THE UNIVERSITY OF TEXAS AT AUSTIN

Astro 358

Galaxies and the Universe

Note: This document has mainly figures and plots illustrating some key concepts in the pre-requisite material on stellar astronomy. Please see the appendix of the textbook (posted on the class site) for derivations, formulae, back-of-the-envelope calculations and other materials.

Pre-requisite for Galaxies Class: Understand stars first!

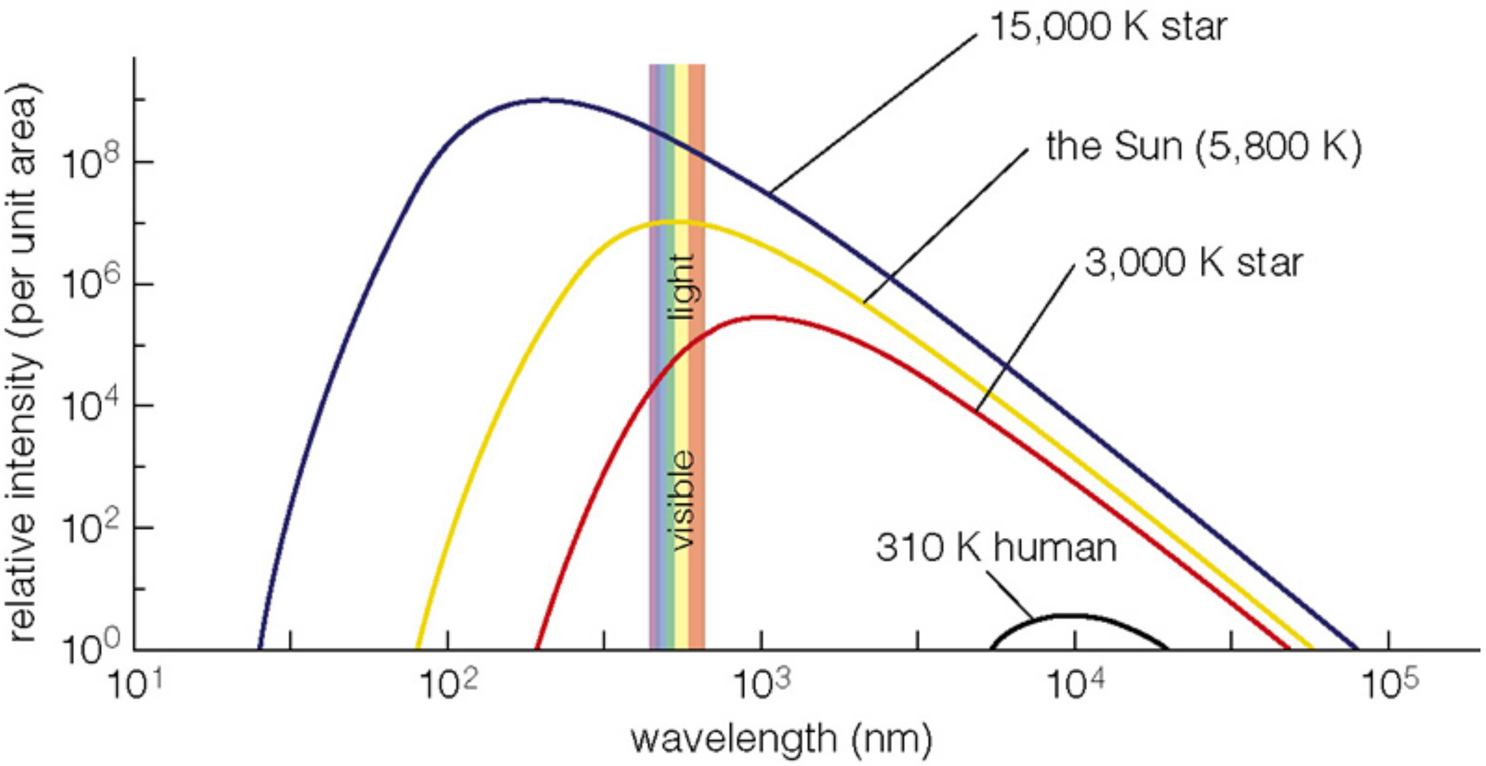
- A galaxy is a collection of stars, gas, dust, and dark matter, which are bound by gravity. It contains a few 1e8 to 1e12 stars, which orbit a common center.

HST image of the barred spiral galaxy NGC 1300

Giant elliptical M87

Peculiar/Interacting galaxies
HST image of The Antennae

Wien's Law: Surface Temperature and Color of Stars

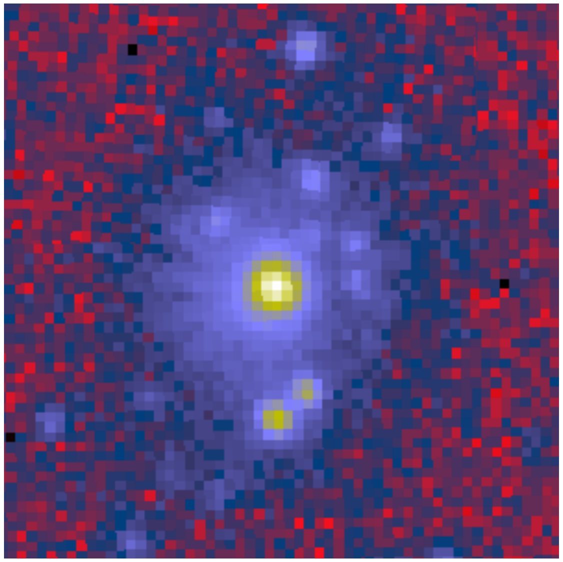


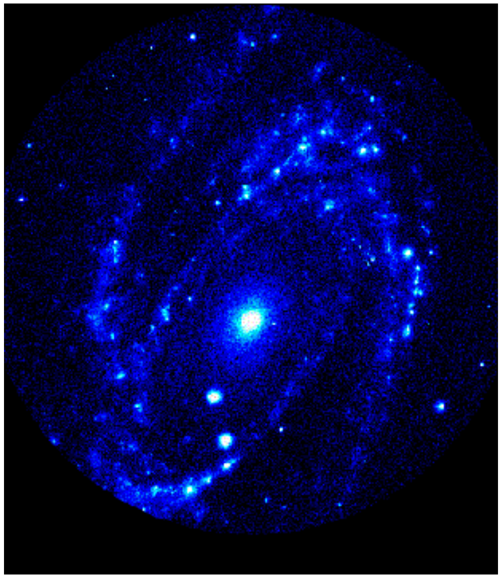
Wien's law: A star or blackbody will emit its maximum flux at a wavelength λ_{peak} that depends   inversely on its surface temperature T

λ_{peak}= W/ T ,   where W = Wien's constant = 2.9 x 10^{-3} m K

Wien's law implies that hotter stars have smaller peak wavelengths λ_{peak}

Implication of Wien's Law for Galaxy Images


X-ray/ROSAT


Ultraviolet/ASTR0-1


Visible light


Near infrared/Spitzer

- UV images: mainly trace very hot (T>10^5K) massive, short-lived young stars
- Visible images: traced moderately hot (T=5800 K), moderate mass longer-lived stars like the Sun (lifetime of 10 billion years)
- Near IR : traces cooler (T~3000 K) low mass, long-lived stars AND penetrates through dust revealing these stars
- Mid-IR: traces warm dust (T~ few 100 K)

Dust Obscures Stars and is heated by Massive Hot Stars

Movie
(NASA/Spitzer)

The optical image of M81 shows intermediate age stars and patches of dusty obscuration.
In the infrared observations of M81 from the Spitzer satellite:

- near-IR light comes from cool (T~3000 K) old stars and it penetrates through dust
- mid-IR light comes warm gas and dust (T~ few 100 K) which look clumpy/fillamentary

Stefan-Boltzmanl Law & L-R-T relation

1) Stefan-Boltzmann law

The flux F_s at the surface of a star with temperature T is proportional to T^4

$$F_s = \sigma T^4$$

where σ = Stefan-Boltzmann constant

2) L-R-T relation

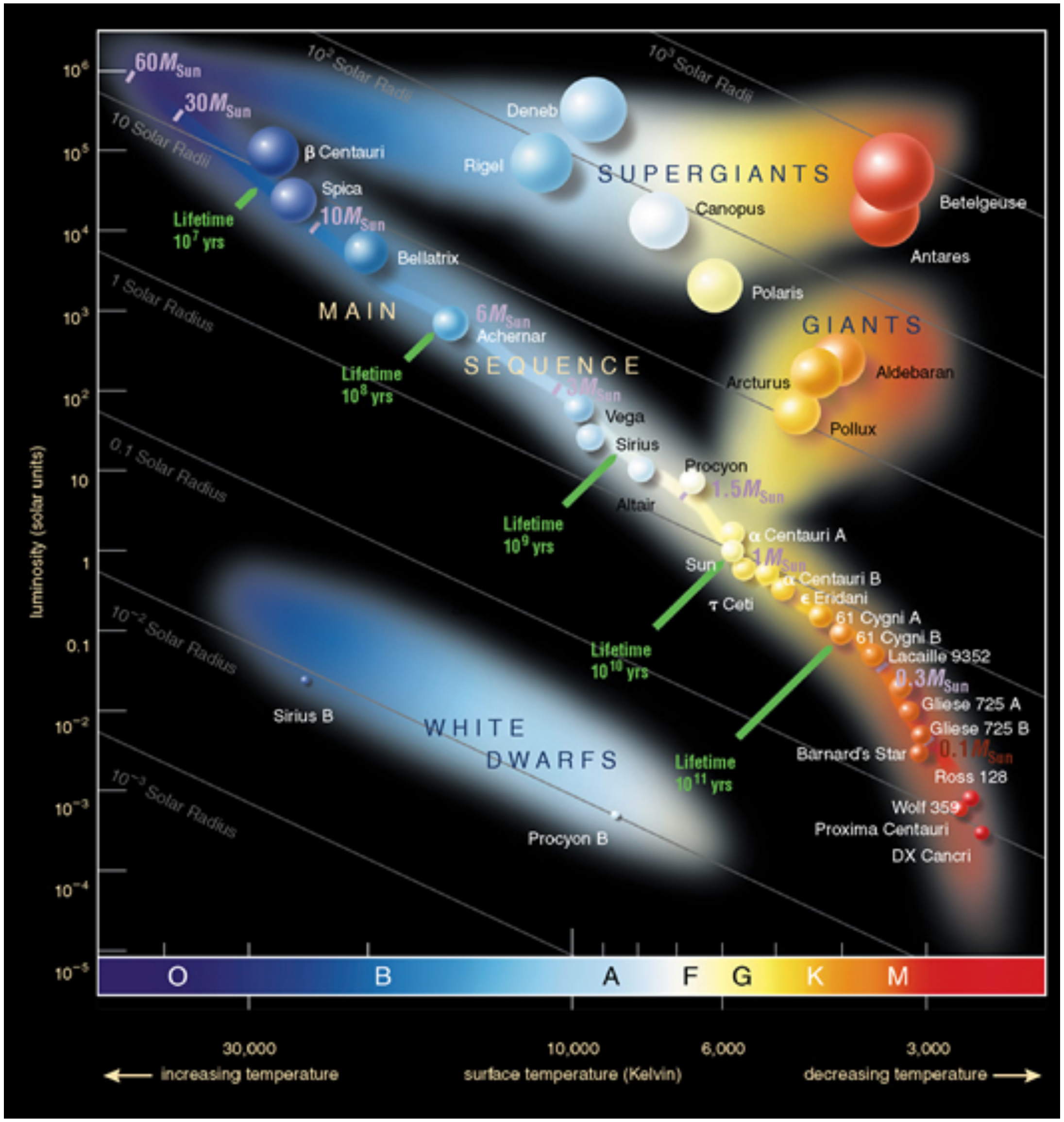
The luminosity of a star of radius R and temperature T is proportional to $T^4 R^2$.

See in-class derivation

$$L = 4 \pi \sigma T^4 R^2$$

Hertzsprung-Russell (H-R) diagram

The H-R diagram plots L versus effective Temperature T for stars
- T is sometimes shown in terms of the spectral type OBAFGKM)
- The color-magnitude diagram is a different version of H-R diagram



1) The position of a star on H-R diagram depends on its mass and age (or evolutionary phase)

2) The main sequence (MS) is populated by stars fusing H to He in their core. Stars stay on the MS for a time call the MS lifetime

3) When stars stop fusing H to He they evolve off the MS and go through different evolutionary phases (e.g.,giants, supergiants, white dwarfs) based on their mass and age

4) Note the L-R-T relation: MS and supergiant stars have different L due to their different R

MK Classification System For Stars

1) MK classification system: stars have a spectral type and a luminosity class

MK = (Spectral Type OBAFGKM , Luminosity Class I to V)

- The spectral type OBAFGKM is now known to be related to temperature (and mass)

OB stars = high temperature and mass
AF star = intermediate temperature and mass
GKM = low temperature and mass

- The luminosity classes I to V refer to

I = Supergiants
II = Bright Giants
III = Normal Giant
IV = Subgiant
V = Dwarfs = Main Sequence Stars

2) Example: The Sun is a star with spectral type G2 (T=5800 K,mass = 1Mo) and has a luminosity class V (is on the main sequence)

3) Stars on the H-R diagram are sometimes referenced
- by their spectral type OBAFGKM rather than temperature on the x-axis
- by their luminosity class. (e.g. see supergiant and giant groupings)

Original description of spectral types OBAFGKM

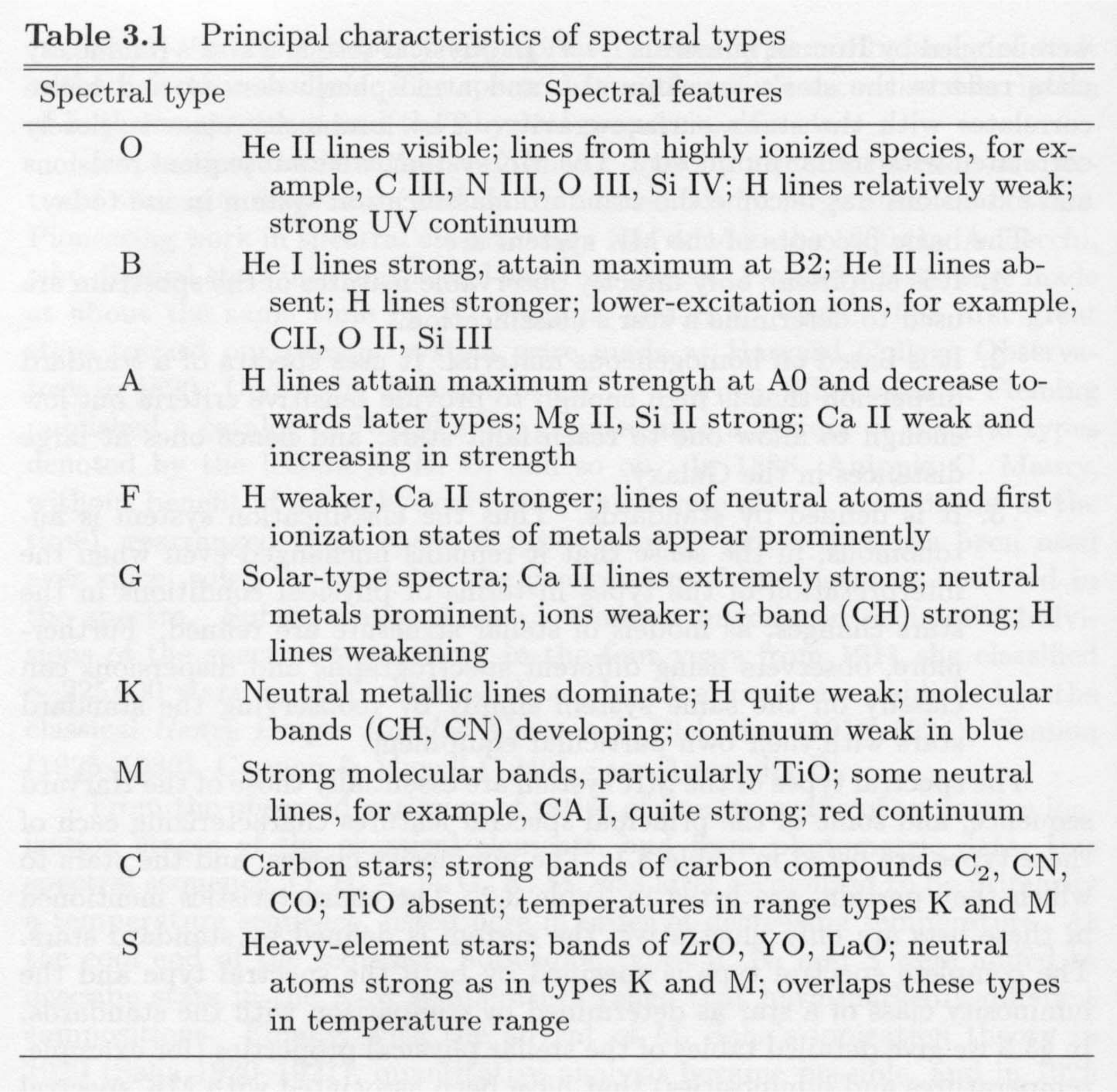


Table 3.1 Principal characteristics of spectral types

Spectral type	Spectral features
O	He II lines visible; lines from highly ionized species, for example, C III, N III, O III, Si IV; H lines relatively weak; strong UV continuum
B	He I lines strong, attain maximum at B2; He II lines absent; H lines stronger; lower-excitation ions, for example, CII, O II, Si III
A	H lines attain maximum strength at A0 and decrease towards later types; Mg II, Si II strong; Ca II weak and increasing in strength
F	H weaker, Ca II stronger; lines of neutral atoms and first ionization states of metals appear prominently
G	Solar-type spectra; Ca II lines extremely strong; neutral metals prominent, ions weaker; G band (CH) strong; H lines weakening
K	Neutral metallic lines dominate; H quite weak; molecular bands (CH, CN) developing; continuum weak in blue
M	Strong molecular bands, particularly TiO; some neutral lines, for example, CA I, quite strong; red continuum
C	Carbon stars; strong bands of carbon compounds C_2, CN, CO; TiO absent; temperatures in range types K and M
S	Heavy-element stars; bands of ZrO, YO, LaO; neutral atoms strong as in types K and M; overlaps these types in temperature range

From GA

Relationship between Spectral type and Surface Temperature

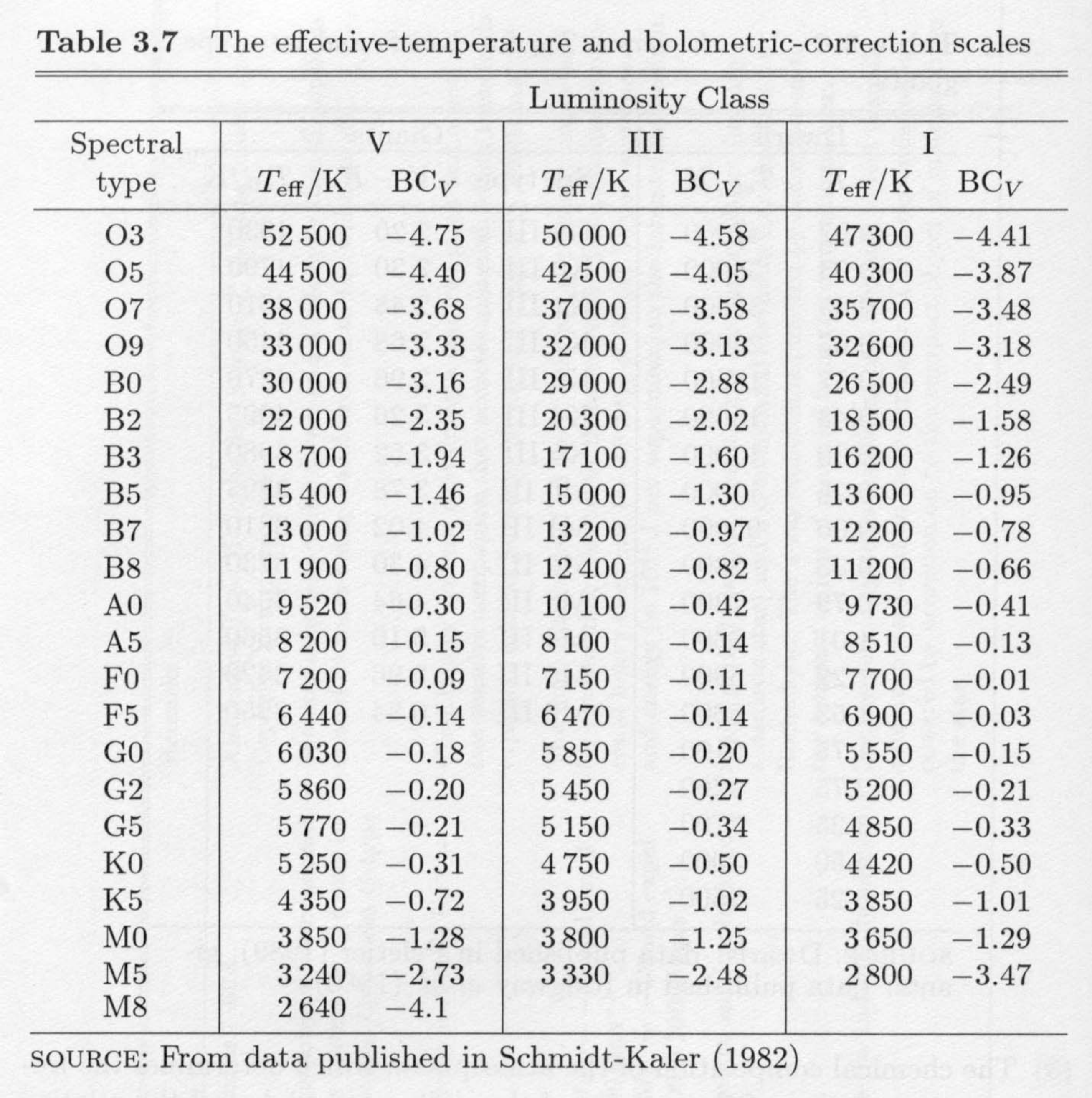


Table 3.7 The effective-temperature and bolometric-correction scales

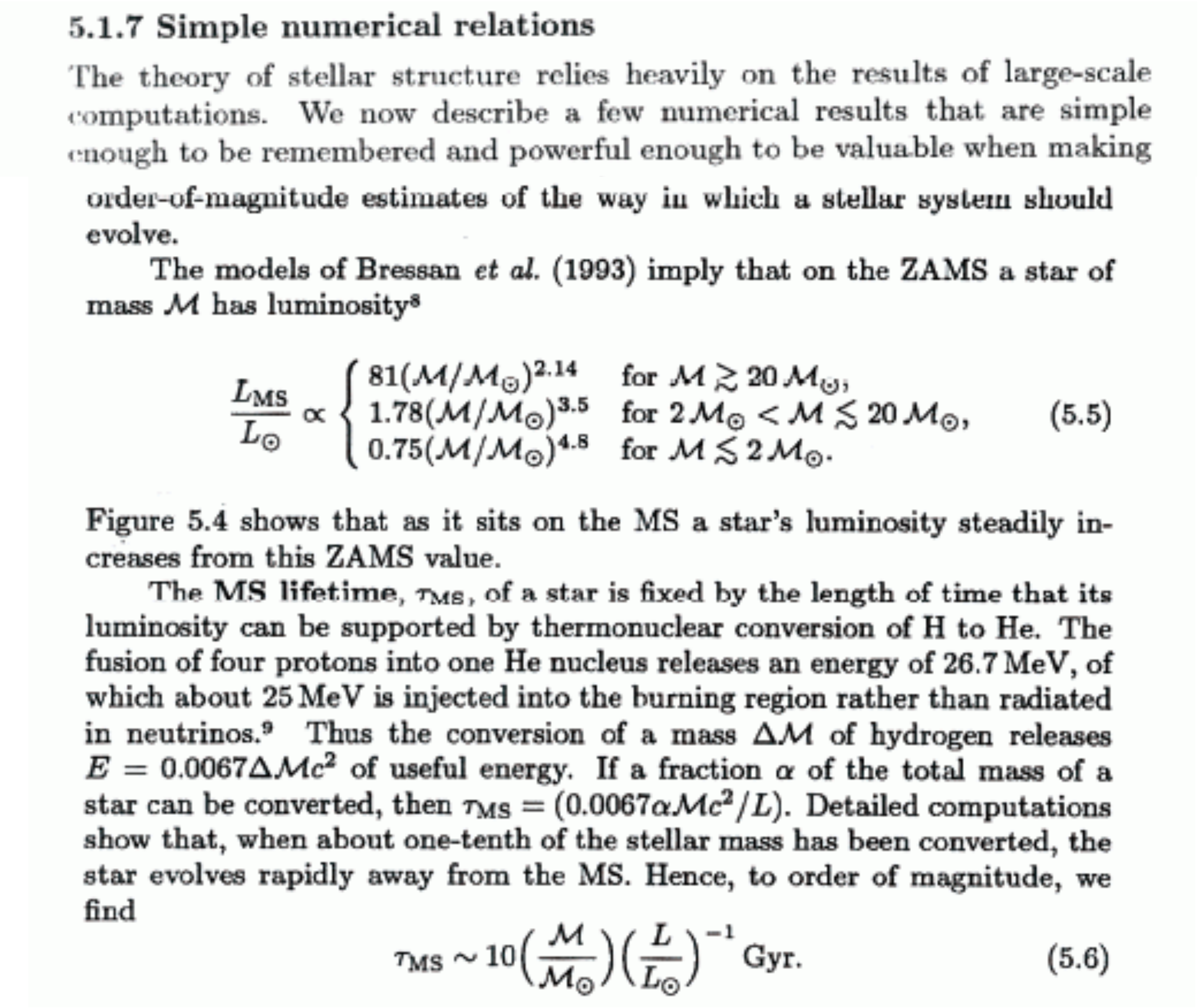
Spectral type	V		III		I	
	$T_{\rm eff}$/K	BC$_V$	$T_{\rm eff}$/K	BC$_V$	$T_{\rm eff}$/K	BC$_V$
O3	52 500	−4.75	50 000	−4.58	47 300	−4.41
O5	44 500	−4.40	42 500	−4.05	40 300	−3.87
O7	38 000	−3.68	37 000	−3.58	35 700	−3.48
O9	33 000	−3.33	32 000	−3.13	32 600	−3.18
B0	30 000	−3.16	29 000	−2.88	26 500	−2.49
B2	22 000	−2.35	20 300	−2.02	18 500	−1.58
B3	18 700	−1.94	17 100	−1.60	16 200	−1.26
B5	15 400	−1.46	15 000	−1.30	13 600	−0.95
B7	13 000	−1.02	13 200	−0.97	12 200	−0.78
B8	11 900	−0.80	12 400	−0.82	11 200	−0.66
A0	9 520	−0.30	10 100	−0.42	9 730	−0.41
A5	8 200	−0.15	8 100	−0.14	8 510	−0.13
F0	7 200	−0.09	7 150	−0.11	7 700	−0.01
F5	6 440	−0.14	6 470	−0.14	6 900	−0.03
G0	6 030	−0.18	5 850	−0.20	5 550	−0.15
G2	5 860	−0.20	5 450	−0.27	5 200	−0.21
G5	5 770	−0.21	5 150	−0.34	4 850	−0.33
K0	5 250	−0.31	4 750	−0.50	4 420	−0.50
K5	4 350	−0.72	3 950	−1.02	3 850	−1.01
M0	3 850	−1.28	3 800	−1.25	3 650	−1.29
M5	3 240	−2.73	3 330	−2.48	2 800	−3.47
M8	2 640	−4.1				

Luminosity Class (spanning V, III, I)

SOURCE: From data published in Schmidt-Kaler (1982)

From GA

Main Sequence Lifetime



5.1.7 Simple numerical relations

The theory of stellar structure relies heavily on the results of large-scale computations. We now describe a few numerical results that are simple enough to be remembered and powerful enough to be valuable when making order-of-magnitude estimates of the way in which a stellar system should evolve.

The models of Bressan *et al.* (1993) imply that on the ZAMS a star of mass $\mathcal{M}$ has luminosity[8]

$$\frac{L_{\rm MS}}{L_\odot} \propto \begin{cases} 81(\mathcal{M}/\mathcal{M}_\odot)^{2.14} & \text{for } \mathcal{M} \gtrsim 20\,\mathcal{M}_\odot, \\ 1.78(\mathcal{M}/\mathcal{M}_\odot)^{3.5} & \text{for } 2\,\mathcal{M}_\odot < \mathcal{M} \lesssim 20\,\mathcal{M}_\odot, \\ 0.75(\mathcal{M}/\mathcal{M}_\odot)^{4.8} & \text{for } \mathcal{M} \lesssim 2\,\mathcal{M}_\odot. \end{cases} \qquad (5.5)$$

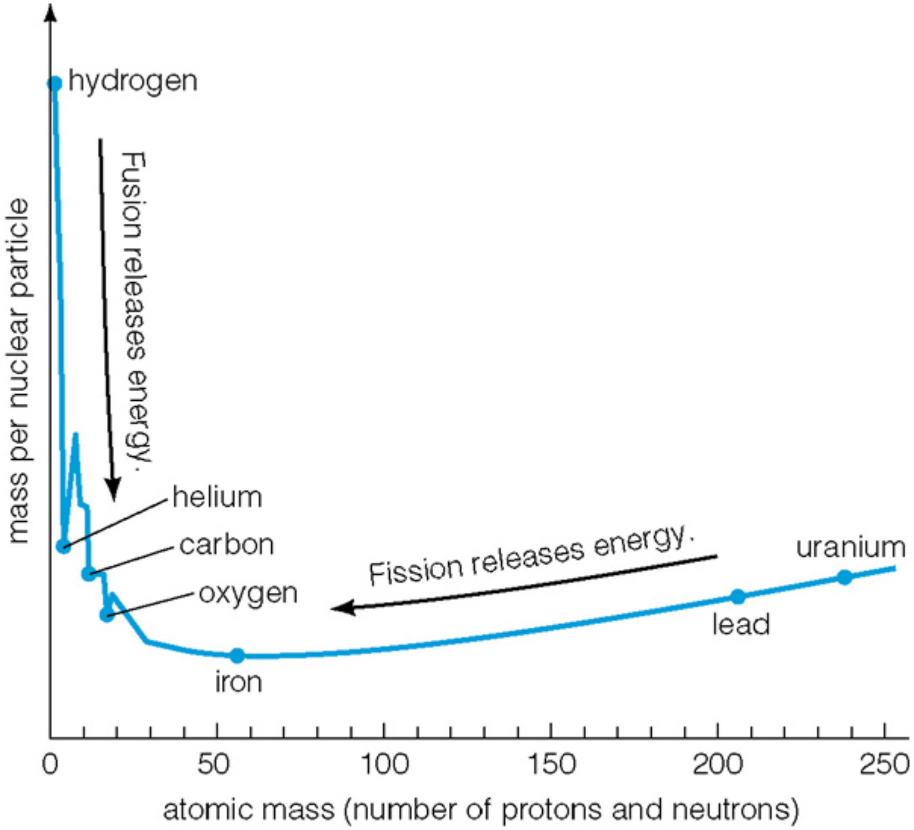
Figure 5.4 shows that as it sits on the MS a star's luminosity steadily increases from this ZAMS value.

The **MS lifetime**, $\tau_{\rm MS}$, of a star is fixed by the length of time that its luminosity can be supported by thermonuclear conversion of H to He. The fusion of four protons into one He nucleus releases an energy of 26.7 MeV, of which about 25 MeV is injected into the burning region rather than radiated in neutrinos.[9] Thus the conversion of a mass $\Delta\mathcal{M}$ of hydrogen releases $E = 0.0067\Delta\mathcal{M}c^2$ of useful energy. If a fraction α of the total mass of a star can be converted, then $\tau_{\rm MS} = (0.0067\alpha\mathcal{M}c^2/L)$. Detailed computations show that, when about one-tenth of the stellar mass has been converted, the star evolves rapidly away from the MS. Hence, to order of magnitude, we find

$$\tau_{\rm MS} \sim 10\left(\frac{\mathcal{M}}{\mathcal{M}_\odot}\right)\left(\frac{L}{L_\odot}\right)^{-1} \text{Gyr}. \qquad (5.6)$$

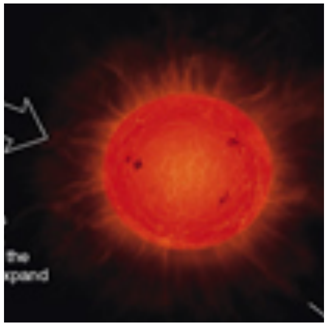
From GA

Energy Generation by Fusion and Fission of Elements

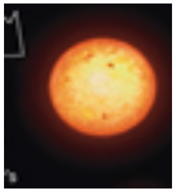


Evolution of low-mass ($M=1\text{-}8\ M_o$) stars

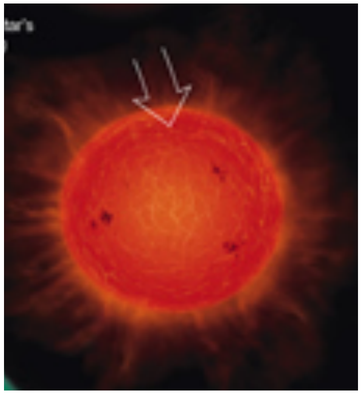
Yellow main sequence star of mass $M=1M_o$
H fusion in core via pp cycle



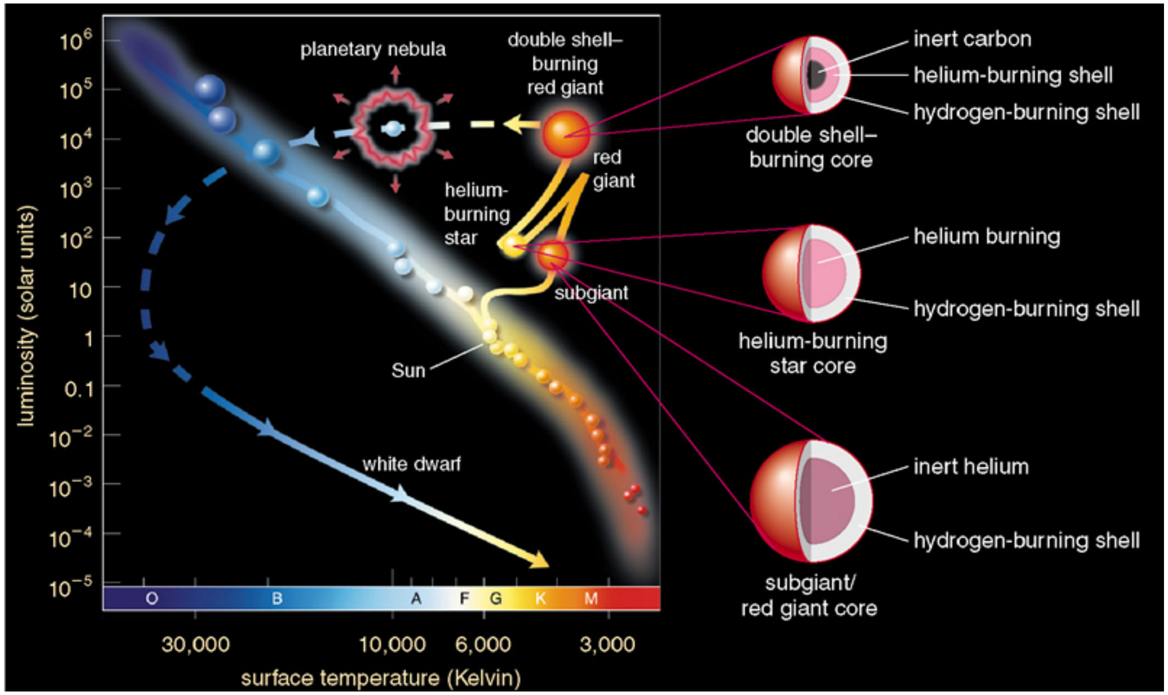
Red subgiant/giant:
Inert He core +
H-burning shell

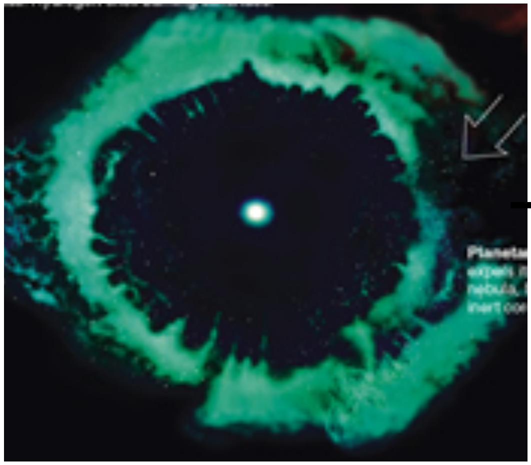


He-burning star:
He-burning core +
some reduced
H-burning in shell



Double shell-burning red giant .
Inert C core + double
shells burning He, H



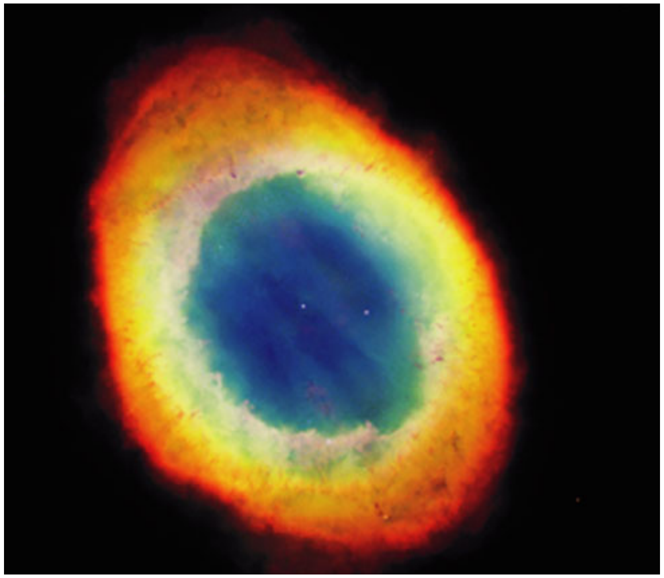
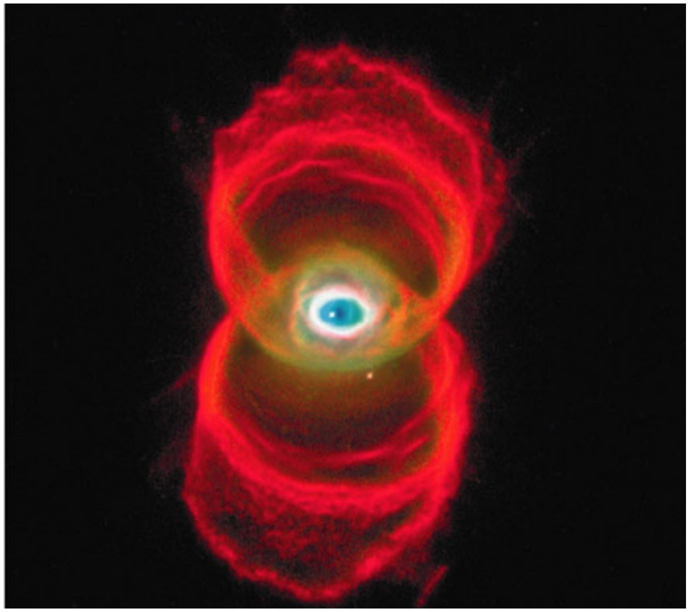


Inert C core collapses to **a white dwarf supported by electron degeneracy pressure.**

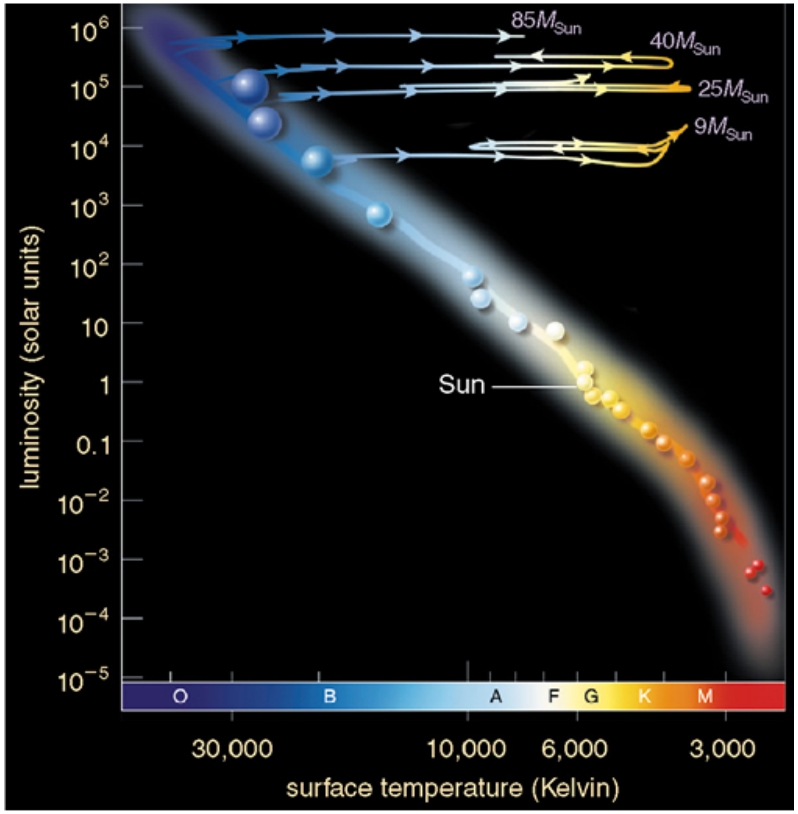
Outer layers are ejected by winds + other processes into an expanding shell of gas. Photons from the hot core ionize the gas to form a glowing **planetary nebula**

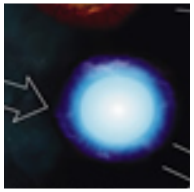
Planetary Nebulae



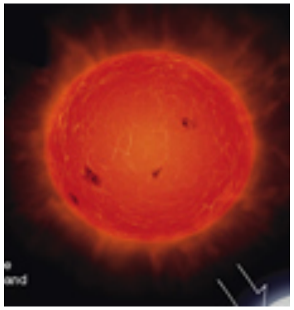



Evolution of massive ($M=9\text{-}40\ M_o$) star

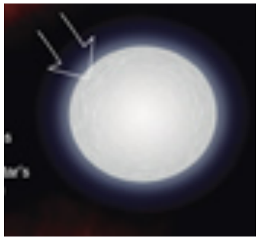




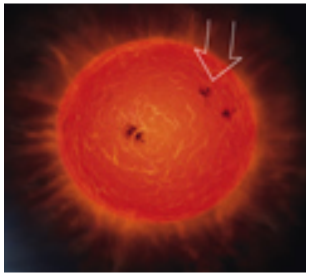
Blue main sequence star with $M=20\ M_o$.
-H fusion in core via CNO cycle



Red supergiant:
Inert He core + H-burning shell



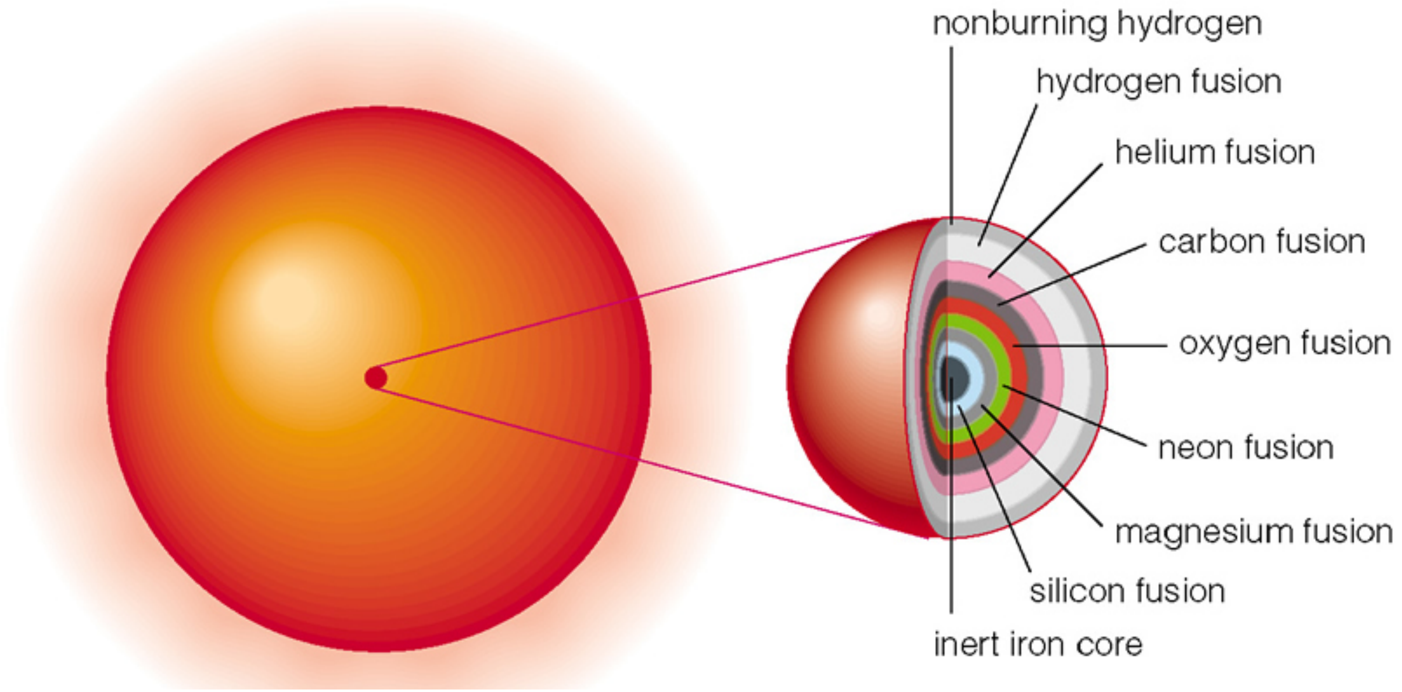
'Blue' supergiant:
He-burning core + reduced H-burning in shell



Multiple supergiant phases:
-Inert C core shrinks till fusion of C starts, then of O, then…of Si until iron collects in core.
- Multiple shells burning C, O, He, H

For 20 M_o star: When iron core is no longer supported by e- degeneracy pressure, it collapses to form a neutron star supported by n degeneracy pressure. Expanding shock wave causes outer layers of star to undergo a Type II supernova explosion.

Evolution of high-mass stars



Visible image of the Crab nebula, which is the remnant of the supernova explosion observed in AD1054

Reference Tables on Next 4 slides

(Note: There is no need to memorize the numbers in these tables. The tables are only provided so that you get a sense of the values of different physical properties (e.g., mass, luminosity, absolute magnitude, radius, surface temperature) of stars in different evolutionary phases and located in different parts of the H-R diagram)

Mean V-band magnitudes and colors for red giant stars

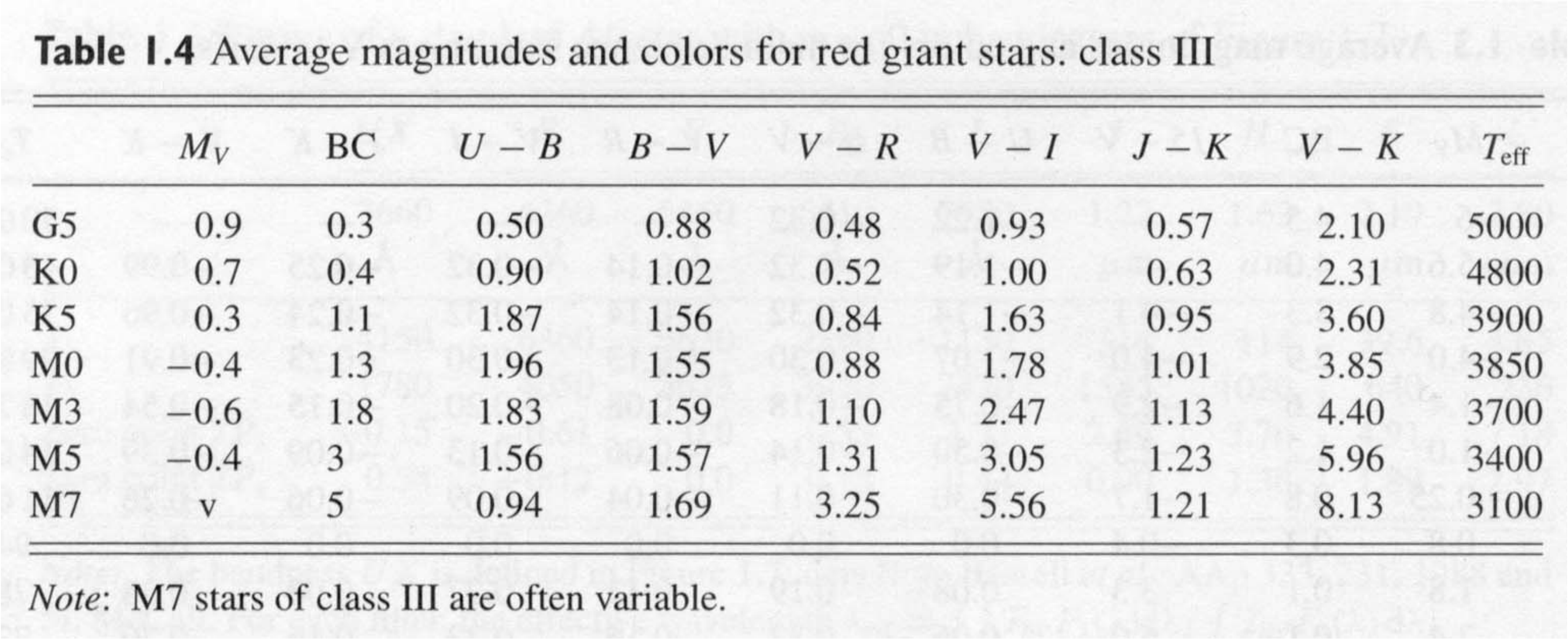


Table 1.4 Average magnitudes and colors for red giant stars: class III

	M_V	BC	$U-B$	$B-V$	$V-R$	$V-I$	$J-K$	$V-K$	T_{eff}
G5	0.9	0.3	0.50	0.88	0.48	0.93	0.57	2.10	5000
K0	0.7	0.4	0.90	1.02	0.52	1.00	0.63	2.31	4800
K5	0.3	1.1	1.87	1.56	0.84	1.63	0.95	3.60	3900
M0	−0.4	1.3	1.96	1.55	0.88	1.78	1.01	3.85	3850
M3	−0.6	1.8	1.83	1.59	1.10	2.47	1.13	4.40	3700
M5	−0.4	3	1.56	1.57	1.31	3.05	1.23	5.96	3400
M7	v	5	0.94	1.69	3.25	5.56	1.21	8.13	3100

Note: M7 stars of class III are often variable.

From GU

Main Sequence Stars

(Mass, Luminosity, Absolute Magnitude, Radius)

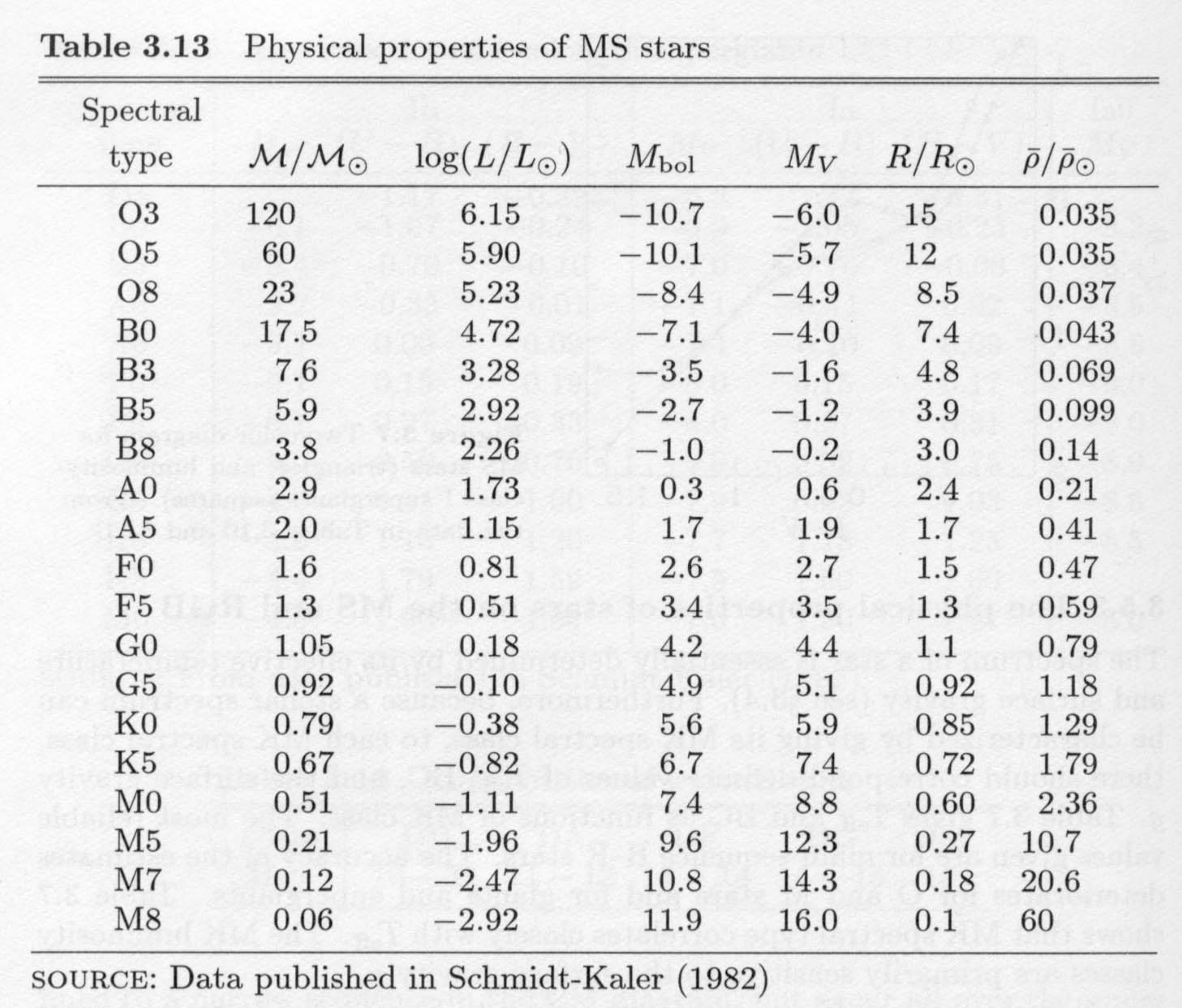


Table 3.13 Physical properties of MS stars

Spectral type	$\mathcal{M}/\mathcal{M}_\odot$	$\log(L/L_\odot)$	$M_{\rm bol}$	M_V	$R/R_\odot$	$\bar{\rho}/\bar{\rho}_\odot$
O3	120	6.15	−10.7	−6.0	15	0.035
O5	60	5.90	−10.1	−5.7	12	0.035
O8	23	5.23	−8.4	−4.9	8.5	0.037
B0	17.5	4.72	−7.1	−4.0	7.4	0.043
B3	7.6	3.28	−3.5	−1.6	4.8	0.069
B5	5.9	2.92	−2.7	−1.2	3.9	0.099
B8	3.8	2.26	−1.0	−0.2	3.0	0.14
A0	2.9	1.73	0.3	0.6	2.4	0.21
A5	2.0	1.15	1.7	1.9	1.7	0.41
F0	1.6	0.81	2.6	2.7	1.5	0.47
F5	1.3	0.51	3.4	3.5	1.3	0.59
G0	1.05	0.18	4.2	4.4	1.1	0.79
G5	0.92	−0.10	4.9	5.1	0.92	1.18
K0	0.79	−0.38	5.6	5.9	0.85	1.29
K5	0.67	−0.82	6.7	7.4	0.72	1.79
M0	0.51	−1.11	7.4	8.8	0.60	2.36
M5	0.21	−1.96	9.6	12.3	0.27	10.7
M7	0.12	−2.47	10.8	14.3	0.18	20.6
M8	0.06	−2.92	11.9	16.0	0.1	60

SOURCE: Data published in Schmidt-Kaler (1982)

From GA

Mean V-band magnitudes & colors for main sequence stars

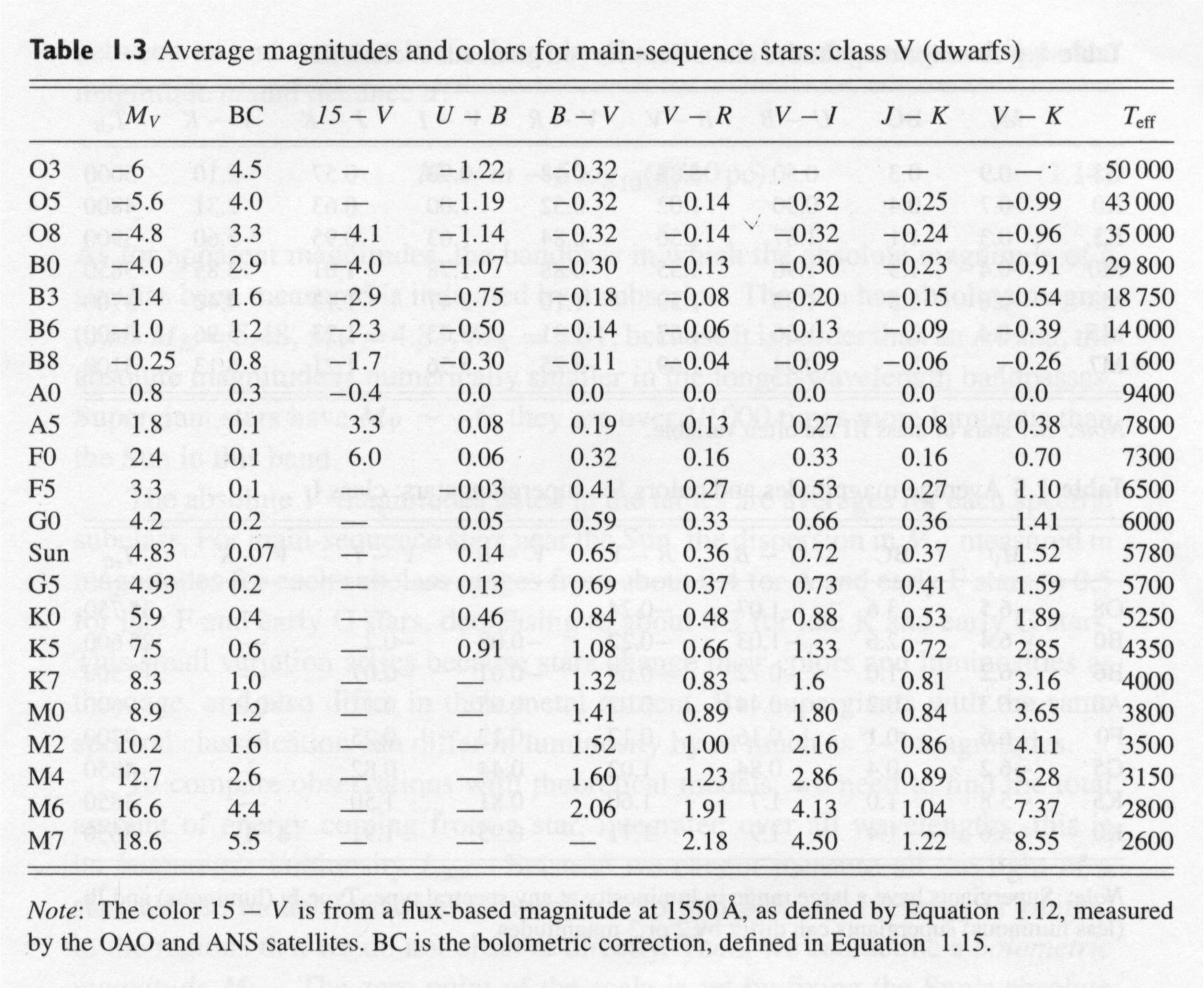


Table 1.3 Average magnitudes and colors for main-sequence stars: class V (dwarfs)

	M_V	BC	$15 - V$	$U - B$	$B - V$	$V - R$	$V - I$	$J - K$	$V - K$	T_{eff}
O3	−6	4.5	—	−1.22	−0.32	—	—	—	—	50 000
O5	−5.6	4.0	—	−1.19	−0.32	−0.14	−0.32	−0.25	−0.99	43 000
O8	−4.8	3.3	−4.1	−1.14	−0.32	−0.14	−0.32	−0.24	−0.96	35 000
B0	−4.0	2.9	−4.0	−1.07	−0.30	−0.13	−0.30	−0.23	−0.91	29 800
B3	−1.4	1.6	−2.9	−0.75	−0.18	−0.08	−0.20	−0.15	−0.54	18 750
B6	−1.0	1.2	−2.3	−0.50	−0.14	−0.06	−0.13	−0.09	−0.39	14 000
B8	−0.25	0.8	−1.7	−0.30	−0.11	−0.04	−0.09	−0.06	−0.26	11 600
A0	0.8	0.3	−0.4	0.0	0.0	0.0	0.0	0.0	0.0	9400
A5	1.8	0.1	3.3	0.08	0.19	0.13	0.27	0.08	0.38	7800
F0	2.4	0.1	6.0	0.06	0.32	0.16	0.33	0.16	0.70	7300
F5	3.3	0.1	—	−0.03	0.41	0.27	0.53	0.27	1.10	6500
G0	4.2	0.2	—	0.05	0.59	0.33	0.66	0.36	1.41	6000
Sun	4.83	0.07	—	0.14	0.65	0.36	0.72	0.37	1.52	5780
G5	4.93	0.2	—	0.13	0.69	0.37	0.73	0.41	1.59	5700
K0	5.9	0.4	—	0.46	0.84	0.48	0.88	0.53	1.89	5250
K5	7.5	0.6	—	0.91	1.08	0.66	1.33	0.72	2.85	4350
K7	8.3	1.0	—	—	1.32	0.83	1.6	0.81	3.16	4000
M0	8.9	1.2	—	—	1.41	0.89	1.80	0.84	3.65	3800
M2	10.2	1.6	—	—	1.52	1.00	2.16	0.86	4.11	3500
M4	12.7	2.6	—	—	1.60	1.23	2.86	0.89	5.28	3150
M6	16.6	4.4	—	—	2.06	1.91	4.13	1.04	7.37	2800
M7	18.6	5.5	—	—	—	2.18	4.50	1.22	8.55	2600

Note: The color $15 - V$ is from a flux-based magnitude at 1550 Å, as defined by Equation 1.12, measured by the OAO and ANS satellites. BC is the bolometric correction, defined in Equation 1.15.

From GU

Mean V-band magnitudes and colors for supergiant stars

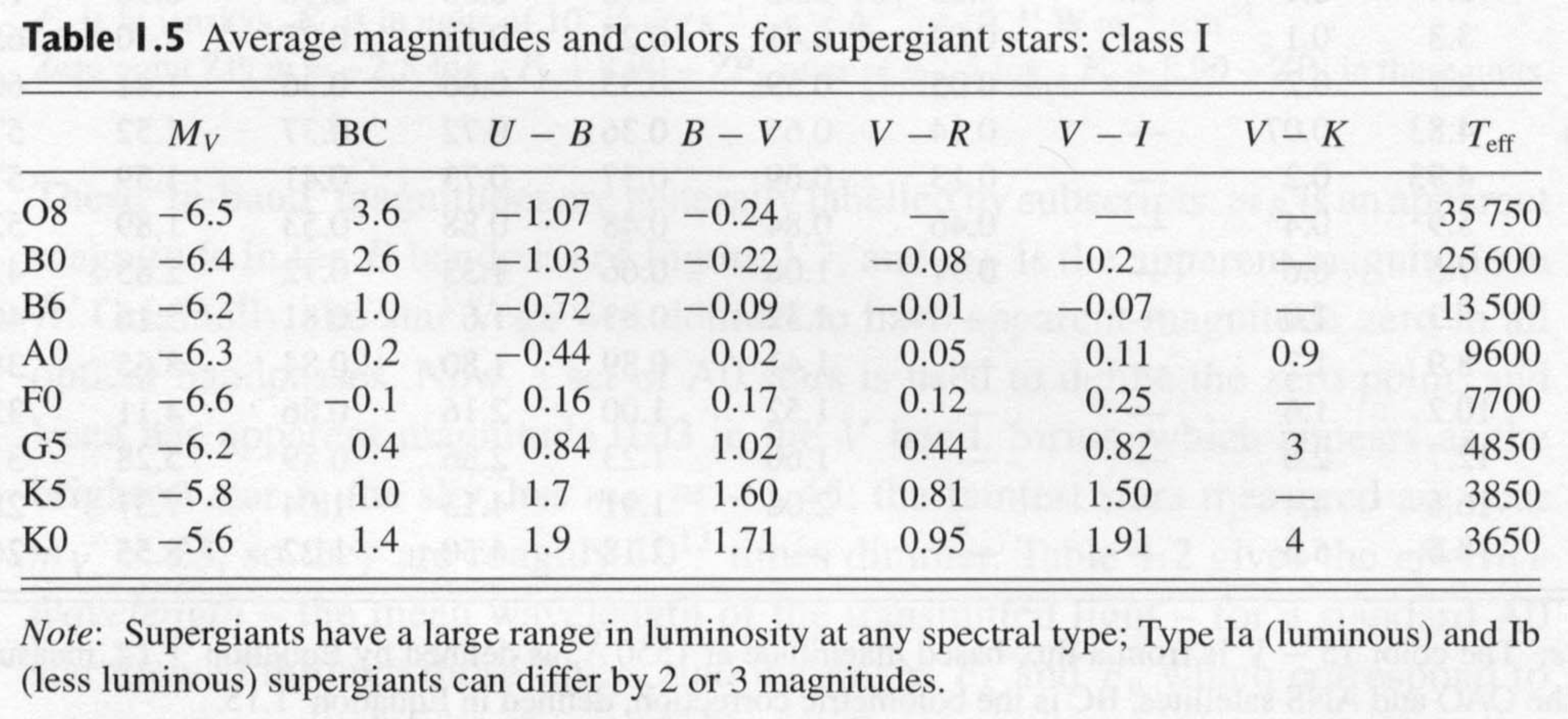


Table 1.5 Average magnitudes and colors for supergiant stars: class I

	M_V	BC	$U-B$	$B-V$	$V-R$	$V-I$	$V-K$	T_{eff}
O8	−6.5	3.6	−1.07	−0.24	—	—	—	35 750
B0	−6.4	2.6	−1.03	−0.22	−0.08	−0.2	—	25 600
B6	−6.2	1.0	−0.72	−0.09	−0.01	−0.07	—	13 500
A0	−6.3	0.2	−0.44	0.02	0.05	0.11	0.9	9600
F0	−6.6	−0.1	0.16	0.17	0.12	0.25	—	7700
G5	−6.2	0.4	0.84	1.02	0.44	0.82	3	4850
K5	−5.8	1.0	1.7	1.60	0.81	1.50	—	3850
K0	−5.6	1.4	1.9	1.71	0.95	1.91	4	3650

Note: Supergiants have a large range in luminosity at any spectral type; Type Ia (luminous) and Ib (less luminous) supergiants can differ by 2 or 3 magnitudes.

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