INTRODUCTION TO THE SOLAR SPECTRUM

Robert J. Rutten

https://webspace.science.uu.nl/~rutte101

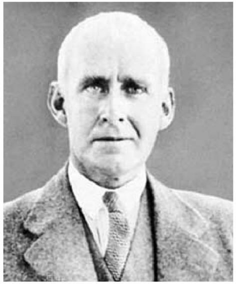
SOLAR CONTINUUM FORMATION

- Eddington's two clouds
- Planck function and approximations
- solar continuum and best-fit Planck curve
- Planck-inverse of the solar continuum
- solar photosphere opacity

SOLAR LINE FORMATION

- Fraunhofer's discovery
- all lines in the optical part
- Bohr sketch and Grotrian diagram for H
- emission and extinction of line photons
- formation of Fraunhofer lines

EDDINGTON’S TWO CLOUDS



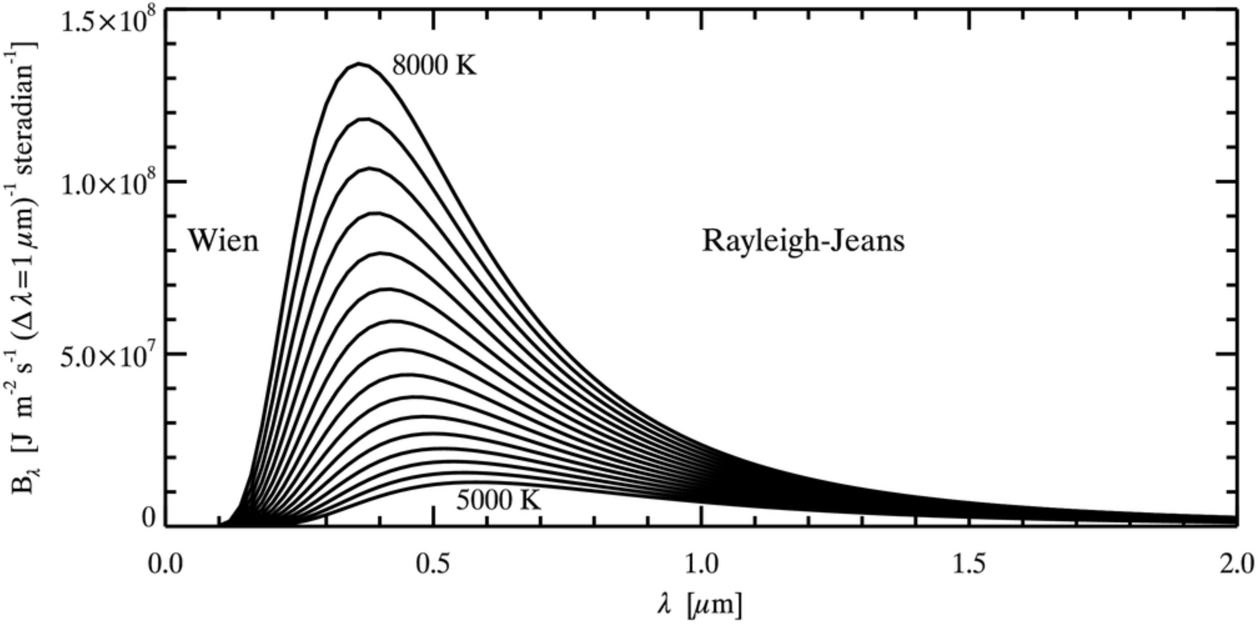
Arthur Stanley Eddington 1882–1944

“The Internal Constitution of the Stars” (1926)

- *concluding sentence*
  - “it is reasonable to hope that in a not too distant future we shall be competent to understand as simple a thing as a star.”
- *“two clouds obscure the theory of the stars”*
  - what is the source of the internal energy by which stars shine?
  - what is the source of the continuous opacity in the atmosphere?
- *answers for the Sun*
  - source of energy: fusion of hydrogen into helium in the solar core
  - source of opacity: H-minus extinction in the solar atmosphere

PLANCK FUNCTION AND APPROXIMATIONS

Planck function: $B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$

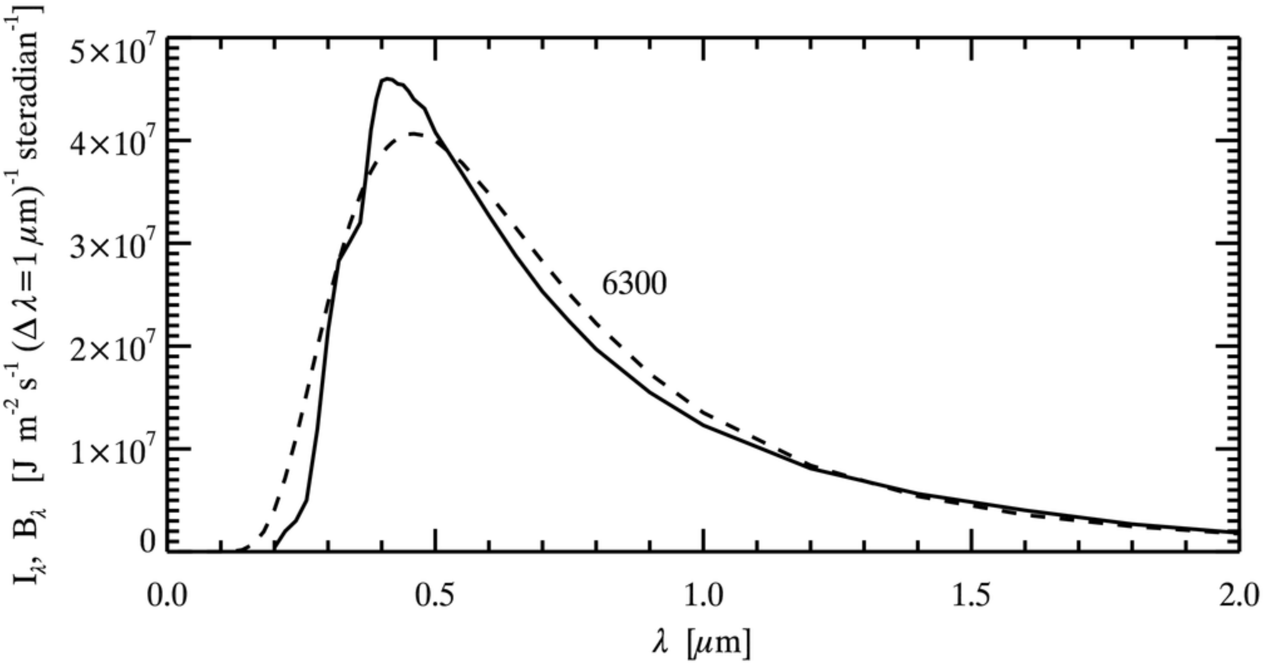


Wien approximation: $e^{hc/\lambda kT} \gg 1: \quad B_\lambda(T) \approx \frac{2hc^2}{\lambda^5} e^{-hc/\lambda kT}$

Rayleigh-Jeans approximation: $hc/\lambda kT \ll 1: \quad B_\lambda(T) \approx \frac{2ckT}{\lambda^4}$

The temperature sensitivity is exponential in the Wien part, linear in the Rayleigh-Jeans part.

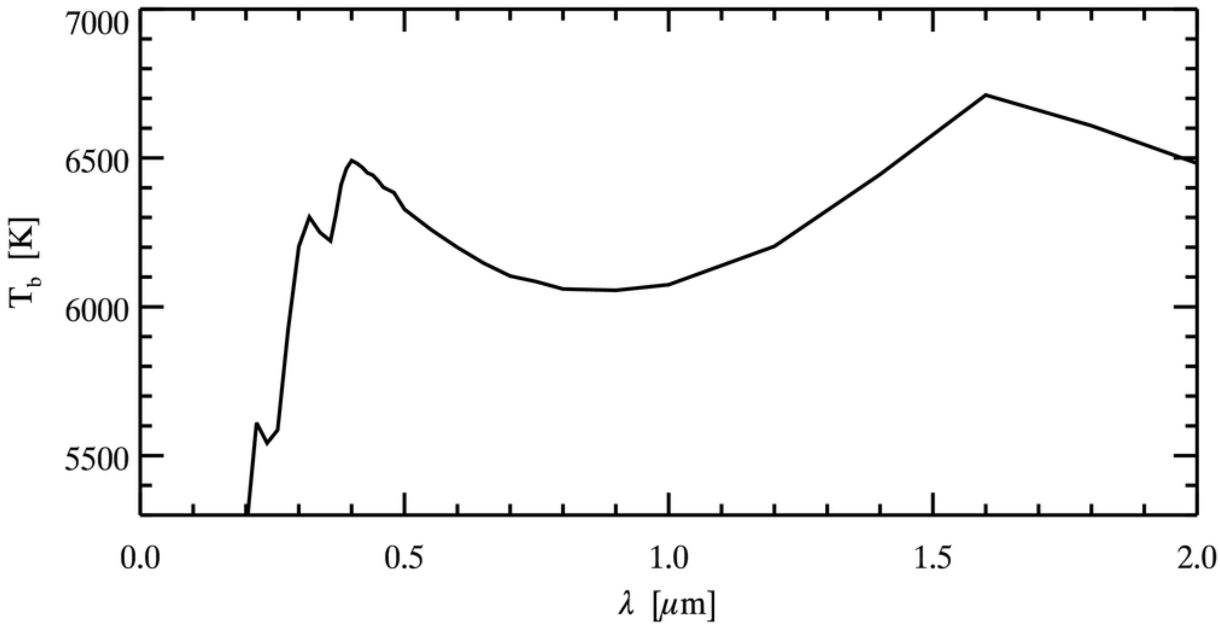
SOLAR SPECTRUM AND BEST-FIT PLANCK CURVE



Solid: solar disk-center continuum (high points between lines).
Dashed: Planck function $B_\lambda(T)$ for $T = 6300$ K.

At which wavelength is solar radiation hottest?

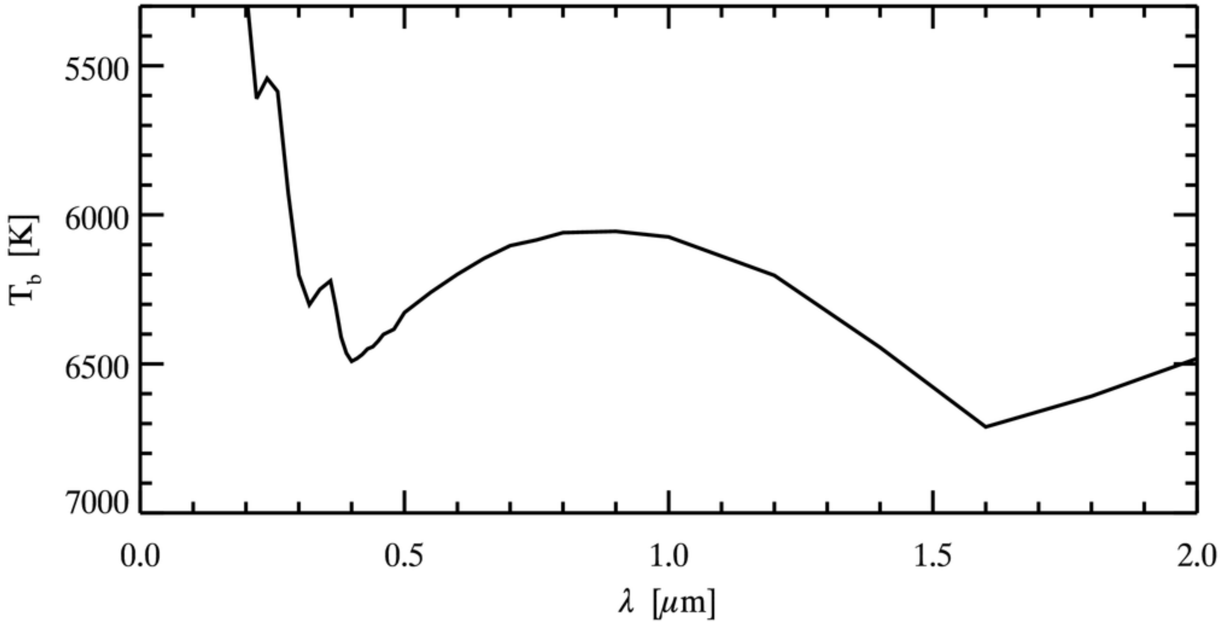
PLANCK INVERSE OF THE SOLAR SPECTRUM



Solar radiation brightness temperature T_b with $B_\lambda(T_b) \equiv I_{\rm sun}$, or $T_b = [B_\lambda]^{-1}(I_{\rm sun})$. This is a formal temperature. It equals the gas temperature where the radiation escapes when that radiation is given by the Planck function for that temperature. This is the case for $\lambda > 0.5$ μm.

Solar radiation is hottest at wavelength $\lambda = 1.6$ μm in the near infrared.

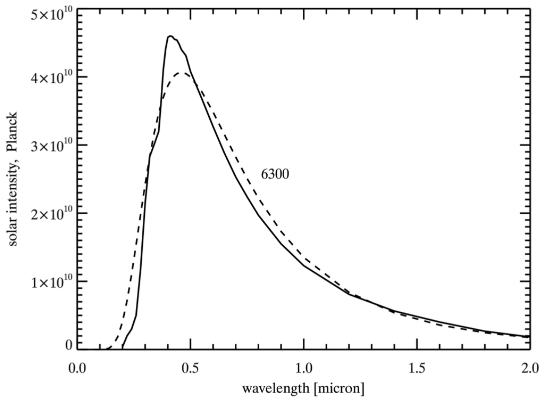
UPSIDE-DOWN PLANCK INVERSE OF THE SOLAR SPECTRUM

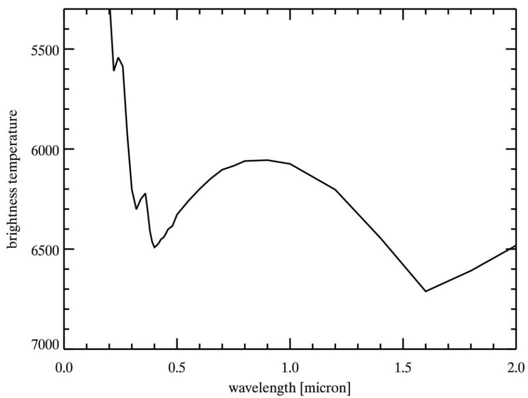


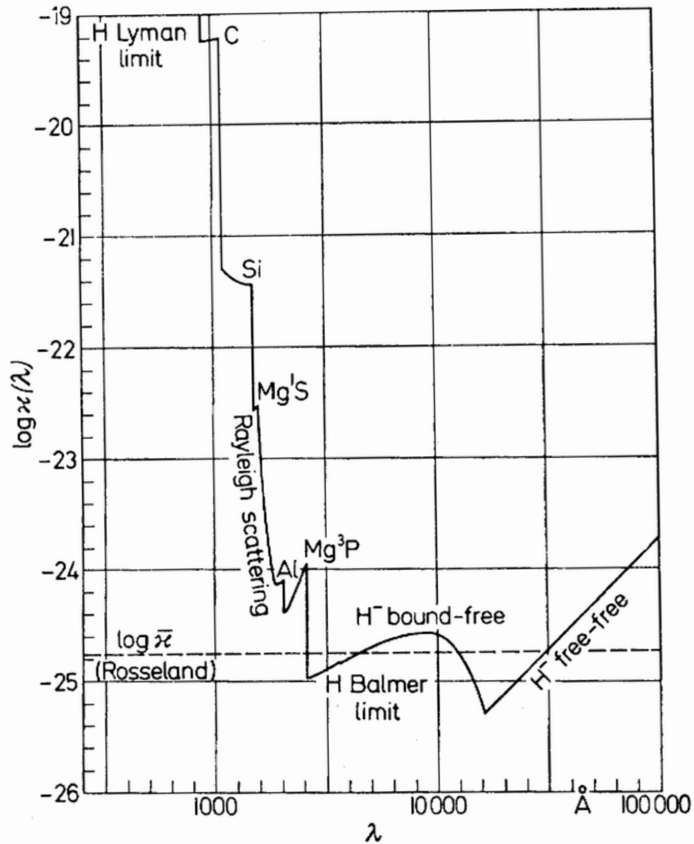
The temperature in the solar photosphere decreases with height, so that the brightness temperature of the escaping radiation is higher at wavelengths where it escapes deeper. This upside-down T_b graph shows that the solar gas is most opaque in the ultraviolet ($\lambda < 0.3$ μm). The opaqueness hump in the visible (0.4–0.8 μm) and near-infrared was a long-standing enigma until H^- (hydrogen with a second electron) was identified as major opacity source.

The solar gas is most transparent at the H^- "ionization" threshold wavelength of 1.6 μm.

SOLAR PHOTOSPHERE OPACITY







Right: photospheric gas opacity against wavelength (logarithmic), labeled with the processes causing it. Ultraviolet: ionization of C, Si, Mg, Al. Visible ($\lambda = 0.4 - 0.8\ \mu$m $= 4000 - 8000$ Å) and near infrared: H^- bound-free (H^- "ionization"). Far infrared: H^- free-free (acceleration of free electrons in the Coulomb field of neutral hydrogen atoms). From E. Böhm-Vitense.

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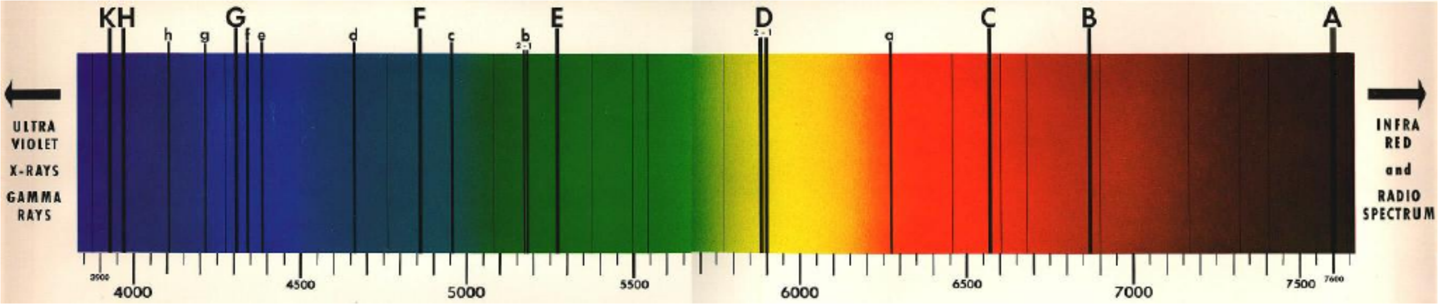
FRAUNHOFER'S DISCOVERY

http://en.wikipedia.org/wiki/Joseph_von_Fraunhofer

In 1814, Fraunhofer invented the spectroscope, and discovered 574 dark lines appearing in the solar spectrum. They are still called Fraunhofer lines. Kirchhoff and Bunsen showed in 1859 that they are atomic absorption features providing diagnostics-at-a-distance of the local conditions in the atmospheres of the Sun and other stars.



wavelength in Ångstrom; 1 Å = 0.1 nm

K & H: resonance lines of calcium ions

G: rotation-vibration band of CH molecules

F: Balmer-β line of hydrogen atoms

b: three lines of magnesium atoms

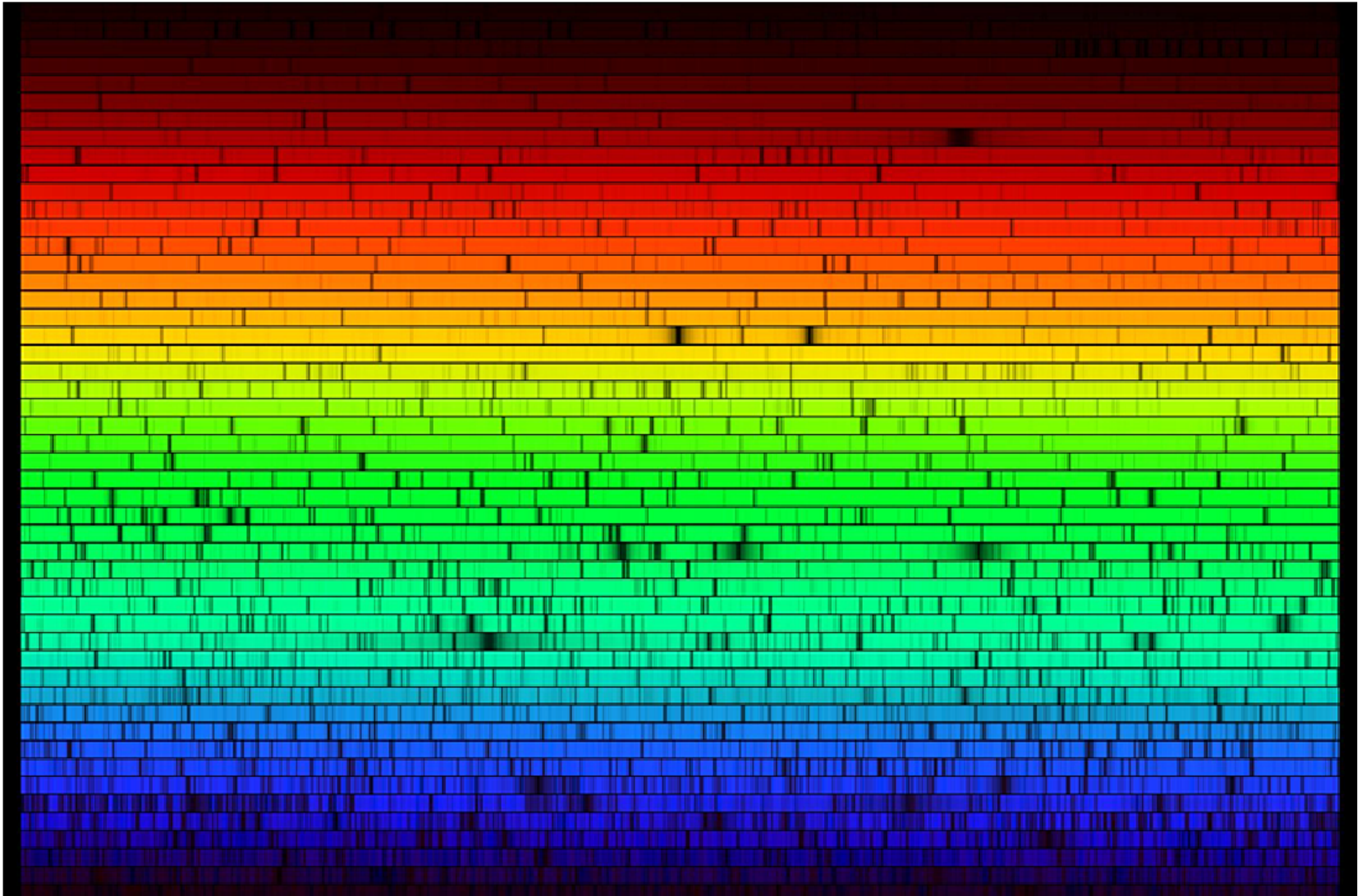
E: a group of lines of iron atoms

D: two resonance lines of sodium atoms (the same as in street lights)

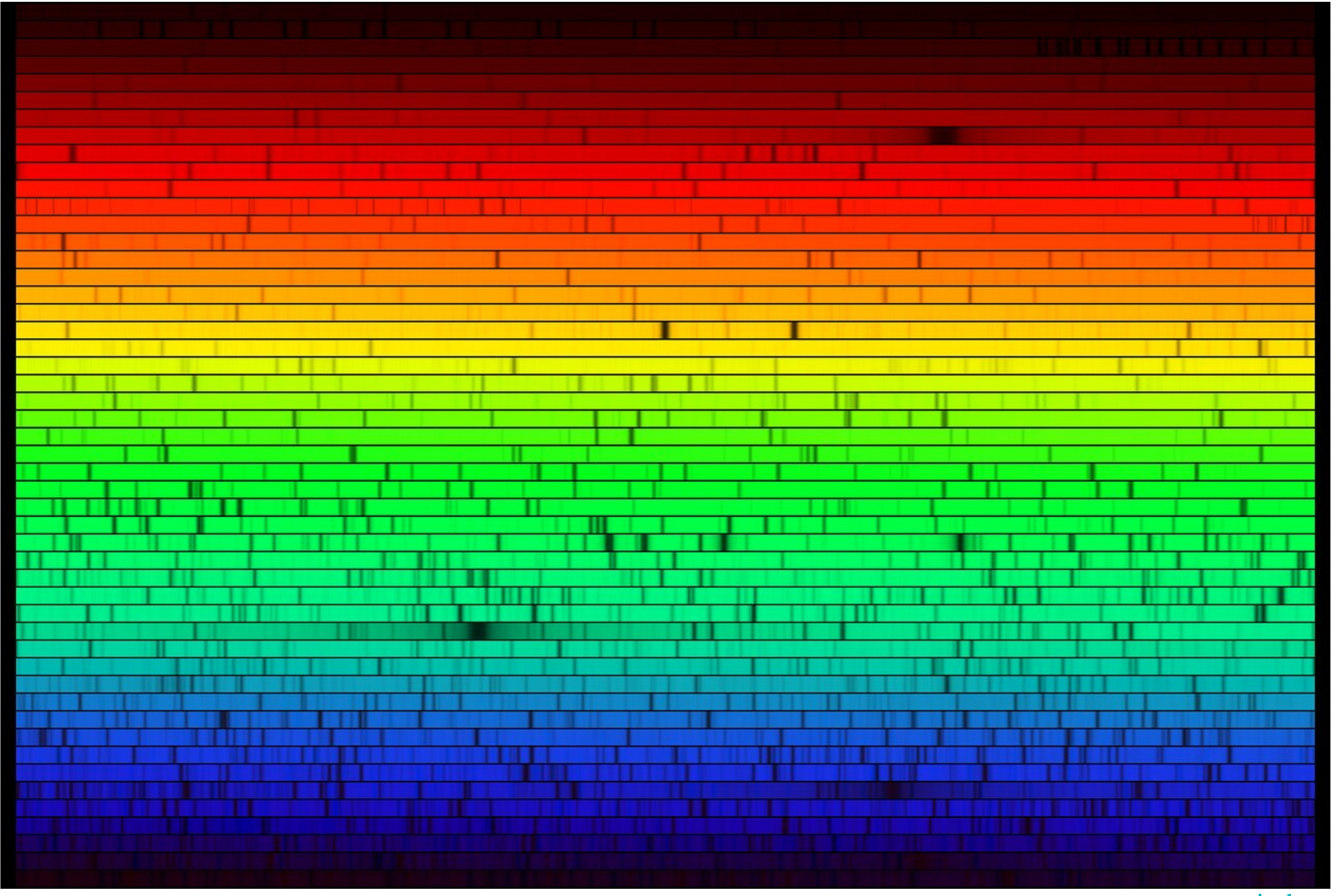
C: Balmer-α line of hydrogen atoms (Hα)

B & A: rotation-vibration band of oxygen molecules in the Earth atmosphere

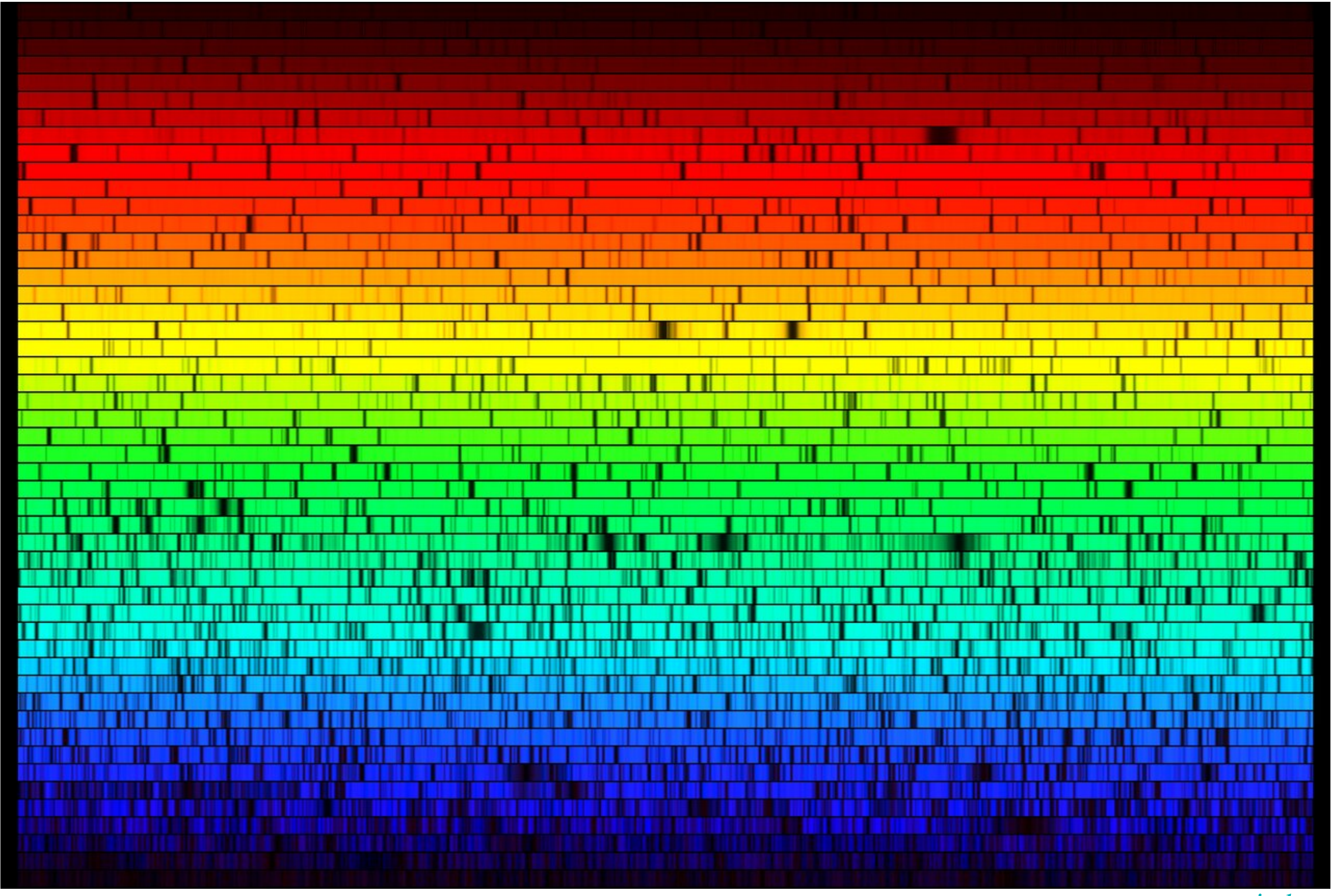
SOLAR SPECTRUM CUT IN RIBBONS



PROCYON α CMi F2

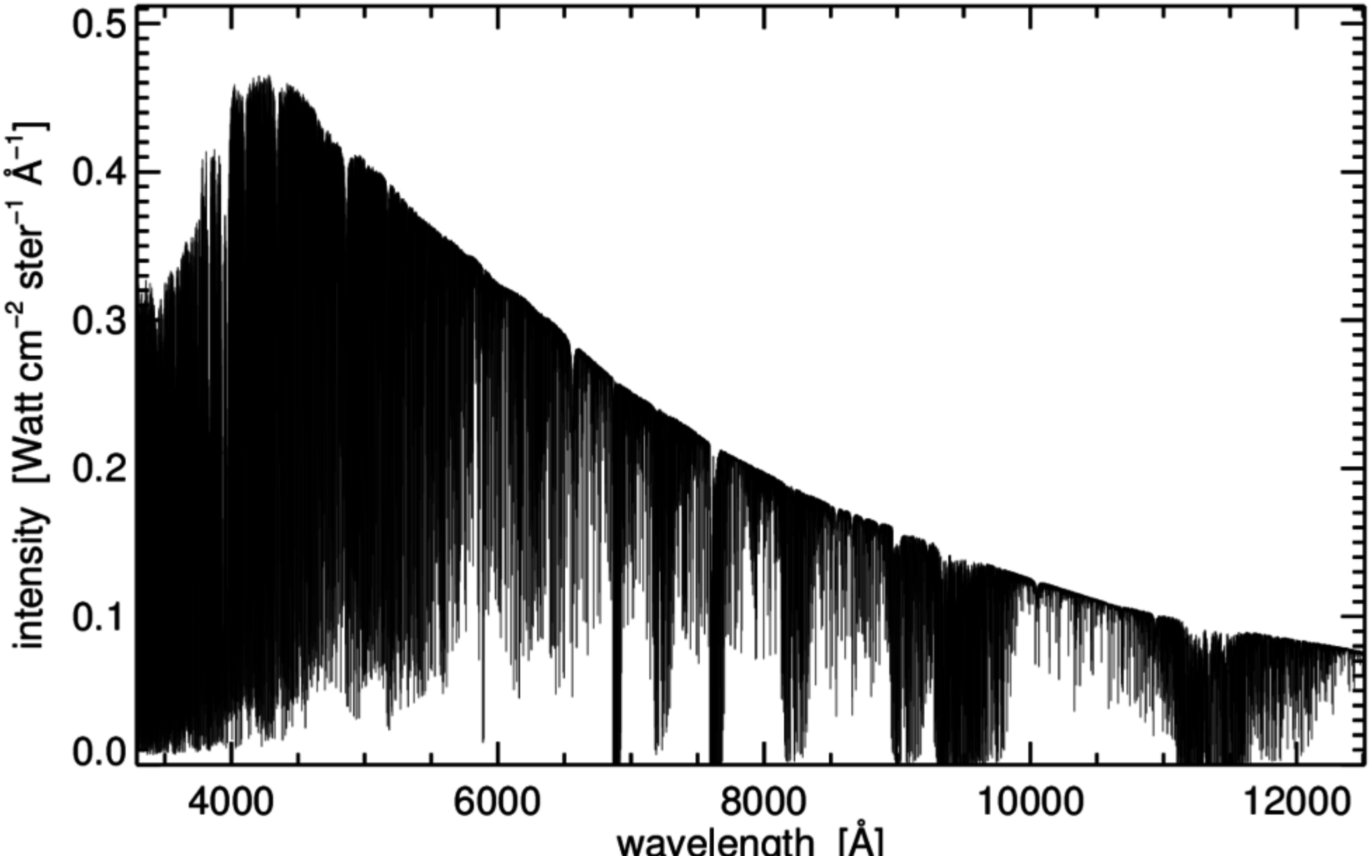


ARCTURUS α Boo K1 III



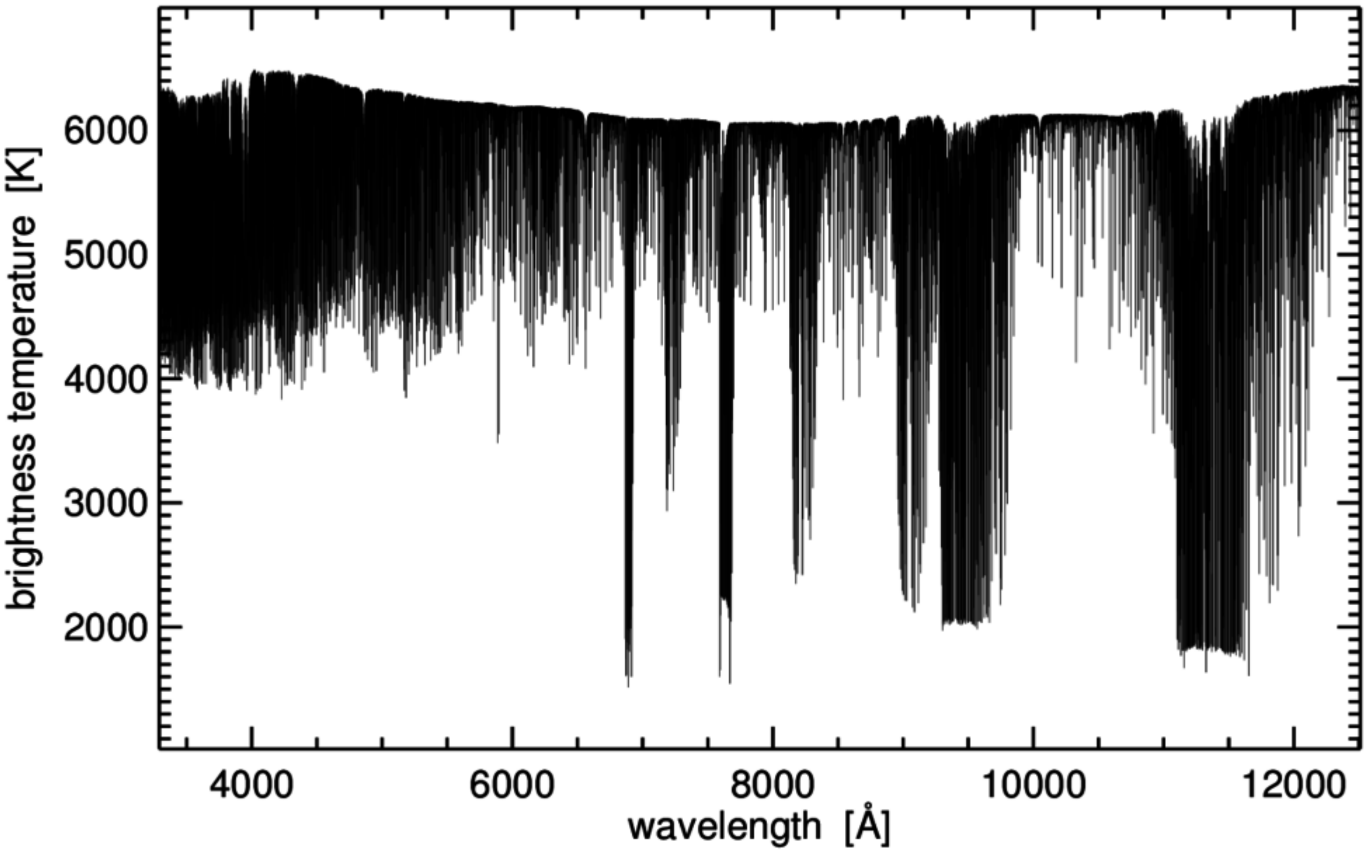
DISK-CENTER INTENSITY AT HIGH RESOLUTION

"Neckel atlas" Neckel & Labs *1984SoPh...90..205N* *[should be "Brault FTS atlas]"*



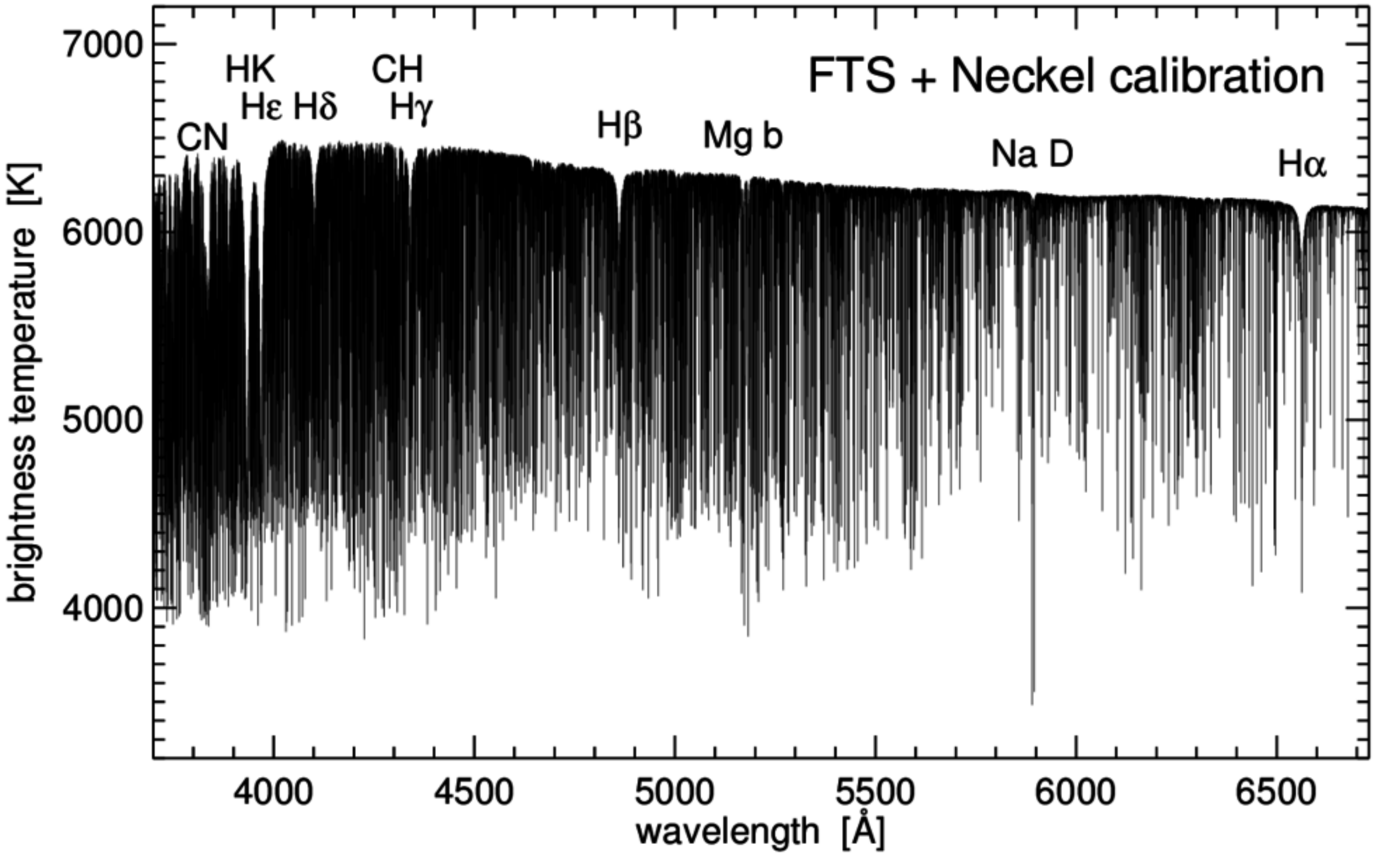
DISK-CENTER BRIGHTNESS TEMPERATURE

Non-scattering lines show $B_\lambda^{-1}(I_\lambda) \equiv T_b \approx T_e$ at their formation height



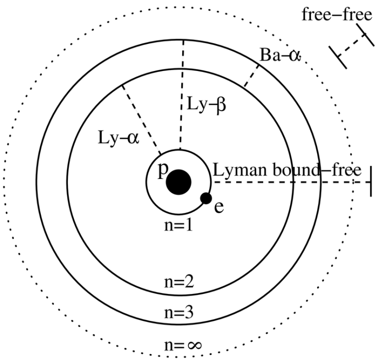
Which lines are telluric?

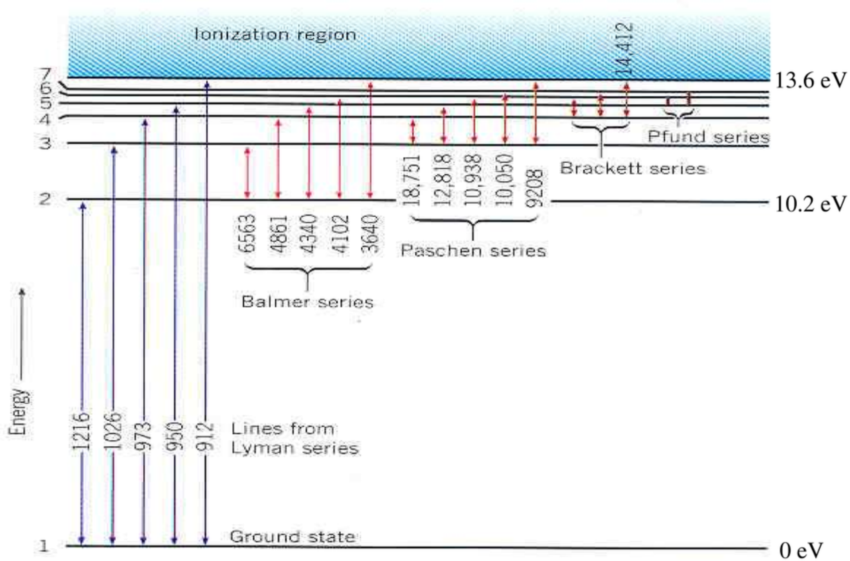
DISK-CENTER BRIGHTNESS TEMPERATURE – VISIBLE SPECTRUM



Na I D lines deepest *H I Balmer lines widest* *Ca II H & K strongest* *HeI lines absent*

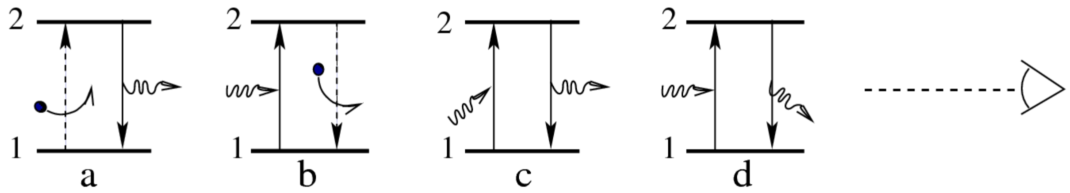
BOHR SKETCH AND GROTRIAN DIAGRAM FOR HYDROGEN





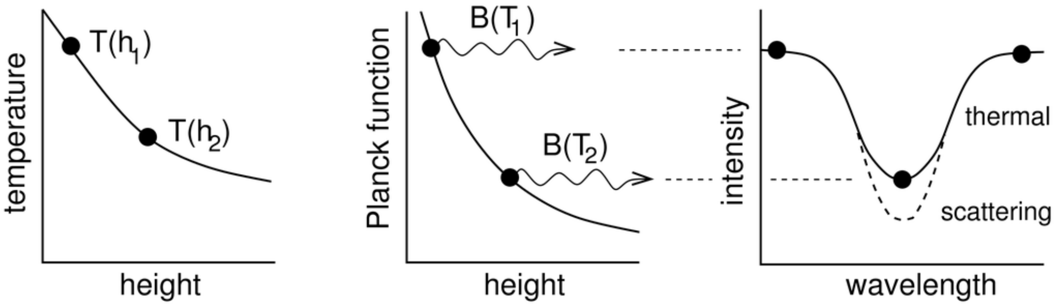
- Hydrogen atom: proton ($+$) and electron ($-$) in discrete orbits = "energy levels"
- Lyman lines: bound electron jumps between ground level n = 1 and higher ("excited") levels.
  Ly-α (1216 Å): between n = 1 and n = 2, Ly-β (1026 Å): n = 1 $\Leftrightarrow$ n = 3, etc.
- Balmer lines: bound electron jumps between n = 2 and higher levels.
  H α (6563 Å): n = 2 $\Leftrightarrow$ n = 3, H β (4861 Å): n = 2 $\Leftrightarrow$ n = 4, etc.
- Bound-free: electron loss = ionization, electron catch by a naked proton = recombination.
  n = 1: Lyman continuum ($\leq$ 912 Å), n = 2: Balmer continuum ($\leq$ 3640 Å), etc.
- Free-free: trajectory change of a free electron near a proton (H ff) or hydrogen atom (H^- ff)

EMISSION AND EXTINCTION OF LINE PHOTONS



- Excitation up occurs either through absorption of a photon with the correct energy (corresponding wavelength), or through loss of kinetic energy in a particle collision.
- Deexcitation down occurs either through emission of a photon at the line wavelength, or through gain of kinetic energy in a particle collision.
- Pair a: collisional excitation followed by emission of a photon in the viewing direction (to the right) = thermal creation of a new photon in the beam to the observer.
- Pair b: absorption of a photon in the viewing direction followed by collisional deexcitation = thermal destruction of an existing photon in the beam to the observer.
- Pair c: photon scattering into the beam to the observer, counts as emission.
- Pair d: photon scattering out of the beam to the oberver, counts as extinction.
- Line source function S_λ: the amount of new beam-photon emission (a+c) normalized by the probability of beam-photon extinction (b+d).
- When there are more collisional jumps then radiative jumps, both up and down, then the emission and extinction are set thermally with $S_\lambda \approx B_\lambda(T)$, with B_λ the Planck function for the local temperature. When scattering dominates $S_\lambda \approx J_\lambda$, with J_λ the mean intensity of the locally impinging photons averaged over all directions.

FORMATION OF FRAUNHOFER LINES



- Spectral lines are due to valence-electron jumps between two discrete energy levels, causing additional emission and extinction only at the line wavelength.
- The extra photon extinction at the line wavelength makes the gas less transparent than at neighboring wavelengths. Therefore, at the line wavelength the solar radiation escapes further out (at larger height in the solar atmosphere).
- The intensity of the escaping radiation is given by the Planck function for the local temperature if frequent collisions couple the source function to the local gas kinetics. This is the case in deep layers where the gas density is high.
- The temperature decreases with height through the solar photosphere. It is lower at the larger height where the radiation at the line wavelength escapes, making the resulting Fraunhofer line dark with respect to nearby wavelengths.
- The darkest lines are formed the furthest out. The low gas density at large height makes scattering dominate over thermal control. It darkens the lines yet more.
- The bell shape of the Fraunhofer lines is caused by the Dopplershifts imposed by atomic motions and by particle collisions in the solar gas.

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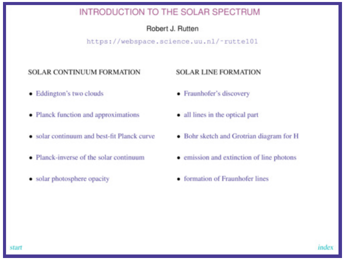
1

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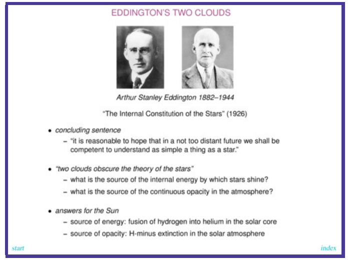
EDDINGTON'S TWO CLOUDS
Arthur Stanley Eddington 1882–1944
"The Internal Constitution of the Stars" (1926)
concluding sentence
– "it is reasonable to hope that in a not too distant future we shall be competent to understand as simple a thing as a star."
"two clouds obscure the theory of the stars"
– what is the source of the internal energy by which stars shine?
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answers for the Sun
– source of energy: fusion of hydrogen into helium in the solar core
– source of opacity: H-minus extinction in the solar atmosphere
start
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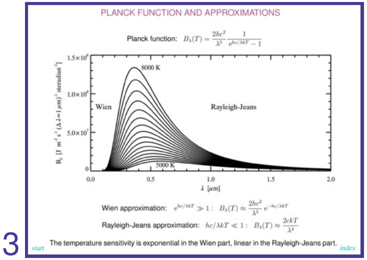
3

PLANCK FUNCTION AND APPROXIMATIONS
Planck function: $B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1}$
8000 K
Wien
Rayleigh-Jeans
5000 K
λ [μm]
Wien approximation: $e^{hc/\lambda kT} \gg 1: \; B_\lambda(T) \approx \frac{2hc^2}{\lambda^5} e^{-hc/\lambda kT}$
Rayleigh-Jeans approximation: $hc/\lambda kT \ll 1: \; B_\lambda(T) \approx \frac{2ckT}{\lambda^4}$
The temperature sensitivity is exponential in the Wien part, linear in the Rayleigh-Jeans part.
start
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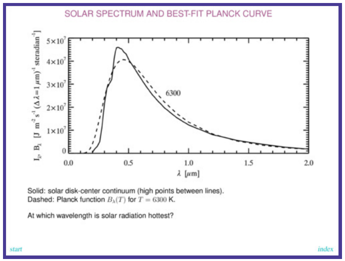
4

SOLAR SPECTRUM AND BEST-FIT PLANCK CURVE
6300
λ [μm]
Solid: solar disk-center continuum (high points between lines).
Dashed: Planck function $B_\lambda(T)$ for $T = 6300$ K.
At which wavelength is solar radiation hottest?
start
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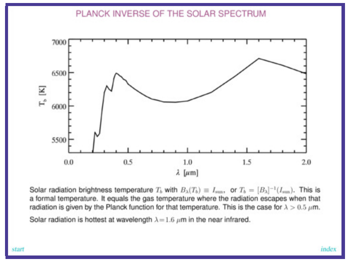
5

PLANCK INVERSE OF THE SOLAR SPECTRUM
T_b [K]
λ [μm]
Solar radiation brightness temperature T_b with $B_\lambda(T_b) \equiv I_{\rm cont}$, or $T_b = [B_\lambda]^{-1}(I_{\rm cont})$. This is a formal temperature. It equals the gas temperature where the radiation escapes when that radiation is given by the Planck function for that temperature. This is the case for $\lambda > 0.5\,\mu$m.
Solar radiation is hottest at wavelength $\lambda = 1.6\,\mu$m in the near infrared.
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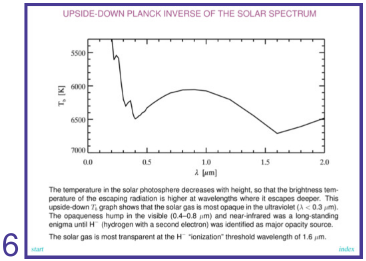
UPSIDE-DOWN PLANCK INVERSE OF THE SOLAR SPECTRUM
T_b [K]
λ [μm]
The temperature in the solar photosphere decreases with height, so that the brightness temperature of the escaping radiation is higher at wavelengths where it escapes deeper. This upside-down T_b graph shows that the solar gas is most opaque in the ultraviolet ($\lambda < 0.3\,\mu$m). The opaqueness hump in the visible (0.4–0.8 μm) and near-infrared was a long-standing enigma until H^- (hydrogen with a second electron) was identified as major opacity source.
The solar gas is most transparent at the H^- "ionization" threshold wavelength of 1.6 μm.
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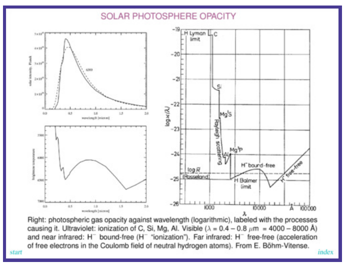
SOLAR PHOTOSPHERE OPACITY
H Lyman limit
Rayleigh scattering
H^- bound-free
H Balmer limit
H^- free-free
log R Rosseland
Right: photospheric gas opacity against wavelength (logarithmic), labeled with the processes causing it. Ultraviolet: ionization of C, Si, Mg, Al. Visible (λ = 0.4 – 0.8 μm = 4000 – 8000 Å) and near infrared: H^- bound-free (H^- "ionization"). Far infrared: H^- free-free (acceleration of free electrons in the Coulomb field of neutral hydrogen atoms). From E. Böhm-Vitense.
start
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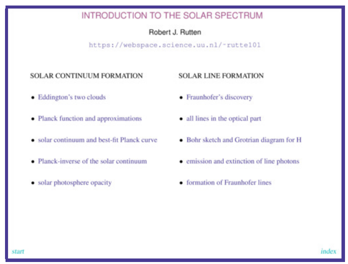
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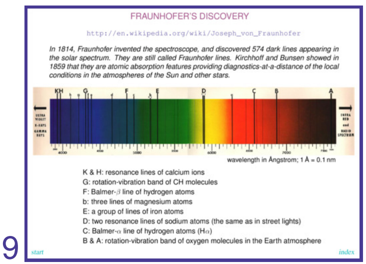
FRAUNHOFER'S DISCOVERY
http://en.wikipedia.org/wiki/Joseph_von_Fraunhofer
In 1814, Fraunhofer invented the spectroscope, and discovered 574 dark lines appearing in the solar spectrum. They are still called Fraunhofer lines. Kirchhoff and Bunsen showed in 1859 that they are atomic absorption features providing diagnostics-at-a-distance of the local conditions in the atmospheres of the Sun and other stars.
KH G F E D C B A
wavelength in Ångstrom; 1 Å = 0.1 nm
K & H: resonance lines of calcium ions
G: rotation-vibration band of CH molecules
F: Balmer-β line of hydrogen atoms
b: three lines of magnesium atoms
E: a group of lines of iron atoms
D: two resonance lines of sodium atoms (the same as in street lights)
C: Balmer-α line of hydrogen atoms (Hα)
B & A: rotation-vibration band of oxygen molecules in the Earth atmosphere
start
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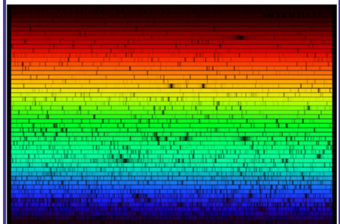
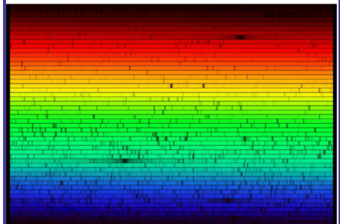
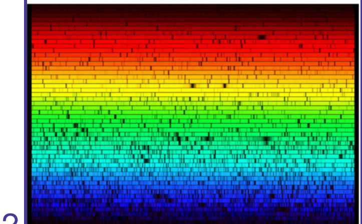
SOLAR SPECTRUM CUT IN RIBBONS



PROCYON α CMi F2

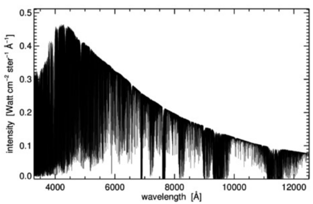


ARCTURUS α Boo K1 III



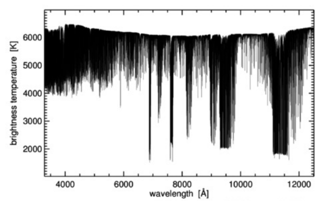
DISK-CENTER INTENSITY AT HIGH RESOLUTION

"Neckel atlas" Neckel & Labs 1984SoPh...90..205N [should be "Brault FTS atlas"]



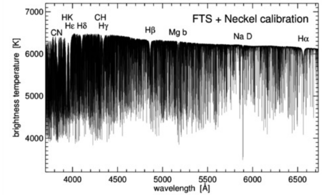
DISK-CENTER BRIGHTNESS TEMPERATURE

Non-scattering lines show $B_\lambda^{-1}(I_\lambda) \equiv T_b \approx T_e$ at their formation height



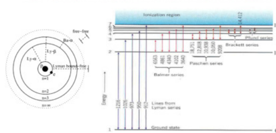
Which lines are telluric?

DISK-CENTER BRIGHTNESS TEMPERATURE – VISIBLE SPECTRUM



Na I D lines deepest   H I Balmer lines widest   Ca II H & K strongest   He I lines absent

BOHR SKETCH AND GROTRIAN DIAGRAM FOR HYDROGEN



- Hydrogen atom: proton (+) and electron (−) in discrete orbits = "energy levels"
- Lyman lines: bound electron jumps between ground level n = 1 and higher ("excited") levels. Ly-α (1216 Å): between n = 1 and n = 2, Ly-β (1026 Å): n = 1 ⇔ n = 3, etc.
- Balmer lines: bound electron jumps between n = 2 and higher levels. Hα (6563 Å): n = 2 ⇔ n = 3, Hβ (4861 Å): n = 2 ⇔ n = 4, etc.
- Bound-free: electron loss = ionization, electron catch by a naked proton = recombination. n = 1: Lyman continuum ($\leq$ 912 Å), n = 2: Balmer continuum ($\leq$ 3640 Å), etc.
- Free-free: trajectory change of a free electron near a proton (H ff) or hydrogen atom (H$^-$ ff)

EMISSION AND EXTINCTION OF LINE PHOTONS

- Excitation up occurs either through absorption of a photon with the correct energy (corresponding wavelength), or through loss of kinetic energy in a particle collision.
- Deexcitation down occurs either through emission of a photon at the line wavelength, or through gain of kinetic energy in a particle collision.
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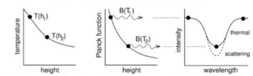
- Pair c: photon scattering into the beam to the observer, counts as emission.
- Pair d: photon scattering out of the beam to the oberver, counts as extinction.
- Line source function S_λ: the amount of new beam-photon emission (a+c) normalized by the probability of beam-photon extinction (b+d).
- When there are more collisional jumps then radiative jumps, both up and down, then the emission and extinction are set thermally with $S_\lambda \approx B_\lambda(T)$, with B_λ the Planck function for the local temperature. When scattering dominates $S_\lambda \approx J_\lambda$, with J_λ the mean intensity of the locally impinging photons averaged over all directions.

FORMATION OF FRAUNHOFER LINES



- Spectral lines are due to valence-electron jumps between two discrete energy levels, causing additional emission and extinction only at the line wavelength.
- The extra photon extinction at the line wavelength makes the gas less transparent than at neighboring wavelengths. Therefore, at the line wavelength the solar radiation escapes further out (at larger height in the solar atmosphere).
- The intensity of the escaping radiation is given by the Planck function for the local temperature if frequent collisions couple the source function to the local gas kinetics. This is the case in deep layers where the gas density is high.
- The temperature decreases with height through the solar photosphere. It is lower at the larger height where the radiation at the line wavelength escapes, making the resulting Fraunhofer line dark with respect to nearby wavelengths.
- The darkest lines are formed the furthest out. The low gas density at large height makes scattering dominate over thermal control. It darkens the lines yet more.
- The bell shape of the Fraunhofer lines is caused by the Dopplershifts imposed by atomic motions and by particle collisions in the solar gas.

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INTRODUCTION TO THE SOLAR SPECTRUM

Robert J. Rutten

https://webspace.science.uu.nl/~rutte101

SOLAR CONTINUUM FORMATION

- Eddington's two clouds
- Planck function and approximations
- solar continuum and best-fit Planck curve
- Planck-inverse of the solar continuum
- solar photosphere opacity

SOLAR LINE FORMATION

- Fraunhofer's discovery
- all lines in the optical part
- Bohr sketch and Grotrian diagram for H
- emission and extinction of line photons
- formation of Fraunhofer lines

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