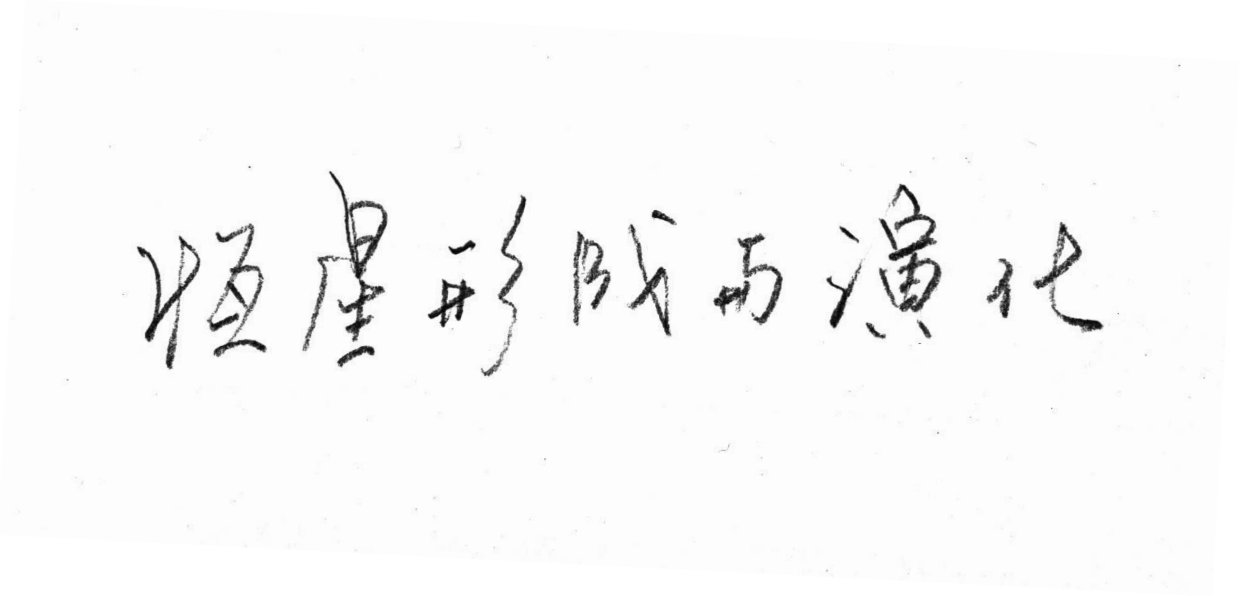
Stellar Formation and Evolution



Wen Ping Chen **陳文屏**

中央大學 天文研究所

http://www.astro.ncu.edu.tw/~wchen/Courses/Stars/Default.htm

Table of Contents

- ✓What is a “star”?
- ✓How hot is the surface of the Sun? How is this known?
  The Sun is gaseous, so how come it has a “surface”?
- ✓How hot is the center of the Sun?
  How is this known?
- ✓How the sun derive its energy to shine? How long can the Sun remain as a shining body?
  How are these known?
- ✓Describe the radial structure of the Sun.
  How is this know?

Stellar Formation and Evolution --- Syllabus

Instructor: Professor Wen-Ping Chen

Office: 906

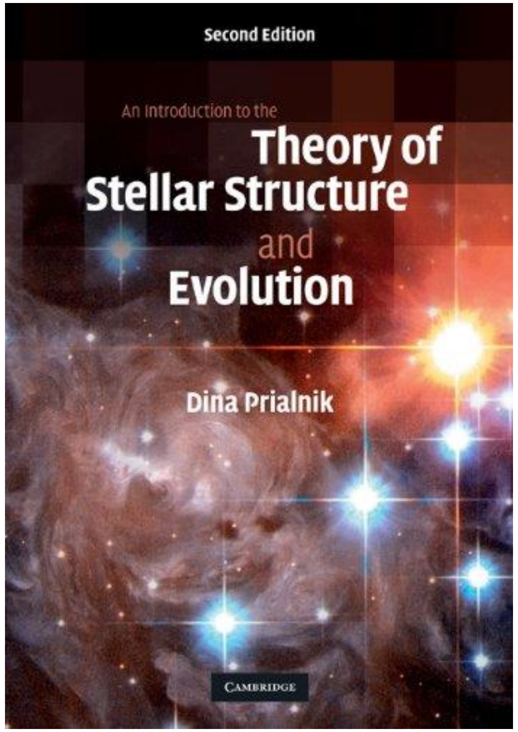
Class Time: Tuesday 3 to 6 pm

Classroom: Room 914

This course deals with the time variations of the structures of a star's interior (and atmosphere). We will discuss the important physical processes governing the life of a star --- from its birth out of a dense, cold molecular cloud core, to shining with the star's own thermonuclear fuels, to rapid changes in structures when these fuels are no longer available, to the end of a star's life, with matter in extremely compact states.

What it may take for a star billions of years, will take us one semester to cover the following subjects:

- Observational Properties of Stars
- Molecular Clouds and the Interstellar Medium
- Cloud Collapse and Fragmentation
- Stars and Statistical Physics
- Protostars and Jets
- Circumstellar Disks and Planet Formation
- Evolution onto the Main Sequence
- Binaries and Star Clusters
- On the Main Sequence --- Nuclear Reactions
- Effects of Rotation
- Instabilities --- Thermally, Dynamically and Convectively
- Post-MS Evolution of Low-Mass Stars --- RG, AGB, HB, PNe
- Post-MS Evolution of Massive Stars --- SN and SNR
- Mass Loss, Stellar Pulsation and Cepheid Variables
- Compact Objects --- White Dwarfs, Neutron Stars, and Black holes
- Violent End Products --- Supernovae and others



Text: "***An Introduction to the Theory of Stellar Structure and Evolution***", by Dina Prialnik, Cambridge, 2nd Ed. 2009

In addition to written midterm (30% grade) and final (30%) exams, there will be homework assignments, plus in-class exercises or projects (35%).

References

All the references you have found useful for the course ***Stellar Atmosphere and Structure*** will be also of use in this course. The following are the ones I refer to often.

- ✓ ***Physics of Stellar Evolution and Cosmology***, by H. Goldberg & Michael Scadron, 1982, Gordon and Breach
- ✓ ***Black Holes, White Dwarfs, and Neutron Stars,*** by Stuart L. Shapiro & Saul A. Teukolsky, 1983, Wiley
- ✓ ***Stellar Structure and Evolution***, by R. Kippenhahn & W. Weigert, 1990, Springer-Verlag
- ✓ ***Stellar Structure and Evolution***, by Huang, R.Q. 黃潤乾, Guoshin, 1990, originally published in Chinese (恆星物理).
- ✓ ***Introduction to Stellar Astrophysics***, Vol 3 --- Stellar Structure and Evolution, by Erika Bohm-Vitense, 1992, Cambridge
- ✓ ***The Physics of Stars***, by A.C. Phillips, 1994, John Wiley & Sons
- ✓ ***Stellar Evolution***, by Amos Harpaz, A K Peters, 1994
- ✓ ***The Stars*** --- Their Structure and Evolution, R. J. Tayler, 1994, Cambridge
- ✓ ***Supernovae and Nucleosynthesis,*** by David Arnett, 1996, Princeton
- ✓ ***Theoretical Astrophysics, Vol II*: Stars and Stellar Systems** by Padmanabhan, T., a hefty, mathematical 3 volume set; comprehensive coverage of basic astrophysical processes in vol. 1, stars in vol. 2, and galaxies and cosmology in vol. 3, 2001, Cambridge
- ✓ ***The Formation of Stars,*** by Steven Stahler & Francesco Palla, 2004, Wiley-VCH
- ✓ ***Evolution of Stars and Stellar Populations***, by Maurizio Salaris & Santi, Cassisi, 2005, Wiley
- ✓ ***The Formation of Stars***, by Steven W. Stahler & Francesco Palla, 2004, Wiley
- ✓ ***From Dust to Stars,*** by Norbert S. Schulz, 2005, Springer
- ✓ ***Stellar Physics, 2: Stellar Evolution and Stability,*** by Bisnovatyi-Kogan, 2nd Ed., 2010, Springer (translated from Russian)
- ✓ ***Astrophysics of Planet Formation,*** by Philip J. Armitage, 2010, Cambridge
- ✓ ***Principles of Star Formation,*** by Peter Bodenheimer, 2011, Springer
- ✓ ***An Introduction to Star Formation,*** by Derek Ward-Thompson & Anthony P. Whitworth, 2011, Cambridge
- ✓ ***Stellar Evolution Physics,*** by Icko Iben, 2013 (two volumes), Cambridge
- ✓ ***Star Formation,*** by Mark R. Krumholz, 2017, World Scientific

For star formation, the book "***Molecular Clouds and Star Formation***", edited by Chi Yuan（袁旂）& Junhan You（尤峻漢）and published by World Scientific in 1993, should be a good reference. Unfortunately this book is currently out of print, but Prof Yuan kindly donated his editor copy.

For an extensive listing of books on "stars" … http://www.ericweisstein.com/encyclopedias/books/Stars.html

Class Schedule

#	Date	Comments
01	02/19	
02	02/26	
03	03/05	
04	03/12	
05	03/19	
06	03/26	
07	04/02	
08	04/09	
09	04/16	Midterm

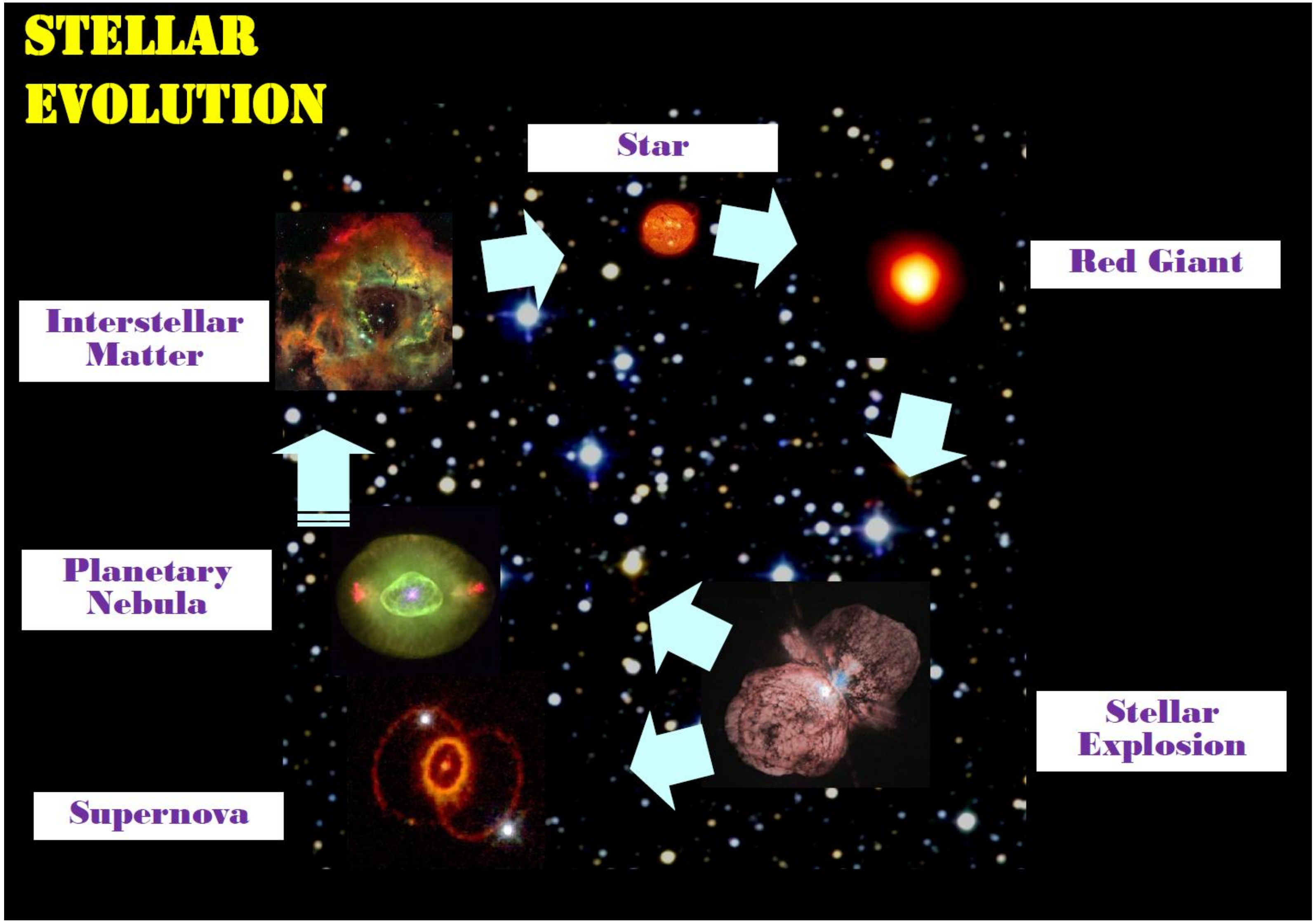
#	Date	Comments
10	04/23	
11	04/30	
12	05/07	
13	05/14	
14	(05/21)	To be made up
15	05/28	
16	06/04	
17	06/11	
18	06/18	Final

Course Goals

- To know the properties of various phases of the interstellar matter;
- To understand how stars form out of molecular clouds; under what conditions;
- To understand the physical properties of stars, and to know how these properties change with time as a star evolves;
- To understand the basic physics underlying complex stellar evolution models;
- To know how to interpret observational parameters of stars;
- To understand how stars of different masses evolve and what the end products of their evolution are.

Stellar structure:
balance of forces

Stellar evolution:
(con)sequence of thermonuclear reactions in different parts of a star, and at different epochs as the star ages



Often used fundamental constants

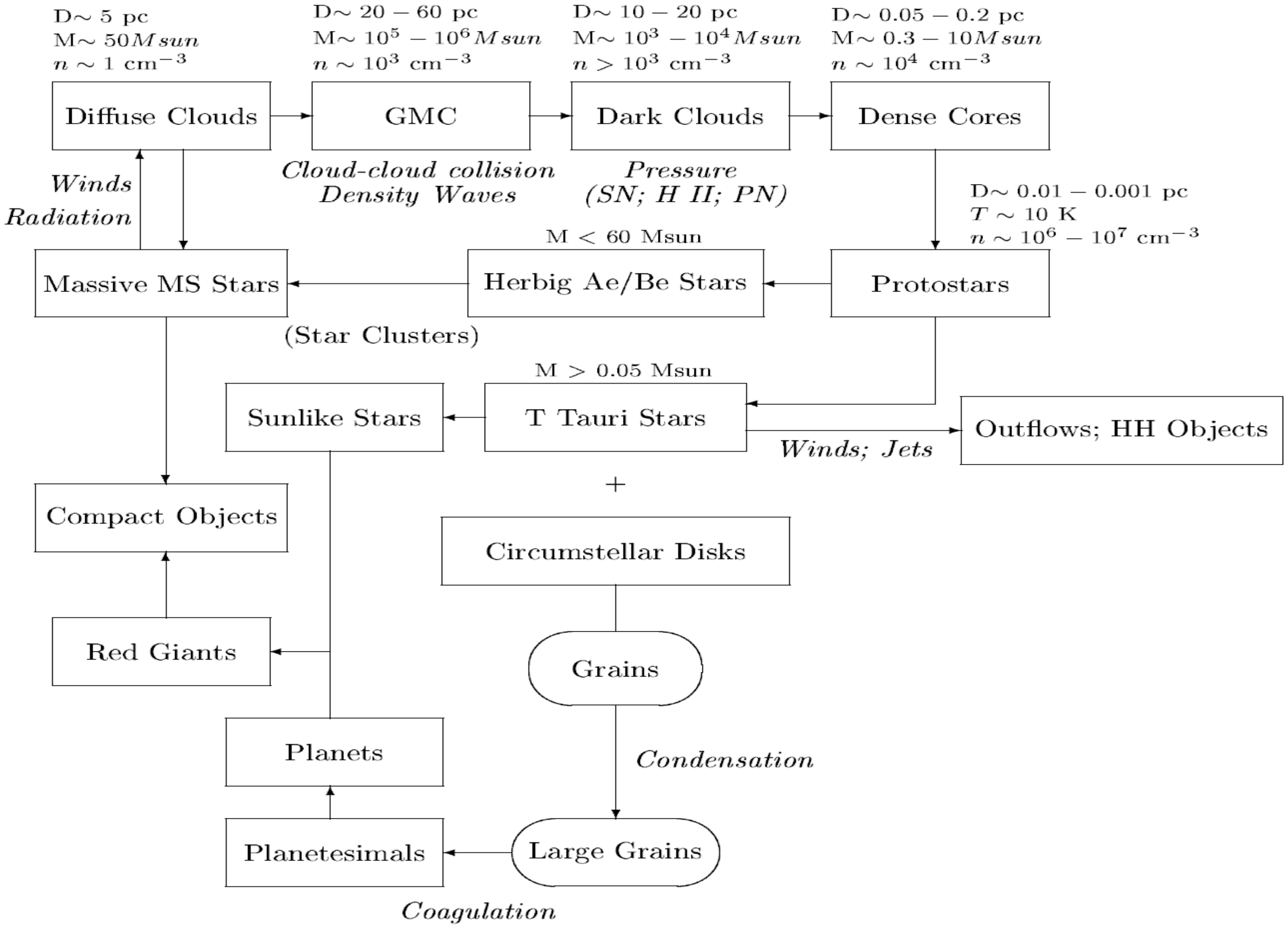
Physical

a	radiation density constant	7.55×10^{-16} J m^{-3} K^{-4}
c	velocity of light	3.00×10^{8} m s^{-1}
G	gravitational constant	6.67×10^{-11} N m^{2} kg^{-2}
h	Planck's constant	6.62×10^{-34} J s
k	Boltzmann's constant	1.38×10^{-23} J K^{-1}
m_e	mass of electron	9.11×10^{-31} kg
m_H	mass of hydrogen atom	1.67×10^{-27} kg
N_A	Avogardo's number	6.02×10^{23} mol^{-1}
σ	Stefan Boltzmann constant	5.67×10^{-8} W m^{-2} K^{-4} (= ac/4)
R	gas constant (k/m_H)	8.26×10^{3} J K^{-1} kg^{-1}
e	charge of electron	1.60×10^{-19} C

Check out http://pdg.lbl.gov/2006/reviews/astrorpp.pdf

Astronomical

$L_\odot$	Solar luminosity	3.86×10^{26} W
$M_\odot$	Solar mass	1.99×10^{30} kg
$T_{eff\odot}$	Solar effective temperature	5780 K
$\mathrm{T}_{c\odot}$	Solar Central temperature	1.6×10^{7} K (theoretical)
$R_\odot$	Solar radius	6.96×10^{8} m
$\mathrm{m}_\odot$	apparent mag of Sun	-26.7 mag (V)
$\mathrm{M}_\odot$	absolute mag of Sun	$+4.8$ mag (V)
θ	apparent size of Sun	32’
$<\rho>$	mean density of Sun	1.4 g cm^{-3}
$(B\text{-}V)_\odot$	Color of the Sun	0.6 mag
Parsec	*unit of distance*	3.09×10^{16} m



Galactic Ecology

Properties of Stars

Vocabulary

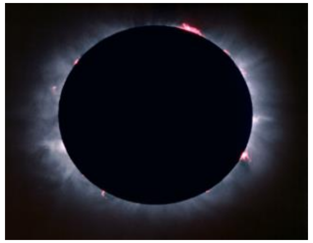
- **Luminosity** [erg s^{-1}] ***L*** = bolometric luminosity = power
- **Spectral luminosity** [erg $s^{-1}\mu m^{-1}$] L_λ $d\lambda = -(c/\nu^2)\, d\nu$
- **flux** [erg $s^{-1}cm^{-2}$] ***f***
- **flux density** [erg s^{-1} cm^{-2} μm^{-1}] f_λ ***or*** f_ν

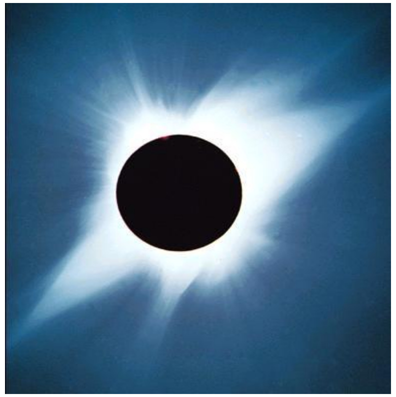
  1 Jansky (Jy) = 10^{-23} [erg $s^{-1}cm^{-2}Hz^{-1}$] $f(m_V = 0) = 3640$ Jy
- **Brightness/intensity** [erg s^{-1} cm^{-2} sr^{-1}] ***B***
- **Specific intensity** [erg s^{-1} $cm^{-2}sr^{-1}$ Hz^{-1}] I_ν
- **Energy density** [erg cm^{-3}] ***u*** = (4 π/c) J
- **J=mean intensity** = (1/4π) $\int I\, d\Omega$
- **Magnitude** … apparent, absolute, bolometric, AB

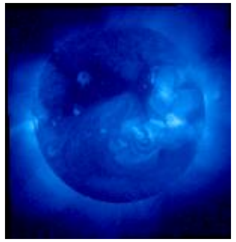
$$m_{AB} = -2.5 \log_{10}\left(\frac{f_\nu}{3631\ \mathrm{Jy}}\right)$$

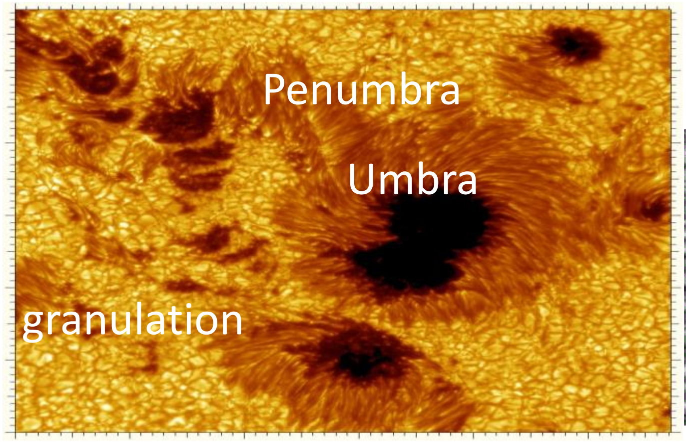
$$S_\nu\ [\mu\mathrm{Jy}] = 10^{(23.9-\mathrm{AB})/2.5}$$

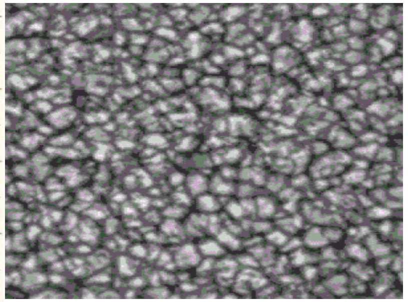
Our Sun ---- the best studied star

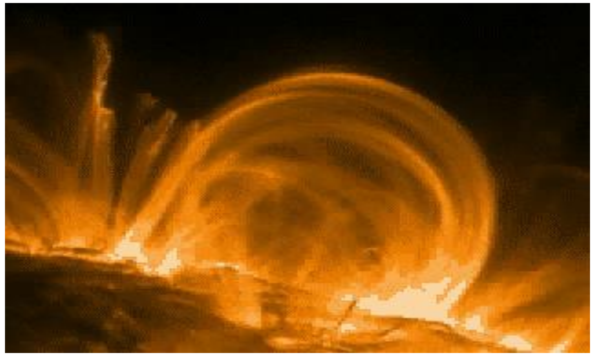


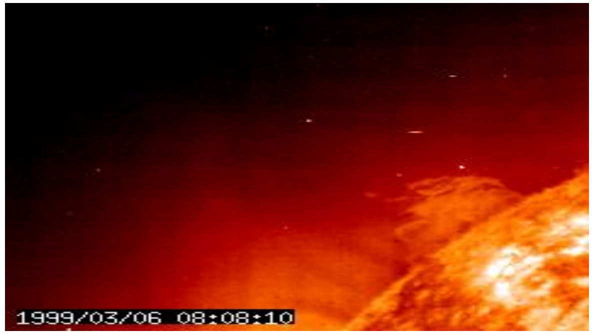


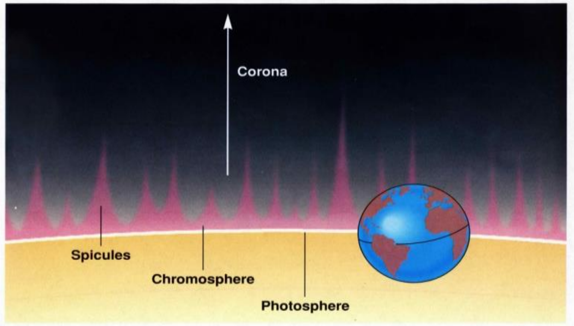




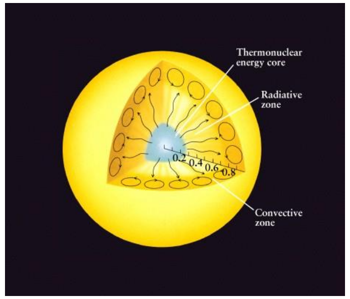


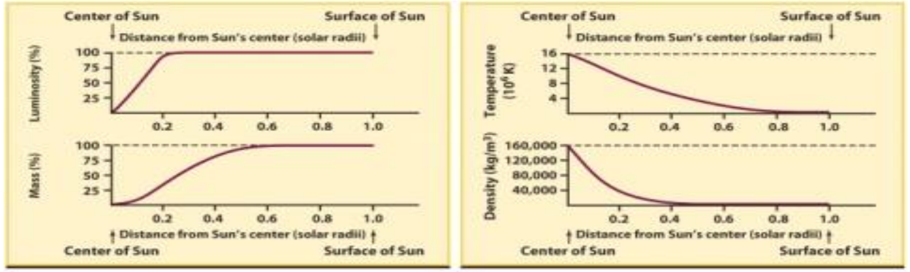


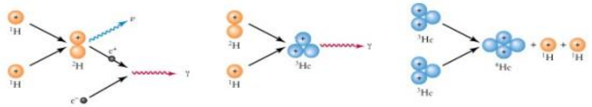




Cross section of photosphere.







Observable properties of stars

Basic parameters to compare between theories and observations

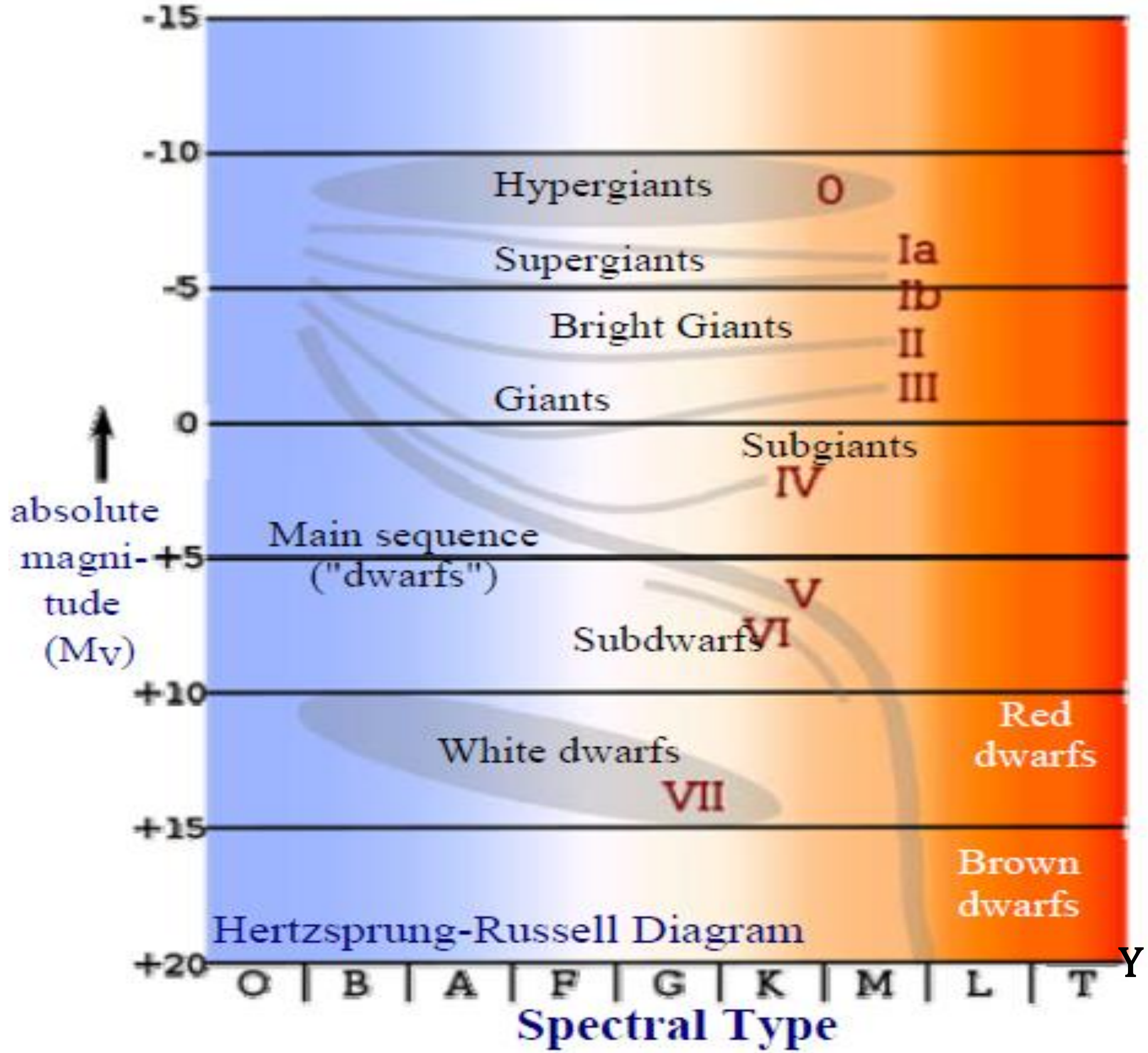
- Mass (M)
- Luminosity (L)
- Radius (R)
- Effective temperature (T_e) $L = 4\pi R^2 \sigma T_e^4$
- Distance → measured flux $F = L/4\pi d^2$

M, R, L and T_e not independent

- L and T_{eff} Hertzsprung-Russell (HR) diagram or color-magnitude diagram (CMD)

- L and M mass-luminosity relation

http://www.astrohandbook.com/links.html



$\mathcal{M}_{\text{Jupiter}} \sim 0.001\, \mathcal{M}_{\odot}$

Stars:

$M > 0.08\, \mathcal{M}_{\odot}$

Brown Dwarfs:

$0.08\, \mathcal{M}_{\odot} > M > 13\, \mathcal{M}_{J}$

Planet-mass Objects:

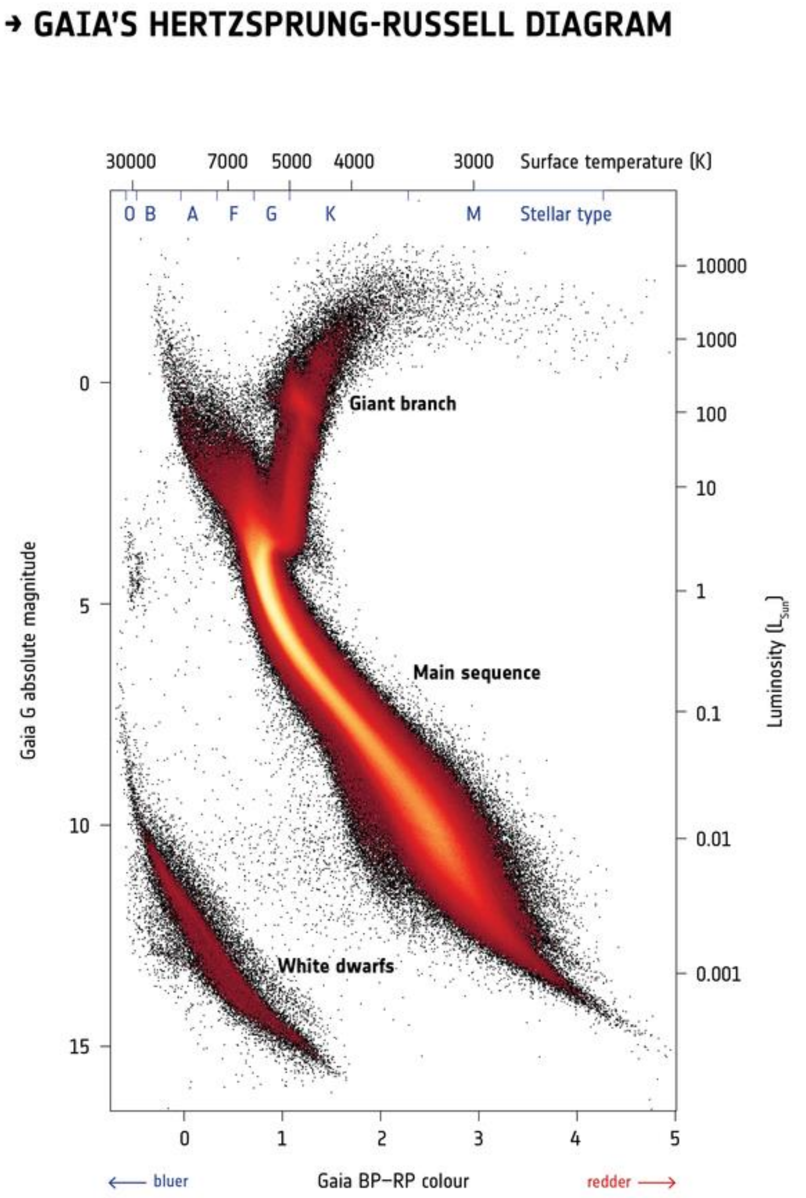
$M < 13\, \mathcal{M}_{J}$

To measure the stellar distance

- ◆ Nearest stars $d > 1$pc → $p < 1''$
- ◆ For a star at d=100 pc, p= 0.01"
- ◆ Ground-based observations angular resolution ~1"; *HST* has 0.05"
- ◆ *Hipparcos* measured the parallaxes of 10^5 bright stars with p~0.001" → reliable distance determinations up to d=100 pc

➔ ~100 stars with good parallax distances

Gaia is measuring 10^9 stars!



Exercise

1. What is *Gaia* as a space telescope mission?
2. What is the size of the telescope?
3. When was it launched? What kind of an orbit does it have? How long is it expect to last? How faint does it go?
4. What its main mission (what does it measure)?

Otherwise, the distance is estimated

- Stars with the same spectra are assumed to have identical set of physical parameters (spectroscopic parallax). For example, a G2V star should have the same absolute magnitude as the Sun.
- By comparison of the apparent brightness of an object with known brightness of that particular kind of objects

$$m_\lambda - M_\lambda = 5 \log d - 5 + A_\lambda(d)$$

  A_λ is usually unknown; it depends on the intervening dust grains that scatter and absorb the star light, and also depends on the distance to the object.

- Main-sequence fitting; moving-cluster method; Cepheid variables
- Other methods for Galactic molecular clouds, galaxies, etc.

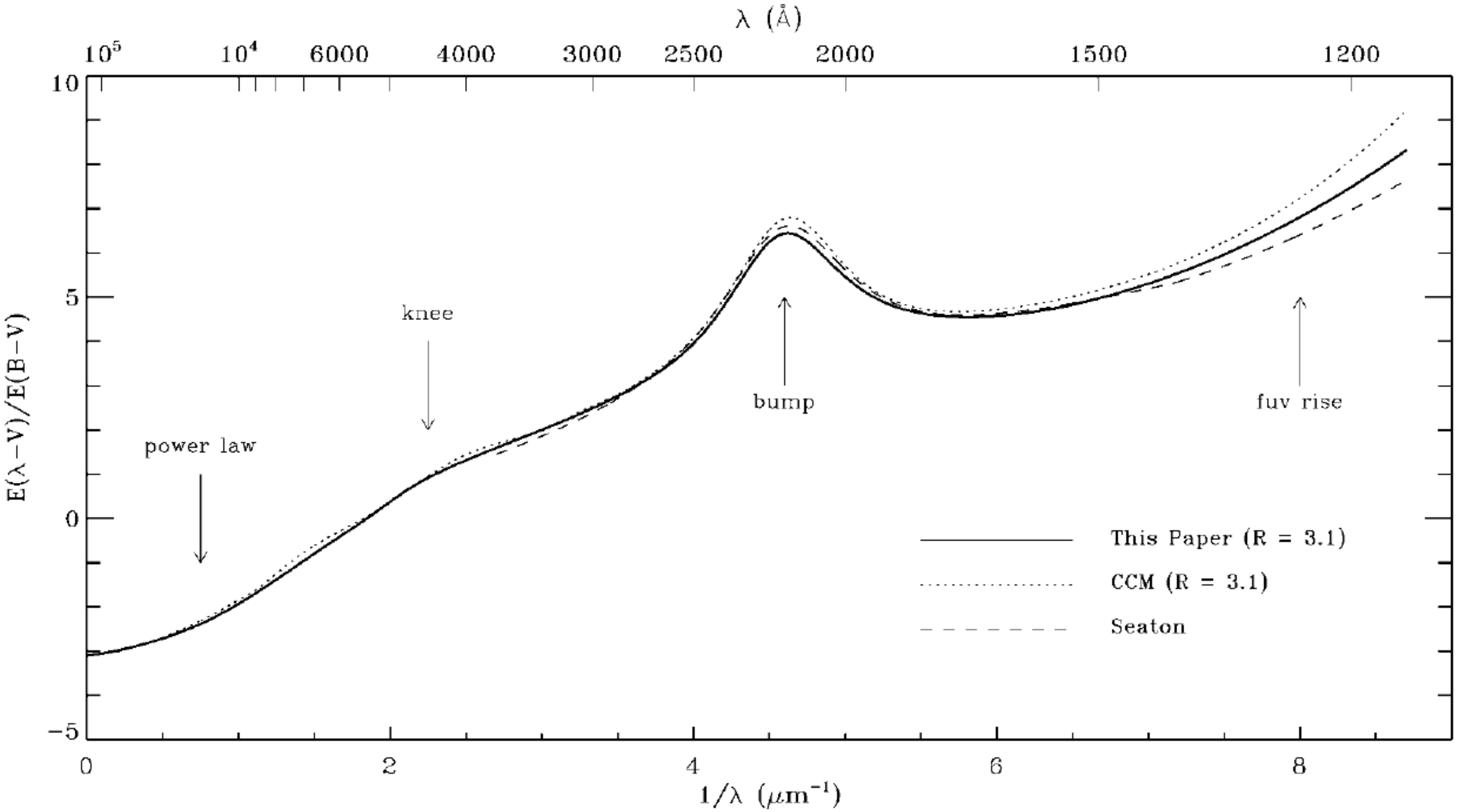
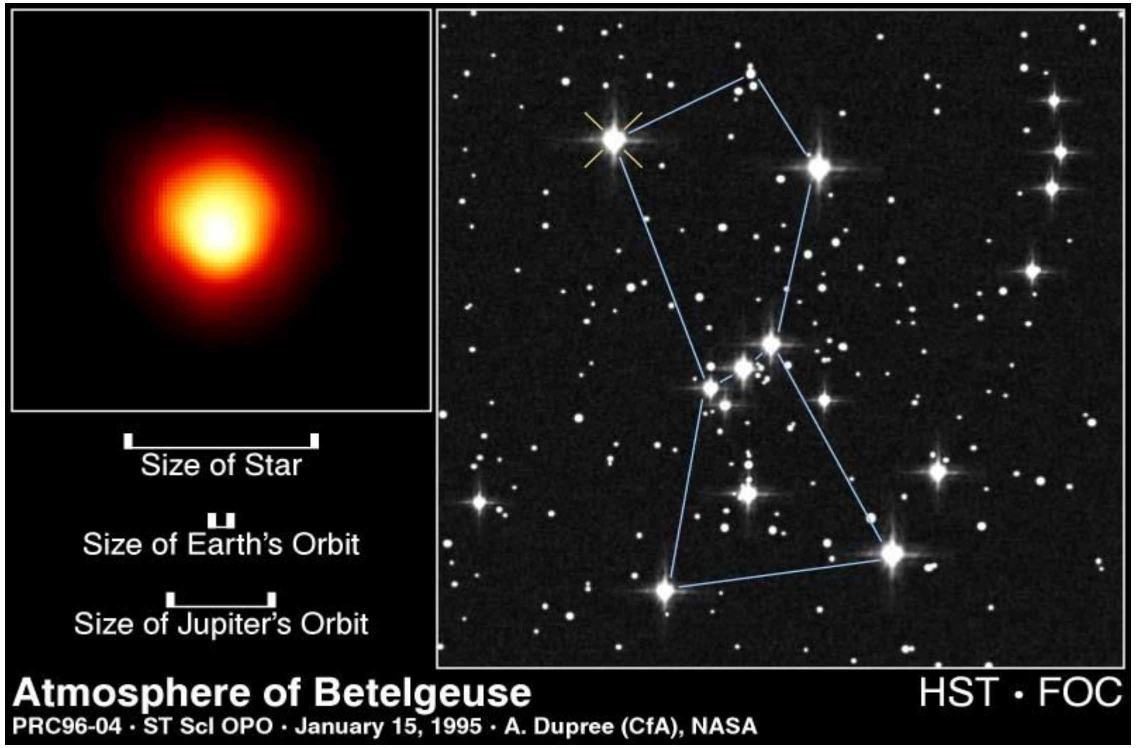


FIG. 1.—Normalized interstellar extinction curves from the far-IR through the UV. Several general features of the curves are noted. The solid and dotted curves are estimates for the case $R \equiv A(V)/E(B-V) = 3.1$ derived in the Appendix of this paper and by Cardelli et al. (1989), respectively. The dashed curve shows the average Galactic UV extinction curve from Seaton (1979).

To measure the stellar size

◆ Angular diameter of sun at 10 pc
$= 2R_\odot/10\text{pc} = 5 \times 10^{-9}$ radians
$= 10^{-3}$ arcsec

◆ Even the *HST* (0.05”) barely capable of measuring directly the sizes of stars, except for the nearest supergiants



◆ Radii of ~600 stars measured with techniques such as interferometry, (lunar) occultation or for eclipsing binaries

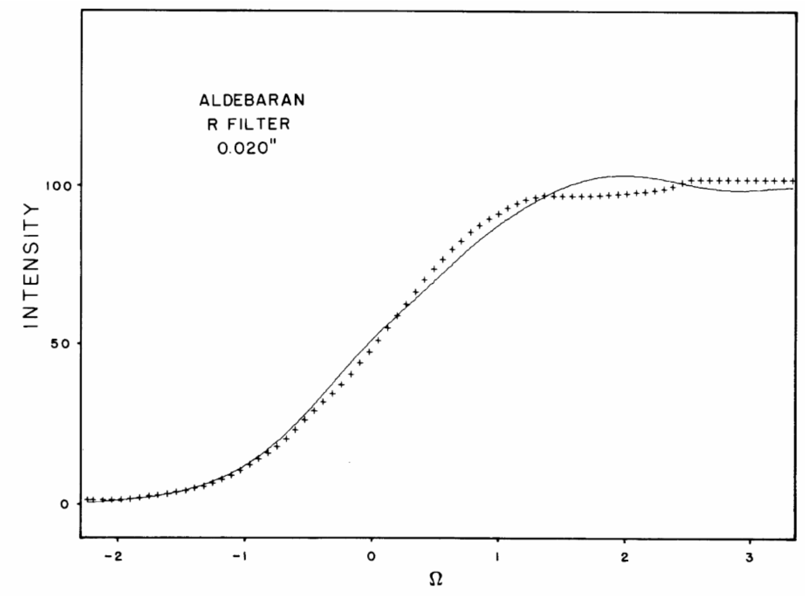


FIG. 1.—A comparison of the (*crosses*) observed points and the (*line*) theoretical pattern for the Aldebaran $\lambda = 7460$ Å record with $\theta = 0''.020$.

Lunar occultation

Beaver & Eitter (1979)

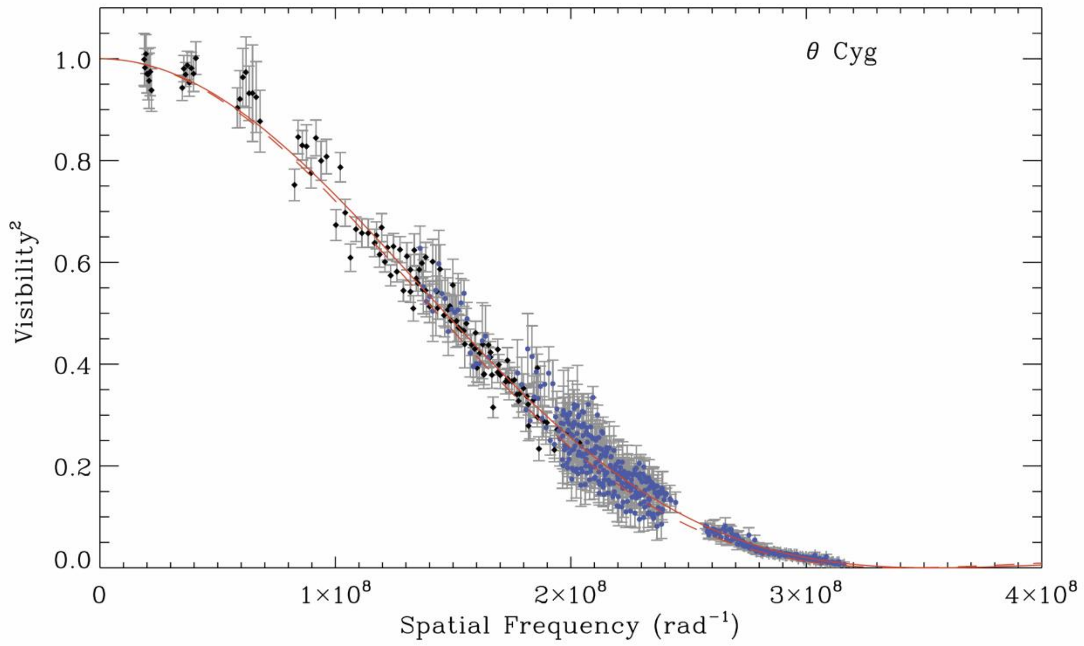


Figure 1. Squared visibility versus spatial frequency for θ Cyg for PAVO (blue circles) and MIRC (black diamonds) data. The red lines show the fitted limb-darkened model to the combined data. The solid line is for $\mu = 0.47 \pm 0.04$ (PAVO) while the dashed line is for $\mu = 0.21 \pm 0.03$ (MIRC).

Optical interferometery CHARA

White et al (2013)

To measure the stellar temperature

◆ What is T_{eff}? What is the "surface" of a star?

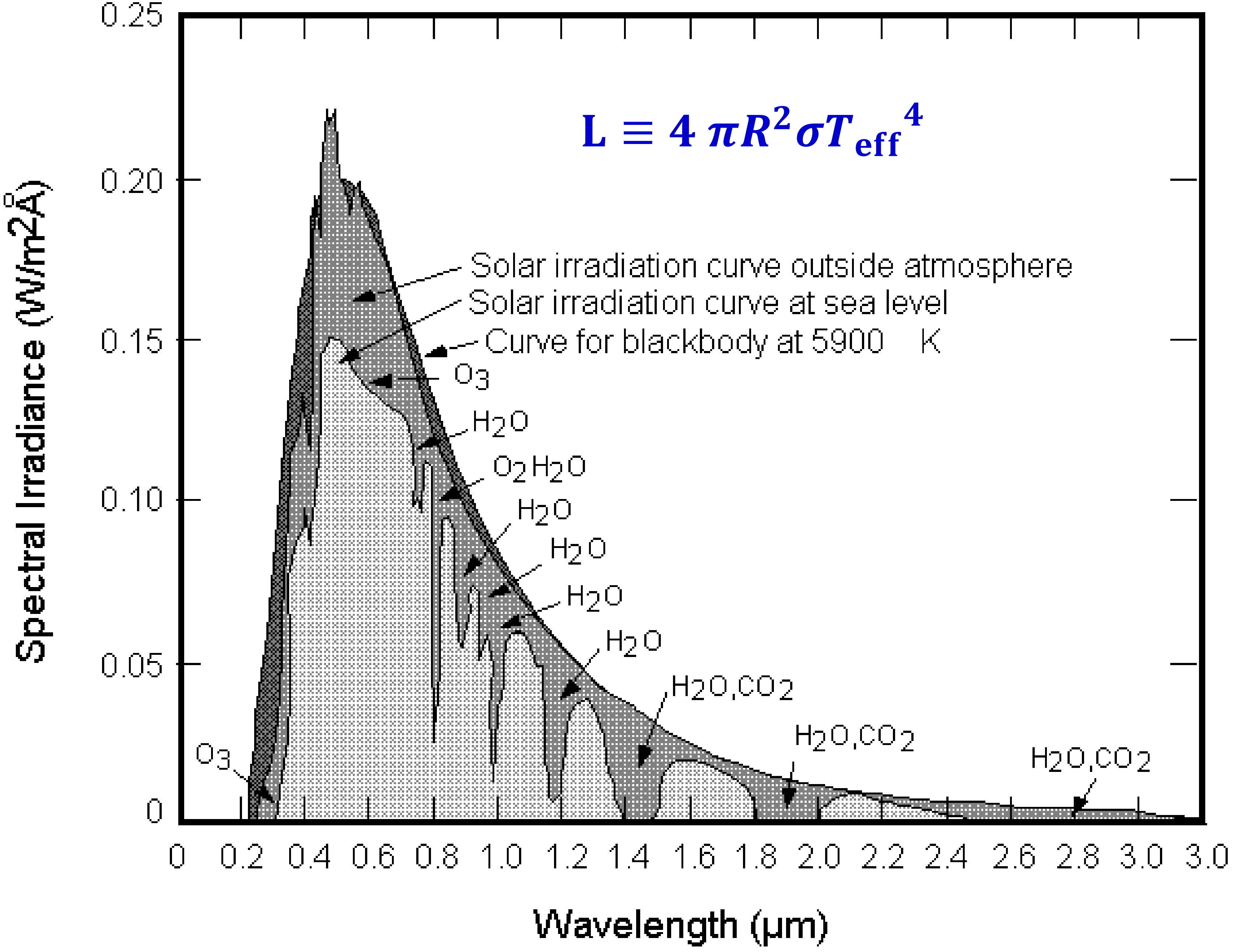
◆ What is T anyway? Temperature is often defined by other physical quantities through an equation ("law") (by radiation or by particles)
blackbody, radiation, color, excitation,
ionization, kinetic, electron, conductive ...

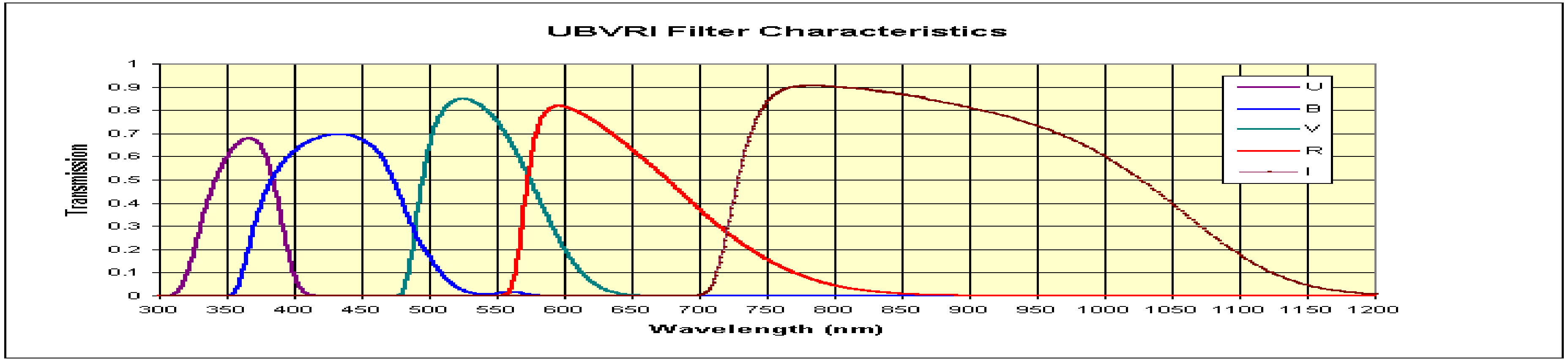
◆ Only <u>in thermal equilibrium</u> are all these temperatures the same.

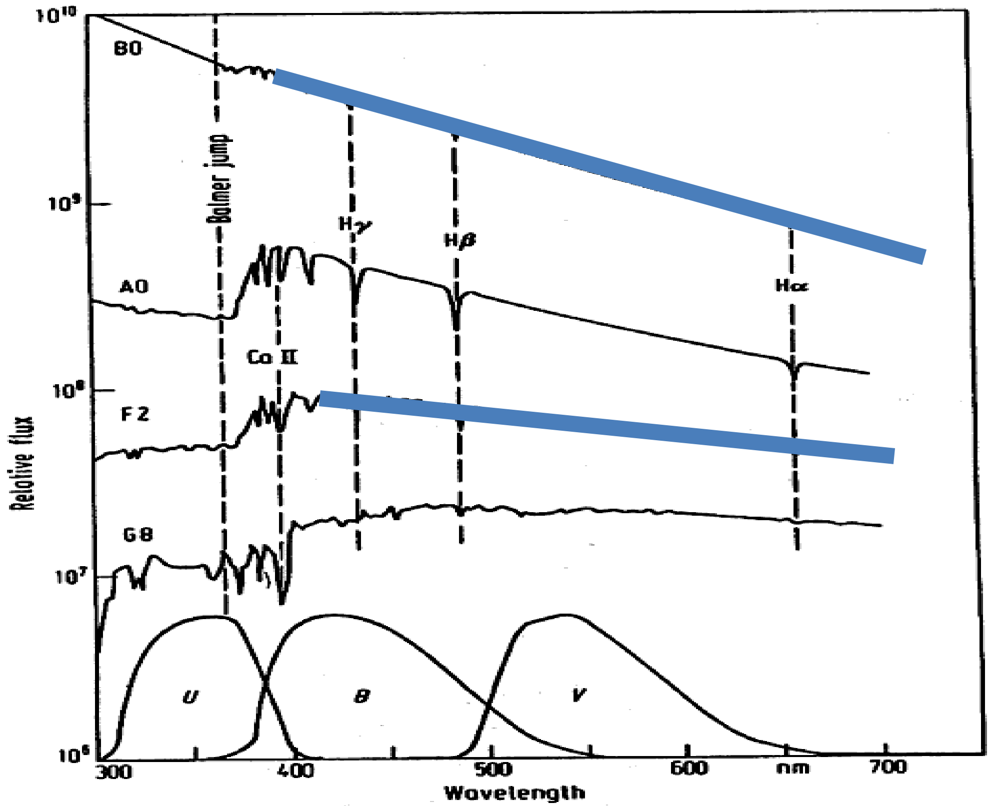
◆ Photometry (spectral energy distribution) gives a **<u>rough</u>** estimate of T, e.g., fluxes/magnitudes measured at different wavelengths, such as the "standard" Johnson system *UBVRI*

Band	U	B	V	R	I
λ/nm	365	445	551	658	806
Δλ/nm	66	94	88	138	149

◆ There are many photometric systems, using broad bands, intermediate bands, special bands, at optical or infrared wavelengths, etc.


$\mathbf{L} \equiv 4\,\pi R^2 \sigma T_{\mathbf{eff}}{}^4$
Solar irradiation curve outside atmosphere
Solar irradiation curve at sea level
Curve for blackbody at 5900 K
O_3
H_2O
O_2 H_2O
H_2O
H_2O
H_2O
H_2O
H_2O, CO_2
H_2O, CO_2
H_2O, CO_2
O_3
Spectral Irradiance (W/m2Å)
0.25
0.20
0.15
0.10
0.05
0
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.0
Wavelength (μm)





Running (slope) between B and V bands, i.e., the $(B-V)$ **color (index)** → photospheric temperature

The larger the value of $(B-V)$, the redder (cooler) the star.

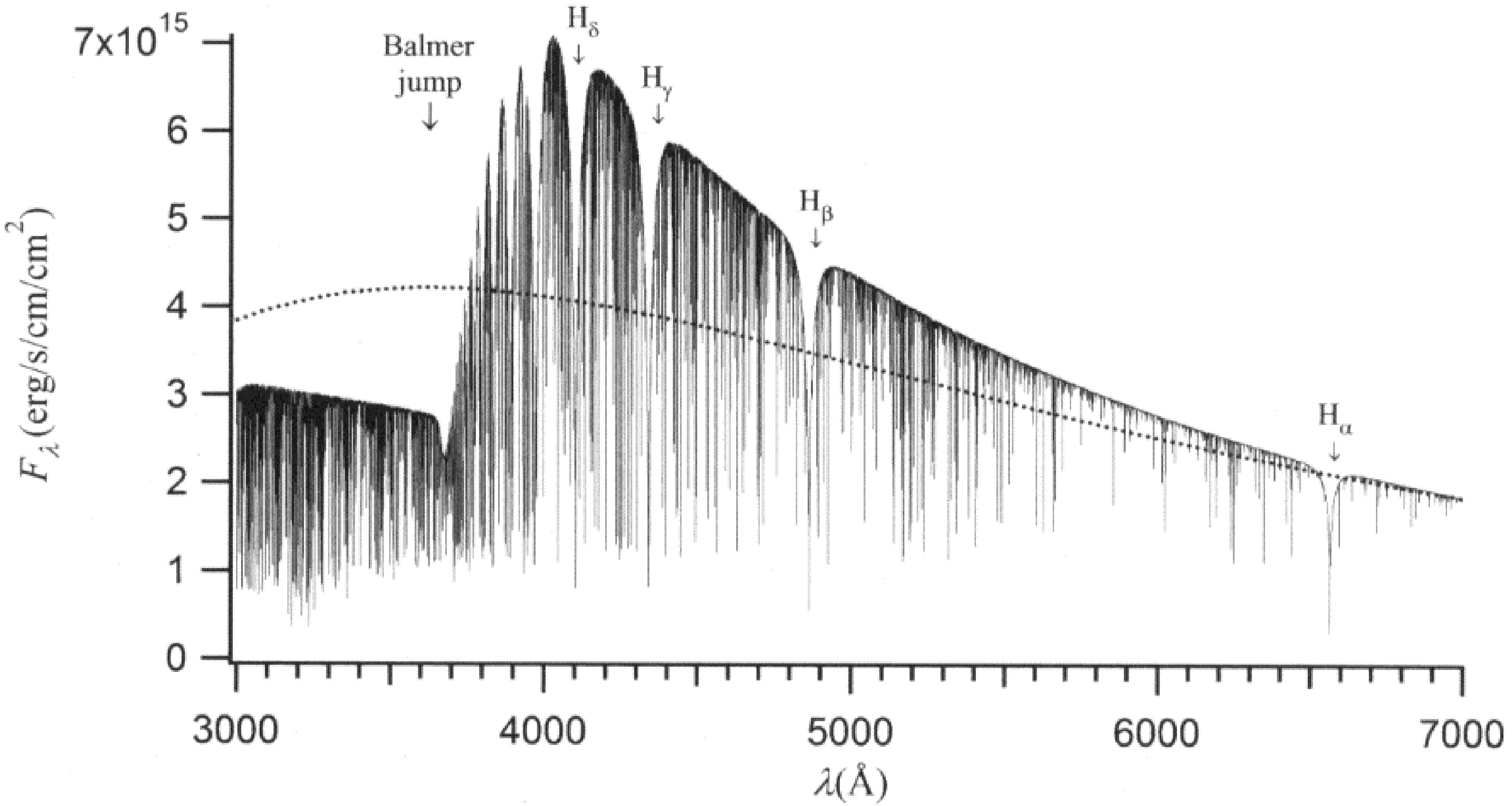
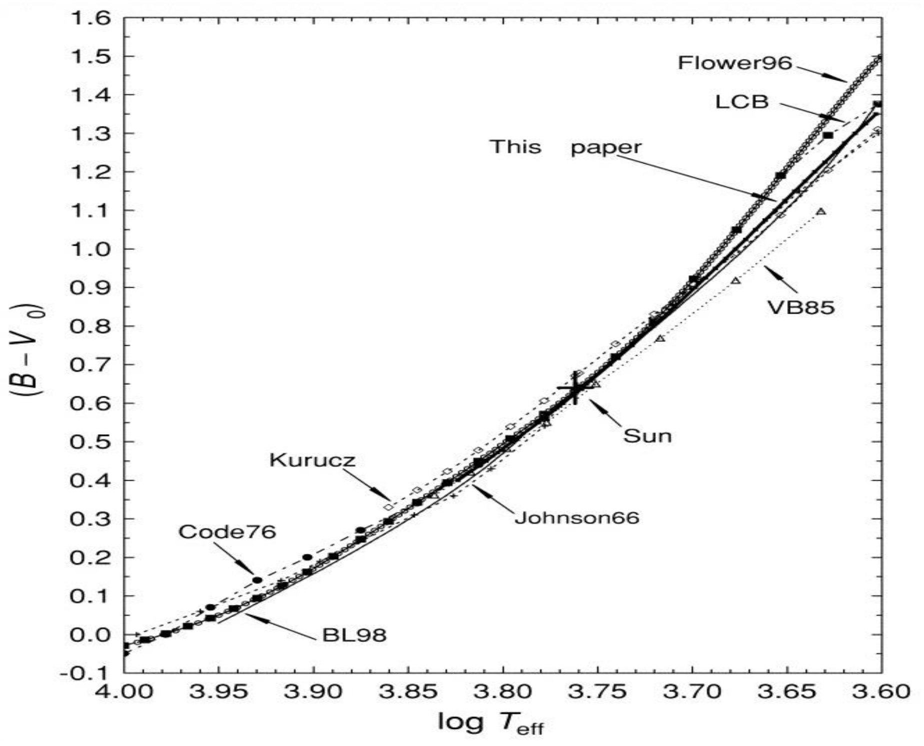


Figure 1.8 Theoretical monochromatic flux emerging form an A type star with $T_{eff} = 8000\,K$. The first four Balmer absorption lines, as well as the Balmer jump, are identified in this figure. Thousands of other absorption atomic lines can also be seen. This theoretical flux was obtained with the Phoenix stellar atmosphere code (Hauschildt, P.H., Allard, F. and Baron, E., *The Astrophysical Journal*, 512, 377 (1999)) while using the elemental abundances found in the Sun. The flux at the surface of a blackbody with $T = 8000\,K$ (dotted curve) is also shown.

LeBlanc

- Calibration for $B - V = f(T_e)$
- The observed $(B - V)$ must be corrected for interstellar extinction in order to derive the stellar intrinsic $(B - V)_0$
- Need more accurate determination of T by spectroscopy and stellar atmosphere models, e.g., the Kurucz's model

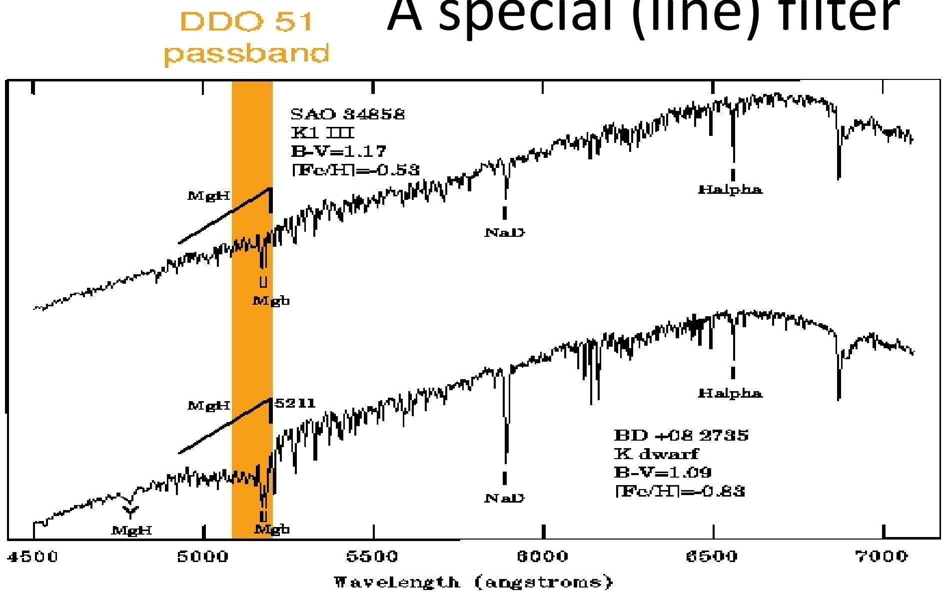


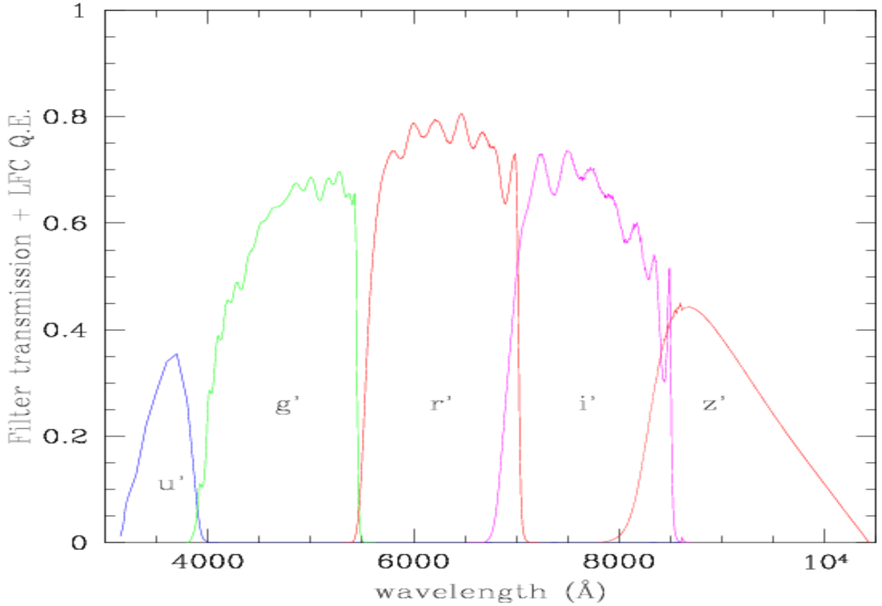
Color Excess

$$E_{B-V} = (B - V)_{\text{obs}} - (B - V)0$$

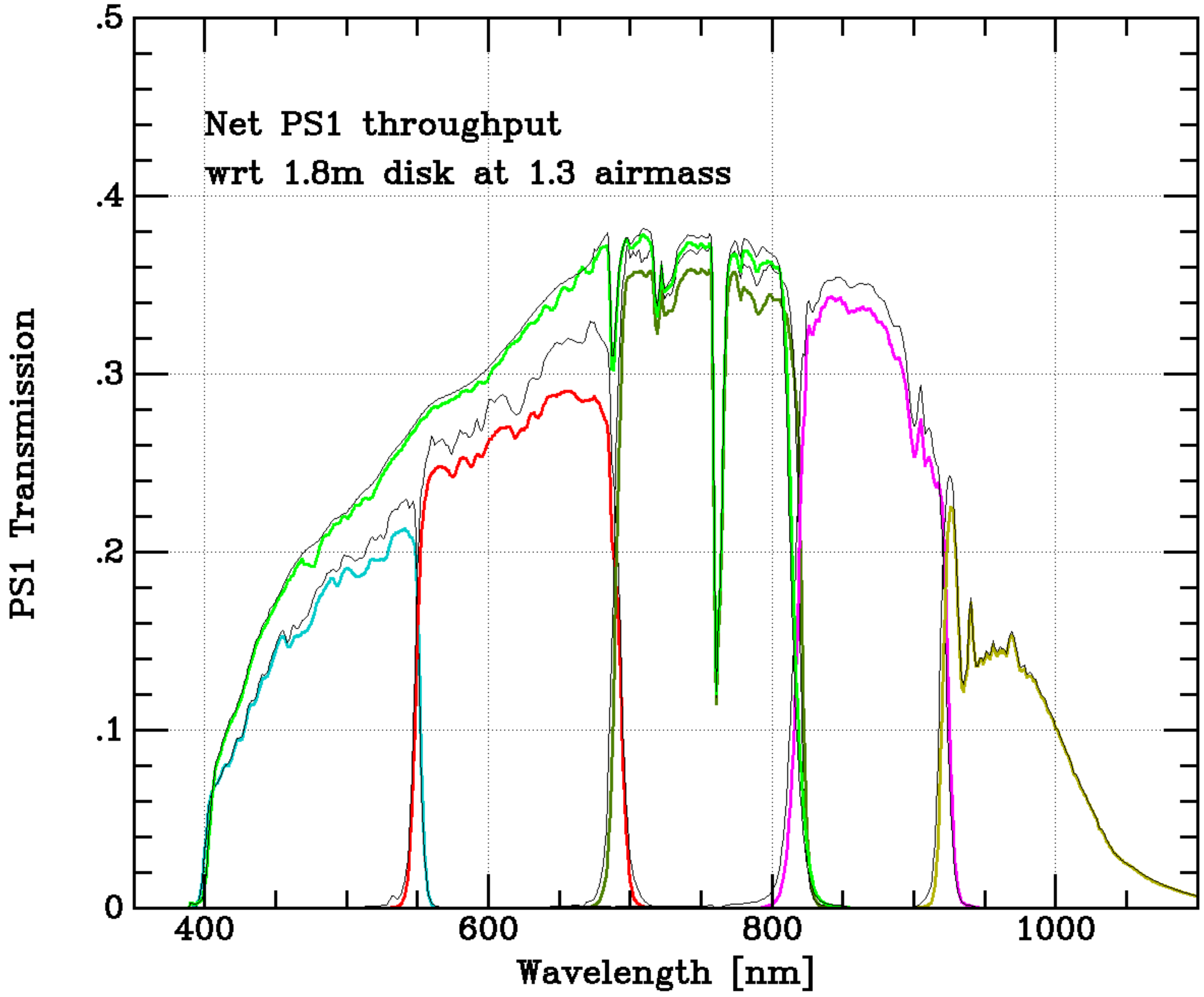
$$(B - V)_{\odot} = 0.656 \pm 0.005$$

A special (line) filter





Sloan Digital Sky Survey



Net PS1 throughput
wrt 1.8m disk at 1.3 airmass
PS1 Transmission
Wavelength [nm]
.5
.4
.3
.2
.1
0
400
600
800
1000

Different temperature, elements (at different excitation and ionization levels) → different set of spectral lines

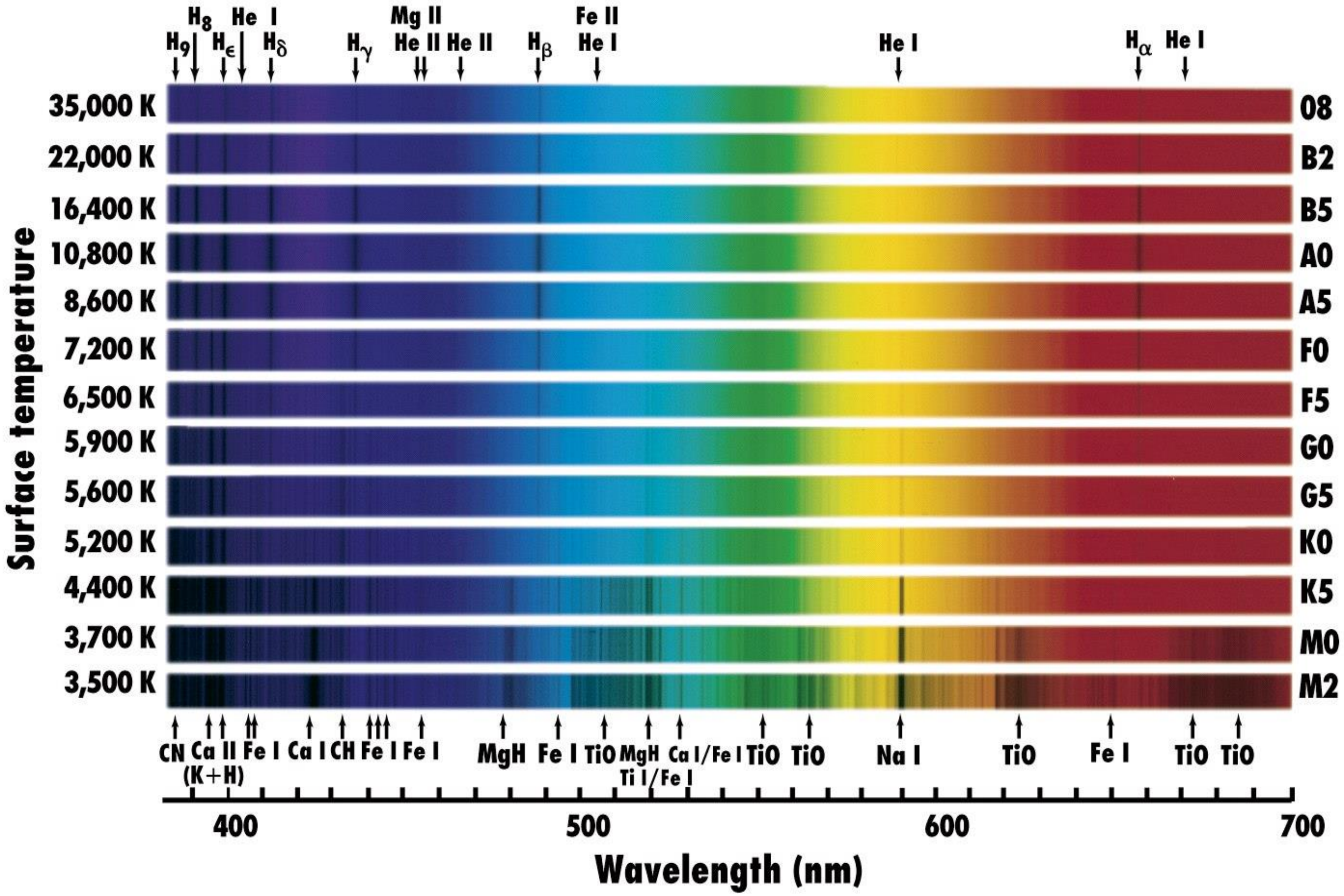
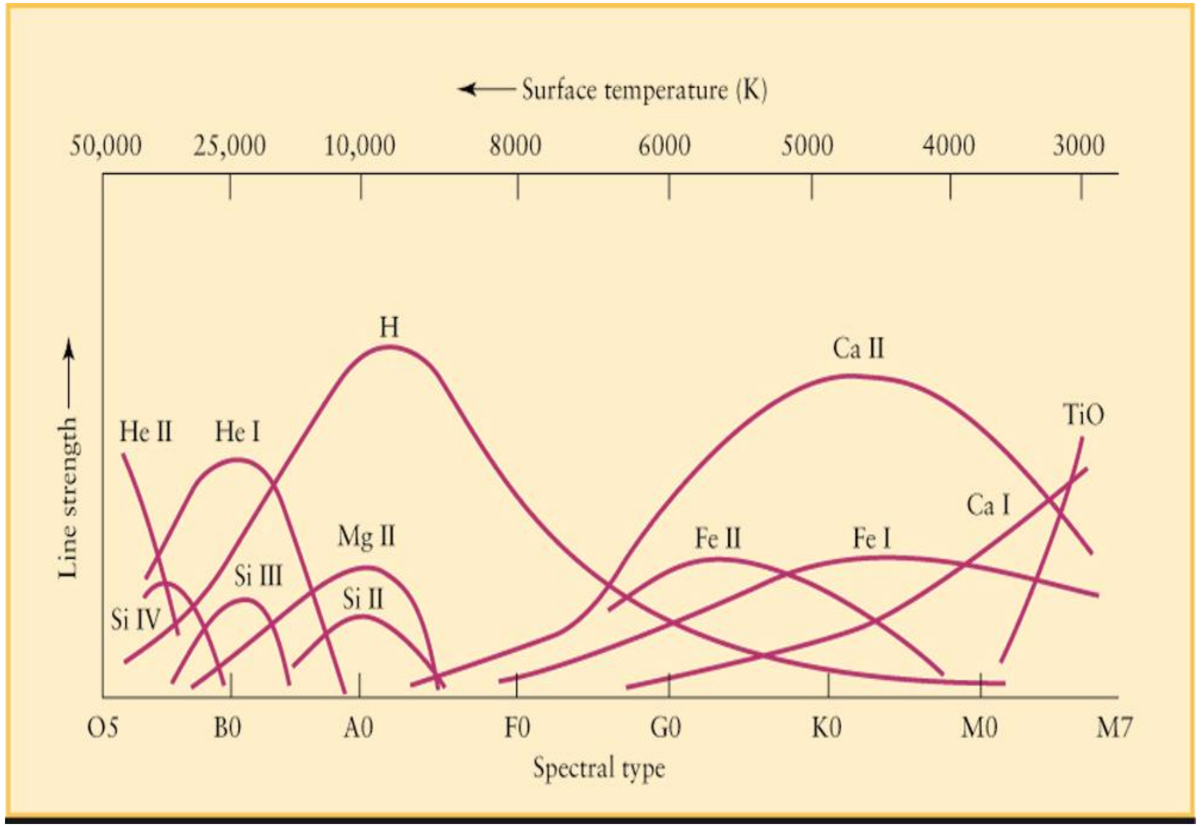


Figure 11-5
Discovering the Universe, Seventh Edition

Line ratios → Temperature



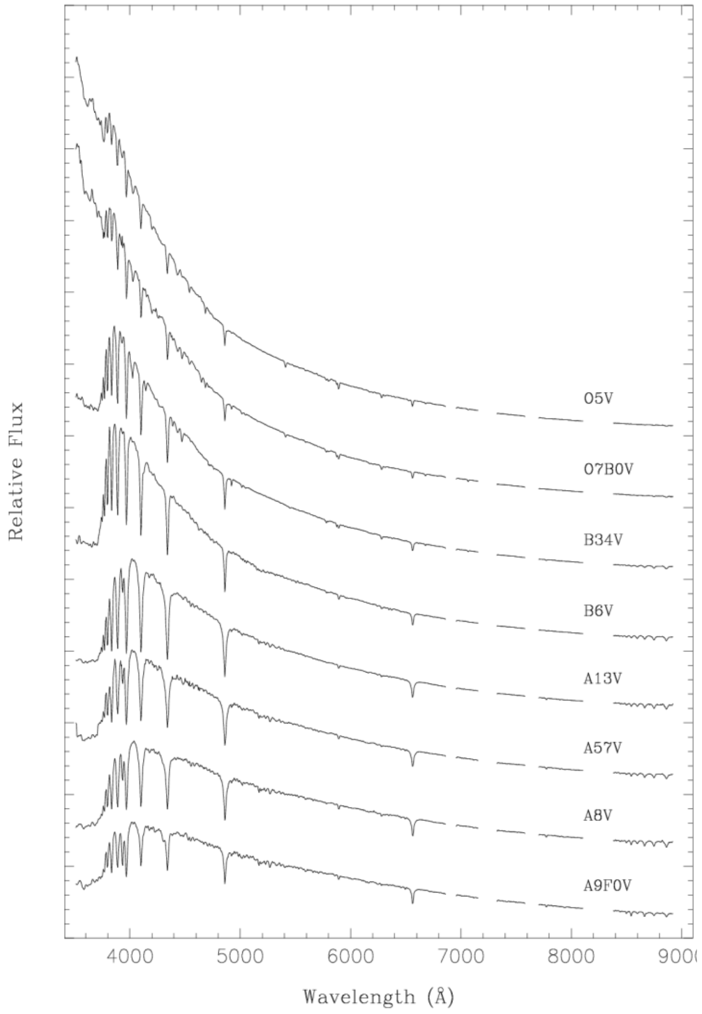
I --- neutral atoms; II --- ionized once; III --- ionized twice; ...

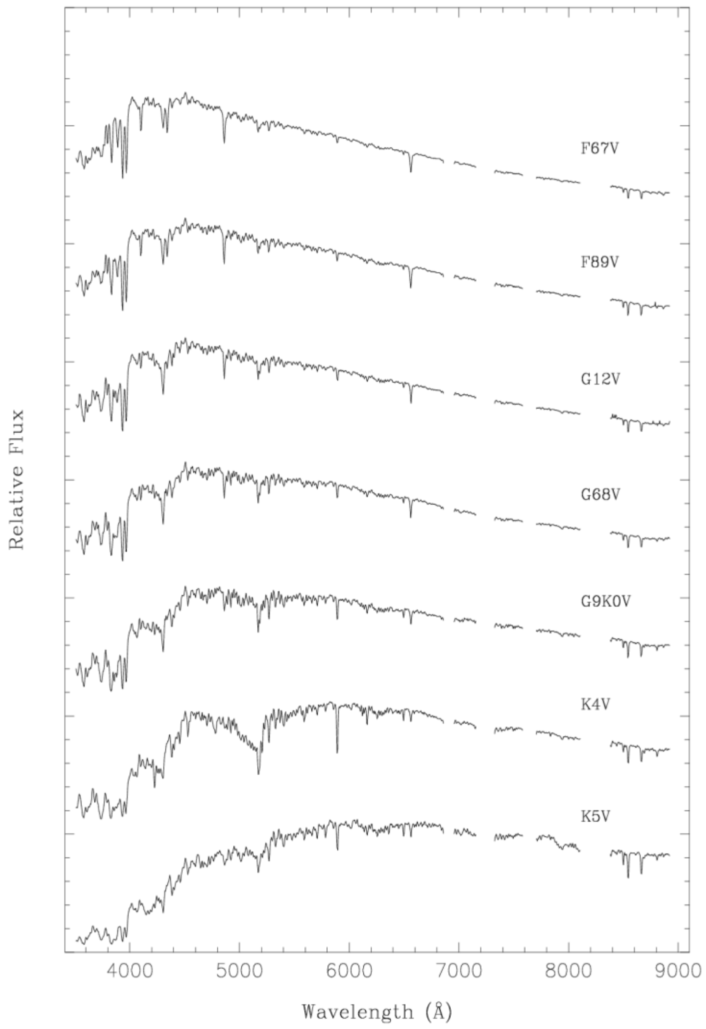
e.g., H I = H^0 ... H II = H^+ ... He III = He^{+2} ... Fe XXVI = Fe^{+25}

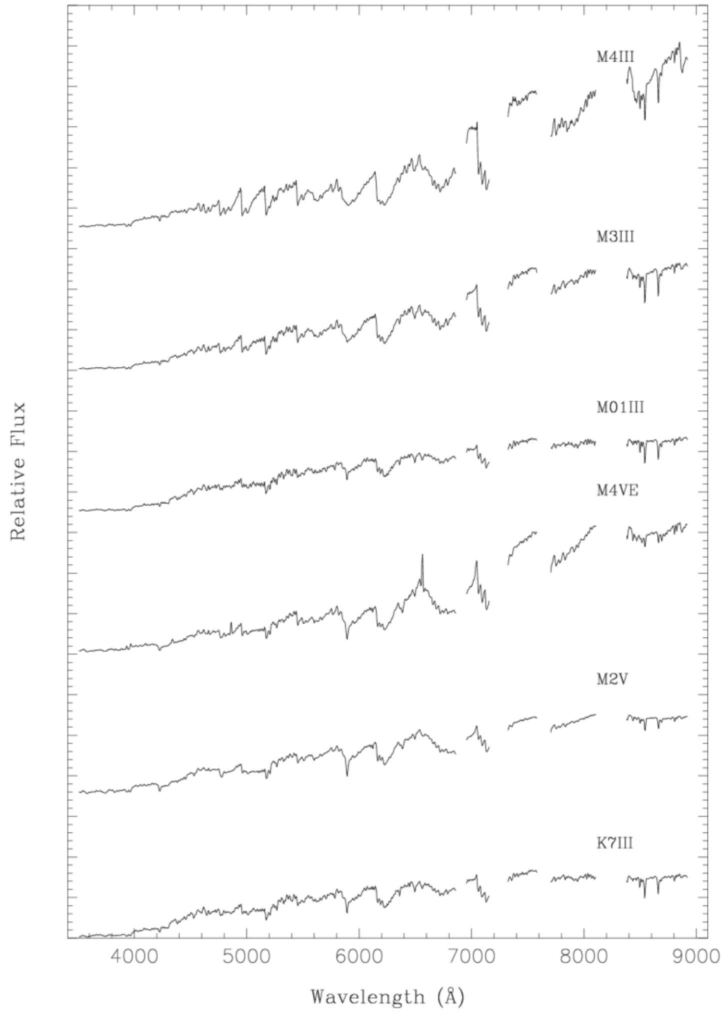
Hot stars --- peaked at short wavelengths (UV); mainly He lines, some H lines

Warm stars --- peaked in the visible wavelengths; H lines prominent

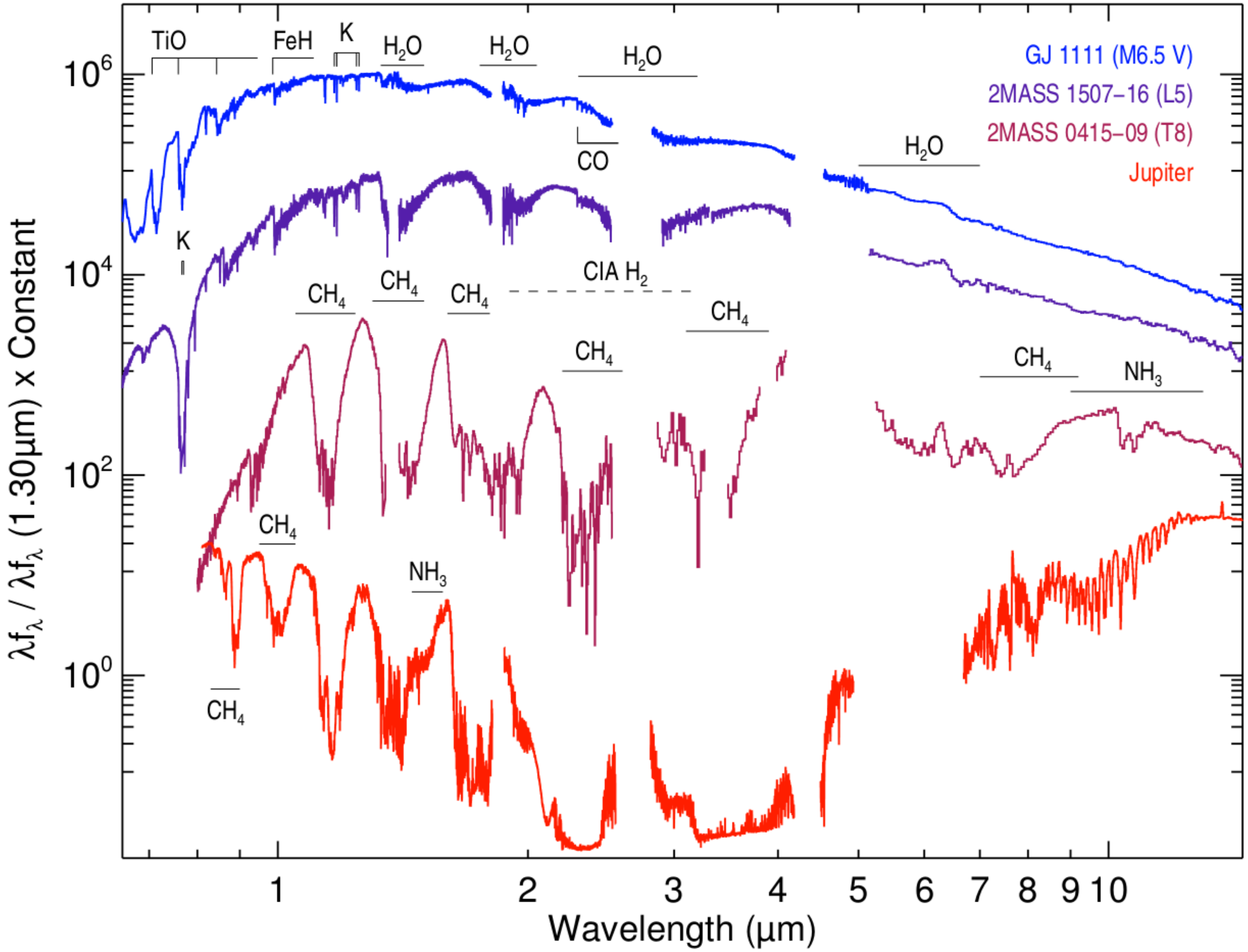
Cool stars --- peaked at long wavelengths (IR); molecular lines/bands



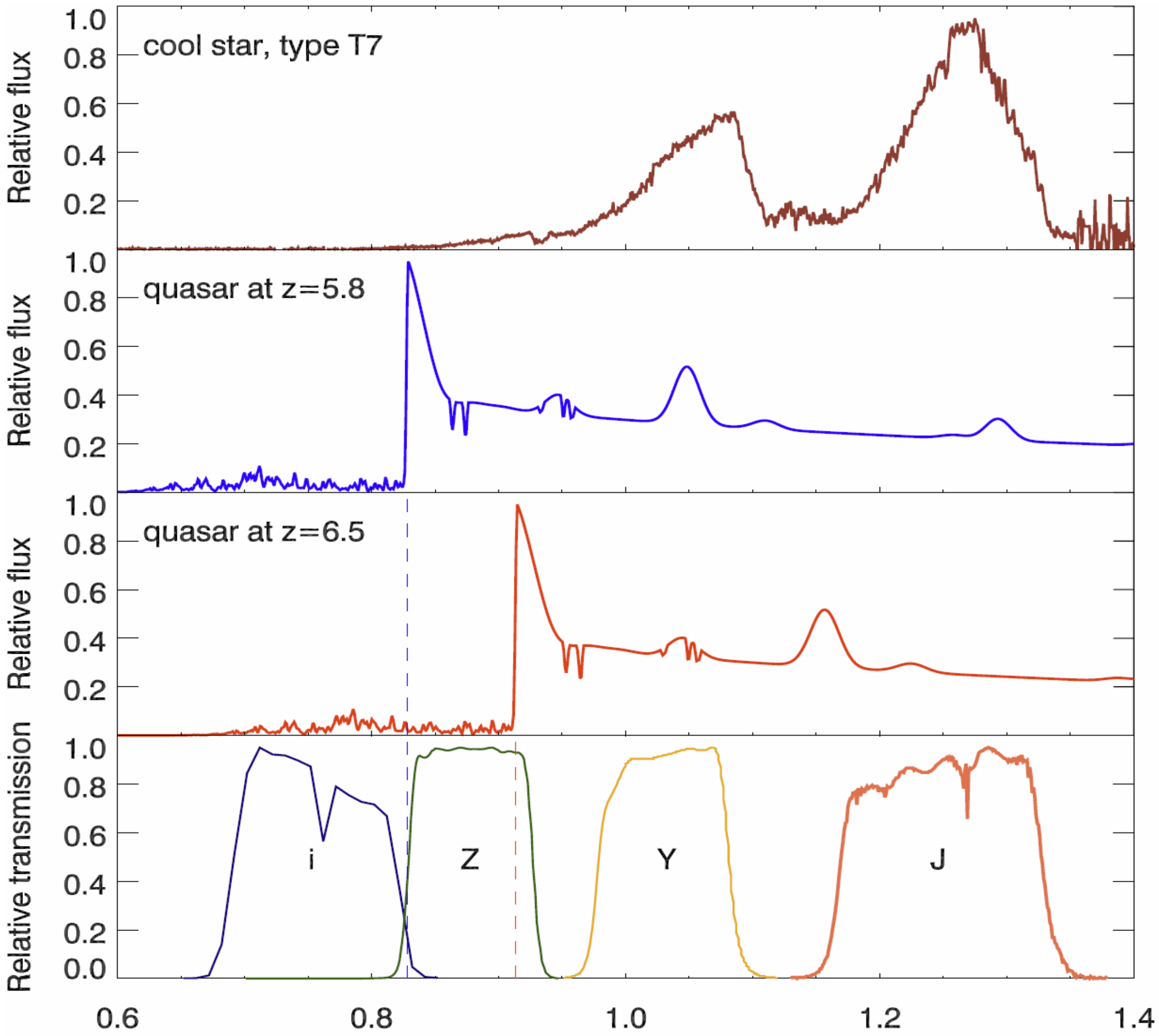




Brown dwarfs and Planetary Objects



http://www.exoclimes.com/paper-outlines/exoplanets-and-brown-dwarfs-ii/



Using imaging photometry (time saving) to trace spectral features

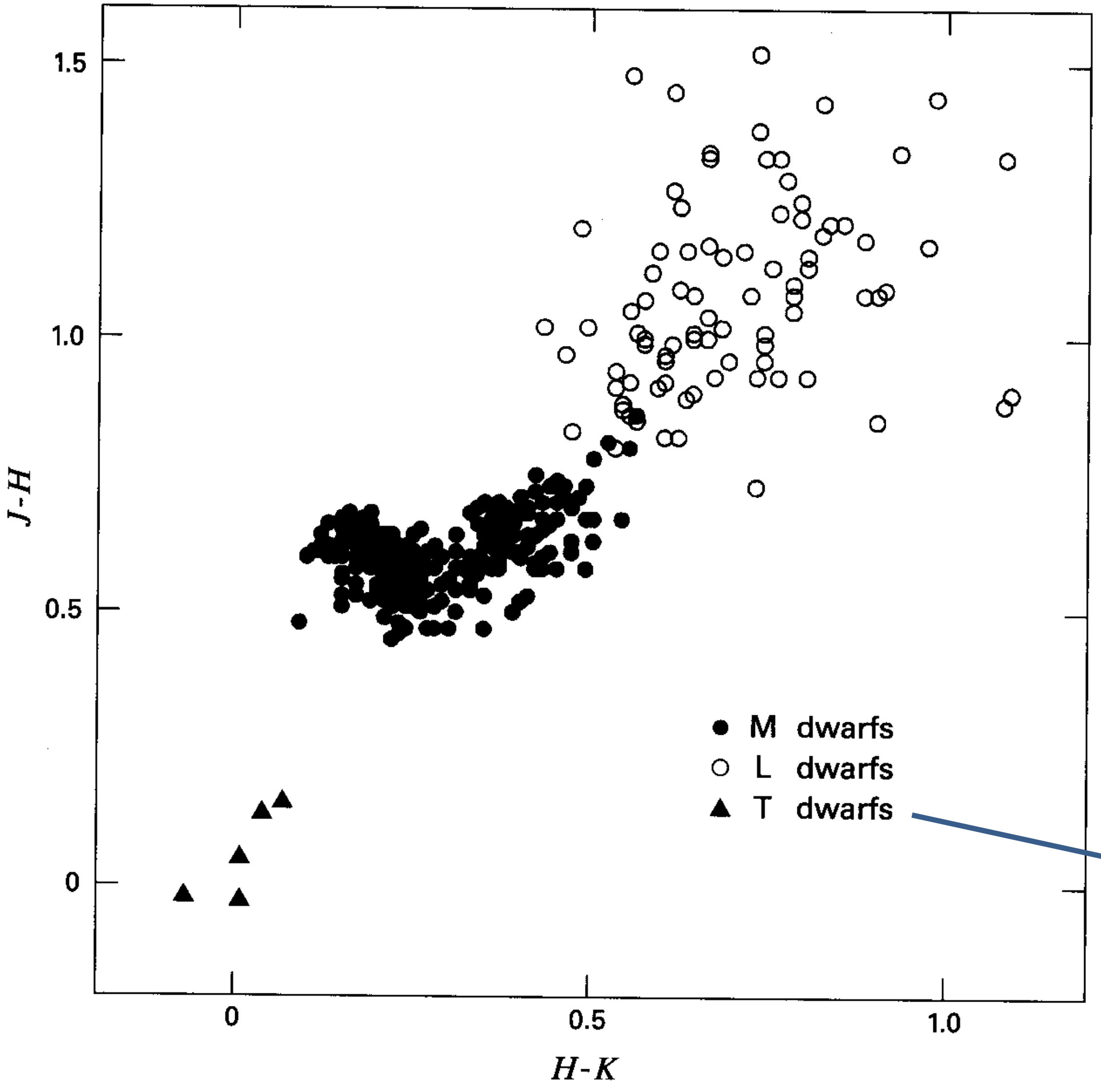


Figure 16.15 Near-infrared color-color plot of M dwarfs (*filled circles*), L dwarfs (*open circles*), and T dwarfs (*filled triangles*). The objects are from a variety of regions. Note that the typical measurement errors for the L- and T-dwarfs are quite large, about 0.13 mag.

T dwarfs are blue in IR.

Stahler & Palla

To measure the stellar luminosity

- **Absolute Magnitude** M defined as apparent magnitude of a star if it were placed at a distance of 10 pc

$$m_\lambda - M_\lambda = 5\log(d_{pc}) - 5$$

But there is extinction … $m_\lambda - M_\lambda = 5\log(d_{pc}) - 5 + A_\lambda$

- **Bolometric magnitude** – the absolute magnitude integrated over all wavelengths. We define the bolometric correction
- **Bolometric Correction** $BC = M_{bol} - M_v$

$$M_{bol}^{\odot} = +4.74$$

is a function of the spectral type (*min at the F type, why?*) and luminosity of a star.

That is, we can apply BC (always negative, why?) to a star to estimate its luminosity (from the photosphere).

Apparent Magnitude $m = -2.5 \log (\text{Flux}) + \textbf{ZeroPoint}$

- The Vega system: 0.0 mag (latest ~0.3 mag) at every Johnson band
- Gunn system: no Vega; use of F subdwarfs as standards (metal poor so smooth spectra), e.g., BD + 17 4708
- The AB system: $\text{AB}_\nu = -2.5 \log_{10} f_\nu - 48.60$
- STMAG system: used for HST photometry

$$\text{STMAG}_\lambda = -2.5 \log_{10} f_\lambda - 21.1$$

Table 7.5. *Filter wavelengths, bandwidths, and flux densities for Vega.*[a]

Filter name	λ_{iso}[b] (μm)	$\Delta\lambda$[c] (μm)	F_λ (W m^{-2} μm^{-1})	F_ν (Jy)	N_ϕ (photons s^{-1} m^{-2} μm^{-1})
V	0.5556[d]	···	3.44×10^{-8}	3 540	9.60×10^{10}
J	1.215	0.26	3.31×10^{-9}	1 630	2.02×10^{10}
H	1.654	0.29	1.15×10^{-9}	1 050	9.56×10^{9}
K_s	2.157	0.32	4.30×10^{-10}	667	4.66×10^{9}
K	2.179	0.41	4.14×10^{-10}	655	4.53×10^{9}
L	3.547	0.57	6.59×10^{-11}	276	1.17×10^{9}
L'	3.761	0.65	5.26×10^{-11}	248	9.94×10^{8}
M	4.769	0.45	2.11×10^{-11}	160	5.06×10^{8}
8.7	8.756	1.2	1.96×10^{-12}	50.0	8.62×10^{7}
N	10.472	5.19	9.63×10^{-13}	35.2	5.07×10^{7}
11.7	11.653	1.2	6.31×10^{-13}	28.6	3.69×10^{7}
Q	20.130	7.8	7.18×10^{-14}	9.70	7.26×10^{6}

$$1 \text{ Jansky} = 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$$
$$= 1.51 \times 10^{7} \text{ photons s}^{-1} \text{ m}^{-2} (\Delta\lambda/\lambda)^{-1}$$

Allen's *Astrophysical Quantities* (4th edition)

Band	λ_0	$d\lambda/\lambda$	f_ν (m=0)	Reference
	µm		Jy	
U	0.36	0.15	1810	Bessel (1979)
B	0.44	0.22	4260	Bessel (1979)
V	0.55	0.16	3640	Bessel (1979)
R	0.64	0.23	3080	Bessel (1979)
I	0.79	0.19	2550	Bessel (1979)
J	1.26	0.16	1600	Campins, Reike, & Lebovsky (1985)
H	1.60	0.23	1080	Campins, Reike, & Lebovsky (1985)
K	2.22	0.23	670	Campins, Reike, & Lebovsky (1985)
g	0.52	0.14	3730	Schneider, Gunn, & Hoessel (1983)
r	0.67	0.14	4490	Schneider, Gunn, & Hoessel (1983)
i	0.79	0.16	4760	Schneider, Gunn, & Hoessel (1983)
z	0.91	0.13	4810	Schneider, Gunn, & Hoessel (1983)

https://www.astro.umd.edu/~ssm/ASTR620/mags.html

Notes

[a] Cohen et al. [1] recommend the use of Sirius rather than Vega as the photometric standard for $\lambda > 20\ \mu m$ because of the infrared excess of Vega at these wavelengths. The magnitude of Vega depends on the photometric system used, and it is either assumed to be 0.0 mag or assumed to be 0.02 or 0.03 mag for consistency with the visual magnitude.

[b] The infrared isophotal wavelengths and flux densities (except for K_s) are taken from Table 1 of [1], and they are based on the UKIRT filter set and the atmospheric absorption at Mauna Kea. See Table 2 of [1] for the case of the atmospheric absorption at Kitt Peak. The isophotal wavelength is defined by $F(\lambda_{iso}) = \int F(\lambda) S(\lambda)\, d\lambda / \int S(\lambda)\, d\lambda$, where $F(\lambda)$ is the flux density of Vega and $S(\lambda)$ is the (detector quantum efficiency) × (filter transmission) × (optical efficiency) × (atmospheric transmission) [2]. λ_{iso} depends on the spectral shape of the source and a correction must be applied for broadband photometry of sources that deviate from the spectral shape of the standard star [3]. The flux density and λ_{iso} for K_s were calculated here. For another filter, K', at 2.11 μm, see [4].

[c] The filter full width at half maximum.

[d] The wavelength at V is a monochromatic wavelength; see [5].

References

1. Cohen, M. et al. 1992, *AJ*, **104**, 1650
2. Golay, M. 1974, *Introduction to Astronomical Photometry* (Reidel, Dordrecht), p. 40
3. Hanner, M.S., et al. 1984, *AJ*, **89**, 162
4. Wainscoat, R.J., & Cowie, L.L. 1992, *AJ*, **103**, 332
5. Hayes, D.S. 1985, in *Calibration of Fundamental Stellar Quantities*, edited by D.S. Hayes, et al., Proc. IAU Symp. No. 111 (Reidel, Dordrecht), p. 225

Exercise

Sirius, the brightest star in the night sky, has been measured $m_B = -1.47,\ m_V = -1.47.$ The star has an annual parallax of $0.379''/\text{yr}$.

1. What is its distance in parsec?
2. What is its absolute V-band magnitude?
3. From the absolute magnitude, what spectral type can be inferred for Sirius?
4. From the observed (B-V) color, what spectral type can be inferred?
5. What kinds of uncertainties/assumptions are associated with the above estimations?

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
GIANTS, III							
G5	+0.9	+0.86	+0.56	0.69	0.48	5 050	−0.34
G8	+0.8	+0.94	+0.70	0.70	0.48	4 800	−0.42
K0	+0.7	+1.00	+0.84	0.77	0.53	4 660	−0.50
K2	+0.5	+1.16	+1.16	0.84	0.58	4 390	−0.61
K5	−0.2	+1.50	+1.81	1.20	0.90	4 050	−1.02
M0	−0.4	+1.56	+1.87	1.23	0.94	3 690	−1.25
M2	−0.6	+1.60	+1.89	1.34	1.10	3 540	−1.62
M5	−0.3	+1.63	+1.58	2.18	1.96	3 380	−2.48

Table 15.7. *(Continued.)*

Sp	$M(V)$	$B-V$	$U-B$	$V-R$	$R-I$	T_{eff}	BC
SUPERGIANTS, I							
O9	−6.5	−0.27	−1.13	−0.15	−0.32	32 000	−3.18
B2	−6.4	−0.17	−0.93	−0.05	−0.15	17 600	−1.58
B5	−6.2	−0.10	−0.72	0.02	−0.07	13 600	−0.95
B8	−6.2	−0.03	−0.55	0.02	0.00	11 100	−0.66
A0	−6.3	−0.01	−0.38	0.03	0.05	9 980	−0.41
A2	−6.5	+0.03	−0.25	0.07	0.07	9 380	−0.28
A5	−6.6	+0.09	−0.08	0.12	0.13	8 610	−0.13
F0	−6.6	+0.17	+0.15	0.21	0.20	7 460	−0.01
F2	−6.6	+0.23	+0.18	0.26	0.21	7 030	−0.00
F5	−6.6	+0.32	+0.27	0.35	0.23	6 370	−0.03
F8	−6.5	+0.56	+0.41	0.45	0.27	5 750	−0.09
G0	−6.4	+0.76	+0.52	0.51	0.33	5 370	−0.15
G2	−6.3	+0.87	+0.63	0.58	0.40	5 190	−0.21
G5	−6.2	+1.02	+0.83	0.67	0.44	4 930	−0.33
G8	−6.1	+1.14	+1.07	0.69	0.46	4 700	−0.42
K0	−6.0	+1.25	+1.17	0.76	0.48	4 550	−0.50
K2	−5.9	+1.36	+1.32	0.85	0.55	4 310	−0.61
K5	−5.8	+1.60	+1.80	1.20	0.90	3 990	−1.01
M0	−5.6	+1.67	+1.90	1.23	0.94	3 620	−1.29
M2	−5.6	+1.71	+1.95	1.34	1.10	3 370	−1.62
M5	−5.6	+1.80	+1.60:	2.18	1.96	2 880	−3.47

Allen's *Astrophysical Quantities* (4th edition)

Table 15.8. *Calibration of MK spectral types.*[a]

Sp	$\mathcal{M}/\mathcal{M}_\odot$	$R/R_\odot$	$\log(g/g_\odot)$	$\log(\bar\rho/\bar\rho_\odot)$	v_{rot} (km s^{-1})
MAIN SEQUENCE, V					
O3	120	15	−0.3	−1.5	
O5	60	12	−0.4	−1.5	
O6	37	10	−0.45	−1.45	
O8	23	8.5	−0.5	−1.4	200
B0	17.5	7.4	−0.5	−1.4	170
B3	7.6	4.8	−0.5	−1.15	190
B5	5.9	3.9	−0.4	−1.00	240
B8	3.8	3.0	−0.4	−0.85	220
A0	2.9	2.4	−0.3	−0.7	180
A5	2.0	1.7	−0.15	−0.4	170
F0	1.6	1.5	−0.1	−0.3	100
F5	1.4	1.3	−0.1	−0.2	30
G0	1.05	1.1	−0.05	−0.1	10
G5	0.92	0.92	+0.05	−0.1	< 10
K0	0.79	0.85	+0.05	+0.1	< 10
K5	0.67	0.72	+0.1	+0.25	< 10
M0	0.51	0.60	+0.15	+0.35	
M2	0.40	0.50	+0.2	+0.8	
M5	0.21	0.27	+0.5	+1.0	
M8	0.06	0.10	+0.5	+1.2	

Table 15.8. *(Continued.)*

Sp	$\mathcal{M}/\mathcal{M}_\odot$	$R/R_\odot$	$\log(g/g_\odot)$	$\log(\bar\rho/\bar\rho_\odot)$	v_{rot} (km s^{-1})
GIANTS, III					
B0	20	15	−1.1	−2.2	120
B5	7	8	−0.95	−1.8	130
A0	4	5		−1.5	100
G0	1.0	6	−1.5	−2.4	30
G5	1.1	10	−1.9	−3.0	< 20
K0	1.1	15	−2.3	−3.5	< 20
K5	1.2	25	−2.7	−4.1	< 20
M0	1.2	40	−3.1	−4.7	
SUPERGIANTS, I					
O5	70	30:	−1.1	−2.6	
O6	40	25:	−1.2	−2.6	
O8	28	20	−1.2	−2.5	125
B0	25	30	−1.6	−3.0	102
B5	20	50	−2.0	−3.8	40
A0	16	60	−2.3	−4.1	40
A5	13	60	−2.4	−4.2	38
F0	12	80	−2.7	−4.6	30
F5	10	100	−3.0	−5.0	< 25
G0	10	120	−3.1	−5.2	< 25
G5	12	150	−3.3	−5.3	< 25
K0	13	200	−3.5	−5.8	< 25
K5	13	400	−4.1	−6.7	< 25
M0	13	500	−4.3	−7.0	
M2	19	800	−4.5	−7.4	

Note

[a] A colon indicates an uncertain value.

Allen's *Astrophysical Quantities* (4th edition)

Table 15.9. *Zero-age main sequence.*

$(B-V)_0$	$(U-B)_0$	M_v
$-0^{\mathrm{m}}.33$	$-1^{\mathrm{m}}.20$	$-5^{\mathrm{m}}.2$
−0.305	−1.10	−3.6
−0.30	−1.08	−3.25
−0.28	−1.00	−2.6
−0.25	−0.90	−2.1
−0.22	−0.80	−1.5
−0.20	−0.69	−1.1
−0.15	−0.50	−0.2
−0.10	−0.30	+0.6
−0.05	−0.10	+1.1
0.00	+0.01	+1.5
+0.05	+0.05	+1.7
+0.10	+0.08	+1.9
+0.15	+0.09	+2.1
+0.20	+0.10	+2.4
+0.25	+0.07	+2.55
+0.30	+0.03	+2.8
+0.35	0.00	+3.1
+0.40	−0.01	+ 3.4
+0.50	0.00	+ 4.1
+0.60	+0.08	+ 4.7
+0.70	+0.23	+ 5.2
+0.80	+0.42	+ 5.8
+0.90	+0.63	+ 6.3
+1.00	+0.86	+ 6.7
+1.10	+1.03	+ 7.1
+1.20	+1.13	+ 7.5
+1.30	+1.20	+ 8.0
+1.40	+1.22	+ 8.8
+1.50	+1.17	+10.3
+1.60	+1.20	+12.0
+1.70	+1.32	+13.2
+1.80	+1.43	+14.2
+1.90	+1.53	+15.5
+2.00	+1.64	+16.7

Allen's *Astrophysical Quantities* (4th edition)

Main-Sequence Stars (Luminosity Class V)

Sp. Type	T_e (K)	$L/L_\odot$	$R/R_\odot$	$M/M_\odot$	M_{bol}	BC	M_V	$U-B$	$B-V$
O5	42000	499000	13.4	60	−9.51	−4.40	−5.1	−1.19	−0.33
O6	39500	324000	12.2	37	−9.04	−3.93	−5.1	−1.17	−0.33
O7	37500	216000	11.0	—	−8.60	−3.68	−4.9	−1.15	−0.32
O8	35800	147000	10.0	23	−8.18	−3.54	−4.6	−1.14	−0.32
B0	30000	32500	6.7	17.5	−6.54	−3.16	−3.4	−1.08	−0.30
B1	25400	9950	5.2	—	−5.26	−2.70	−2.6	−0.95	−0.26
B2	20900	2920	4.1	—	−3.92	−2.35	−1.6	−0.84	−0.24
B3	18800	1580	3.8	7.6	−3.26	−1.94	−1.3	−0.71	−0.20
B5	15200	480	3.2	5.9	−1.96	−1.46	−0.5	−0.58	−0.17
B6	13700	272	2.9	—	−1.35	−1.21	−0.1	−0.50	−0.15
B7	12500	160	2.7	—	−0.77	−1.02	+0.3	−0.43	−0.13
B8	11400	96.7	2.5	3.8	−0.22	−0.80	+0.6	−0.34	−0.11
B9	10500	60.7	2.3	—	+0.28	−0.51	+0.8	−0.20	−0.07
A0	9800	39.4	2.2	2.9	+0.75	−0.30	+1.1	−0.02	−0.02
A1	9400	30.3	2.1	—	+1.04	−0.23	+1.3	+0.02	+0.01
A2	9020	23.6	2.0	—	+1.31	−0.20	+1.5	+0.05	+0.05
A5	8190	12.3	1.8	2.0	+2.02	−0.15	+2.2	+0.10	+0.15
A8	7600	7.13	1.5	—	+2.61	−0.10	+2.7	+0.09	+0.25
F0	7300	5.21	1.4	1.6	+2.95	−0.09	+3.0	+0.03	+0.30
F2	7050	3.89	1.3	—	+3.27	−0.11	+3.4	+0.00	+0.35
F5	6650	2.56	1.2	1.4	+3.72	−0.14	+3.9	−0.02	+0.44
F8	6250	1.68	1.1	—	+4.18	−0.16	+4.3	+0.02	+0.52

Carroll & Ostelie

Main-Sequence Stars (Luminosity Class V)

Sp. Type	T_e (K)	$L/L_\odot$	$R/R_\odot$	$M/M_\odot$	M_{bol}	BC	M_V	$U-B$	$B-V$
G0	5940	1.25	1.06	1.05	+4.50	−0.18	+4.7	+0.06	+0.58
G2	5790	1.07	1.03	—	+4.66	−0.20	+4.9	+0.12	+0.63
Sun[a]	5777	1.00	1.00	1.00	+4.74	−0.08	+4.82	+0.195	+0.650
G8	5310	0.656	0.96	—	+5.20	−0.40	+5.6	+0.30	+0.74
K0	5150	0.552	0.93	0.79	+5.39	−0.31	+5.7	+0.45	+0.81
K1	4990	0.461	0.91	—	+5.58	−0.37	+6.0	+0.54	+0.86
K3	4690	0.318	0.86	—	+5.98	−0.50	+6.5	+0.80	+0.96
K4	4540	0.263	0.83	—	+6.19	−0.55	+6.7	—	+1.05
K5	4410	0.216	0.80	0.67	+6.40	−0.72	+7.1	+0.98	+1.15
K7	4150	0.145	0.74	—	+6.84	−1.01	+7.8	+1.21	+1.33
M0	3840	0.077	0.63	0.51	+7.52	−1.38	+8.9	+1.22	+1.40
M1	3660	0.050	0.56	—	+7.99	−1.62	+9.6	+1.21	+1.46
M2	3520	0.032	0.48	0.40	+8.47	−1.89	+10.4	+1.18	+1.49
M3	3400	0.020	0.41	—	+8.97	−2.15	+11.1	+1.16	+1.51
M4	3290	0.013	0.35	—	+9.49	−2.38	+11.9	+1.15	+1.54
M5	3170	0.0076	0.29	0.21	+10.1	−2.73	+12.8	+1.24	+1.64
M6	3030	0.0044	0.24	—	+10.6	−3.21	+13.8	+1.32	+1.73
M7	2860	0.0025	0.20	—	+11.3	−3.46	+14.7	+1.40	+1.80

Carroll & Ostelie

Giant Stars (Luminosity Class III)									
Sp. Type	T_e (K)	$L/L_\odot$	$R/R_\odot$	$M/M_\odot$	M_{bol}	BC	M_V	$U-B$	$B-V$
O5	39400	741000	18.5	—	−9.94	−4.05	−5.9	−1.18	−0.32
O6	37800	519000	16.8	—	−9.55	−3.80	−5.7	−1.17	−0.32
O7	36500	375000	15.4	—	−9.20	−3.58	−5.6	−1.14	−0.32
O8	35000	277000	14.3	—	−8.87	−3.39	−5.5	−1.13	−0.31
B0	29200	84700	11.4	20	−7.58	−2.88	−4.7	−1.08	−0.29
B1	24500	32200	10.0	—	−6.53	−2.43	−4.1	−0.97	−0.26
B2	20200	11100	8.6	—	−5.38	−2.02	−3.4	−0.91	−0.24
B3	18300	6400	8.0	—	−4.78	−1.60	−3.2	−0.74	−0.20
B5	15100	2080	6.7	7	−3.56	−1.30	−2.3	−0.58	−0.17
B6	13800	1200	6.1	—	−2.96	−1.13	−1.8	−0.51	−0.15
B7	12700	710	5.5	—	−2.38	−0.97	−1.4	−0.44	−0.13
B8	11700	425	5.0	—	−1.83	−0.82	−1.0	−0.37	−0.11
B9	10900	263	4.5	—	−1.31	−0.71	−0.6	−0.20	−0.07
A0	10200	169	4.1	4	−0.83	−0.42	−0.4	−0.07	−0.03
A1	9820	129	3.9	—	−0.53	−0.29	−0.2	+0.07	+0.01
A2	9460	100	3.7	—	−0.26	−0.20	−0.1	+0.06	+0.05
A5	8550	52	3.3	—	+0.44	−0.14	+0.6	+0.11	+0.15
A8	7830	33	3.1	—	+0.95	−0.10	+1.0	+0.10	+0.25

Carroll & Ostelie

F0	7400	27	3.2	—	+1.17	−0.11	+1.3	+0.08	+0.30
F2	7000	24	3.3	—	+1.31	−0.11	+1.4	+0.08	+0.35
F5	6410	22	3.8	—	+1.37	−0.14	+1.5	+0.09	+0.43
G0	5470	29	6.0	1.0	+1.10	−0.20	+1.3	+0.21	+0.65
G2	5300	31	6.7	—	+1.00	−0.27	+1.3	+0.39	+0.77
G8	4800	44	9.6	—	+0.63	−0.42	+1.0	+0.70	+0.94
K0	4660	50	10.9	1.1	+0.48	−0.50	+1.0	+0.84	+1.00
K1	4510	58	12.5	—	+0.32	−0.55	+0.9	+1.01	+1.07
K3	4260	79	16.4	—	−0.01	−0.76	+0.8	+1.39	+1.27
K4	4150	93	18.7	—	−0.18	−0.94	+0.8	—	+1.38
K5	4050	110	21.4	1.2	−0.36	−1.02	+0.7	+1.81	+1.50
K7	3870	154	27.6	—	−0.73	−1.17	+0.4	+1.83	+1.53
M0	3690	256	39.3	1.2	−1.28	−1.25	+0.0	+1.87	+1.56
M1	3600	355	48.6	—	−1.64	−1.44	−0.2	+1.88	+1.58
M2	3540	483	58.5	1.3	−1.97	−1.62	−0.4	+1.89	+1.60
M3	3480	643	69.7	—	−2.28	−1.87	−0.4	+1.88	+1.61
M4	3440	841	82.0	—	−2.57	−2.22	−0.4	+1.73	+1.62
M5	3380	1100	96.7	—	−2.86	−2.48	−0.4	+1.58	+1.63
M6	3330	1470	116	—	−3.18	−2.73	−0.4	+1.16	+1.52

Carroll & Ostelie

Supergiant Stars (Luminosity Class Approximately Iab)

Sp. Type	T_e (K)	$L/L_\odot$	$R/R_\odot$	$M/M_\odot$	M_{bol}	BC	M_V	$U-B$	$B-V$
O5	40900	1140000	21.2	70	−10.40	−3.87	−6.5	−1.17	−0.31
O6	38500	998000	22.4	40	−10.26	−3.74	−6.5	−1.16	−0.31
O7	36200	877000	23.8	—	−10.12	−3.48	−6.6	−1.14	−0.31
O8	34000	769000	25.3	28	−9.98	−3.35	−6.6	−1.13	−0.29
B0	26200	429000	31.7	25	−9.34	−2.49	−6.9	−1.06	−0.23
B1	21400	261000	37.3	—	−8.80	−1.87	−6.9	−1.00	−0.19
B2	17600	157000	42.8	—	−8.25	−1.58	−6.7	−0.94	−0.17
B3	16000	123000	45.8	—	−7.99	−1.26	−6.7	−0.83	−0.13
B5	13600	79100	51.1	20	−7.51	−0.95	−6.6	−0.72	−0.10
B6	12600	65200	53.8	—	−7.30	−0.88	−6.4	−0.69	−0.08
B7	11800	54800	56.4	—	−7.11	−0.78	−6.3	−0.64	−0.05
B8	11100	47200	58.9	—	−6.95	−0.66	−6.3	−0.56	−0.03
B9	10500	41600	61.8	—	−6.81	−0.52	−6.3	−0.50	−0.02
A0	9980	37500	64.9	16	−6.70	−0.41	−6.3	−0.38	−0.01
A1	9660	35400	67.3	—	−6.63	−0.32	−6.3	−0.29	+0.02
A2	9380	33700	69.7	—	−6.58	−0.28	−6.3	−0.25	+0.03
A5	8610	30500	78.6	13	−6.47	−0.13	−6.3	−0.07	+0.09
A8	7910	29100	91.1	—	−6.42	−0.03	−6.4	+0.11	+0.14

Carroll & Ostelie

F0	7460	28800	102	12	−6.41	−0.01	−6.4	+0.15	+0.17
F2	7030	28700	114	—	−6.41	0.00	−6.4	+0.18	+0.23
F5	6370	29100	140	10	−6.42	−0.03	−6.4	+0.27	+0.32
F8	5750	29700	174	—	−6.44	−0.09	−6.4	+0.41	+0.56
G0	5370	30300	202	10	−6.47	−0.15	−6.3	+0.52	+0.76
G2	5190	30800	218	—	−6.48	−0.21	−6.3	+0.63	+0.87
G8	4700	32400	272	—	−6.54	−0.42	−6.1	+1.07	+1.15
K0	4550	33100	293	13	−6.56	−0.50	−6.1	+1.17	+1.24
K1	4430	34000	314	—	−6.59	−0.56	−6.0	+1.28	+1.30
K3	4190	36100	362	—	−6.66	−0.75	−5.9	+1.60	+1.46
K4	4090	37500	386	—	−6.70	−0.90	−5.8	—	+1.53
K5	3990	39200	415	13	−6.74	−1.01	−5.7	+1.80	+1.60
K7	3830	43200	473	—	−6.85	−1.20	−5.6	+1.84	+1.63
M0	3620	51900	579	13	−7.05	−1.29	−5.8	+1.90	+1.67
M1	3490	60300	672	—	−7.21	−1.38	−5.8	+1.90	+1.69
M2	3370	72100	791	19	−7.41	−1.62	−5.8	+1.95	+1.71
M3	3210	89500	967	—	−7.64	−2.13	−5.5	+1.95	+1.69
M4	3060	117000	1220	—	−7.93	−2.75	−5.2	+2.00	+1.76
M5	2880	165000	1640	24	−8.31	−3.47	−4.8	+1.60	+1.80
M6	2710	264000	2340	—	−8.82	−3.90	−4.9	—	—

Carroll & Ostelie

TABLE II

Adopted calibration of MK spectral types in absolute magnitudes M_V

Sp	ZAMS	V	IV	III	II	Ib	Iab	Ia
O5	−4.6	−5.6	−5.8	−6.0	−6.3	−6.6	−6.9	−7.2
O6	−4.0	−5.4	−5.7	−5.9	−6.3	−6.6	−6.9	−7.2
O7	−3.9	−5.2	−5.5	−5.8	−6.2	−6.5	−6.8	−7.2
O8	−3.7	−4.9	−5.2	−5.6	−6.1	−6.4	−6.7	−7.2
O9	−3.5	−4.5	−4.9	−5.3	−5.9	−6.3	−6.6	−7.2
B0	−3.1	−4.0	−4.4	−4.9	−5.6	−6.1	−6.5	−7.2
B1	−2.3	−3.3	−3.9	−4.5	−5.2	−5.9	−6.4	−7.2
B2	−1.6	−2.5	−3.1	−3.7	−5.0	−5.9	−6.4	−7.2
B3	−1.0	−1.7	−2.3	−3.0	−4.8	−5.9	−6.4	−7.2
B5	−0.1	−0.8	−1.2	−1.7	−4.6	−5.9	−6.4	−7.2
B6	0.3	−0.5	−0.9	−1.3	−4.4	−5.8	−6.4	−7.2
B7	0.6	−0.2	−0.6	−1.0	−4.2	−5.8	−6.4	−7.2
B8	1.0	0.1	−0.3	−0.7	−3.9	−5.8	−6.4	−7.2
B9	1.4	0.5	0.1	−0.4	−3.6	−5.7	−6.4	−7.2
A0	1.6	0.8	0.4	−0.1	−3.4	−5.5	−6.4	−7.2
A1	1.7	1.1	0.7	0.2	−3.2	−5.3	−6.4	−7.2
A2	1.8	1.3	0.9	0.4	−3.1	−5.2	−6.4	−7.3
A3	1.9	1.5	1.0	0.5	−3.0	−5.1	−6.4	−7.3
A5	2.3	1.9	1.4	0.8	−2.9	−5.0	−6.5	−7.5
A7	2.6	2.3	1.7	1.1	−2.8	−5.0	−6.7	−7.7
F0	3.0	2.8	2.2	1.5	−2.7	−5.0	−6.9	−7.9
F2	3.2	3.1	2.4	1.8	−2.6	−4.9	−7.0	−8.0
F5	3.7	3.6	2.6	2.0	−2.6	−4.8	−7.1	−8.0
F8	4.2	4.1	2.8		−2.5	−4.7	−7.2	−8.1
G0	4.5	4.4	2.9		−2.4	−4.6	−7.2	−8.2
G2		4.7	3.0	1.1:	−2.4	−4.5	−7.2	−8.2
G5		5.1	3.1	1.0	−2.4	−4.4	−7.2	−8.2
G8		5.6	3.2	0.9	−2.5	−4.3	−7.0	−8.1
K0		6.0	3.2	0.8	−2.5	−4.3	−6.8	−7.9
K1		6.2	3.2	0.8	−2.5	−4.3	−6.7	−7.7
K2		6.5		0.7	−2.5	−4.3	−6.6	−7.6
K3		6.7		0.6	−2.5	−4.3	−6.5	−7.5
K4		7.0		0.5	−2.6	−4.4	−6.4	−7.4
K5		7.3		0.3	−2.6	−4.4	−6.2	−7.2
K7		8.1		0.0	−2.7	−4.5	−6.0	−7.0
M0		8.9		−0.6	−2.8	−4.6	−5.8	−6.9
M1		9.4		−0.8	−2.9	−4.6	−5.8	−6.8
M2		10.0		−0.9	−3.0	−4.7	−5.8	−6.7
M3		10.5		−1.0	−3.0	−4.7	−5.8	−6.7
M4		11.5		−0.6	−3.1	−4.7	−5.8	−6.7
M5		13.5		−0.1	−3.1	−4.7	−5.8	−6.7

TABLE III

Adopted temperatures and bolometric corrections for MK spectral types

	log T_{eff}			Bol. Correction		
Sp	V	III	I–II	V	III	I–II
O5	4.626		4.618	−4.15		−3.80
O6	4.593		4.585	−3.90		−3.55
O7	4.568		4.556	−3.65		−3.30
O8	4.550		4.535	−3.40		−3.15
O9	4.525		4.512	−3.15		−2.95
B0	4.498		4.431	−2.95		−2.50
B1	4.423		4.371	−2.60		−2.15
B2	4.362		4.307	−2.20		−1.75
B3	4.286		4.243	−1.85		−1.40
B5	4.188		4.137	−1.30		−0.90
B6	4.152		4.100	−1.05		−0.75
B7	4.107		4.068	−0.80		−0.60
B8	4.061		4.041	−0.55		−0.45
B9	4.017		4.013	−0.35		−0.35
A0	3.982		3.991	−0.25		−0.25
A1	3.973		3.978	−0.16		−0.16
A2	3.961		3.964	−0.10		−0.10
A3	3.949		3.949	−0.03		−0.03
A5	3.924		3.919	0.02		0.05
A7	3.903		3.897	0.02		0.09
F0	3.863		3.869	0.02		0.13
F2	3.845		3.851	0.01		0.11
F5	3.813		3.813	−0.02		0.08
F8	3.789	3.782	3.778	−0.03		0.03
G0	3.774	3.763	3.756	−0.05		0.00
G2	3.763	3.740	3.732	−0.07		−0.05
G5	3.740	3.712	3.699	−0.09	−0.22	−0.13
G8	3.720	3.695	3.663	−0.13	−0.28	−0.22
K0	3.703	3.681	3.643	−0.19	−0.37	−0.29
K1	3.695	3.663	3.633		−0.43	−0.35
K2	3.686	3.648	3.623	−0.30	−0.49	−0.42
K3	3.672	3.628	3.613		−0.66	−0.57
K4	3.663	3.613			−0.86	−0.75
K5	3.643	3.602	3.585	−0.62	−1.15	−1.17
K7	3.602			−0.89		
M0	3.591	3.591	3.568	−1.17	−1.25	−1.25
M1	3.574	3.580	3.556	−1.45	−1.45	−1.40
M2	3.550	3.574	3.544	−1.71	−1.65	−1.60
M3	3.531	3.562	3.518	−1.92	−1.95	−2.0
M4	3.512	3.550	3.491	−2.24	−2.4	−2.6
M5	3.491	3.531	3.470	−2.55	−3.1	−3.3
M6		3.512		−4.4	−4.0	

Straižys & Kuriliene (1981)

TABLE IV

Bolometric absolute magnitudes M_{bol} for MK spectral types

Sp	ZAMS	V	IV	III	II	Ib	Iab	Ia
O5	−8.7	−9.8	−10.0	−10.2	−10.3	−10.4	−10.7	−11.0
O6	−8.0	−9.3	−9.6	−9.8	−9.9	−10.2	−10.4	−10.8
O7	−7.5	−8.8	−9.1	−9.3	−9.5	−9.8	−10.1	−10.5
O8	−7.2	−8.3	−8.6	−8.9	−9.2	−9.6	−9.8	−10.4
O9	−6.7	−7.6	−8.1	−8.4	−8.9	−9.3	−9.6	−10.2
B0	−6.2	−7.0	−7.4	−7.9	−8.1	−8.6	−9.0	−9.7
B1	−4.9	−5.8	−6.3	−6.8	−7.4	−8.0	−8.6	−9.4
B2	−4.0	−4.7	−5.3	−5.9	−6.8	−7.6	−8.2	−9.0
B3	−2.8	−3.6	−4.1	−4.7	−6.2	−7.3	−7.8	−8.6
B5	−1.4	−2.1	−2.5	−3.0	−5.4	−6.8	−7.3	−8.1
B6	−0.9	−1.6	−2.0	−2.4	−5.2	−6.6	−7.2	−7.9
B7	−0.2	−1.0	−1.4	−1.8	−4.8	−6.4	−7.0	−7.8
B8	0.4	−0.4	−0.8	−1.2	−4.4	−6.2	−6.9	−7.6
B9	1.0	0.1	−0.2	−0.8	−4.0	−6.0	−6.8	−7.5
A0	1.4	0.7	0.2	−0.3	−3.6	−5.7	−6.6	−7.4
A1	1.6	0.9	0.5	−0.1	−3.3	−5.5	−6.6	−7.4
A2	1.7	1.2	0.7	0.1	−3.1	−5.3	−6.5	−7.4
A3	1.9	1.5	1.0	0.4	−3.0	−5.2	−6.4	−7.4
A5	2.3	1.9	1.4	0.8	−2.8	−5.0	−6.4	−7.4
A7	2.6	2.3	1.8	1.1	−2.7	−4.9	−6.5	−7.6
F0	3.0	2.9	2.2	1.6	−2.6	−4.8	−6.7	−7.8
F2	3.2	3.1	2.4	1.8	−2.5	−4.8	−6.8	−7.9
F5	3.7	3.6	2.6	2.0	−2.5	−4.7	−7.0	−7.9
F8	4.2	4.1	2.8		−2.4	−4.6	−7.1	−8.0
G0	4.4	4.4	2.9		−2.4	−4.6	−7.2	−8.1
G2	4.6	4.6	2.9	1.0	−2.4	−4.6	−7.2	−8.2
G5		5.1	3.0	0.8	−2.5	−4.5	−7.3	−8.3
G8		5.5	3.1	0.6	−2.7	−4.5	−7.2	−8.3
K0		5.8	3.0	0.5	−2.8	−4.6	−7.1	−8.2
K1		5.9	3.0	0.4	−2.9	−4.6	−7.1	−8.1
K2		6.0		0.2	−3.0	−4.7	−7.0	−8.0
K3		6.2		−0.1	−3.1	−4.9	−7.0	−8.0
K4		6.4		−0.4				
K5		6.7		−0.9	−3.7	−5.4	−7.0	−8.0
K7		7.3						
M0		7.5		−1.8	−4.0	−5.8	−7.0	−8.1
M1		7.9		−2.4	−4.3	−6.0	−7.2	−8.2
M2		8.3		−2.6	−4.5	−6.2	−7.4	−8.3
M3		8.8		−2.9	−5.1	−6.7	−7.8	−8.7
M4		9.3		−3.1	−5.7	−7.3	−8.4	−9.3
M5		11.0		−3.2	−6.3	−8.0	−9.1	−10.0
M6				−3.6				

TABLE VI

Stellar masses log $\mathfrak{M}/\mathfrak{M}_\odot$ for different MK spectral types derived from the evolutionary tracks

Sp	ZAMS	V	IV	III	II	Ib	Iab	Ia
O5	1.60	1.81	1.85	1.89	1.90	1.92	1.99	
O6	1.48	1.70	1.76	1.80	1.80	1.87	1.91	2.00
O7	1.40	1.59	1.65	1.68	1.71	1.76	1.83	1.92
O8	1.34	1.48	1.54	1.60	1.65	1.72	1.76	1.90
O9	1.28	1.38	1.45	1.49	1.58	1.66	1.72	1.83
B0	1.20	1.30	1.34	1.40	1.40	1.48	1.56	1.70
B1	1.04	1.11	1.18	1.23	1.28	1.38	1.46	1.64
B2	0.92	0.99	1.04	1.08	1.18	1.30	1.38	1.54
B3	0.78	0.84	0.88	0.94	1.11	1.23	1.32	1.45
B5	0.62	0.68	0.72	0.75	1.00	1.18	1.26	1.40
B6	0.56	0.61	0.64	0.68	0.94	1.15	1.26	1.38
B7	0.49	0.53	0.57	0.60	0.91	1.11	1.23	1.36
B8	0.43	0.48	0.49	0.52	0.88	1.08	1.20	1.34
B9	0.36	0.41	0.45	0.49	0.85	1.04	1.20	1.32
A0	0.32	0.35	0.39	0.43	0.81	1.04	1.18	1.30
A1	0.31	0.34	0.36	0.41	0.78	1.00	1.18	1.30
A2	0.29	0.32	0.34	0.39	0.75	0.98	1.15	1.30
A3	0.27	0.30	0.32	0.36	0.75	0.97	1.11	1.30
A5	0.23	0.26	0.29	0.33	0.74	0.95	1.11	1.30
A7	0.20	0.22	0.26	0.30	0.73	0.94	1.15	1.32
F0	0.16	0.16	0.20	0.23	0.72	0.93	1.20	1.38
F2	0.13	0.13	0.16	0.20	0.72	0.93	1.20	1.40
F5	0.08	0.08	0.13	0.18	0.72	0.93	1.26	1.40
F8	0.04	0.04	0.11		0.72	0.93	1.28	1.41
G0	0.02	0.02	0.10		0.72	0.93	1.30	1.43
G2	0.00	0.00	0.10	0.33	0.72	0.93	1.30	1.45
G5		−0.02	0.08	0.39	0.73	0.94	1.32	1.46
G8		−0.04	0.08	0.42	0.76	0.94	1.32	1.46
K0		−0.07	0.11	0.46	0.78	0.96	1.30	1.45
K1		−0.10	0.13	0.46	0.78	0.96	1.30	1.45
K2		−0.10		0.45	0.79	0.98	1.28	1.43
K3		−0.12		0.38	0.80	1.00	1.30	1.43
K4		−0.15		0.36				
K5		−0.19		0.37	0.83	1.08	1.30	1.45
K7		−0.22						
M0		−0.26		0.48	0.83	1.15	1.32	1.46
M1		−0.30		0.54	0.83	1.18	1.34	1.48
M2		−0.35		0.54	0.81	1.18	1.36	1.50
M3		−0.40		0.52	0.84	1.20	1.38	1.56
M4		−0.52		0.51				
M5		(−0.82)		(0.41)				
M6				(0.40)				

Straižys & Kuriliene (1981)

TABLE VII

Calibration of MK spectral types in surface gravities (log g)

Sp	ZAMS	V	IV	III	II	Ib	Iab	Ia
O5	4.13	3.90	3.86	3.82	3.76	3.74	3.69	
O6	4.16	3.86	3.80	3.76	3.69	3.64	3.60	3.53
O7	4.18	3.85	3.80	3.74	3.64	3.57	3.52	3.45
O8	4.17	3.87	3.81	3.75	3.62	3.53	3.49	3.39
O9	4.21	3.95	3.82	3.74	3.58	3.50	3.44	3.31
B0	4.22	4.00	3.88	3.74	3.39	3.27	3.19	3.05
B1	4.28	4.00	3.86	3.71	3.31	3.17	3.01	2.87
B2	4.28	4.06	3.88	3.68	3.19	3.00	2.84	2.68
B3	4.31	4.06	3.89	3.71	3.12	2.79	2.68	2.49
B5	4.32	4.10	3.98	3.81	2.90	2.52	2.40	2.22
B6	4.32	4.09	3.96	3.84	2.77	2.42	2.29	2.13
B7	4.35	4.07	3.95	3.82	2.77	2.33	2.21	2.02
B8	4.34	4.07	3.92	3.79	2.79	2.27	2.11	1.97
B9	4.34	4.03	3.94	3.75	2.81	2.20	2.04	1.88
A0	4.32	4.07	3.91	3.75	2.85	2.23	2.01	1.81
A1	4.35	4.10	3.96	3.78	2.88	2.22	1.96	1.76
A2	4.32	4.16	3.98	3.78	2.87	2.23	1.92	1.71
A3	4.34	4.20	4.03	3.83	2.85	2.20	1.86	1.65
A5	4.36	4.22	4.06	3.86	2.81	2.14	1.74	1.53
A7	4.36	4.26	4.10	3.86	2.75	2.08	1.65	1.38
F0	4.32	4.28	4.05	3.83	2.67	2.00	1.51	1.25
F2	4.30	4.26	4.01	3.81	2.63	1.92	1.39	1.15
F5	4.32	4.28	3.93	3.74	2.48	1.81	1.22	1.00
F8	4.39	4.35	3.89		2.38	1.71	1.06	0.83
G0	4.39	4.39	3.84		2.29	1.62	0.95	0.72
G2	4.40	4.40	3.77	3.20	2.20	1.53	0.86	0.61
G5		4.49	3.71	3.07	2.04	1.45	0.71	0.45
G8		4.55	3.64	2.95	1.84	1.30	0.60	0.30
K0		4.57	3.57	2.89	1.74	1.20	0.54	0.25
K1		4.55	3.55	2.78	1.66	1.16	0.54	0.25
K2		4.55		2.63	1.59	1.10	0.48	0.23
K3		4.56		2.36	1.52	1.00	0.46	0.19
K4		4.57		2.16				
K5		4.57		1.93	1.20	0.77	0.35	0.10
K7		4.62						
M0		4.61		1.63	1.01	0.61	0.30	0.00
M1		4.67		1.41	0.84	0.51	0.19	−0.07
M2		4.69		1.31	0.70	0.39	0.09	−0.13
M3		4.71		1.12	0.38	0.10	−0.16	−0.34
M4		4.77		0.98				
M5		5.06		(0.76)				
M6				(0.52)				

TABLE VIII

Stellar radii $\log R/R_\odot$ for different MK spectral types

Sp	ZAMS	V	IV	III	II	Ib	Iab	Ia
O5	0.95	1.17	1.21	1.25	1.28	1.30	1.36	
O6	0.87	1.13	1.19	1.23	1.27	1.33	1.37	1.45
O7	0.82	1.08	1.14	1.18	1.25	1.31	1.37	1.45
O8	0.80	1.02	1.08	1.14	1.23	1.31	1.35	1.47
O9	0.75	0.93	1.03	1.09	1.22	1.30	1.36	1.48
B0	0.70	0.86	0.94	1.04	1.20	1.32	1.40	1.54
B1	0.59	0.77	0.87	0.97	1.20	1.32	1.44	1.60
B2	0.54	0.68	0.80	0.92	1.21	1.37	1.49	1.65
B3	0.45	0.61	0.71	0.83	1.21	1.43	1.53	1.69
B5	0.36	0.50	0.58	0.68	1.27	1.55	1.65	1.81
B6	0.34	0.48	0.56	0.64	1.30	1.58	1.70	1.84
B7	0.29	0.45	0.53	0.61	1.28	1.60	1.72	1.88
B8	0.26	0.42	0.50	0.58	1.26	1.62	1.76	1.90
B9	0.23	0.41	0.47	0.59	1.23	1.63	1.79	1.93
A0	0.22	0.36	0.46	0.56	1.20	1.62	1.80	1.96
A1	0.19	0.33	0.41	0.53	1.16	1.60	1.82	1.98
A2	0.20	0.30	0.40	0.52	1.15	1.59	1.83	2.01
A3	0.18	0.26	0.36	0.48	1.16	1.60	1.84	2.04
A5	0.15	0.23	0.33	0.45	1.18	1.62	1.90	2.10
A7	0.13	0.19	0.29	0.43	1.21	1.65	1.97	2.19
F0	0.13	0.15	0.29	0.41	1.24	1.68	2.06	2.28
F2	0.13	0.15	0.29	0.41	1.26	1.72	2.12	2.34
F5	0.09	0.11	0.31	0.43	1.30	1.77	2.23	2.41
F8	0.04	0.06	0.33		1.38	1.82	2.32	2.50
G0	0.03	0.03	0.34		1.43	1.87	2.39	2.57
G2	0.01	0.01	0.38	0.78	1.48	1.92	2.44	2.64
G5		−0.04	0.41	0.88	1.56	1.96	2.52	2.72
G8		−0.08	0.43	0.95	1.67	2.03	2.57	2.79
K0		−0.11	0.48	1.00	1.73	2.09	2.59	2.81
K1		−0.11	0.50	1.05	1.77	2.11	2.61	2.81
K2		−0.11		1.12	1.81	2.15	2.61	2.81
K3		−0.12		1.22	1.85	2.21	2.63	2.83
K4		−0.15		1.31				
K5		−0.17		1.44	2.03	2.37	2.69	2.89
K7		−0.20						
M0		−0.22		1.64	2.12	2.48	2.72	2.92
M1		−0.27		1.78	2.21	2.55	2.78	2.99
M2		−0.30		1.83	2.27	2.61	2.85	3.03
M3		−0.36		1.92	2.44	2.76	2.98	3.16
M4		−0.42		1.98				
M5		−0.72		(2.04)				
M6				(2.16)				

Straižys & Kuriliene (1981)

SIMBAD Astronomical Database

2015/4/21 sirius

Portal Simbad VizieR Aladin X-Match Other Help

sirius

other query modes : Identifier query · Coordinate query · Criteria query · Reference query · Basic query · Script submission · Output options · Help

Query : sirius

Available data : Basic data • Identifiers • Plot & images • Bibliography • Measurements • External archives • Notes • Ann

Basic data :

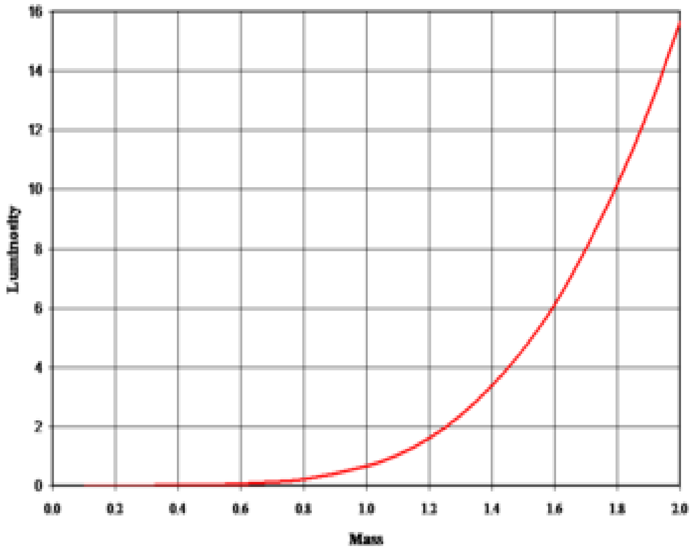
* alf CMa -- Double or multiple star

Other object types:	***** (* ,BD,GC,HD,HIC,HIP,HR,SAO,UBV) , **IR** (AKARI ,IRAS,IRC,2MASS,RAFGL) , ****** (** ,WDS) , **PM*** (LHS) , **V*** (NSV) , **UV** (TD1)
ICRS coord. *(ep=J2000) :*	**06 45 08.91728 -16 42 58.0171** (Optical) [**11.70 10.90 90**] A 2007A&A...474..653V
FK5 coord. *(ep=J2000 eq=2000) :*	**06 45 08.917 -16 42 58.02** [**11.70 10.90 90**]
FK4 coord. *(ep=B1950 eq=1950) :*	**06 42 56.72 -16 38 45.4** [**67.39 63.09 0**]
Gal coord. *(ep=J2000) :*	**227.2303 -08.8903** [**11.70 10.90 90**]
Proper motions *mas/yr* :	**-546.01 -1223.07** [1.33 1.24 0] A 2007A&A...474..653V
Radial velocity / Redshift / cz :	**V(km/s) -5.50** [0.4] / z(~) -0.000018 [0.000001] / cz -5.50 [0.40] (~) A 2006AstL...32..759G
Parallaxes *mas*:	**379.21** [1.58] A 2007A&A...474..653V
Spectral type:	**A1V+DA** C 2013yCat....1.2023S
Fluxes (8) :	**U -1.51** [~] C 2002yCat.2237....0D
	B -1.46 [~] C 2002yCat.2237....0D
	V -1.46 [~] C 2002yCat.2237....0D
	R -1.46 [~] C 2002yCat.2237....0D
	I -1.43 [~] C 2002yCat.2237....0D
	J -1.36 [~] C 2002yCat.2237....0D
	H -1.33 [~] C 2002yCat.2237....0D
	K -1.35 [~] C 2002yCat.2237....0D

http://simbad.u-strasbg.fr/simbad/

To measure the stellar mass

- Stellar mass difficult to measure, direct measurements, except the Sun, only by binary systems
  (but uncertain even for these, why?)
- Then one gets the m*ass-luminosity relation* $L \propto M^{\alpha}$ where the slope α=3 to 5, <u>depending on the mass range</u>
- The main-sequence (MS) is a sequence of stellar mass under hydrostatic equilibrium
- Why are lower mass stars cooler on the surface and fainter in luminosity?

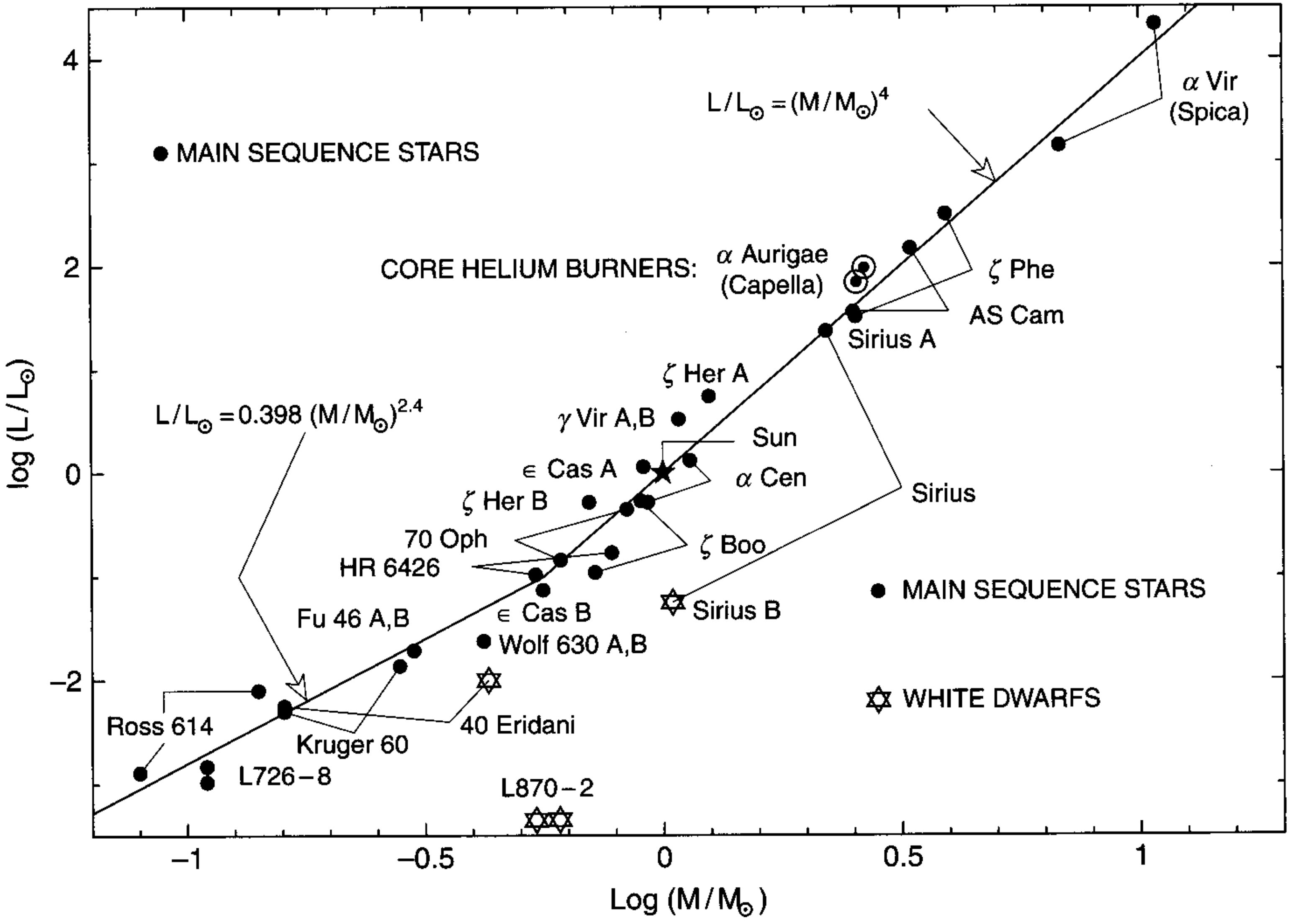


$M_{max} \sim 120\ M_\odot$

$M_{min} \sim 0.08\ M_\odot$

$L_{max} \sim 10^{+6}\ L_\odot$

$L_{min} \sim 10^{-4}\ L_\odot$



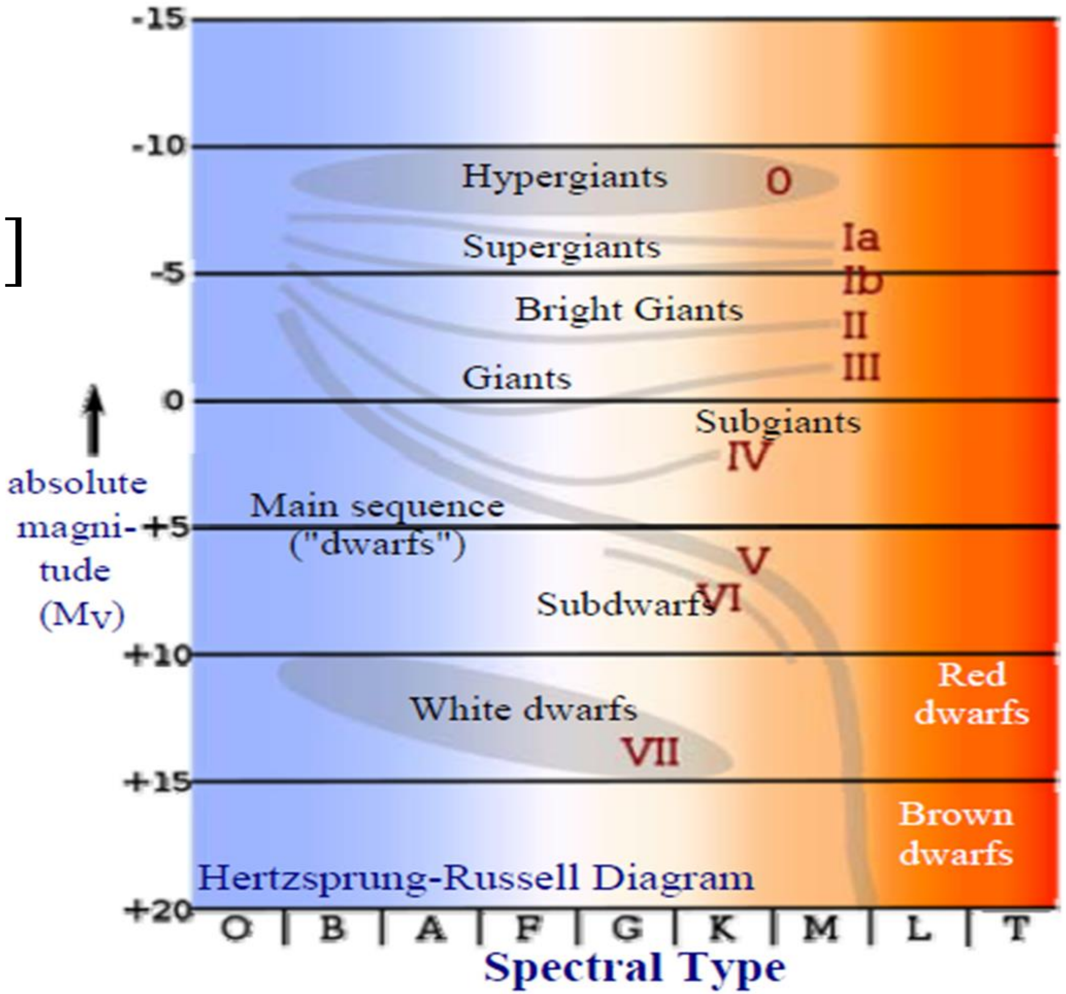
Luminosity versus mass for a selection of stars in binaries

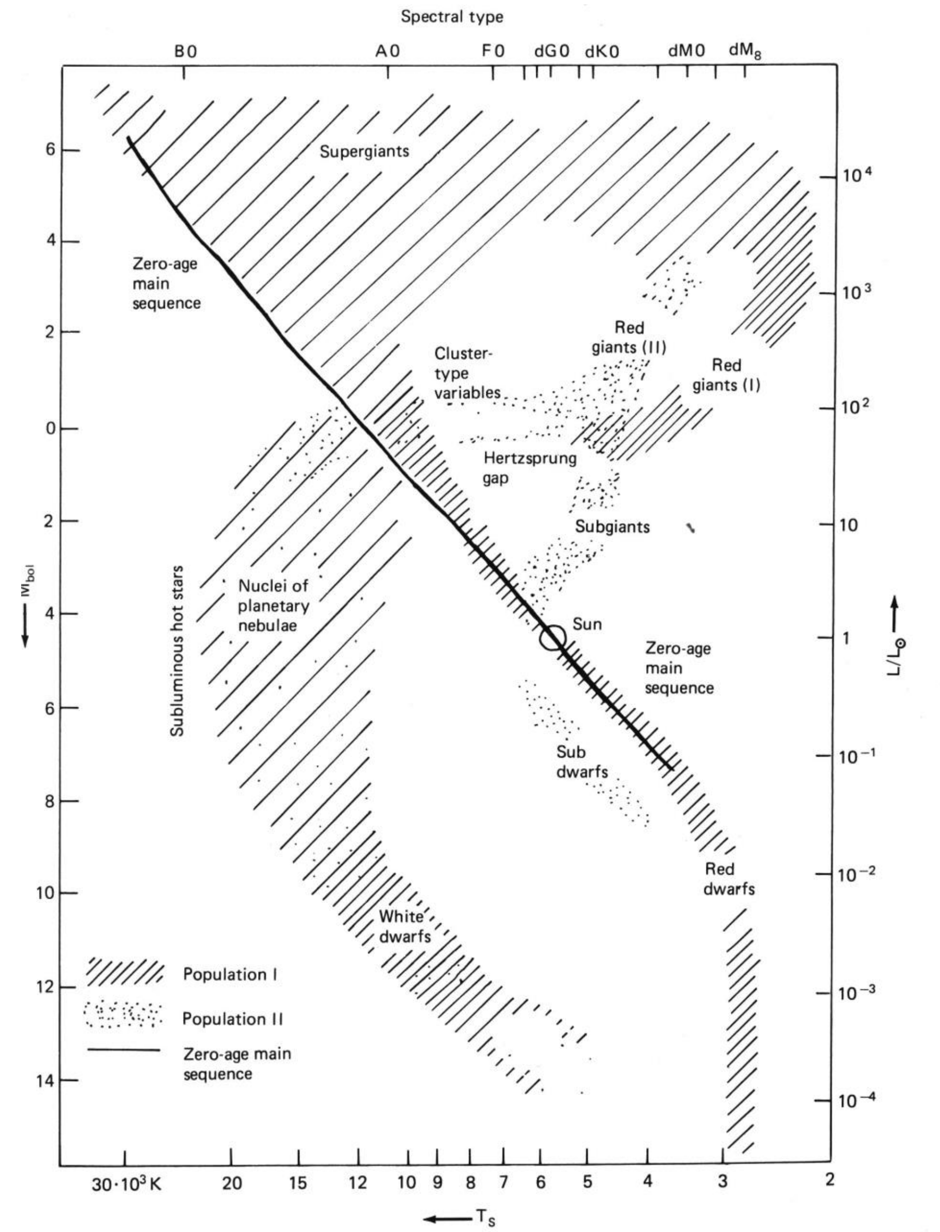
Iben (2013)

Luminosity class and surface gravity

$$\log g = \log GM/R^2$$

- Betelgeuse … (M2 I) $\log g \approx -0.6$ [cgs]
- Jupiter … $\log g = 3.4$
- Sun (G2 V) … $\log g = 4.44$
- Gℓ229B … (T6.5) $\log g \approx 5$
- Sirius B… (WD) $\log g \approx 8$





Composite Hertzsprung-Russell Diagram. Stars of different absolute luminosity, L - right axis, or bolometric absolute magnitude, M_{bol} - left axis, are plotted as a function of surface temperature, T_S - bottom axis, or spectral type - top axis. (Adapted from L. Goldberg and E.R. Dyer, Science in Space, eds. L.V. Berkner and H. Odishaw (1961).)

Lang "Data"

Exercise

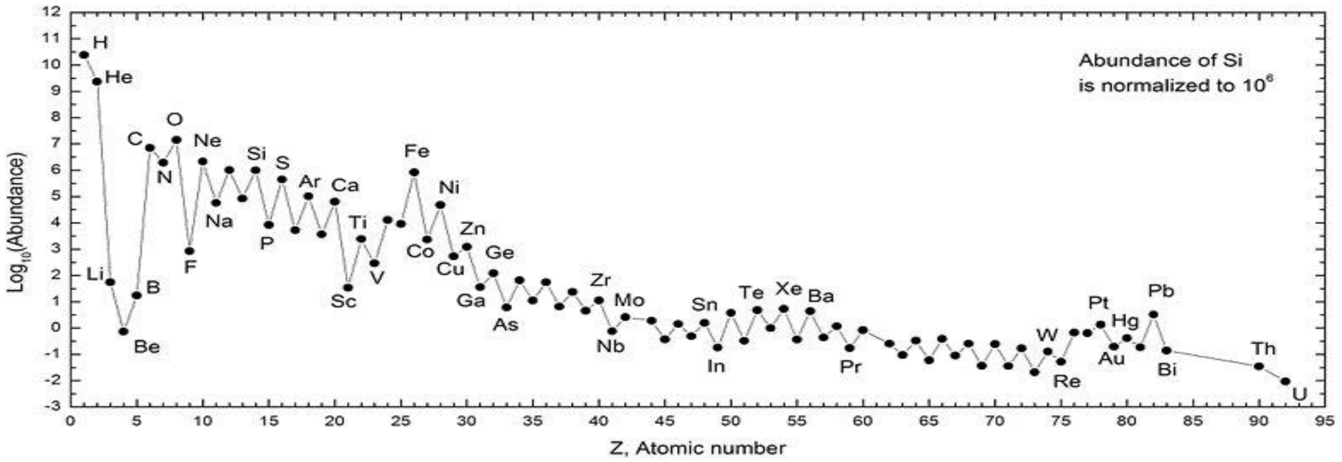
1. What is the spectral type of Alpha Scorpii?
2. What is its apparent magnitude? Expected absolute magnitude? Bolometric luminosity?
3. What is its distance estimated from its apparent magnitude? Measured directly by parallax? Why do these differ?
4. What is the expected diameter of the star in km, in $R_\odot$ and in AU? What is then the expected angular diameter seen from Earth? Can it be resolved by the *HST*?

(Always show your work clearly, and cite the references.)

To measure the stellar abundance

- By spectroscopy
- Stellar composition $X, Y, Z =$ mass fraction of H, He and all other elements ("metals") *Z: metallicity* *X+Y+Z=1*
- Solar abundance: $X_\odot = 0.747$; $Y_\odot = 0.236$; $Z_\odot = 0.017$
- One often compares the iron abundance of a star to that of the sun. Iron is not the most abundant (only 0.001), but easy to measure in spectra. *Why?*

$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{\mathrm{N_{Fe}}}{\mathrm{N_H}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{\mathrm{N_{Fe}}}{\mathrm{N_H}}\right)_\odot$$



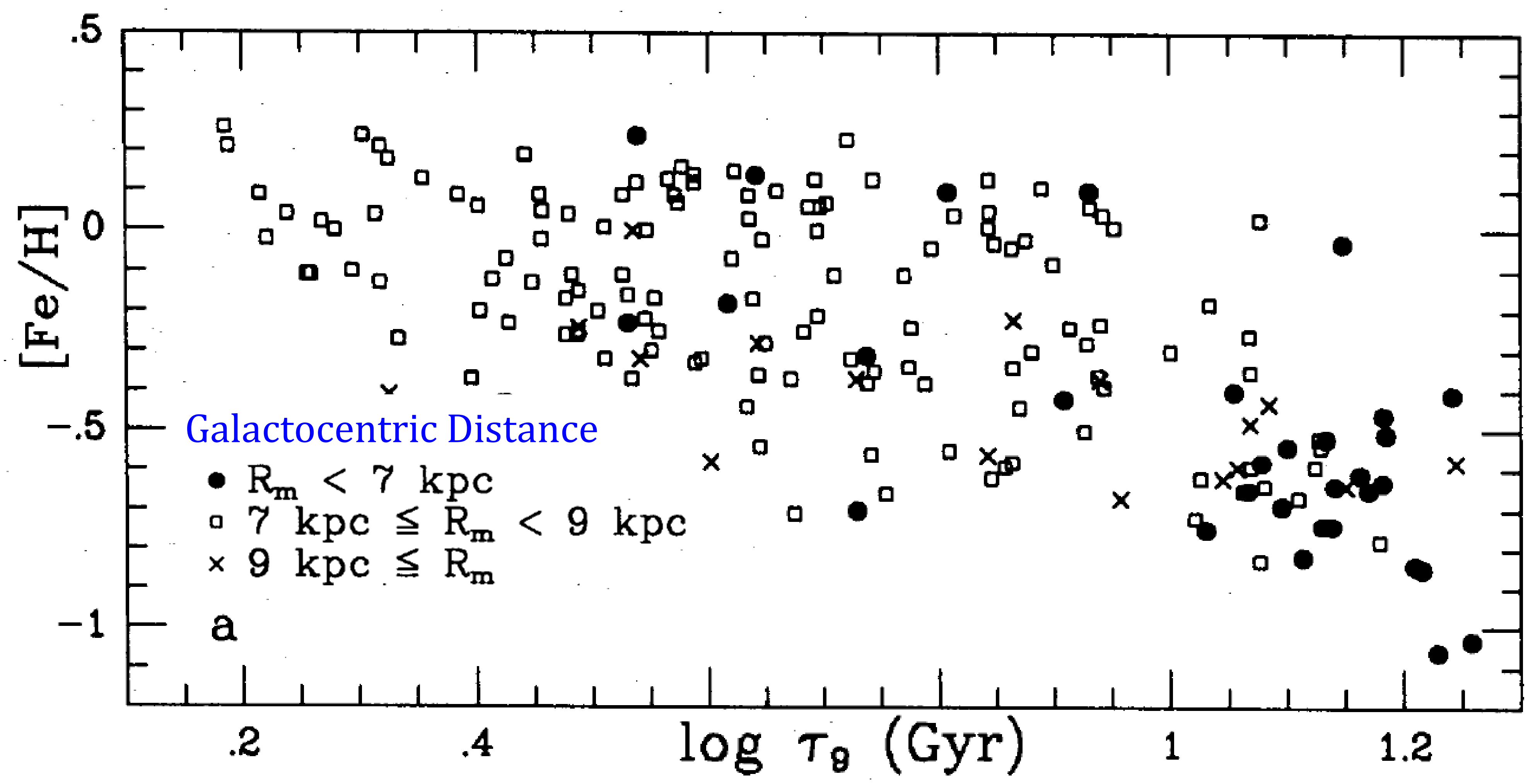
$$\log\left(\frac{N_{Fe}}{N_H}\right)_\odot = -4.33$$

i.e., 1 iron atom for 20,000 H atoms

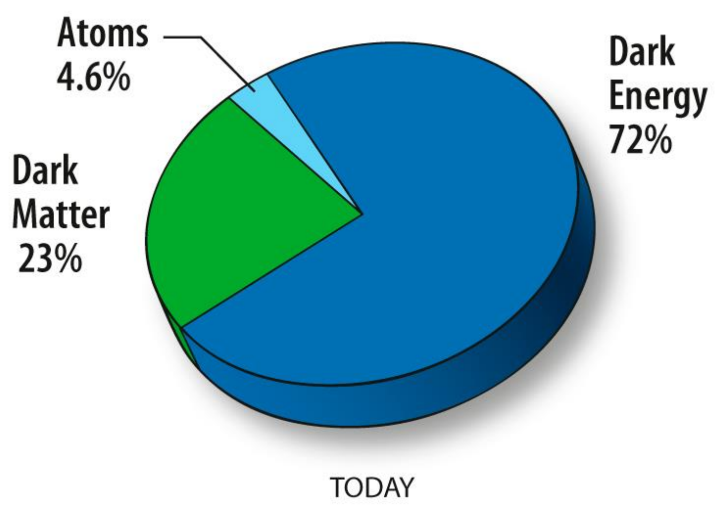
$$[M/H] \approx \log(Z/Z_\odot)$$

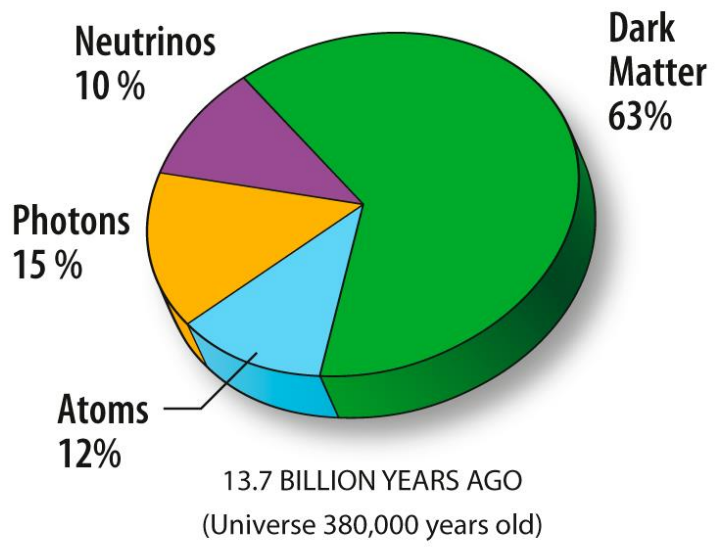
Data from: Katharina Lodders (2003) ApJ, 591, 1220

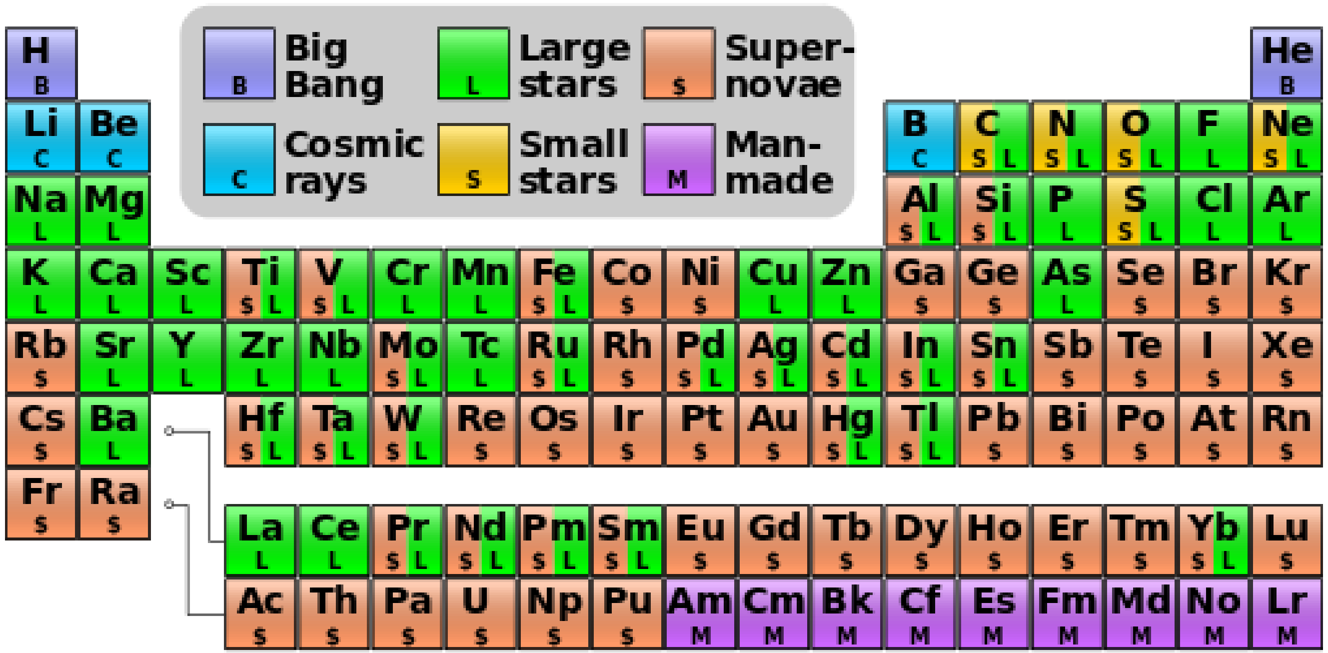
Younger stars tend to be more metal-rich. Stars older than 10 Gyr almost all have [Fe/H] $\lesssim -0.5$; stars younger than 5 Gyr have [Fe/H] $\gtrsim -0.5$.



Edvardsson et al. (1993)







Cosmic element factories --- the Big Bang, stellar nucleosynthesis, supernova explosions, and compact mergers

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

To measure the stellar age

- Very tricky. Often one relies on measurements of M_V, T_{eff}, [Fe/H], and then uses some kind of theoretically computed isochrones to interpolate the age (and mass)
- Crude diagnostics include
  - ✓ Lithium absorption line, e.g., 6707A
  - ✓ Chromospheric activities, e.g., X-ray or Ca II emission
  - ✓ Evolving off the main sequence
- … hence subject to large uncertainties

References:

Edvardsson et al., 1993, A&A, 275, 101
Nordström et al., 2004, A&A, 418, 989

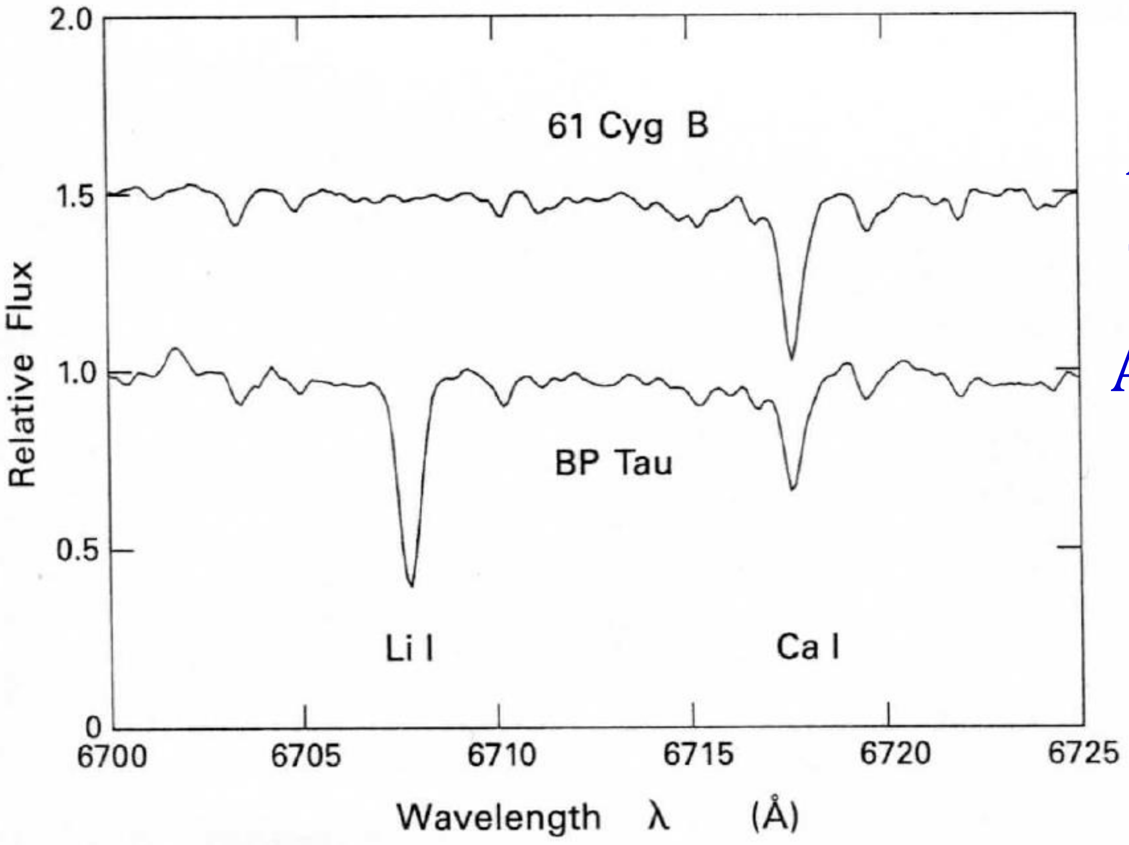


Figure 16.9 Lithium absorption in a pre-main-sequence star. Shown is a portion of the optical spectrum of BP Tau, a T Tauri star of spectral type K7, corresponding to an effective temperature of 4000 K. Also shown, for comparison, is a main-sequence star of the same spectral type, 61 Cyg B. Only in the first star do we see the Li I absorption line at 6708 Å. Both objects also have a strong line due to neutral calcium.

An MS star of the same spectral type

A PMS (young) star

Stahler

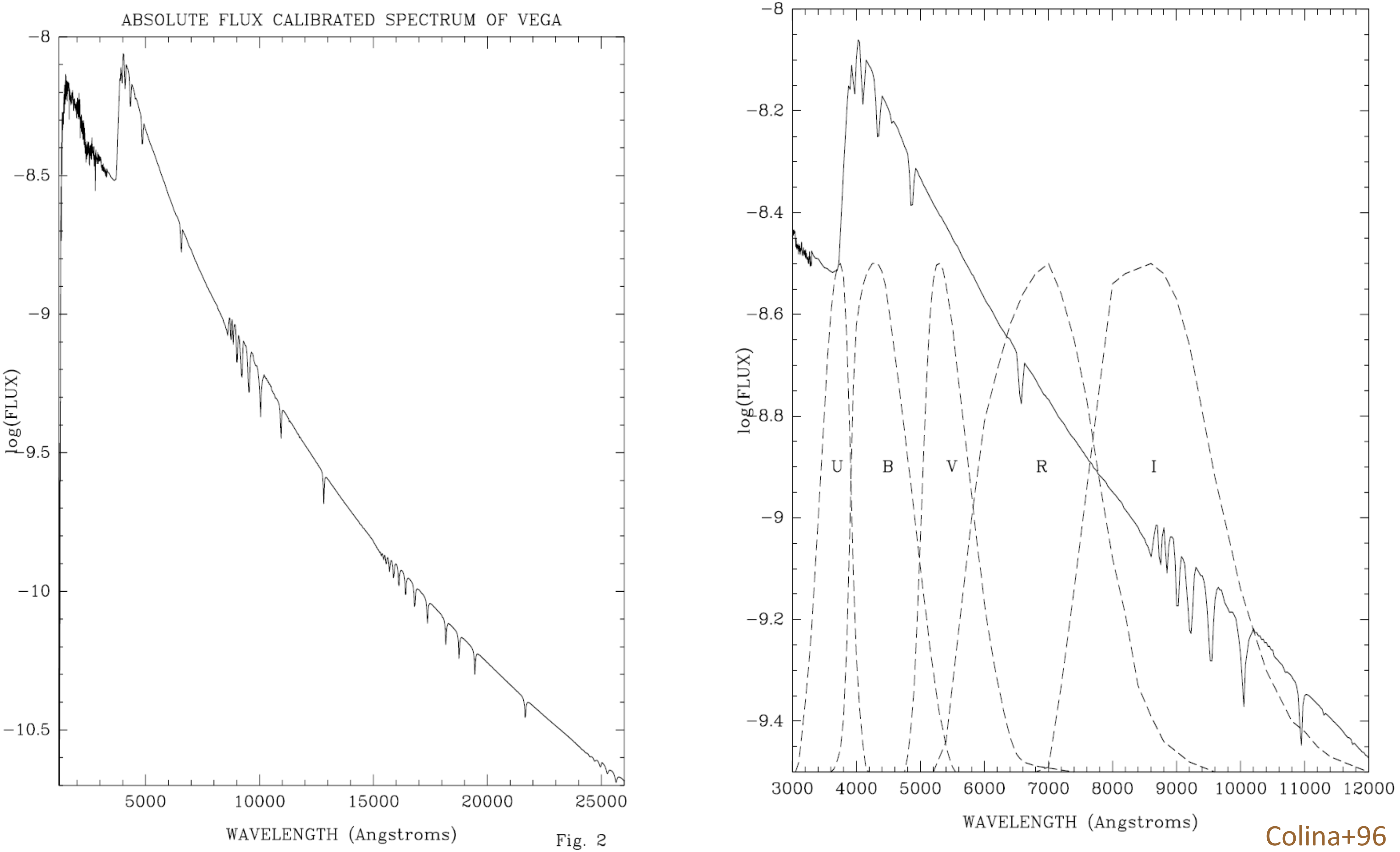


Fig. 2

Colina+96

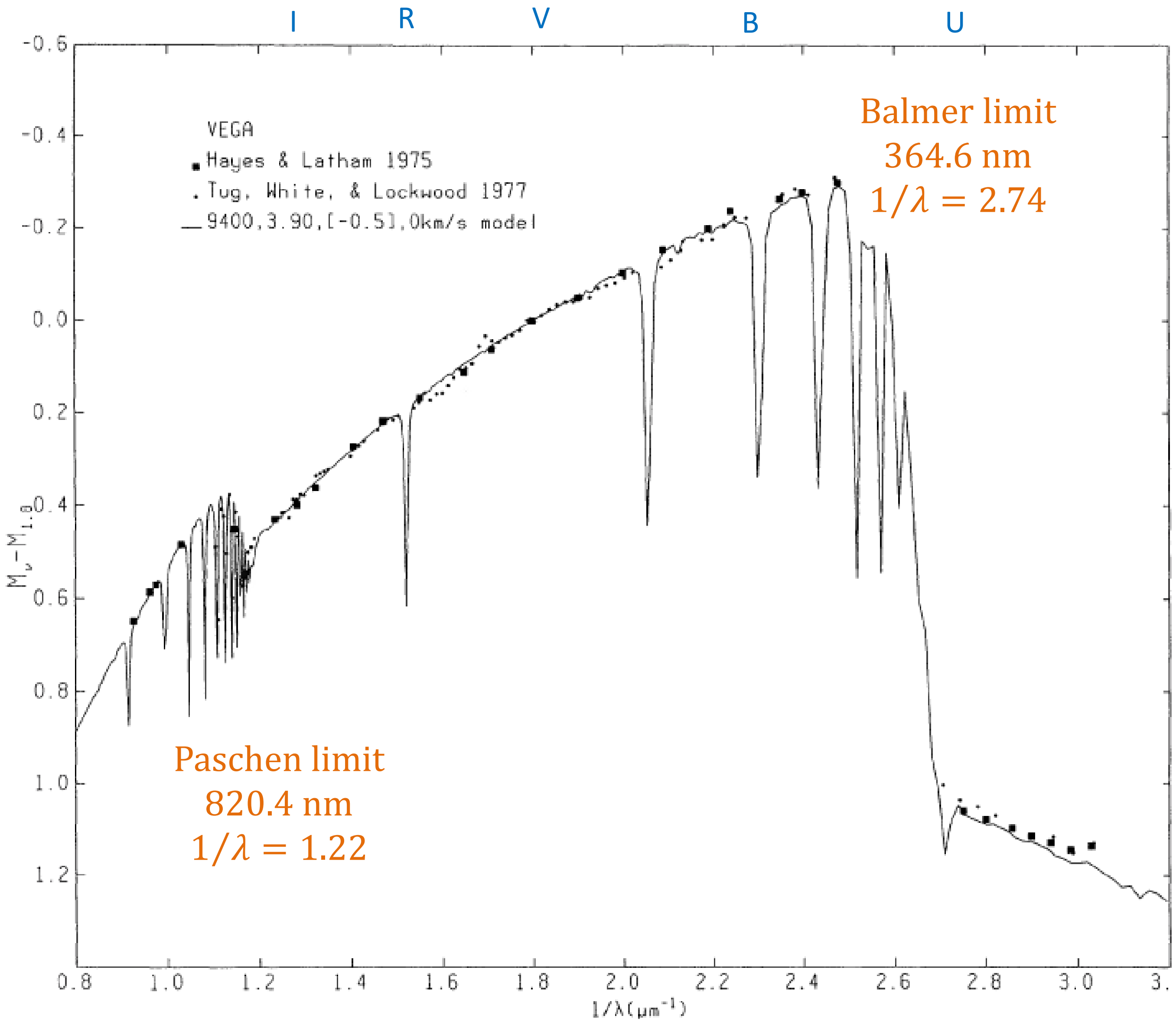
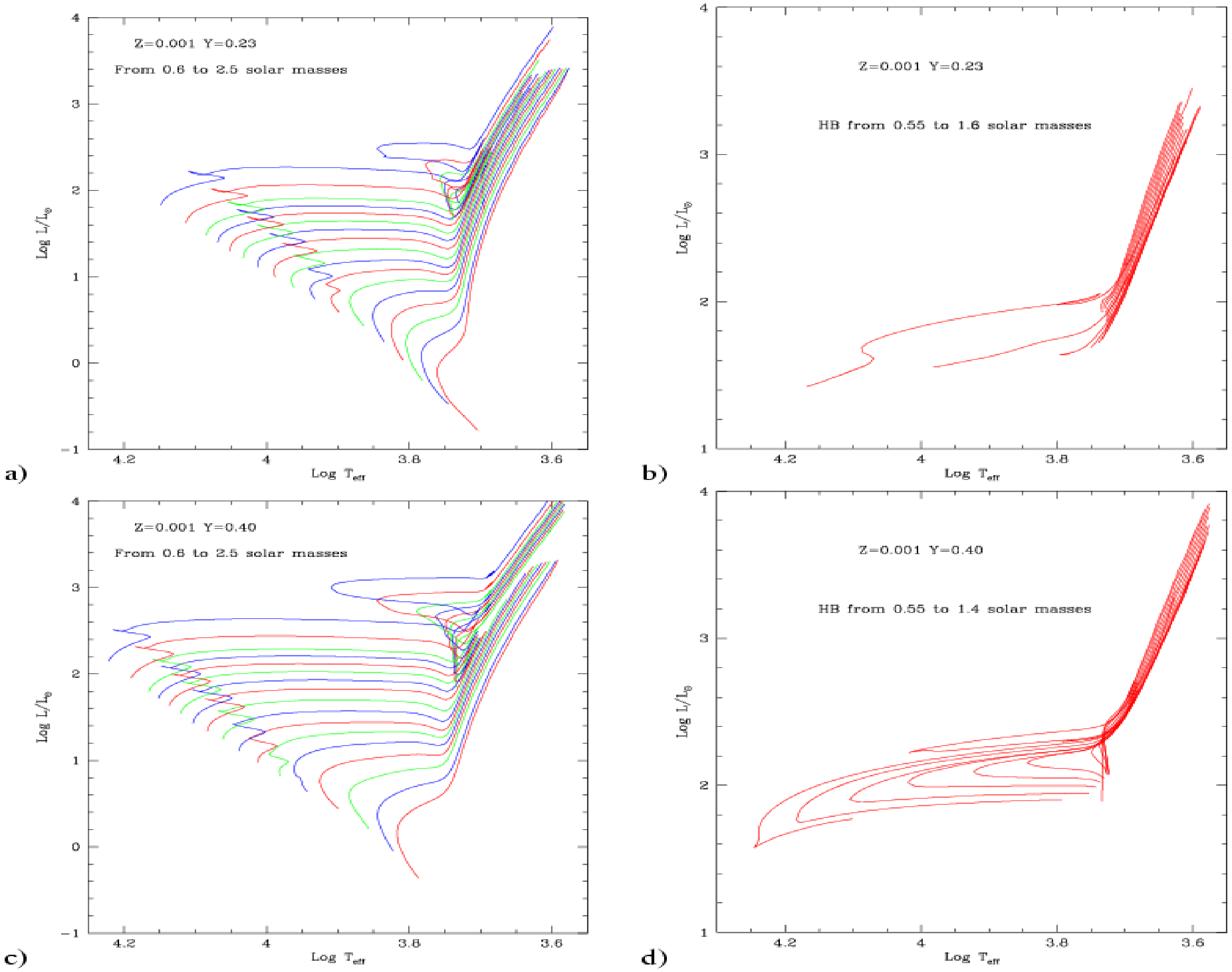


FIG. 1. Kurucz's (1991a) new model for Vega compared with a series of independent UV optical measurements, specifically those by Hayes & Latham (1985) and by Tug *et al.* (1977).

Cohen+92

Check out Aumann+84 for discovery of debris materials by IRAS.

Pre-main sequence evolutionary models (tracks)



http://stev.oapd.inaf.it/

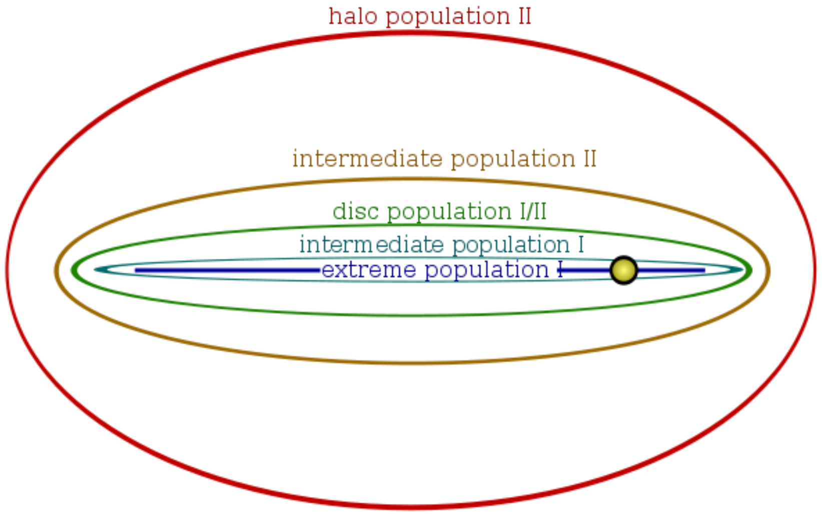
Bertelli et al, 2008, A&A, 484, 815

Stellar **populations**

◆ Population I ……. Stars in the Galactic disk; like the Sun; *metal rich*

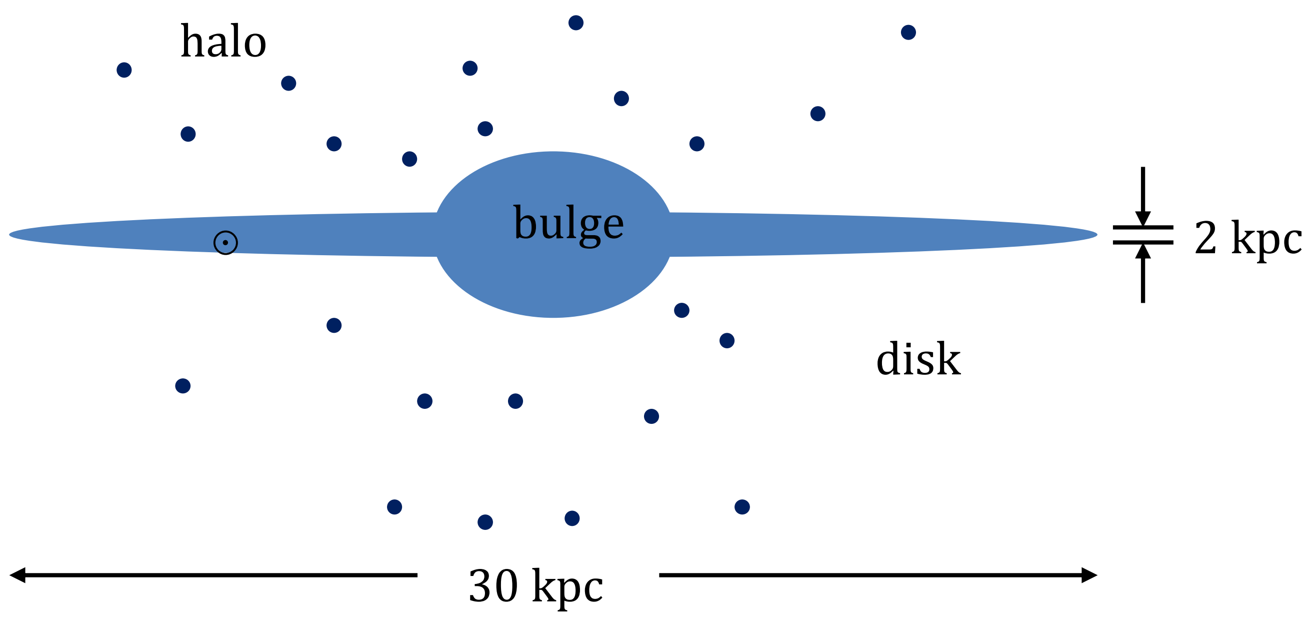
◆ Population II ….. Stars like those in the globular clusters; *metal poor*

◆ Population III …. Stars formed in the early universe; perhaps very hot and luminous; *metal free*



Distribution of Star Populations in Milky Way

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



Typical properties of Stellar Populations in the Milky Way

	Population I		Population II	
	very young	young	old	very old
Scale height [kpc]	60	100	500	2000
Σ_w [km s^{-1}]	8	10	25	75
Z	> 0.02	0.01	0.005	<0.002
Age (rel. to the Universe)	<0.05	0.25	0.75	1
Distribution	generally in aggregates		spherical	

Radial abundance gradient in the disk

Age and metallicity for open clusters

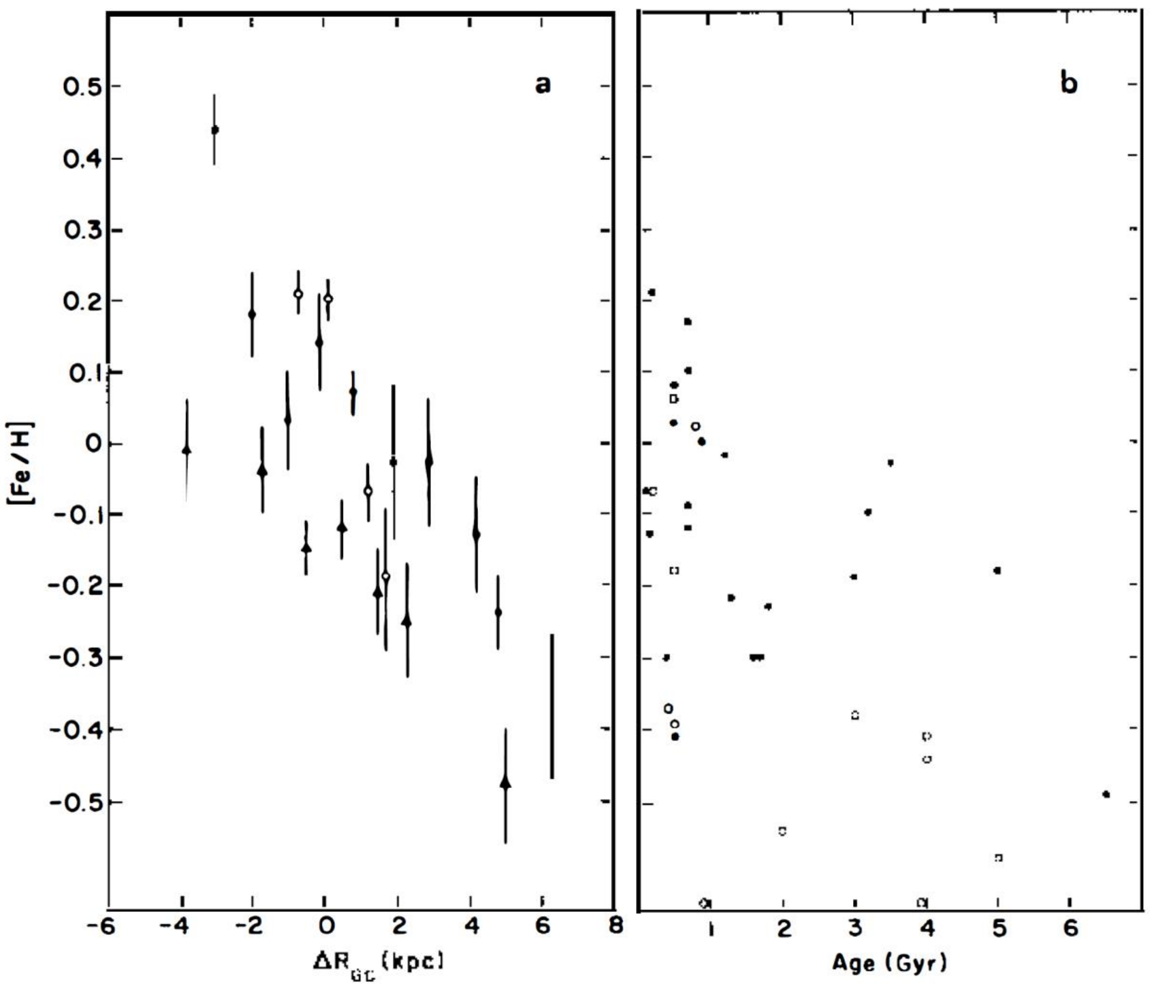


Figure 2 (*a*) The radial abundance gradient in the galactic disk. Mean metallicities from DDO and *UBV* photometry from Janes (1979) (*triangles*) are plotted versus galactocentric distance relative to the Sun. Also shown are results from Washington photometry of classical Cepheids by Harris (1981) (*solid circles*) and high-dispersion abundance analysis of G to M supergiants by Luck & Bond (1980) (*open circles*); (*b*) The relation between age and metallicity for the open cluster samples of Janes (1979, Table 8). Ages are taken from McClure & Twarog (1978), Jennens & Helfer (1975), Cannon (1970), and sources quoted by Janes. (Reliable ages were not found for six clusters.) Open circles distinguish clusters with galactocentric radius larger than the solar value by more than 1 kpc. No correction has been made for any vertical abundance gradient.

Mould, 1982, ARA&A, 20, 91