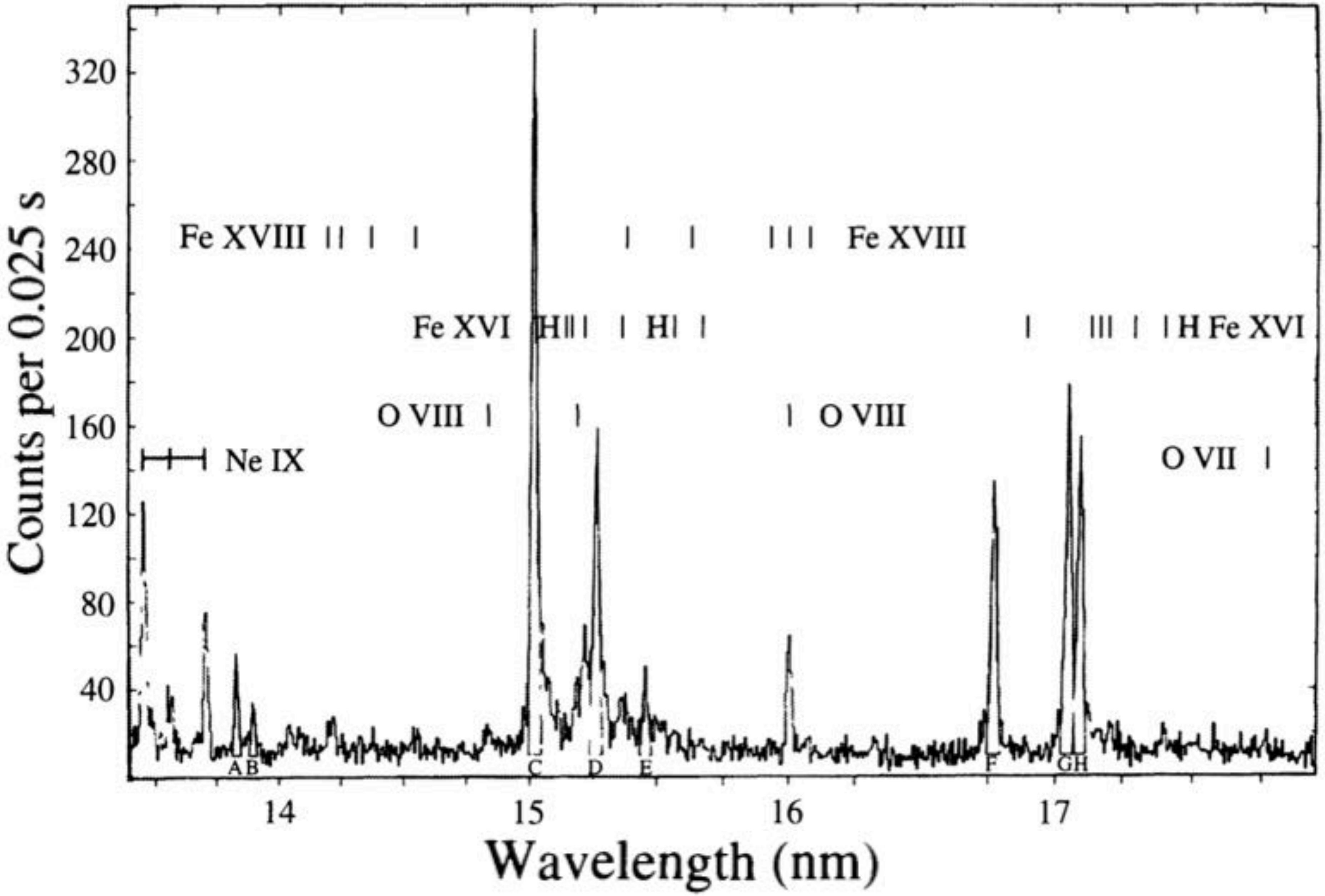


FIGURE 11.21 A section of the X-ray emission spectrum of the solar corona. (Figure adapted from Parkinson, *Astron. Astrophys.*, *24*, 215, 1973.)

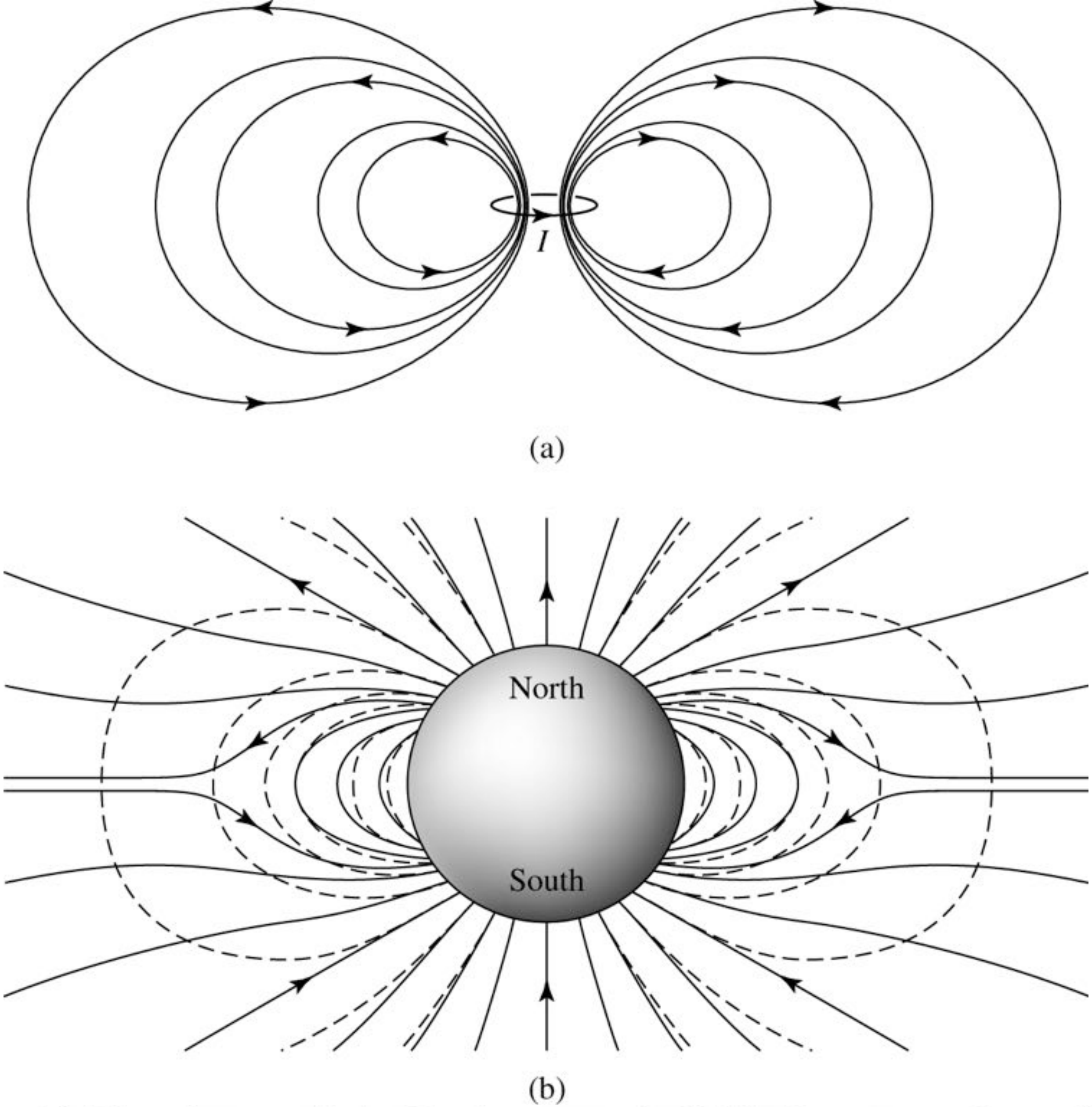
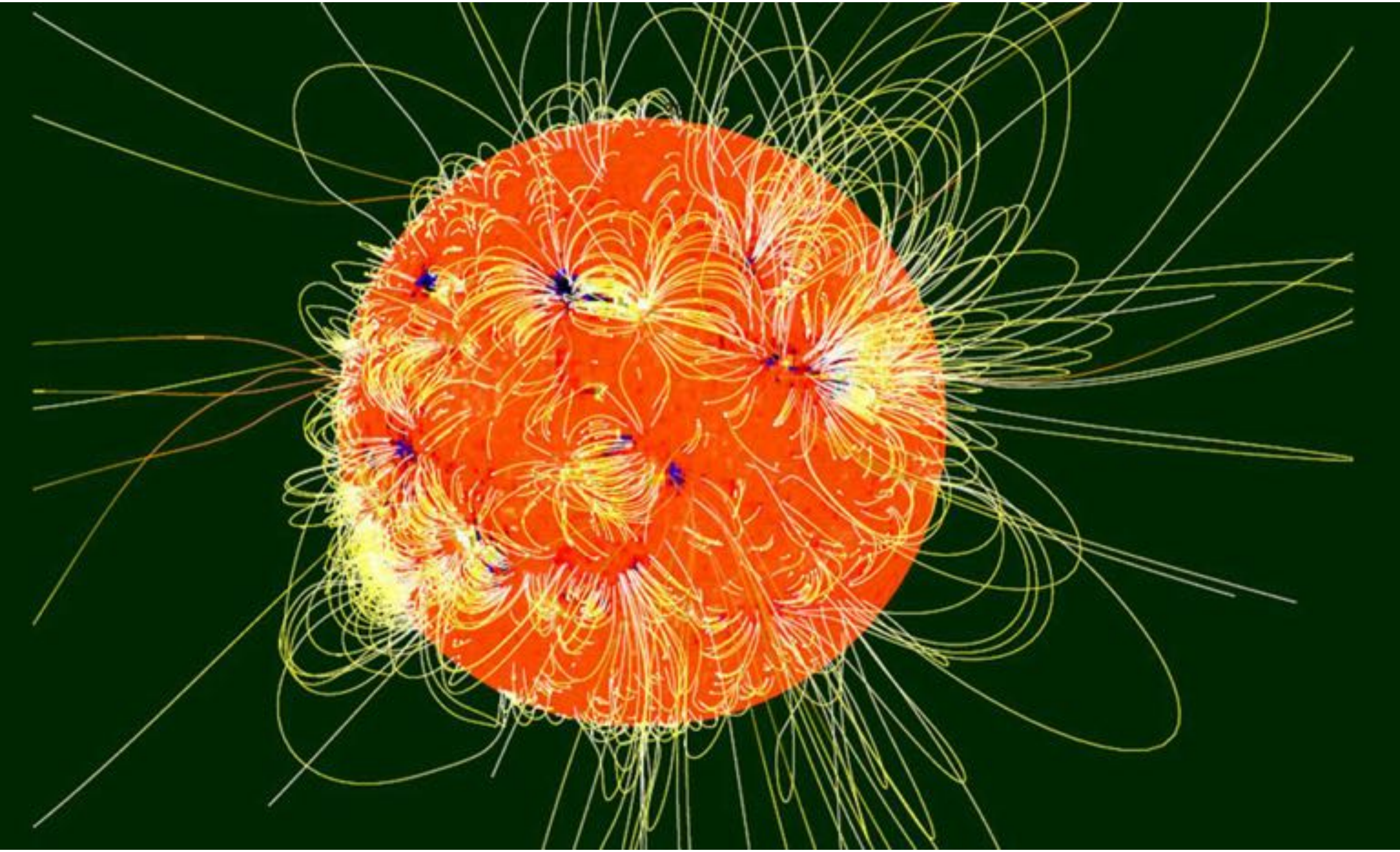


FIGURE 11.23 (a) The characteristic dipole magnetic field of a current loop. (b) A generalized depiction of the global magnetic field of the Sun. The dashed lines show the field of a perfect magnetic dipole.

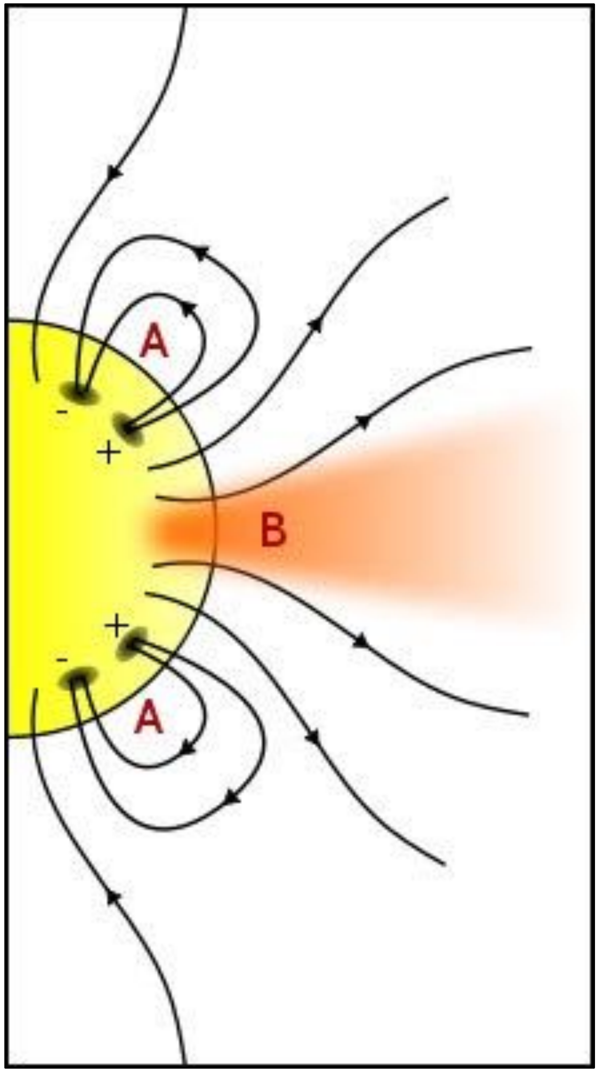
Reconstrução do campo magnético coronal

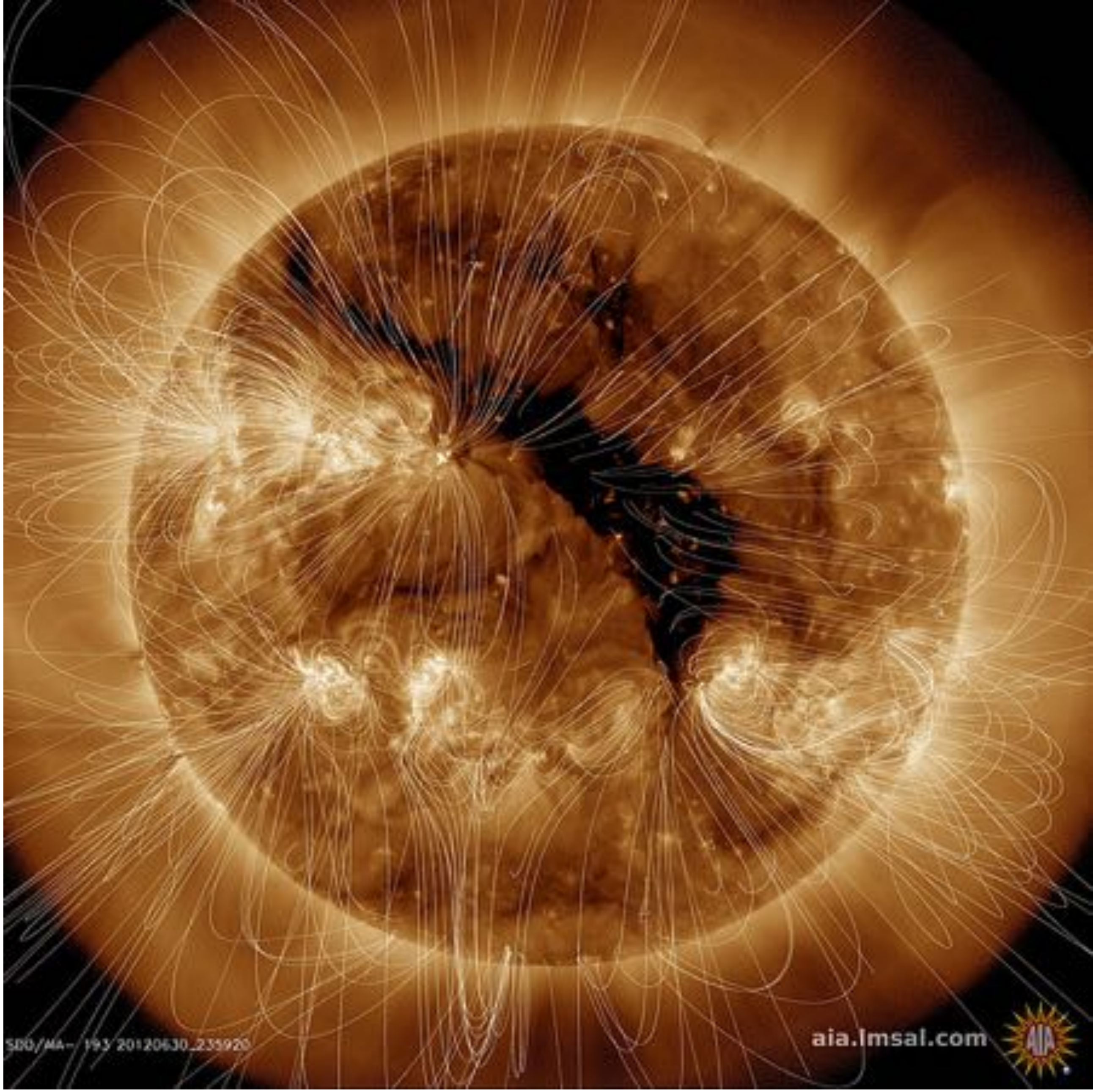


https://www2.mps.mpg.de/de/projekte/solar-corona3d/index_print.html

Coronal holes

fast solar wind





https://physik.uni-graz.at/en/astrophysics/research/solar-and-heliospheric-physics/coronal-holes-and-their-relation-to-the-solar-wind/

Equação de força de Lorentz:

$$\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

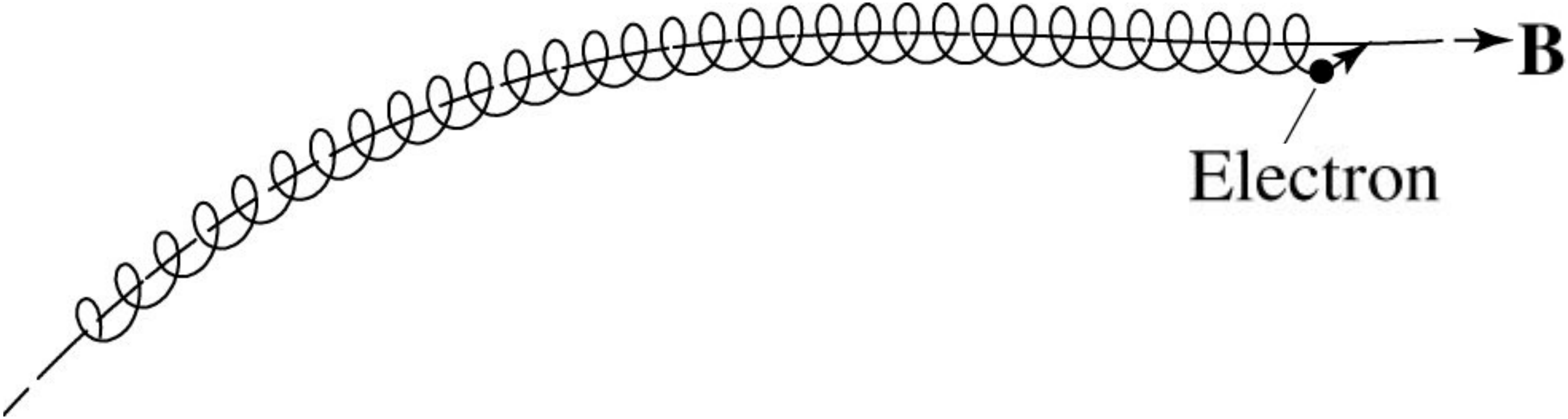
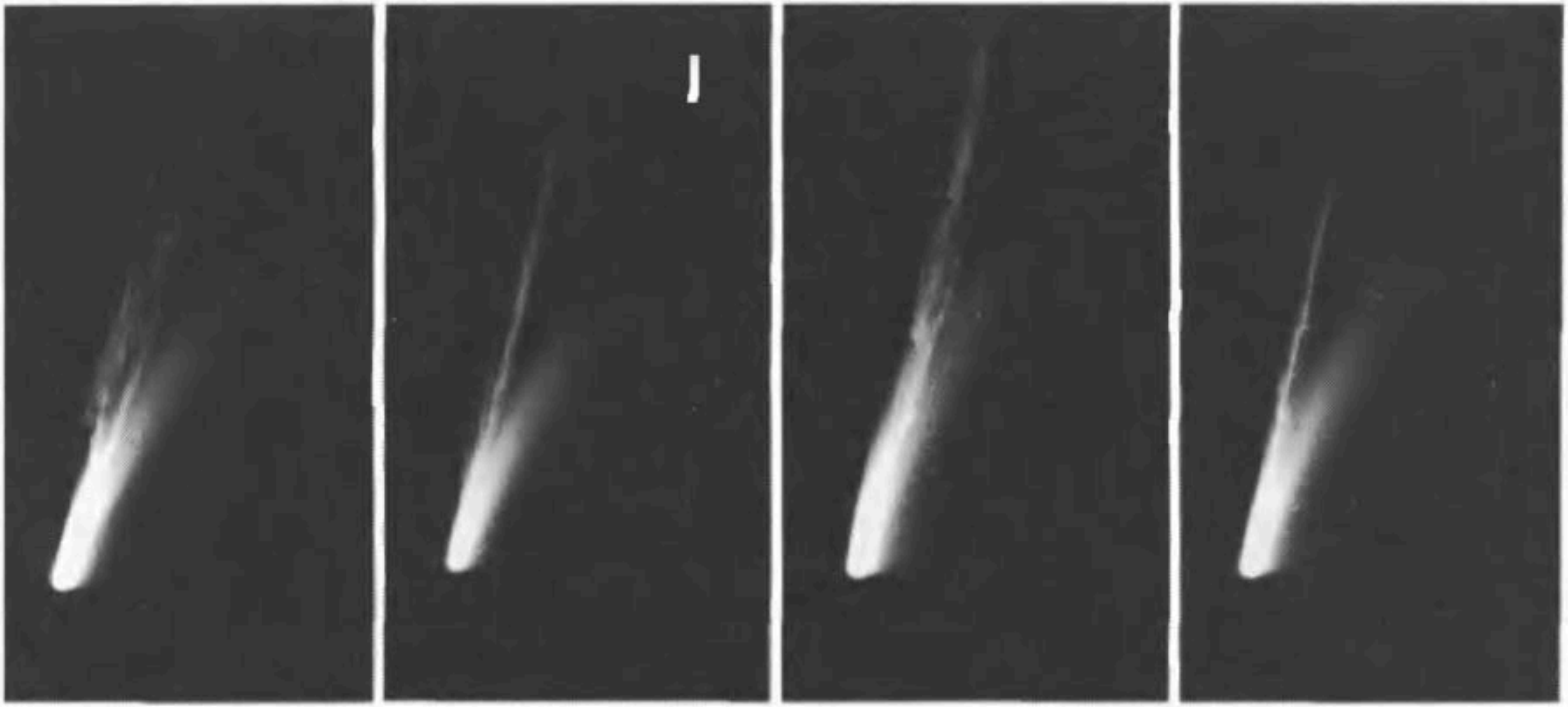


FIGURE 11.24 A charged particle is forced to spiral around a magnetic field line because the Lorentz force is mutually perpendicular to both the velocity of the particle and the direction of the magnetic field.

Evidência de vento solar: *ion tail* em cometas



AUGUST 22 AUGUST 24 AUGUST 26 AUGUST 27

FIGURE 11.25 Comet Mrkos in 1957. The dust tail of a comet is curved and its ion tail is straight. (Courtesy of Palomar/Caltech.)

Vento solar: auroras

Aurora na Suécia

the solar wind velocity ranges from approximately 200 km s^{-1} to 750 km s^{-1}

Example 11.2.1. The mass loss rate of the Sun may be estimated from the data given above. We know that all of the mass leaving the Sun must also pass through a sphere of radius 1 AU centered on the Sun; otherwise it would collect at some location in space. If we further assume (for simplicity) that the mass loss rate is spherically symmetric, then the amount of mass crossing a spherical surface of radius r in an amount of time t is just the mass density of the gas multiplied by the volume of the shell of gas that can travel across the sphere during that time interval, or

$$dM = \rho\, dV = (nm_H)(4\pi r^2\, v\, dt)$$

where n is the number density of ions (mostly hydrogen), m_H is approximately the mass of a hydrogen ion, v is the ion velocity, and $dV = A\, dr \simeq 4\pi r^2\, v\, dt$ is the volume of a shell that crosses a spherical surface in an amount of time dt. Dividing both sides by dt, we obtain the mass loss rate,

$$\frac{dM}{dt} = 4\pi r^2\, nm_H v = 4\pi r^2\, \rho v \qquad (11.3)$$

By convention, stellar mass loss rates are generally given in *solar masses per year* and symbolized by $\dot{M} \equiv dM/dt$. Using $v = 500\ \mathrm{km\ s^{-1}}$, $r = 1\ \mathrm{AU}$, and $n = 7 \times 10^6\ \mathrm{protons\ m^{-3}}$, we find that

$$\dot{M}_\odot \simeq 3 \times 10^{-14}\ \mathrm{M_\odot\ yr^{-1}}$$