LAGRANGE

Université Nice Sophia Antipolis

CNRS dépasser les frontières

Observatoire de la CÔTE d'AZUR

Master I.M.A.G.2E

Imagerie et Modélisation Astrophysique et Géophysique, Espace et Environnement

Master 2– Stellar Physics

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Slides mainly from P. Crowther

Recommended Texts

- Bohm-Vitense, *Introduction to Stellar Astrophysics: Vol 2*, ISBN 0521348706 Essential (full derivation of important equations)
- Gray, *Observations and analysis of stellar photospheres*, ISBN 0521408687, Recommended (good background reading, but complex maths)

cgs (cm/gram/second) units

Fundamental:

- Gravitational constant, $G=6.679 \times 10^{-8}$ cm^3/g/s^2
- Stefan-Boltzmann: $\sigma=5.6705 \times 10^{-5}$ erg/cm^2/s/K^4
- Speed of light, $c=2.99792 \times 10^{10}$cm,
- Electron mass: $m_e=9.109 \times 10^{-28}$ g
- Planck constant $h=6.626 \times 10^{-27}$ erg s
- Electron charge: 4.803×10^{-10} e.s.u.
- Boltzmann const: $k=1.380 \times 10^{-16}$ erg/s or 8.617×10^{-5} eV/K
- Gas constant $R=8.314 \times 10^{7}$ erg/mol K

Solar

- Radius $R_\odot=6.955 \times 10^{10}$ cm,
- Luminosity $L_\odot= 3.845 \times 10^{33}$ erg/s,
- Mass $M_\odot=1.989 \times 10^{33}$ g

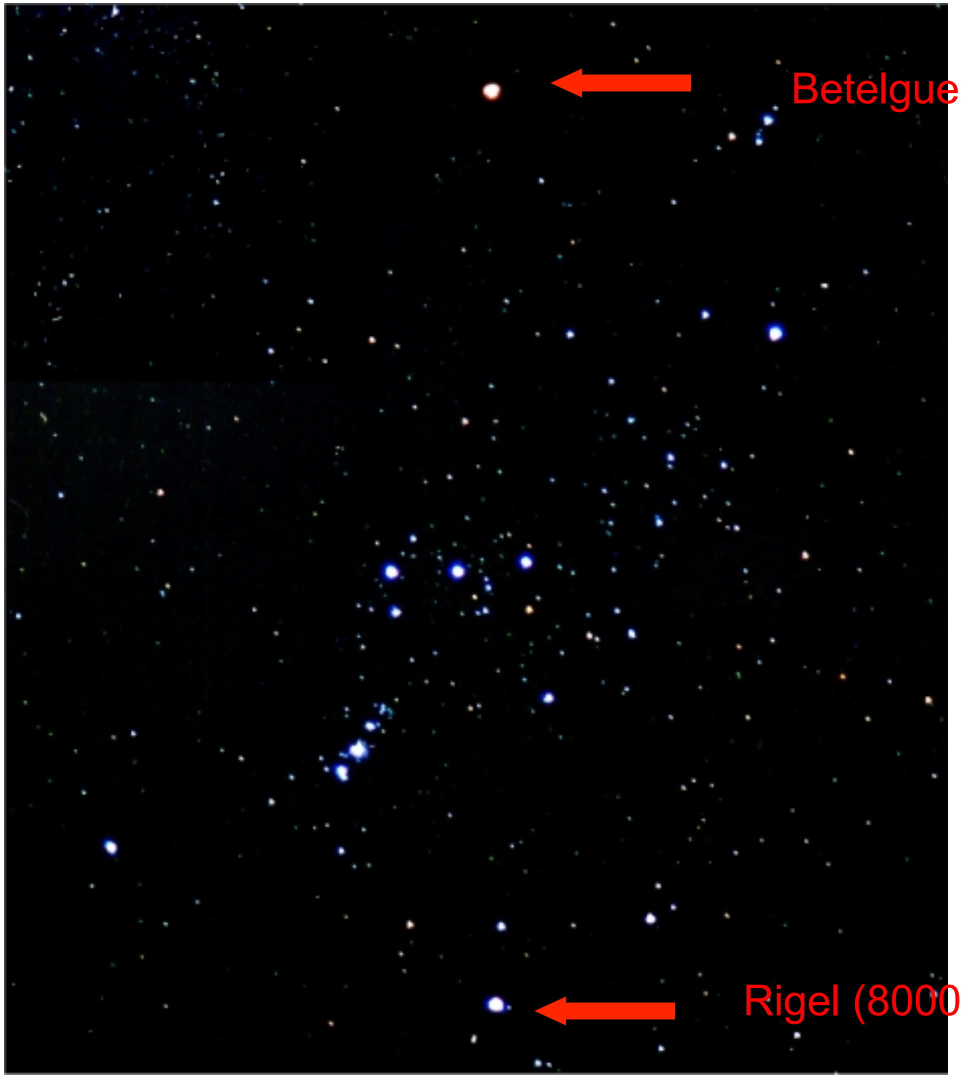
Astronomical:

- Parsec, pc: 3.085×10^{18}cm
- Astronomical Unit, AU: 1.496×10^{13} cm

Miscellaneous

- Energy of 1ev=1.602×10^{-26} erg

Color/Temperature Relation

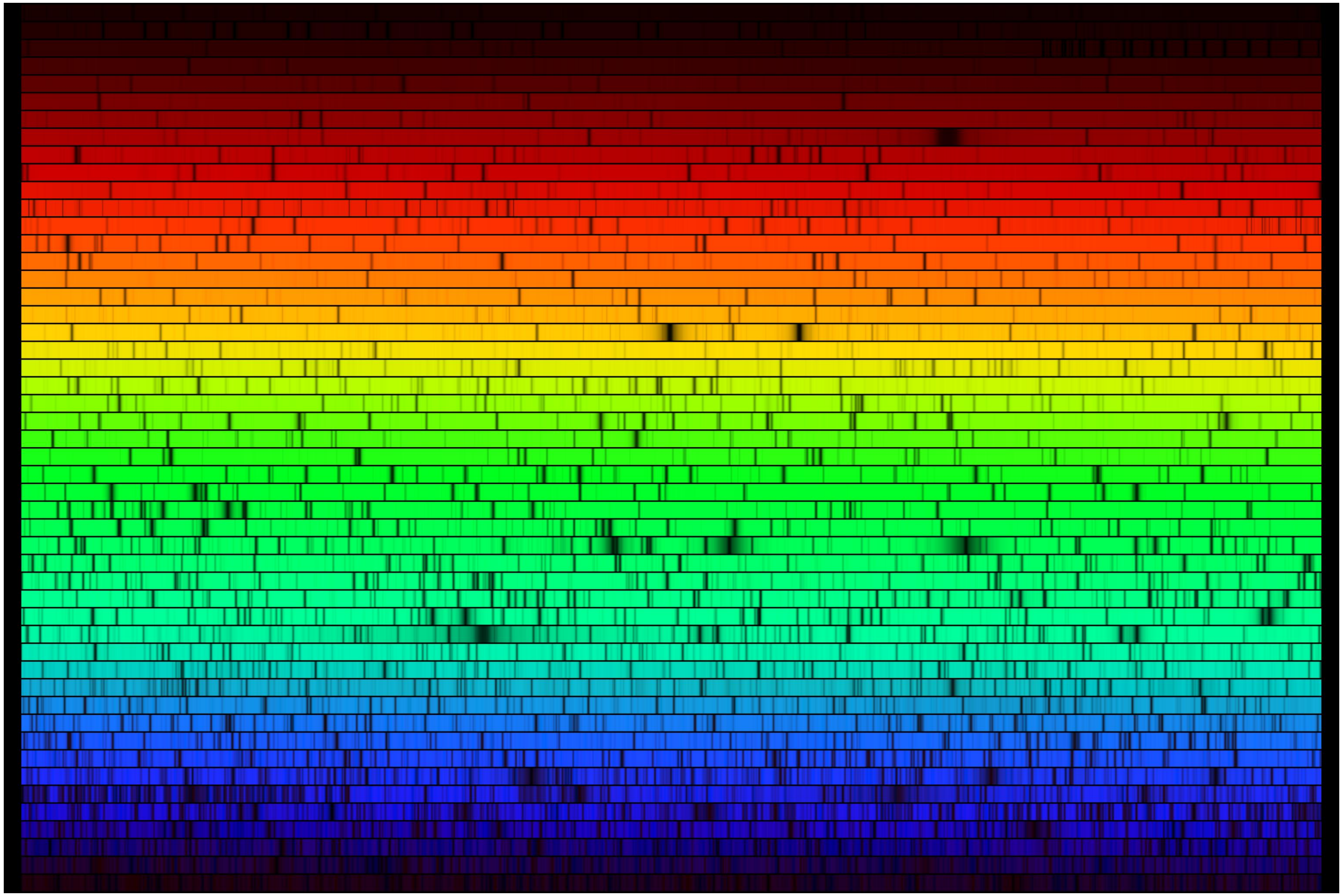


Betelguese(3100-3900K)

Rigel (8000-13,000K)

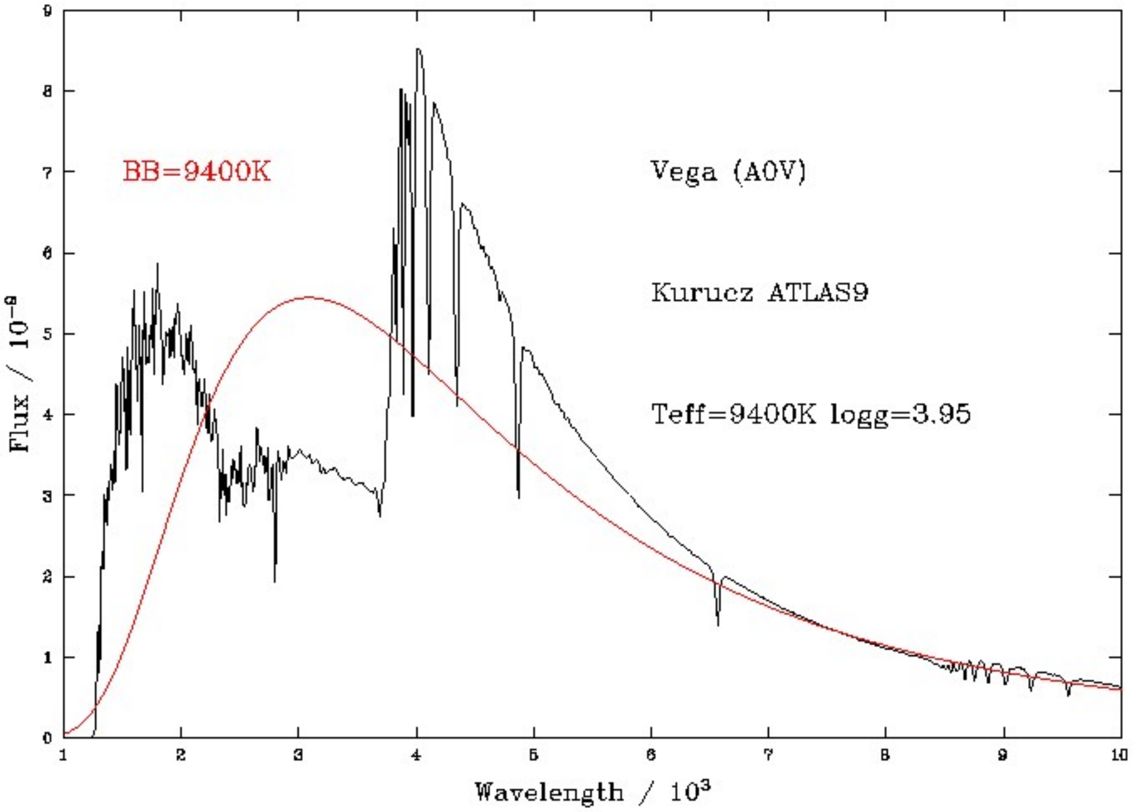
What does the color of a celestial object tell us?

Line Spectrum (e.g. Sun)



Fraunhofer (1814)

Continuous Spectrum (e.g. Vega)



What is a stellar atmosphere?

- Thin, tenuous transition zone between (invisible) stellar interior and (essentially vacuum) exterior.
- The `photosphere’ is the visible disk, whilst the `atmosphere’ also includes coronae and winds.
- In contrast with the interior, where convection dominates, the energy transport mechanism of the atmosphere is radiation.
- Stellar atmospheres are primarily characterized by two parameters: (Teff, log g)

(T_{eff}, log g)

- Effective temperature (K), is defined by $L=4\pi R^2\sigma T_{eff}^4$ related to *ionization*.
- Surface gravity (cm/s^2), $g = GM/R^2$, related to *pressure*.
- The Sun has T_{eff}=5777K, log g=4.44 – its atmosphere is only a few hundred km deep, <0.1% of the stellar radius.
- Solar atmosphere most easily studied during total eclipse (lunar limb occults at rate of 0.5 arcsec/s or 300km/s at 1AU, so brightness variation during last second before totality provides physical size).
- A red giant has log g~1 (extended atmosphere) whilst a white dwarf has log g~8 (no atmosphere).

Spectral Types

M-K (Morgan-Keenan) classification scheme orders stars via “OBAFGKM” spectral types using ratios of line strength. O-types have the bluest B-V & highest Teff’s . Each are subdivided into (up to) ten divisions – e.g. O2 .. O9, B0, B1 .. B9, A0, A1 .. etc

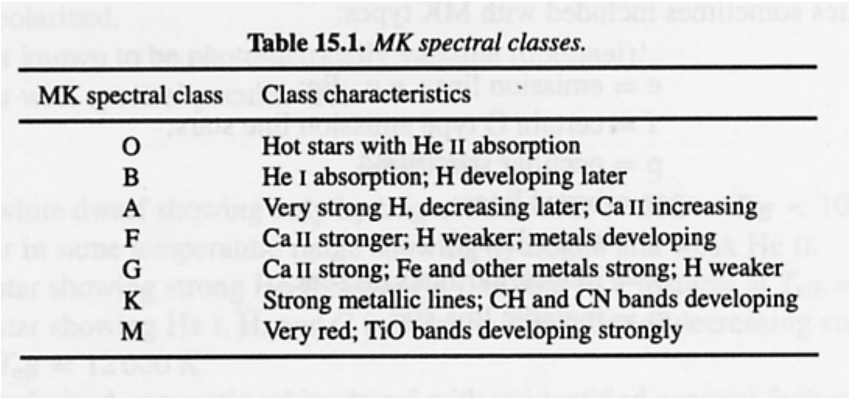


Table 15.1. *MK spectral classes.*

MK spectral class	Class characteristics
O	Hot stars with He II absorption
B	He I absorption; H developing later
A	Very strong H, decreasing later; Ca II increasing
F	Ca II stronger; H weaker; metals developing
G	Ca II strong; Fe and other metals strong; H weaker
K	Strong metallic lines; CH and CN bands developing
M	Very red; TiO bands developing strongly

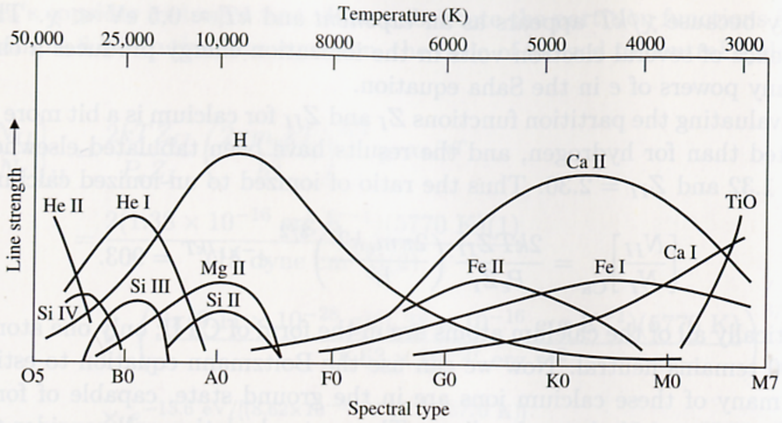
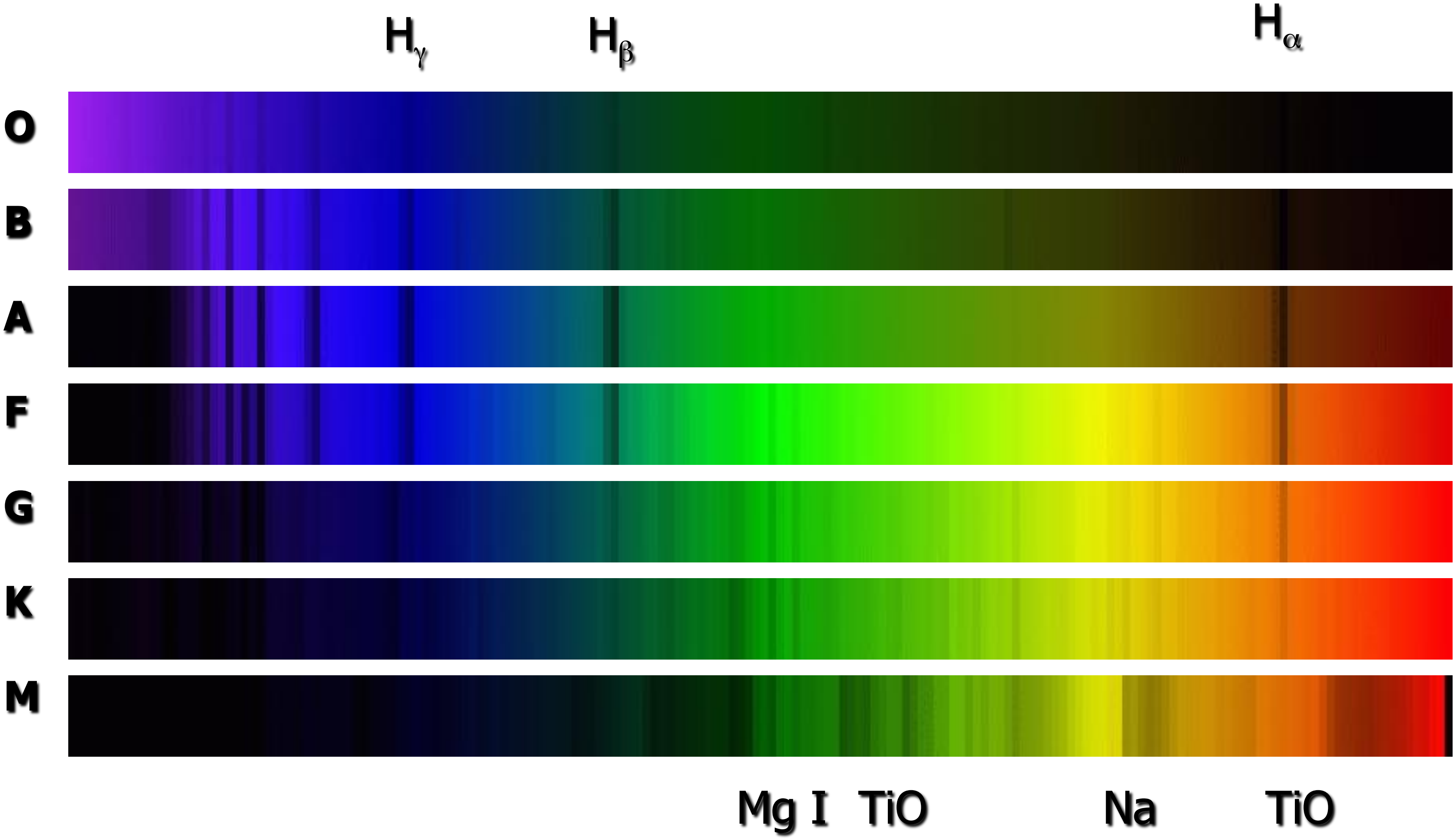


Figure 8.9 The dependence of spectral line strengths on temperature.

Stellar Spectra



Luminosity Class

Luminosity class information is often added from line widths:
V (dwarfs), III (giants), I (supergiants),
e.g. B0III is an early B giant, which is itself an `early-type' star (along with O and A-types), whilst cooler stars are `late-type'

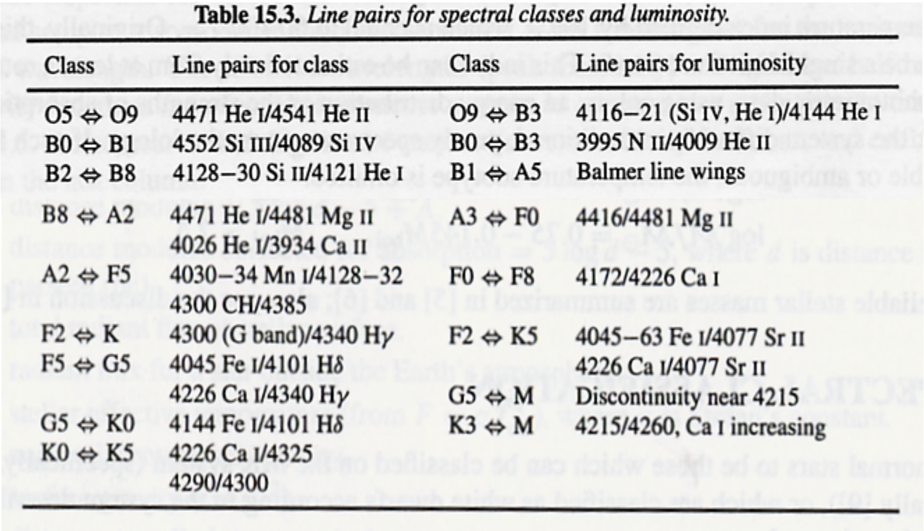


Table 15.3. *Line pairs for spectral classes and luminosity.*

Class	Line pairs for class	Class	Line pairs for luminosity
O5 ⇔ O9	4471 He I/4541 He II	O9 ⇔ B3	4116–21 (Si IV, He I)/4144 He I
B0 ⇔ B1	4552 Si III/4089 Si IV	B0 ⇔ B3	3995 N II/4009 He II
B2 ⇔ B8	4128–30 Si II/4121 He I	B1 ⇔ A5	Balmer line wings
B8 ⇔ A2	4471 He I/4481 Mg II	A3 ⇔ F0	4416/4481 Mg II
	4026 He I/3934 Ca II		
A2 ⇔ F5	4030–34 Mn I/4128–32	F0 ⇔ F8	4172/4226 Ca I
	4300 CH/4385		
F2 ⇔ K	4300 (G band)/4340 $H\gamma$	F2 ⇔ K5	4045–63 Fe I/4077 Sr II
F5 ⇔ G5	4045 Fe I/4101 $H\delta$		4226 Ca I/4077 Sr II
	4226 Ca I/4340 $H\gamma$	G5 ⇔ M	Discontinuity near 4215
G5 ⇔ K0	4144 Fe I/4101 $H\delta$	K3 ⇔ M	4215/4260, Ca I increasing
K0 ⇔ K5	4226 Ca I/4325		
	4290/4300		

Luminosity classes

- Ia bright supergiant
- Ib Supergiant
- II bright giant
- III giant
- IV subgiant
- V main-sequence star

Example Luminosity Classes

- Our Sun: G2 star on the Main Sequence:

G2V

- Polaris: G2 star with Supergiant luminosity:

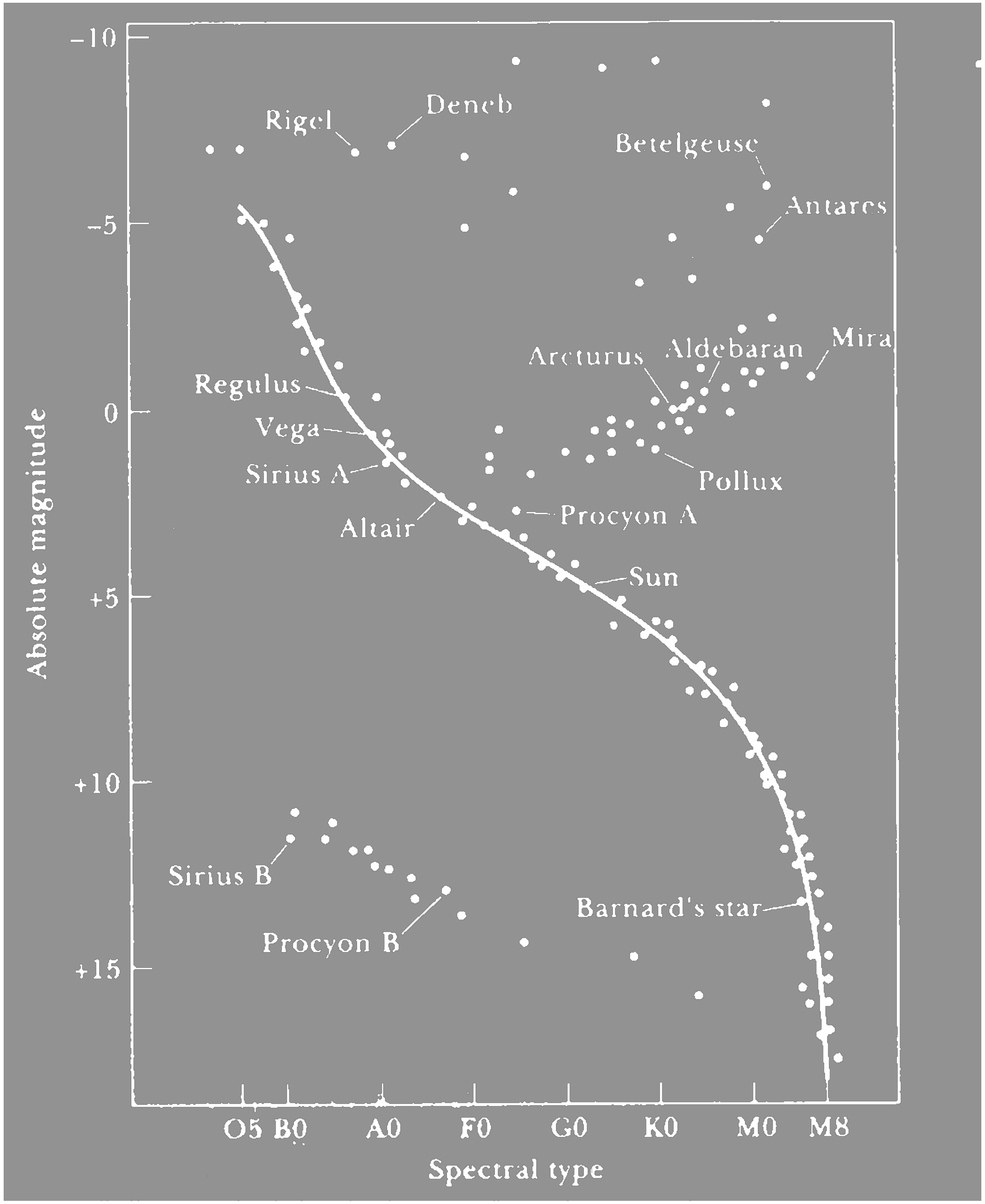
G2Ib

Stellar Spectra

Class	Colour	Temp. (x10^3 K)	Spectral lines	Examples
O	Blue-violet	28 – 50	Ionised atoms	z Pup[1], d Ori[2]
B	Blue-white	10 – 28	He, some H	a Vir[3], b Ori[4]
A	White	7.5 – 10	Strong H, some ionised metals	a Cma[5], a Lyr[6]
F	Yellow-white	6 – 7.5	H and Ca^{n+}, Fe^{n+}.	a Car[7], a Cmi[8]
G	Yellow	5 – 6	Ca^{n+}, other ionised and neutral metals	Sun, a Aur[9]
K	Orange	3.5 – 5	Neutral metals	a Boo[10], a Tau[11]
M	Red-orange	2.5 – 3.5	TiO and Ca	a Sco[12], a Ori[13]

Common names: [1]Naos, [2]Mintaka, [3]Spica, [4]Rigel, [5]Sirius, [6]Vega, [7]Canopus, [8]Procyon, [9]Capella, [10]Arcturus, [11]Aldebaran, [12]Antares

- H-R Diagram for a number of the brightest and nearest stars



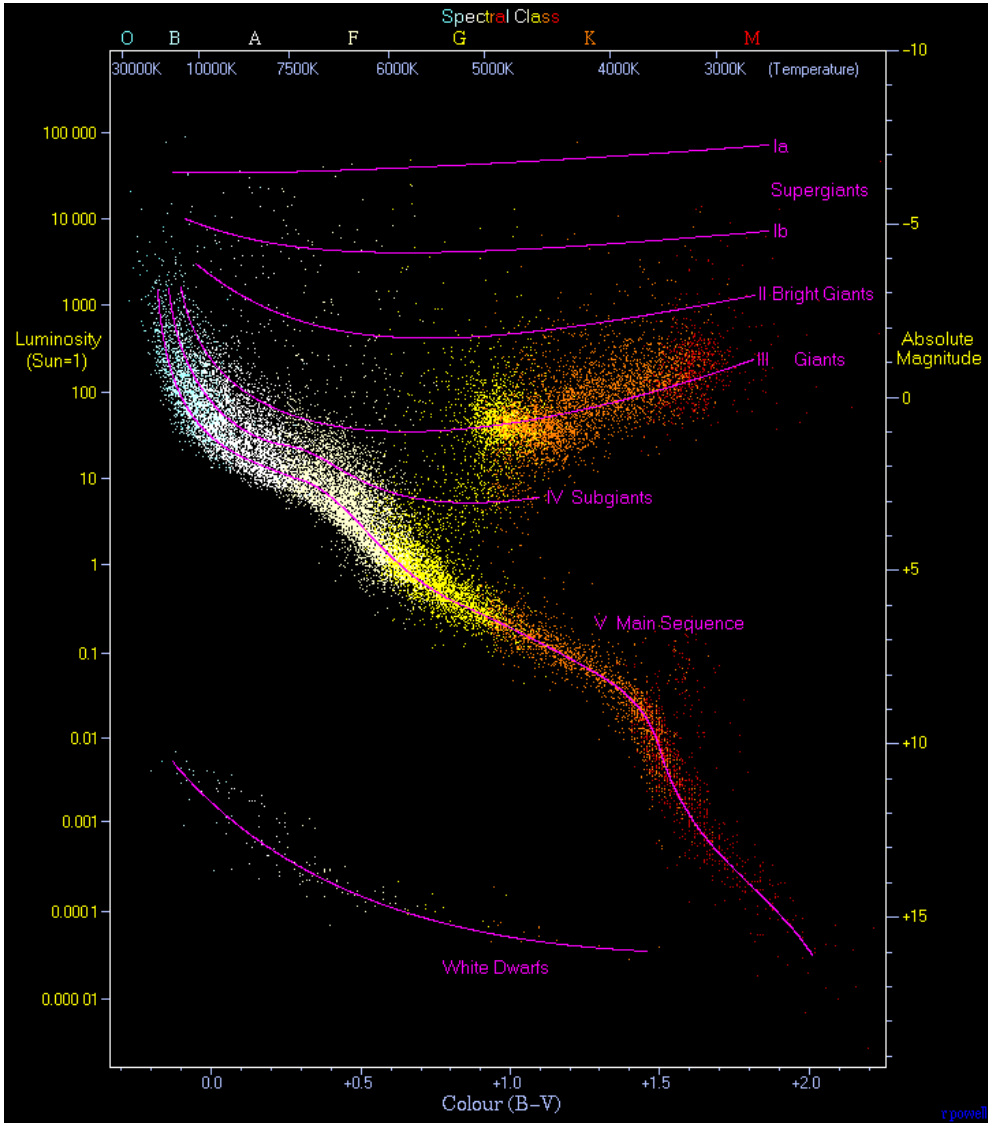
The H-R Diagram

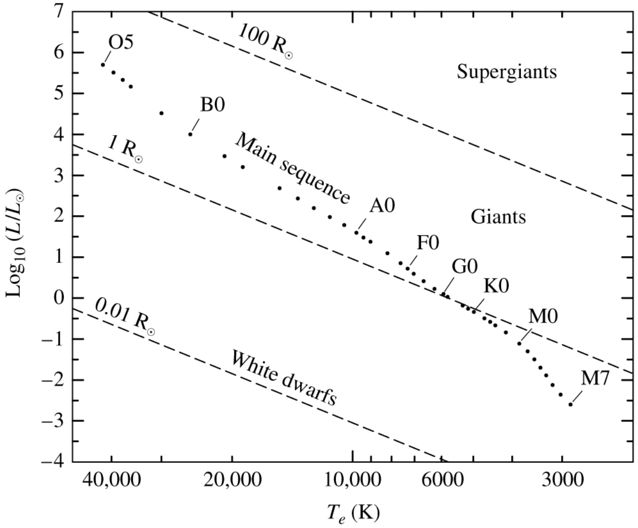
- Points to note:
  - The narrow band of stars scattered close to the solid line.
  - Most stars occur along this band – an indication that this is where stars spend most of their lives. For this reason, it is known as the *Main Sequence*.

The H-R Diagram

- Other regions to note are stars of high luminosity but low temperature (indicating they are large – hence the term *red giant*) and stars of high temperature but low luminosity (indicating small diameters, hence *white dwarf*)
- As we shall see, the H-R diagram is extremely useful in many aspects of stellar physics

Hertzsprung-Russell Diagram





Magnitude scale

- We measure the flux F from astronomical objects via a logarithmic magnitude scale (like the eye).
- A star which is 5 mags more negative than another implies it is a factor of 100 times brighter
- Often involves broad-band filters (UBV at optical wavelengths), e.g. for V-band

  $m_v - m_0 = -2.5 \log(F_v/F_0)$
- Vega (A0V) defines the photometric `zero point' m_0 at all wavelengths (U=B=V=0.0 mag etc).

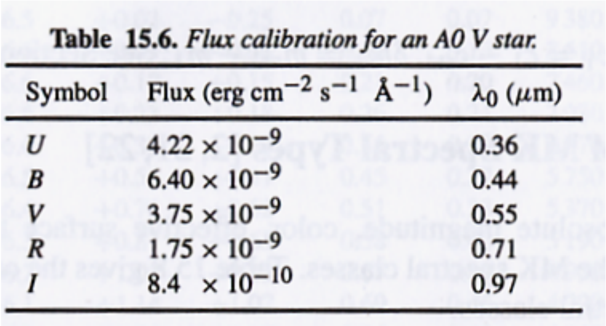


Table 15.6. *Flux calibration for an A0 V star.*

Symbol	Flux (erg cm^{-2} s^{-1} $Å^{-1}$)	λ_0 (μm)
U	4.22×10^{-9}	0.36
B	6.40×10^{-9}	0.44
V	3.75×10^{-9}	0.55
R	1.75×10^{-9}	0.71
I	8.4×10^{-10}	0.97

IR magnitudes

Vega (or Sirius) also defines `zero point’ in Infrared. IR filters chosen to match transmission through Earth’s atmosphere which is low at some wavelengths even from high, dry sites such as Mauna Kea:

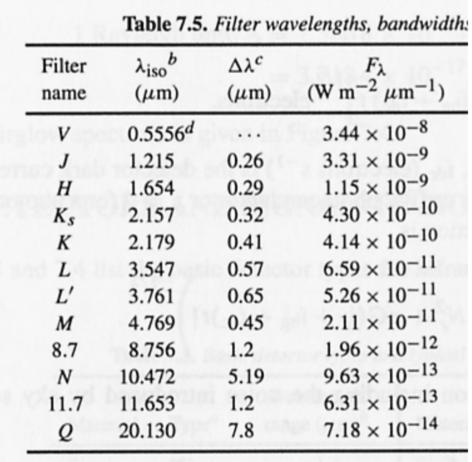
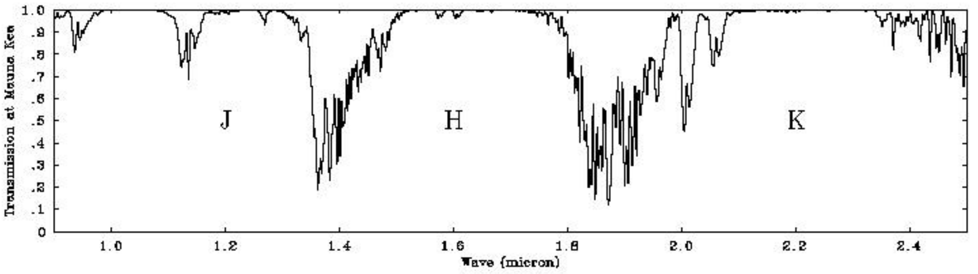
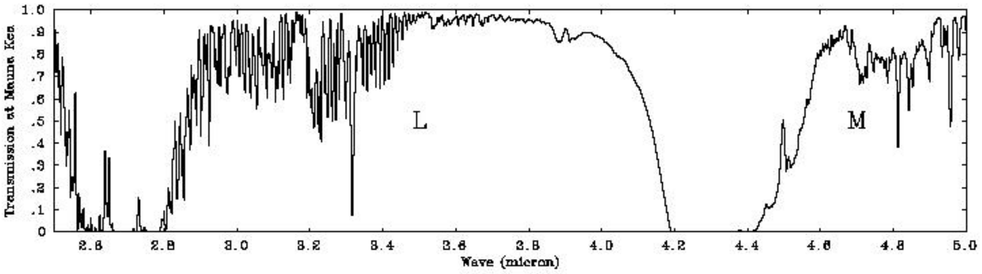


Table 7.5. *Filter wavelengths, bandwidths*

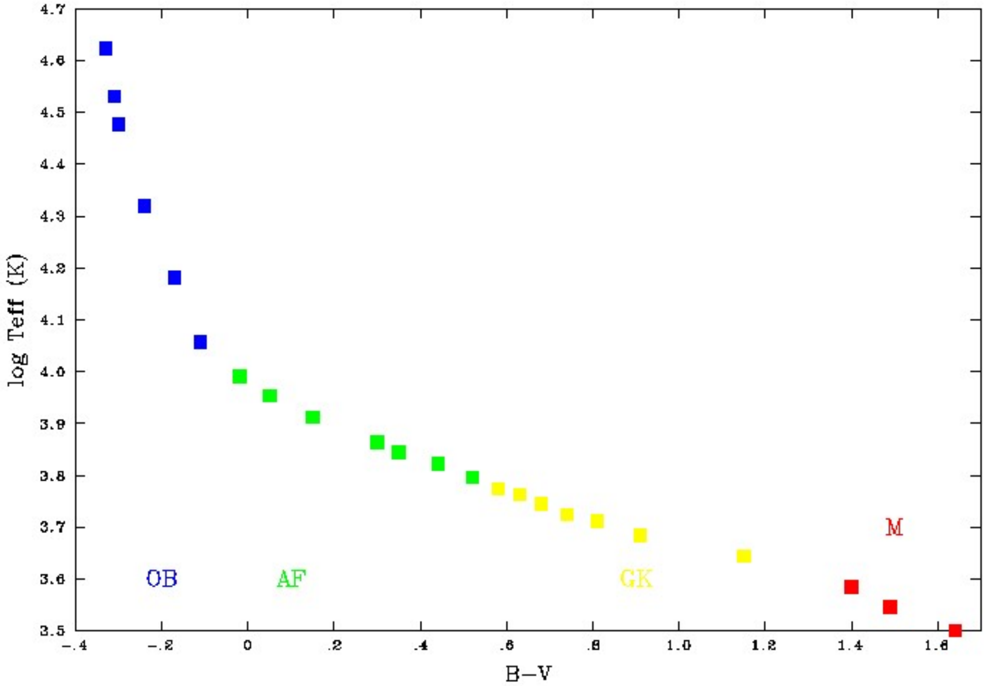
Filter name	$\lambda_{\mathrm{iso}}{}^{b}$ (μm)	$\Delta\lambda^{c}$ (μm)	F_λ (W m^{-2} μm^{-1})
V	0.5556^{d}	…	3.44×10^{-8}
J	1.215	0.26	3.31×10^{-9}
H	1.654	0.29	1.15×10^{-9}
K_s	2.157	0.32	4.30×10^{-10}
K	2.179	0.41	4.14×10^{-10}
L	3.547	0.57	6.59×10^{-11}
L'	3.761	0.65	5.26×10^{-11}
M	4.769	0.45	2.11×10^{-11}
8.7	8.756	1.2	1.96×10^{-12}
N	10.472	5.19	9.63×10^{-13}
11.7	11.653	1.2	6.31×10^{-13}
Q	20.130	7.8	7.18×10^{-14}





Colour index

We can define a colour index as the difference between filters relative to Vega e.g. B-V = m_B-$m_{V,}$ such that stars bluer than A0 have a –ve B-V colour and red stars a +ve colour. The Sun has B-V=+0.65 mag.



More on magnitudes

- We define the absolute (visual) magnitude (M_V) as the apparent (visual) magnitude of a star of m_V lying at a distance of 10pc:

$$M_V = m_V - 5\log(d/pc) + 5 - A_V.$$

- For the Sun ($d=4.85\ 10^{-6}$ pc), $m_V=-26.75$ and $M_V=+4.82$ mag. The distance modulus is M_v-m_v.

- Interstellar extinction requires the A_V term, where $A_V\sim 3.1\ E(B-V)$ for most sight lines with

$$E(B-V) = B-V - (B-V)_o,$$

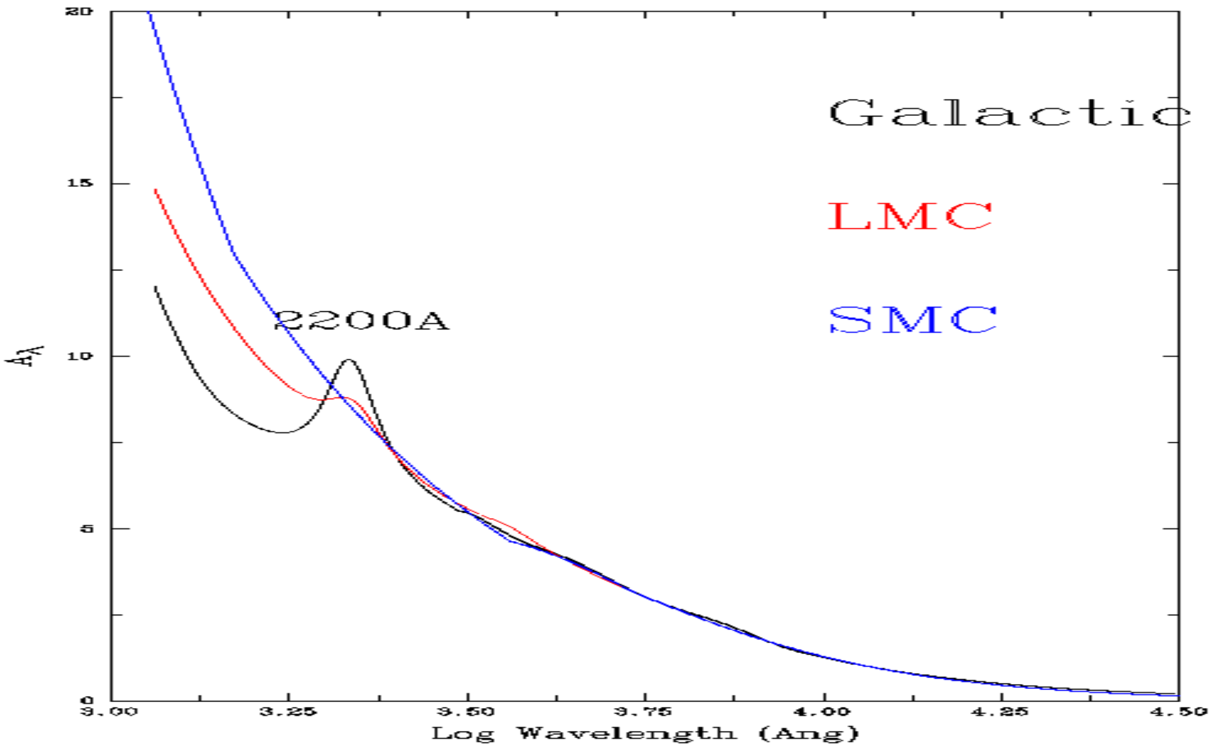
i.e. the difference between the observed and intrinsic colour.

Interstellar Reddening

One also needs to correct color indices for interstellar reddening. As the light propagates through interstellar dust, the blue light is scattered preferentially making objects appear to be redder than they actually are…

Interstellar Extinction

Extinction is MUCH higher at shorter wavelengths, so IR observations of e.g. Milky Way disk probe much further. The extinction to the Galactic Centre (8kpc) is approx A_V=30 mag (at 5500A) versus A_K=3 mag (at 2micron).



Bolometric Flux

The bolometric flux from a star (erg cm^{-2} s^{-1}) received at the top of the Earth's atmosphere is the integral of the spectral flux (measured at a frequency $F\nu$) over all wavelengths:

$$F_{Bol} = \int_0^\infty F_\nu d\nu$$

The luminosity (erg/s) is the bolometric flux from the star integrated over a full sphere (at distance d):

$$L = 4\pi d^2 F_{Bol}$$

Since the Earth's atmosphere is opaque to UV and some IR radiation one cannot always directly measure the bolometric flux.

Bolometric Corrections

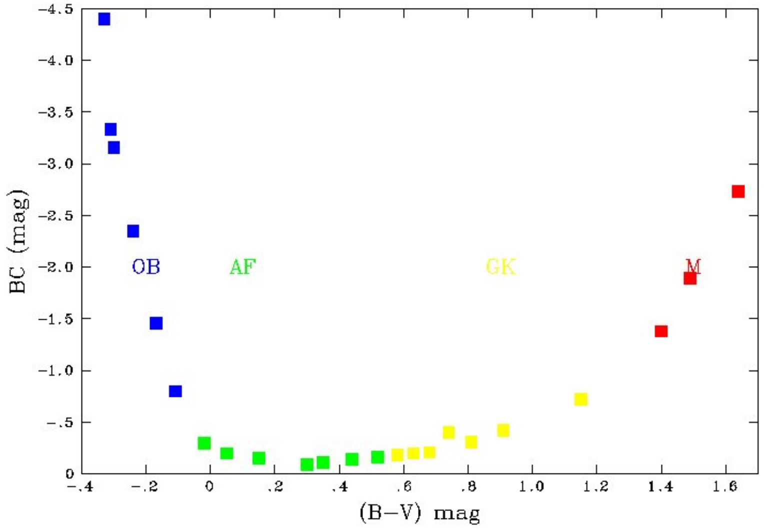
One can calculate bolometric corrections (BC) from atmospheric models to correct measured fluxes (usually in the V band) for the total flux. Usually expressed in magnitudes:

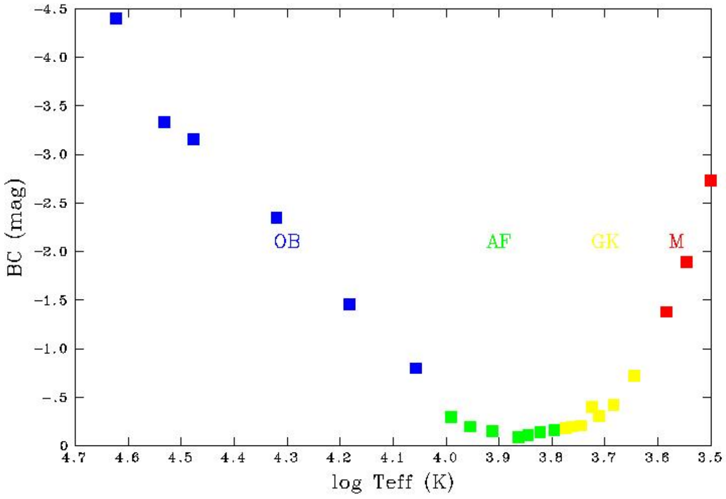
$$BC = M_{bol} - M_V \quad \text{with} \quad M_{bol} = 4.74 - 2.5\log(L/L_{\odot})$$

BC=-0.08 mag for the Sun is a small correction since it emits most radiation in the visual. Hot OB stars have very negative BC's, since most of the energy is emitted in the UV, as are cool M stars with most energy emitted in the IR.

Bolometric Corrections

Bolometric corrections can be estimated from intrinsic colours (B-V)o as shown here for dwarfs:





Or from the Spectral Type, using a Teff-Spectral Type calibration (e.g. Astrophysical Quantities see next slide)

Properties of Main-Sequence Stars

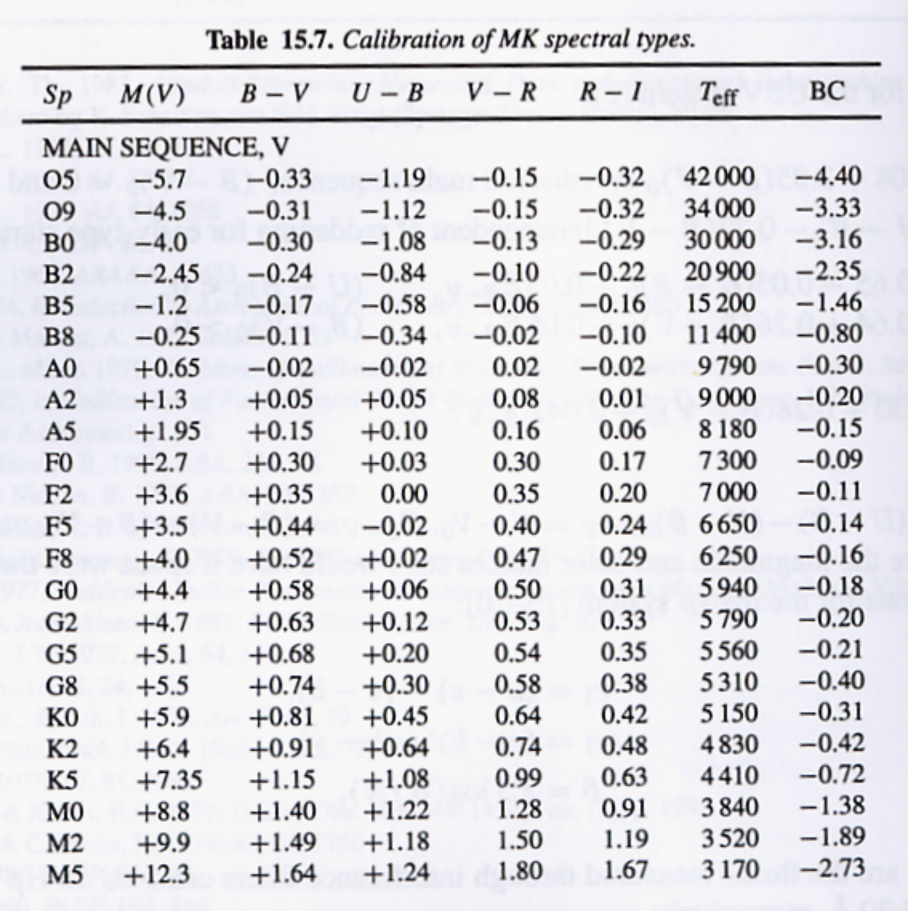


Table 15.7. *Calibration of MK spectral types.*

Sp	*M(V)*	*B − V*	*U − B*	*V − R*	*R − I*	T_{eff}	BC
MAIN SEQUENCE, V							
O5	−5.7	−0.33	−1.19	−0.15	−0.32	42 000	−4.40
O9	−4.5	−0.31	−1.12	−0.15	−0.32	34 000	−3.33
B0	−4.0	−0.30	−1.08	−0.13	−0.29	30 000	−3.16
B2	−2.45	−0.24	−0.84	−0.10	−0.22	20 900	−2.35
B5	−1.2	−0.17	−0.58	−0.06	−0.16	15 200	−1.46
B8	−0.25	−0.11	−0.34	−0.02	−0.10	11 400	−0.80
A0	+0.65	−0.02	−0.02	0.02	−0.02	9 790	−0.30
A2	+1.3	+0.05	+0.05	0.08	0.01	9 000	−0.20
A5	+1.95	+0.15	+0.10	0.16	0.06	8 180	−0.15
F0	+2.7	+0.30	+0.03	0.30	0.17	7 300	−0.09
F2	+3.6	+0.35	0.00	0.35	0.20	7 000	−0.11
F5	+3.5	+0.44	−0.02	0.40	0.24	6 650	−0.14
F8	+4.0	+0.52	+0.02	0.47	0.29	6 250	−0.16
G0	+4.4	+0.58	+0.06	0.50	0.31	5 940	−0.18
G2	+4.7	+0.63	+0.12	0.53	0.33	5 790	−0.20
G5	+5.1	+0.68	+0.20	0.54	0.35	5 560	−0.21
G8	+5.5	+0.74	+0.30	0.58	0.38	5 310	−0.40
K0	+5.9	+0.81	+0.45	0.64	0.42	5 150	−0.31
K2	+6.4	+0.91	+0.64	0.74	0.48	4 830	−0.42
K5	+7.35	+1.15	+1.08	0.99	0.63	4 410	−0.72
M0	+8.8	+1.40	+1.22	1.28	0.91	3 840	−1.38
M2	+9.9	+1.49	+1.18	1.50	1.19	3 520	−1.89
M5	+12.3	+1.64	+1.24	1.80	1.67	3 170	−2.73

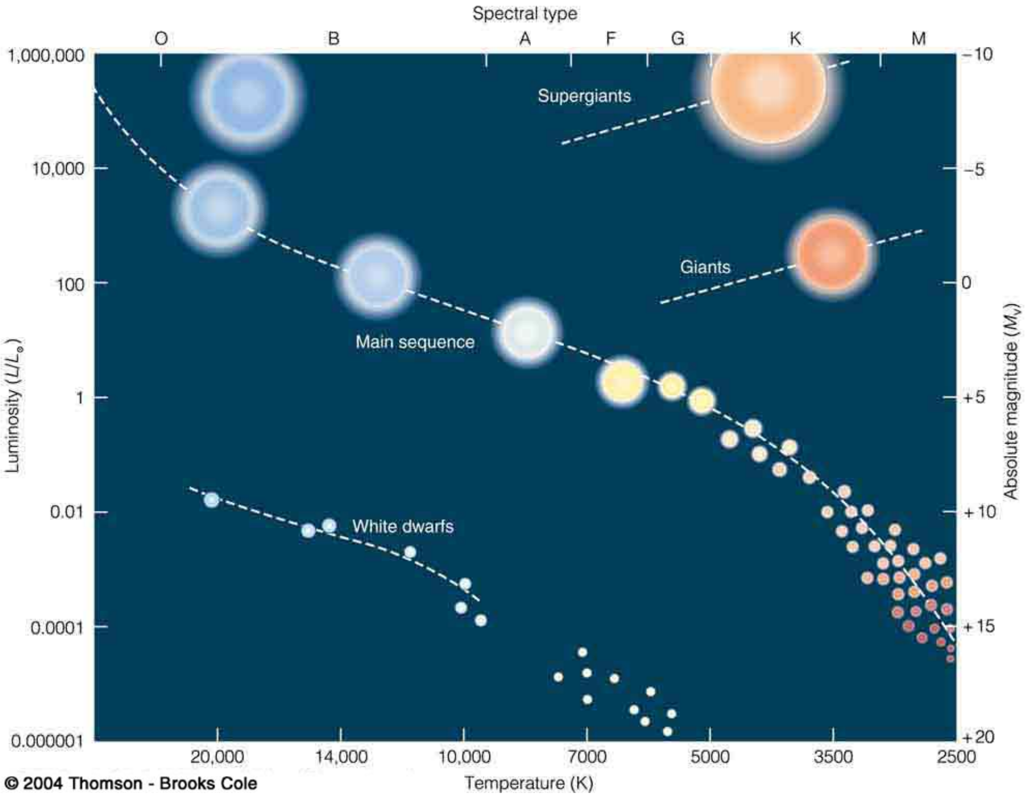
Example

- *A B0V in the LMC (distance 50kpc) has V=13.0 mag and B-V=-0.20 mag. What is its bolometric luminosity, relative to the Sun?*

1. From the Table, E(B-V)=(B-V)-(B-V)o=0.1 mag for a B0 dwarf, so A_V=0.3 mag (the star is lightly reddened).
2. Using $M_V=m_V-5\log(d/pc)+5-A_V$, we obtain M_v=13-23.5+5-0.3=-5.8 mag.
3. From the Table, BC(B0V)=-3.16, so $-3.16=M_{bol}-(-5.8)$, hence M_{bol}=-9 mag
4. From $M_{bol}=4.74-2.5\times\log(L/L_{\odot})$, we obtain $\log(L/L_{\odot})=5.5$, some 300,000 times brighter than the Sun after integrating over all λ

H-R diagram

- 90% of stars are on the main sequence and obey the mass-luminosity dependence $L \sim M^{3.5}$
- Stars on the main sequence generate energy due to nuclear fusion of hydrogen
- In the end of their lives stars move to the upper right corner of the H-R diagram



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Check this hypothesis

- Mass should be most important parameter
- It determines the pressure in the star center and the central temperature
- It determines the surface temperature

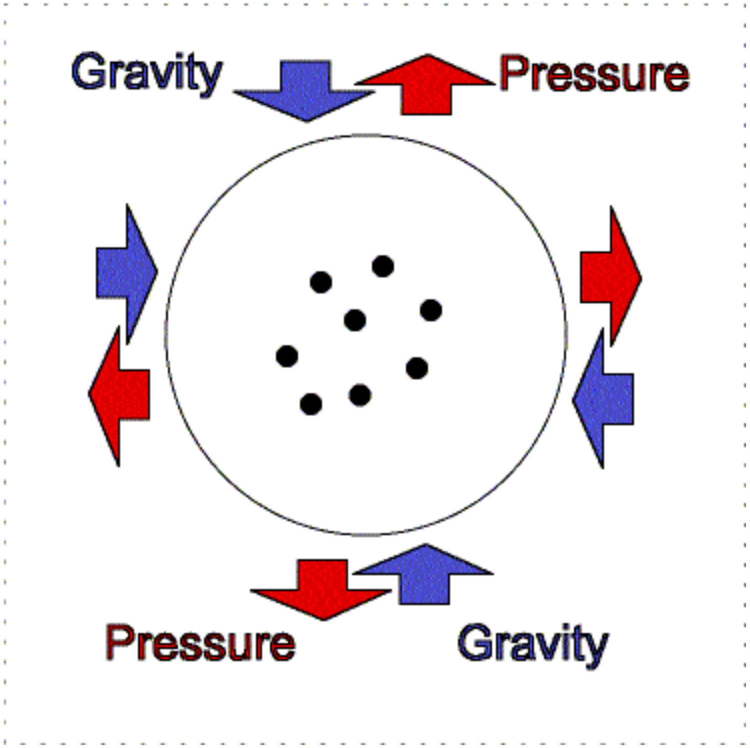
$$L \propto M^{3.5}$$

$$\frac{L}{L_{sun}} = \left(\frac{M}{M_{sun}} \right)^{3.5}$$

Gravity Holds a Star Together

Stars are held together by gravity. Gravity tries to compress everything to the center. What holds an ordinary star up and prevents total collapse is thermal and radiation pressure. The thermal and radiation pressure tries to expand the star layers outward to infinity.

1. Newton's gravitation law
2. Hydrostatic equilibrium
3. Equation of state
4. Energy transport



Mass determines all star's properties

$$\text{Lifetime} = \frac{\text{Amount of hydrogen fuel}}{\text{Rate of energy loss}}$$

Lifetime $T \sim M/L \sim 1/M^{3.5-1} = 1/M^{2.5}$

$M = 4M_{\odot}$;

$$\frac{T}{T_{sun}} = \left(\frac{M_{sun}}{M}\right)^{2.5} = \frac{1}{32}$$

$T \sim 3\text{x}10^{8}$ years

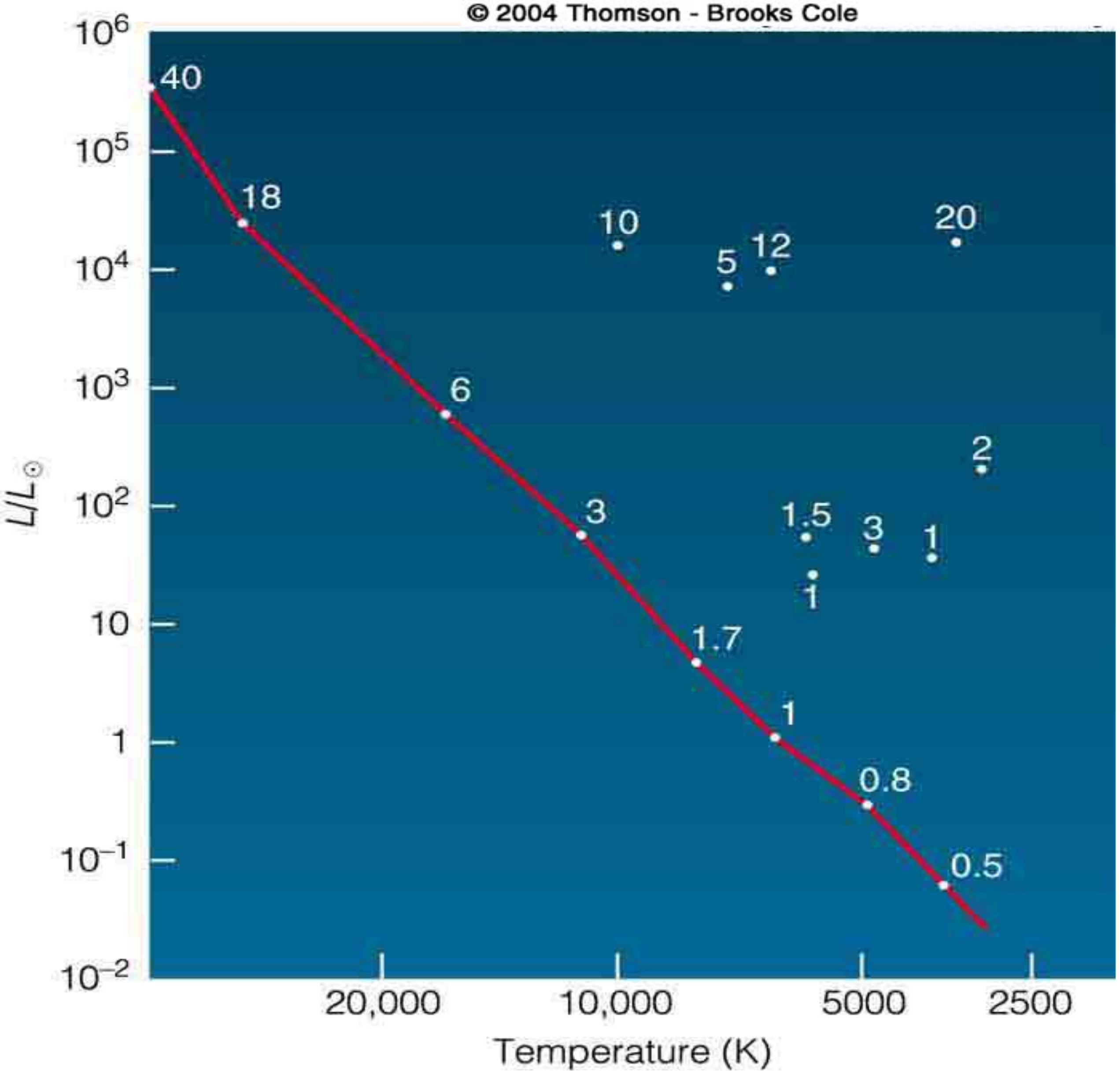
star mass (solar masses)	time (years)	Spectral type
60	3 million	O3
30	11 million	O7
10	32 million	B4
3	370 million	A5
1.5	3 billion	F5
1	10 billion	G2 (Sun)
0.1	1000's billions	M7

TABLE 9-2

Main-Sequence Stars

Spectral Type	Mass (Sun = 1)	Luminosity (Sun = 1)	Years on Main Sequence
O5	40	405,000	1×10^6
B0	15	13,000	11×10^6
A0	3.5	80	440×10^6
F0	1.7	6.4	3×10^9
G0	1.1	1.4	8×10^9
K0	0.8	0.46	17×10^9
M0	0.5	0.08	56×10^9

How to explain the cutoff at masses > 100 M_{sun} and < 0.08 M_{sun}

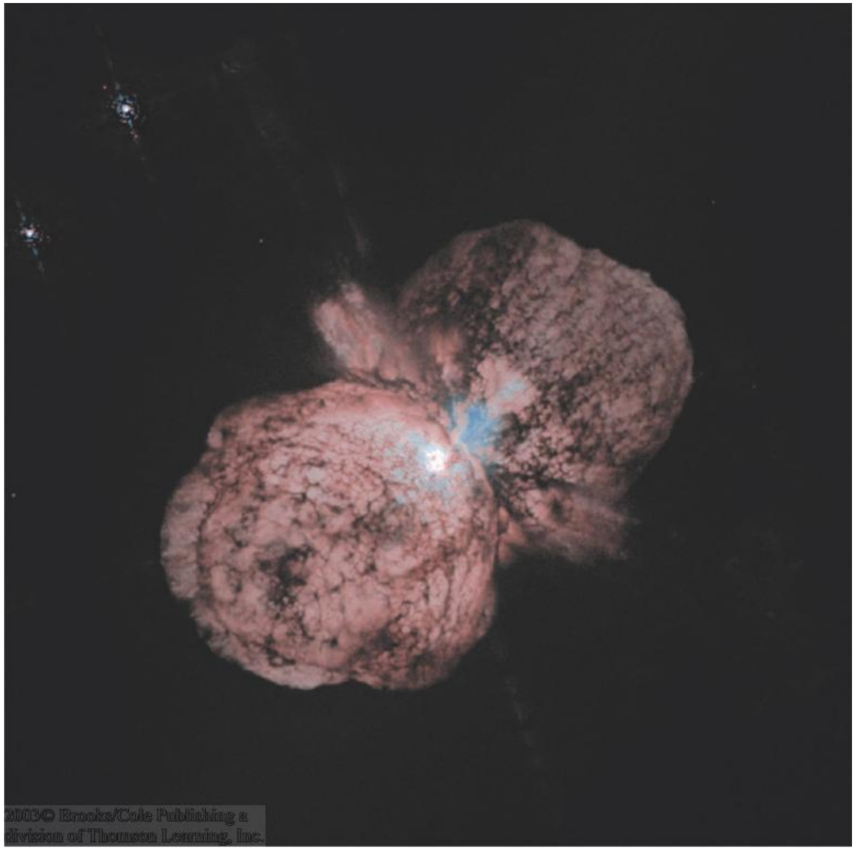


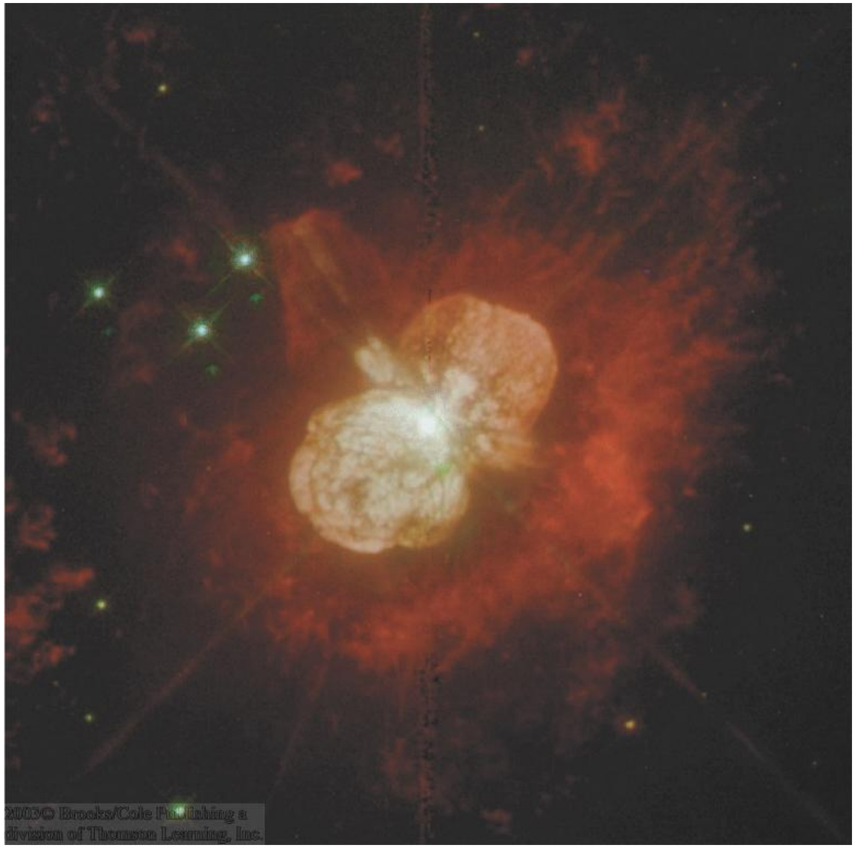
Maximum Masses of Main-Sequence Stars

M_{max} ~ 50 - 100 solar masses

a) More massive clouds fragment into smaller pieces during star formation.

b) Very massive stars lose mass in strong stellar winds



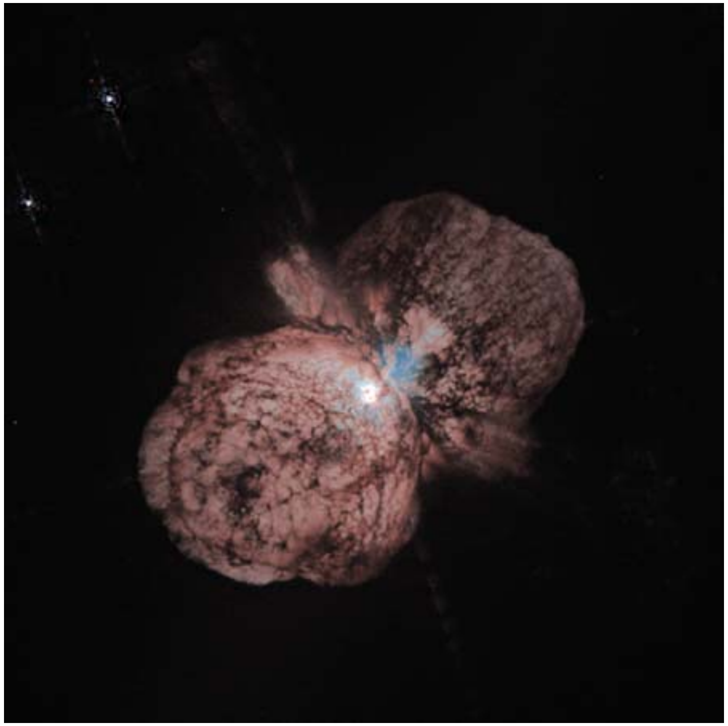


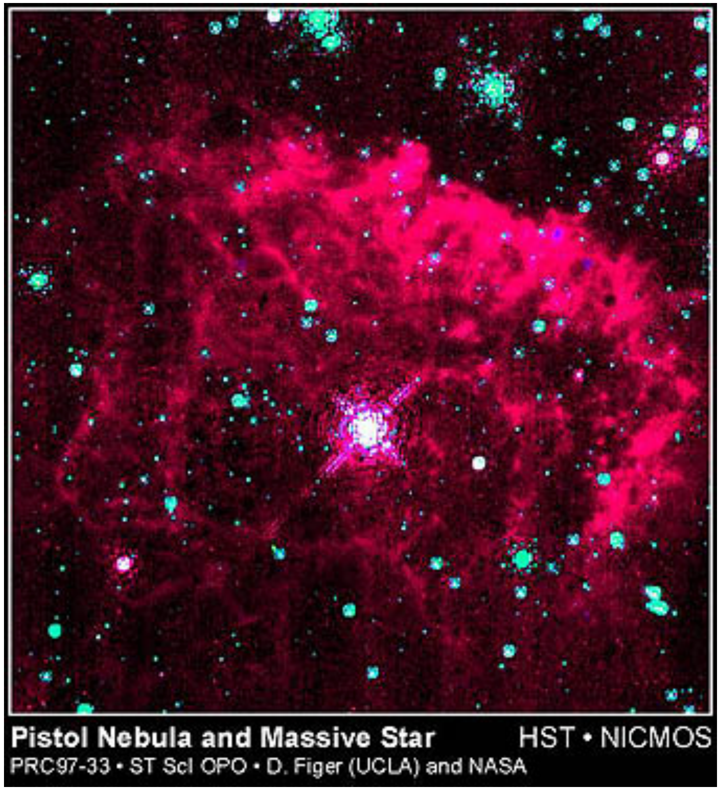
Example: η Carinae: Binary system of a 60 M_{sun} and 70 M_{sun} star. Dramatic mass loss; major eruption in 1843 created double lobes.

High-mass cutoff at $M \sim 100\ M_{sun}$

Too massive and luminous stars throw off their outer layers due to radiation pressure

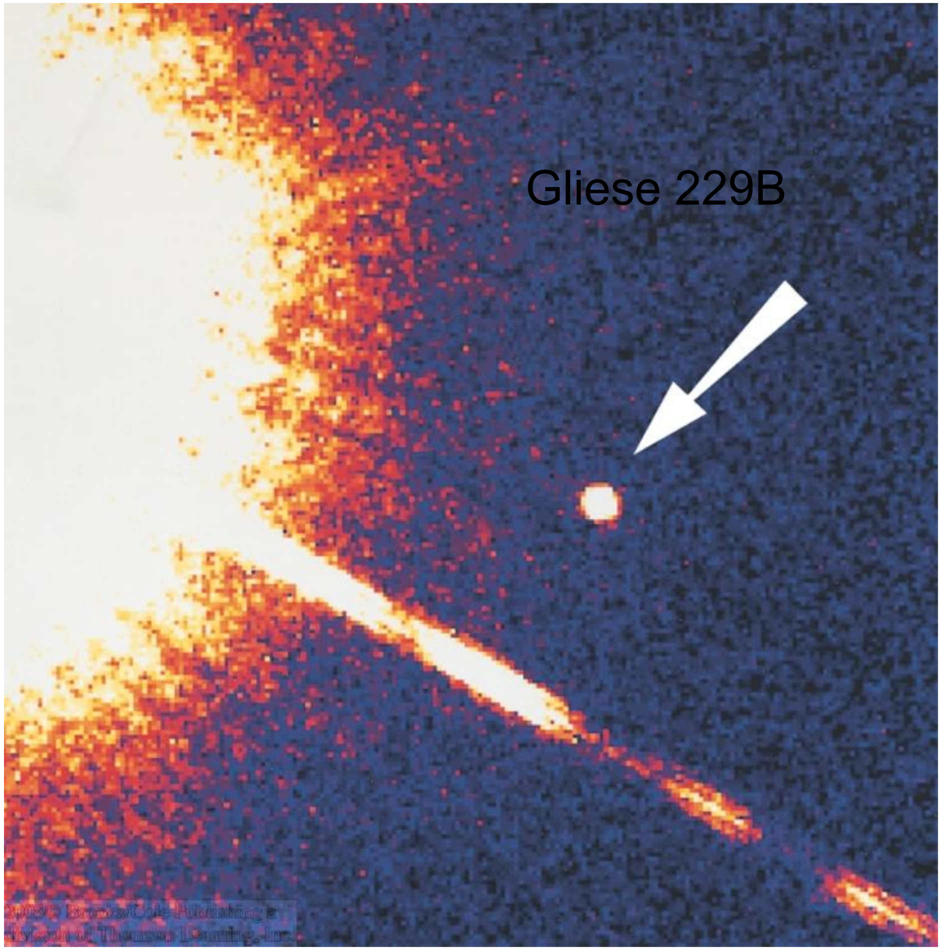
Eta Carinae





Minimum Mass of Main-Sequence Stars

$M_{min} = 0.08\ M_{sun}$

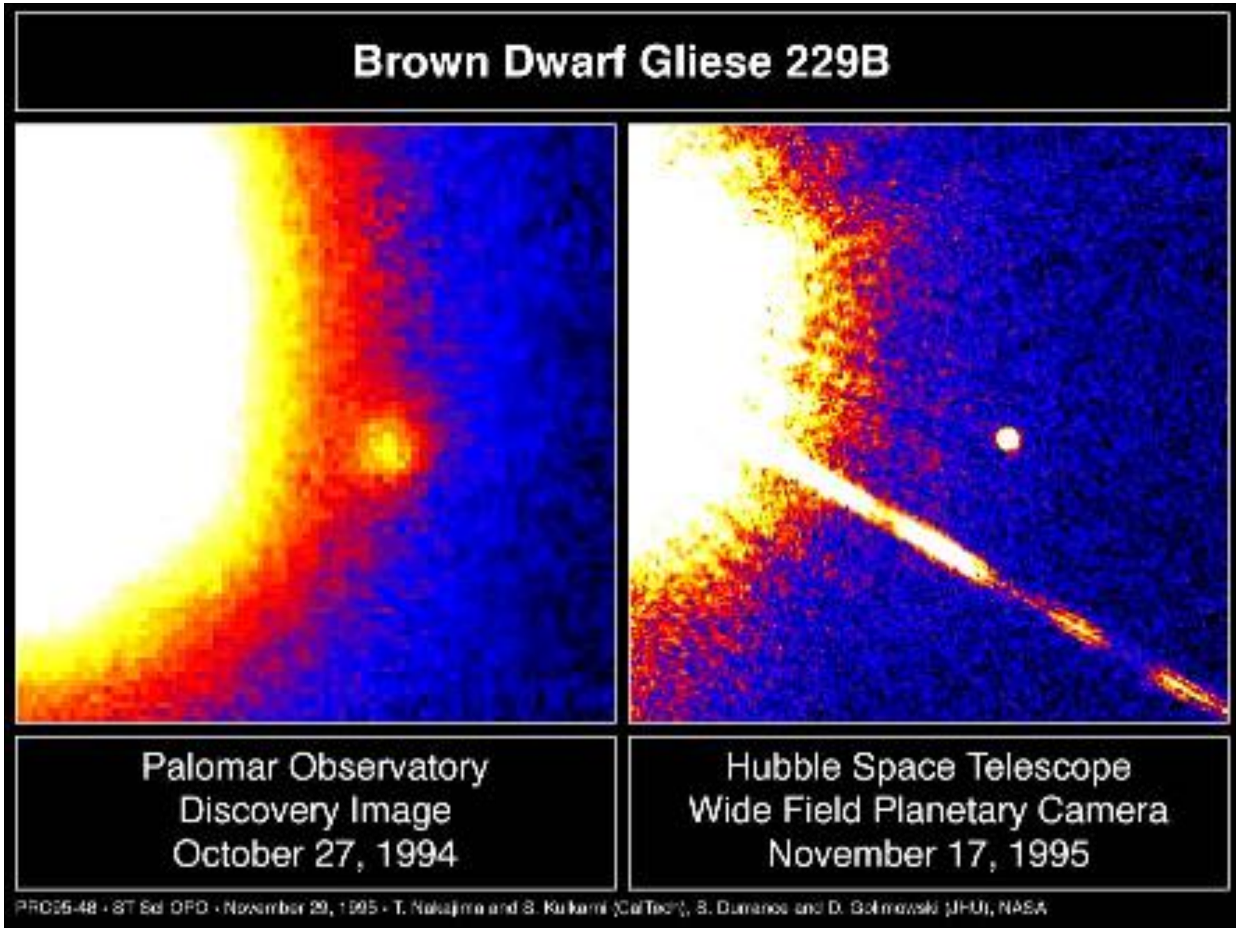


At masses below 0.08 M_{sun}, stellar progenitors do not get hot enough to ignite thermonuclear fusion.

→ Brown Dwarfs

Low-mass cutoff of the main sequence: M ~ 0.08 M_{sun}

Brown dwarfs: temperature is too low to ignite nuclear fusion



Brown Dwarf Gliese 229B

Palomar Observatory
Discovery Image
October 27, 1994

Hubble Space Telescope
Wide Field Planetary Camera
November 17, 1995

PRC95-48 · ST ScI OPO · November 29, 1995 · T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA

Gliese 229B: only 0.02 M_{sun}

Conclusion

Based on this evidence, we conclude:

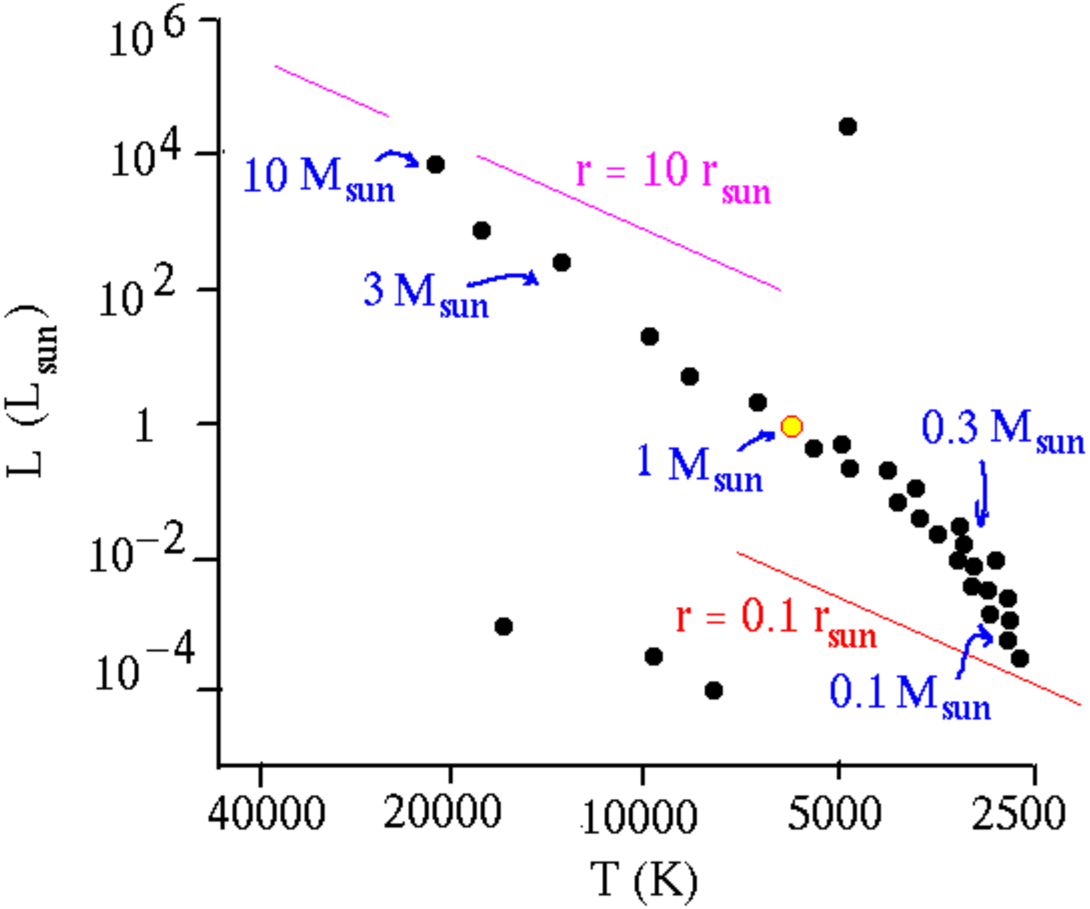
Stars spend most of their lives as main sequence stars.

During its lifetime, the surface temperature and luminosity stays almost constant.

- Something else could happen in the star birth process.
- Something else could happen in the star death process.

The star's mass determines what the temperature and luminosity is during the star's main sequence lifetime.

- More mass -> hotter.
- More mass -> more luminous.
- Also, more mass -> bigger.

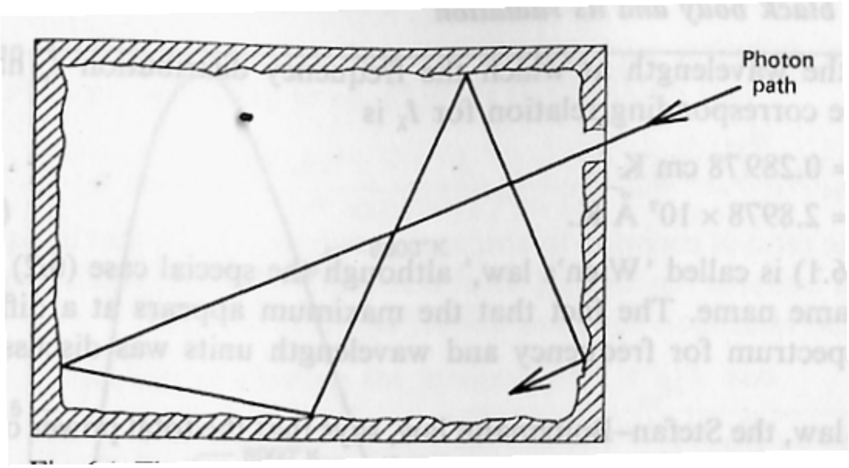


Radiation Terms

Black body radiation (Planck function)
Effective Temperature (Stefan-Boltzmann)
Specific and mean Intensity

The Black Body

Imagine a box which is completely closed except for a small hole. Any light entering the box will have a very small likely hood of escaping & will eventually be absorbed by the gas or walls. For constant temperature walls, this is in thermodynamic equilibrium.



If this box is heated the walls will emit photons, filling the inside with radiation. A small fraction of the radiation will leak out of the hole, but so little that the gas within it remains in equilibrium. The emitted radiation is that of a black-body. Stars share properties of the black-body emitter, in the sense that a negligibly small fraction of the radiation escapes from each.

Stars do differ from black bodies

The observed flux distributions of real stars deviate from black body curves, as indicated here for the UBV colours of dwarfs and supergiants. This difference is due to sources of continuous and line opacity in the stellar photospheres.