INTRODUCTION TO THE SOLAR SPECTRUM

Robert J. Rutten

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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:  
\[ e^{hc/\lambda kT} \gg 1 : B_\lambda(T) \approx \frac{2hc^2}{\lambda^5} e^{-hc/\lambda kT} \]

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.
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?
Solar radiation brightness temperature $T_b$ with $B_\lambda(T_b) \equiv I_{\text{sun}}$, or $T_b = [B_\lambda]^{-1}(I_{\text{sun}})$. 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 $\lambda > 0.5 \ \mu m$.

Solar radiation is hottest at wavelength $\lambda = 1.6 \ \mu m$ in the near infrared.
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 $\mu$m) and near-infrared was a long-standing enigma until $H^- \ (\text{hydrogen with a second electron})$ was identified as major opacity source.

The solar gas is most transparent at the $H^-$ “ionization” threshold wavelength of 1.6 $\mu$m.
SOLAR PHOTOSPHERE OPACITY

Right: photospheric gas opacity against wavelength (logarithmic), labeled with the processes causing it. Ultraviolet: ionization of C, Si, Mg, Al. Visible ($\lambda = 0.4 - 0.8 \mu m = 4000 - 8000 \text{ Å}$) 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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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.

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
DISK-CENTER INTENSITY AT HIGH RESOLUTION

“Neckel atlas” Neckel & Labs 1984SoPh...90..205N [should be “Brault FTS atlas"]
Non-scattering lines show $B^{-1}_\lambda(I_\lambda) \equiv T_b \approx T_e$ at their formation height.
Na I D lines deepest  H I Balmer lines widest  Ca II H & K strongest  HeI lines absent
• 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-$\alpha$ (1216 Å): between $n=1$ and $n=2$, Ly-$\beta$ (1026 Å): $n=1 \leftrightarrow n=3$, etc.

• Balmer lines: bound electron jumps between $n=2$ and higher levels. H$\alpha$ (6563 Å): $n=2 \leftrightarrow n=3$, H$\beta$ (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 observer, counts as extinction.

• Line source function $S_\lambda$: 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 $B_\lambda$ the Planck function for the local temperature. When scattering dominates $S_\lambda \approx J_\lambda$, with $J_\lambda$ the mean intensity of the locally impinging photons averaged over all directions.
• 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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