Electromagnetic Radiation

http://apod.nasa.gov/apod/astropix.html

CLASSICALLY -- ELECTROMAGNETIC RADIATION

Maxwell (1865)

Classically, an electromagnetic wave can be viewed as a self-sustaining wave of electric and magnetic field.

$$\boxed{\nabla \times B = \frac{1}{c}\frac{\partial E}{\partial t} + 4\pi j}$$

$$\nabla \bullet B = 0$$

$$\boxed{\nabla \times E = -\frac{1}{c}\frac{\partial B}{\partial t}}$$

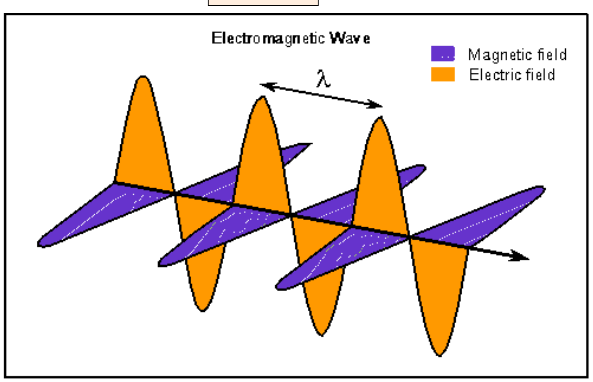
$$\nabla \bullet E = 4\pi\rho$$

These equations imply the existence of a propagating self - sustaning wave. A change in B creates a changing $\nabla \times E$, which creates a changing E which creates a changing $\nabla \times B$ which creates a changing B etc. Crudely, one can say that a changing B produces a changing E, but that implies an out of phase oscillation which is not the case.

Electromagnetic radiation is characterized by a frequency ν and a wavelength λ. The product of wavelength and frequency is the speed of light. The time for one wavelength to pass at speed c is $1/\nu$, so $c/\nu = \lambda$.

$$\boxed{\nu\lambda = c}$$

c = 2.998…. x 10^{10} cm s^{-1}



(B and E oscillations are actually in phase as shown)

Wavelength is measured in units of length that sometimes vary depending upon what sort of radiation you are talking about.

m, cm, and mm for radio emission

Angstroms for x-rays and near optical light: $\overset{\circ}{A} = 10^{-8}$ cm

micron = μ = 10^{-6} m = 10^{-4} cm = 10,000 $\overset{\circ}{A}$ for infrared and microwave

Frequency is measured in Hertz = s^{-1}

kiloHertz (kHz)
MegaHertz, etc as on your radio (MHz)

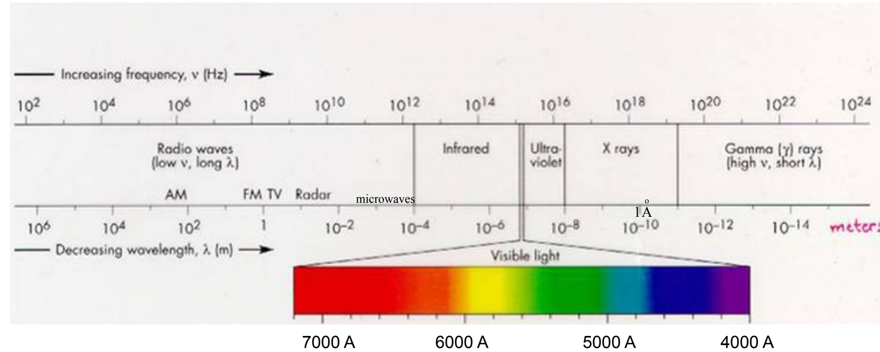
"optical" light is approximately 4000 - 7000 $\overset{\circ}{A}$

$$\nu = \frac{c}{\lambda} = \frac{2.99\times 10^{10}\ \text{cm}}{(5000)(10^{-8}\ \text{cm})\ \text{sec}} = 6\times 10^{14}\ \text{Hz}$$

Classically, electromagnetic radiation is produced whenever electric charge is accelerated.

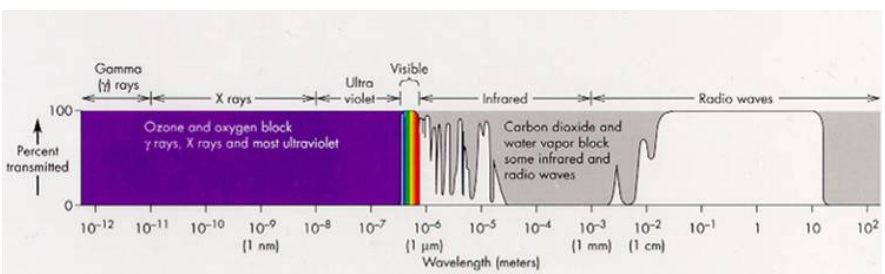
Examples:

- Electrons flowing in a current up and down in a radio antenna
- Electrons colliding with nuclei and each other in a hot gas - emission depends on temperature
- Electrons spiraling in a magnetic field



The light we can see is a very small part of the whole electromagnetic spectrum.

Transparency of the Earth's Atmosphere



1 μ = 10^{-6} m = 10^{-4} cm = 10,000 A

Most electromagnetic radiation, except for optical light and radio waves, does not make it to the surface of the Earth.

Blackbody Radiation

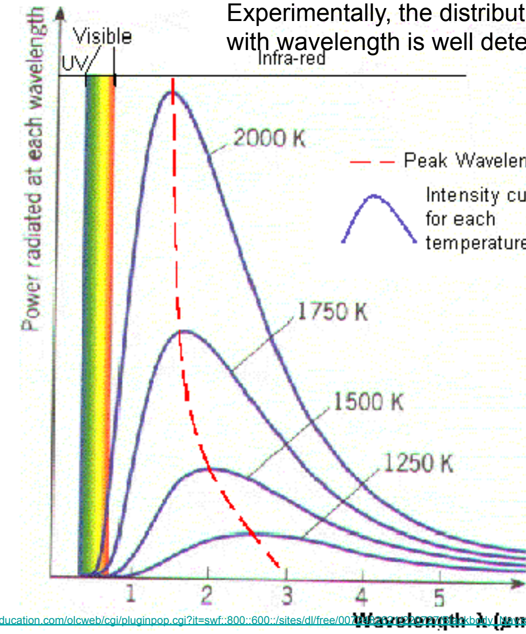
In physics, a black body is an idealized object that absorbs all electromagnetic radiation that falls onto it. No radiation passes through it and none is reflected. Similarly, a black body is one that radiates energy at every possible wavelength and that emission is sensitive only to the temperature, i.e., not the composition.

Blackbody Radiation

Blackbodies below around 800 K (530 °C) produce very little radiation at visible wavelengths and appear black (hence the name). Blackbodies above this temperature, however, begin to produce radiation at visible wavelengths starting at red, going through orange, yellow, and white before ending up at blue as the temperature increases. The term "blackbody" was introduced by Gustav Kirchhoff in 1860.

Today the term has a technical meaning, an emitter or absorber whose spectrum depends only on its temperature and not its composition.

Experimentally, the distribution of intensity with wavelength is well determined

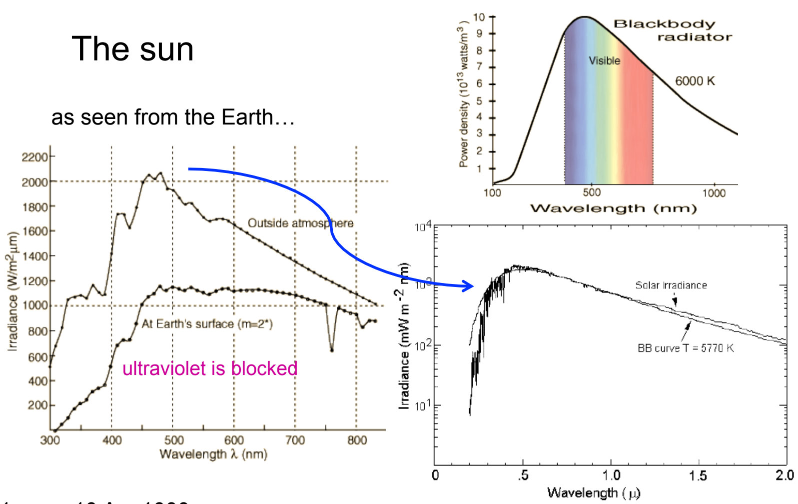


As the temperature Is raised you get more energy (flux) at every wavelength, but the peak also moves

http://highered.mheducation.com/olcweb/cgi/pluginpop.cgi?it=swf::800::600::/sites/dl/free/00... Blackbody Radiation Interactive

The sun

as seen from the Earth…



1 nm = 10 A = 1000 μ
1 μ = 10,000 A

The sun's radiation is to fair approximation a black body with a temperature around 5800 K

Why do these curves look like they do?

The classical solution to blackbody radiation assumed that electrons vibrating at any frequency ν had ~kT of energy to put into radiation at that frequency. It ignored the fact that the radiation had energy that depended on its frequency. There was, in fact, more "room" (phase space) for radiation with short wavelengths, hence its emission was preferred.

The fact that the probability for emitting short wavelength radiation increased without bound did not violate the conservation of energy, because there was no relation between energy and wavelength.

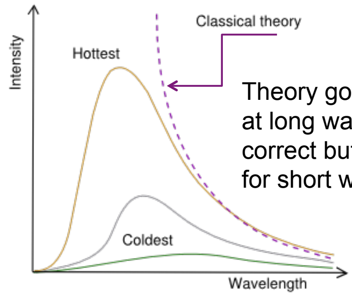
But this was totally at odds with what was seen…

Problem:
Divergent for large values of ν

Classically the intensity of radiation having frequency ν was given by the Rayleigh-Jeans formula (e.g., Feynman, Leighton and Sands, Vol 1 p 41.5)

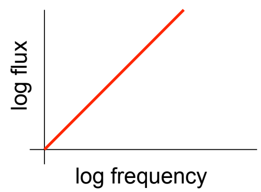
$$I_\nu = \frac{2\nu^2 kT}{c^2}$$

where $I_\nu \, d\nu$ is the flux of radiation emitted by a blackbody of temperature T (erg cm^{-2} s^{-1}) with a frequency in the range ν to $\nu + d\nu$. k is Botzmann's constant and c the speed of light.



Theory got the behavior at long wavelengths correct but was wrong for short wavelengths

At a constant T



http://www.cv.nrao.edu/course/astr534/BlackBodyRad.html

If you opened an oven you would be overwhelmed by x-rays and gamma-rays pouring out (at all temperatures). Optical light too would be emitted at all temperatures.

PLANCK - 1900

The solution to the dilemma posed by the classical solution was to require that electromagnetic radiation be quantized, that is it comes in individual particle-like packets of energy called "photons". Each photon has an energy proportional to the frequency of the radiation. High frequency (short wavelength) radiation thus had greater energy and was increasingly hard to produce at a given temperature. x-rays have more energy than optical light and are harder to produce.

$$\boxed{E_\gamma = h\nu}$$

where h is "Planck's constant" h = 6.626 x 10^{-27} erg sec

This particle like property of light also meant that light carried momentum and could exert a pressure.

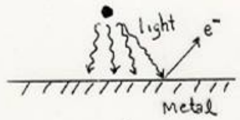
$Energy = momentum \times speed$ (for relativistic particles there is no $\frac{1}{2}$ out front as in 1/2 mv^2)

$$E_\gamma = pc = h\nu$$

$$p = h\frac{\nu}{c} = h\lambda$$

• Another motivation - the photoelectric effect (Hertz 1887; Einstein 1905)

Shine ultraviolet light on a metal



Observe:

1) Below a certain frequency, no electrons ejected, no matter what the intensity of the light.

2) For light above a threshold (called the "work function" of the metal) the number of ejected electrons is proportional to the intensity of the light

3) The kinetic energy of the electrons is given by $\frac{1}{2}m_e v^2 = (h\nu - h\nu_{thresh})$.

WITHOUT PROOF

Planck's Result: For a blackbody with temperature T the emitted flux as a function of frequency ν was

$$I_\nu = \frac{2h\nu^3}{c^2}\left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]^{-1} \qquad \frac{\text{erg}}{\text{cm}^2\ \text{s}\ \text{Hz}}$$

For $h\nu << kT$ this reduces to the classical expression

$$e^x \approx 1 + x \quad if\ x << 1 \quad \text{so } \exp\left(\frac{h\nu}{kT}\right) - 1 \rightarrow \frac{h\nu}{kT}$$

$$\Rightarrow I_\nu \rightarrow \frac{2\nu^2 kT}{c^2} \quad if\ \ h\nu << kT$$

but for $h\nu \gg kT$

$$I_\nu \rightarrow \frac{2h\nu^3}{c^2}\exp\left(-\frac{h\nu}{kT}\right) \rightarrow 0$$

http://en.wikipedia.org/wiki/Planck%27s_law

Aside:

e is the base of Napierian logarithms. It is also known as the "exponential function"

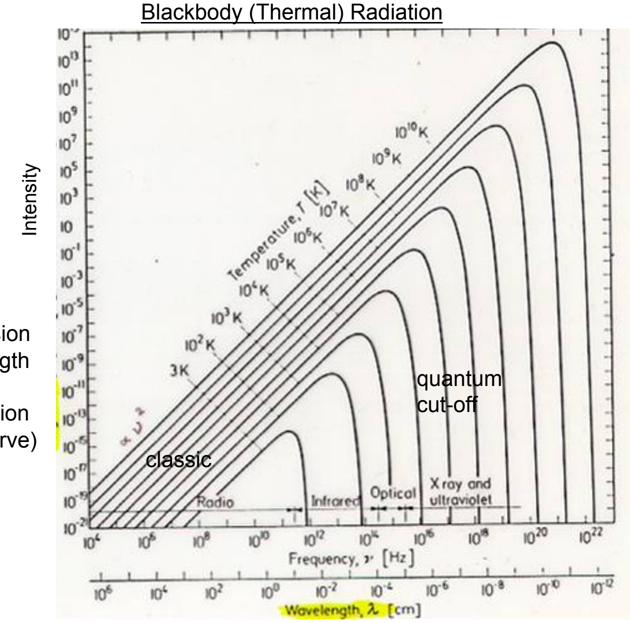
$e = 2.71828....$

It can be taken to a power like any other number

$e^0 = 1 \qquad e^{-\infty} = 0 \qquad etc.$

The "natural logarithm" of a number, ln, is the power to which e is raised to get that number.

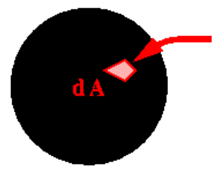
Blackbody (Thermal) Radiation



As T rises:

- more radiation at all wavelengths
- shift of peak emission to shorter wavelength
- greater total emission (area under the curve)

Intensity I = Power (erg/sec) radiated for a range of frequencies between ν and ν+dν through unit surface area, dA



$Flux(\nu) = I_\nu \, d\nu \, dA$

Blackbody surface

Rewriting in terms of the wavelenth $\lambda = c/\nu$

$$I_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

We are interested in the emission summed over all wavelengths

$$\mathrm{F(T)} = \int_0^\infty I_\lambda d\lambda$$

$$= \frac{2\pi^5 k^4}{15 h^3 c^2} T^4$$

or $\boxed{\mathrm{F(T)} = \sigma T^4 \ \ \mathrm{erg\ \ cm^{-2}\ s^{-1}}}$

where σ is the Stephan-Boltzmann constant

$$\sigma = 5.6704 \text{ x } 10^{-5} \ \mathrm{erg/(cm^2\ \ s\ K^4)}$$

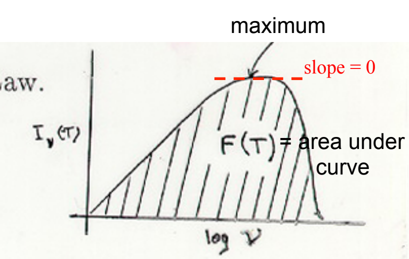
i..e., when multiplied by $\mathrm{T^4}$ the units are those of flux.

The maximum occurs where $\frac{dI}{d\lambda} = 0$, which is

$$\boxed{\lambda_{\max} = \frac{0.28978 \ \ \mathrm{cm}}{T}}$$

$$= \frac{2.8978 \ \times 10^7 \ \ A}{T}$$

This is also know as Wien's Law.



For our purposes, you only need to know

1) Each square cm of a blackbody radiator with temperature T emits $\boxed{\sigma T^4}$ erg s^{-1}

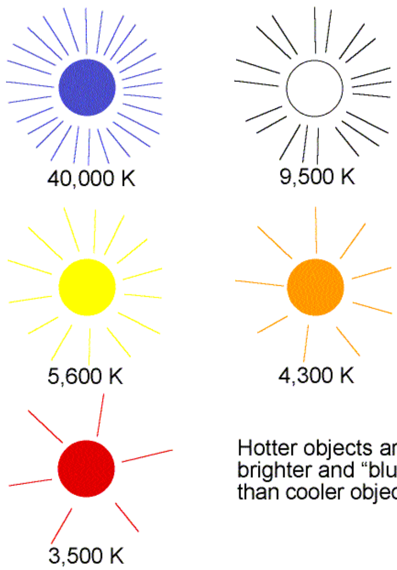
2) Most of the emission occurs at a wavelength given by

$$\boxed{\lambda_{\max} = \frac{0.2899 \ \mathrm{cm}}{\mathrm{T}} = \frac{2.899 \ \times 10^7 \ \ \mathrm{A}}{\mathrm{T}}}$$

σ is the Stefan Boltzmann radiation constant

$$5.6704 \ \times 10^{-5} \ \frac{\mathrm{erg}}{\mathrm{s\ cm^2\ \ K^4}}$$

From Nick Strobel's Astronomy Notes



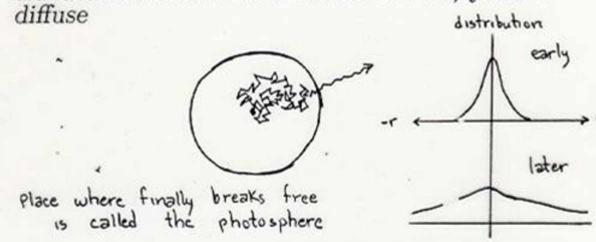
$$\lambda = \frac{2.8987\times10^{7}\ \text{Å}}{T}$$

Hotter objects are brighter and "bluer" than cooler objects.

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

WHY APPLICABLE TO STARS?

- Obviously photons emitted in the center do not travel outwards without interaction. They must *diffuse*



Let l_{mfp} be the average distance a photon travels without being scattered (or absorbed and re-emitted). The number of collisions required to diffuse a distance R is $(R/l_{mfp})^2$. The mean free path of a photon in the sun is about 1 cm. Hence it experiences about $R_\odot^2 = (6.9\times10^{10})^2 \sim 10^{21}$ collisions on the way out. At each radius, equilibrium between the electrons and photons exists to very high precision.

* i.e. $R = \sqrt{n}\, l_{mfp}$

DIFFUSION TIME FOR THE SUN

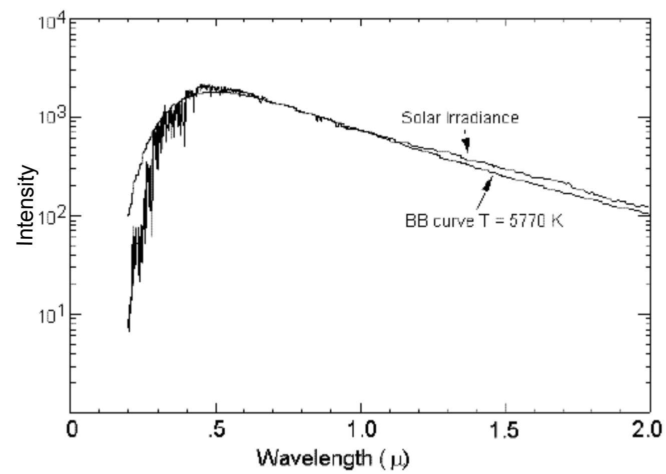
How long does it take?

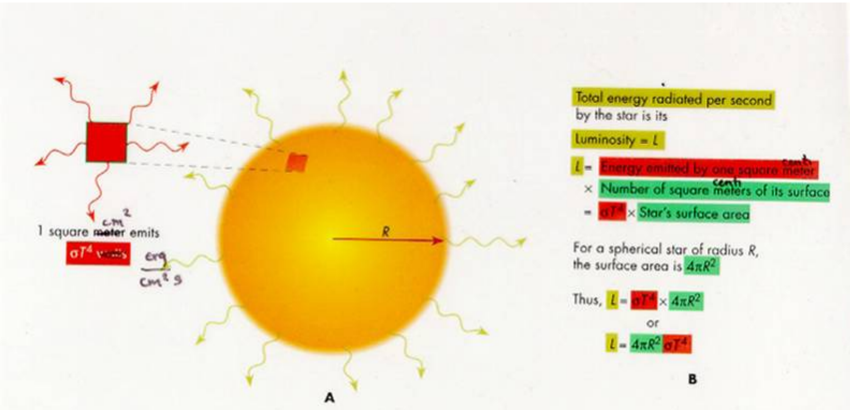
$$\tau_{\text{Diff}} \approx \underbrace{\left(\frac{R}{\ell}\right)^2}_{\text{number collisions}} \underbrace{\left(\frac{\ell}{c}\right)}_{\text{time between each}} = \frac{R^2}{\ell c}$$

$$\ell \sim 0.1\ \text{cm}$$

$$\frac{(6.9\times10^{10}\ \text{cm})^2\ \text{s}}{(0.1\ \text{cm})(3\times10^{10}\ \text{cm})} = 1.6\times10^{12}\ \text{s} \approx 50{,}000\ \text{years}$$

The sun - a typical star





$$L = Area * \sigma T^4$$

$$\boxed{L = 4\pi R^2 \sigma T^4}$$

THE LUMINOSITY OF THE SUN

$$L = 4\pi\ R_\odot^2\ \sigma T^4 \qquad \text{T= 5800 K}$$

$$= \frac{4(3.14)(6.96\times10^{10}\ \text{cm})^2(5.67\times10^{-5}\ \text{erg})(5800\ \text{K})^4}{\text{cm}^2\ \text{s}\ \text{K}^4}$$

$$= 3.90\times10^{33}\ \ \text{erg/s}$$

(Could have gotten 5800 K from Wien's Law)

The actual value is 3.83×10^{33} erg/s

Better still one could measure the luminosity and determine the radius

$$R = \left(\frac{L}{4\pi\sigma T^4}\right)^{1/2}$$

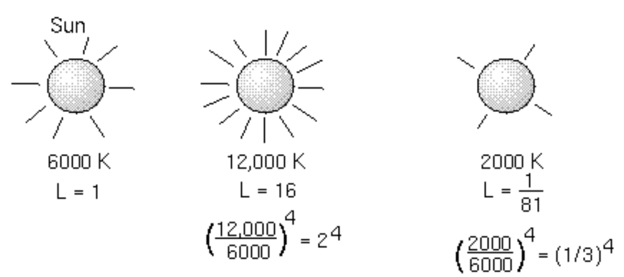
i.e. can get radius without a direct angular measure of the size.

For a given L, cooler stars have larger radii

From Nick Strobel's Astronomy Notes

If radius is held constant,

Luminosity is proportional to *fourth* power of temperature.



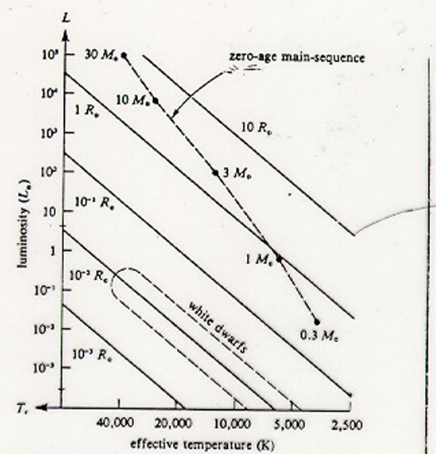


Figure 8.2. Main-sequence dwarfs and white dwarfs. The solid diagonal lines give loci of constant radii. Thus, a $1M_\odot$ zero-age main-sequence star has a radius just slightly less than $1R_\odot$; a $10M_\odot$ zero-age main-sequence star, somewhat less than $10R_\odot$. A typical white dwarf might have radius $10^{-2}R_\odot$, and as it cools, it would slide down the H-R diagram along the appropriate locus of constant radius.

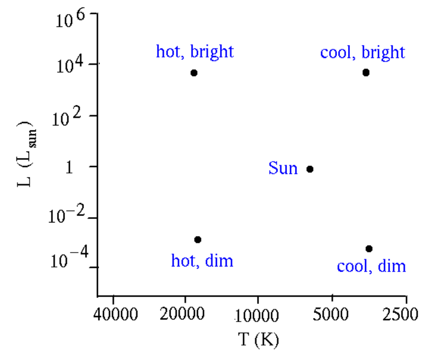
On the main sequence, approximately

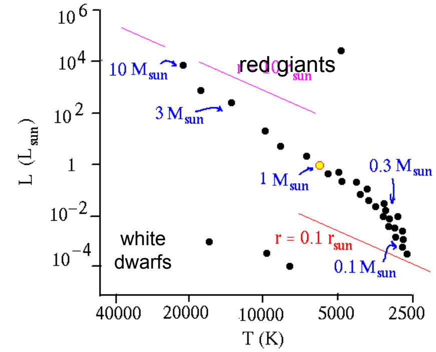
$$R \propto M^{0.65}$$

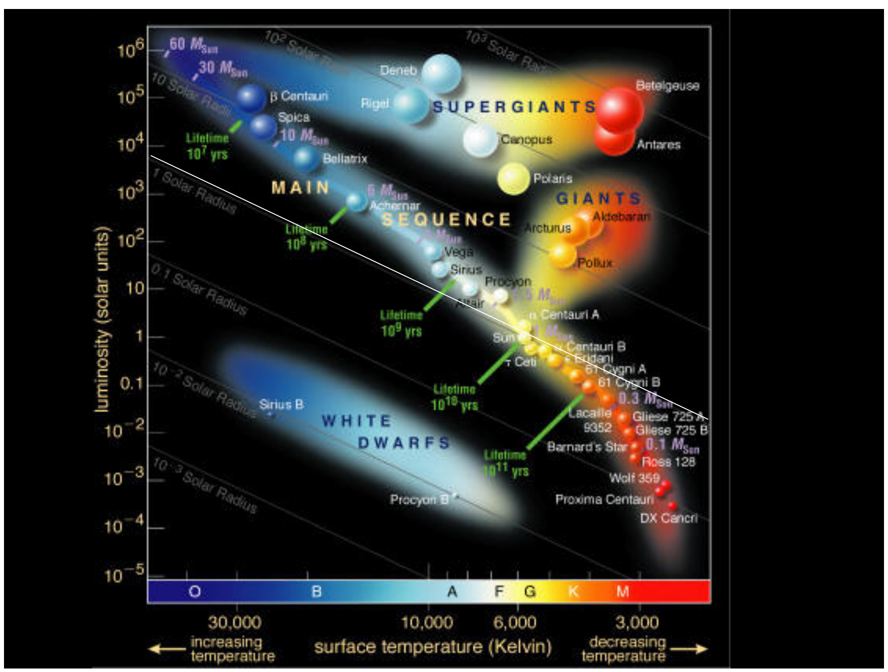
So

$$R = R_\odot \left(\frac{M}{M_\odot}\right)^{0.65}$$

This implies more massive main sequence stars are less dense

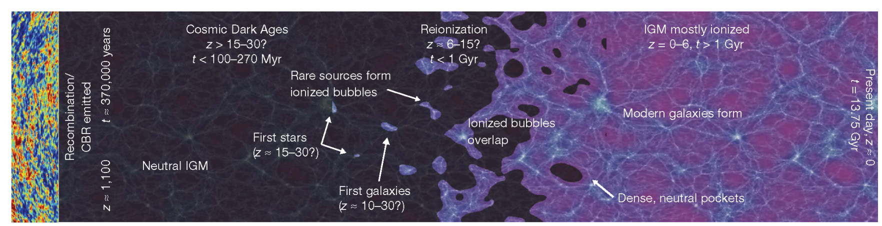




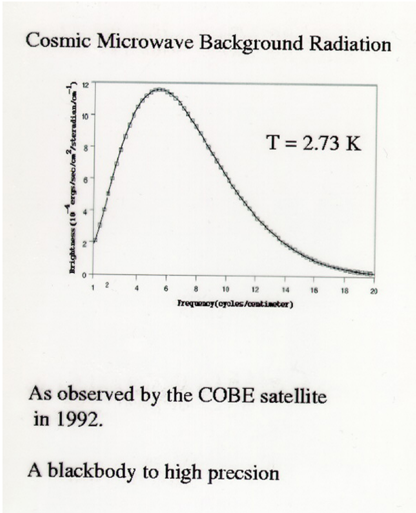


Another Example of a Blackbody

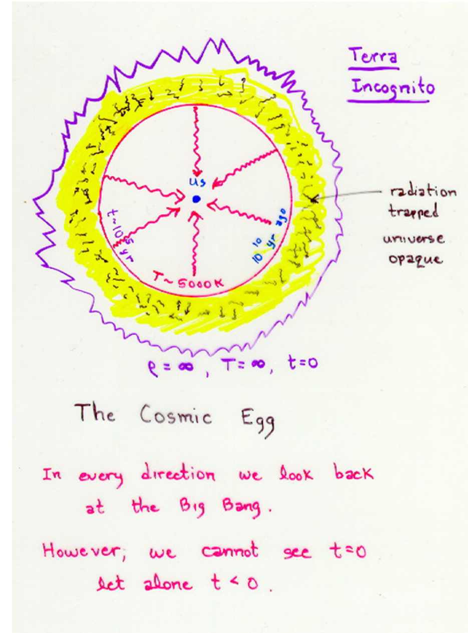
The Universe



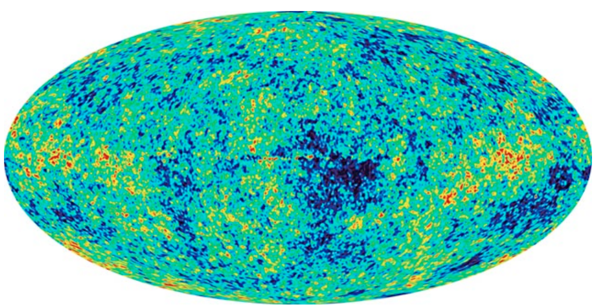
Z = 1100 30 10 2 0



$$2.73\ \mathrm{K} \approx \frac{3000\ \mathrm{K}}{1100}$$ i.e., the temperature at recomination divided by 1+z at recombination

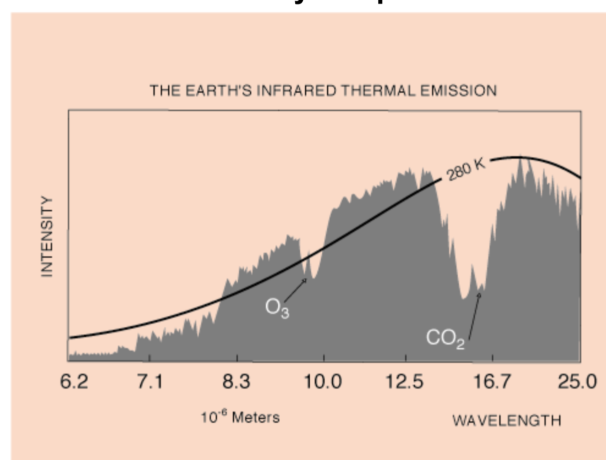


*
T = 2.7249 – 2.7251 K

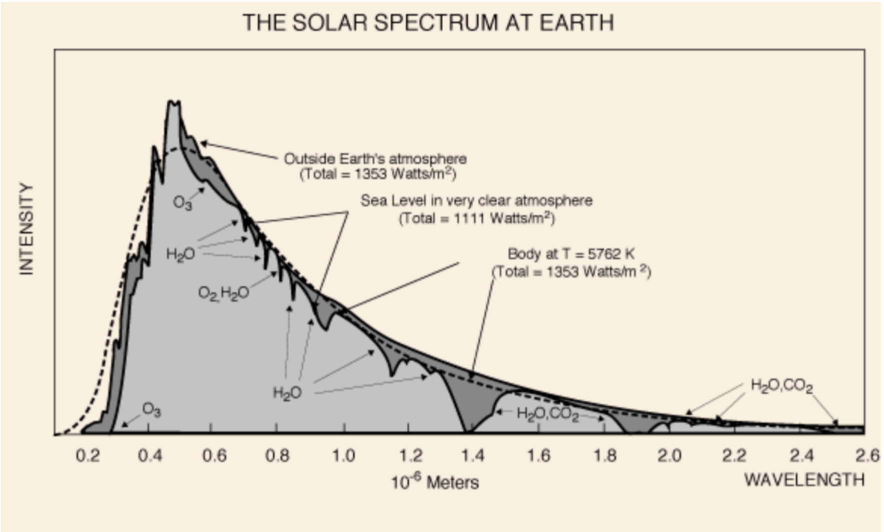


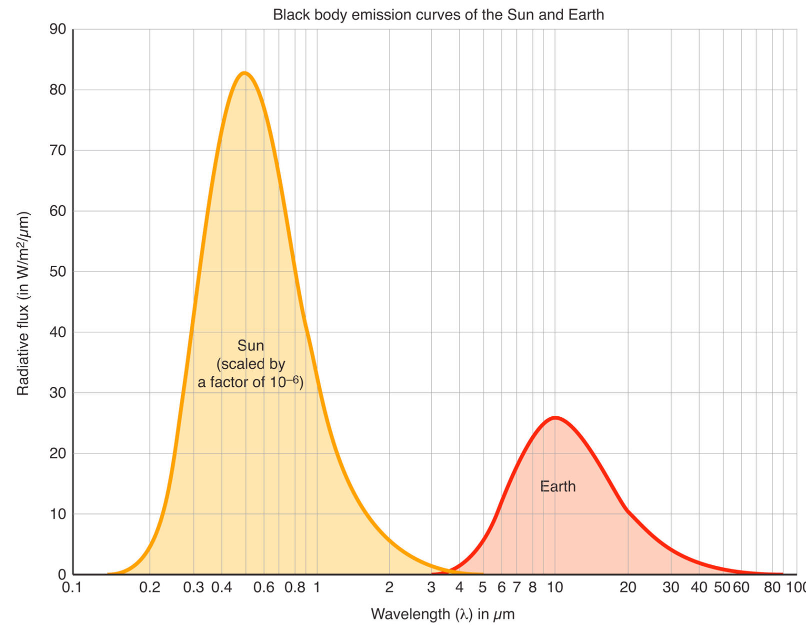
A picture of the universe when it was only 379,000 years old (WMAP – 2003)

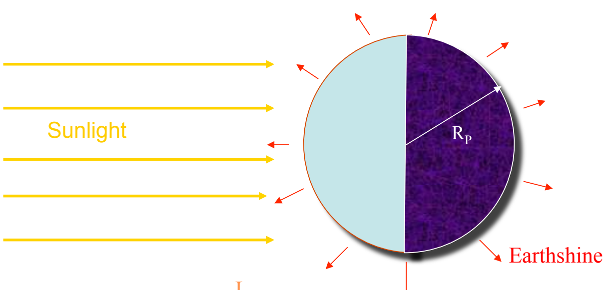
And another example of blackbody radiation Planetary Temperatures



http://lasp.colorado.edu/~bagenal/1010/SESSIONS/13.Light.html







Assume planet is rapidly rotating

Received from sun: $\frac{L}{4\pi d^2}\times \pi R_p^2$

Absorbed: f times this

Reflected: (1 - f) times this

Reradiated: $4\pi R_p^2\ \sigma T_p^4$

In steady state: $\frac{f\,L}{4\pi d^2}\,\pi \cancel{R_p^2} = 4\pi \cancel{R_p^2}\ \sigma T_p^4$

$$\boxed{T_p = \left(\frac{f\,L}{16\pi d^2\,\sigma}\right)^{1/4}}$$

n.b., $T_p \propto \frac{L^{1/4}}{\sqrt{d}}$

and independent of R_p

For Earth:

$$T_p = \left[\frac{\left(3.83\times10^{33}\right)\left(f\right)}{16\pi\left(1.49\times10^{13}\right)^2\left(5.67\times10^{-5}\right)}\right]^{1/4}$$

$= 281$ K f = 1 (8° C, 46° F)

$= 249$ K f = 0.633 (-24° C, -12° F)

But actually the Earth's average temperature is about 288° K (15° C)

Define temperature

T (K) measured from absolute zero

-273.15 C

-459.67 F

$1°C = 9/5 °F$

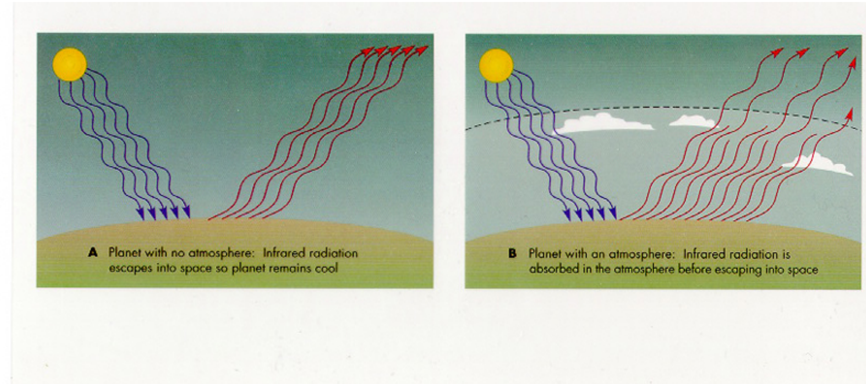
$0°C = 32°F$

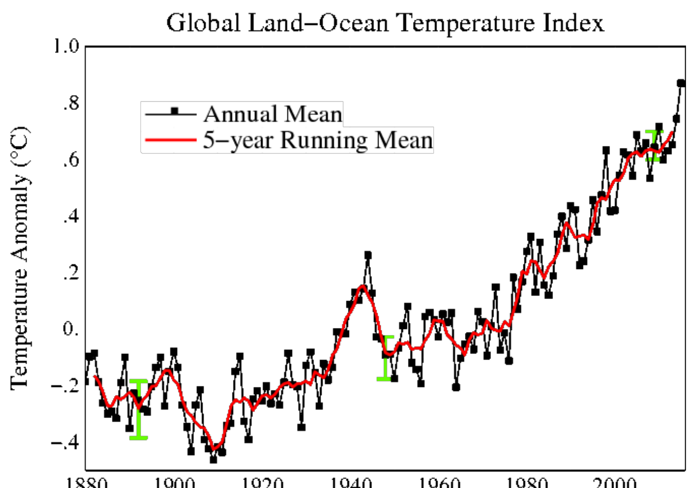
$F = 9/5\, C + 32$

$C = 5/9\,(F - 32)$

$K = C + 273.15$

$\bar{T}_{\oplus} \approx 288\,°K$





http://data.giss.nasa.gov/gistemp/

In last 100 years temperature has increased about 0.9 K (or 0.9 C or 1.6 F). In the next century it is expected to increase several more degrees K (http://en.wikipedia.org/wiki/Global_warming)

For other planets that orbit the sun one can take L to be constant and the calculation is the same except that the temperature varies as $1/\sqrt{d}$.

$$T_P = 281\, f^{1/4} \left(\frac{1\text{ AU}}{d}\right)^{1/2}$$

For example, for Mars at 1.52 AU

$$T_P = 281\;\; f^{1/4} \left(\frac{1}{1.52}\right)^{1/2} = 228°\text{ K } f^{1/4}$$

	$= 228°$ K	$f = 1$	(-45 C	-49 F)
if absorbed like the Earth	$= 200°$ K	$f = 0.6$	(-73 C	-99 F)
	$= 217°$ K	$f = 0.84$	(-56 C	-69 F)

actually measured 218

correct f for Mars

VENUS

$$T_p = \left(\frac{f_p L_\odot}{16\pi d^2 \sigma}\right)^{1/4}$$

$$= T_{Earth}\left(\frac{f_p}{f_{Earth}}\right)^{1/4}\left(\frac{AU}{d}\right)^{1/2}$$

$$= 281\, f_p^{1/4}\left(\frac{AU}{d}\right)^{1/2}$$

for any planet around the sun

$$= 281\,(0.28)^{1/4}\left(\frac{1}{0.7233}\right)^{1/2}$$

for Venus; nb only 28% of the light it receives reaches the surface

$= 240$ K (for Earth we got 247 K without greenhouse; 288 K with it)

So Venus, with its measured albedo, should in fact be cooler than the Earth, even though

$$\phi_{\text{Venus}} = \left(\frac{1}{0.7233}\right)^2 \phi_{Earth} = 1.91\,\phi_{Earth}$$

This is because only 28% of the light gets through so the flux at the base of Venus' atmosphere is

$$\left(\frac{0.28}{0.63}\right)1.91 = 87\% \text{ that of Earth}$$

The "moist greenhouse effect" occurs when sunlight causes increased evaporation from the oceans to the point that the gradient of water vapor in the earth's atmosphere does not decrease rapidly with altitude (it currently does). As a result water is present at high altitude where it can be broken broken down into hydrogen and oxygen by ultraviolet radiation. The hydrogen escapes and the water is permanently lost from the earth. Kasting (1988) showed that this happens when the luminosity from the sun exceeds a minimum of 1.1 times its present value. Clouds may increase this threshold value.

A true "runaway greenhouse effect" happens when the luminosity of the sun is 1.4 times greater than now. The oceans completely evaporate. The extra water vapor in the atmosphere increases the greenhouse effect which raises the temperature still more leading to faster evaporation ...

Kasting et al. February, 1988 Scientific American "How Climate Evolved on the Terrestrial Planets"

But the observed temperature on Venus is 730 K. The atmospheric pressure is about 90 Earth atmospheres, mostly made of CO_2 This is hotter than the planet Mercury and hotter than the melting point of lead.

(850 F)

On the other hand, below a certain temperature the carbon dioxide condenses out of the atmosphere and there is no greenhouse effect. This happens for fluxes about 55% that of the present sun at the Earth's orbit. This may be why Mars is so cold.

Together these conditions restrict the "Habitable Zone" of our present sun to 0.95 to 1.37 AU.

Mars is at 1.52 AU.

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OUR SUN. III. PRESENT AND FUTURE

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ABSTRACT

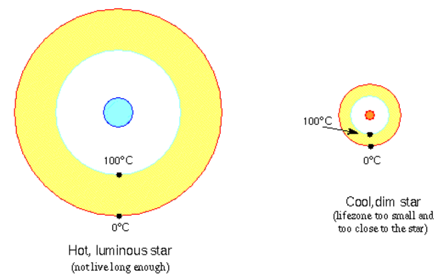
Self-consistent evolutionary models were computed for our Sun, using Los Alamos interior opacities and Sharp molecular opacities, starting with contraction on the Hayashi track, and fitting the observed present solar L, R, and Z/X at the solar age. This resulted in presolar $Y = 0.274$ and $Z = 0.01954$, and in present solar ^{37}Cl and ^{71}Ga neutrino capture rates of 6.53 and 123 SNU, respectively.

We explored the Sun's future. While on the hydrogen-burning main sequence, the Sun's luminosity grows from 0.7 $L_\odot$, 4.5 Gyr ago, to 2.2 $L_\odot$, 6.5 Gyr from now. A luminosity of 1.1 $L_\odot$ will be reached in 1.1 Gyr, and 1.4 $L_\odot$ in 3.5 Gyr; at these luminosities, Kasting predicts "moist greenhouse" and "runaway greenhouse" catastrophes, respectively, using a cloud-free climate model of the Earth; clouds could delay these catastrophes somewhat. As the Sun ascends the red giant branch (RGB), its convective envelope encompasses 75% of its mass (diluting remaining ^{7}Li by two orders of magnitude; ^{4}He is enhanced by 8%, ^{3}He by a factor of 5.7, ^{13}C by a factor of 3, and ^{14}N by a factor of 1.5). The Sun eventually reaches a luminosity of 2300 $L_\odot$ and a radius of 170 $R_\odot$ on the RGB, shedding 0.275 $M_\odot$ and engulfing the planet Mercury. After the horizontal branch stage (core helium burning), the Sun climbs the asymptotic giant branch (AGB), encountering four thermal pulses there; at the first thermal pulse, the Sun reaches its largest radial extent of 213 $R_\odot$ (0.99 AU), which is surprisingly close to Earth's present orbit. However, at this point the Sun's mass has been reduced to 0.591 $M_\odot$, and the orbits of Venus and Earth have moved out to 1.22 and 1.69 AU, respectively—they both escape being engulfed. The Sun reaches a peak luminosity of 5200 $L_\odot$ at the fourth thermal pulse. It ends up as a white dwarf with a final mass of 0.541 $M_\odot$, shifting the orbits of the planets outward such that Venus and Earth end up at 1.34 and 1.85 AU, respectively. These events on the AGB are strongly mass-loss dependent; somewhat less mass loss can result in engulfment of Venus, or even Earth. Our preferred mass-loss rate was a Reimers wind with a mass-loss parameter $\eta = 0.6$ normalized from inferred mass loss in globular cluster stars. For reasonable mass-loss rates ($0.8 > \eta > 0.4$), the Sun's final white dwarf mass is between 0.51 and 0.58 $M_\odot$.

The Sun spends 11 Gyr on the main sequence, 0.7 Gyr cooling toward the RGB, 0.6 Gyr ascending the RGB, 0.1 Gyr on the horizontal branch, 0.02 Gyr on the early AGB, 0.0004 Gyr on the thermally pulsing AGB, and 0.0001 Gyr on the traverse to the planetary nebula stage (the last three of these time scales depend sensitively on the amount of mass loss).

Subject headings: solar system: general — stars: evolution — Sun: general — Sun: interior

From Nick Strobel's *Astronomy Notes*



Lifezones (habitability zones) for two different luminosity stars. The hot, luminous star has a large, wide lifezone while the cool, dim star has a small, thin lifezone. Stars with masses between 0.7 and 1.5 solar masses will live long enough for intelligent life to develop and have lifezones that are far enough from the star.

Stars that are too big don't live long enough for life to develop (3 by?). Stars that are too small have life zones that are too close to the star and the planets become tidally locked (0.5 – 0.7 solar masses??).

BACK TO THE STARS

The fact that the stars are all blackbody radiators allows astronomers to prepare very useful tables that for example give the bolometric correction and interesting physical quantities such as the radius and temperature

For main sequence stars only (red giants and white dwarfs would have different tables)

Sp	log T_{eff}	T_{eff} (°K)	$(CI)_o$ (mag)	M_V (mag)	BC (mag)	M_{bol} (mag)	L ($L_\odot$)
			$(U-B)_o$				
O3	4.720	52500	−1.22	−6.0	−4.75	−10.7	1.4×10^6
4	4.680	48000	−1.20	−5.9	−4.45	−10.3	9.9×10^5
5	4.648	44500	−1.19	−5.7	−4.40	−10.1	7.9×10^5
6	4.613	41000	−1.17	−5.5	−3.93	−9.4	4.2×10^5
7	4.580	38000	−1.15	−5.2	−3.68	−8.9	2.6×10^5
8	4.555	35800	−1.14	−4.9	−3.54	−8.4	1.7×10^5
9	4.518	33000	−1.12	−4.5	−3.33	−7.8	9.7×10^4
B0	4.486	30000	−1.08	−4.0	−3.16	−7.1	5.2×10^4
1	4.405	25400	−0.95	−3.2	−2.70	−5.9	1.6×10^4
2	4.342	22000	−0.84	−2.4	−2.35	−4.7	5.7×10^3
3	4.271	18700	−0.71	−1.6	−1.94	−3.5	1.9×10^3
5	4.188	15400	−0.58	−1.2	−1.46	−2.7	8.3×10^2
6	4.146	14000	−0.50	−0.9	−1.21	−2.1	500
7	4.115	13000	−0.43	−0.6	−1.02	−1.6	320
8	4.077	11900	−0.34	−0.2	−0.80	−1.0	180
9	4.022	10500	−0.20	+0.2	−0.51	−0.3	95
			$(B-V)_o$				
AO	3.978	9520	−0.02	+0.6	−0.30	+0.3	54
1	3.965	9230	+0.01	+1.0	−0.23	+0.8	35
2	3.953	8970	+0.05	+1.3	−0.20	+1.1	26
3	3.940	8720	+0.08	+1.5	−0.17	+1.3	21

Sp	log T_{eff}	T_{eff} (°K)	$(CI)_o$ (mag)	M_V (mag)	BC (mag)	M_{bol} (mag)	L ($L_\odot$)
			$(B-V)_o$				
A5	3.914	8200	+0.15	+1.9	− 0.15	+1.7	14
7	3.895	7850	+0.20	+2.2	− 0.12	+2.1	10.5
8	3.880	7580	+0.25	+2.4	− 0.10	+2.3	8.6
F0	3.857	7200	+0.30	+2.7	− 0.09	+2.6	6.5
2	3.838	6890	+0.35	+3.6	− 0.11	+3.5	2.9
5	3.809	6440	+0.44	+3.5	− 0.14	+3.4	3.2
8	3.792	6200	+0.52	+4.0	− 0.16	+3.8	2.1
G0	3.780	6030	+0.58	+4.4	− 0.18	+4.2	1.5
2	3.768	5860	+0.63	+4.7	− 0.20	+4.5	1.1
5	3.760	5770	+0.68	+5.1	− 0.21	+4.9	0.79
8	3.746	5570	+0.74	+5.5	− 0.40	+5.1	0.66
K0	3.720	5250	+0.81	+5.9	− 0.31	+5.6	0.42
1	3.706	5080	+0.86	+6.1	− 0.37	+5.7	0.37
2	3.690	4900	+0.91	+6.4	− 0.42	+6.0	0.29
3	3.675	4730	+0.96	+6.6	− 0.50	+6.1	0.26
4	3.662	4590	+1.05	+7.0	− 0.55	+6.4	0.19
5	3.638	4350	+1.15	+7.4	− 0.72	+6.7	0.15
7	3.609	4060	+1.33	+8.1	− 1.01	+7.1	0.10
			$(R-I)_o$				
M0	3.585	3850	+0.92	+8.8	− 1.38	+7.4	7.7×10^{-2}
1	3.570	3720	+1.03	+9.3	− 1.62	+7.7	6.1×10^{-2}
2	3.554	3580	+1.17	+9.9	− 1.89	+8.0	4.5×10^{-2}
3	3.540	3470	+1.30	+10.4	− 2.15	+8.2	3.6×10^{-2}
4	3.528	3370	+1.43	+11.3	− 2.38	+8.9	1.9×10^{-2}
5	3.510	3240	+1.61	+12.3	− 2.73	+9.6	1.1×10^{-2}
6	3.485	3050	+1.93	+13.5	− 3.21	+10.3	5.3×10^{-3}
7	3.468	2940	+2.1	+14.3	− 3.46	+10.8	3.4×10^{-3}
8	3.422	2640	+2.4	+16.0	− 4.1	+11.9	1.2×10^{-3}

Mass and Radius - Main Sequence Stars

Stellar mass, M, and radius, R, in units of the Sun's values, $M_\odot$ and $R_\odot$, for the main-sequence stars (luminosity class LC = V) for different spectral types, Sp. Representative values of the surface gravity and mean density can be found in the following table under the V column. Schmidt-Kaler (1982).

Sp	M ($M_\odot$)	R ($R_\odot$)	Sp	M ($M_\odot$)	R ($R_\odot$)
O3	120	15	F0	1.6	1.5
O5	60	12	F5	1.3	1.3
O8	23	8.5	G0	1.05	1.1
O9	19	7.8	G5	0.92	0.92
B0	17.5	7.4	K0	0.79	0.85
B1	13	6.4	K5	0.67	0.72
B2	9.8	5.6	M0	0.51	0.60
B3	7.6	4.8	M3	0.33	0.45
B5	5.9	3.9	M5	0.21	0.27
B8	3.8	3.0	M7	0.12	0.18
A0	2.9	2.4	M8	0.06	0.1
A5	2.0	1.7			

If know L and T
then also know R.

M comes from other
measurements - TBD