Stellar Atmospheres
(765629S)

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Contact details

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Aim of the Course

- The course aims on giving the students basic knowledge about physics of formation of stellar spectra and radiation transport,
- The student should know in the end of the course the main opacity sources in various types of stars, understand theory of line formation and be able to determine chemical composition from stellar spectra.

Course Plan

- Introduction
- Radiation terms and definitions
- Stellar photospheres
- Stellar atmospheres
- Stellar winds
- Interstellar Medium
- Accretion disks
- …

Syllabus (1)

1. **Introduction:** What is a stellar atmosphere? Spectral Types, Luminosity Classes, Magnitudes, Bolometric Flux and Bolometric Correction
2. **Radiation terms:** Blackbody radiation, Effective Temperature, Specific Intensity, Flux, Optical depth, Source function
3. **Local Thermodynamic Equilibrium (LTE):** Maxwellian distribution, Boltzmann and Saha equations
4. **Radiation transfer equation:** basic definitions and solutions
5. **Radiative Transfer:** Parallel ray and plane-parallel transfer equation, surface intensity, limb darkening, Eddington-Barbier relation, Eddington approximation, grey atmosphere, radiative equilibrium

Syllabus (2)

6. **Continuous absorption:** bound-bound, bound-free, free-free opacity, atomic H, H- ion, He, metals, molecules, Thompson & Rayleigh scattering
7. **Temperatures and pressures of stars:** Direct determination of radii, T_{eff} and P from discontinuities, hydrostatic equilibrium, electron pressure from gas pressure using Saha equation, radiation pressure, Eddington limit, electron degeneracy pressure
8. **Line formation:** Equivalent widths, line broadening, spectroscopic notation, optically thin and thick lines, curve of growth, abundances
9. **Deviations from LTE:** level populations, Einstein coefficients, statistical equilibrium equations

Syllabus (3)

10. **Stellar winds:** Solar wind, diagnostics and mechanisms of mass-loss from late- and early-type stars
11. **Recent developments:** Spectroscopic observations & models for supernovae, brown dwarfs
12. **Interstellar Medium**
13. **Accretion disks:** Emission and absorption spectra
14. **etc…**

Recommended Text Books

- E. Böhm-Vitense, *Introduction to Stellar Astrophysics: Vol 2*. CUP Available 1 paper book in the library.
- D. F. Gray, *Observations and analysis of stellar photospheres*, CUP Ordered
- Lecture notes (**not enough!**)

Assessment

Your grade will be based on:

- 70% Exams: intermediate and final
- 30% Homeworks: at least 5 sets of compulsory problems (return by the deadline)

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
- Angstrom, 1 Å = 10^{-8}cm

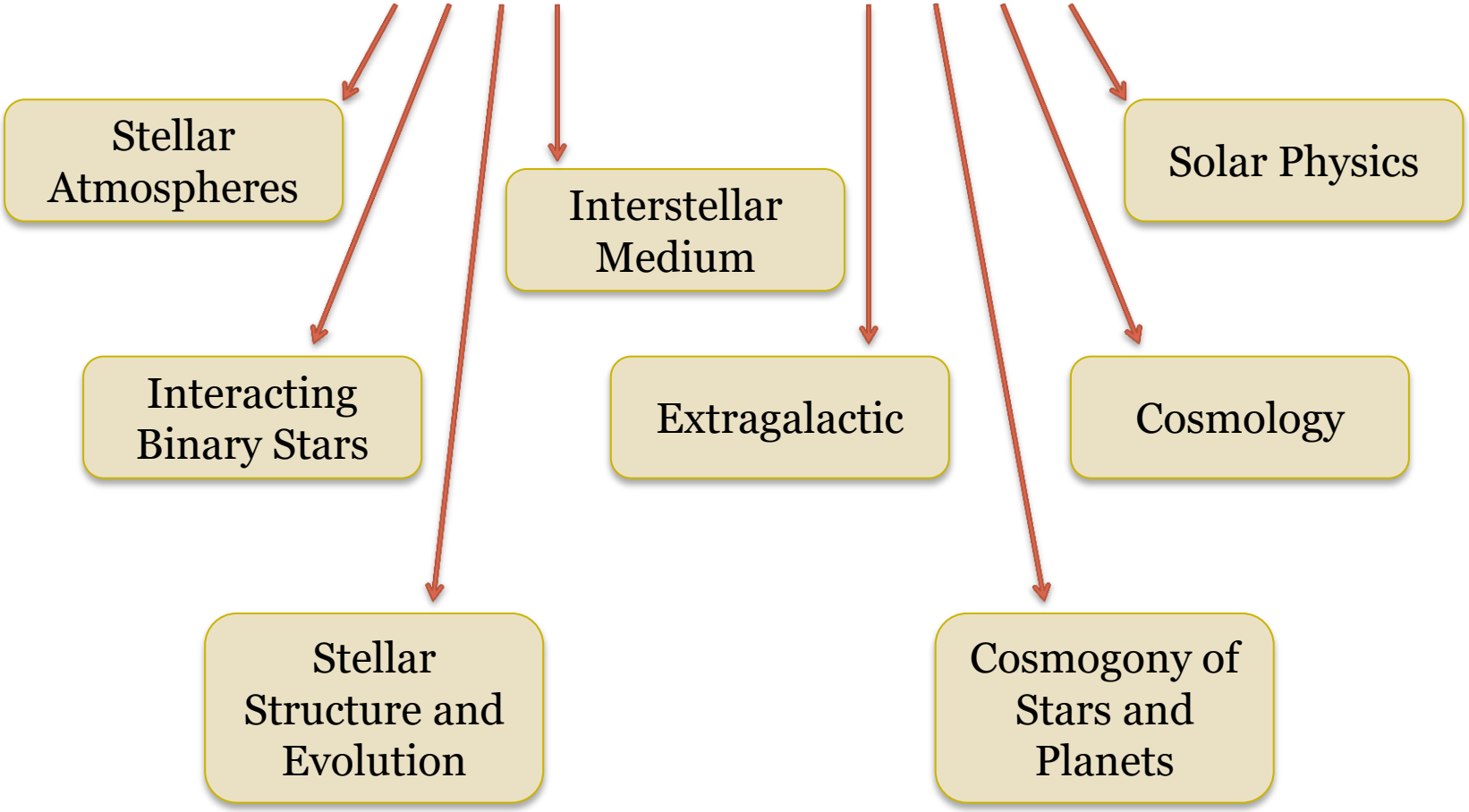
Miscellaneous

- Energy of 1ev=1.602×10^{-26} erg

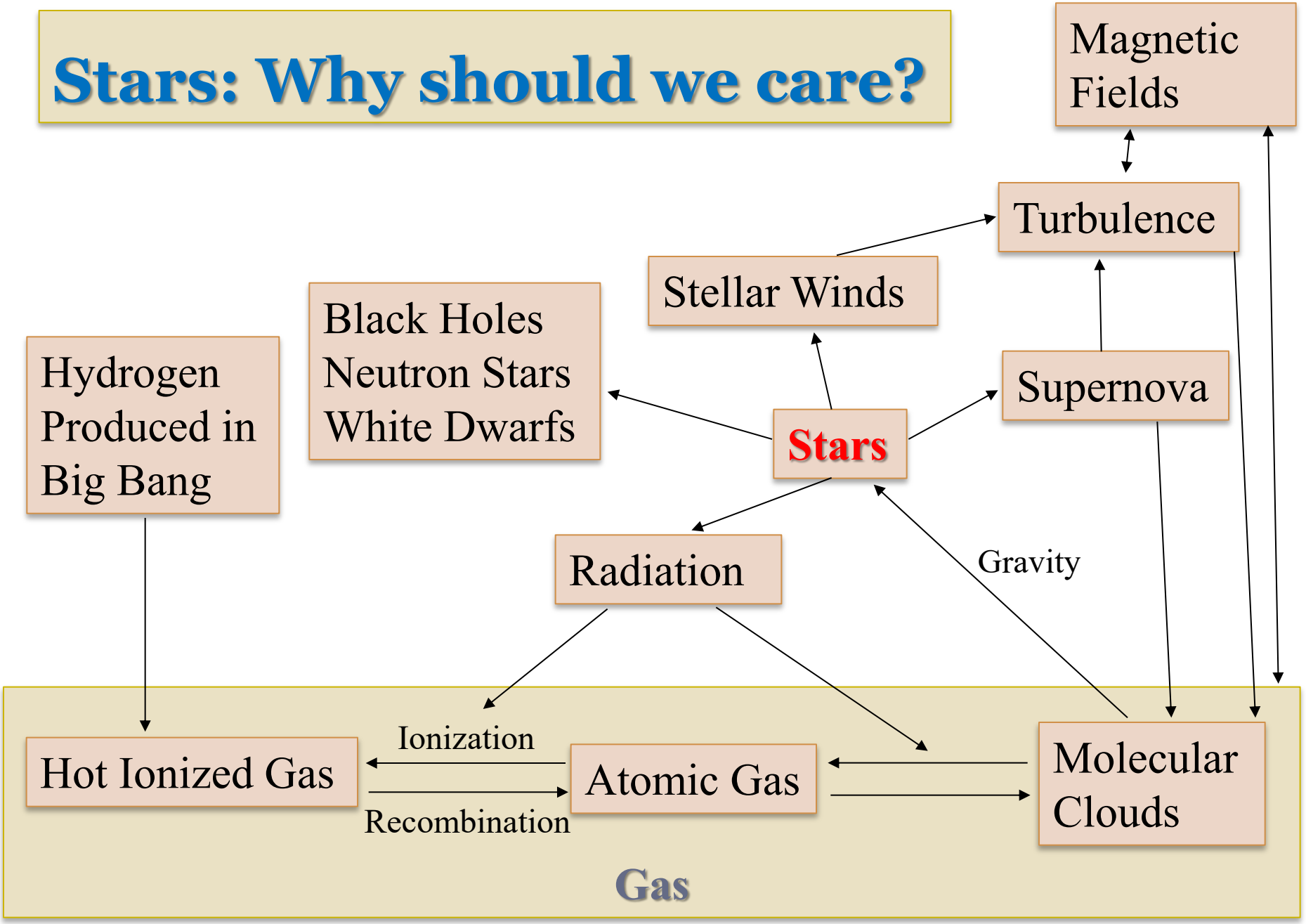
Introduction

WHAT IS A STELLAR ATMOSPHERE? SPECTRAL TYPES, LUMINOSITY CLASSES, MAGNITUDES, BOLOMETRIC FLUX AND BOLOMETRIC CORRECTION

Theoretical Astrophysics

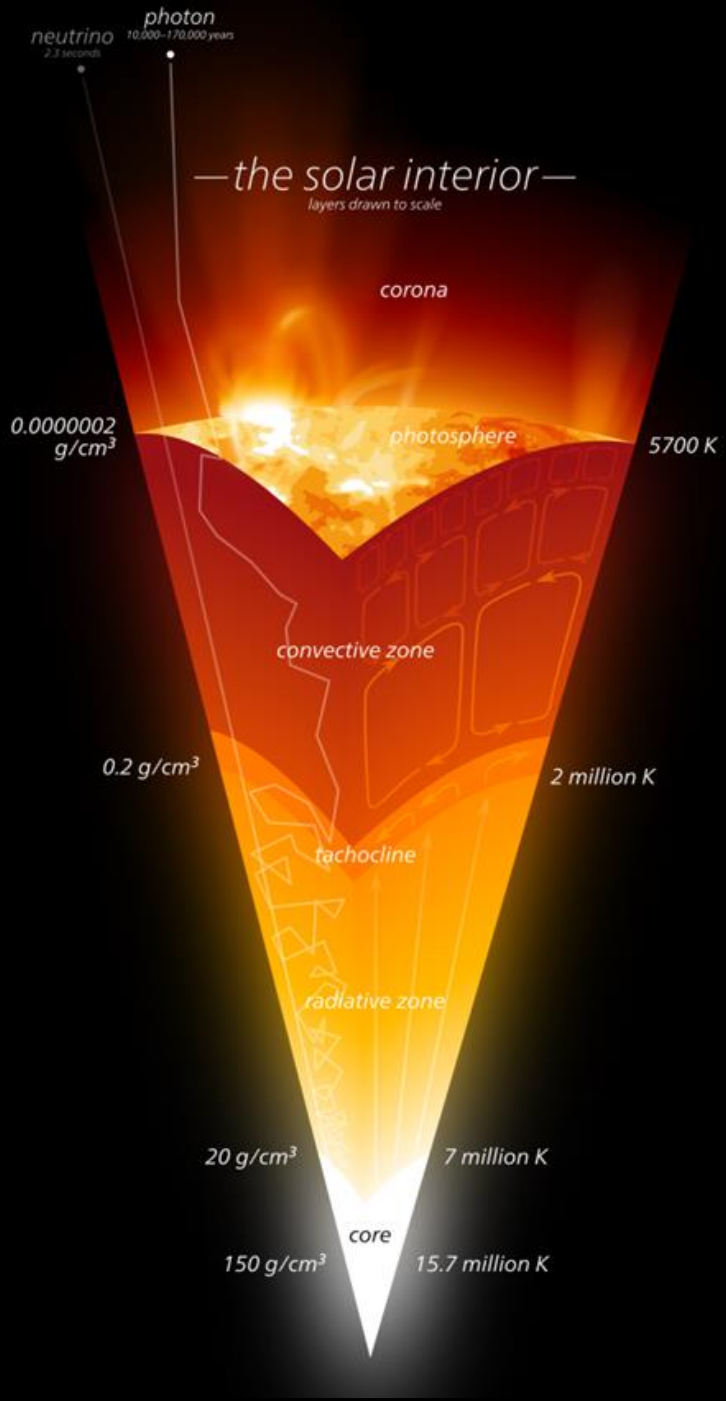


Stars: Why should we care?



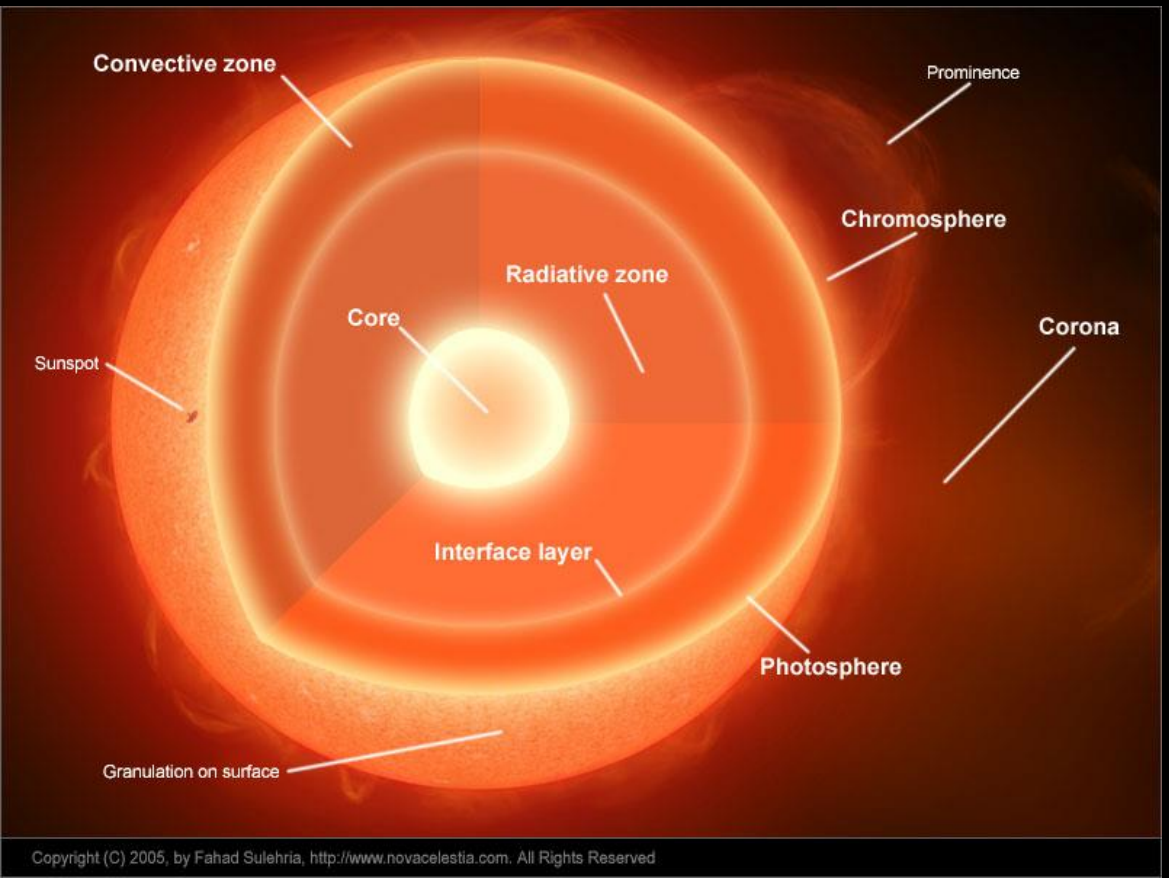
What is a stellar atmosphere?

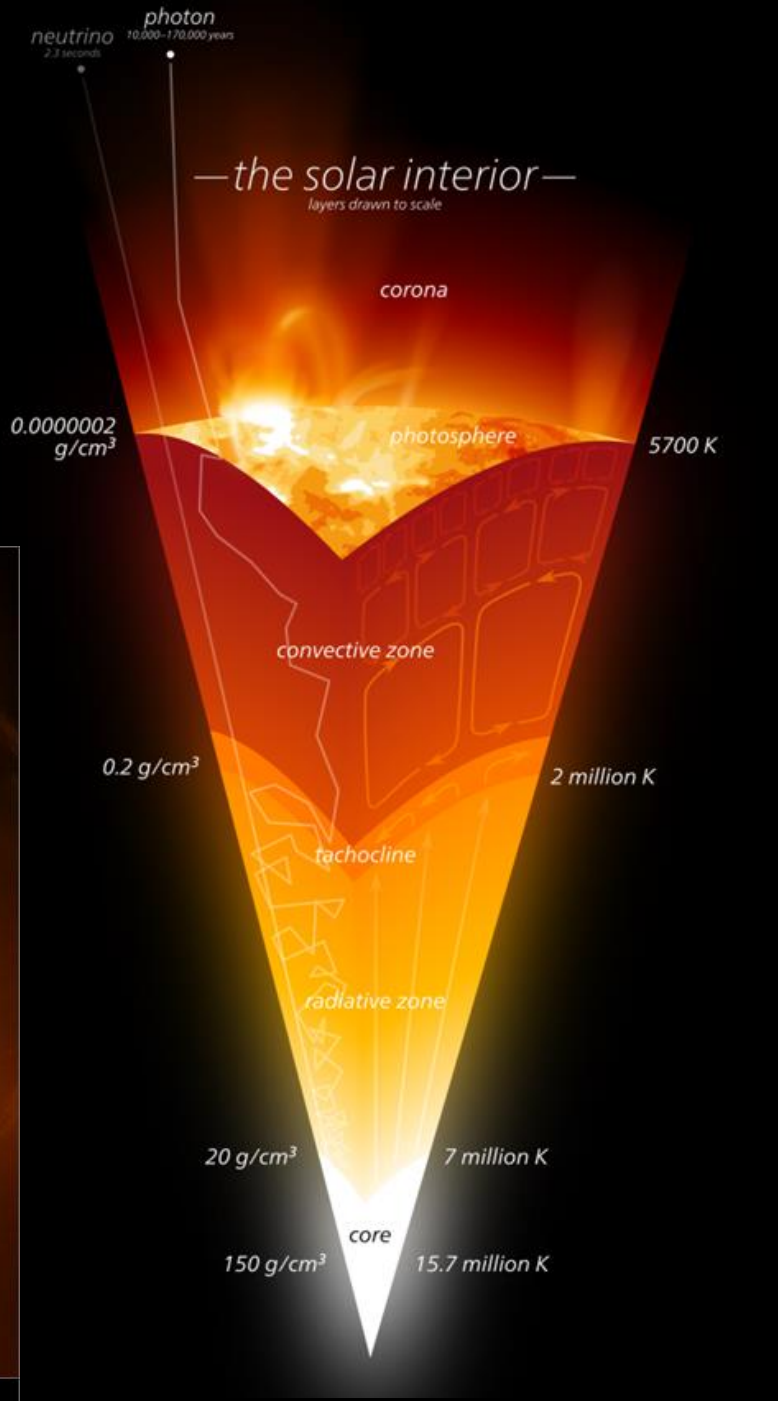
- Thin, tenuous transition zone between (invisible) stellar interior and (essentially vacuum) exterior.
- The “photosphere” is the visible disk, whilst the “atmosphere” also includes coronae and winds.
- In contrast with the interior, where convection may dominate, the energy transport mechanism of the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



What is a stellar atmosphere?

Thin zone between stellar interior and exterior:
ΔR_{sun}=a few×10^7cm, M_{atm}~2×10^{21}g=~$10^{-12}M_{sun}$

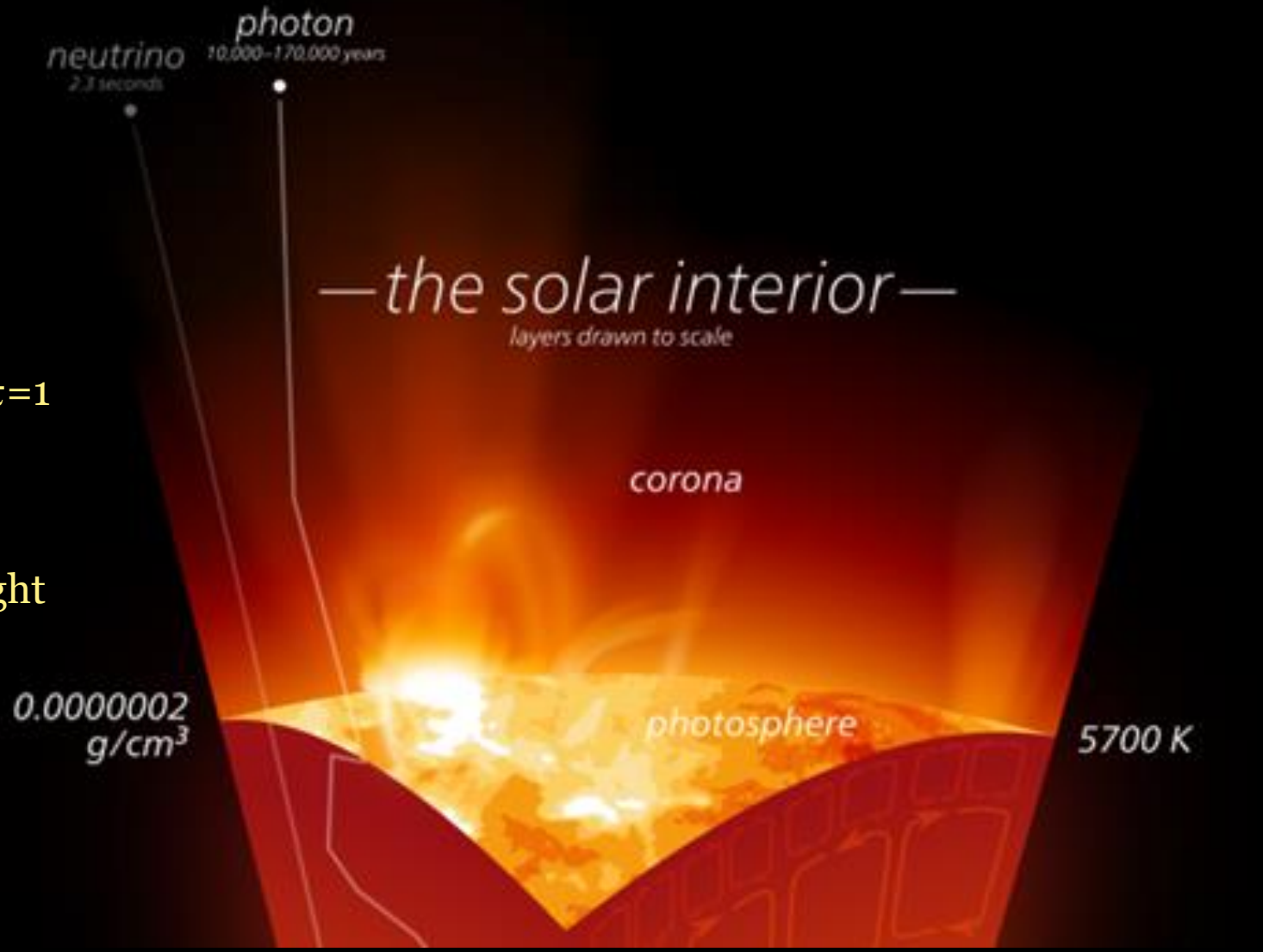




Stellar atmospheres: why should we care?

The optical depth $\tau=1$

about 2/3 of the light is absorbed



Stellar atmospheres?

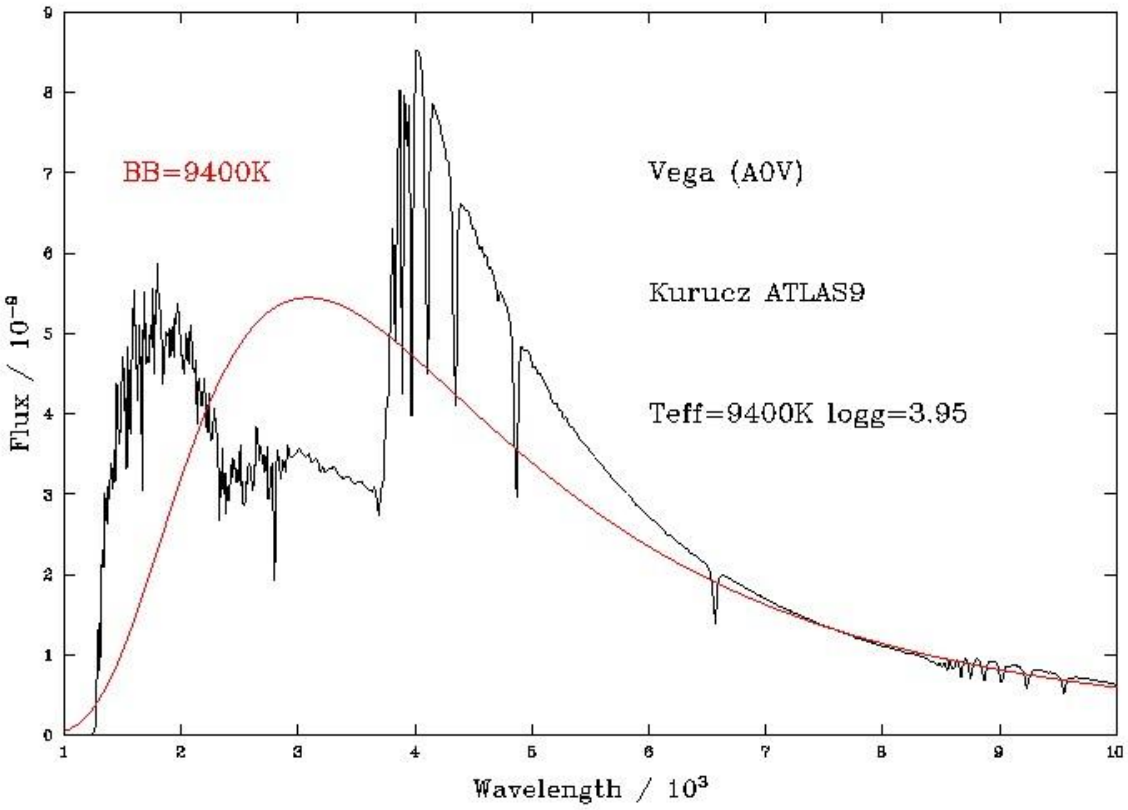
- Stellar interiors are effectively invisible to external observers (apart for e.g. astroseismology) so all the information we receive from stars originates from their atmospheres. Understanding how radiation interacts with matter affecting the emergent line and continuous spectrum is at the heart of this course.

- Knowledge of **plasma physics** (e.g. line broadening), **atomic physics** (microscopic interaction between light and matter), **radiative transfer** (macroscopic interaction between light and matter), **thermodynamics** (LTE vs non-LTE), **hydrodynamics** (velocity fields) yields stellar properties, chemical composition, outflow properties.

- Inputs for stellar/galactic evolution and structure.

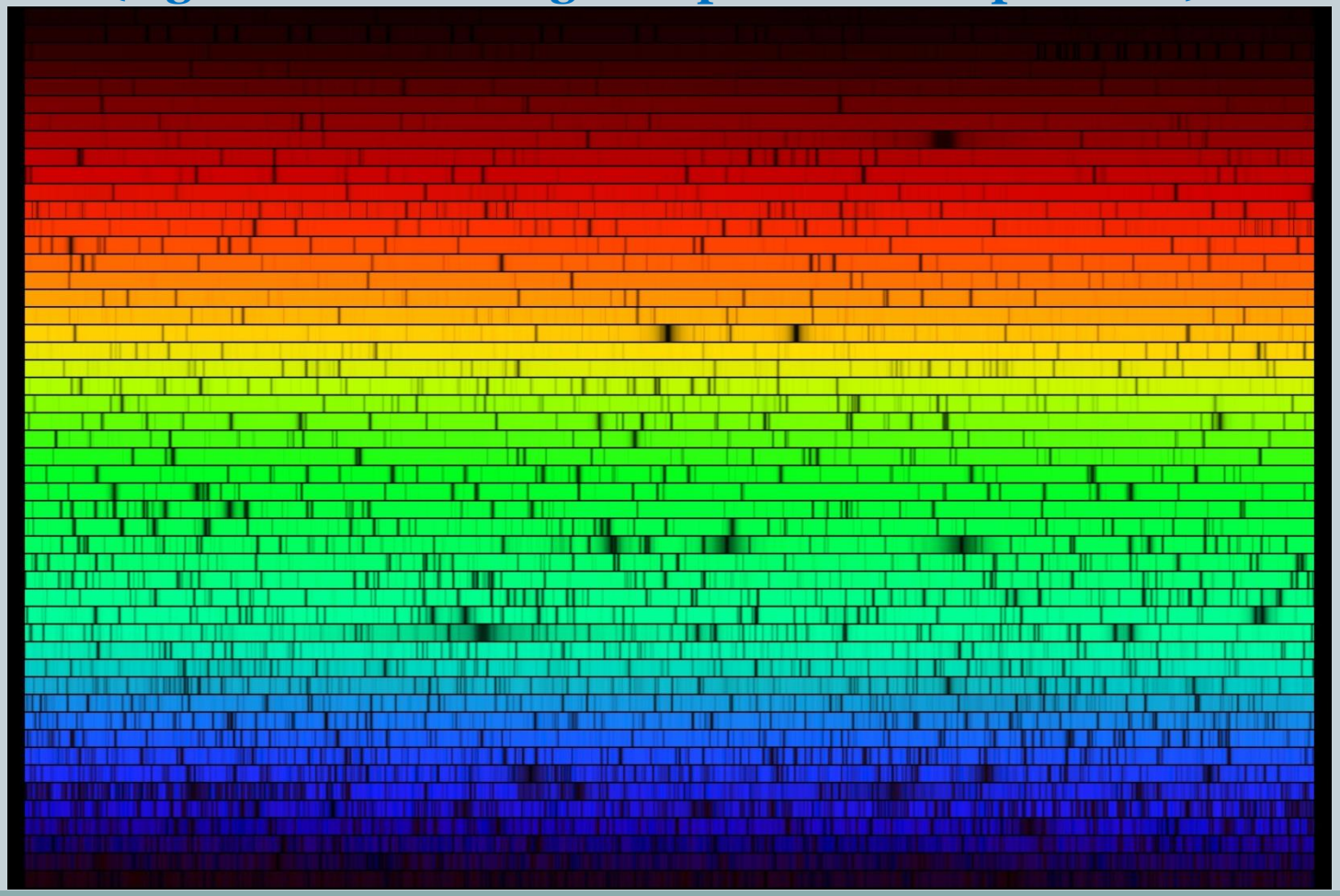
Continuous Energy Distribution

(e.g. UV-optical spectrophotometry of Vega)



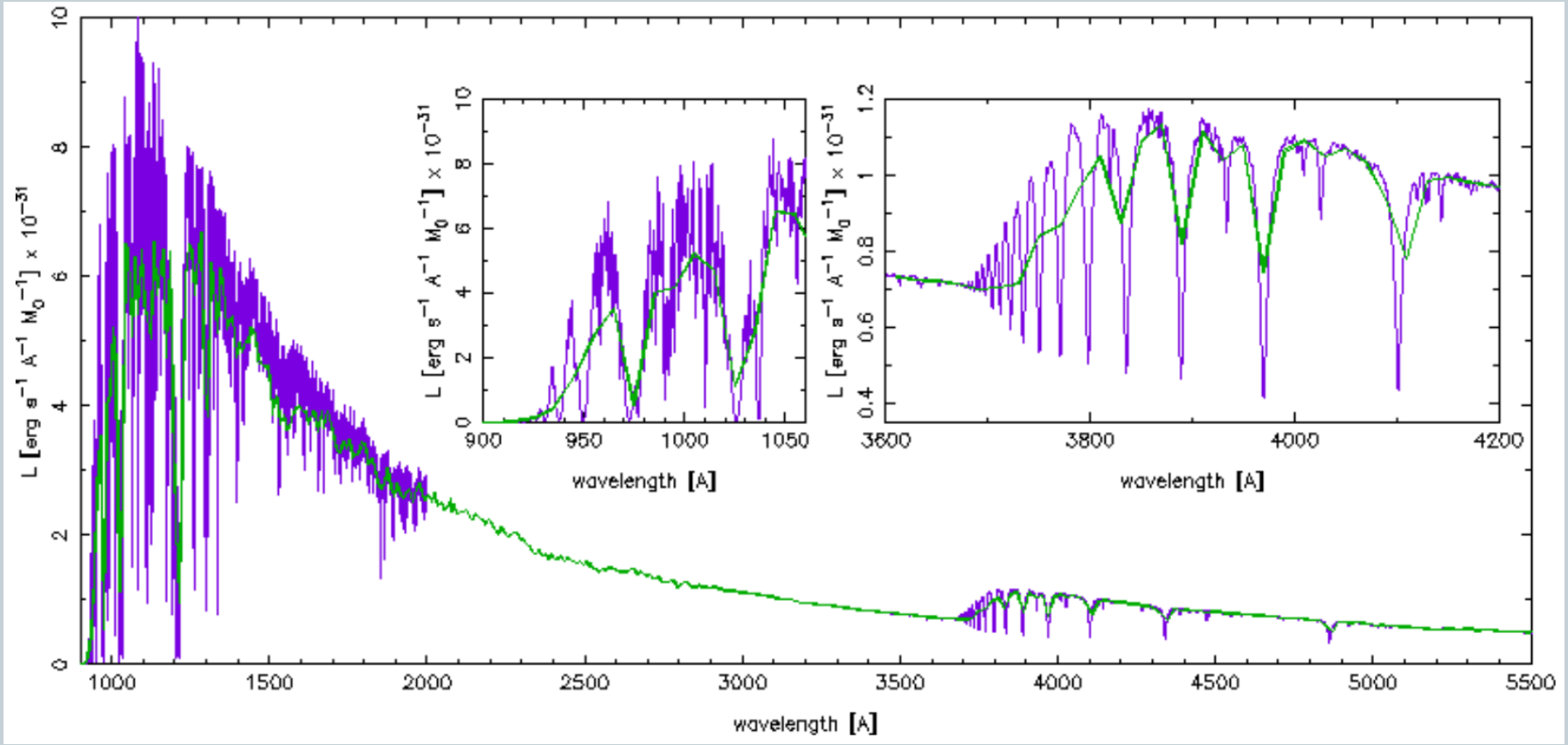
Spectral Lines

(e.g. 2D echelle image of optical Solar spectrum)



Spectral Lines

Impact of Spectral Resolution



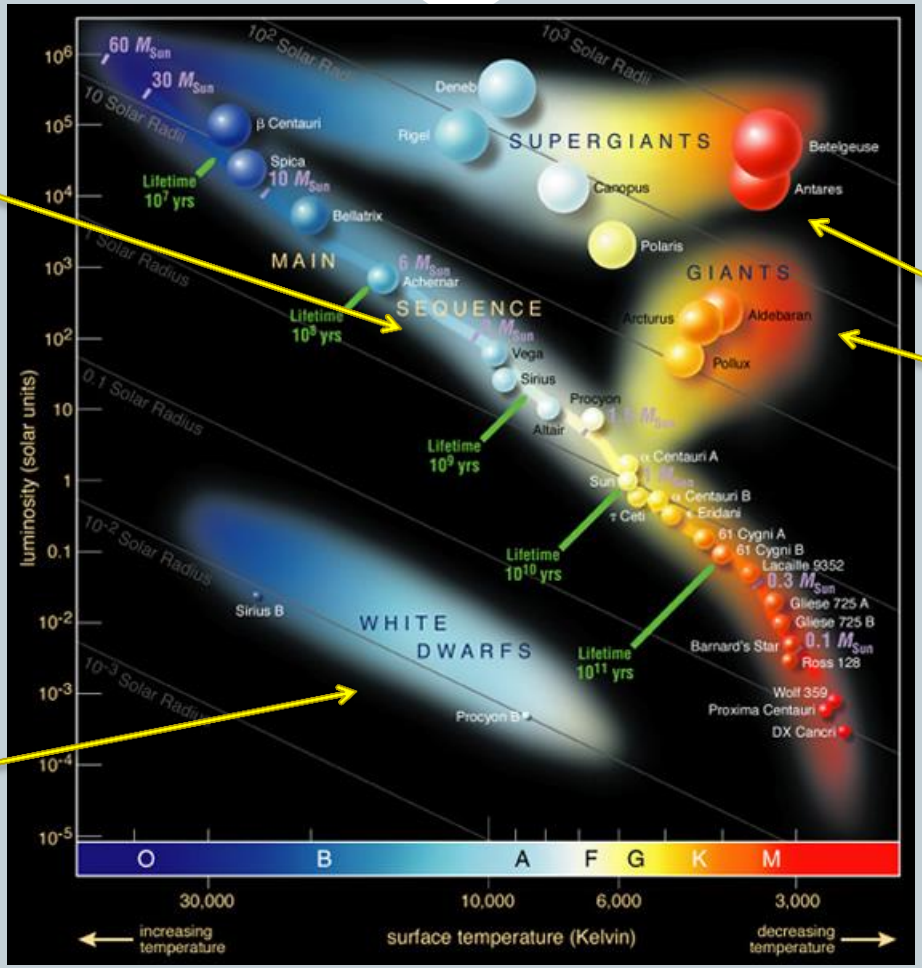
(T_{eff}, log g)

- Effective temperature (in K) is defined by $L=4\pi R^2 \sigma T_{eff}^4$ (here L - luminosity, R - stellar radius), related to *ionization*.
- Surface gravity (cm/s²), $g = GM/R^2$, 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.
- The Solar atmosphere is 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 the final second before totality provides the physical size).
- A red giant has log g~1 (extended atmosphere), whilst a white dwarf has log g~8 (effectively zero atmosphere), and neutron stars have log g~14-15

Hertzsprung-Russell (HR) diagram

Most of the stars lie on the Main Sequence, with increasing L as T increases



A relatively cool star can be quite luminous if it has a large enough radius (10-100 $R_\odot$): Red Giants and Supergiants

A relatively hot star can have very low luminosity, if its radius is very small (0.01 $R_\odot$): White Dwarfs

Spectral Types

Morgan-Keenan (M-K) classification scheme orders stars via "OBAFGKM" spectral classes using ratios of line strength.

O-types have the bluest B-V & highest T_{eff}'s . OBA stars are "early-type" star, whilst cooler stars are "late-type".

Spectral classes are each 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

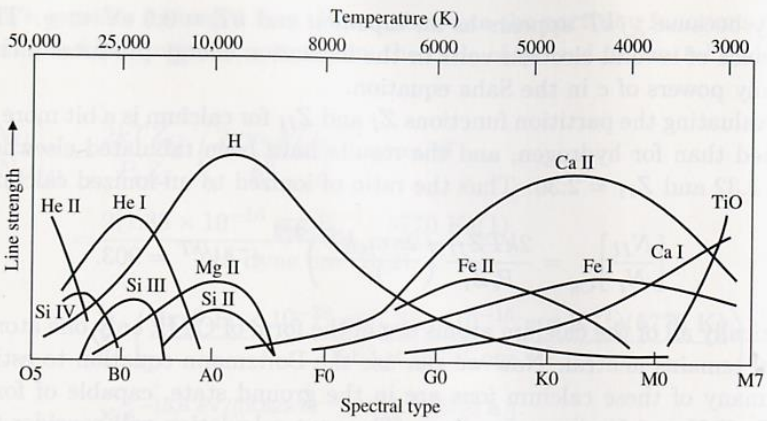


Figure 8.9 The dependence of spectral line strengths on temperature.

Luminosity Class

- Luminosity class information is often added, based upon line widths:

  V (dwarfs), **III** (giants), **I** (supergiants),

- Dwarfs have high pressures (large line widths) and supergiants have lower pressures (smaller line widths).

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 Hγ	F2 ⇔ K5	4045–63 Fe I/4077 Sr II
F5 ⇔ G5	4045 Fe I/4101 Hδ		4226 Ca I/4077 Sr II
	4226 Ca I/4340 Hγ	G5 ⇔ M	Discontinuity near 4215
G5 ⇔ K0	4144 Fe I/4101 Hδ	K3 ⇔ M	4215/4260, Ca I increasing
K0 ⇔ K5	4226 Ca I/4325		
	4290/4300		

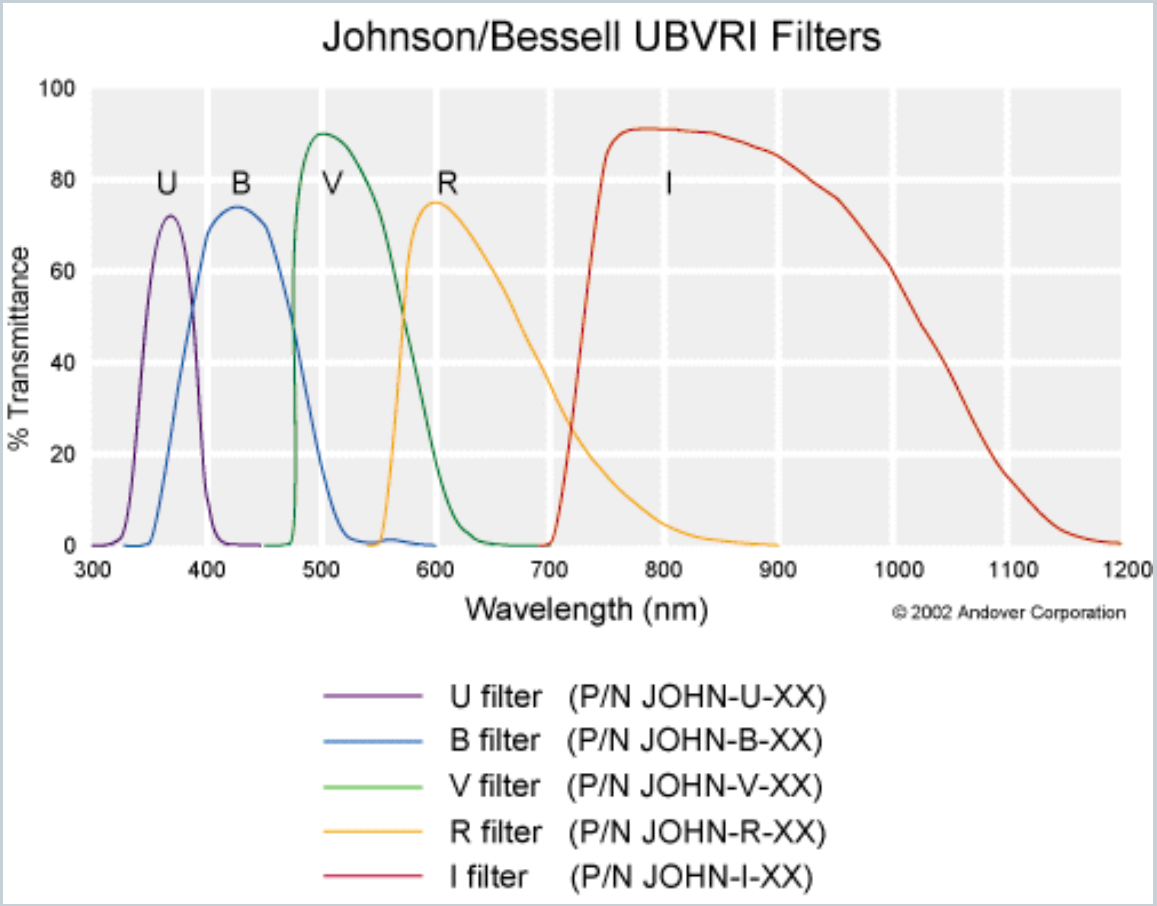
Magnitude scale

- We measure the flux F (erg/cm²/s) from astronomical objects via a logarithmic magnitude scale (like the eye).
- The brightest stars have apparent magnitude of approximately one, whilst the faintest naked eye stars (from a dark site) have magnitude six, a factor of 100 times fainter.
- Magnitudes almost universally involve a set of broad-band filters (e.g. Johnson *UBVRI* or Sloan *u'g'r'i'z'*)
  $\mathbf{m_v - m_o = -2.5 \log(F_v/F_o)}$
  where Vega (A0V) defines the photometric `zero point' m_o at all wavelengths ($U=B=V=R=I=0.0$ 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

Standard broad-band filters

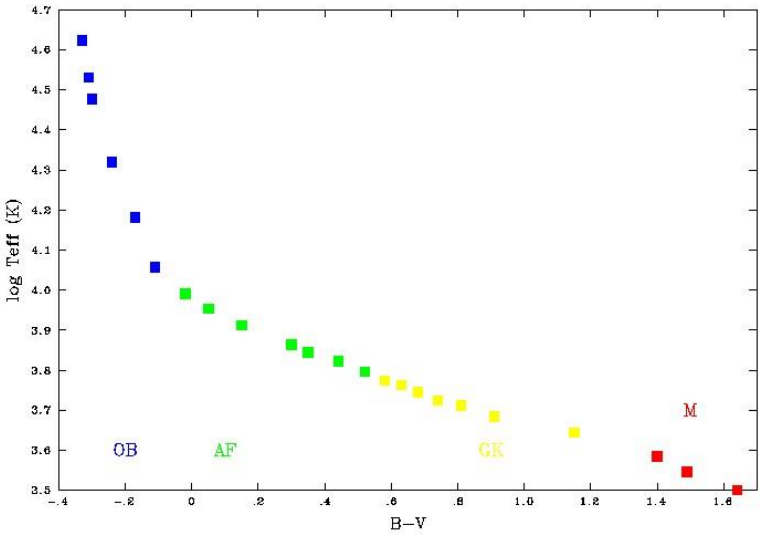


$$m = -2.5 \log \int_0^\infty F_\nu W(\nu)\, \mathrm{d}\nu + \text{constant}$$

F_ν – a star SED
$W(\nu)$ – a filter passband

Colour index

- We can define a colour index as the difference between filters relative to Vega e.g. $B\text{-}V = m_B - m_V$, such that stars bluer than A0 have a negative B-V colour and stars redder than Vega have a positive colour e.g. $(B\text{-}V)_{Sun} = +0.65$ mag.



$$B - V = -2.5 \log\left(\frac{\int F_\nu W_B(\nu)\,d\nu}{\int F_\nu W_V(\nu)\,d\nu}\right) + 0.710$$

$$U - B = -2.5 \log\left(\frac{\int F_\nu W_U(\nu)\,d\nu}{\int F_\nu W_B(\nu)\,d\nu}\right) - 1.093.$$

e.g., for $T_{eff}<10000$K:

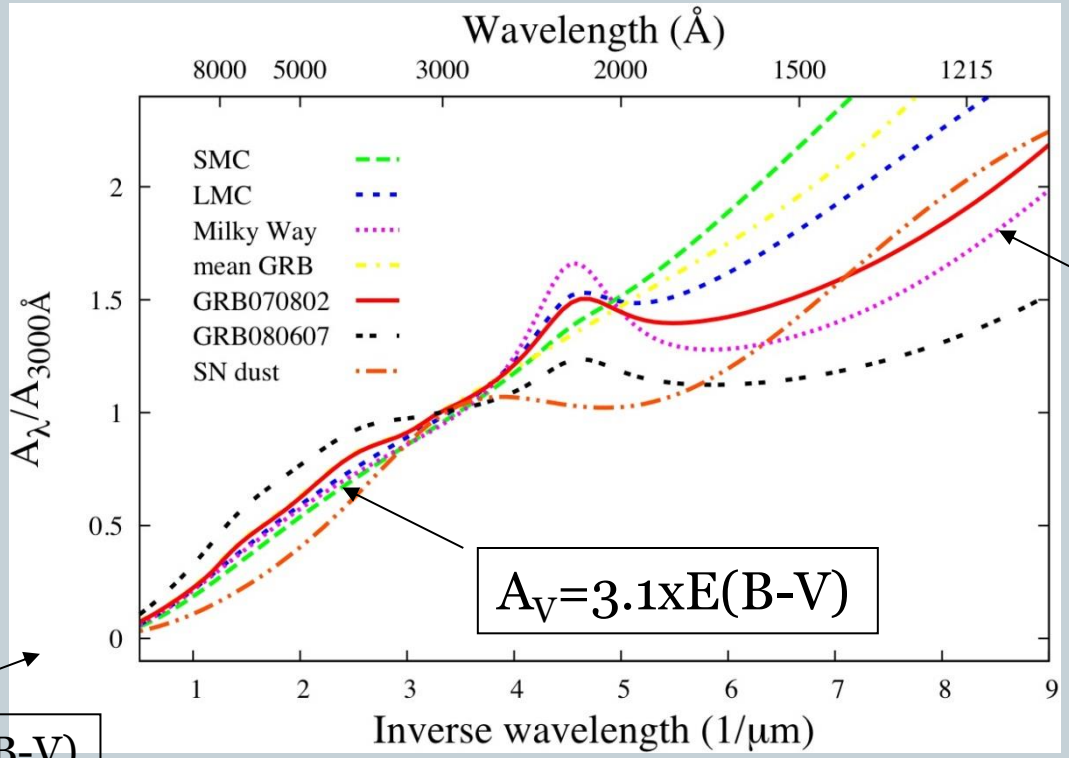
$$T = \frac{7090}{(B-V) + 0.71} K$$

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 d=10pc: $M_V=m_V$ (10 pc).
- Because $F \propto d^{-2}$
  $M_V-m_V= -2.5 \log[F(10pc)/F(d)] = -5\log(d/10pc)=5 - 5 \log(d/pc)$
- For the Sun (d=4.85 10^{-6} pc), m_V=-26.75 and M_V=+4.82 mag.
  The "distance modulus" M_v-m_v=31.57 mag
- Because interstellar medium is not completely transparent we write
  $M_V - m_V= 5 - 5 \log(d/pc) - A_V$.
- The A_V term is due to interstellar extinction.
  Visually, $A_V \sim 3.1$ E(B-V) for most sight lines.
  $E(B-V)=B-V - (B-V)_o$, i.e. the difference between the observed and intrinsic B-V colour.

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 (d=8kpc) is approx A_V=30 mag (5500A) versus A_K=3 mag (2μm).



A_{1200A}=10xE(B-V)

A_V=3.1xE(B-V)

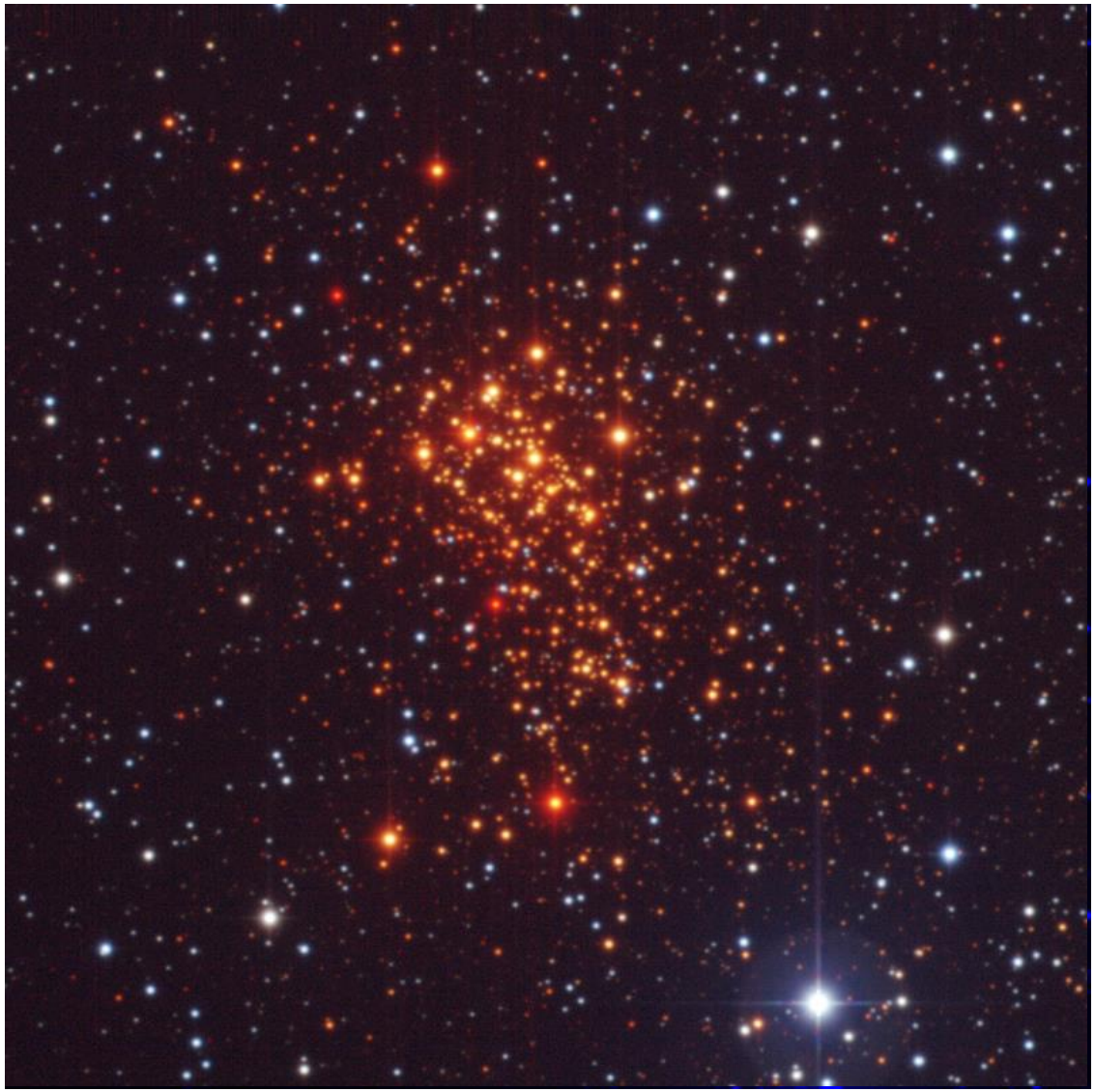
A_K=0.3xE(B-V)

Illustration of interstellar extinction

V-band (5500Å)

R-band (7000Å)

I-band (9000Å)



VRI-composite
of highly reddened
cluster Wd1 (E_{B-V}~4)

Bolometric Flux

- The bolometric flux (erg cm^{-2} s^{-1}) from a star received at the top of the Earth's atmosphere is the integral of the spectral flux (measured at a frequency ν or a wavelength λ) over all all frequencies or wavelengths:

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

- 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

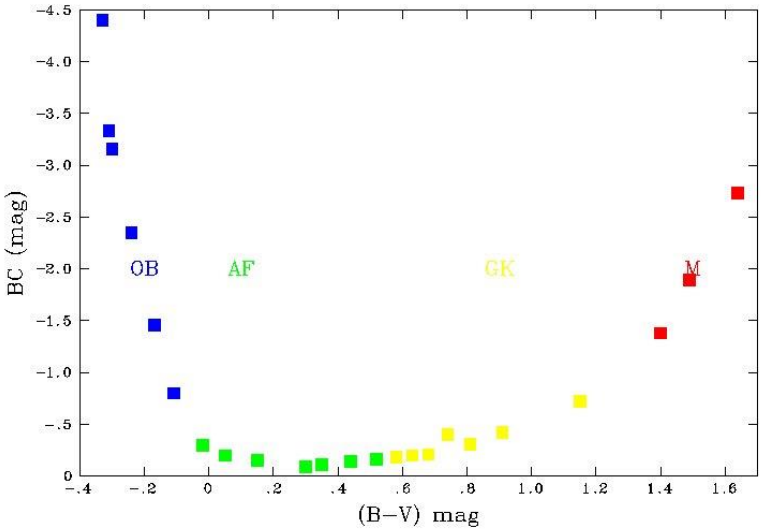
One can calculate bolometric corrections (BC), primarily from atmospheric models to correct measured fluxes (usually in the V band) for the total (bolometric) flux. Usually expressed in magnitudes:

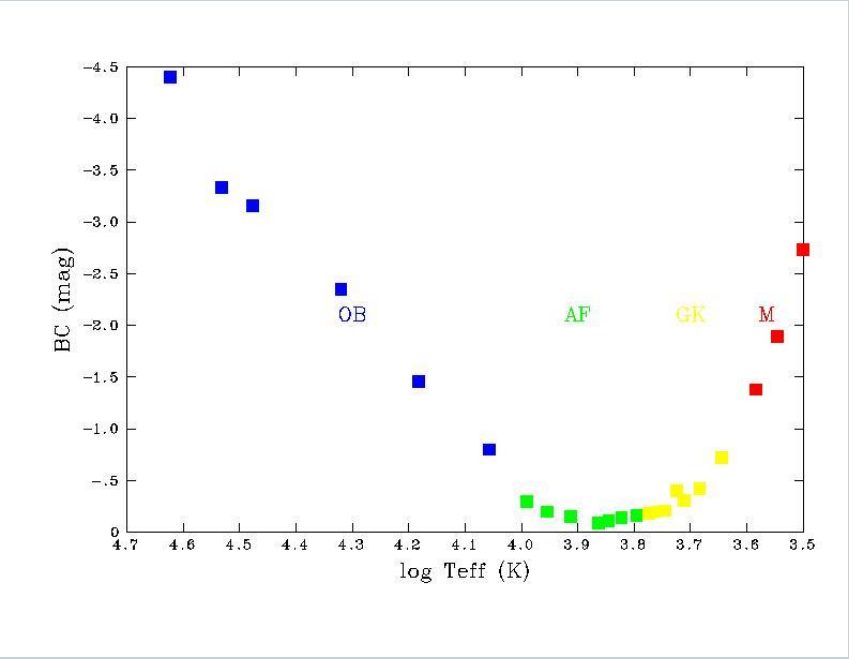
$$BC = M_{bol} - M_V \quad \text{with} \quad M_{bol} = 4.74 - 2.5 \log(L/L_\odot)$$

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.

BC calibrations

Bolometric corrections can be estimated from intrinsic colours $(B\text{-}V)_0$ as shown here for dwarfs:





Or from the Spectral Type, using a T_{eff}-Spectral Type calibration.

See the 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*	$T_{\rm eff}$	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

From Allen's Astrophysical Quantities (4th edition)

Solve a problem

A B5V star in the LMC (distance 50kpc) has V=13.5 mag, B-V=-0.07 mag.

What is its bolometric luminosity, relative to the Sun?

Summary

- Stellar atmosphere is region connecting unseen interior to vacuum exterior, and includes photosphere, chromosphere and corona.
- Characterized by (T_{eff}, log g) which links physical properties of atmosphere to spectral classification (Spectral Type, Luminosity class).
- Primary energy transport mechanism via radiation.
- Stellar flux measured in magnitudes via broad-band filters, using Vega as zero point.
- Bolometric flux represents integral over all wavelengths (related to visual flux via bolometric correction).