PHYSICS OF (ECLIPSED) SUNSHINE

Rob Rutten

BUCKET LIST

Rob Rutten

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March 20 2015

http://www.staff.science.uu.nl/~rutte101   (google "rob rutten website")

employment
1963 – 2007: Utrecht University, The Netherlands
2002 – 2007: Oslo University, Norway
2007 – present: retired but active (excepting totality)

research: solar chromosphere (spectrum, structure, dynamics)
teaching: solar and stellar spectrum formation

eclipse flash spectrometry as student

May 20 1966 Greece	Nov 12 1966 Brazil	Mar 7 1970 Mexico

eclipse flash observation as tourist

Jul 11 1991 Mexico	Aug 11 1999 Hungary	Jun 21 2001 Zambia
Mar 29 2006 Libya	Aug 1 2008 Mongolia	Jul 21 2009 China
Nov 14 2012 Australia	[Mar 20 2015 Faroe]	Mar 9 2016 Indonesia
Aug 21 2017 USA	Jul 2 2019 Argentina	

FROM WHITE TO COLOR

comet-made molten-rock Manicouagan Reservoir, Quebec, August 2006

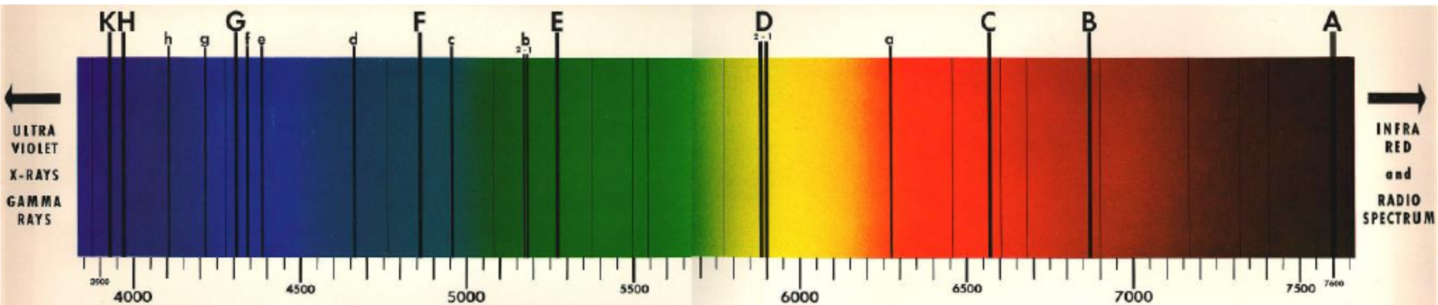
- rain droplets disperse sunlight across wavelength as reflective prisms
- visible sunlight is a continuum made up of violet – blue – green – yellow - red
- "white light" = sum of colors with "radiation temperature" about 6000 C
- just as white-hot iron, the solar photosphere ("surface") is about 6000 C

Appreciate that bluish stars (Sirius) are hotter, reddish stars (Betelgeuse) are cooler

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

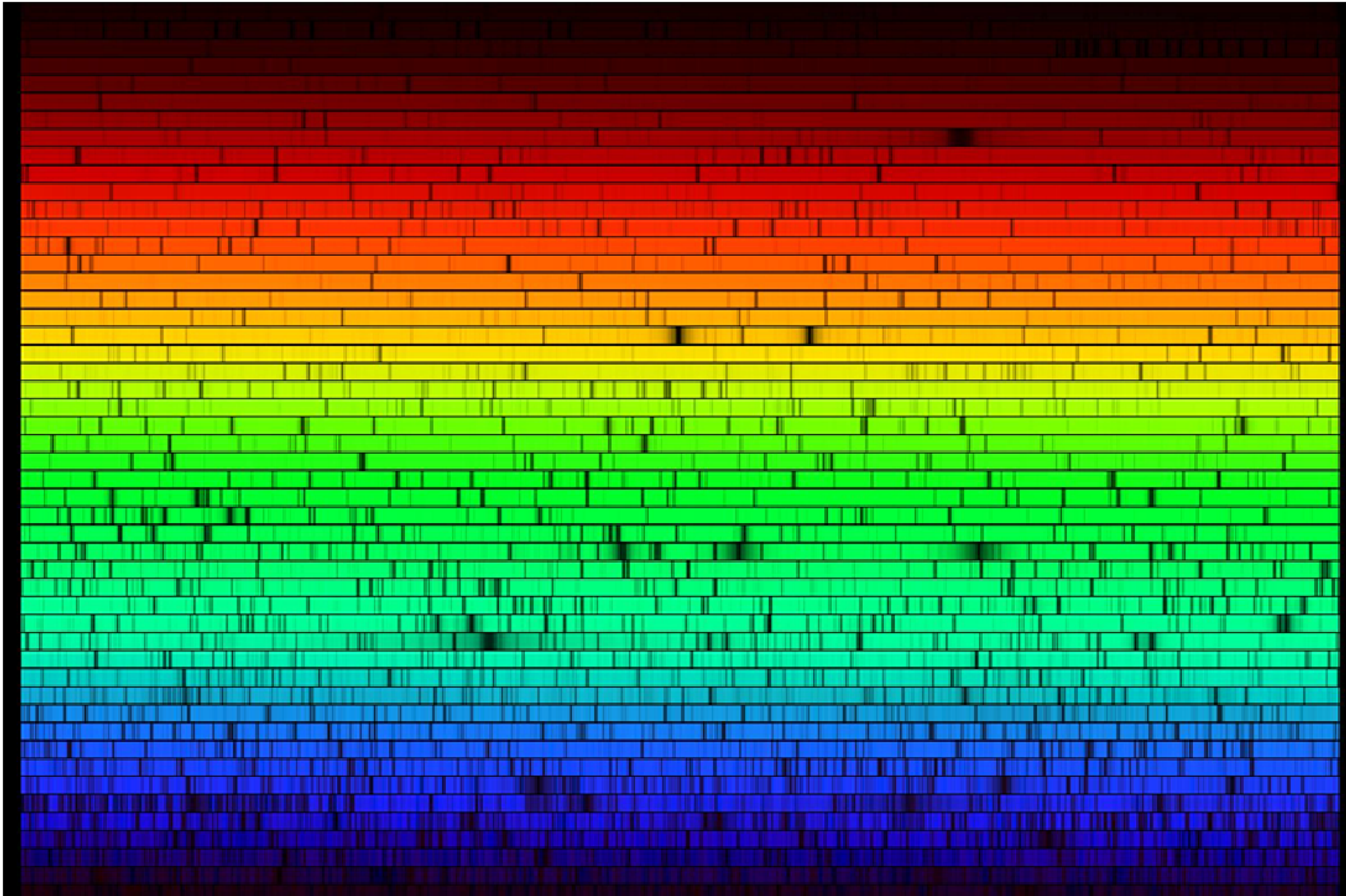
E: a group of lines of iron atoms

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



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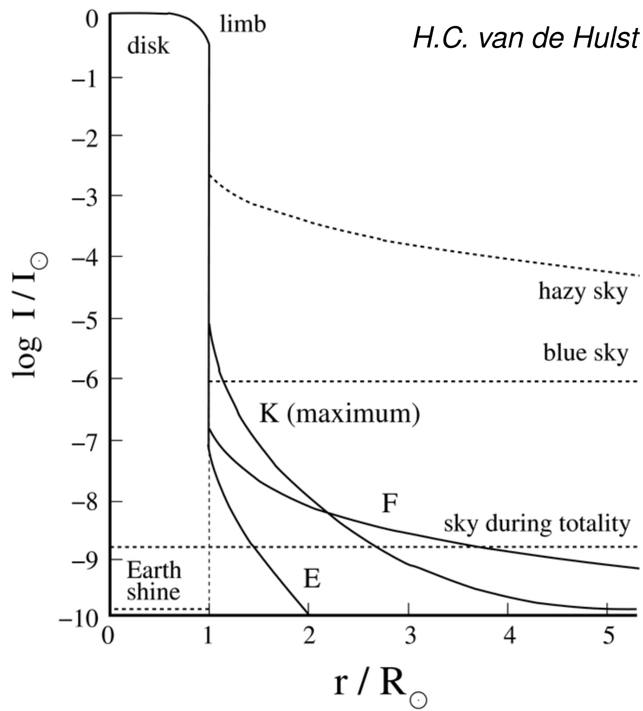
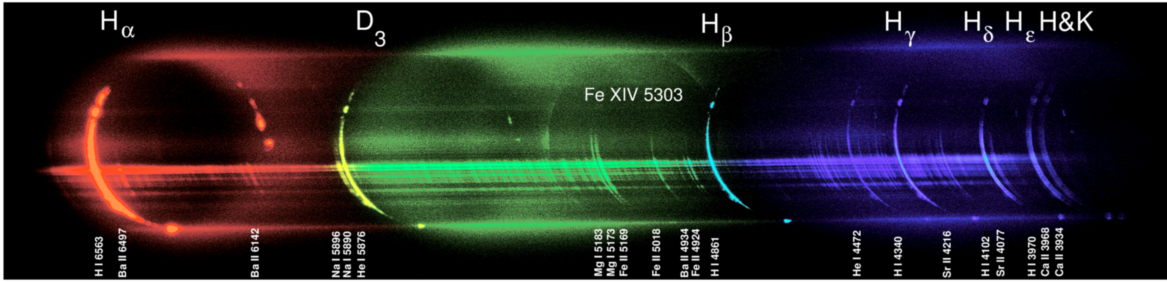
SOLAR ECLIPSE VISIBILITY

P. den Hartog



- dusty sky has 0.1 – 0.01% of the solar brighness (10^{-3} – 10^{-4}), brighter closer to Sun
- "coronal" blue sky (Rayleigh scattering) is one millionth (10^{-6}), even distribution across sky
- during totality the sky brightness is only one billionth (10^{-9}), less than the coronal brightness
- "K" = continuum component, "F" = Fraunhofer component, "E" = emission-line component
- earthshine (10^{-10}): new-moon brightness from full-earth-with-spot irradiation

ECLIPSE CHROMOSPHERE

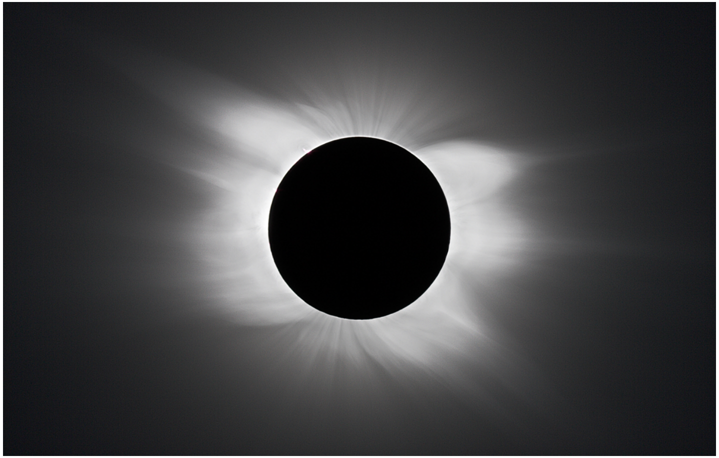


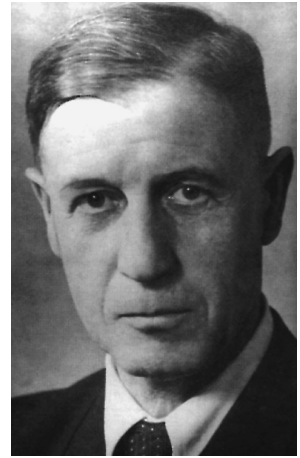
EurAstro Team Szeged I *August 11, 1999*

- *chromosphere = purple rim just after second contact and just before third contact. Name given by Norman Lockyer 1868, outside eclipse; Jules Janssen saw it first, two days after the August 18 1868 eclipse. The chromospheric "flash" spectrum contains:*
  - H I Balmer lines: Hα, Hβ, Hγ, Hδ, Hϵ
  - He I D_3 (name "helios" also from Lockyer while Janssen discovered it first)
  - Ca II H & K
  - weaker: Na I D_1 & D_2 (left of D_3), lines of Mg I, Fe II, Sr II, Ba II
- *chromosphere enigma*
  - spatial extent (purple rim width) $\gg$ equilibrum scale height $\Rightarrow$ highly dynamic
  - both hot (He I D_3) and cool (Na I D_1 & D_2) $\Rightarrow$ highly inhomogeneous
  - "the most difficult domain of the solar atmosphere"

Appreciate that when you see the chromosphere you see the intrinsic color of the stuff the Universe is made of: hydrogen and a bit of helium!

CORONAL WHITE LIGHT

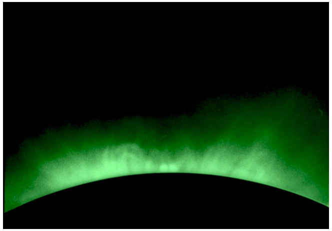




- Walter Grotrian (Potsdam, 1931)
  white $\Rightarrow$ Thomson scattering of photospheric photons by free electrons
  weak $\Rightarrow$ low electron density (electron cross-section only 10^{-25} cm^2)
  absence of photospheric Fraunhofer lines $\Rightarrow$ washed out by large Dopplershifts
  required electron speeds 4000 km/s [$\Rightarrow$ if motions thermal: 1 million degrees !?]
- linear polarisation from right-angle scattering
- fine structure maps variatons in electron density dictated by magnetic fields
- the F component further out results from photon scattering by slower-moving interplanetary dust particles; its spectrum shows the photospheric Fraunhofer lines

Appreciate that during totality you are illuminated by normal photospheric light — but only a 10^{-7} fraction bounced around the moon, without Fraunhofer lines, and polarized too!

“CORONIUM” LINES



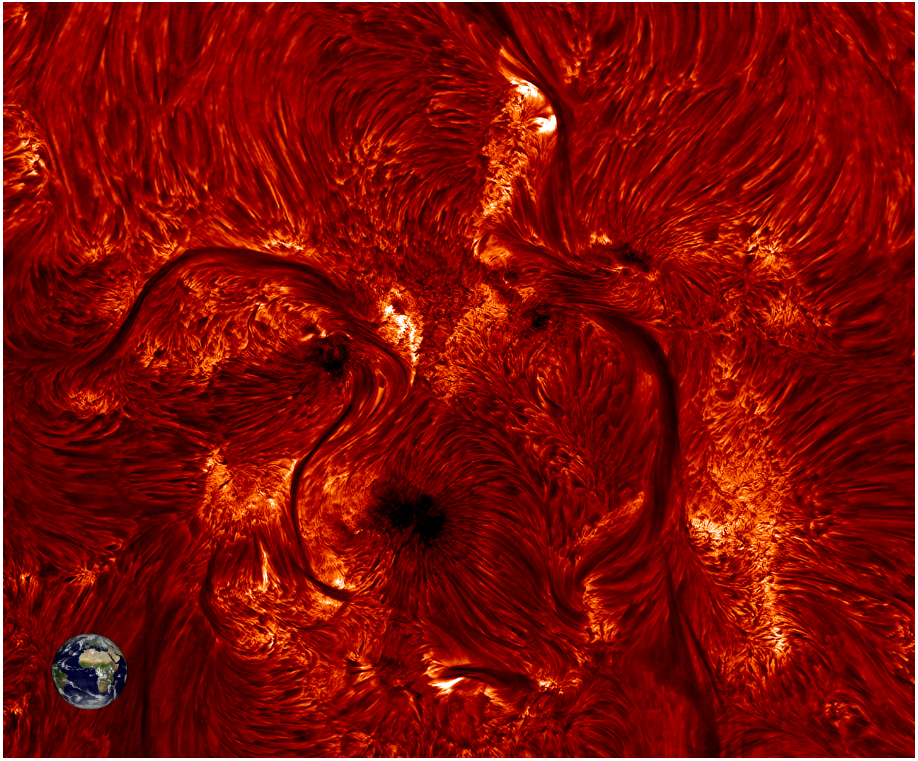
narrow-band totality image 5302.9 Å

The coronal spectrum during totality is a continuum with a few bright lines initially ascribed to an element “coronium”. However, in 1939 Grotrian suggested that two lines are transitions of highly ionized iron, suggesting an “ionization temperature” of 1 million degrees. In 1942 Edlén identified nineteen lines, proving that the corona is indeed very hot. The large electron speeds washing out the Fraunhofer lines are thermal motions. The third proof of high temperature, also in 1942, was the detection of thermal solar radiation at long (1 m) radio wavelengths.

name	wavelength	identification
green line	5302.9 Å	Fe XIV
yellow line	5694.5 Å	Ca XV
red line	6374.5 Å	Fe XI

Appreciate during totality that the corona is hot! Its temperature is 1–2 million degrees, much hotter than the 6000 C of the photosphere. Violating the second law of thermodynamics? No, the bulk of solar energy is visible radiation to which the corona is transparent. The high temperature results from the magnetic activity which the Sun displays, just as all other “cool” stars with a convection zone below the surface acting as a magnetism-generating dynamo. The coronal heating mechanisms are magnetic field reconnection and magnetic wave dissipation, but these are not precisely identified – nor is the dynamo understood.

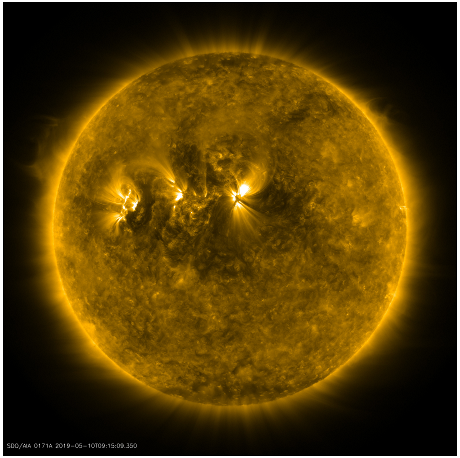
ON-DISK CHROMOSPHERE IN H-ALPHA

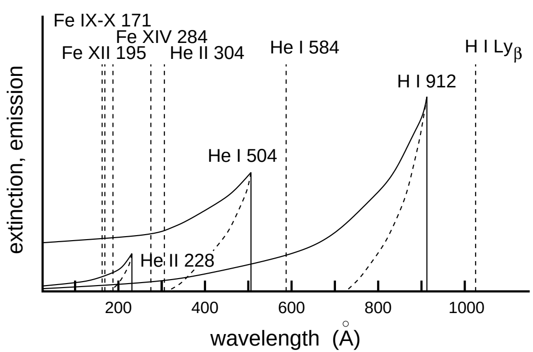


Dutch Open Telescope, Earth to scale http://www.staff.science.uu.nl/~rutte101/dot

- hydrogen Balmer-alpha dominates the flash spectrum
- on the solar disk Hα shows intricate forests of long fibrils and filaments
- I suspect that these are "contrails" that outline the trajectory of hot disturbances traveling along magnetic fields

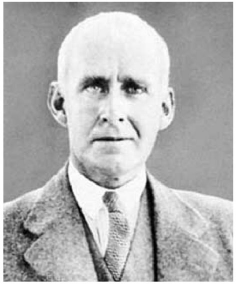
ON-DISK CORONA IN THE ULTRAVIOLET





- *iron lines*
  - Fe IX/X 171 Å: about 1 million degrees
  - Fe XII 195 Å: about 1.5 million degrees
  - Fe XIV 284 Å: about 2 million degrees
- *bright*
  - collision up, radiation down
  - thermal photon creation + photon loss
  - one line: selected loops = special trees in forest
- *dark*
  - lack of emissivity or bound-free scattering
  - scattering: radiation up, re-radiation at bound-free threshold ⇒ black in narrow passband
  - scattering: neutral hydrogen, some helium
- *movies* `http://sdo.gsfc.nasa.gov`
  - recent 171 Å movie
  - birthday 171 Å movie

EDDINGTON'S TWO CLOUDS



Arthur Stanley Eddington 1882–1944

"The Internal Constitution of the Stars" (1926)

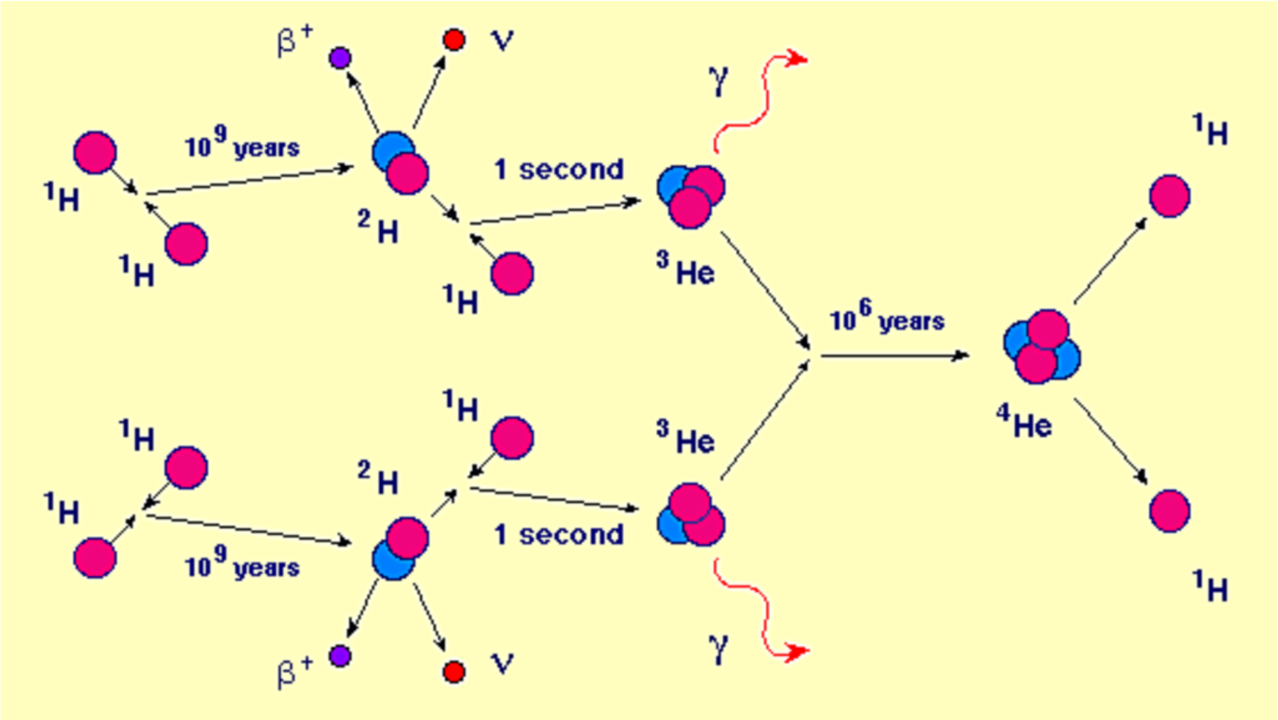
- *concluding sentence*
  - "it is reasonable to hope that in a not too distant future we shall be competent to understand as simple a thing as a star."

- *"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

PROTON-PROTON REACTION CYCLE

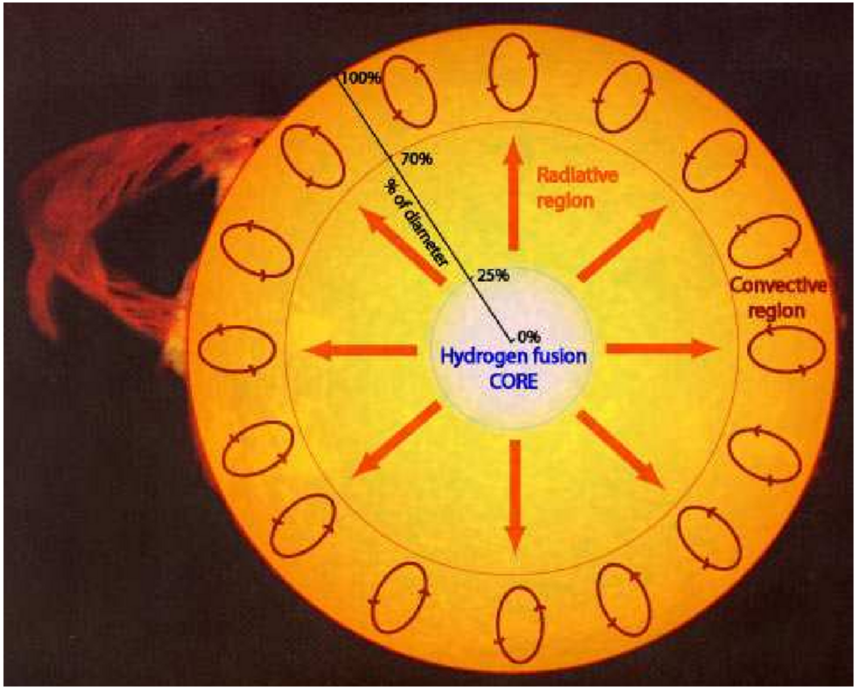
http://en.wikipedia.org/wiki/Proton-proton_chain_reaction



+ positron-electron annihilation: $\beta^+ + \beta^- \Rightarrow 2\gamma$

net: 4 protons ($^1_1\mathrm{H}$) + 2 electrons (β^-) $\Rightarrow$ 1 alpha particle ($^4_2\mathrm{He}$) + neutrinos (ν) + gamma radiation (γ)

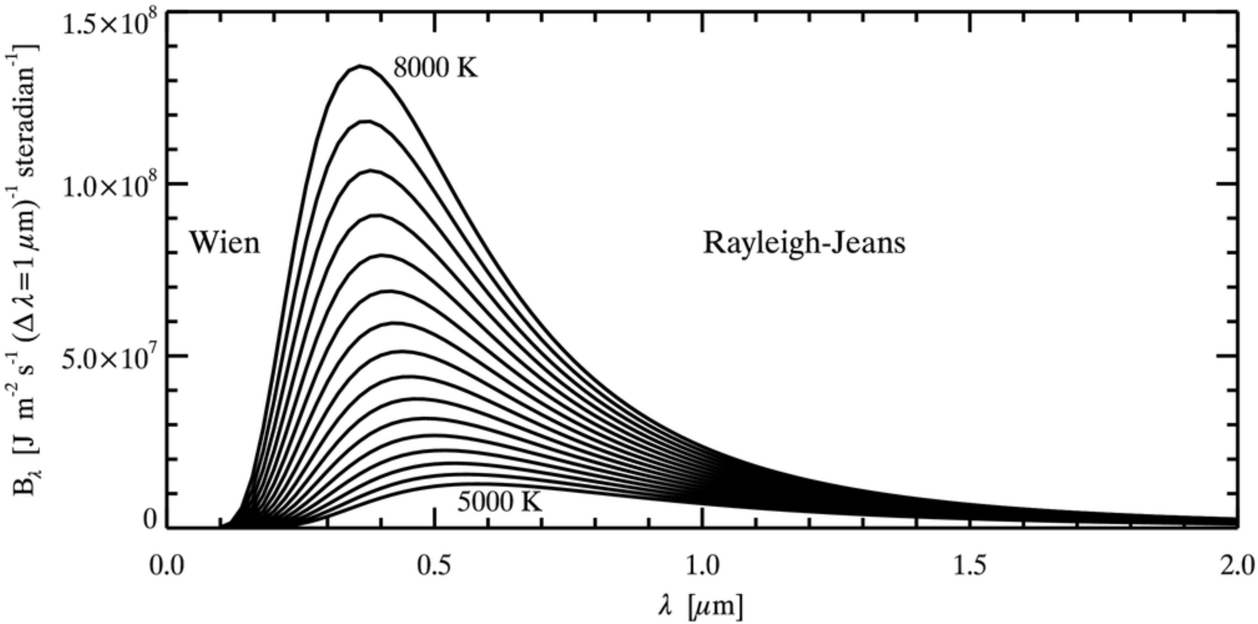
ENERGY FLOW THROUGH THE SOLAR INTERIOR



- core: gamma radiation from fusion of hydrogen into helium
- inner two-thirds: radiative energy diffusion (absorption – re-emission)
- outer one-third: convective energy transfer (“boiling”)
- energy transfer takes about ten million years from core to surface
- mean photon energy “cools” five million times from gamma to visible

PLANCK FUNCTION AND APPROXIMATIONS

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

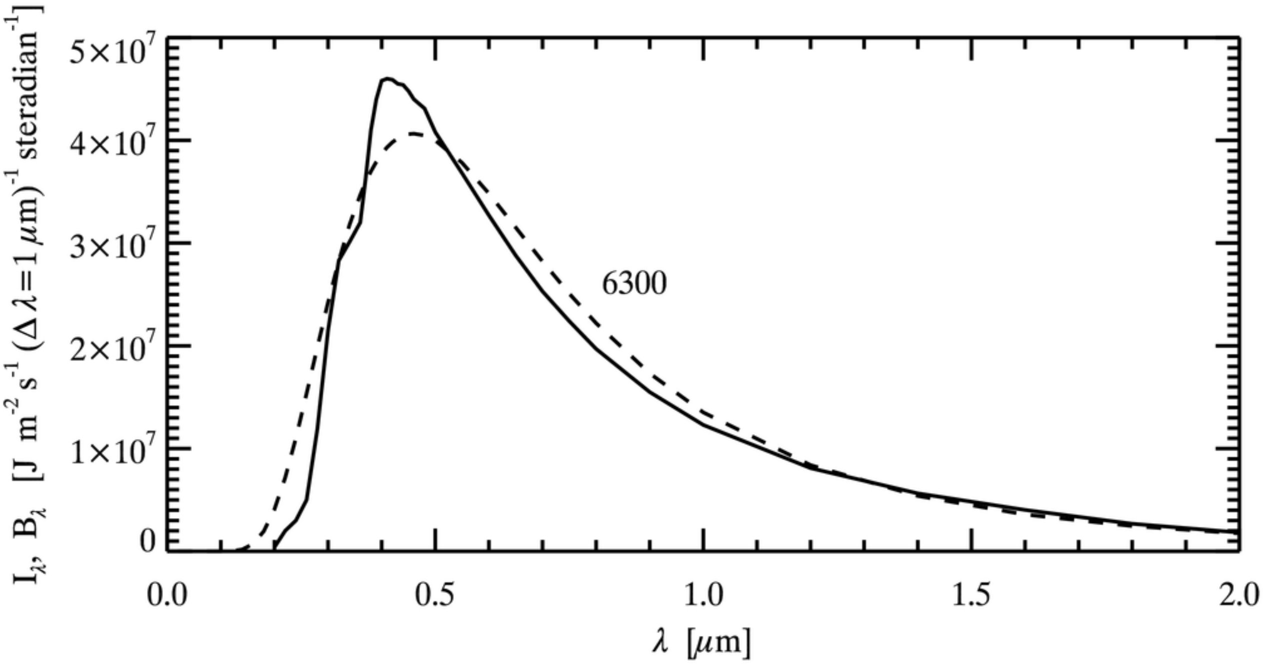


Wien approximation: $$e^{hc/\lambda kT} \gg 1: \quad B_\lambda(T) \approx \frac{2hc^2}{\lambda^5} e^{-hc/\lambda kT}$$

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.

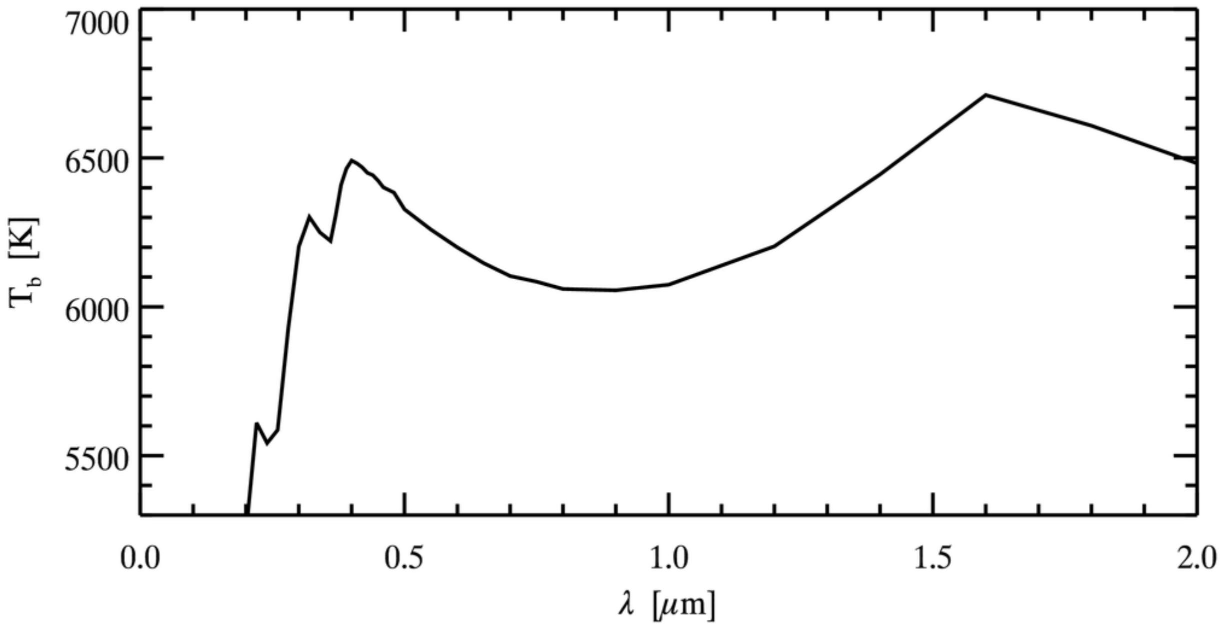
SOLAR SPECTRUM AND BEST-FIT PLANCK CURVE



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?

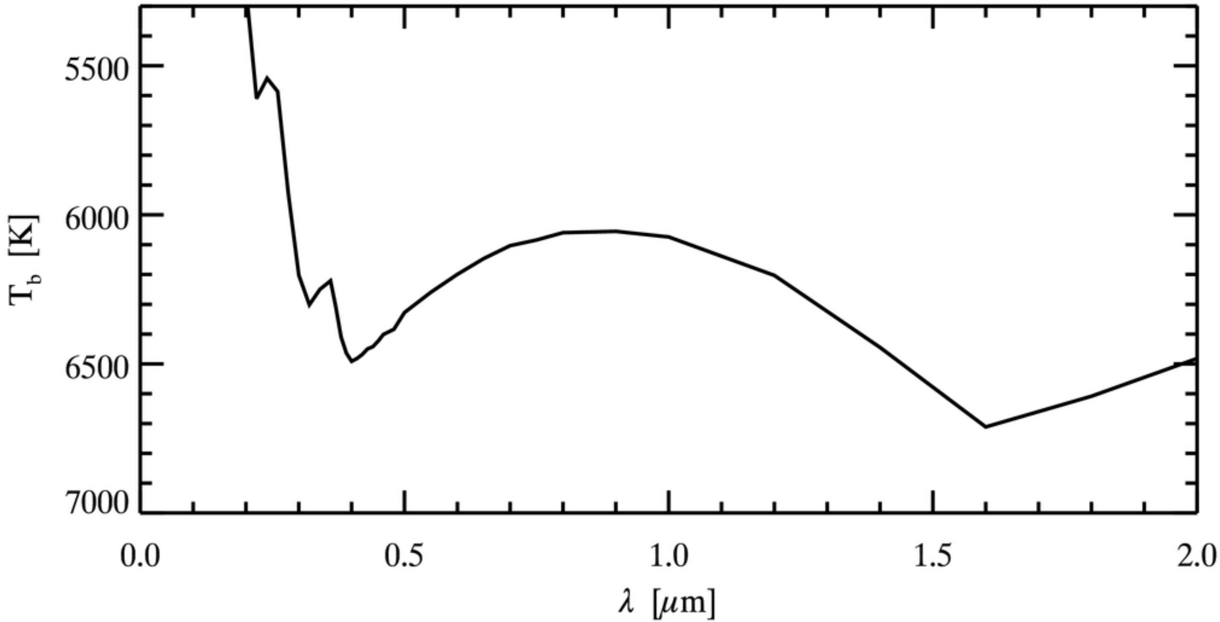
PLANCK INVERSE OF THE SOLAR SPECTRUM



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.

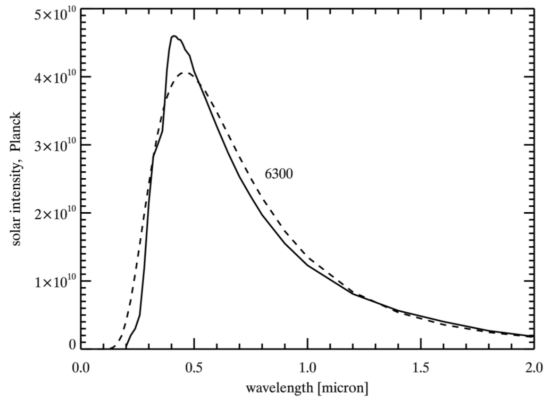
UPSIDE-DOWN PLANCK INVERSE OF THE SOLAR SPECTRUM

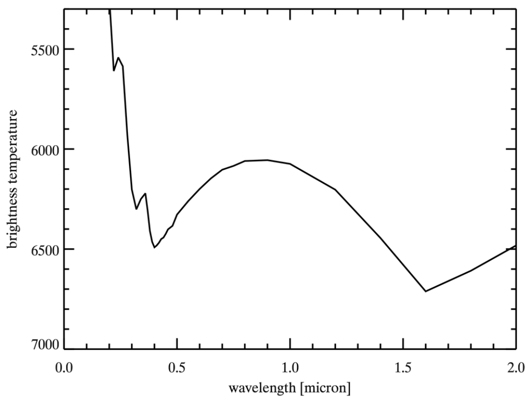


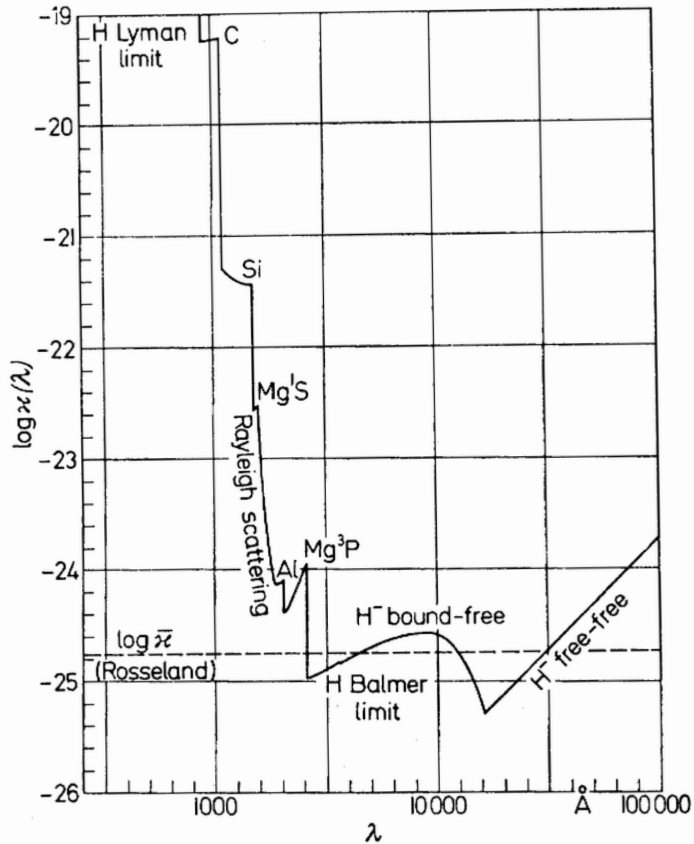
The temperature in the solar photosphere decreases with height, so that the brightness temperature of the escaping radiation is higher at wavelengths where it escapes deeper. This upside-down T_b graph shows that the solar gas is most opaque in the ultraviolet ($\lambda < 0.3$ μm). The opaqueness hump 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

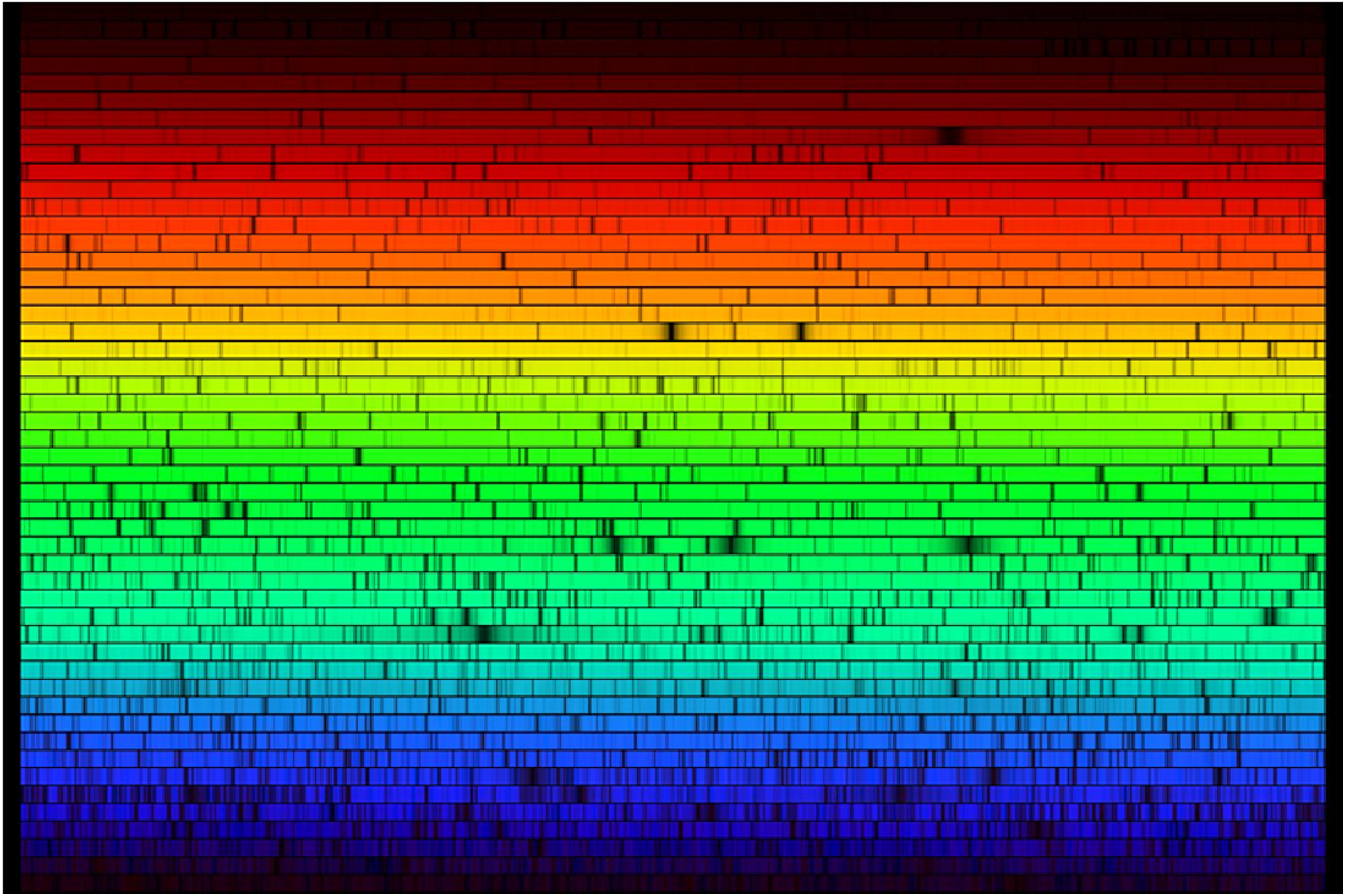






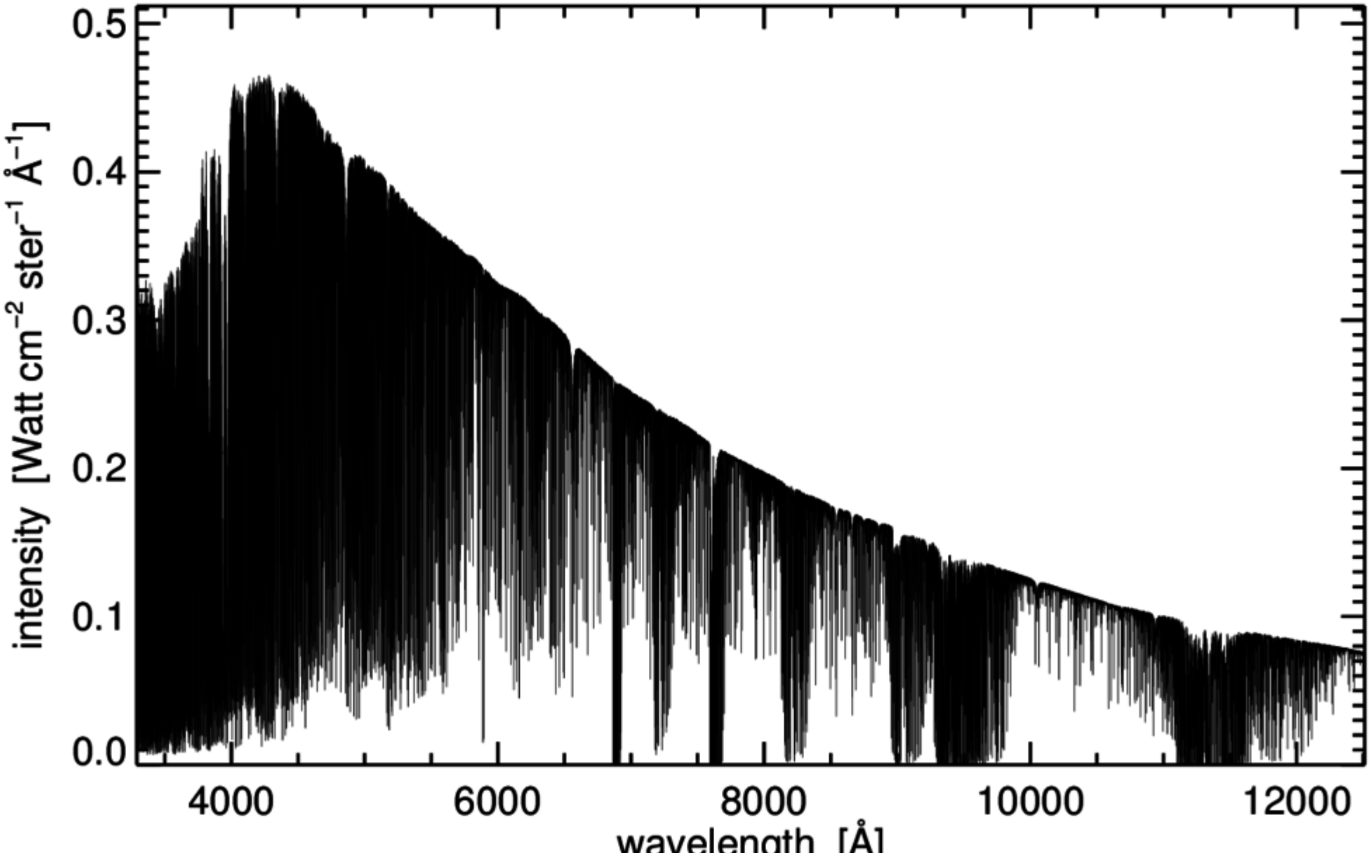
Right: photospheric gas opacity against wavelength (logarithmic), labeled with the processes causing it. Ultraviolet: ionization of C, Si, Mg, Al. Visible ($\lambda = 0.4 - 0.8\ \mu$m $= 4000 - 8000$ Å) and near infrared: H^- bound-free (H^- "ionization"). Far infrared: H^- free-free (acceleration of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

SOLAR SPECTRUM CUT IN RIBBONS



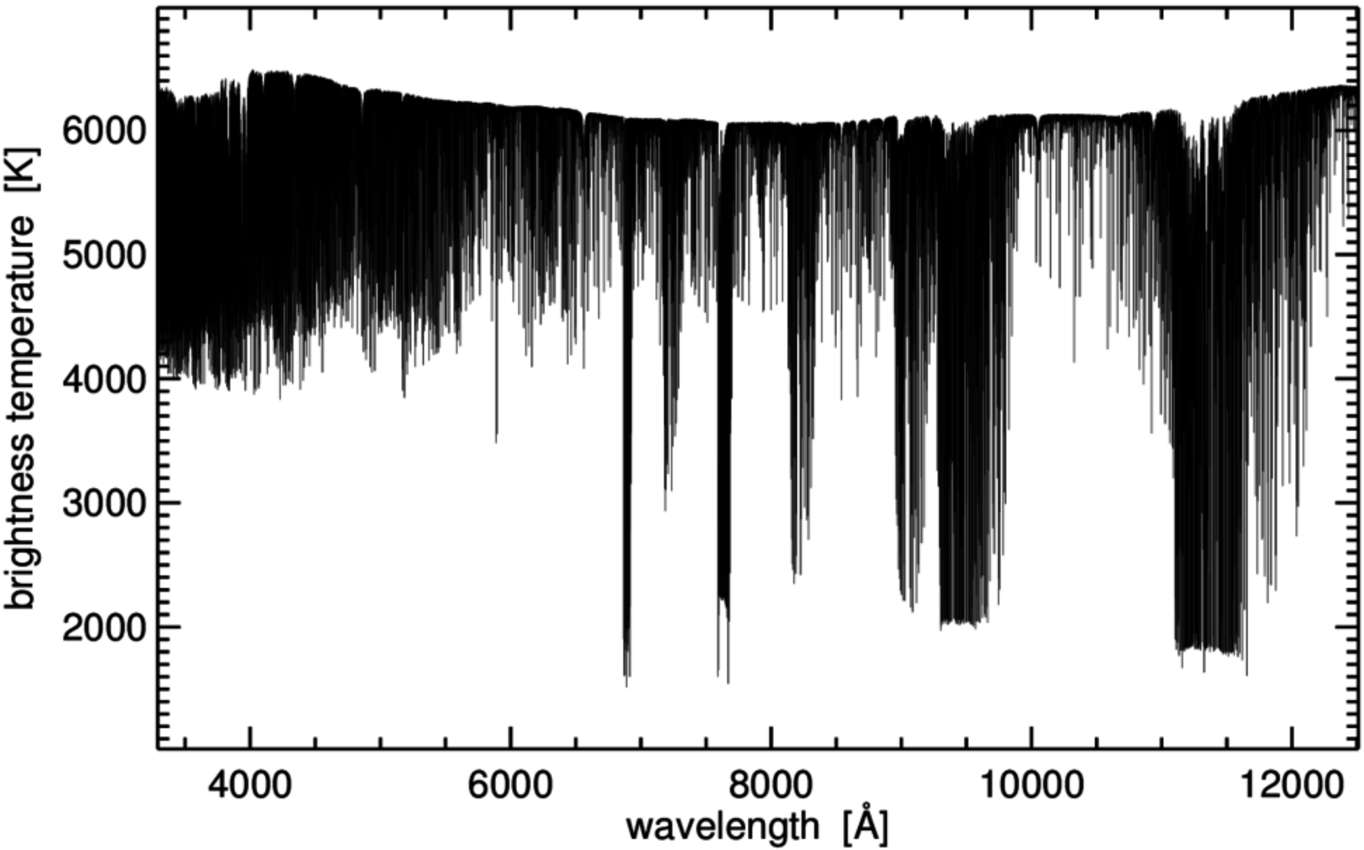
DISK-CENTER INTENSITY AT HIGH RESOLUTION

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



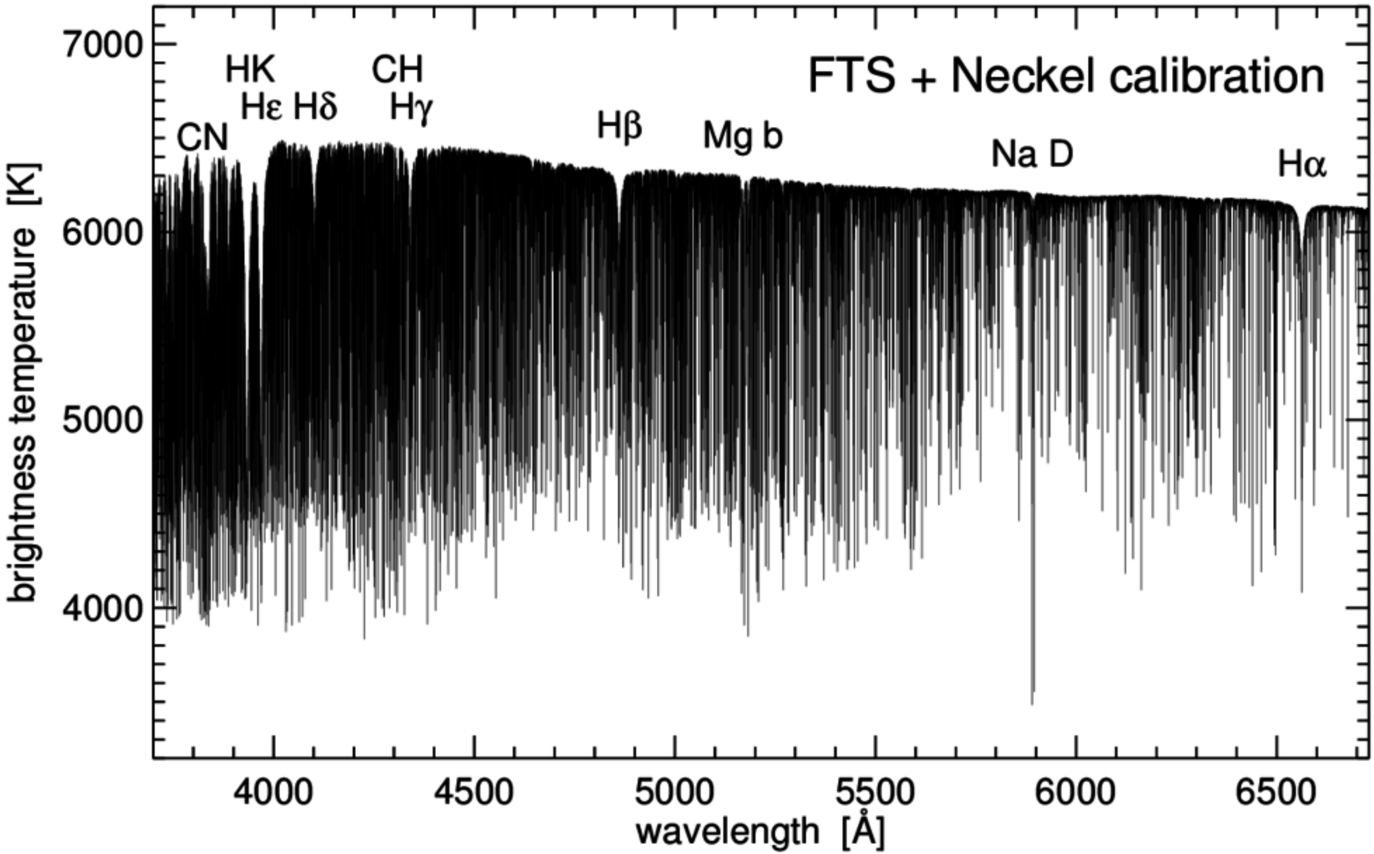
DISK-CENTER BRIGHTNESS TEMPERATURE

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



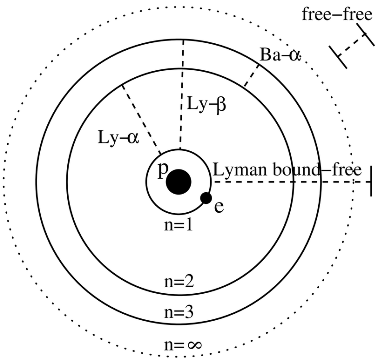
Which lines are telluric?

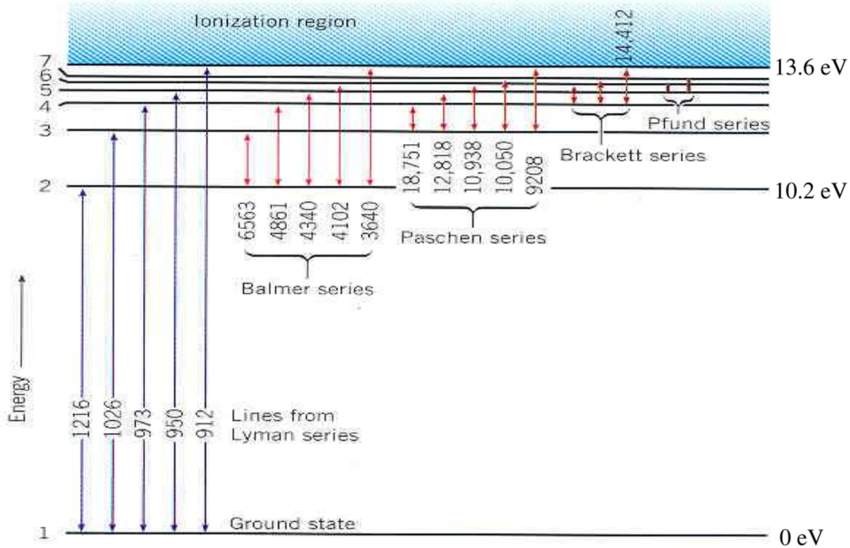
DISK-CENTER BRIGHTNESS TEMPERATURE – VISIBLE SPECTRUM



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

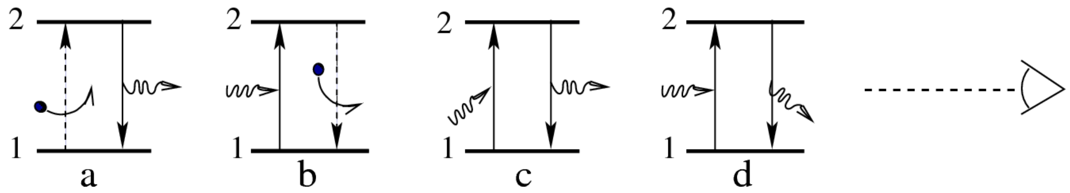
BOHR SKETCH AND GROTRIAN DIAGRAM FOR HYDROGEN





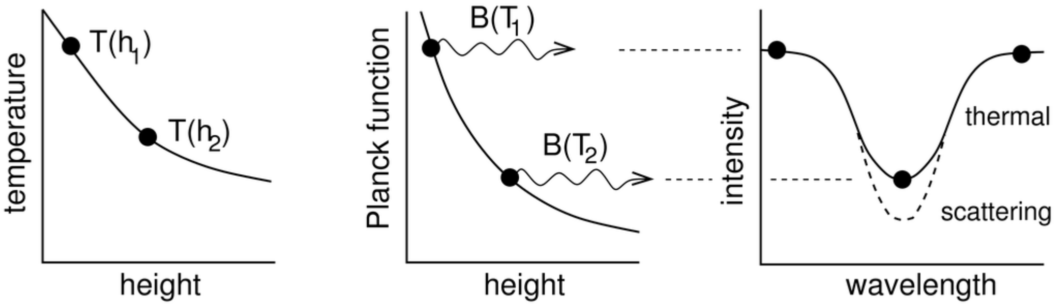
- Hydrogen atom: proton (+) and electron (−) in discrete orbits = "energy levels"
- Lyman lines: bound electron jumps between ground level n = 1 and higher ("excited") levels.
  Ly-α (1216 Å): between n = 1 and n = 2, Ly-β (1026 Å): n = 1 $\Leftrightarrow$ n = 3, etc.
- Balmer lines: bound electron jumps 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



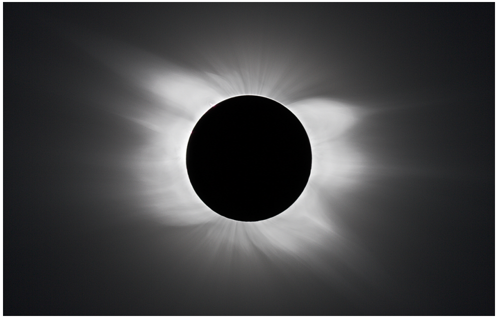
- Excitation up occurs either through absorption of a photon with the correct energy (corresponding wavelength), or through loss of kinetic energy in a particle collision.
- Deexcitation down occurs either through emission of a photon at the line wavelength, or through gain of kinetic energy in a particle 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.

SUMMARY



P. den Hartog

- The energy freed by fusion of hydrogen into helium in the solar core diffuses slowly outward and escapes as visible sunlight in the photosphere.
- The photospheric gas is more opaque than the transparent air around us, due to the presence of H^- particles (hydrogen atoms with a second electron).
- The solar spectrum is full of Fraunhofer lines that represent diagnostics of local circumstances at the level of atomic interactions ("the astronomer's treasure chest").
- At the onset and near the end of totality the chromosphere presents itself through purple radiation ("flash spectrum") consisting mainly of hydrogen and helium lines.
- During totality the corona presents itself through pearly white radiation which is a minute fracton of the photospheric light, scattered towards us by free electrons. At the million-degree temperature the electrons move so fast that the Fraunhofer lines are washed out by Doppler shifts. The intrinsic coronal emission is in ultraviolet lines from highly ionized elements and at long radio wavelengths from H free-free (proton-electron collisions).

Appreciate the beauty of the chromosphere in displaying the stuff the Universe is made of, and that the corona is the hottest thing you may see in your life!

1

PHYSICS OF (ECLIPSED) SUNSHINE

Rob Rutten

— solar radiation during eclipse —

- colors and lines
- eclipse visibility
- eclipse chromosphere
- eclipse corona

— chromospheric and coronal radiation outside eclipse —

- disk chromosphere
- disk corona

— quick course on solar spectrum formation —

- photospheric continuum formation
- photospheric line formation

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BUCKET LIST

Rob Rutten

M/F Norröna, Tórshavn, Faroe
March 20 2015

http://www.staff.science.uu.nl/~rutte101 (google "rob rutten website")

employment
1963 – 2007: Utrecht University, The Netherlands
2002 – 2007: Oslo University, Norway
2007 – present: retired but active (excepting totality)

research: solar chromosphere (spectrum, structure, dynamics)
teaching: solar and stellar spectrum formation

eclipse flash spectrometry as student

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eclipse flash observation as tourist

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FROM WHITE TO COLOR

comet-made molten-rock Manicouagan Reservoir, Quebec, August 2006

- rain droplets disperse sunlight across wavelength as reflective prisms
- visible sunlight is a continuum made up of violet – blue – green – yellow - red
- "white light" = sum of colors with "radiation temperature" about 6000 C
- just as white-hot iron, the solar photosphere ("surface") is about 6000 C

Appreciate that bluish stars (Sirius) are hotter, reddish stars (Betelgeuse) are cooler

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4

FRAUNHOFER'S DISCOVERY

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

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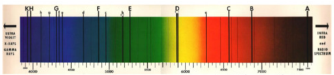

wavelength in Ångstrom; 1 Å = 0.1 nm

K & H: resonance lines of calcium ions
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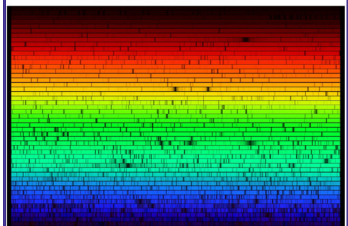

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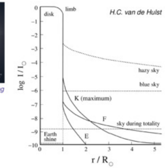
6

SOLAR ECLIPSE VISIBILITY

P. den Hartog



- dusty sky has 0.1 – 0.01% of the solar brighness (10^{-3} – 10^{-4}), brighter closer to Sun
- "coronal" blue sky (Rayleigh scattering) is one millionth (10^{-6}), even distribution across sky
- during totality the sky brightness is only one billionth (10^{-9}), less than the coronal brightness
- "K" = continuum component, "F" = Fraunhofer component, "E" = emission-line component
- earthshine (10^{-10}): new-moon brightness from full-earth-with-spot irradiation

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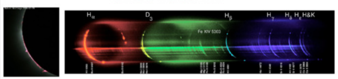
ECLIPSE CHROMOSPHERE



EurAstro Team Szeged I August 11, 1999

- *chromosphere = purple rim just after second contact and just before third contact. Name given by Norman Lockyer 1868, outside eclipse; Jules Janssen saw it first, two days after the August 18 1868 eclipse. The chromospheric "flash" spectrum contains:*
  - H I Balmer lines: Hα, Hβ, Hγ, Hδ, Hϵ
  - He I D_3 (name "helios" also from Lockyer while Janssen discovered it first)
  - Ca II H & K
  - weaker: Na I D_1 & D_2 (left of D_3), lines of Mg I, Fe II, Sr II, Ba II
- *chromosphere enigma*
  - spatial extent (purple rim width) ≫ equilibrum scale height ⇒ highly dynamic
  - both hot (He I D_3) and cool (Na I D_1 & D_2) ⇒ highly inhomogeneous
  - "the most difficult domain of the solar atmosphere"

Appreciate that when you see the chromosphere you see the intrinsic color of the stuff the Universe is made of: hydrogen and a bit of helium!

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CORONAL WHITE LIGHT

- Walter Grotrian (Potsdam, 1931)
  white ⇒ Thomson scattering of photospheric photons by free electrons
  weak ⇒ low electron density (electron cross-section only 10^{-25} cm^2)
  absence of photospheric Fraunhofer lines ⇒ washed out by large Dopplershifts
  required electron speeds 4000 km/s [⇒ if motions thermal: 1 million degrees !?]
- linear polarisation from right-angle scattering
- fine structure maps variatons in electron density dictated by magnetic fields
- the F component further out results from photon scattering by slower-moving interplanetary dust particles; its spectrum shows the photospheric Fraunhofer lines

Appreciate that during totality you are illuminated by normal photospheric light — but only a 10^{-7} fraction bounced around the moon, without Fraunhofer lines, and polarized too!

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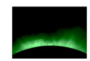
"CORONIUM" LINES



narrow-band totality image 5302.9 Å

The coronal spectrum during totality is a continuum with a few bright lines initially ascribed to an element "coronium". However, in 1939 Grotrian suggested that two lines are transitions of highly ionized iron, suggesting an "ionization temperature" of 1 million degrees. In 1942 Edlén identified nineteen lines, proving that the corona is indeed very hot. The large electron speeds washing out the Fraunhofer lines are thermal motions. The third proof of high temperature, also in 1942, was the detection of thermal solar radiation at long (1 m) radio wavelengths.

name	wavelength	identification
green line	5302.9 Å	Fe XIV
yellow line	5694.5 Å	Ca XV
red line	6374.5 Å	Fe XI

Appreciate during totality that the corona is hot! Its temperature is 1–2 million degrees, much hotter than the 6000 C of the photosphere. Violating the second law of thermodynamics? No, the bulk of solar energy is visible radiation to which the corona is transparent. The high temperature results from the magnetic activity which the Sun displays, just as all other "cool" stars with a convection zone below the surface acting as a magnetism-generating dynamo. The coronal heating mechanisms are magnetic field reconnection and magnetic wave dissipation, but these are not precisely identified – nor is the dynamo understood.

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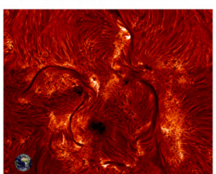
ON-DISK CHROMOSPHERE IN H-ALPHA



Dutch Open Telescope, Earth to scale http://www.staff.science.uu.nl/~rutte101/dot

- hydrogen Balmer-alpha dominates the flash spectrum
- on the solar disk Hα shows intricate forests of long fibrils and filaments
- I suspect that these are "contrails" that outline the trajectory of hot disturbances traveling along magnetic fields

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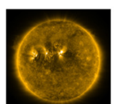
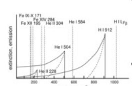
ON-DISK CORONA IN THE ULTRAVIOLET





- *iron lines*
  - Fe IX/X 171 Å: about 1 million degrees
  - Fe XII 195 Å: about 1.5 million degrees
  - Fe XIV 284 Å: about 2 million degrees
- *bright*
  - collision up, radiation down
  - thermal photon creation + photon loss
  - one line: selected loops = special trees in forest
- *dark*
  - lack of emissivity or bound-free scattering
  - scattering: radiation up, re-radiation at bound-free threshold ⇒ black in narrow passband
  - scattering: neutral hydrogen, some helium
- *movies* http://sdo.gsfc.nasa.gov
  - recent 171 Å movie
  - birthday 171 Å movie

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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?
  - 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

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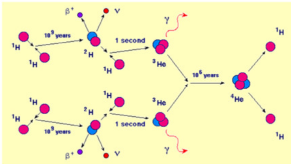
PROTON-PROTON REACTION CYCLE

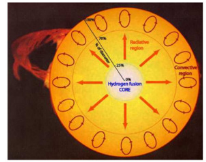
http://en.wikipedia.org/wiki/Proton-proton_chain_reaction



+ positron-electron annihilation: $\beta^+ + \beta^- \Rightarrow 2\gamma$

net: 4 protons ($^1_1$H) + 2 electrons (β^-) ⇒ 1 alpha particle ($^4_2$He) + neutrinos (ν) + gamma radiation (γ)

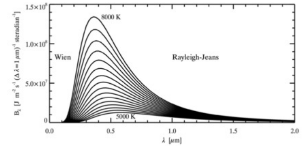
ENERGY FLOW THROUGH THE SOLAR INTERIOR



- core: gamma radiation from fusion of hydrogen into helium
- inner two-thirds: radiative energy diffusion (absorption – re-emission)
- outer one-third: convective energy transfer ("boiling")
- energy transfer takes about ten million years from core to surface
- mean photon energy "cools" five million times from gamma to visible

PLANCK FUNCTION AND APPROXIMATIONS

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

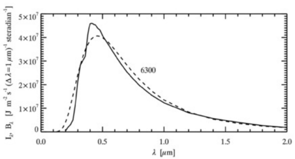


Wien approximation: $e^{hc/\lambda kT} \gg 1: \quad B_\lambda(T) \approx \frac{2hc^2}{\lambda^5} e^{-hc/\lambda kT}$

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.

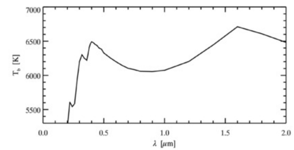
SOLAR SPECTRUM AND BEST-FIT PLANCK CURVE



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?

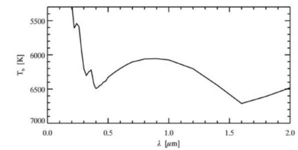
PLANCK INVERSE OF THE SOLAR SPECTRUM



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

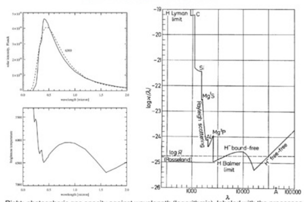
UPSIDE-DOWN PLANCK INVERSE OF THE SOLAR SPECTRUM



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.

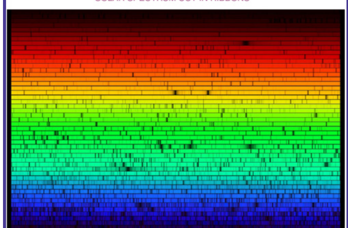
The solar gas is most transparent at the H^- "ionization" threshold wavelength of 1.6 μm.

SOLAR PHOTOSPHERE OPACITY



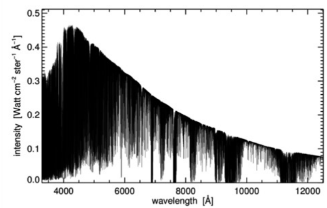
Right: photospheric gas opacity against wavelength (logarithmic), labeled with the processes causing it. Ultraviolet: ionization of C, Si, Mg, Al. Visible ($\lambda = 0.4 - 0.8$ μm = 4000 – 8000 Å) and near infrared: H^- bound-free (H^- "ionization"). Far infrared: H^- free-free (acceleration of free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

SOLAR SPECTRUM CUT IN RIBBONS



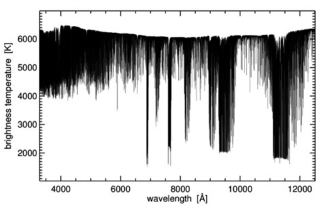
DISK-CENTER INTENSITY AT HIGH RESOLUTION

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



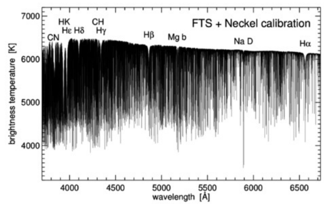
DISK-CENTER BRIGHTNESS TEMPERATURE

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



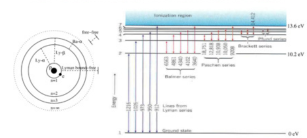
Which lines are telluric?

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 ⇔ 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 (≤ 912 Å), n = 2: Balmer continuum (≤ 3640 Å), etc.
- Free-free: trajectory change of a free electron near a proton (H ff) or hydrogen atom (H^- ff)

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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.

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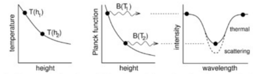
FORMATION OF FRAUNHOFER LINES



- 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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SUMMARY

P. den Hartog

- The energy freed by fusion of hydrogen into helium in the solar core diffuses slowly outward and escapes as visible sunlight in the photosphere.
- The photospheric gas is more opaque than the transparent air around us, due to the presence of H^- particles (hydrogen atoms with a second electron).
- The solar spectrum is full of Fraunhofer lines that represent diagnostics of local circumstances at the level of atomic interactions ("the astronomer's treasure chest").
- At the onset and near the end of totality the chromosphere presents itself through purple radiation ("flash spectrum") consisting mainly of hydrogen and helium lines.
- During totality the corona presents itself through pearly white radiation which is a minute fracton of the photospheric light, scattered towards us by free electrons. At the million-degree temperature the electrons move so fast that the Fraunhofer lines are washed out by Doppler shifts. The intrinsic coronal emission is in ultraviolet lines from highly ionized elements and at long radio wavelengths from H free-free (proton-electron collisions).

Appreciate the beauty of the chromosphere in displaying the stuff the Universe is made of, and that the corona is the hottest thing you may see in your life!

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