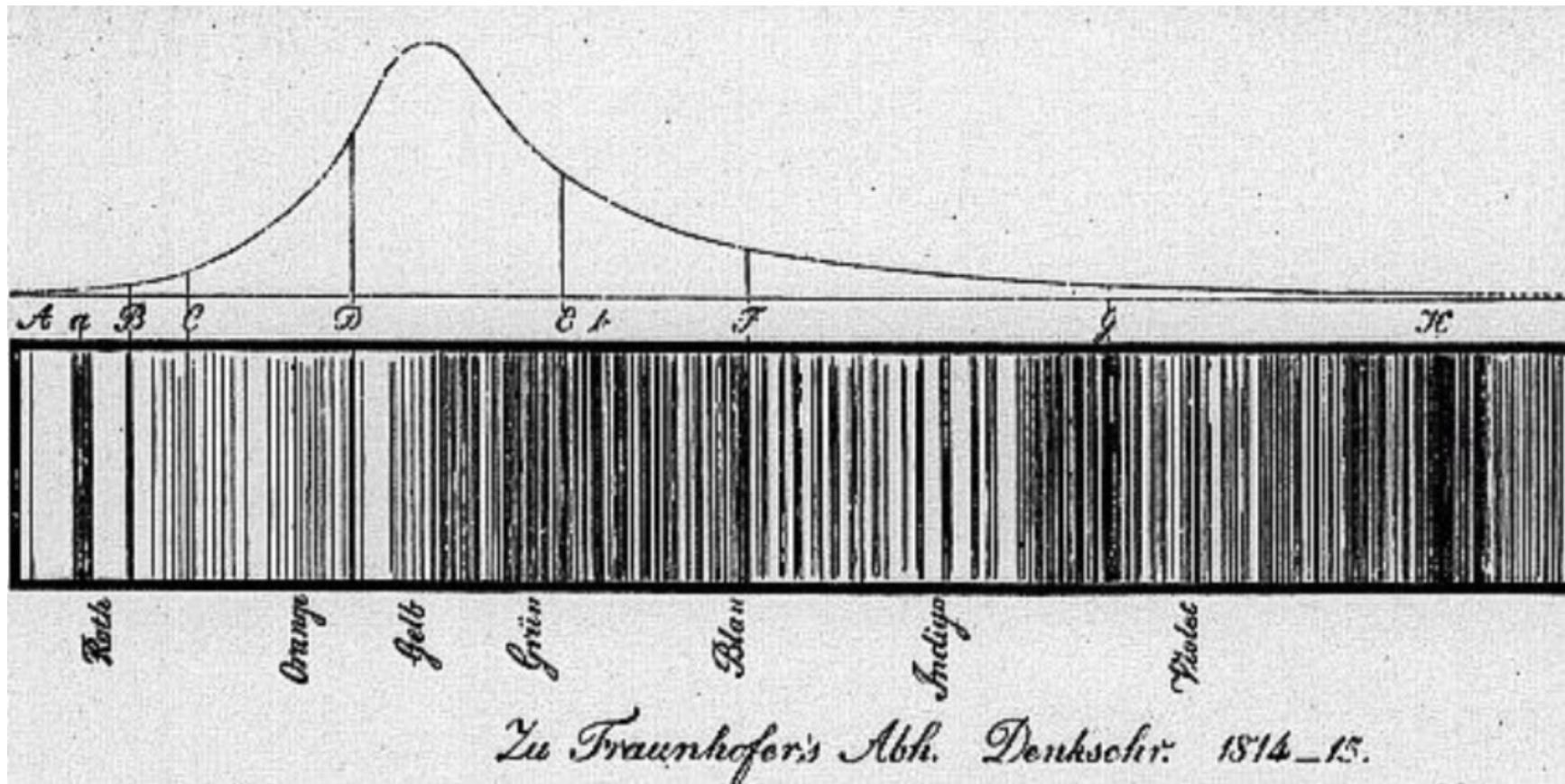


Fraunhofer



Sole

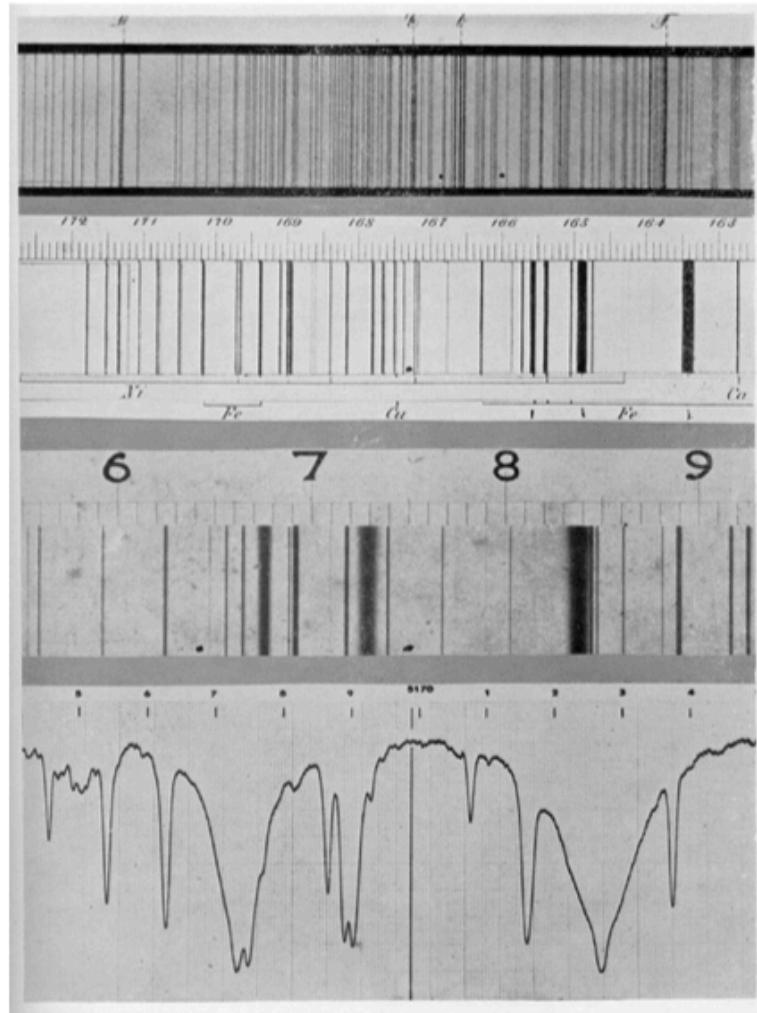
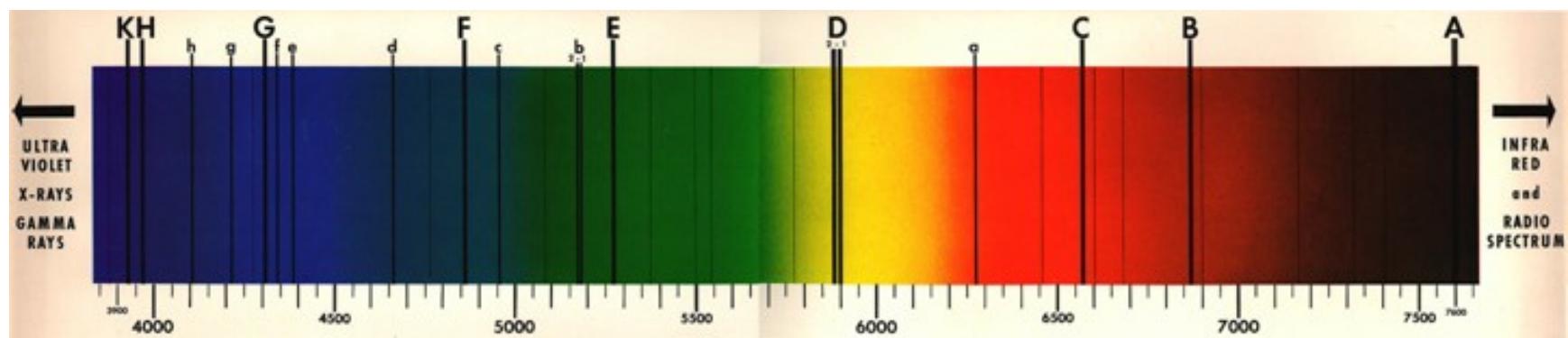


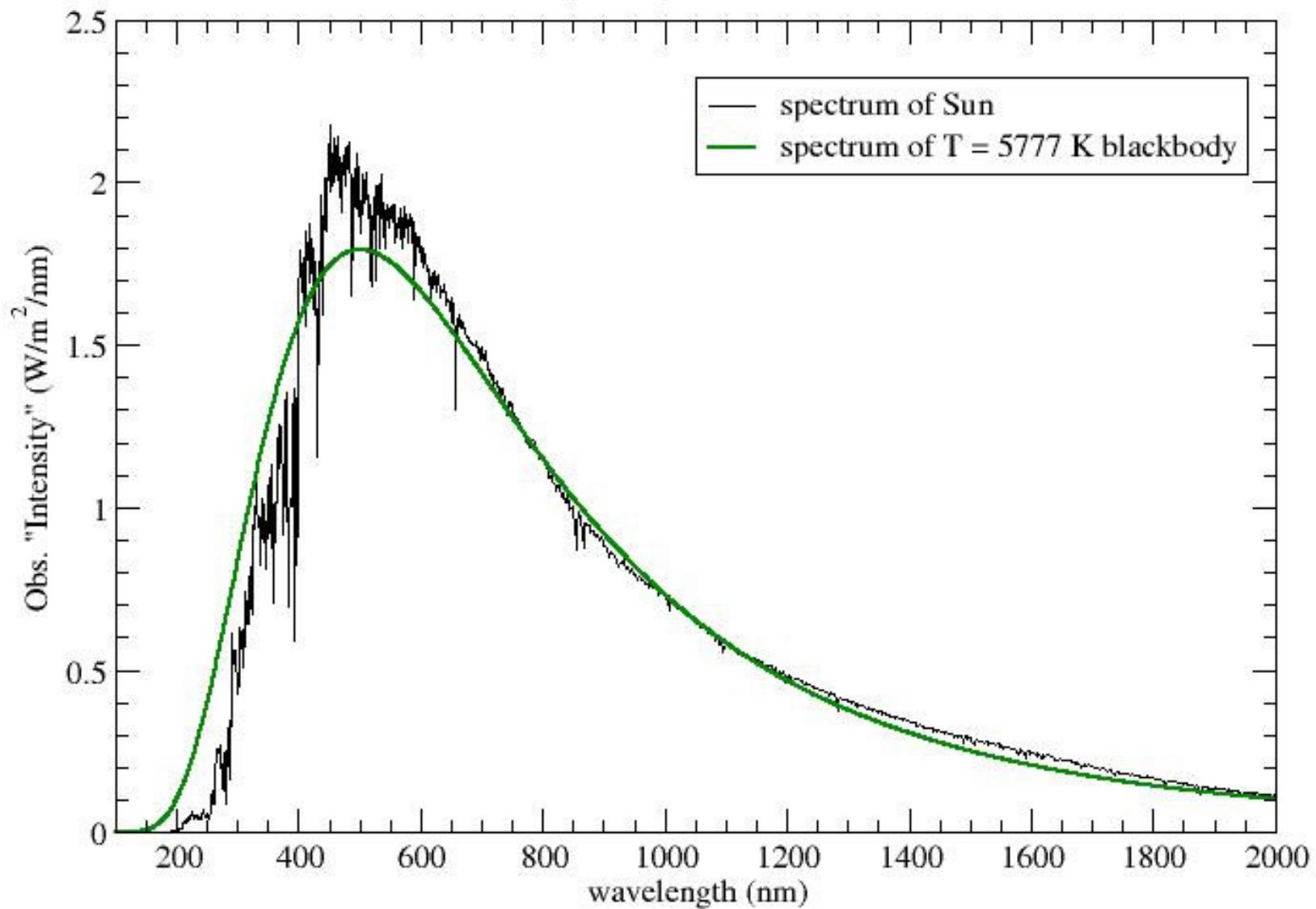
Figure 1.3: Segments of four solar spectrum atlases, respectively the engravings by Fraunhofer (top, 1815) and Kirchhoff (1861), the photographic Rowland atlas (1897) and the Utrecht intensity atlas (1940). The top segment has wavelength increasing to the left. The black dots in the first three segments mark the extent of the next segment. The three strongest lines in the second and third segments constitute the Mg I b triplet in the green part of the spectrum; Fraunhofer marked them b at the top of the figure. The Na I D lines are marked by a beautifully written \mathcal{D} at left, here cut off by Pannekoek's bounding box but present with Fraunhofer's solar energy distribution in Figure 2.4 of [Hearnshaw \(1986\)](#). In the bottom segment, the lefthand Mg I b line is blended with an overlapping Fe I line. The righthand one displays a distinct transition between Doppler core and damping wings. From [Pannekoek \(1961\)](#).

Sole

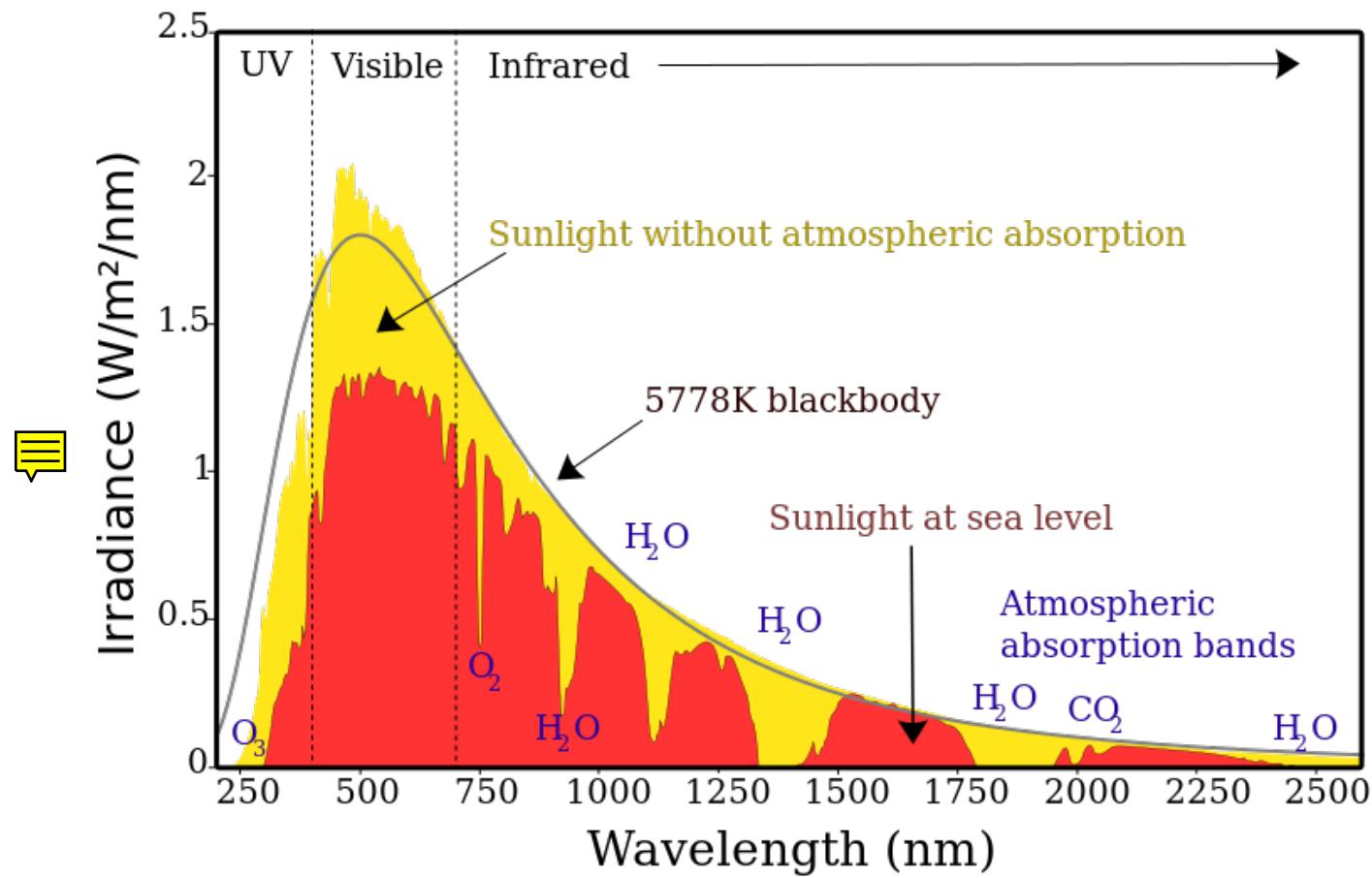


Sun's Spectrum vs. Thermal Radiator

of a single temperature $T = 5777 \text{ K}$

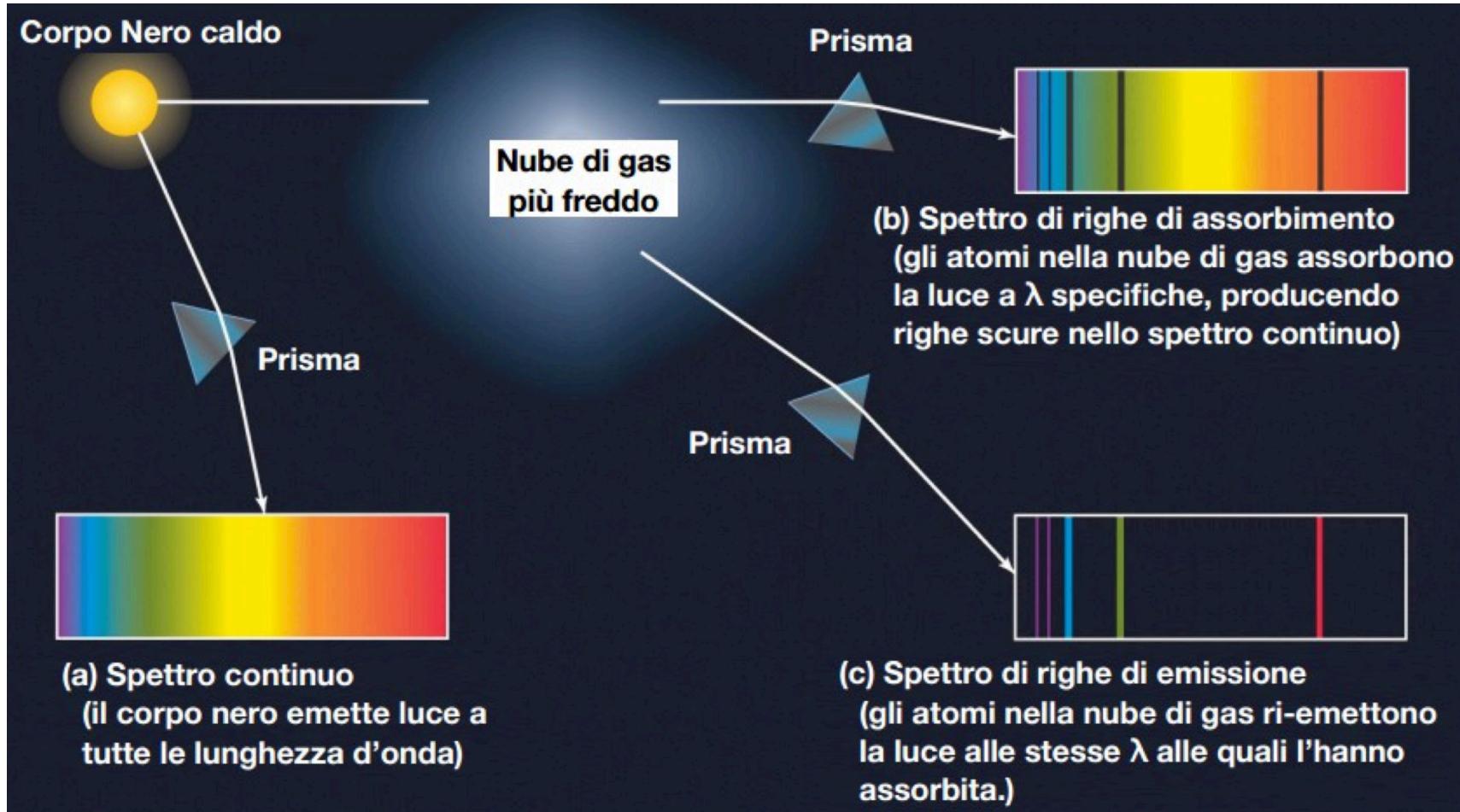


Spectrum of Solar Radiation (Earth)



- Gustav Kirchhoff (1824-1887)
- Robert Bunsen (1811 - 1899)
- Henry Roscoe (1833-1915)

Leggi della radiazione di Kirchhoff



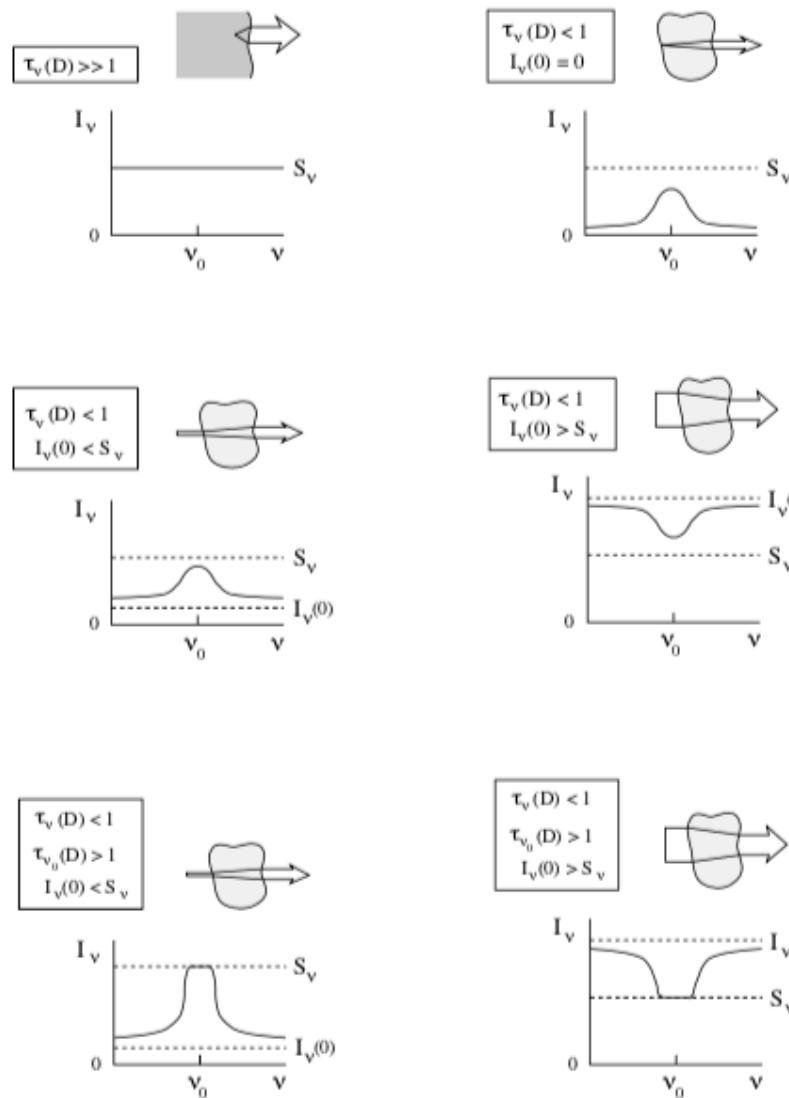
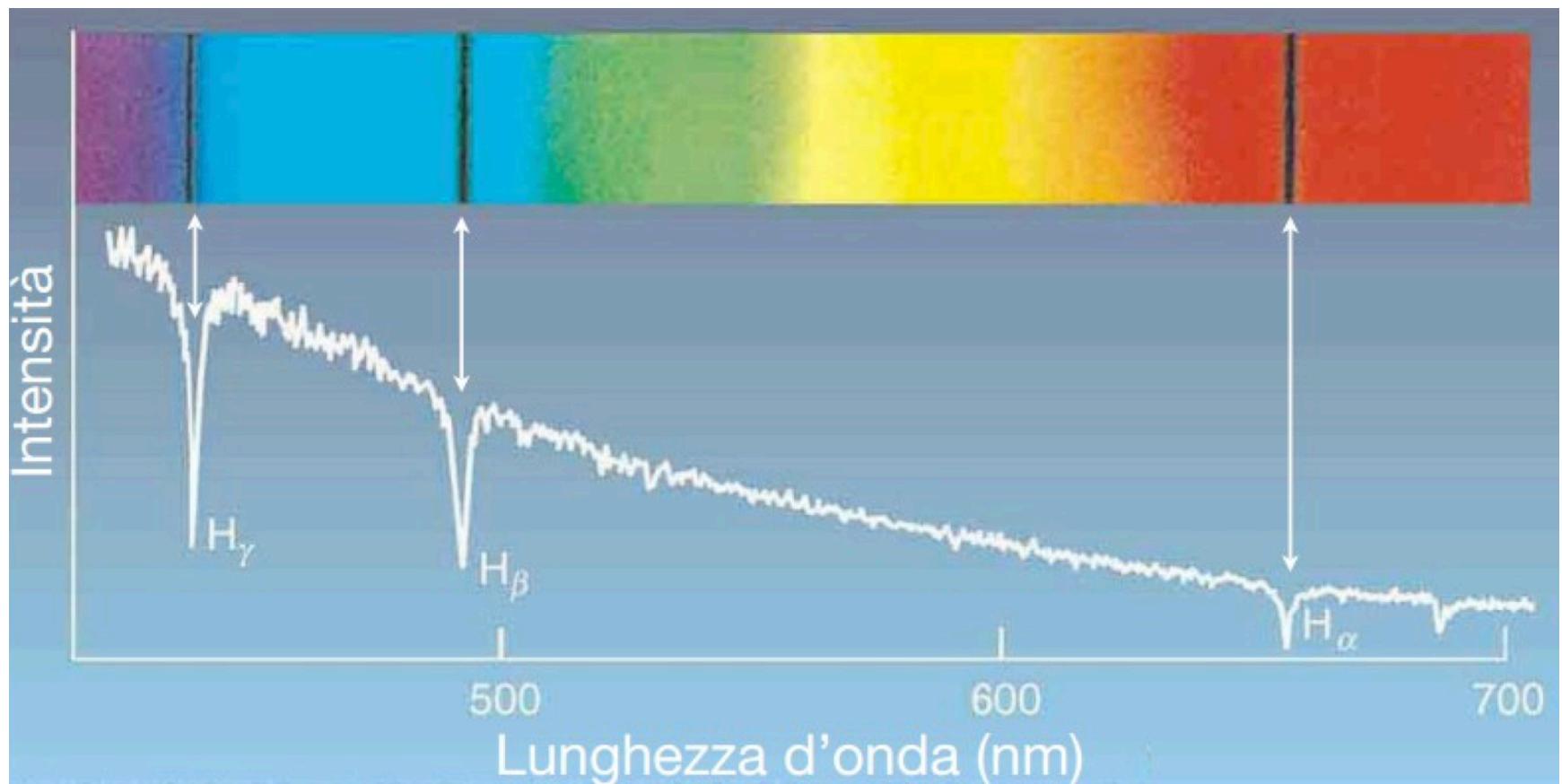


Figure 2.2: Spectral lines from a homogeneous object with $S_v^l = S_v^e = S_v$ everywhere, according to [2.33]–[2.36]. No lines emerge when the object is optically thick (top left). When it is optically thin, emission lines emerge when the object is not back-lit ($I_v(0) = 0$, top right), or when it is illuminated with $I_v(0) < S_v$. Absorption lines emerge only when the object is optically thin and $I_v(0) > S_v$. The emergent lines saturate to $I_v \approx S_v$ when the object is optically thick at line center.

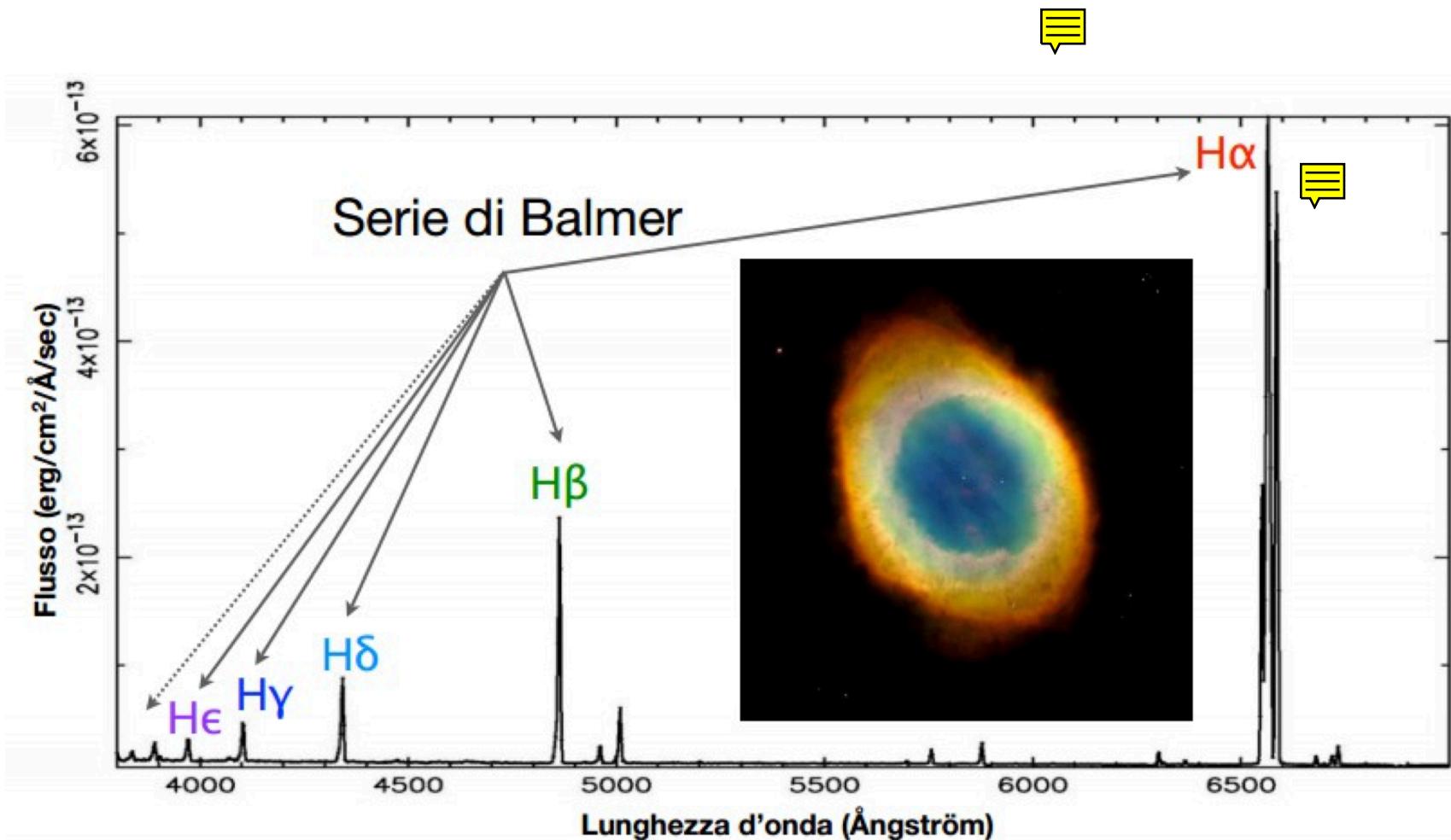


Spettro di una stella



Righe di assorbimento e continuo

Spettro di una nebulosa planetaria

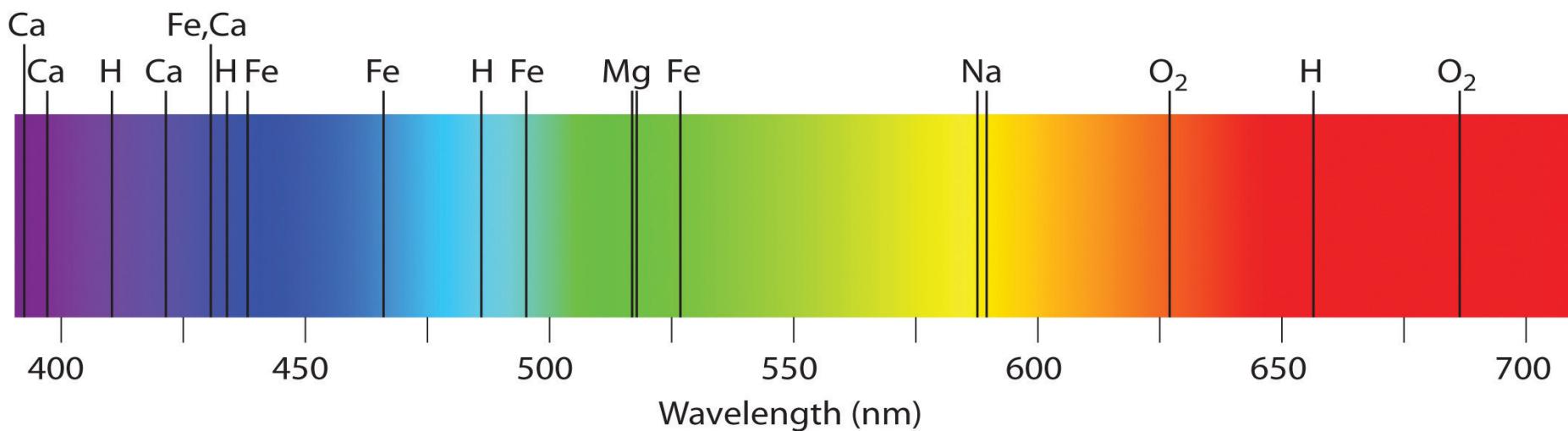
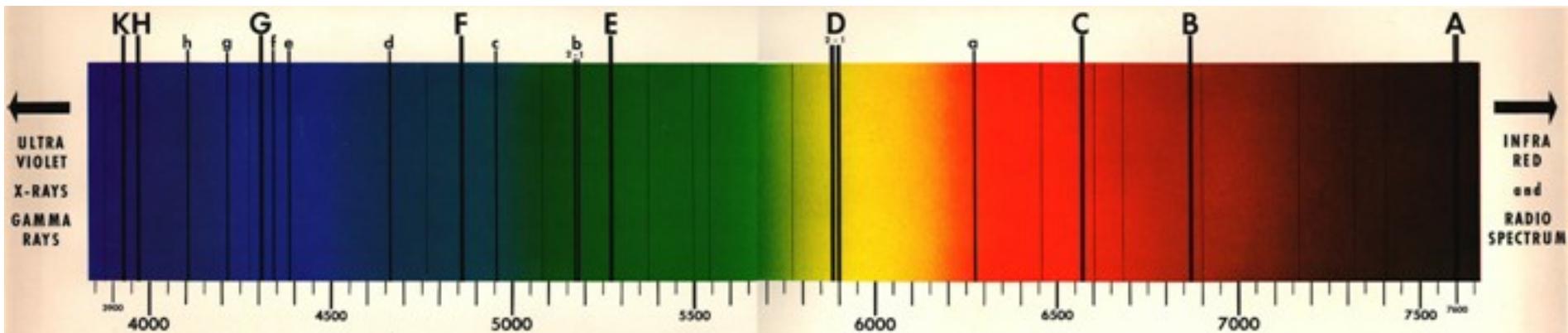


Righe di emissione

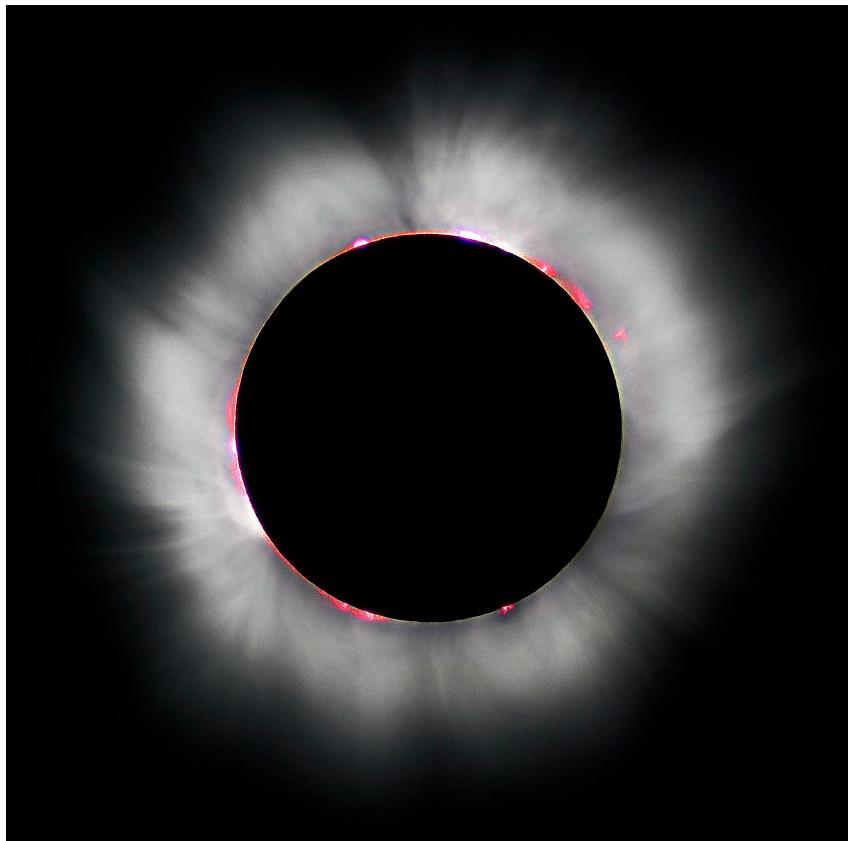
Sole: Identificazione delle righe

Lines	Due To	Wavelengths (Å)
A band	O ₂ (molecular oxygen in Earth's atmosphere)	7594–7621
B band	O ₂ (molecular oxygen in Earth's atmosphere)	6867–6884
C (H-alpha)	H (hydrogen)	6563
a band	O ₂ (molecular oxygen in Earth's atmosphere)	6276–6287
D ₁ & D ₂	Na (sodium)	5896 & 5890
E	Fe (iron)	5270
b ₁ , b ₂ , b ₃ , b ₄	Mg (magnesium)	5184, 5173, 5169, 5167
c	Fe (iron)	4958
F (H-beta)	H (hydrogen)	4861
d	Fe (iron)	4668
e	Fe (iron)	4384
f	H (hydrogen)	4340
G	Fe (iron)	4308
g	Ca (calcium)	4227
h (H-delta)	H (hydrogen)	4102
H & K	Ca (calcium)	3968 & 3934

Sole



Sole



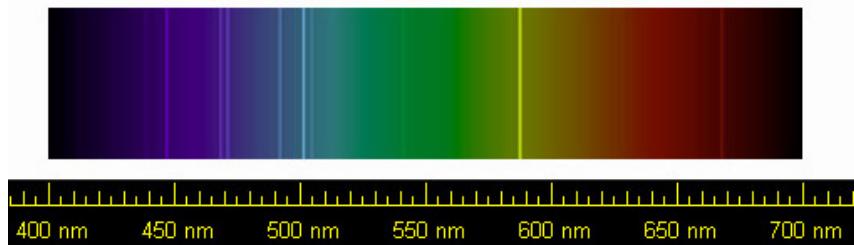
- Eclisse totale del 1868
- spettro della cromosfera

Sole

- Eclisse totale del 1868

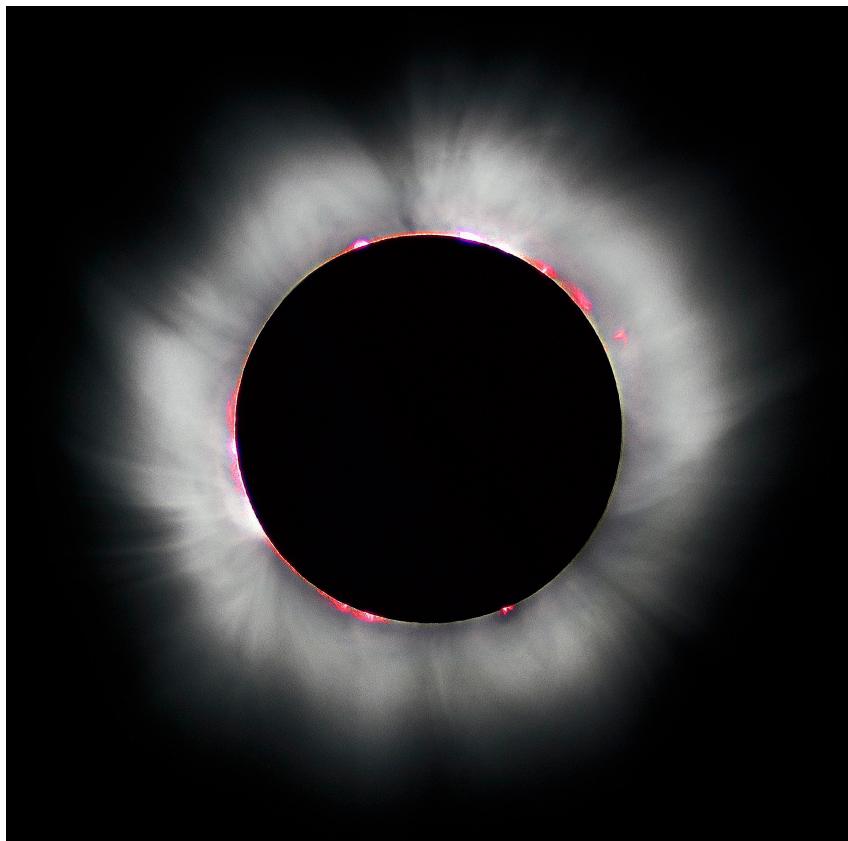


- Riga gialla a **587,49 nm** nello spettro della cromosfera



- Elemento sconosciuto
- Elio

Sole



- 1869, Young
- Riga verde a **530,3 nm** nello spettro della corona
- Elemento sconosciuto:
Coronio 
- 1930, FeXIV (Fe^{13+})

Angelo Secchi

Fig. 1. (1^{st} type: Sirius, Vega, Altair, Regulus, etc.)

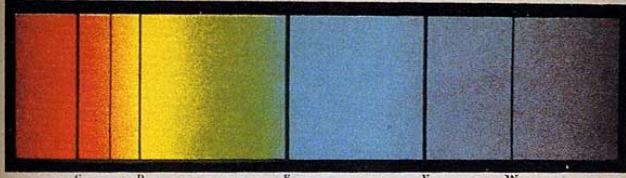


Fig. 2. (2^{nd} type. Sun, Pollux, Arcturus, Procyon, etc.)

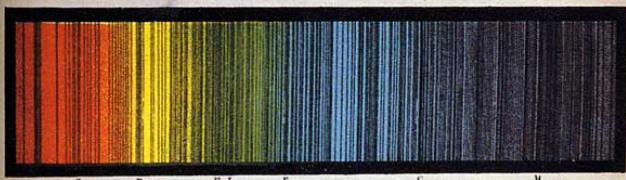


Fig. 3. (3^{rd} type: α Hercules, β Pegasus, α of Orion, Antares, etc.)

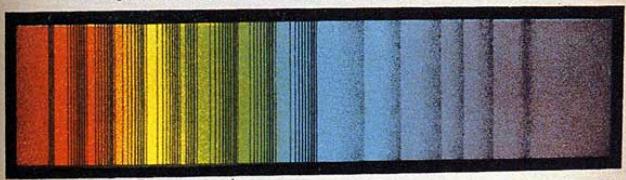
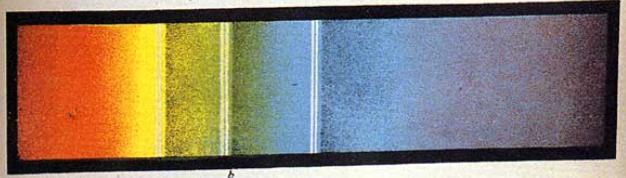
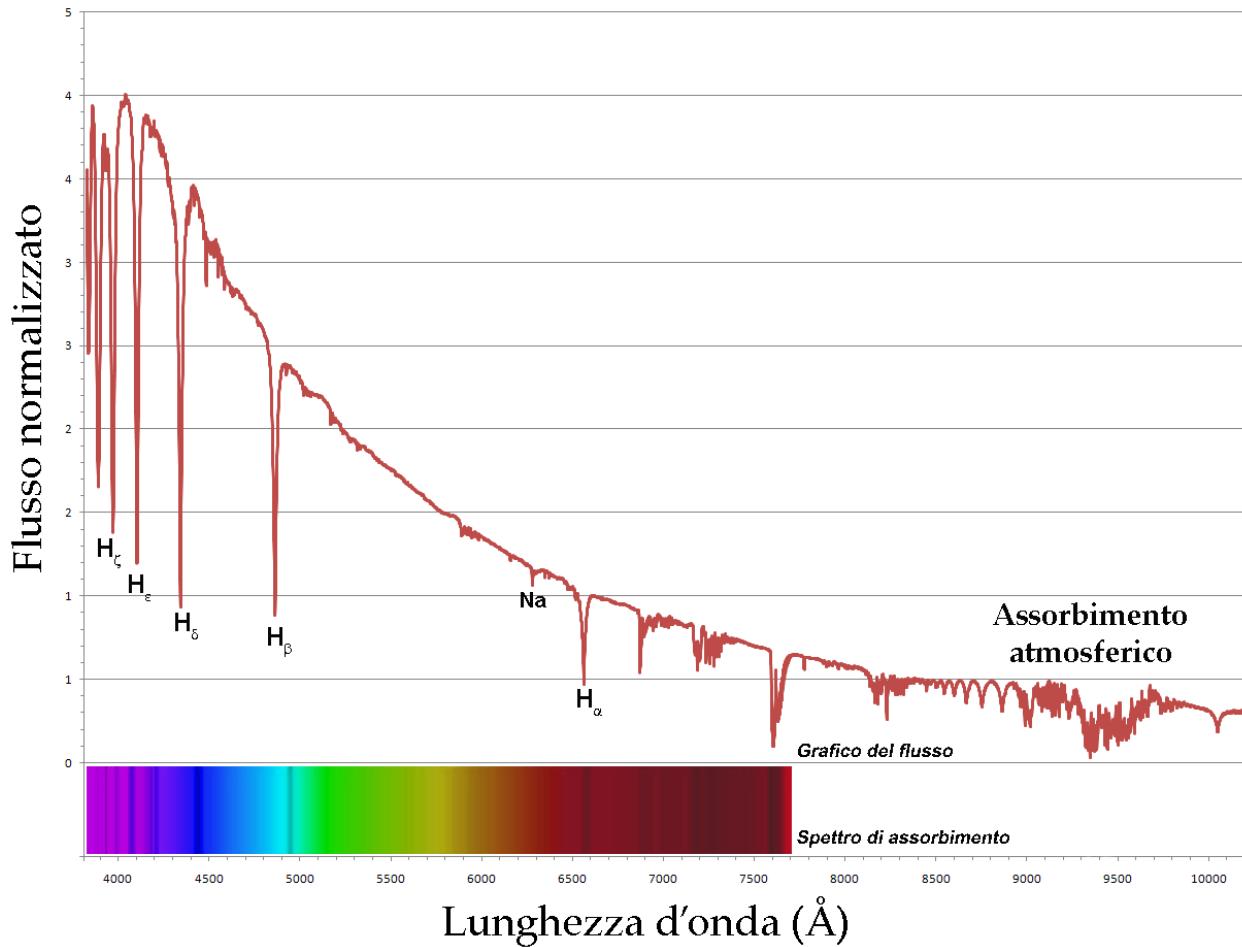


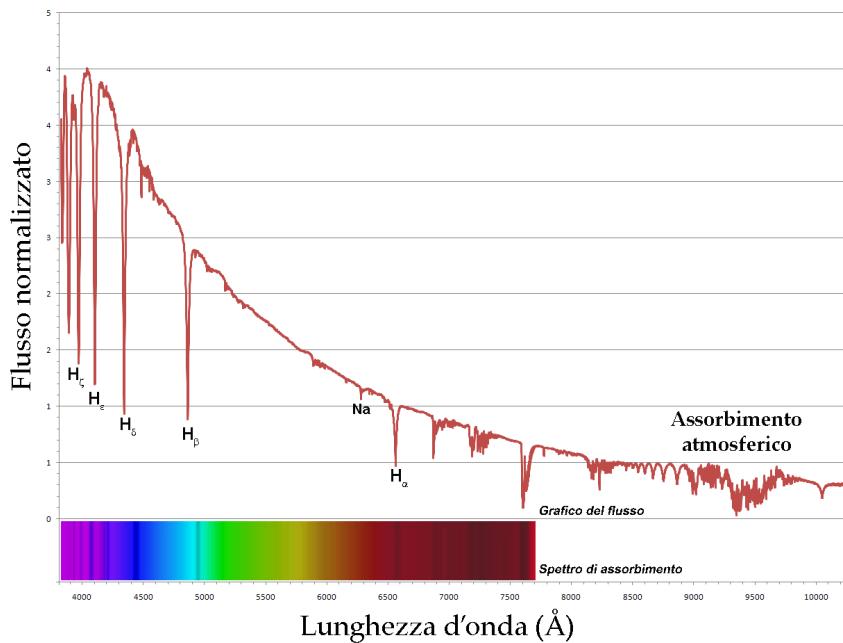
Fig. 4. (4^{th} type: 15° of Schjellerup.)



Vega (α Lyrae)



Vega (α Lyrae)

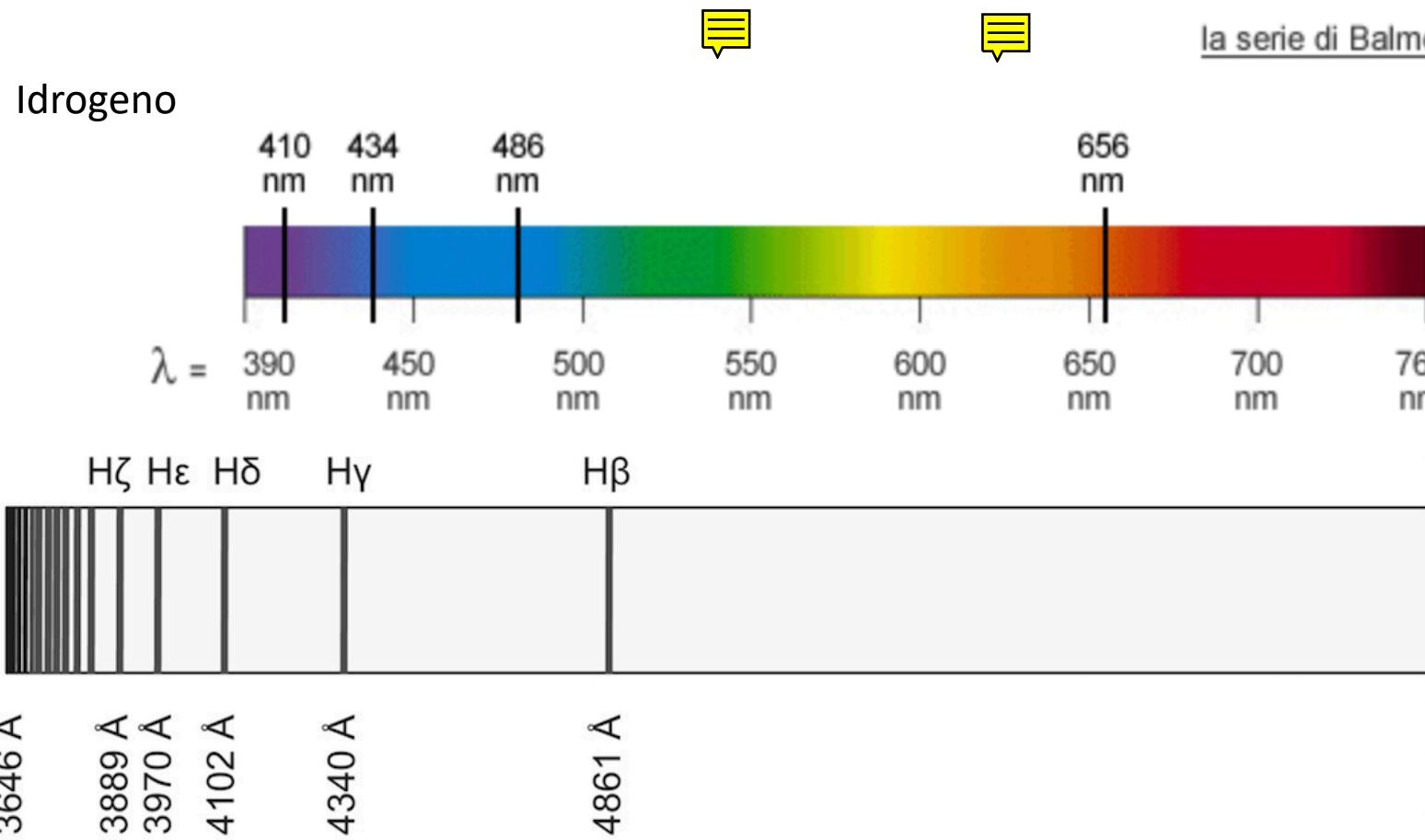


- 1872, Henry Draper



- William Huggins

Formula di Balmer, 1885

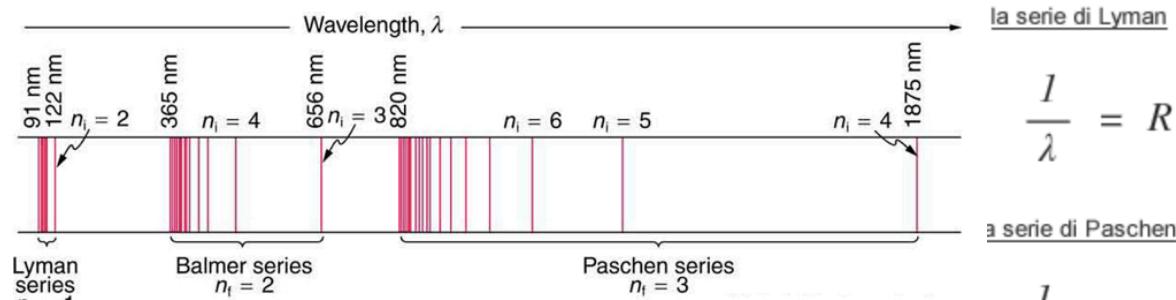


$$\lambda = (364,6 \text{ nm}) \frac{n^2}{n^2 - 4}$$

Legge di Rydberg-Ritz 1888-1890

la formula di Balmer

$$\frac{1}{\lambda} = R \left(\frac{1}{2^2} - \frac{1}{n^2} \right) \quad n=3,4,\dots$$



la serie di Lyman

$$\frac{1}{\lambda} = R \left(\frac{1}{1^2} - \frac{1}{n^2} \right) \quad n=2,3\dots$$

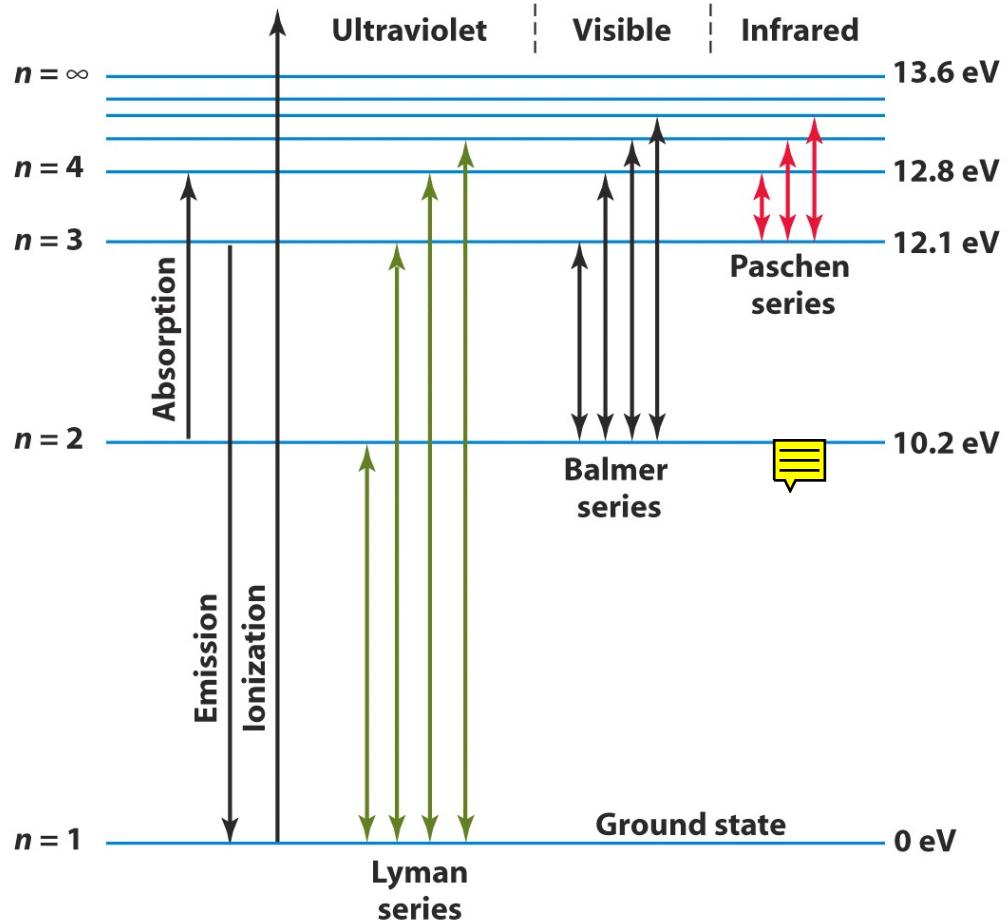
a serie di Paschen

$$\frac{1}{\lambda} = R \left(\frac{1}{3^2} - \frac{1}{n^2} \right) \quad n=4,5\dots$$

$$\frac{1}{\lambda} = R \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$$

$$R = 1.097 \cdot 10^7 \text{ m}^{-1}$$

Idrogeno: Bohr (1913)

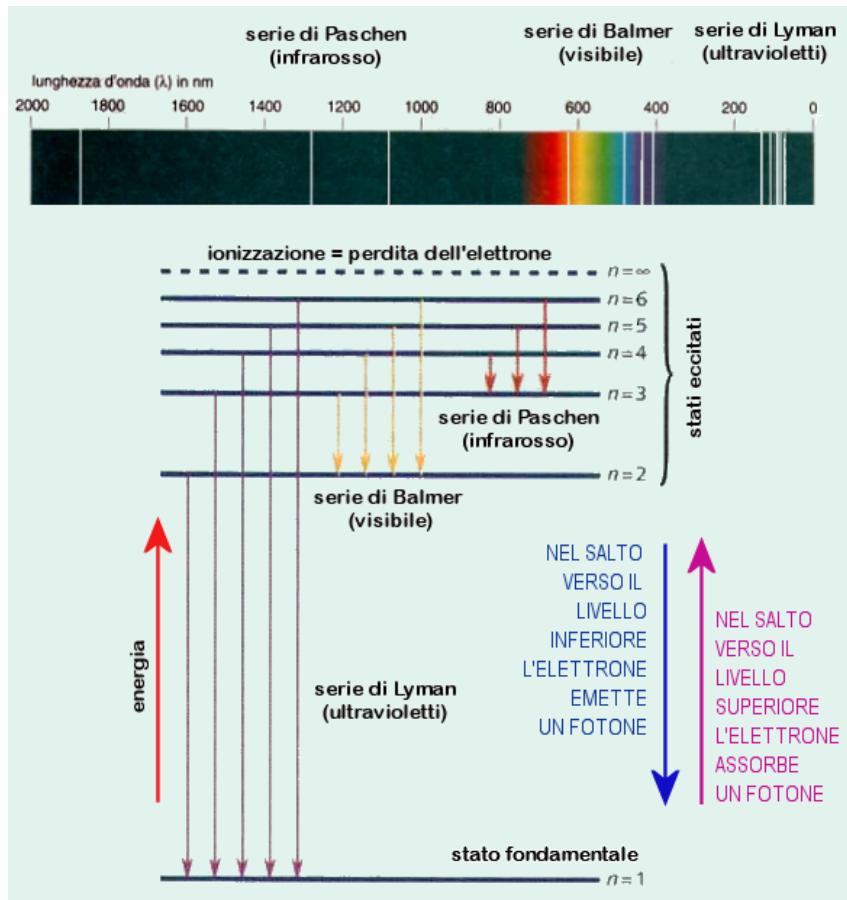


$$E_n = -\frac{1}{n^2} \cdot \frac{2\pi^2 me^4}{h^2}$$

$$v = \frac{E}{h} = \frac{E_2 - E_1}{h} = \frac{2\pi^2 me^4}{h^3} \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$$

$$R = \frac{2\pi^2 me^4}{h^3 c}$$

Legge di Rydberg-Ritz 1888-1890



la formula di Balmer

$$\frac{1}{\lambda} = R \left(\frac{1}{2^2} - \frac{1}{n^2} \right) \quad n=3,4,\dots$$

la serie di Lyman

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$$\frac{1}{\lambda} = R \left(\frac{1}{3^2} - \frac{1}{n^2} \right) \quad n=4,5\dots$$

$$\frac{1}{\lambda} = R \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$$

$$R = 1.097 \cdot 10^7 \text{ m}^{-1}$$

Hell (He^+)

- 1896, Pickering: spettro di ζ Puppis
- Serie di Pickering-Fowler
- 1913, Bohr: He^+



Angelo Secchi

Fig. 1. (1^{st} type: Sirius, Vega, Altair, Regulus, etc.)

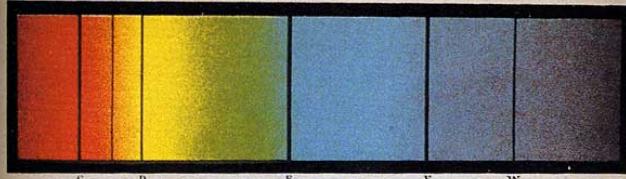


Fig. 2. (2^{nd} type. Sun, Pollux, Arcturus, Procyon, etc.)

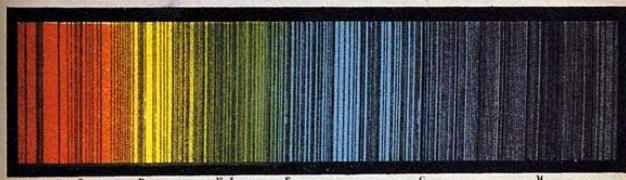


Fig. 3. (3^{rd} type: α Hercules, β Pegasus, α of Orion, Antares, etc.)

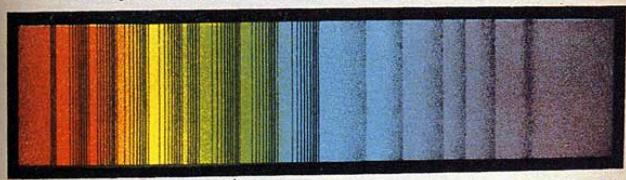
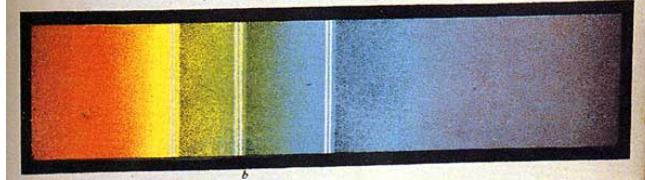


Fig. 4. (4^{th} type: 15° of Schjellerup.)



- Harvard College Observatory
- Edward C. Pickering: survey a partire 1880
- 1890, Draper Catalogue of Stellar Spectra
- Williamina Fleming
- 1897, Antonia Maury
- 1901, 1912, Annie Cannon

Classificazione spettrale

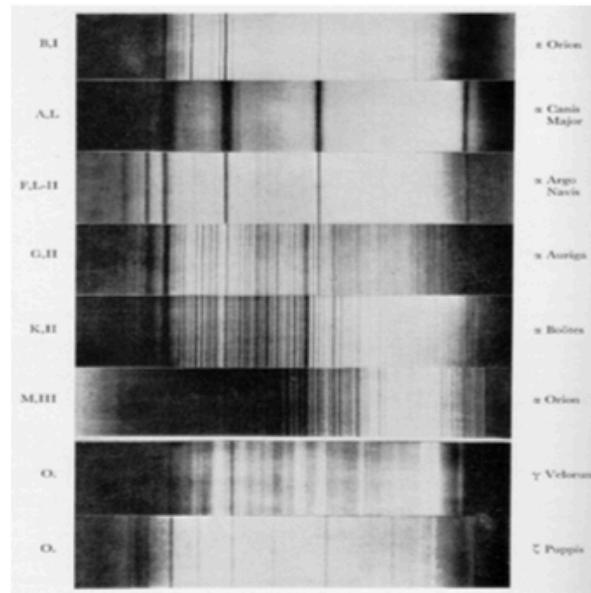
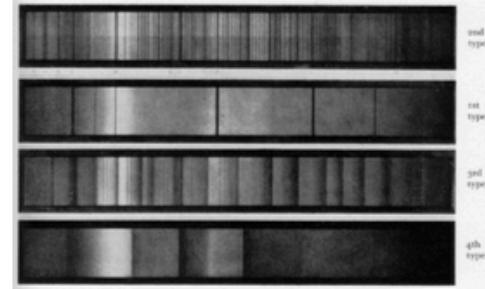
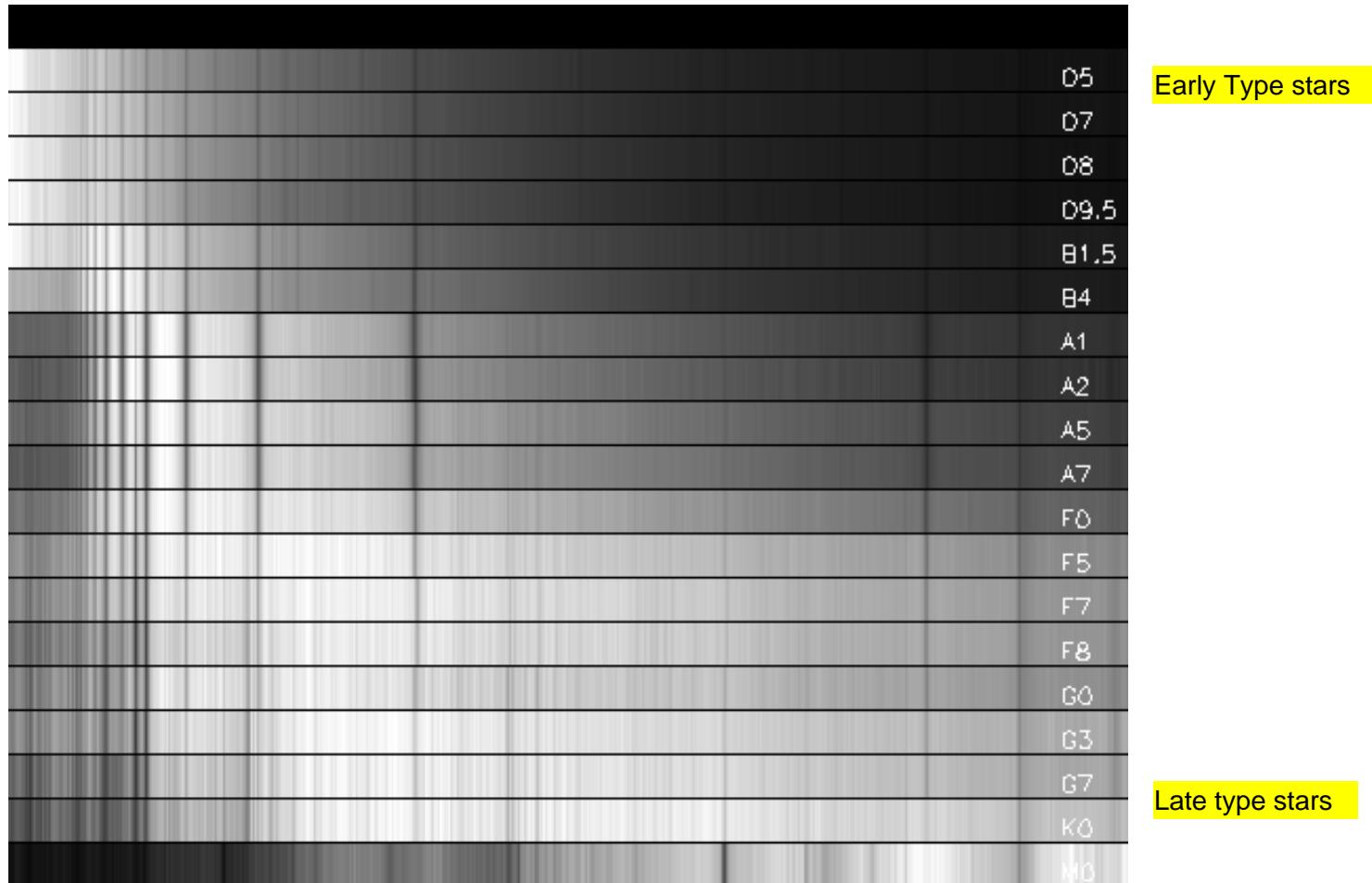
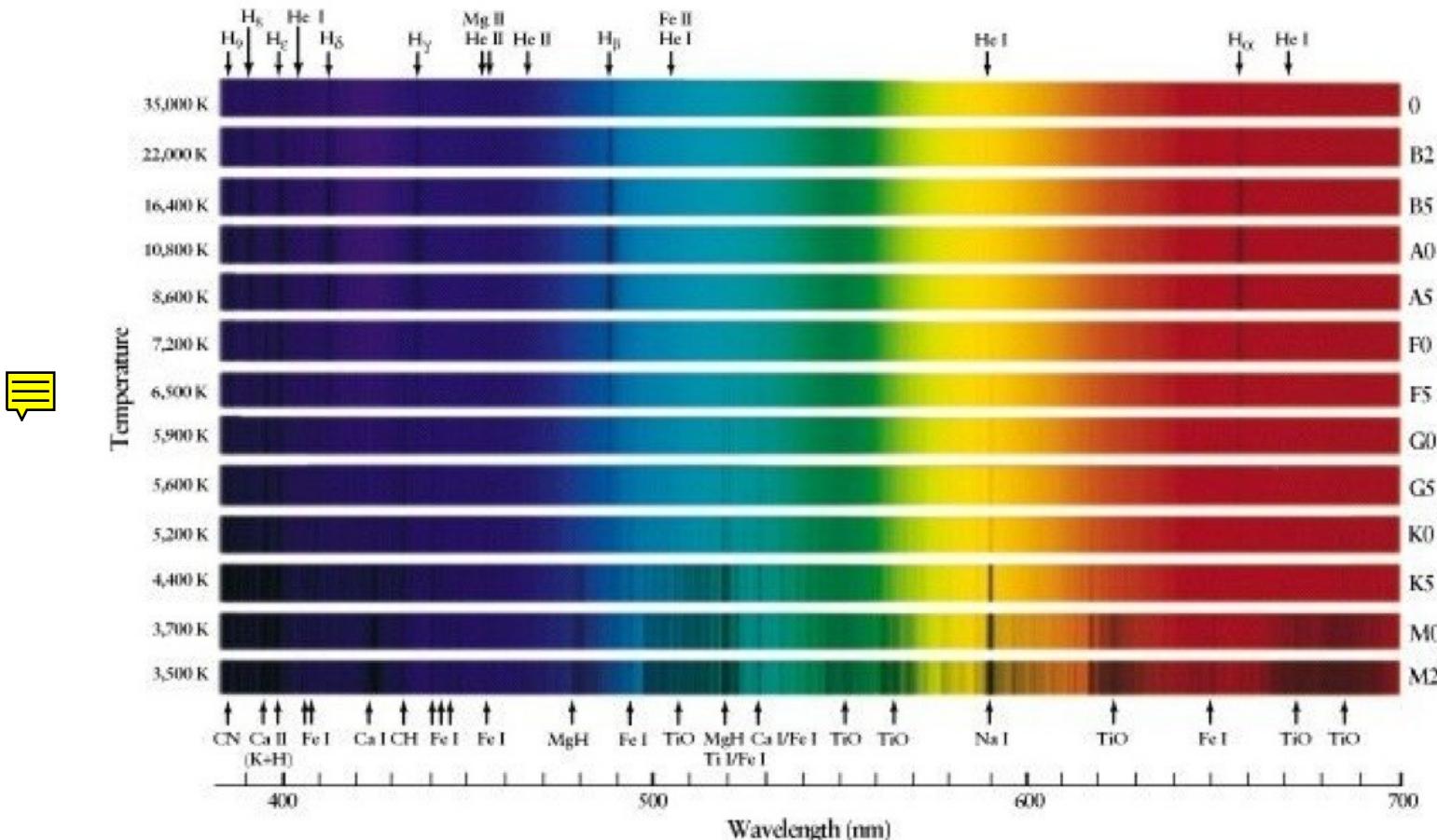


Figure 1.5: Spectral classifications. *Top:* Secchi's (1864) four-category scheme. The upper spectrum illustrates type 2 yellow solar-like spectra with many fine lines (Capella, Procyon, Arcturus, Aldebaran). The second spectrum (Secchi type 1) represents white or bluish-white Sirius-like stars with four strong hydrogen lines. The third (type 3) is Betelgeuse-like, with wide bands. The fourth (type 4) was a rare class of faint dark-red stars with fuzzy bands that Secchi correctly identified as having to do with carbon. *Bottom:* Harvard classification. At the bottom, ζ Puppis displays the Pickering series (at least on Pannekoek's non-fringed print). From [Pannekoek \(1961\)](#).

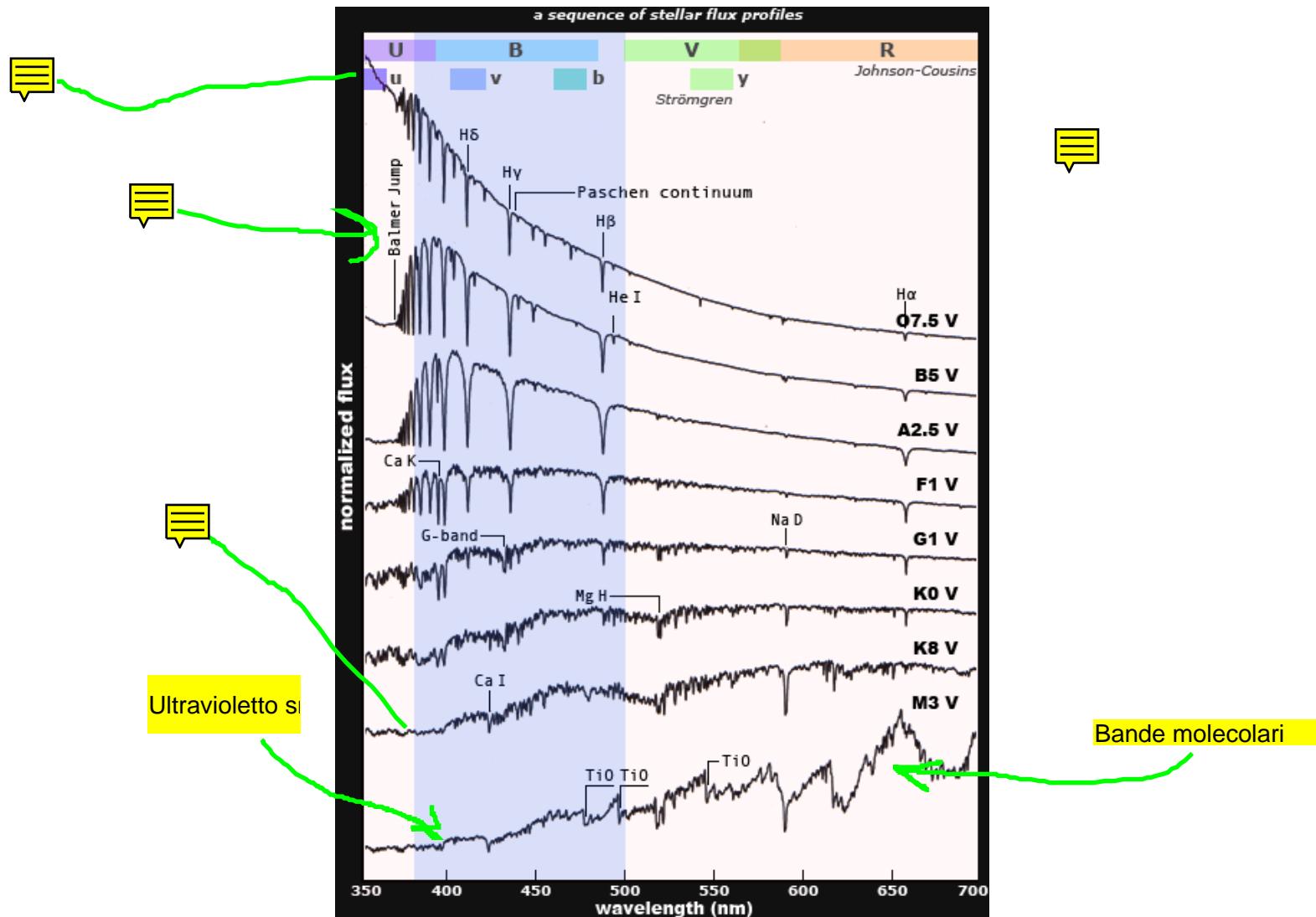
Classificazione spettrale di Harvard



Classificazione spettrale di Harvard



Classificazione spettrale



Classificazione spettrale di Harvard

Da sapere!

O	B	A	F	G Sole	K	M
violet	blue	blue	blue-white	white-yellow	orange-red	red
more than 28,000K	10,000-28,000K	7,500-10,000K	6,000-7,500K	5,000-6,000K	3,500-5,000K	less than 3,500K
few visible absorption lines, weak Balmer lines , ionised helium	neutral hydrogen lines, more prominent Balmer lines	strongest Balmer lines, other strong lines	weaker Balmer lines, many lines including neutral metals	Balmer lines weaker still, dominant ionised calcium lines	neutral metal lines most prominent	strong neutral metal lines and molecular bands

Classificazione spettrale di Harvard

- Sequenza di temperature:
- B2, $T_{\text{eff}}=22000$ K: massima intensità righe di Helium
- A0, $T_{\text{eff}}=9520$ K: massima intensità righe di Balmer
- K0, $T_{\text{eff}}=5250$ K: massima intensità righe di Calcium

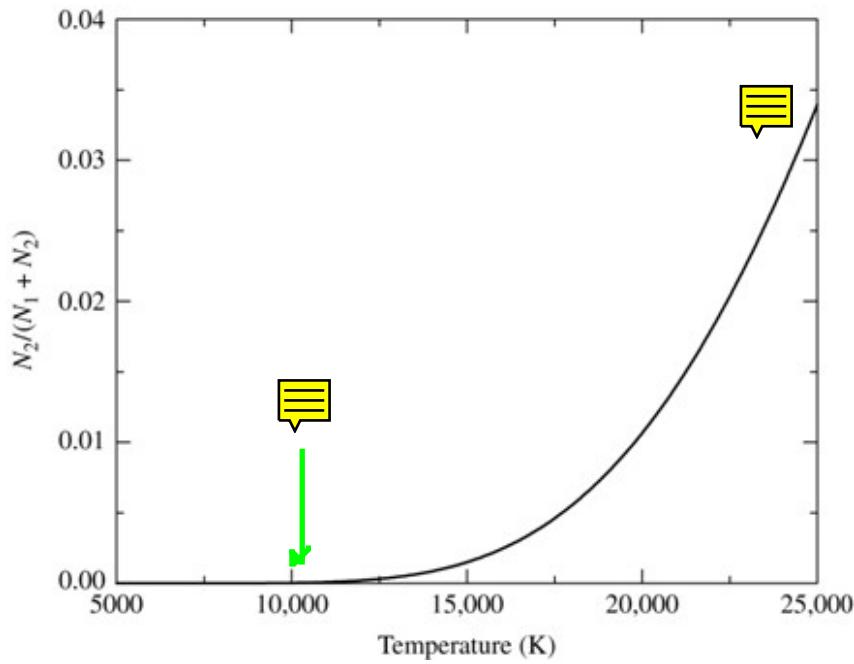
■ Temperatura di eccitazione

- Legge di Boltzmann

$$\left[\frac{N_2}{N_1} \right]_{\text{H I}} = \frac{g_2}{g_1} e^{-(E_2 - E_1)/kT}$$



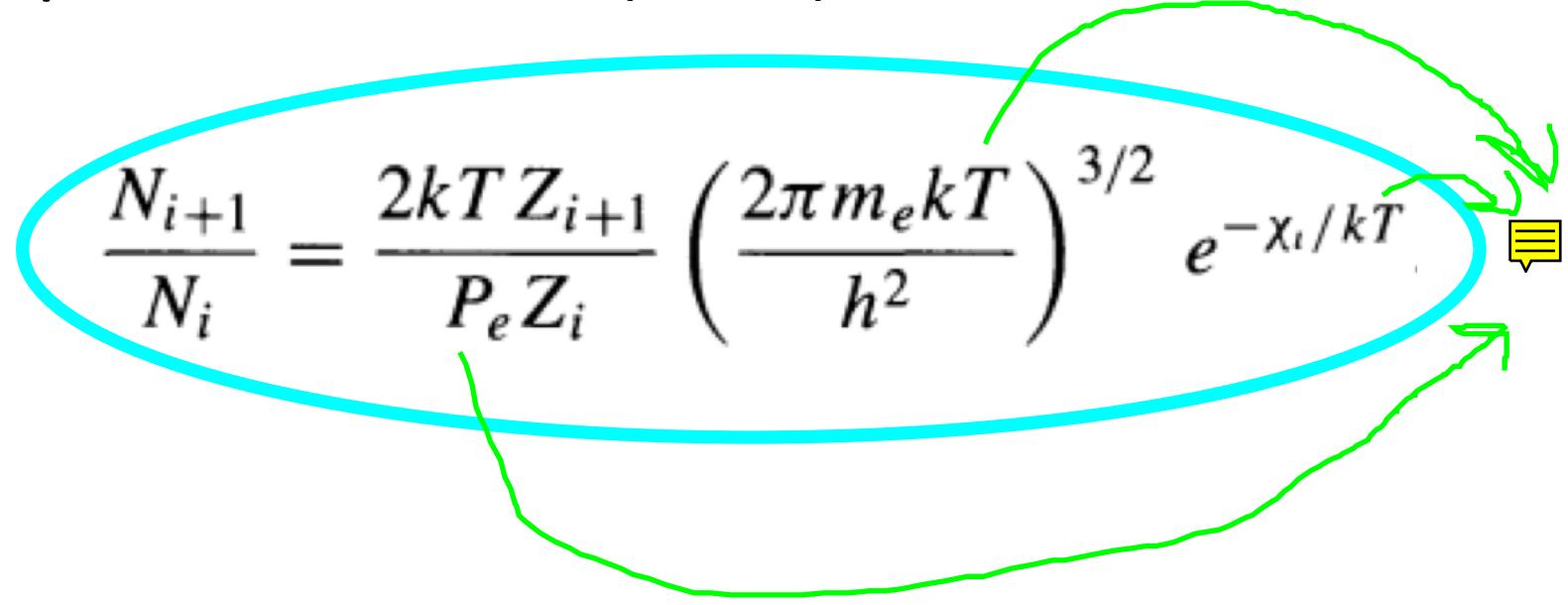
Atmosfera di puro idrogeno



- H neutro
- Popolamento del primo livello eccitato
- N_2/N_{tot} continua ad aumentare al crescere di T ben oltre la T di A0
- Perché da A0 → O5 le righe di Balmer diventano più deboli?

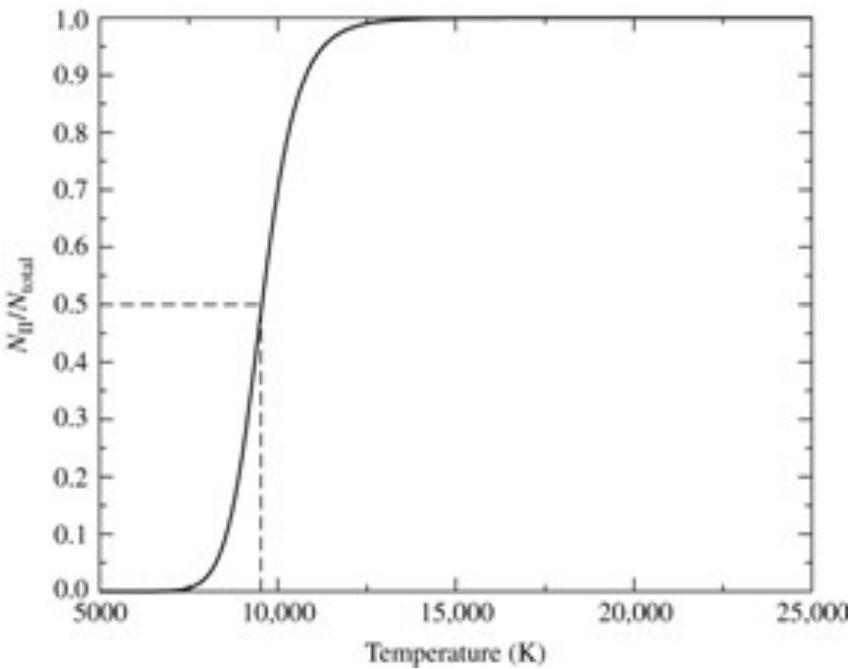
Temperatura di ionizzazione

- Equazione di Saha (1920)

$$\frac{N_{i+1}}{N_i} = \frac{2kT Z_{i+1}}{P_e Z_i} \left(\frac{2\pi m_e k T}{h^2} \right)^{3/2} e^{-\chi_i/kT}$$


- Z_{i+1} e Z_i sono le funzioni di partizione

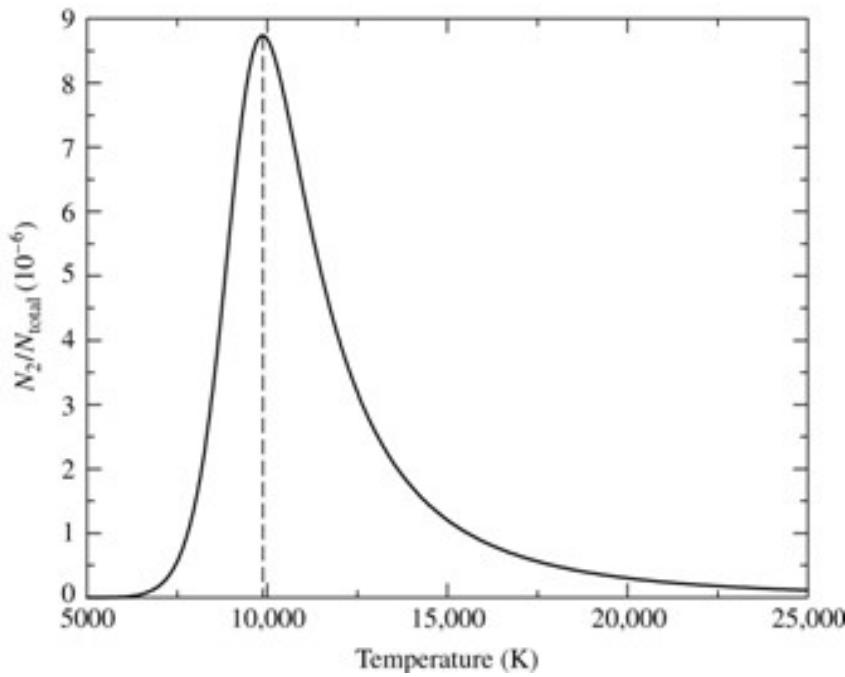
Atmosfera di puro idrogeno



- Ionizzazione
- Equazione di Saha (1920)
- A $T= 8300$ K il 5% dell'idrogeno è ionizzato
- A $T= 9600$ K il 50% dell'idrogeno è ionizzato
- A $T= 11300$ il 95% dell'idrogeno è ionizzato

$$P_e = 20 \text{ N/m}^2$$

Atmosfera di puro idrogeno

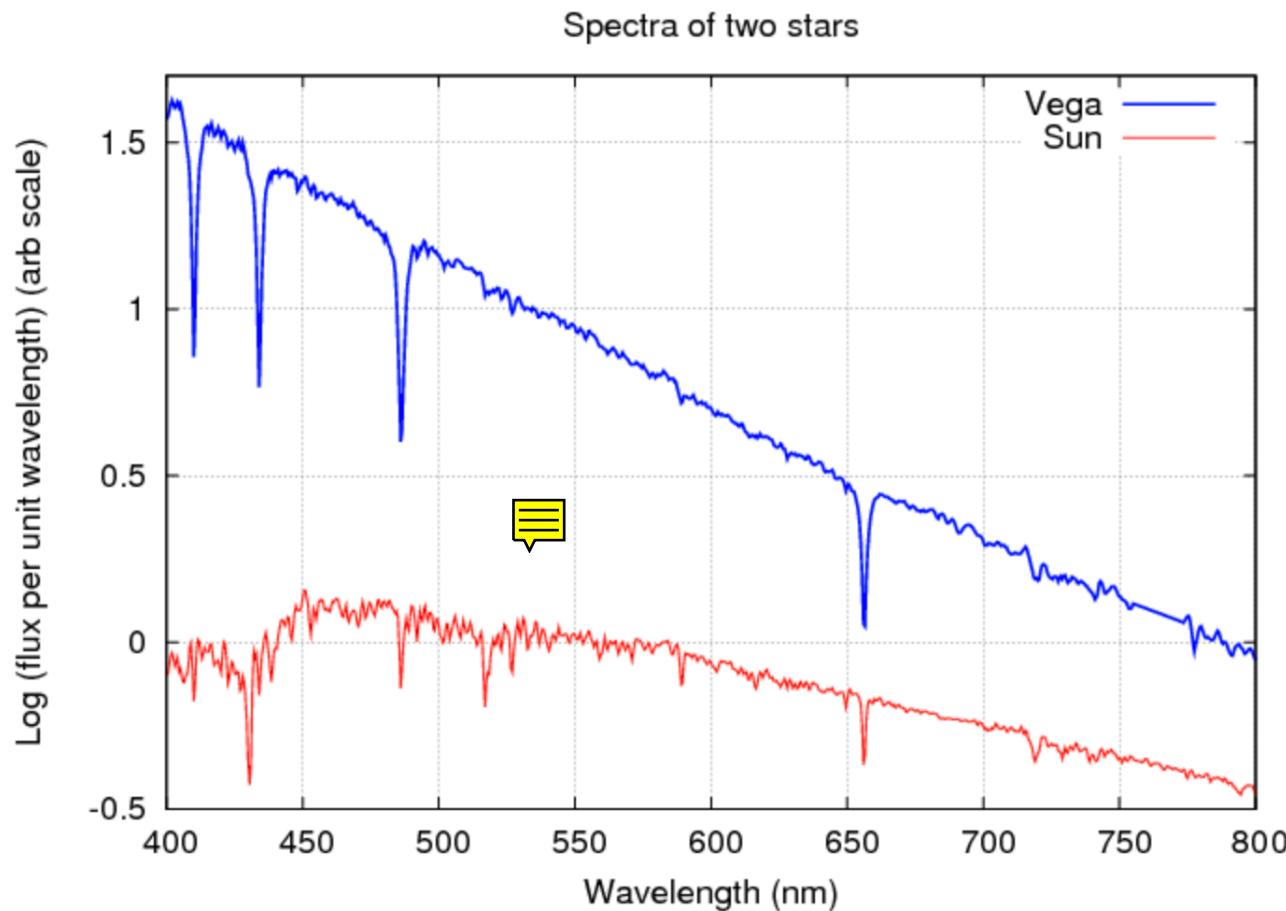


$$P_e = 20 \text{ N/m}^2$$

- Boltzamann + Saha
- N_2/N_{tot} ha un massimo a $T \approx 9900 \text{ K}$
- A $T \approx 9900 \text{ K}$ righe di Balmer più intense

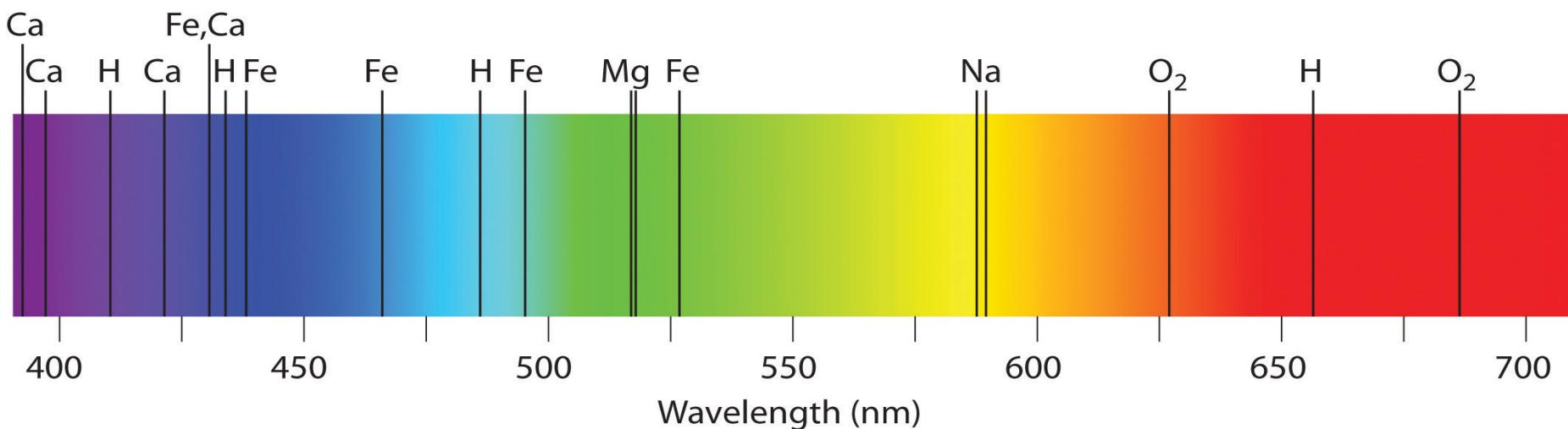
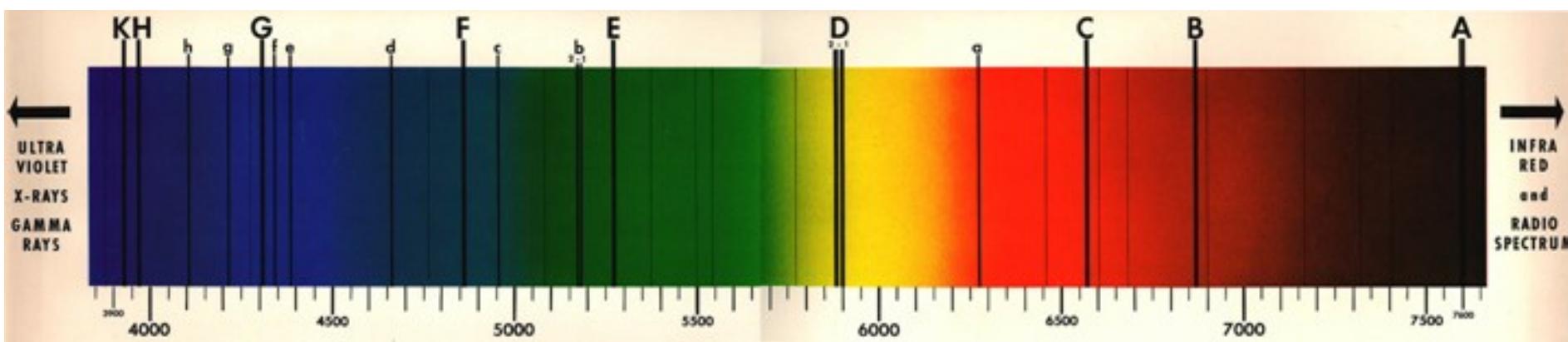


Vega - Sole



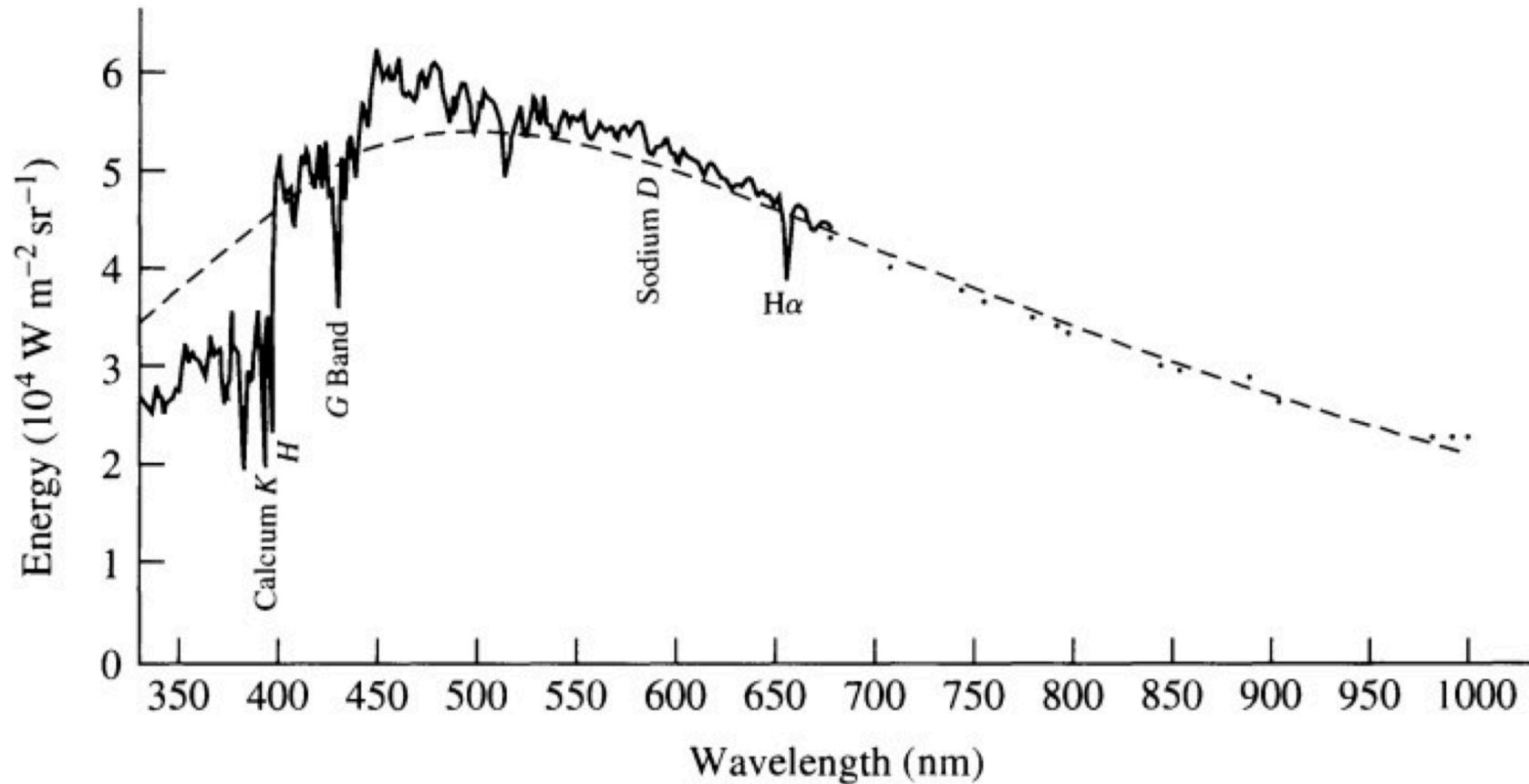
Sole

Come mai si vedono le righe H e K, dovute al CaII, nonostante il Ca sia molto meno abbondante dell'idrogeno?



Sole

Come mai le righe H e K, dovute al CaII, sono più intense delle righe di Balmer nonostante il calcio sia molto meno abbondante dell'idrogeno?



Profondità relativa delle righe di Ca e H nel Sole

Fotosfera:

- $T_{\text{eff}} = 5777 \text{ K}$
- $P_e = 1,5 \text{ N m}^{-2}$
- 1 Ca ogni 500000 H

Profondità relativa delle righe di Ca e H nel Sole

Idrogeno, $\chi_i = 13,6 \text{ eV}$

$$\left[\frac{N_2}{N_1} \right]_{\text{H I}} = \frac{g_2}{g_1} e^{-(E_2 - E_1)/kT} = 5.06 \times 10^{-9} \simeq \frac{1}{198,000,000}.$$

$$\left[\frac{N_{\text{II}}}{N_{\text{I}}} \right]_{\text{H}} = \frac{2kT Z_{i+1}}{P_e Z_i} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} e^{-\chi_i/kT} = 7.70 \times 10^{-5} \simeq \frac{1}{13,000}.$$

- H in gran parte neutro e nello stato fondamentale

$$\frac{N_2}{N_{\text{total}}} = \left(\frac{N_2}{N_1 + N_2} \right) \left(\frac{N_{\text{I}}}{N_{\text{total}}} \right) = 5.06 \times 10^{-9}$$

- Solo 1 H ogni $2 \cdot 10^8$ nel primo eccitato e in grado di produrre righe di Balmer

Profondità relativa delle righe di Ca e H nel Sole

Calcio I, $\chi_i = 6,11 \text{ eV}$

- A $T_{\text{eff}} = 5777 \text{ K}$, le funzioni di partizione $Z_I = 1,32$ e $Z_{II} = 2,30$ e quindi

$$\left[\frac{N_{II}}{N_I} \right]_{\text{Ca}} = \frac{2kT Z_{II}}{P_e Z_I} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} e^{-\chi_I/kT} = 918$$

- Il calcio è quasi tutto ionizzato, i.e. Ca II
- Solo 1 Ca I ogni 918 Ca II

Profondità relativa delle righe di Ca e H nel Sole

- le righe H (396,8 nm) e K (393, 3 nm) prodotte da transizioni dallo stato fondamentale del Ca II
- Riga K: $E_2 - E_1 = 3,12 \text{ eV}$, $g_1 = 2$, $g_2 = 4$

$$\left[\frac{N_2}{N_1} \right]_{\text{Ca II}} = \frac{g_2}{g_1} e^{-(E_2 - E_1)/kT} = 3.79 \times 10^{-3} = \frac{1}{264}$$

- Molti atomi di Ca sono nello stato fondamentale del Ca II e quindi in grado di produrre la riga K

Profondità relativa delle righe di Ca e H nel Sole

$$\begin{aligned} \left[\frac{N_1}{N_{\text{total}}} \right]_{\text{Ca II}} &\simeq \left[\frac{N_1}{N_1 + N_2} \right]_{\text{Ca II}} \left[\frac{N_{\text{II}}}{N_{\text{total}}} \right]_{\text{Ca}} \\ &= \left(\frac{1}{1 + [N_2/N_1]_{\text{Ca II}}} \right) \left(\frac{[N_{\text{II}}/N_{\text{I}}]_{\text{Ca}}}{1 + [N_{\text{II}}/N_{\text{I}}]_{\text{Ca}}} \right) \\ &= \left(\frac{1}{1 + 3.79 \times 10^{-3}} \right) \left(\frac{918}{1 + 918} \right) \\ &= 0.995. \end{aligned}$$

- Quasi tutto il Ca è ionizzato una volta (Ca II) e nello stato fondamentale, quindi in grado di produrre le righe K e H

Profondità relativa delle righe di Ca e H nel Sole

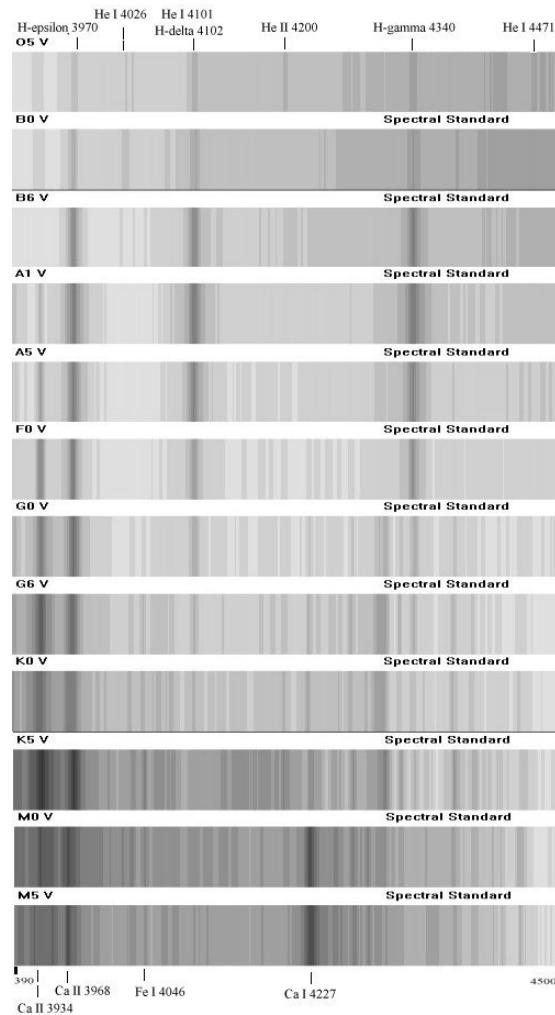
- 500000 atomi di H ogni atomo di Ca
- Degli H, solo una frazione $5.06 \cdot 10^{-9}$ si trova nel primo livello eccitato di HI e quindi in grado di produrre una riga di Balmer

$$500000 \times 5.06 \cdot 10^{-9} \approx 0.00252 = \frac{1}{395}$$

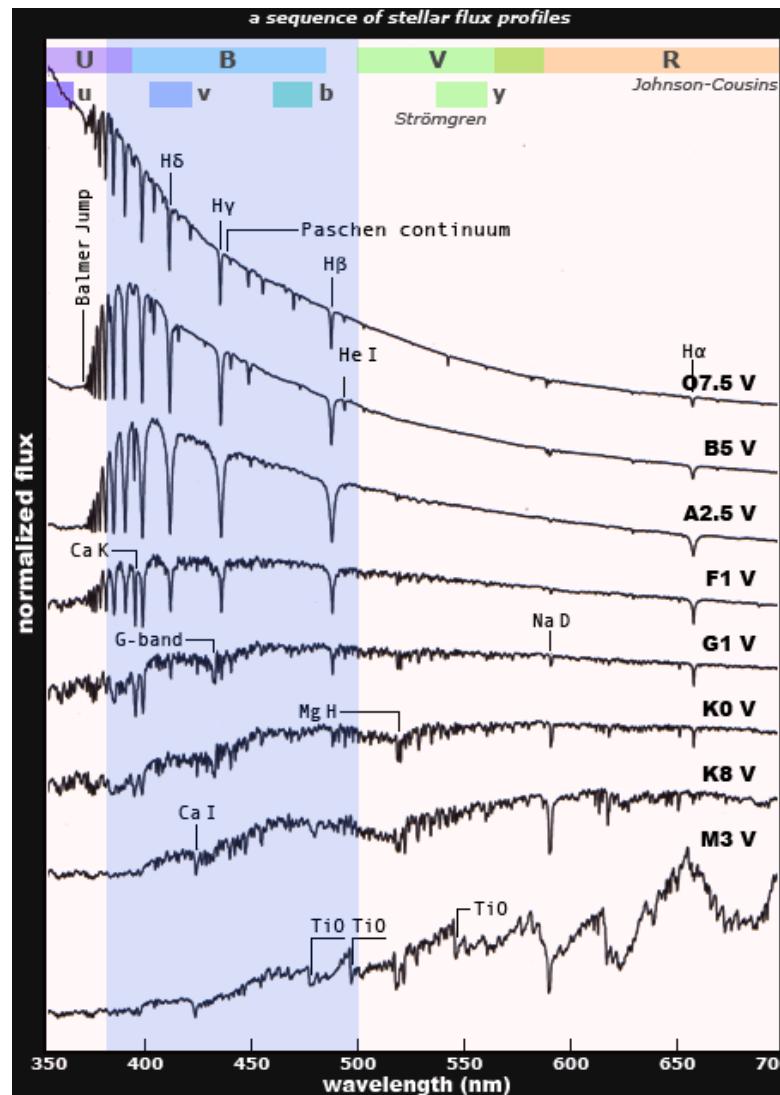
Profondità relativa delle righe di Ca e H nel Sole

- Ogni H I nel primo livello eccitato (in grado di produrre righe di Balmer) ci sono ~ 400 Ca II nel fondamentale (in grado di produrre righe H e K Ca)
- Righe H e K di Ca nel Sole sono più intense delle righe di Balmer
- Eccitazione e ionizzazione degli atomi dipende molto sensibilmente dalla temperatura

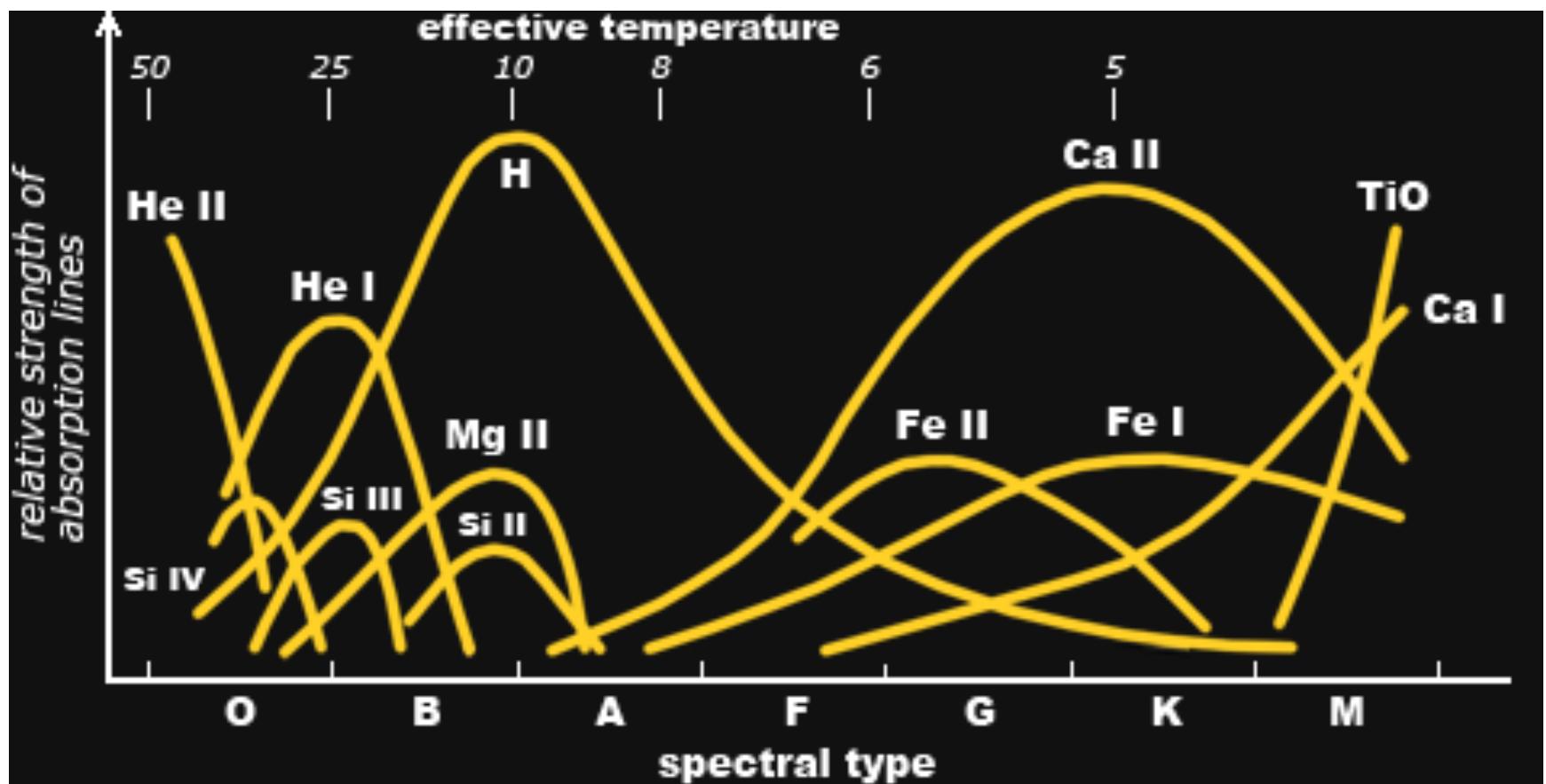
Classificazione spettrale di MKK



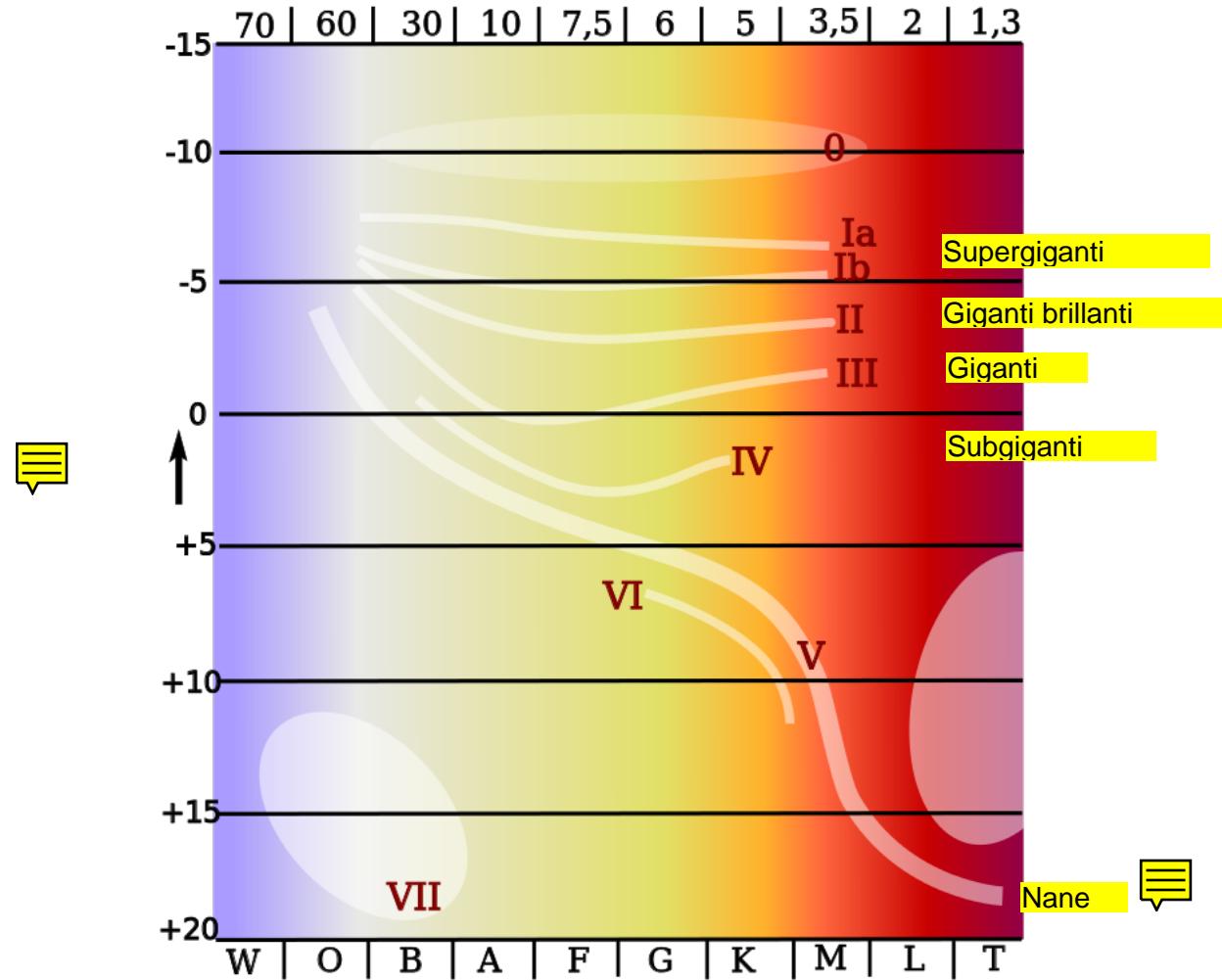
Classificazione spettrale di MKK



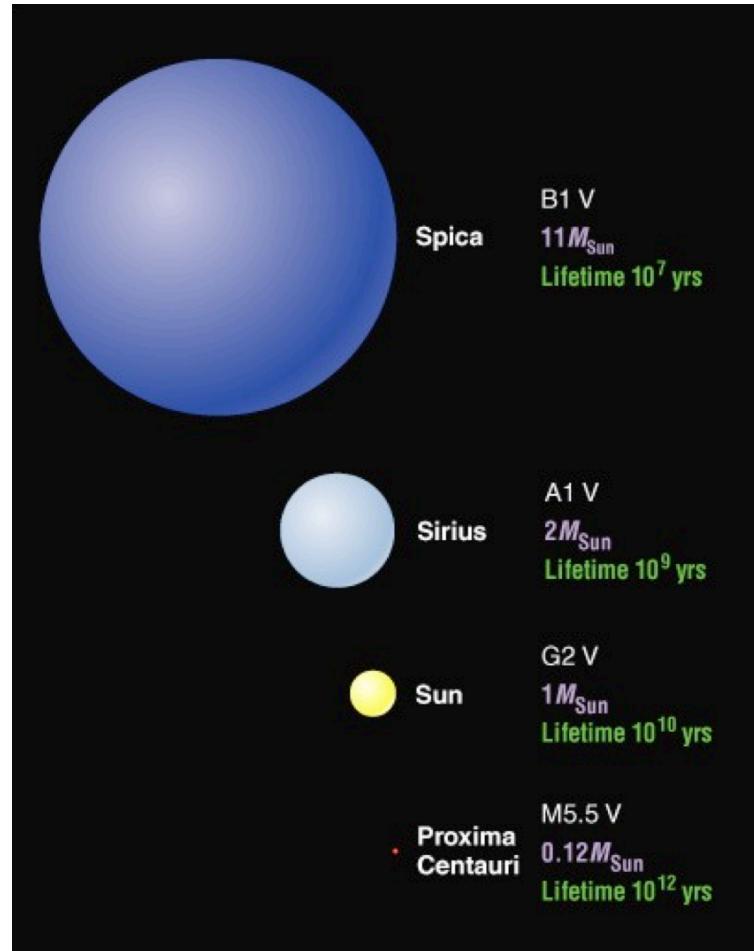
Classificazione spettrale di MKK



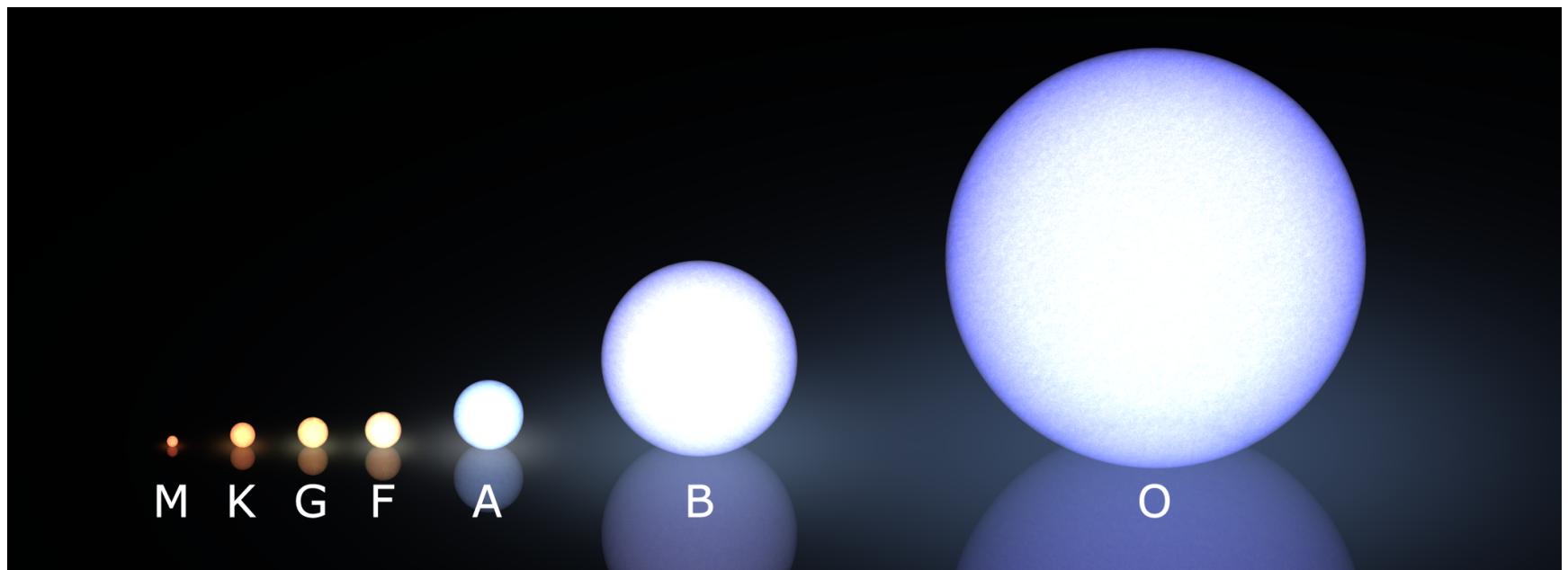
Classificazione spettrale di MKK



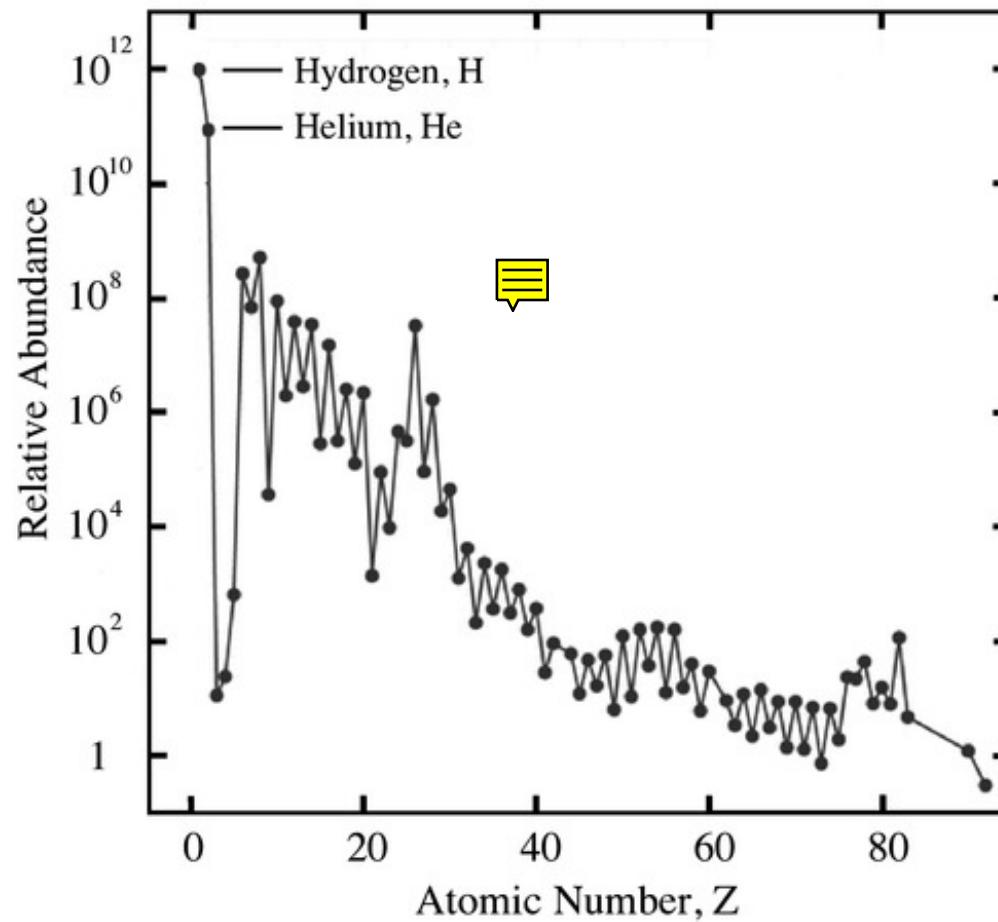
Classificazione spettrale di MKK



Classificazione spettrale di MKK



Sole



Abbondanze relative degli elementi nella fotosfera del Sole (Asplund et al. 2009)

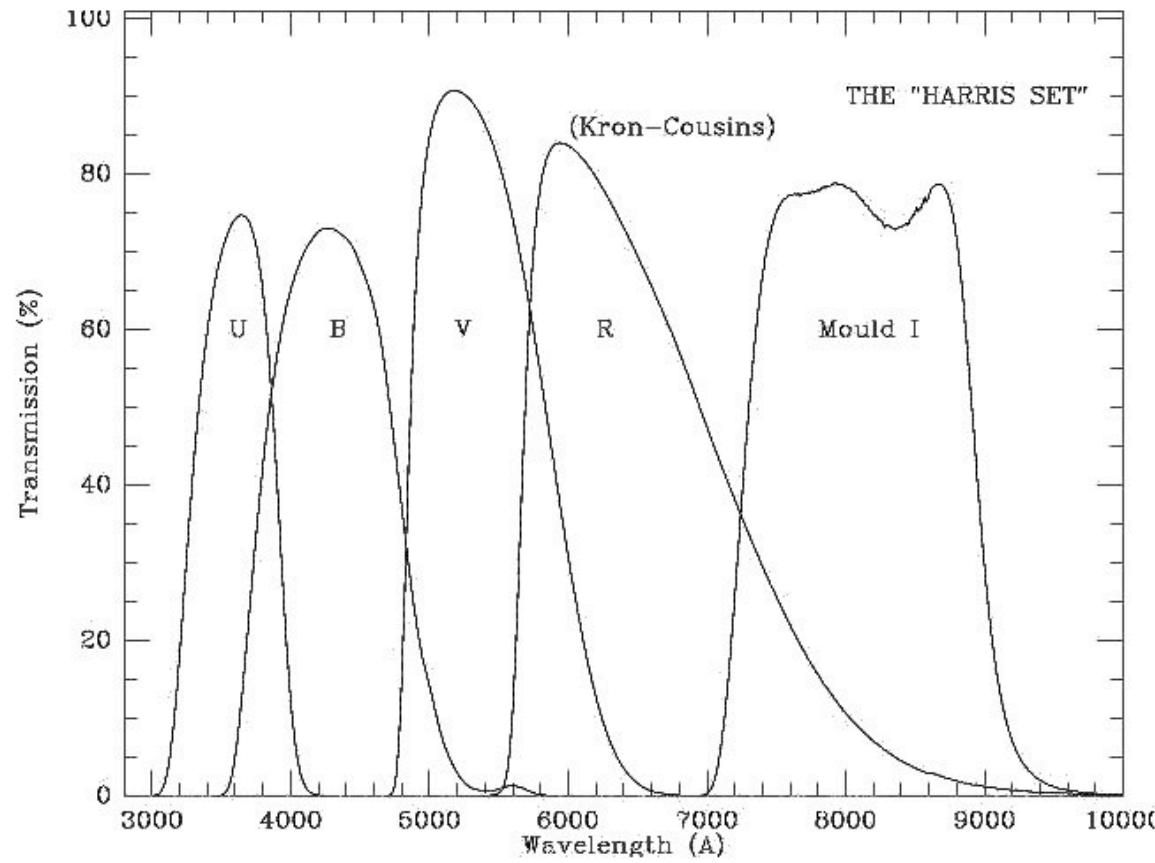
Sole

Table 1: Element abundances in the present-day solar photosphere. Also given are the corresponding values for CI carbonaceous chondrites (Lodders, Palme & Gail 2009). Indirect photospheric estimates have been used for the noble gases (Sect. 3.3).

	Elem.	Photosphere	Meteorites		Elem.	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
10	Ne	[7.93 ± 0.10]	-1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24 ± 0.06]	-1.95
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02
18	Ar	[6.40 ± 0.13]	-0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02
20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02
21	Sc	3.15 ± 0.04	3.05 ± 0.02	65	Tb	0.30 ± 0.10	0.32 ± 0.03
22	Ti	4.95 ± 0.05	4.91 ± 0.03	66	Dy	1.10 ± 0.04	1.13 ± 0.02
23	V	3.93 ± 0.08	3.96 ± 0.02	67	Ho	0.48 ± 0.11	0.47 ± 0.03
24	Cr	5.64 ± 0.04	5.64 ± 0.01	68	Er	0.92 ± 0.05	0.92 ± 0.02
25	Mn	5.43 ± 0.05	5.48 ± 0.01	69	Tm	0.10 ± 0.04	0.12 ± 0.03
26	Fe	7.50 ± 0.04	7.45 ± 0.01	70	Yb	0.84 ± 0.11	0.92 ± 0.02
27	Co	4.99 ± 0.07	4.87 ± 0.01	71	Lu	0.10 ± 0.09	0.09 ± 0.02
28	Ni	6.22 ± 0.04	6.20 ± 0.01	72	Hf	0.85 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.04	4.25 ± 0.04	73	Ta		-0.12 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04	74	W	0.85 ± 0.12	0.65 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.38 ± 0.07	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.92 ± 0.10	0.80 ± 0.04
36	Kr	[3.25 ± 0.06]	-2.27	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.10	2.36 ± 0.03	81	Tl	0.90 ± 0.20	0.77 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04	90	Th	0.02 ± 0.10	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		-0.54 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				

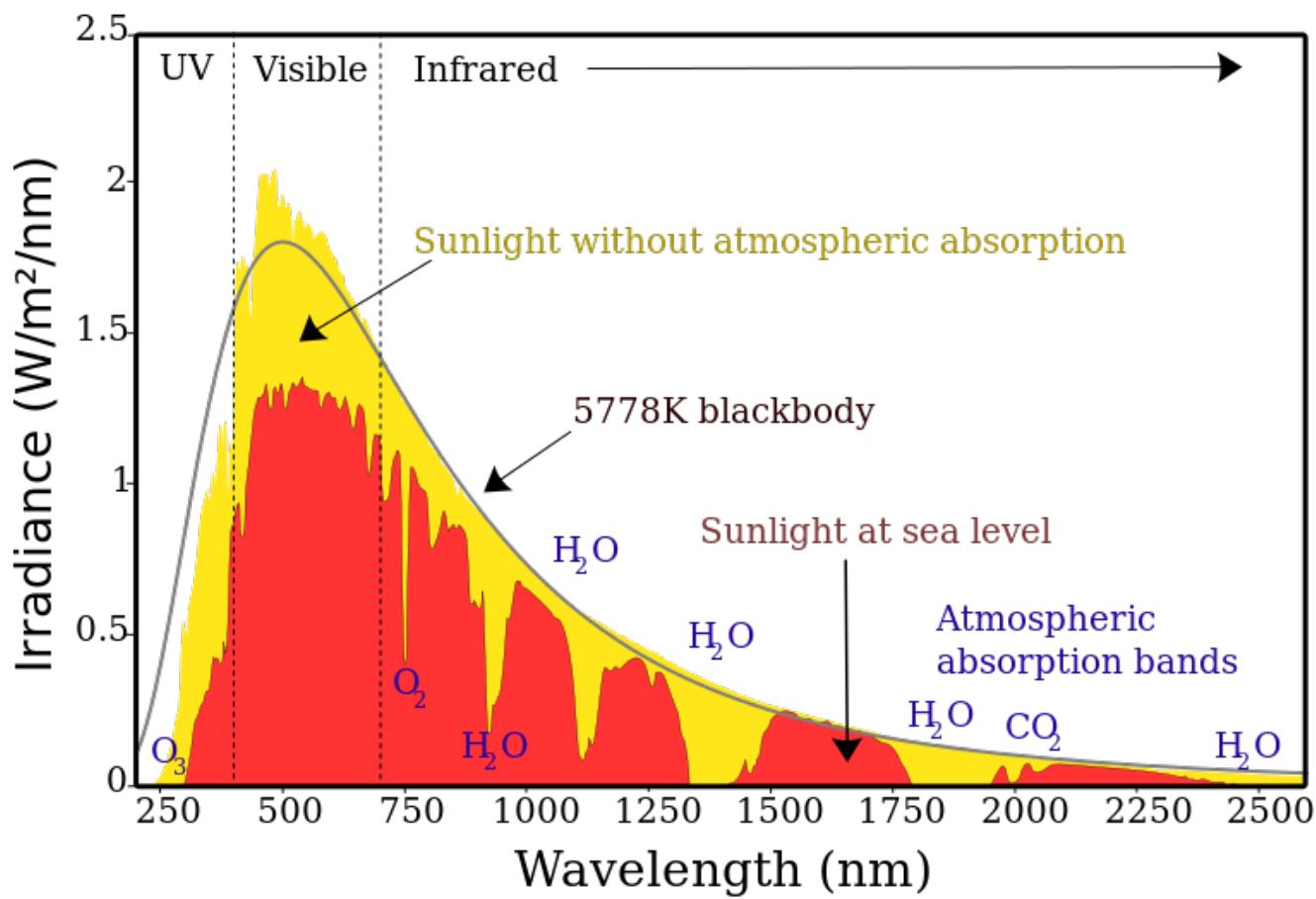
Abbondanze relative degli elementi nella fotosfera del Sole (Asplund et al. 2009)

Sistemi fotometrici

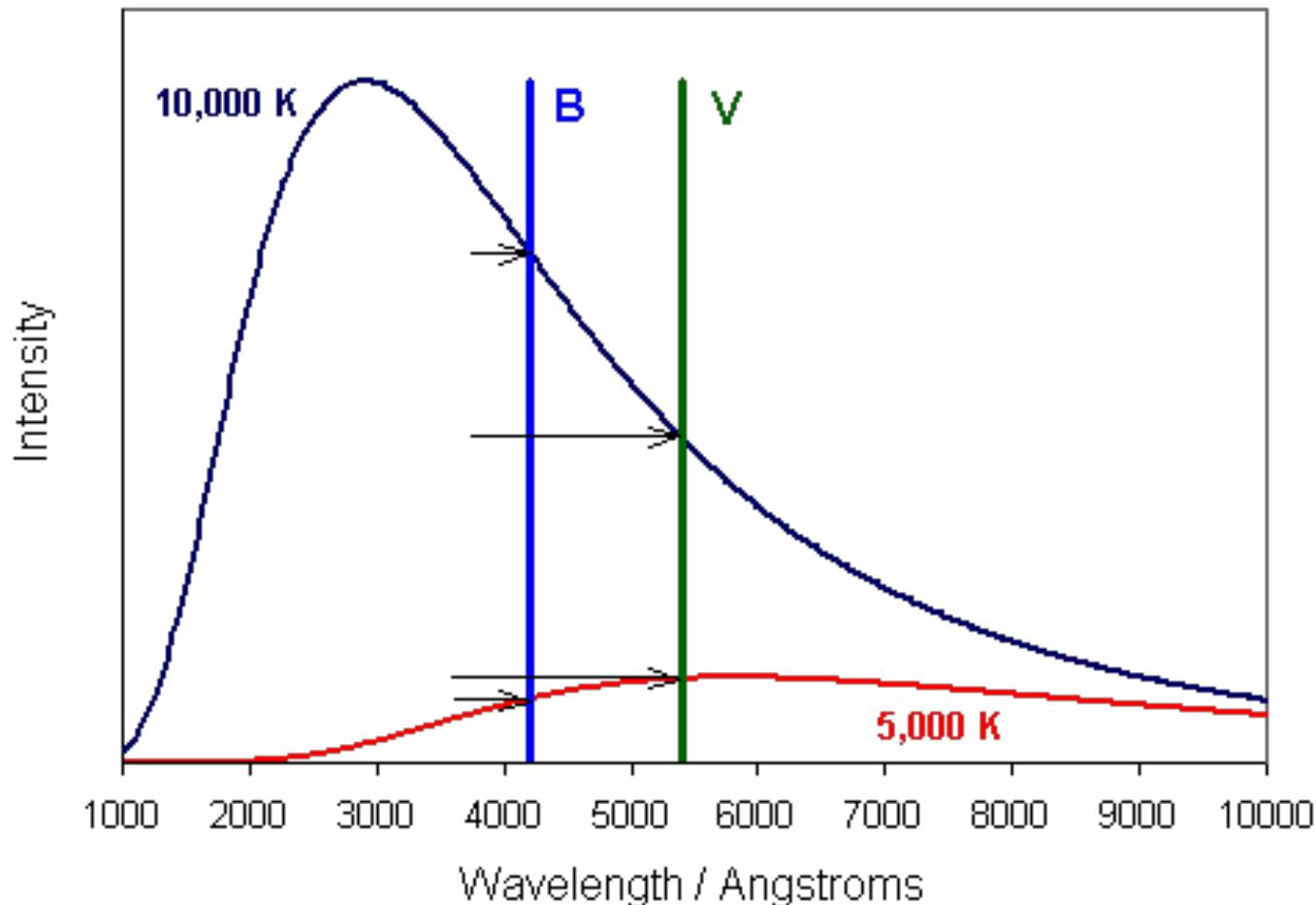


The relative transmissions of the standard Kitt Peak UBVR filter set are shown here.

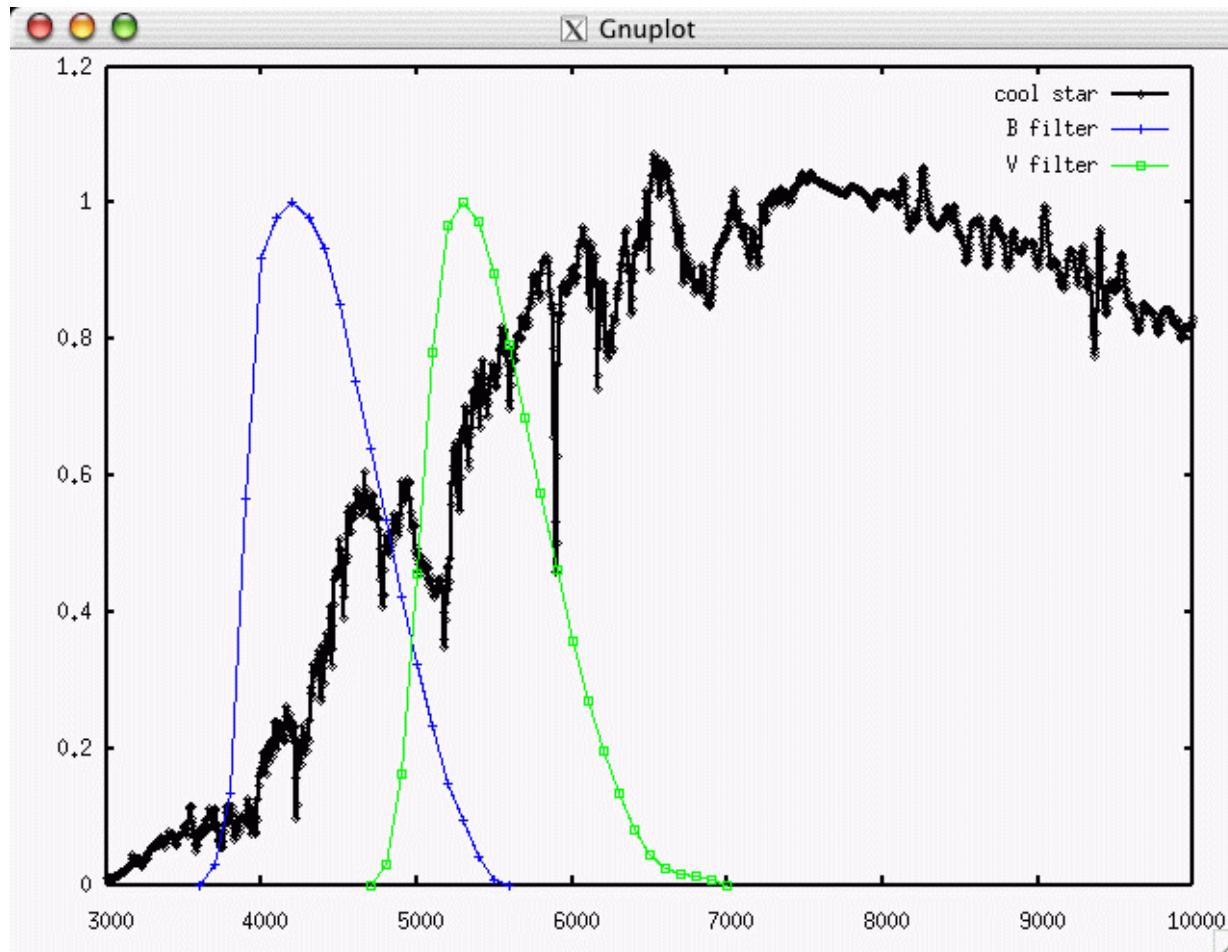
Spectrum of Solar Radiation (Earth)



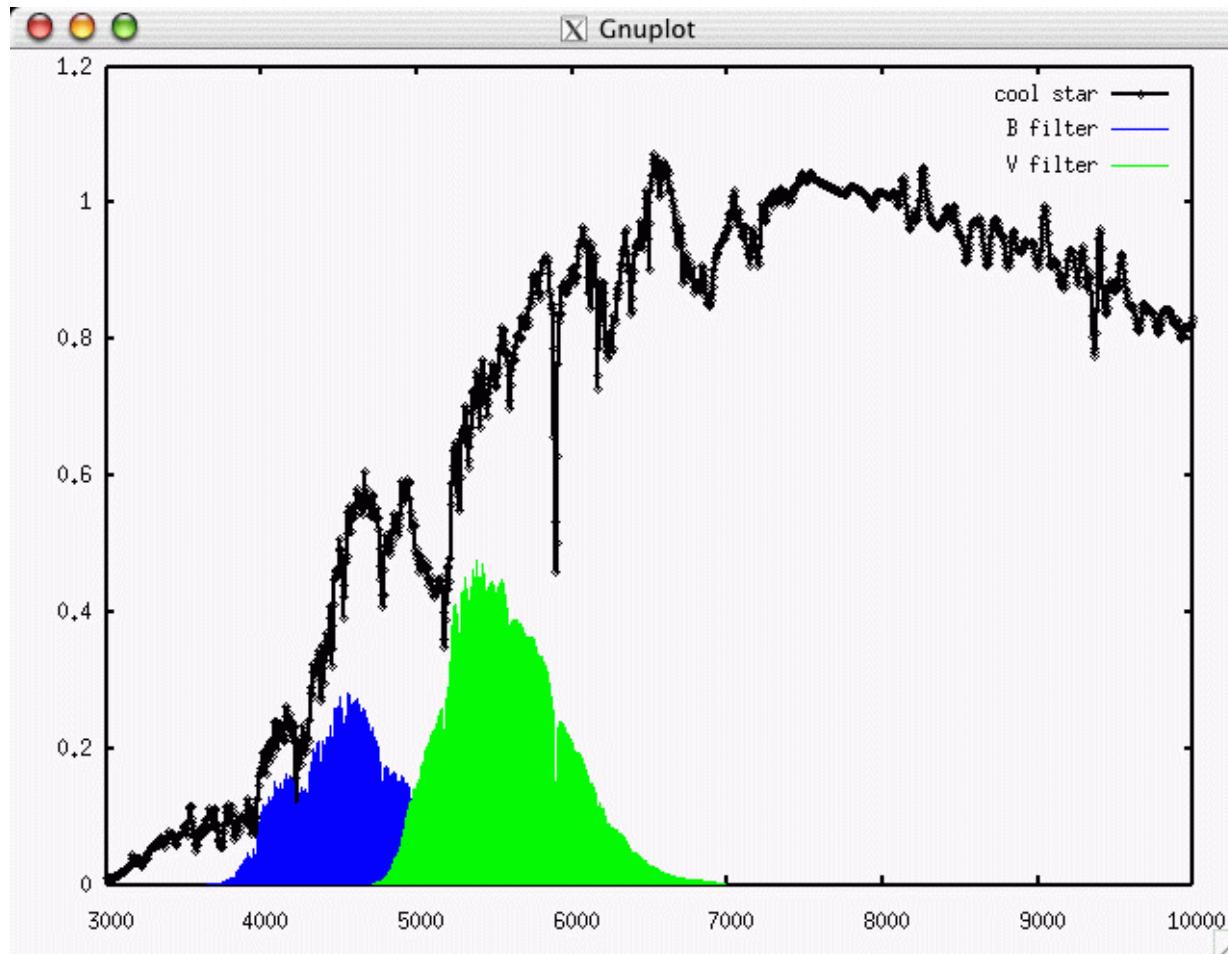
Indice di colore



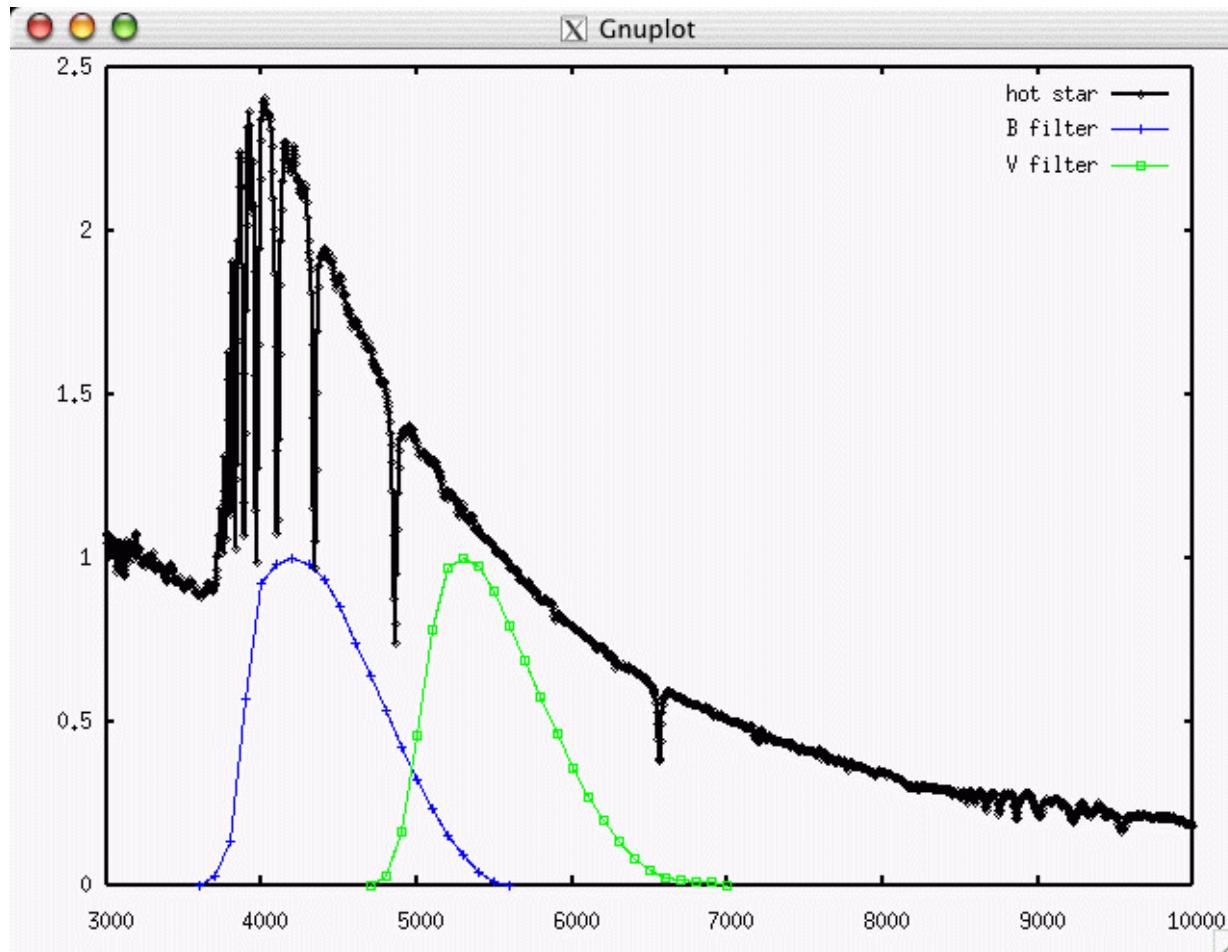
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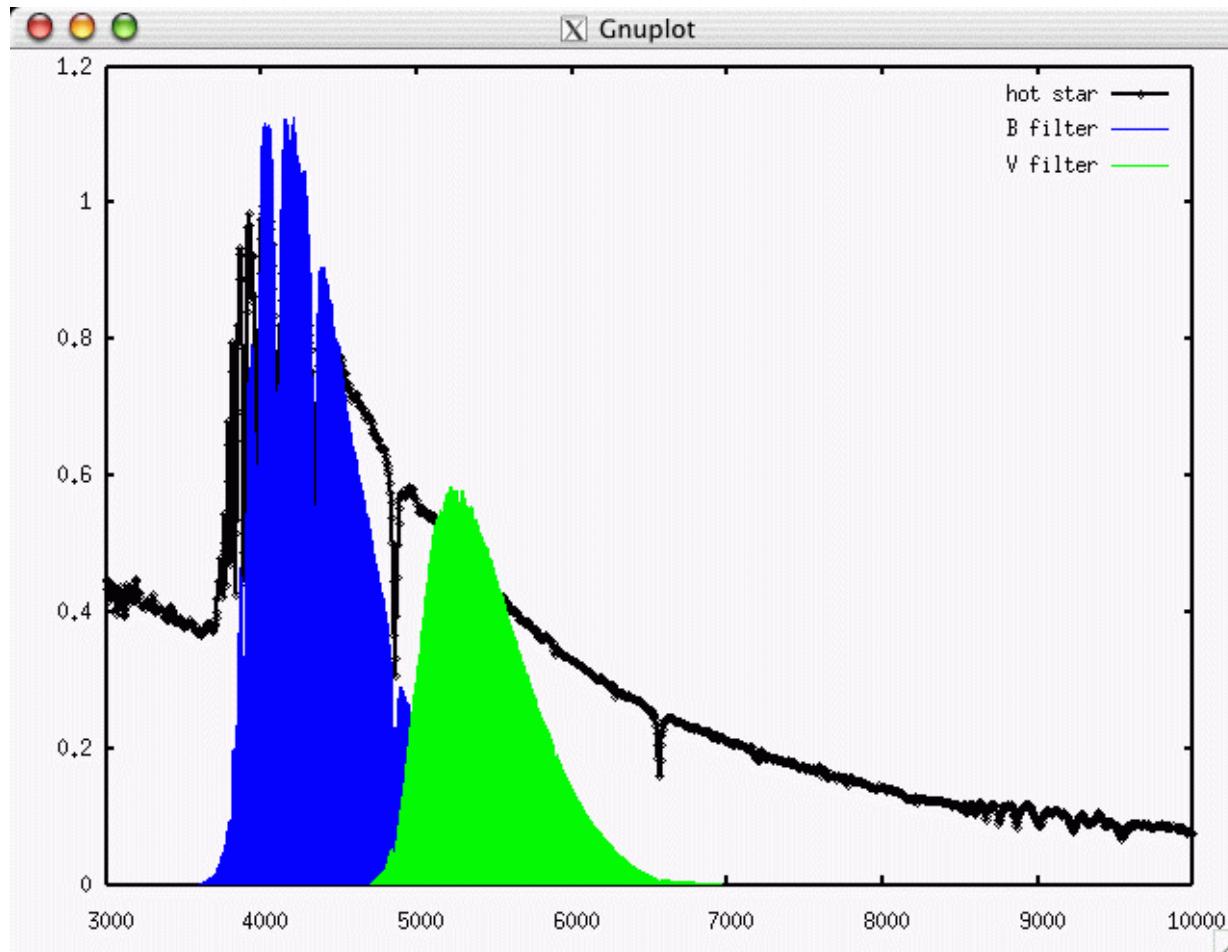
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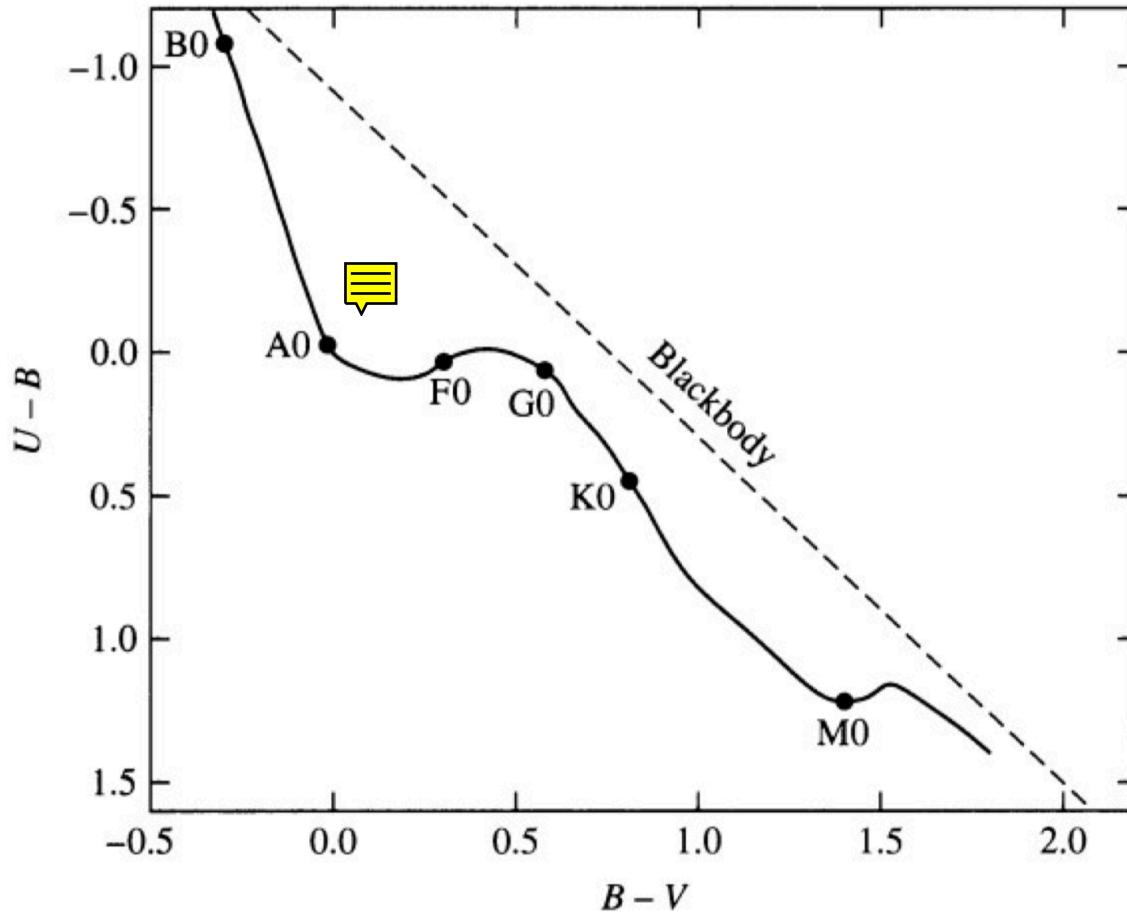
Indice di colore



Indice di colore

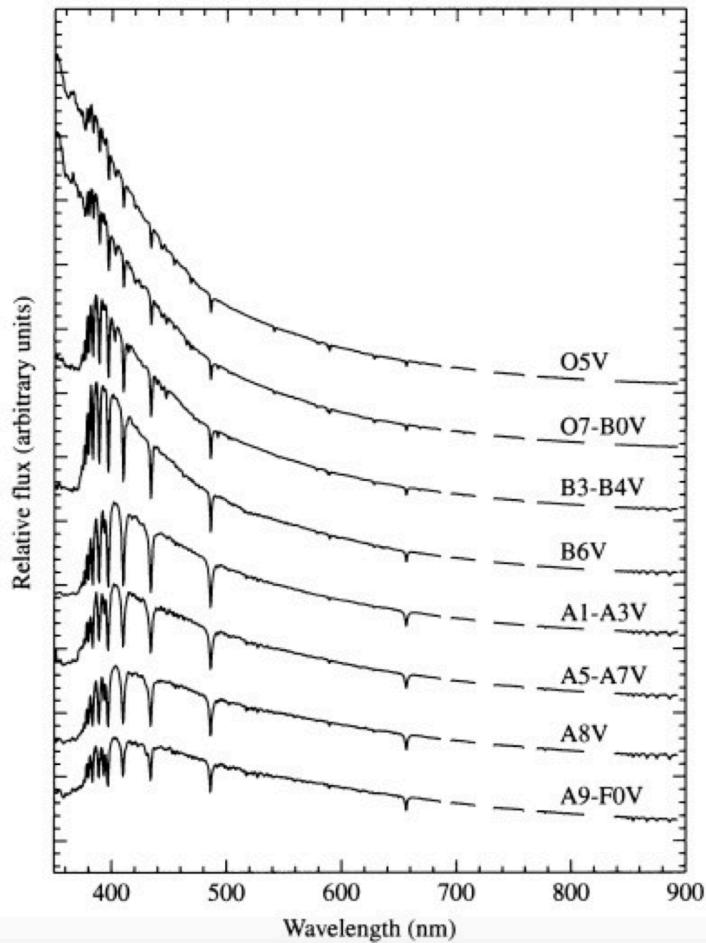


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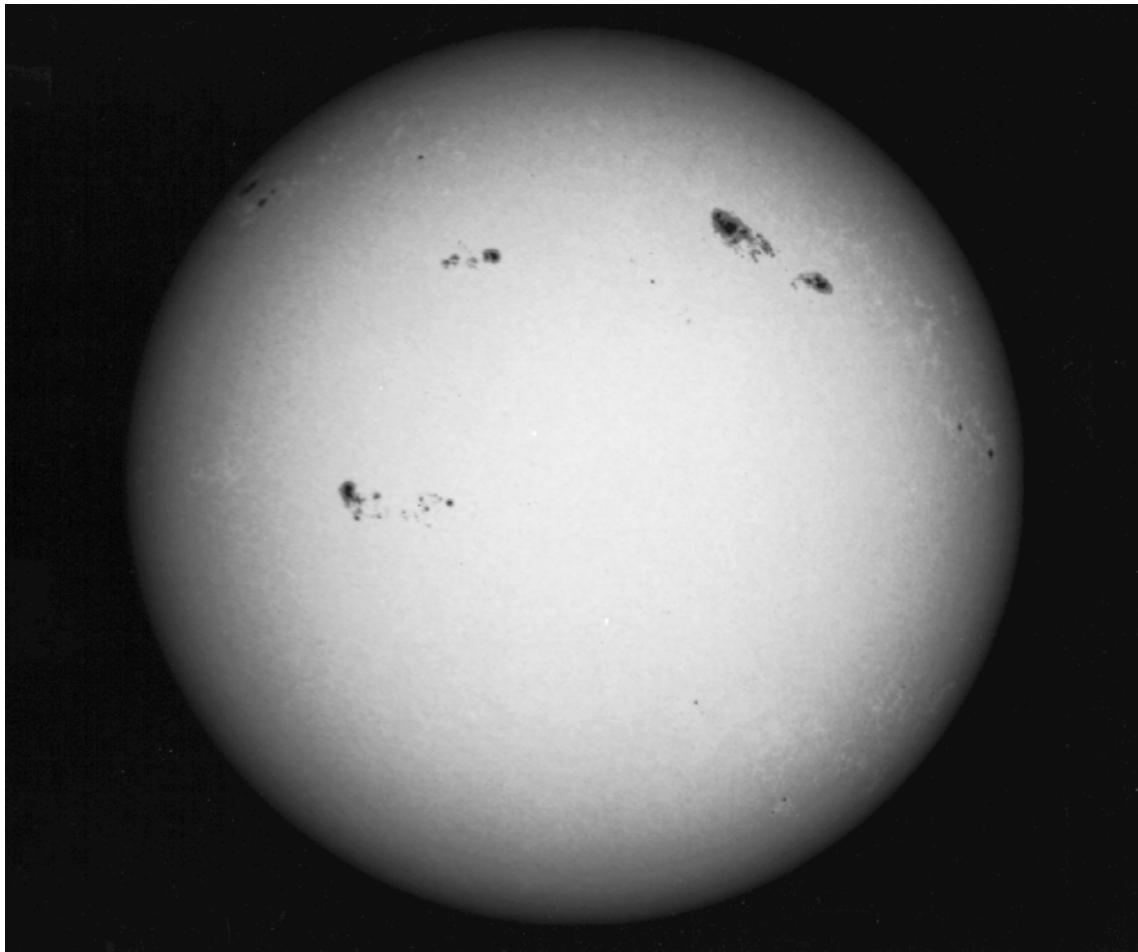
Deviazione maggiore dal corpo nero per le stelle A0

Indice di colore



- Il massimo numero di atomi di HI nel primo livello eccitato a $T=9900$ K
- Stelle A0
- Salto di Balmer (364,7 nm) è al centro della banda U
- Queste stelle sono meno luminose in U, quindi U-B più grande

Limb darkening, Sole



Limb darkening, Sole



Limb darkening, Sole

