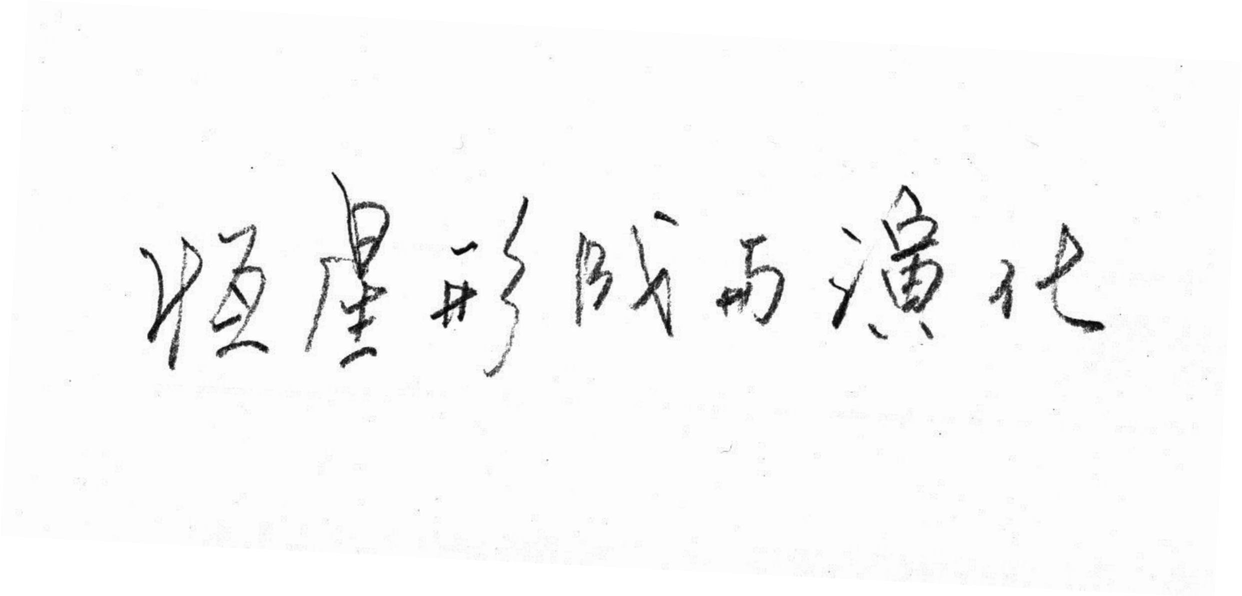
Stellar Formation and Evolution



恆星形成與演化

Wen Ping Chen

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

- ✓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 long can the Sun remain as a shining body? How is this 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 evening 5 to 8 scheduled (subject to change)

Class venue: 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

Text:

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

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 have been using or were published in recent years.

- ✓ ***Physics of Stellar Evolution and Cosmology***, by H. Goldberg & Michael Scadron, 1982, Gordon and Breach
- ✓ ***Stellar Structure and Evolution***, by R. Kippenhahn & W. Weigert, 1990, Springer-Verlag
- ✓ ***Introduction to Stellar Astrophysics***, Vol 3 --- Stellar Structure and Evolution, by Erika Bohm-Vitense, 1992, Cambridge
- ✓ ***Stellar Structure and Evolution***, by Huang, R.Q. 黄潤乾, Guoshin, 1990
  This book, originally in Chinese, has an English version, and has recently been revised. The Chinese version（恆星物理）has also been revised
- ✓ ***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
- ✓ ***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
- ✓ ***Evolution of Stars and Stellar Populations***, by Maurizio Salaris and 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, Spinger
- ✓ ***Stellar Physics, 2: Stellar Evolution and Stability,*** by Bisnovatyi-Kogan, 2nd Ed., 2010, Springer (translated from Russian)

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.

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

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

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

Often used fundamental constants

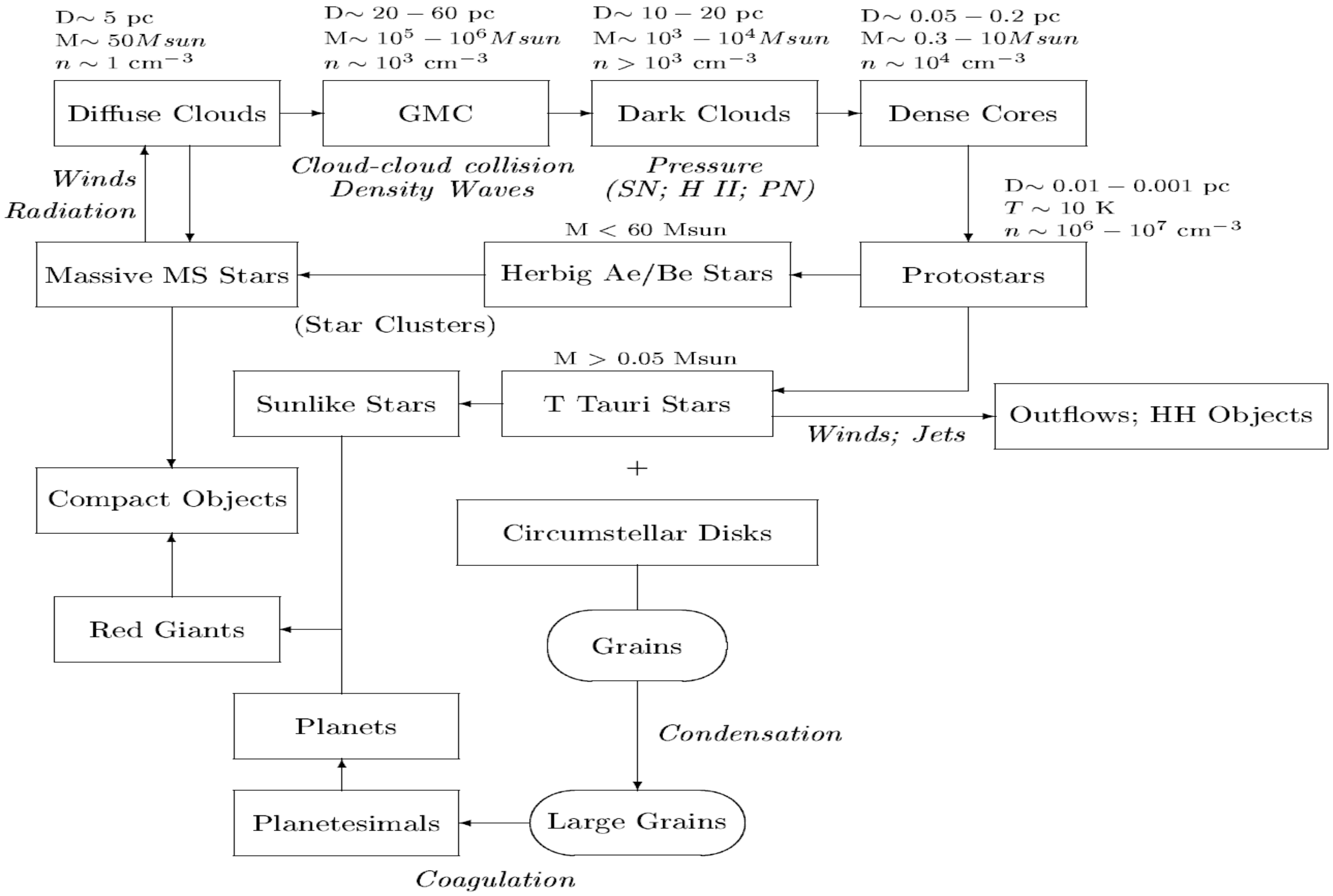
Physical

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



D$\sim$ 5 pc
M$\sim 50 Msun$
$n \sim 1$ cm^{-3}

Diffuse Clouds

D$\sim$ 20 – 60 pc
M$\sim 10^5 - 10^6 Msun$
$n \sim 10^3$ cm^{-3}

GMC

Cloud-cloud collision
Density Waves

D$\sim$ 10 – 20 pc
M$\sim 10^3 - 10^4 Msun$
$n > 10^3$ cm^{-3}

Dark Clouds

Pressure
(SN; H II; PN)

D$\sim$ 0.05 – 0.2 pc
M$\sim 0.3 - 10 Msun$
$n \sim 10^4$ cm^{-3}

Dense Cores

D$\sim$ 0.01 – 0.001 pc
$T \sim 10$ K
$n \sim 10^6 - 10^7$ cm^{-3}

Protostars

M < 60 Msun

Herbig Ae/Be Stars

Massive MS Stars

Winds
Radiation

(Star Clusters)

M > 0.05 Msun

T Tauri Stars

Winds; Jets

Outflows; HH Objects

Sunlike Stars

+

Circumstellar Disks

Grains

Condensation

Large Grains

Coagulation

Planetesimals

Planets

Red Giants

Compact Objects

Galactic Ecology

Properties of Stars

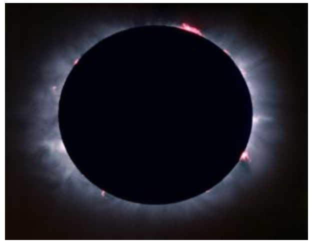
Vocabulary

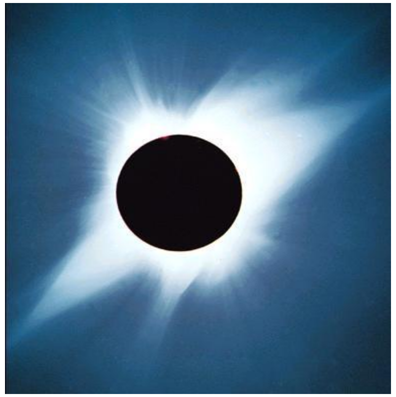
- **Luminosity** [erg s^{-1}] L = bolometric luminosity = power
- **Spectral luminosity** [erg $s^{-1}\mu m^{-1}$] L_λ $d\lambda = -(c/\nu^2)\, d\nu$
- **flux** [erg s^{-1} cm^{-2}] f
- **flux density** [erg s^{-1} cm^{-2} μm^{-1}] f_λ or f_ν 1 Jansky (Jy) = 10^{-23} [erg $s^{-1} cm^{-2} Hz^{-1}$]
  $f(\nu=0)=3640$ 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}] $u = (4\,\pi/c)\, J$
  J=mean intensity $= (1/4\pi) \int I \, d\,\Omega$
- **Magnitude** … apparent, absolute, bolometric, AB

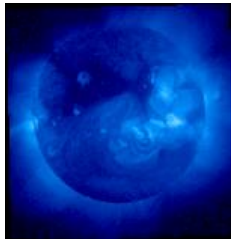
$$\boxed{S_\nu\ [\mu\text{Jy}] = 10^{(23.9-\text{AB})/2.5}}$$

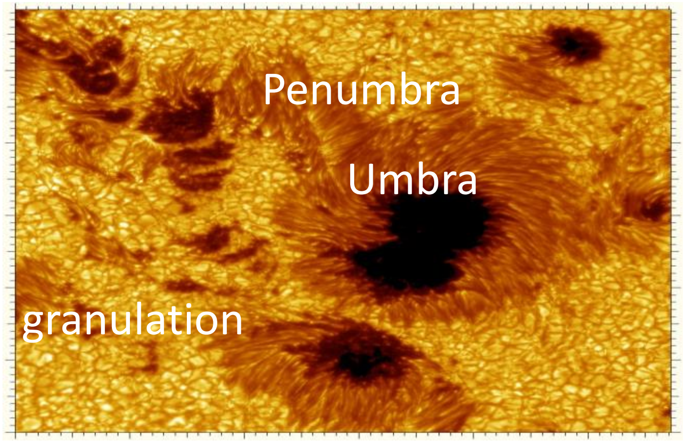
$$\boxed{m_{\text{AB}} = -2.5\log_{10}\left(\frac{f_\nu}{3631\ \text{Jy}}\right)}$$

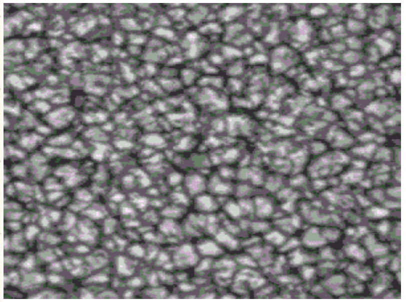
Our Sun ---- the best studied star

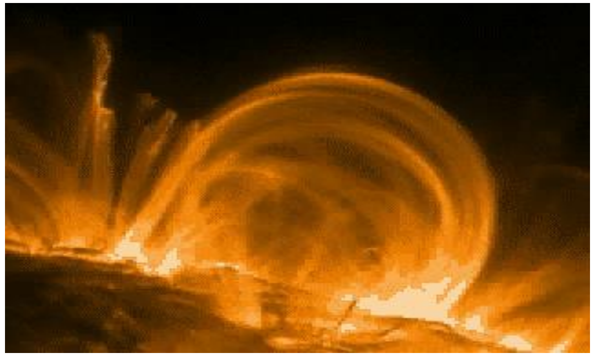


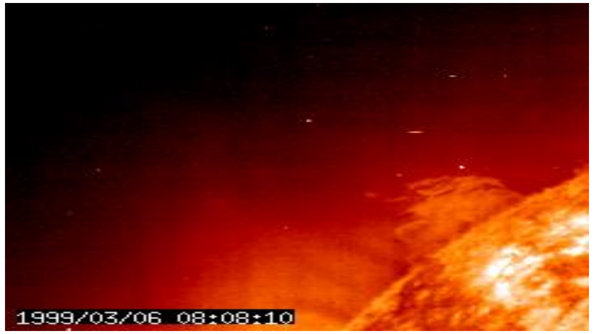


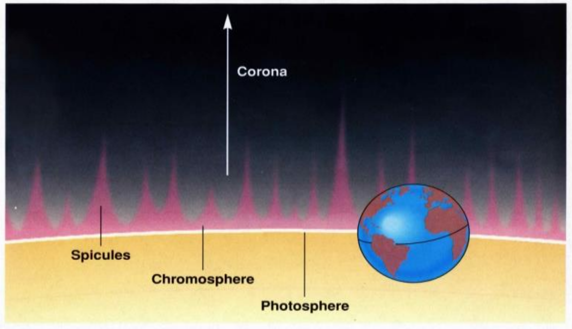




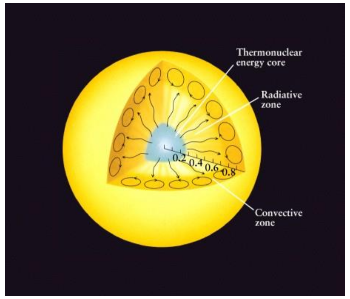


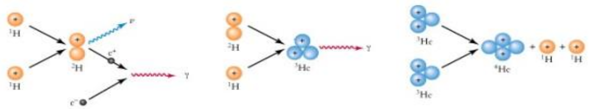


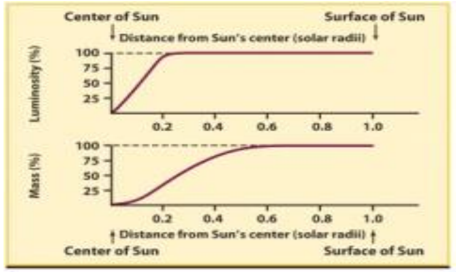


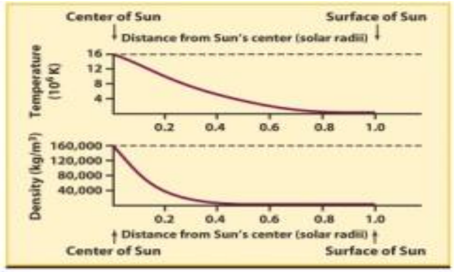


Cross section of photosphere.









Observable properties of stars

Basic parameters to compare between theories and observations

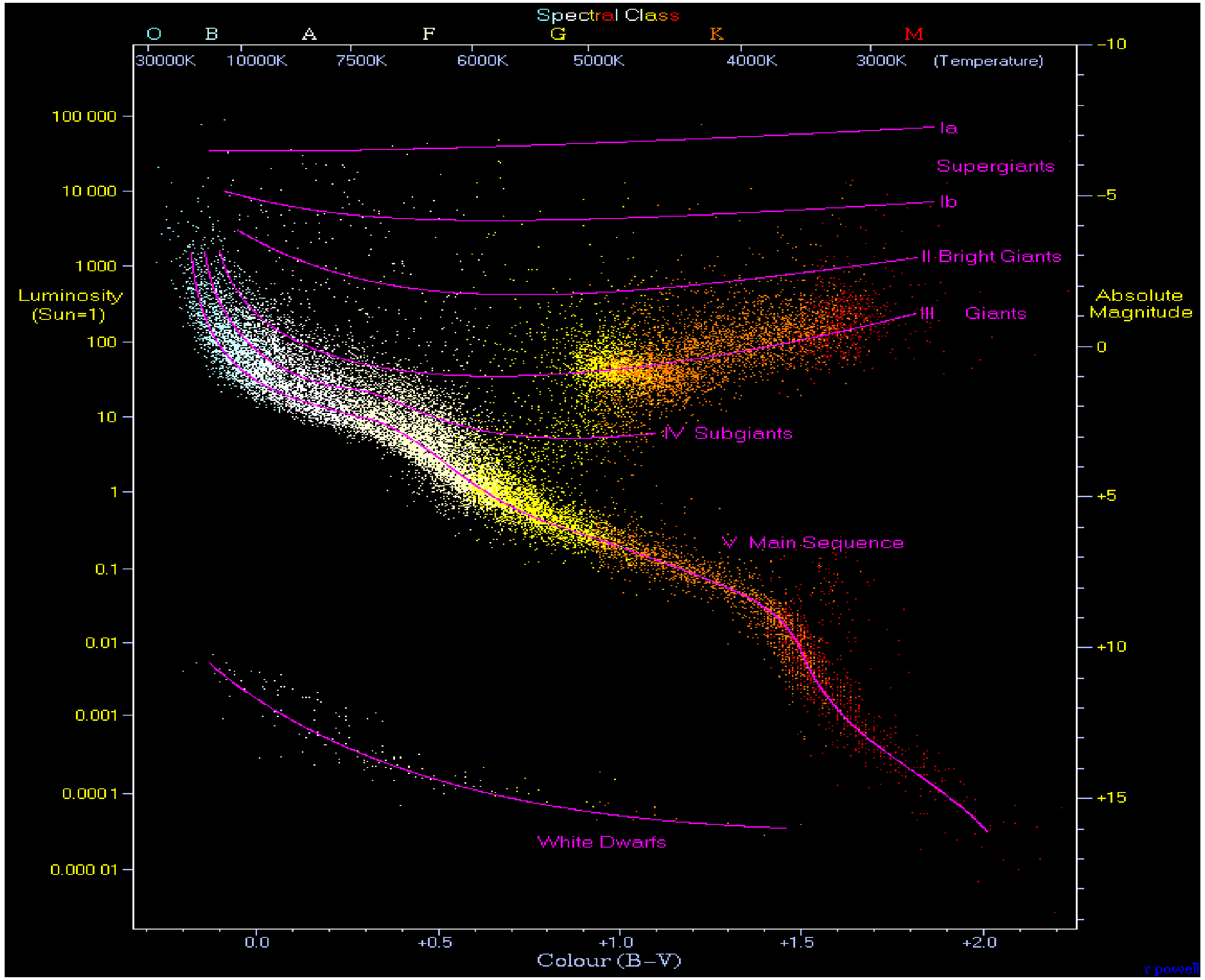
- Mass (M)
- Luminosity (L)
- Radius (R)
- Effective temperature (T_e) $L = 4\pi R^2 \sigma T_e^4$
- Distance → measured flux $F = L / 4\pi d^2$

M, R, L and T_e not independent

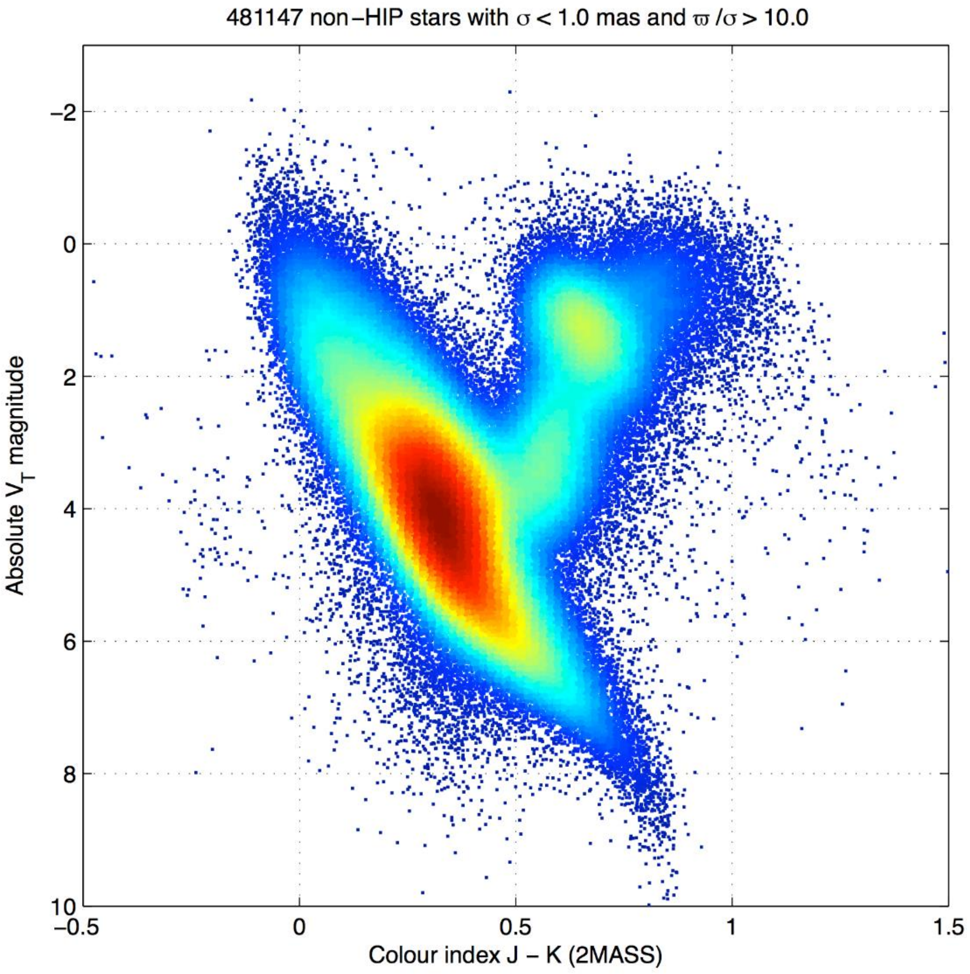
- L and T_{eff} Hertzsprung-Russell (HR) diagram or color-magnitude diagram (CMD)

- L and M mass-luminosity relation

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

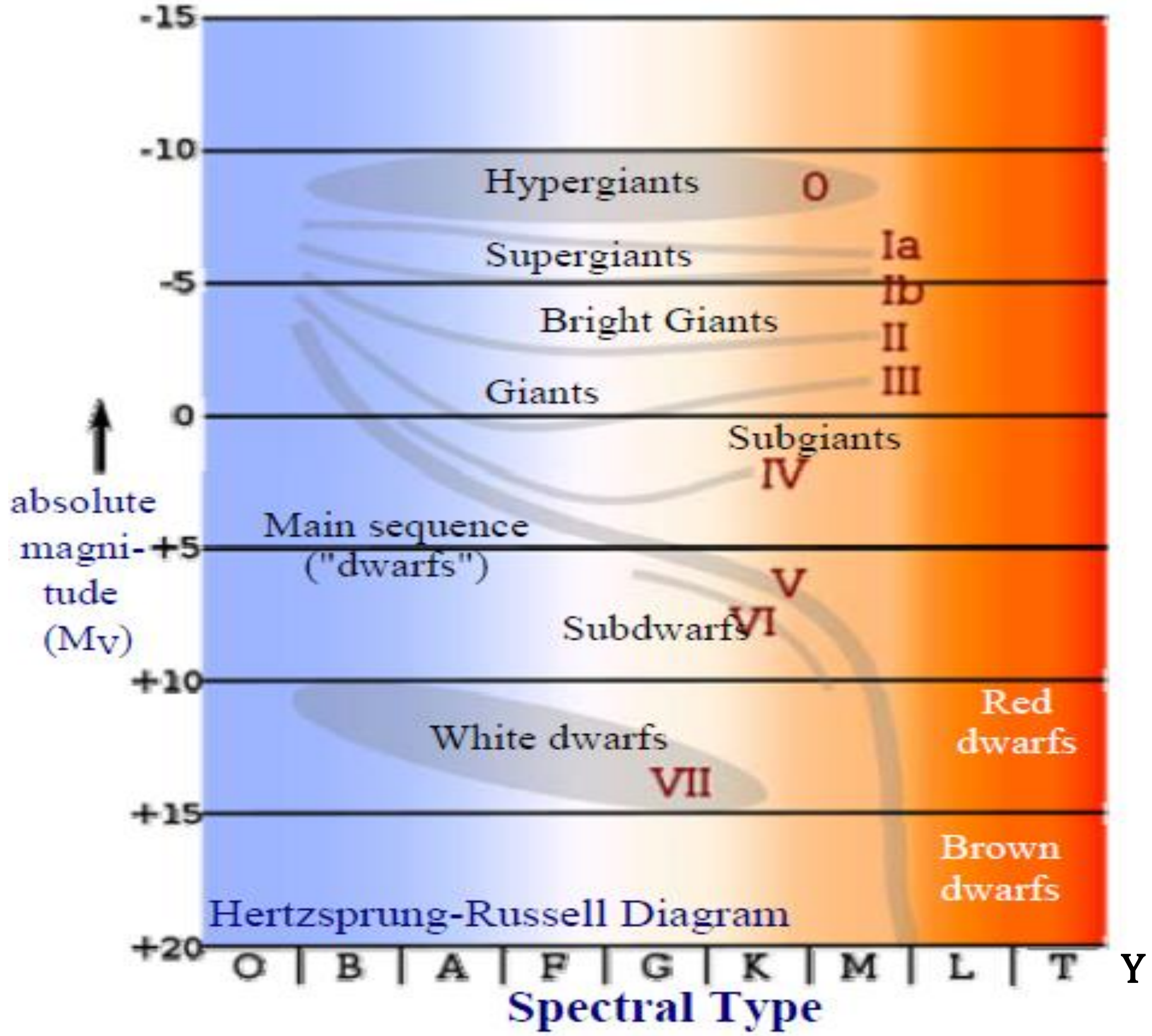


From wikipedia by Richard Powell based on *Hipparcos* data and Gliese catalog



https://www.cosmos.esa.int/web/gaia/news_20150807

For (nearby) star databases http://www.projectrho.com/public_html/starmaps/catalogues.php



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

Stars:

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

Brown Dwarfs:

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

Planet-mass Objects:

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

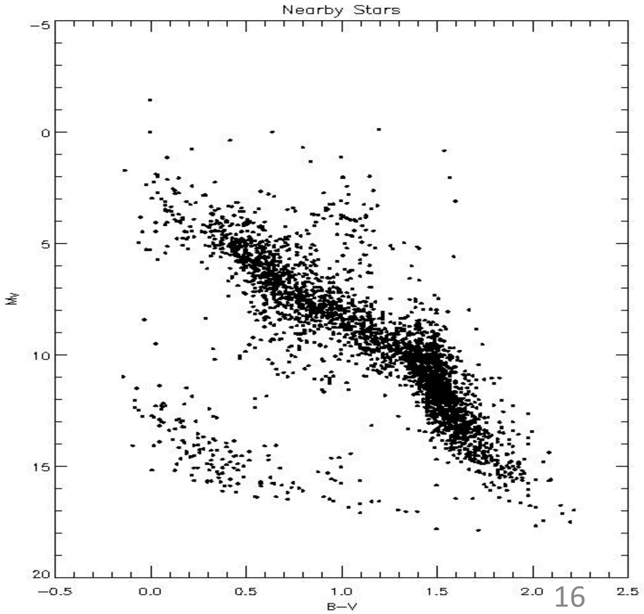
To measure the stellar distance

- ◆ 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 for stars up to d=100 pc

→ ~100 stars with good parallax distances

Preliminary Version of the Third Catalogue of Nearby Stars
Gliese & Jahreiss (1991)

CDS catalog number: V/10A
2964/3803 complete entries



GAIA will measure 10^9 stars!

In most cases, 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 the known brightness of that particular kind of objects

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

  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.

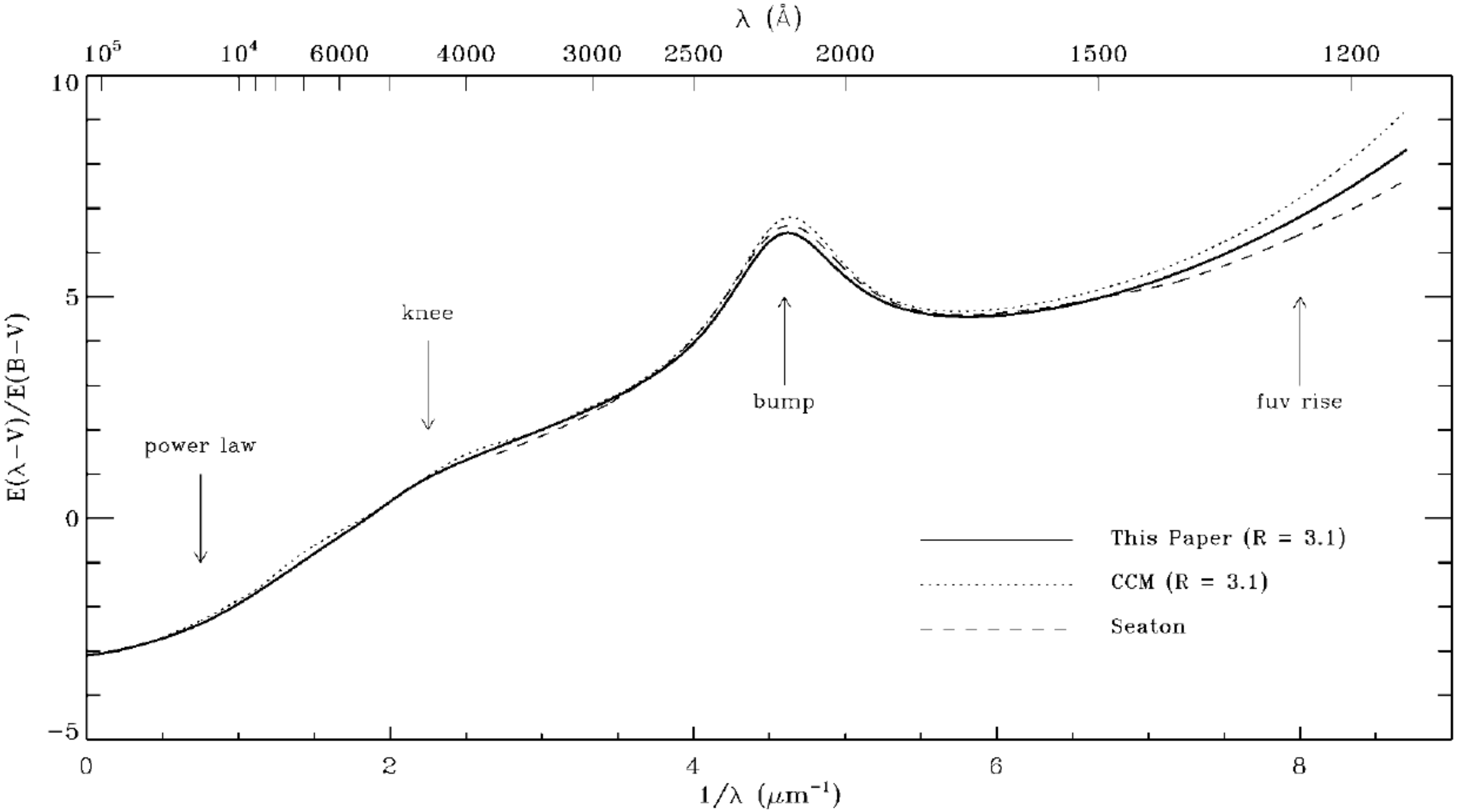
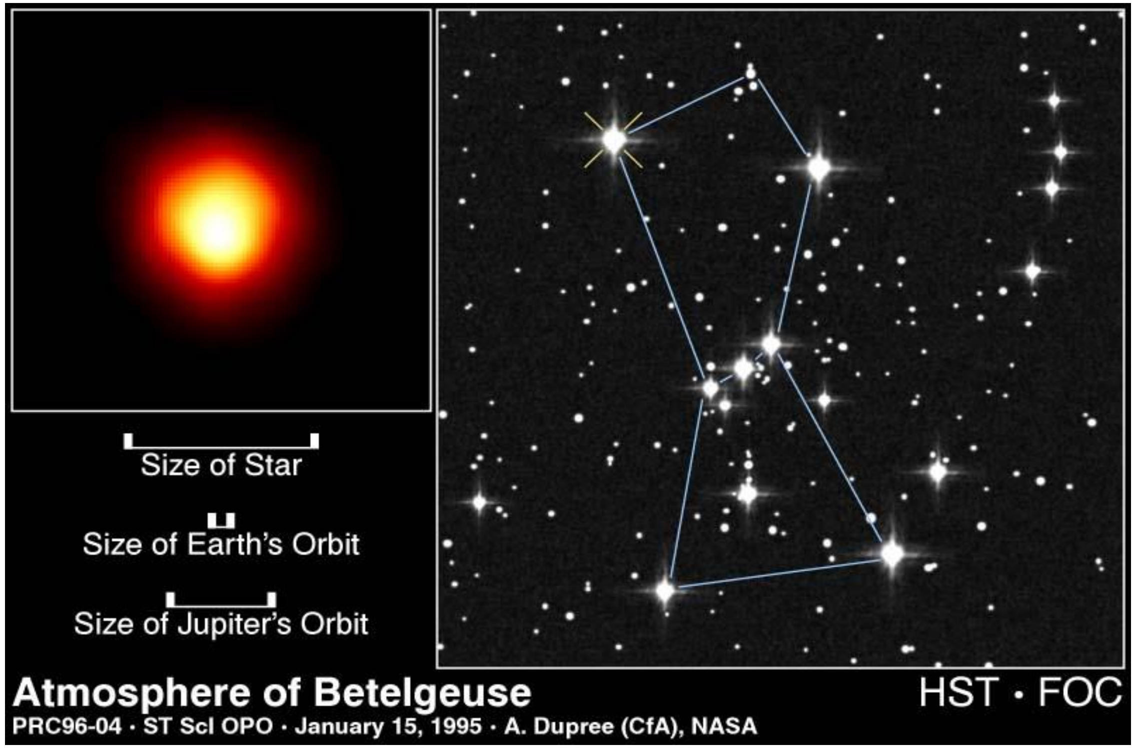


FIG. 1.—Normalized interstellar extinction curves from the far-IR through the UV. Several general features of the curves are noted. The solid and dotted curves are estimates for the case $R \equiv A(V)/E(B-V) = 3.1$ derived in the Appendix of this paper and by Cardelli et al. (1989), respectively. The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



Atmosphere of Betelgeuse

PRC96-04 • ST ScI OPO • January 15, 1995 • A. Dupree (CfA), NASA

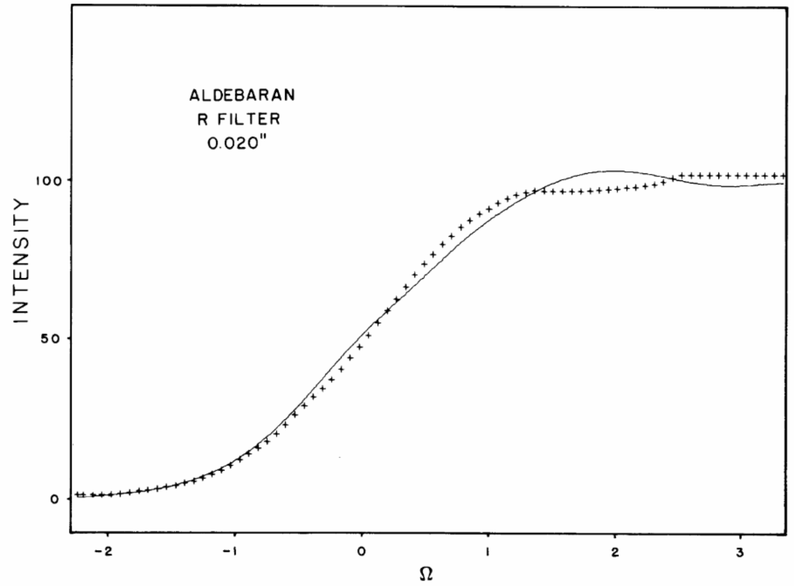


FIG. 1.—A comparison of the (*crosses*) observed points and the (*line*) theoretical pattern for the Aldebaran λ = 7460 Å record with $\theta = 0''.020$.

Lunar occultation

Beaver & Eitter (1979)

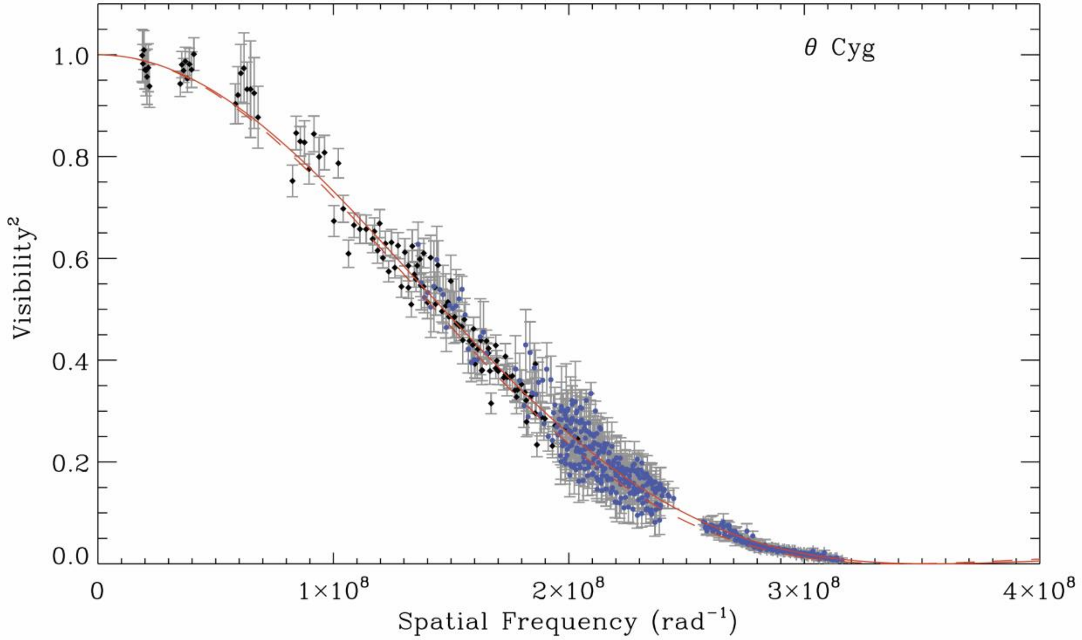


Figure 1. Squared visibility versus spatial frequency for θ Cyg for PAVO (blue circles) and MIRC (black diamonds) data. The red lines show the fitted limb-darkened model to the combined data. The solid line is for $\mu = 0.47 \pm 0.04$ (PAVO) while the dashed line is for $\mu = 0.21 \pm 0.03$ (MIRC).

Optical interferometery CHARA

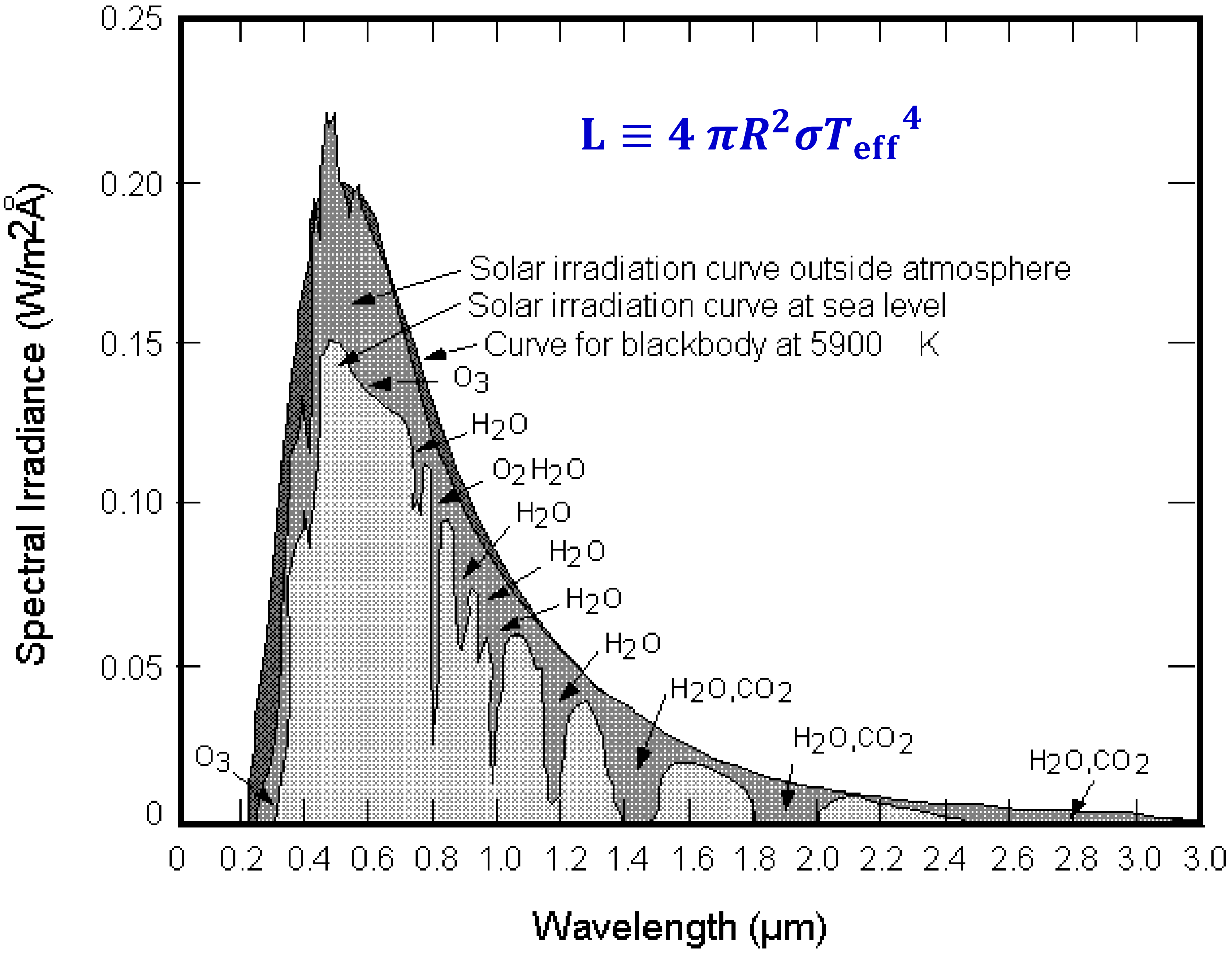
White et al (2013)

To measure the stellar temperature

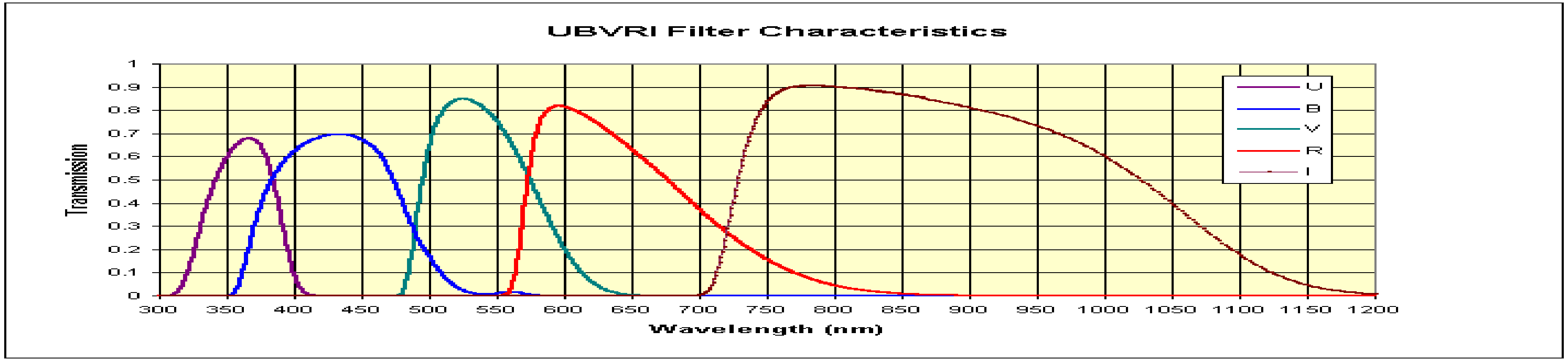
- What is T_{eff}? What is the "surface" of a star?
- What is T anyway? Temperature is often defined by other physical quantities through an equation ("law") (by radiation or by particles)
  - blackbody, radiation, color, excitation,
  - ionization, kinetic, electron, conductive ...
- Only in thermal equilibrium are all these temperatures the same.
- Photometry (spectral energy distribution) gives a **rough** estimate of T, e.g., fluxes/magnitudes measured at different wavelengths, such as the "standard" Johnson system *UBVRI*

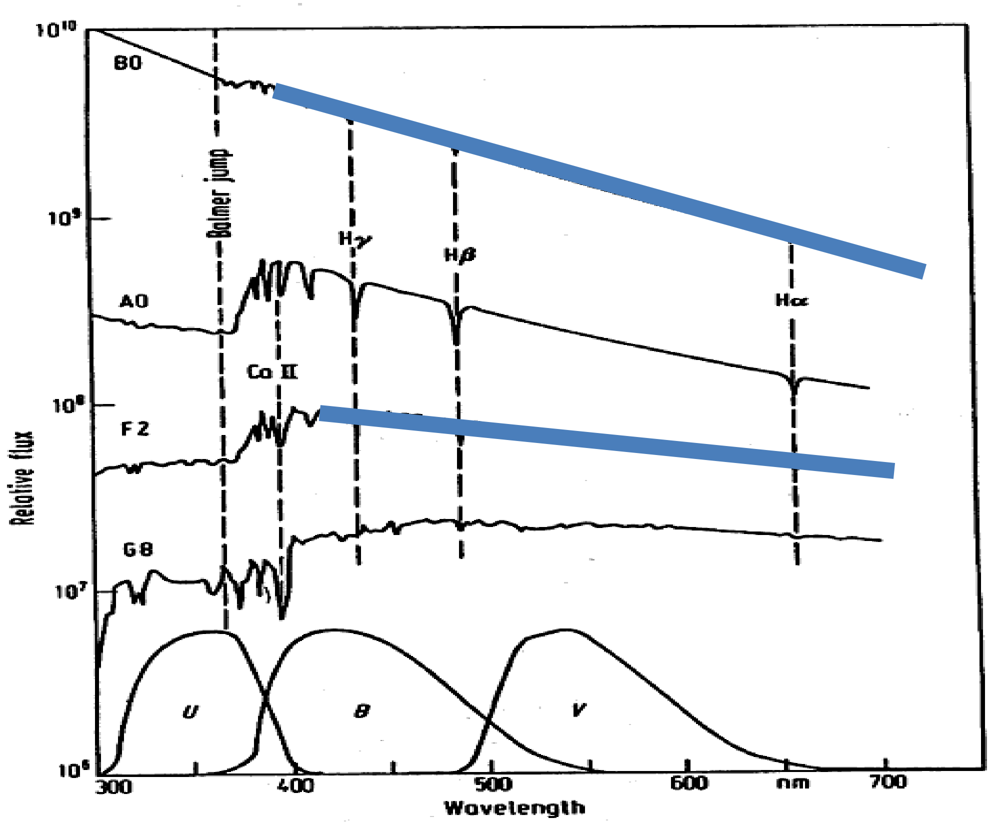
Band	U	B	V	R	I
λ/nm	365	445	551	658	806
$\Delta\lambda$/nm	66	94	88	138	149

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



$$\mathbf{L} \equiv 4\,\pi R^2 \sigma T_{\mathbf{eff}}{}^4$$





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.

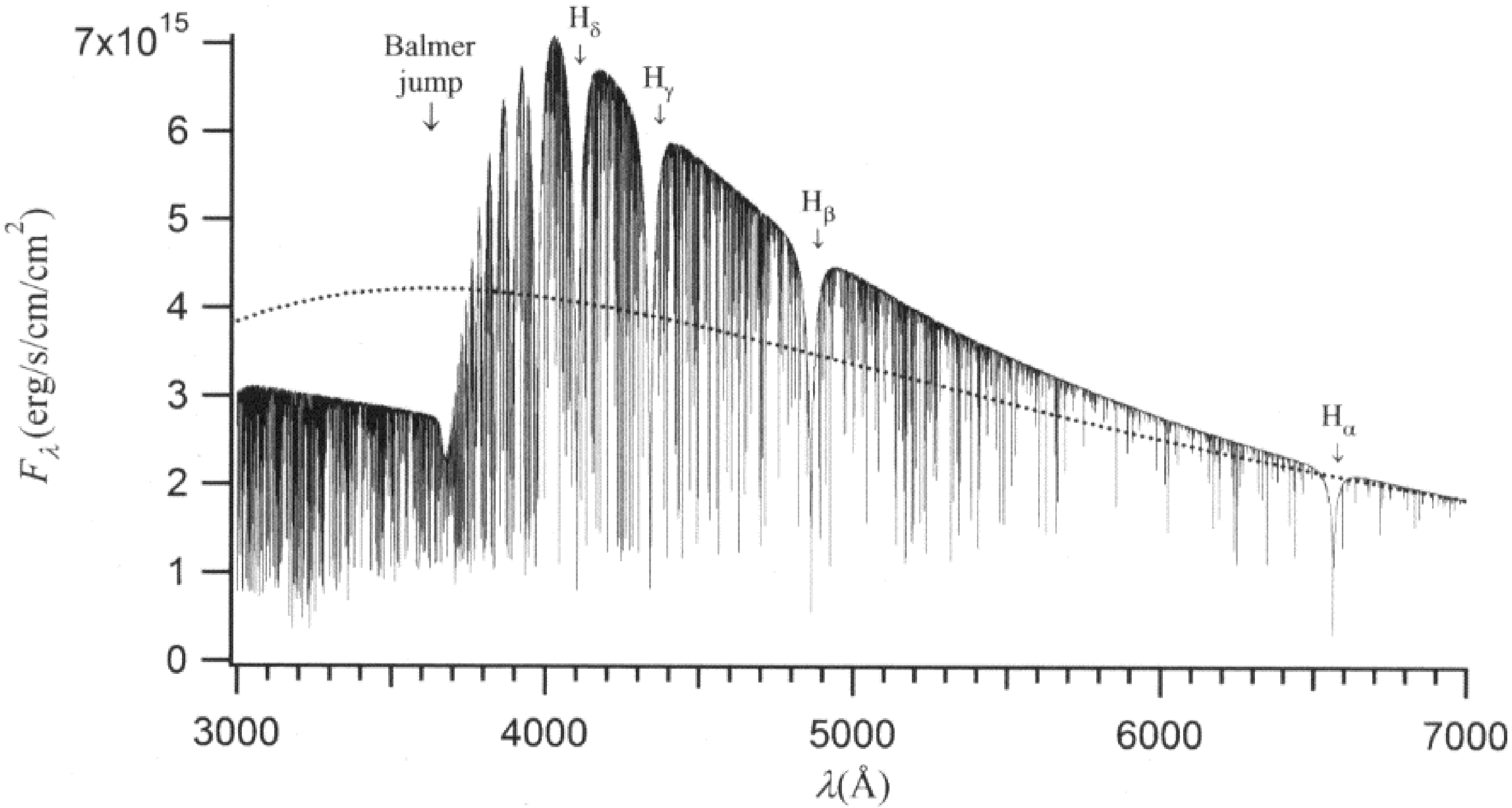
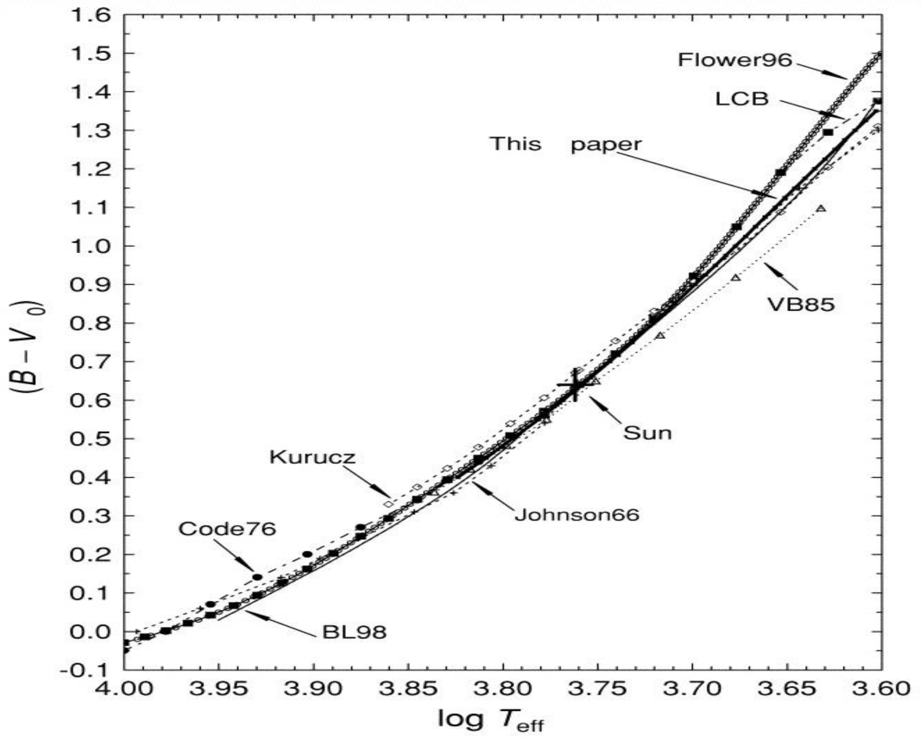


Figure 1.8 Theoretical monochromatic flux emerging form an A type star with $T_{\text{eff}} = 8000\,\text{K}$. The first four Balmer absorption lines, as well as the Balmer jump, are identified in this figure. Thousands of other absorption atomic lines can also be seen. This theoretical flux was obtained 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 $T = 8000\,\text{K}$ (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 $(B - V)0$
- More accurate determination of T by spectra and stellar atmosphere models, e.g., the Kurucz’s model

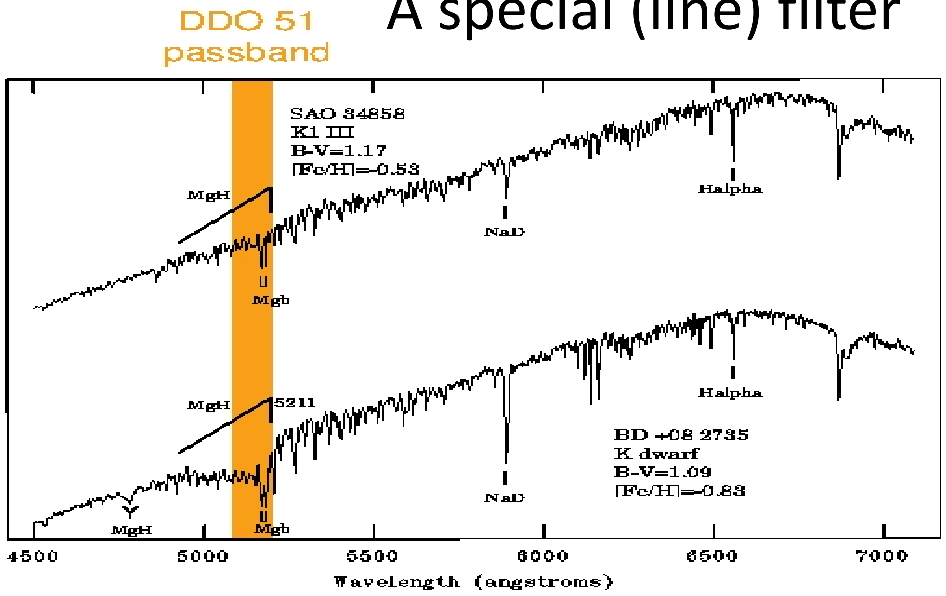


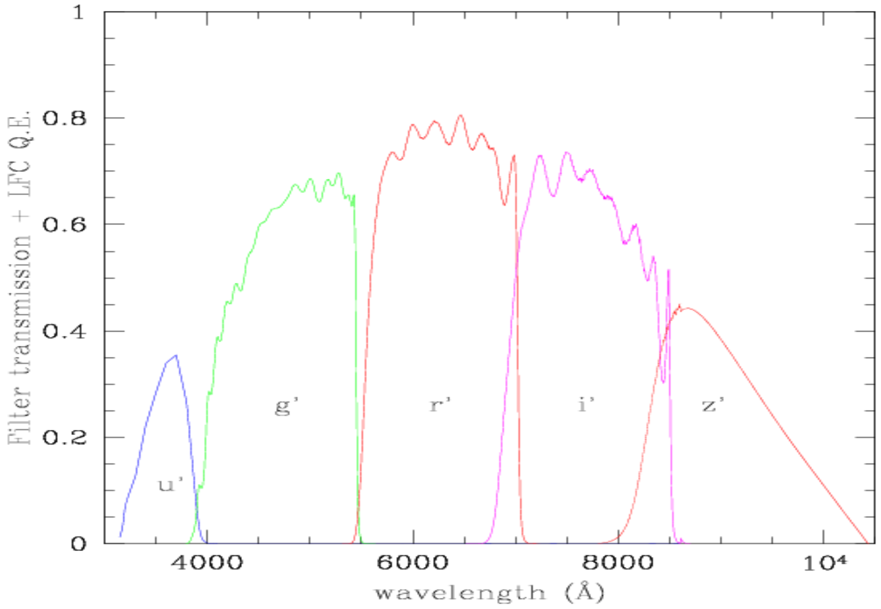
Color Excess

$$E_{B-V} = (B - V)_{\rm obs} - (B - V)_{\rm int}$$

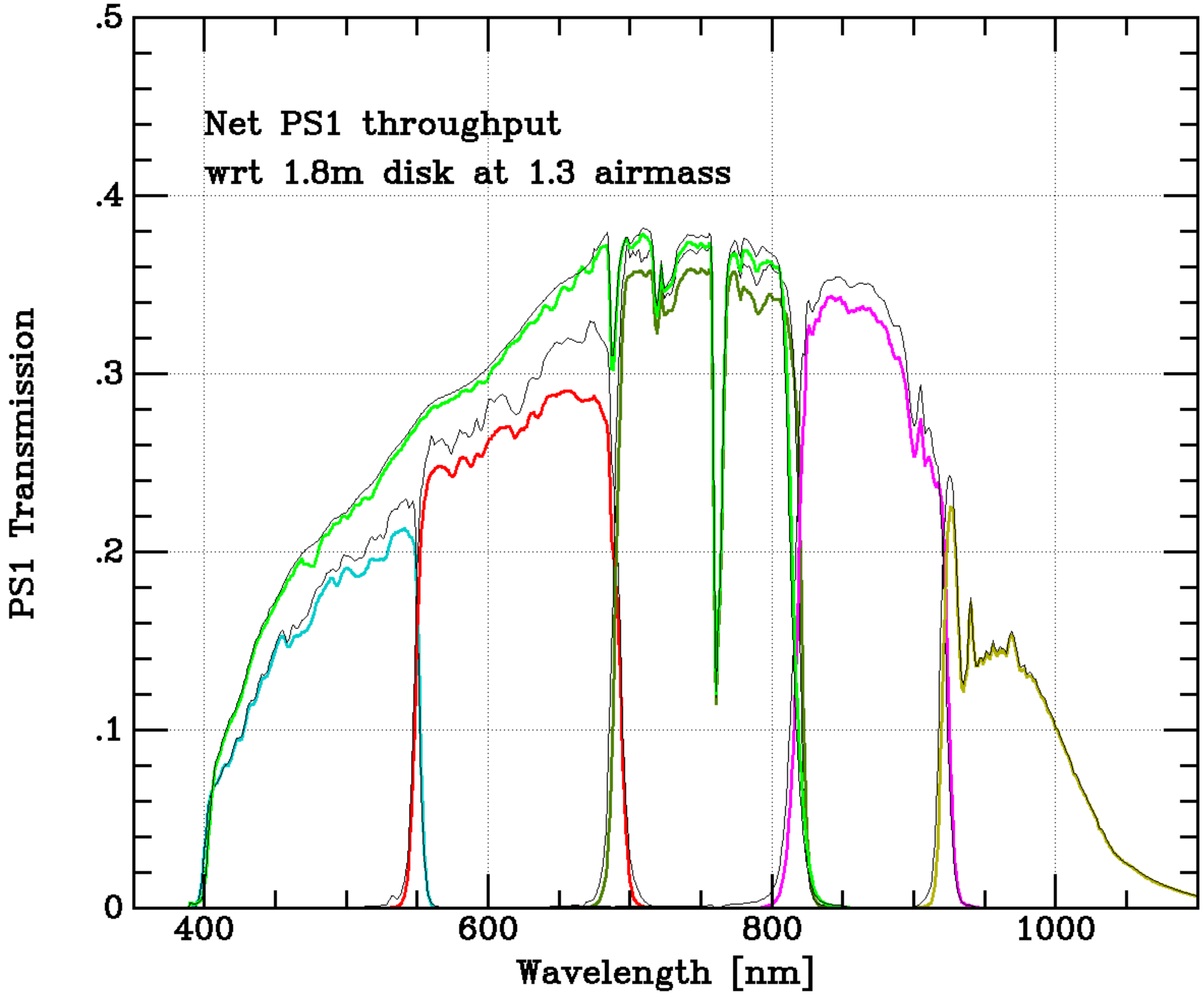
$$(B - V)_\odot = 0.656 \pm 0.005$$

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

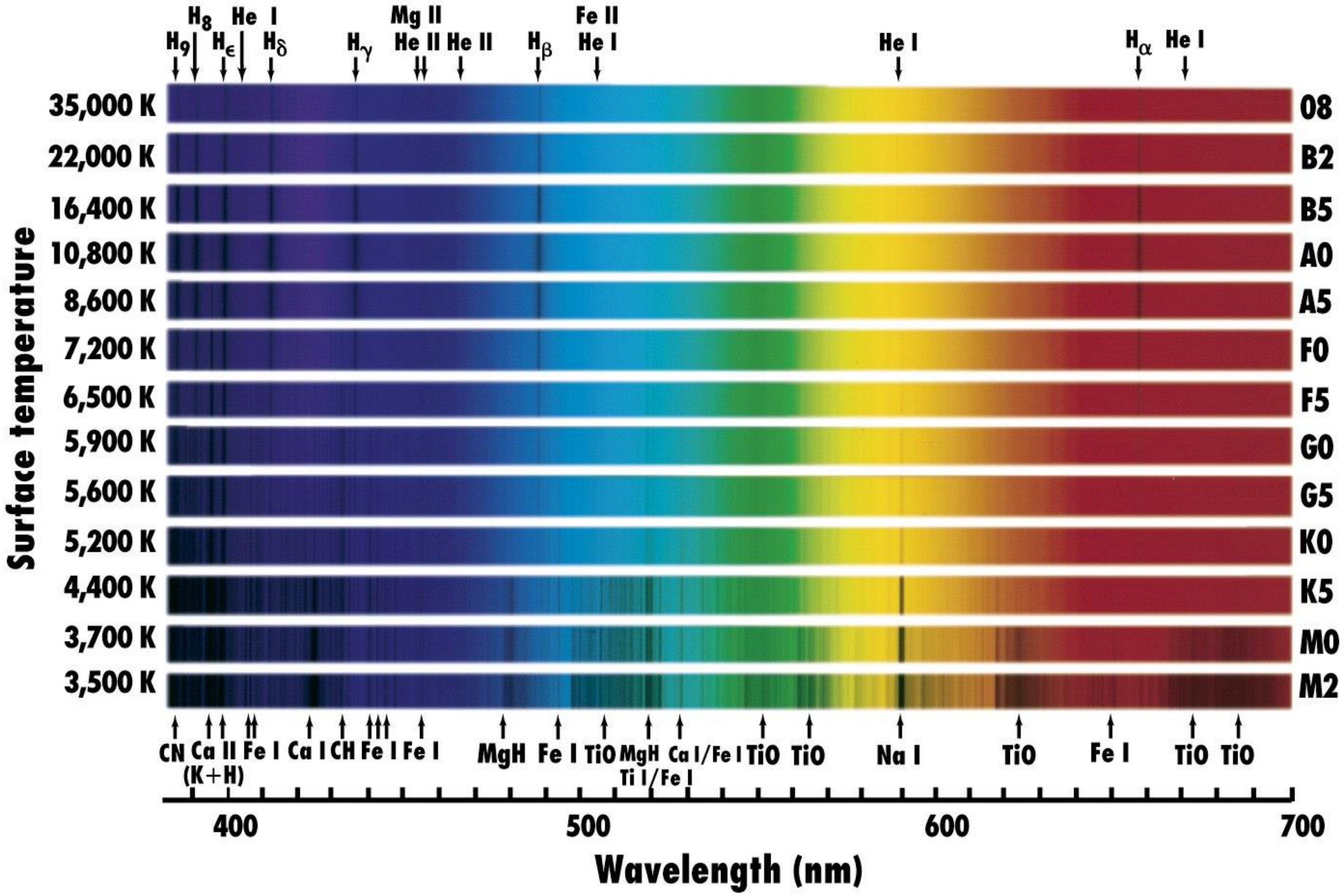
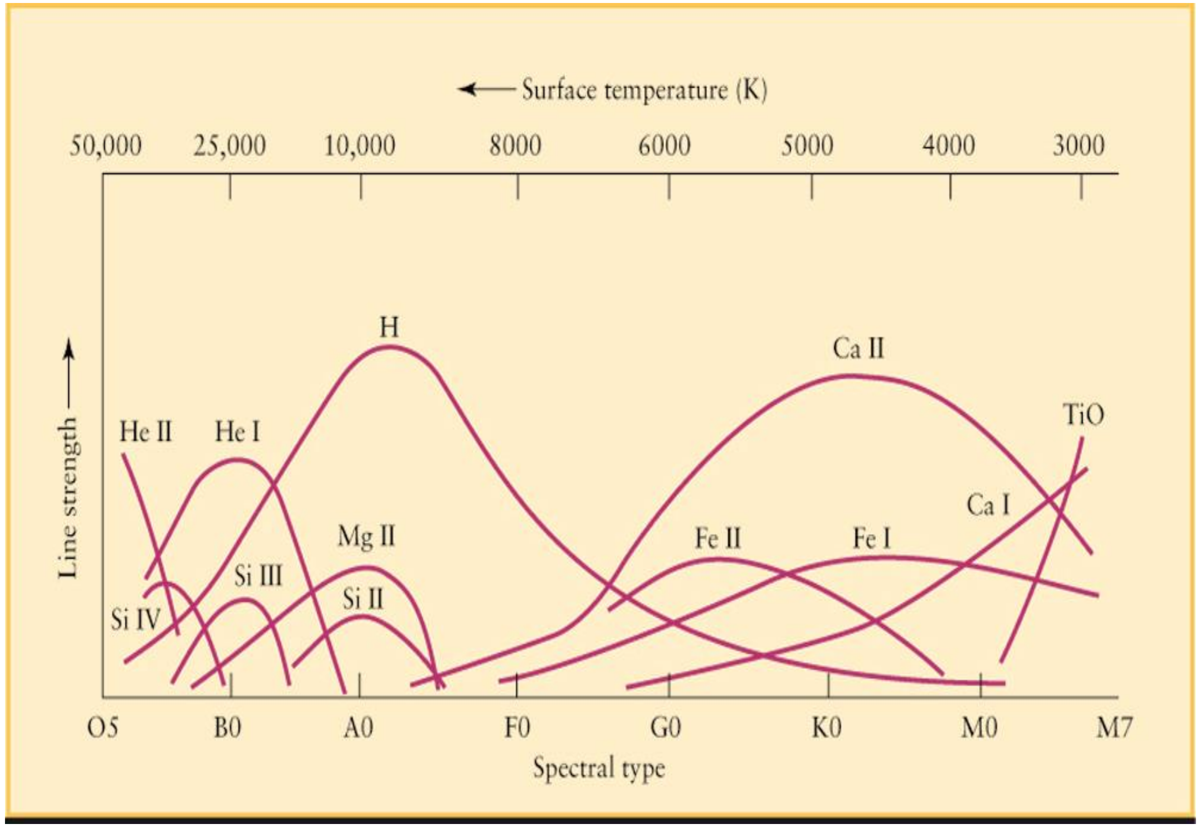


Figure 11-5
Discovering the Universe, Seventh Edition

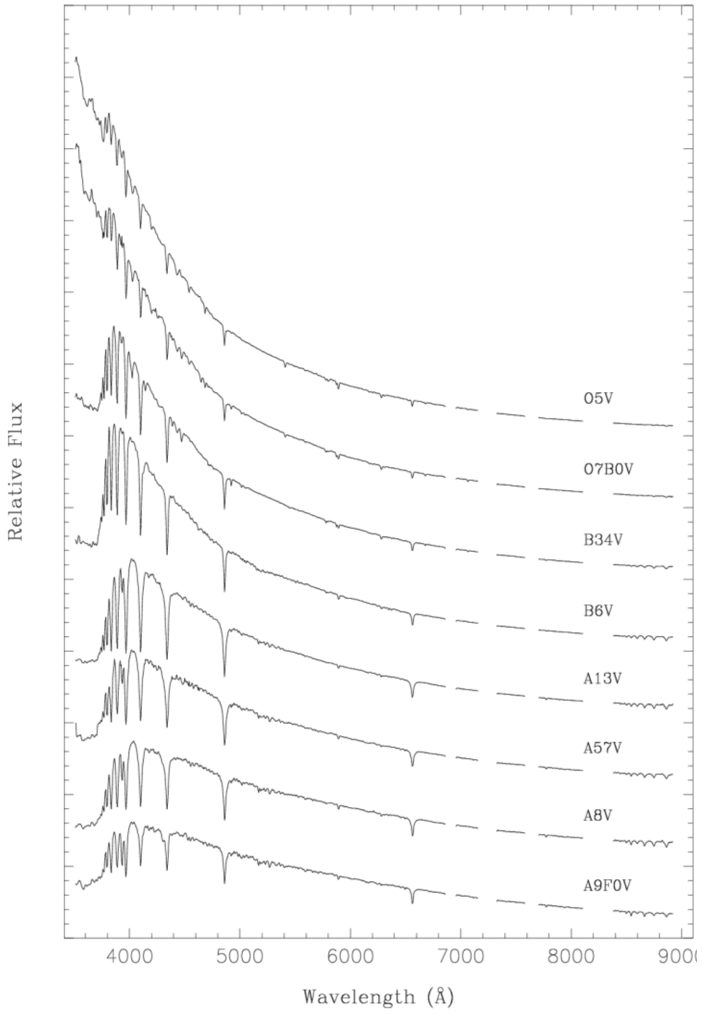
Line ratios → Temperature



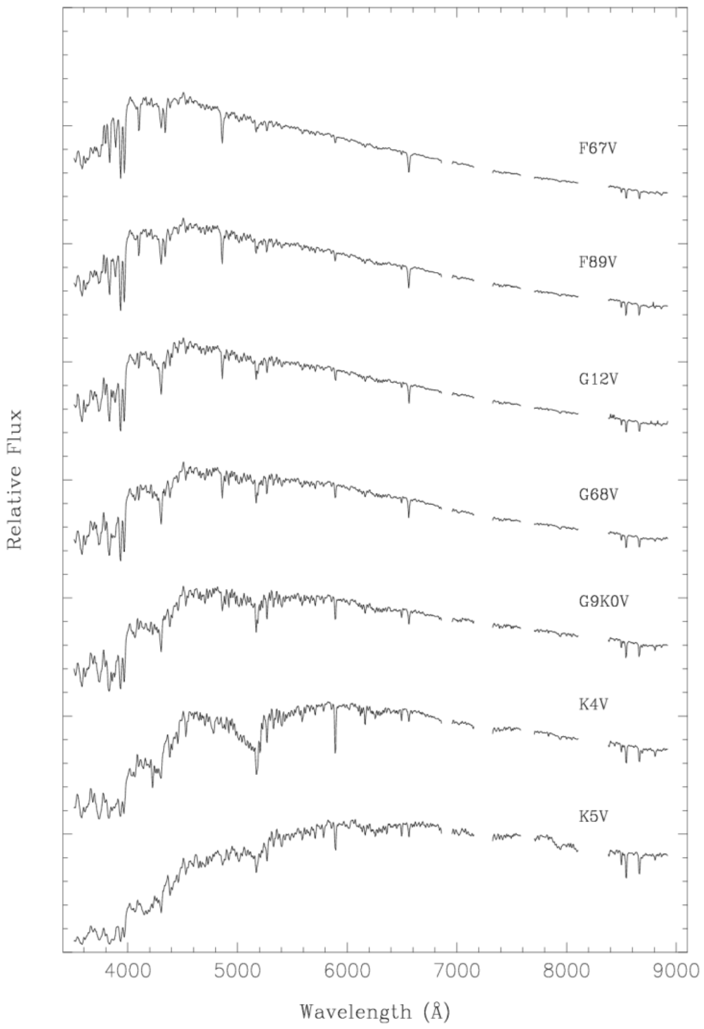
I --- neutral atoms; II --- ionized once; III --- ionized twice; …

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

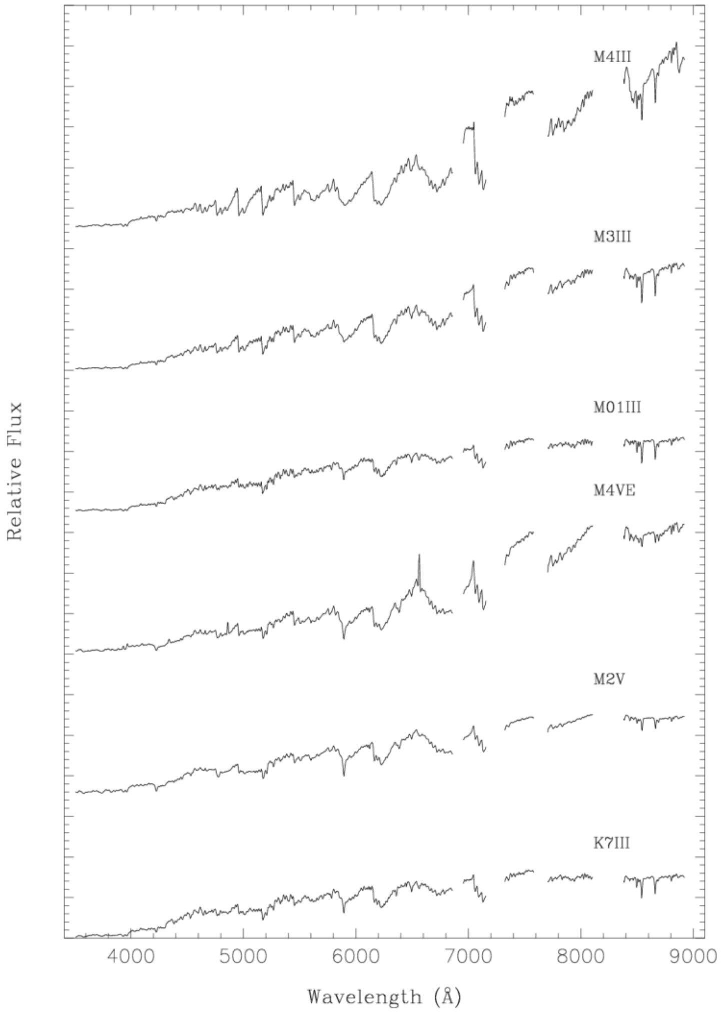
Hot stars --- peaked at short wavelengths (UV); mainly He lines, some H lines



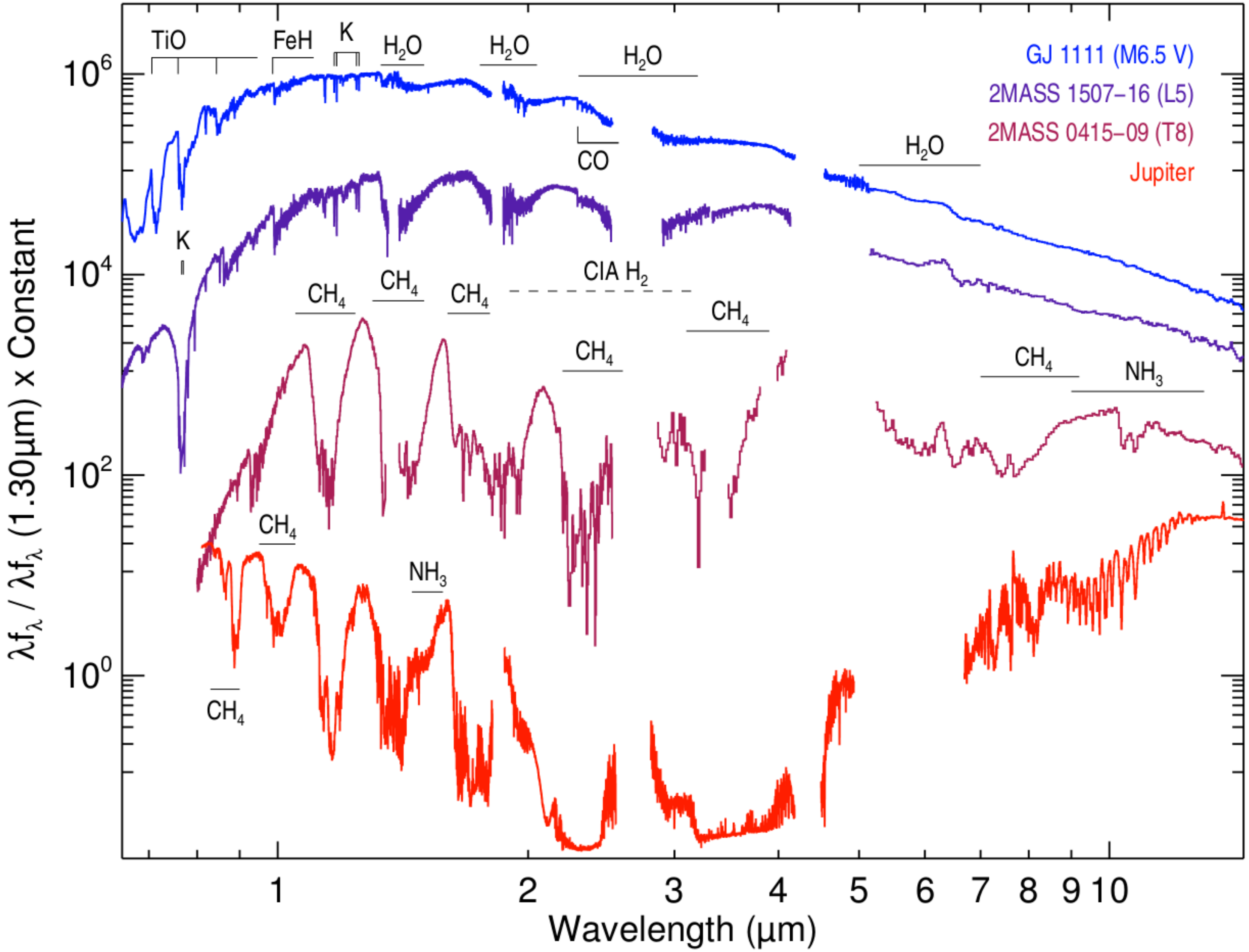
Warm stars --- peaked in the visible wavelengths; H lines prominent



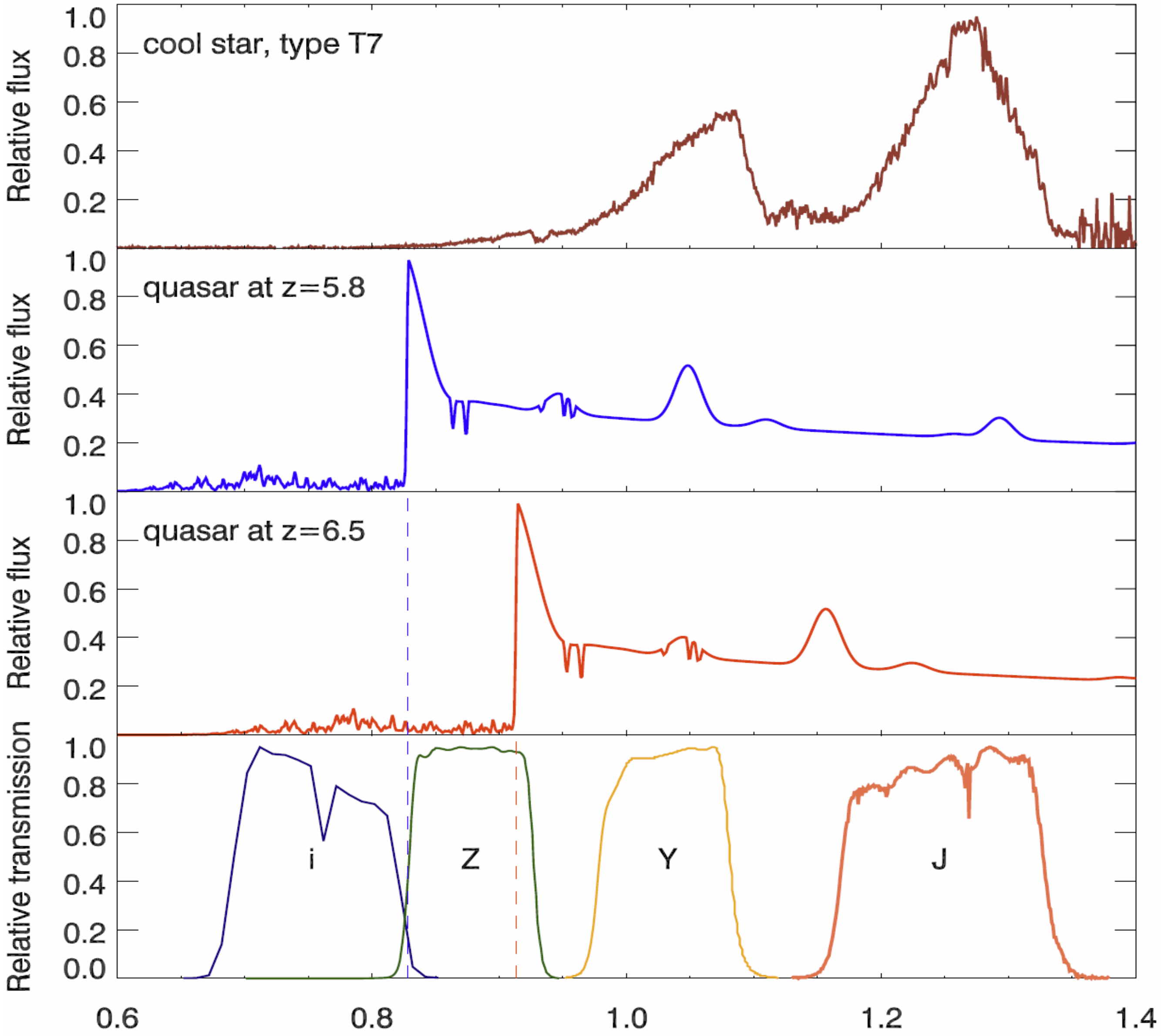
Cool stars --- peaked at long wavelengths (IR); molecular lines/bands



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

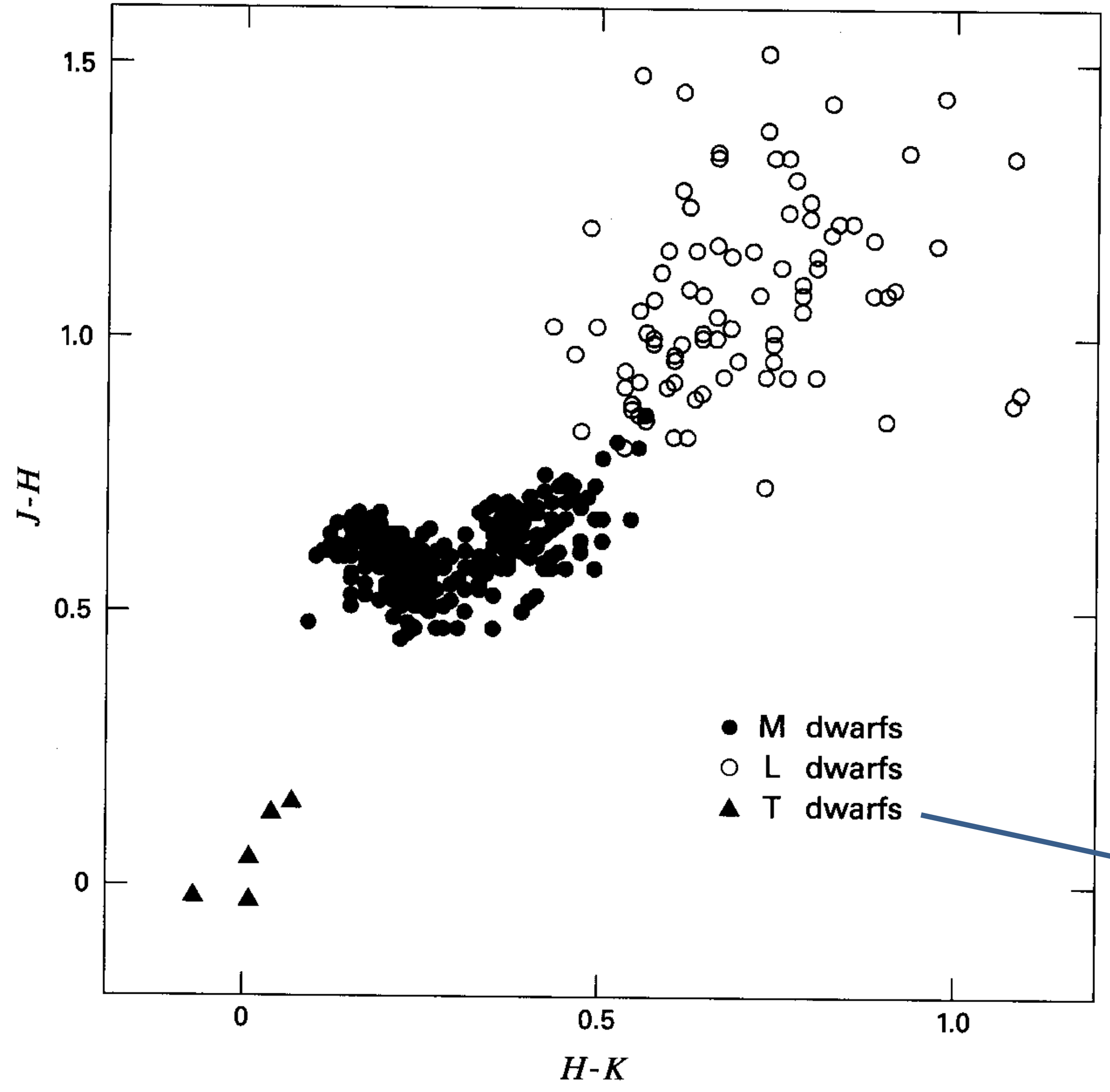


Figure 16.15 Near-infrared color-color plot of M dwarfs (*filled circles*), L dwarfs (*open circles*), and T dwarfs (*filled triangles*). The objects are from a variety of regions. Note that the typical measurement errors for the L- and T-dwarfs are quite large, about 0.13 mag.

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

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

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

- **Bolometric magnitude** – the absolute magnitude integrated over all wavelengths. We define the bolometric correction

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

- **Bolometric Correction** $\boxed{BC = M_{bol} - M_v}$

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 $m = -2.5\ \log\ (\mathrm{Flux}) + \mathrm{ZeroPoint}$

- 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: $\boxed{\mathrm{AB}_\nu = -2.5\ \log_{10} f_\nu - 48.60}$
- STMAG system: used for HST photometry

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

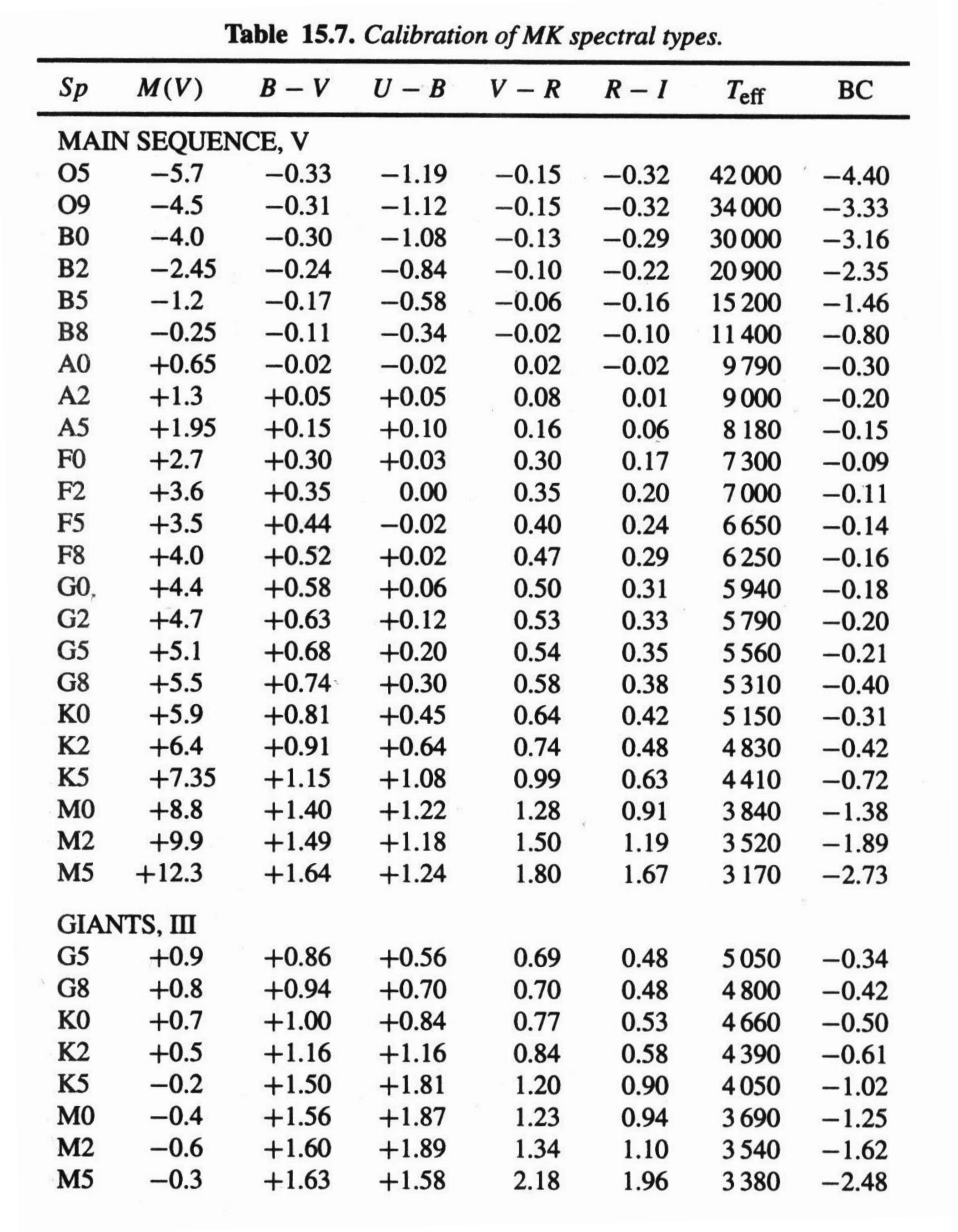


Table 15.7. *Calibration of MK spectral types.*

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

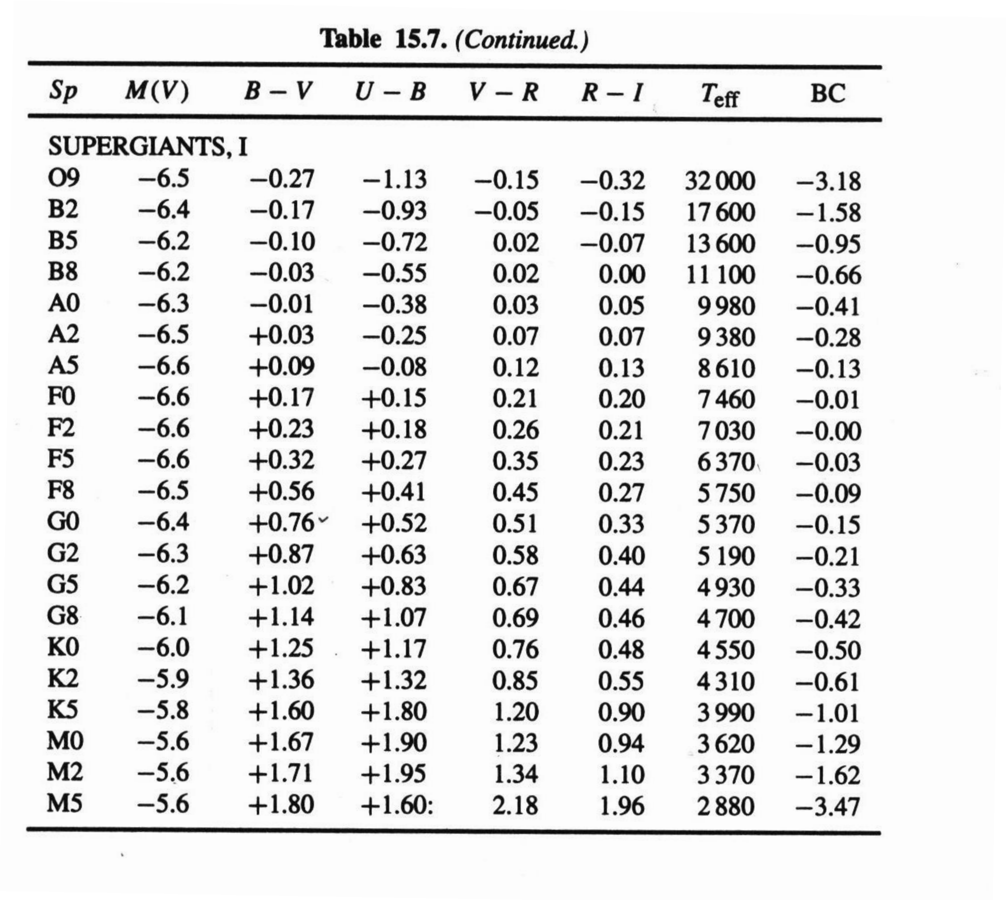


Table 15.7. *(Continued.)*

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

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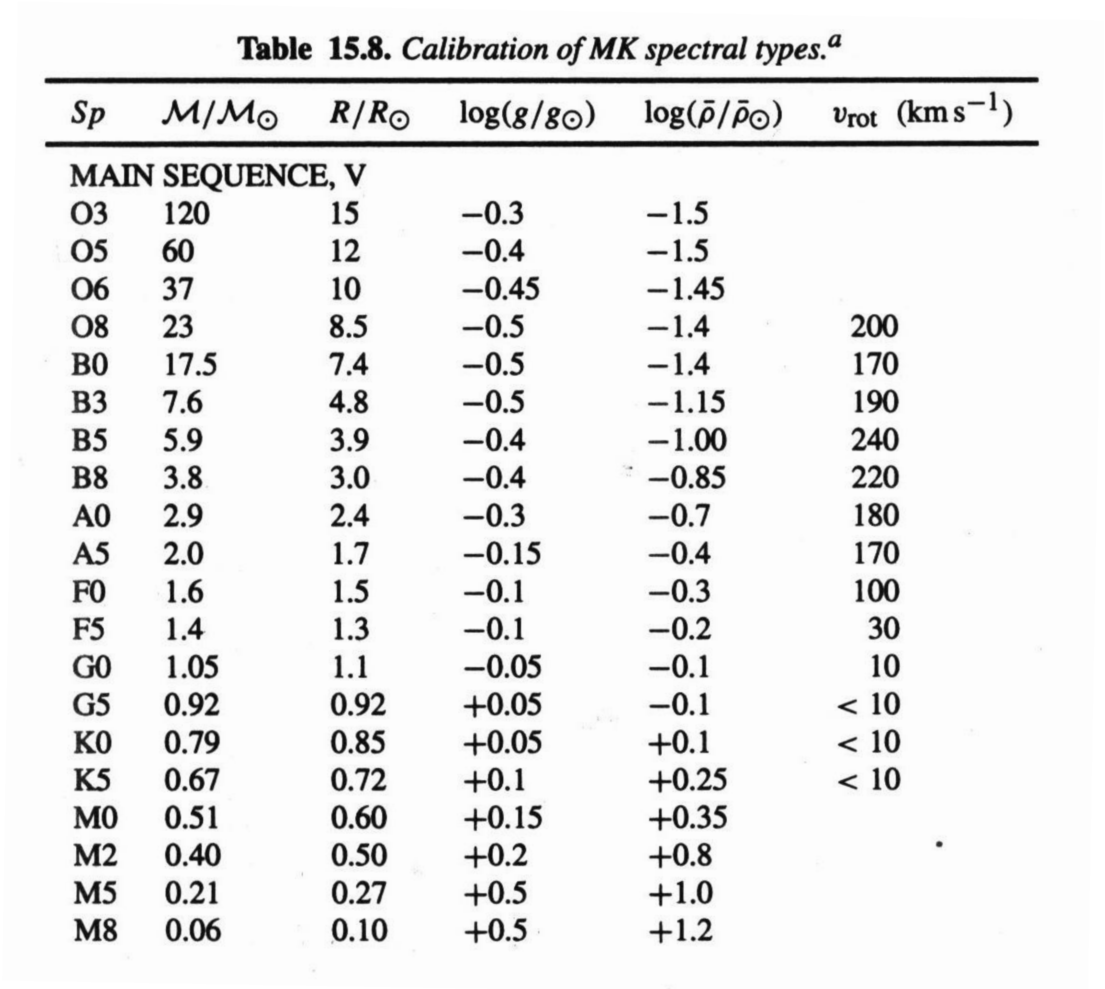

Table 15.8. *Calibration of MK spectral types.*[a]

Sp	$\mathcal{M}/\mathcal{M}_\odot$	$R/R_\odot$	$\log(g/g_\odot)$	$\log(\bar\rho/\bar\rho_\odot)$	$v_{\rm rot}$ (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	

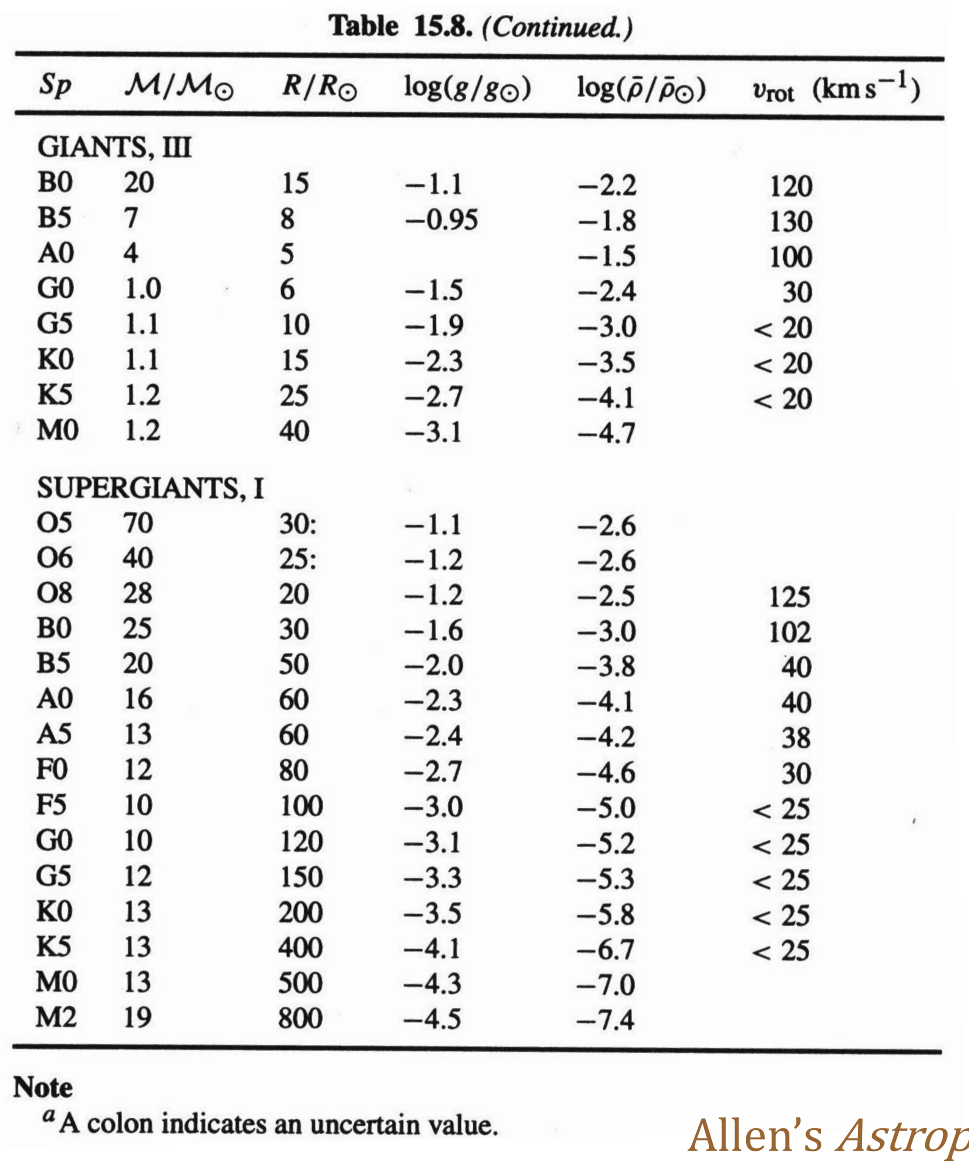

Table 15.8. *(Continued.)*

Sp	$\mathcal{M}/\mathcal{M}_\odot$	$R/R_\odot$	$\log(g/g_\odot)$	$\log(\bar\rho/\bar\rho_\odot)$	$v_{\rm rot}$ (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.

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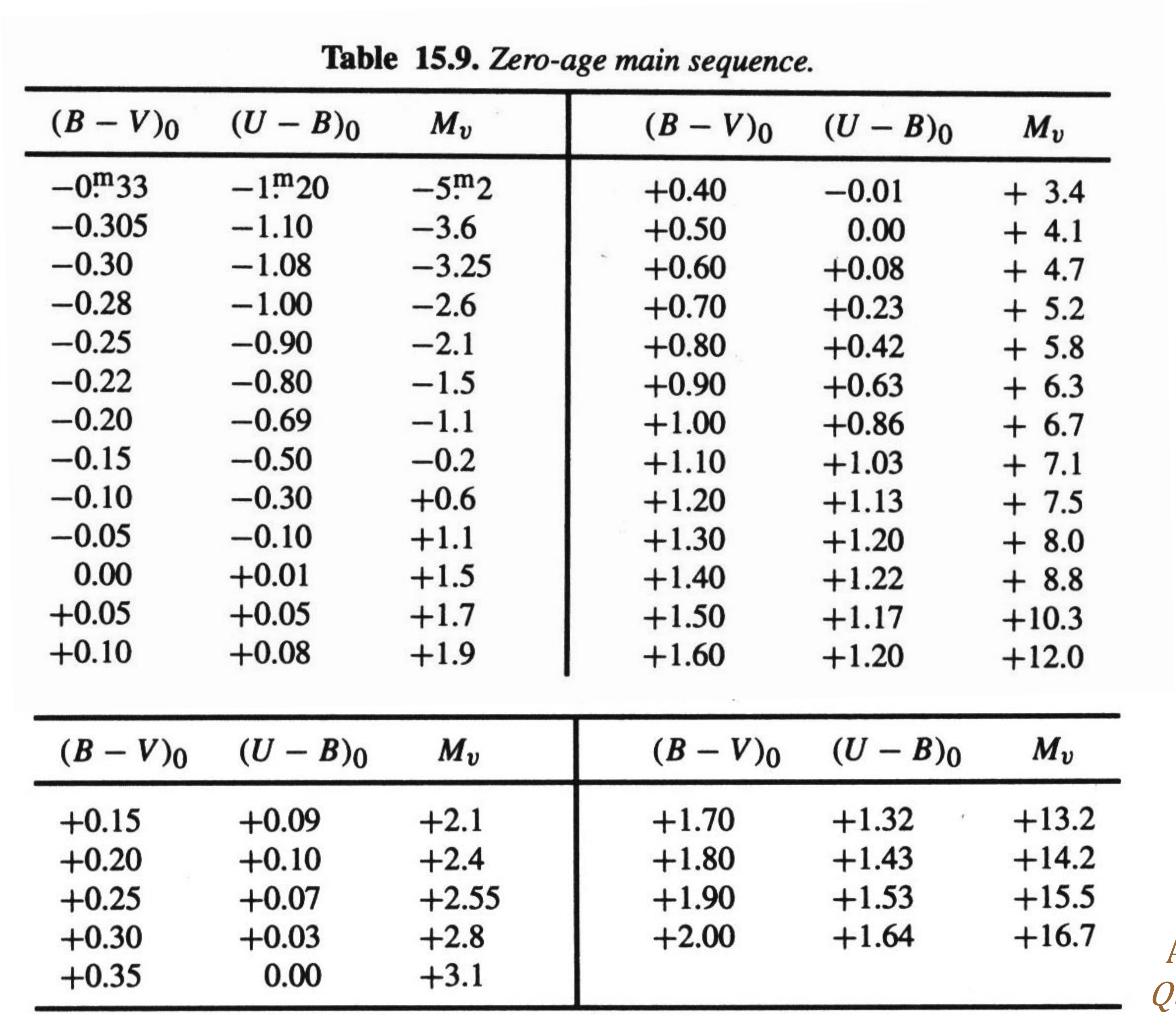

Table 15.9. *Zero-age main sequence.*

$(B-V)_0$	$(U-B)_0$	M_v
$-0\overset{\text{m}}{.}33$	$-1\overset{\text{m}}{.}20$	$-5\overset{\text{m}}{.}2$
−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

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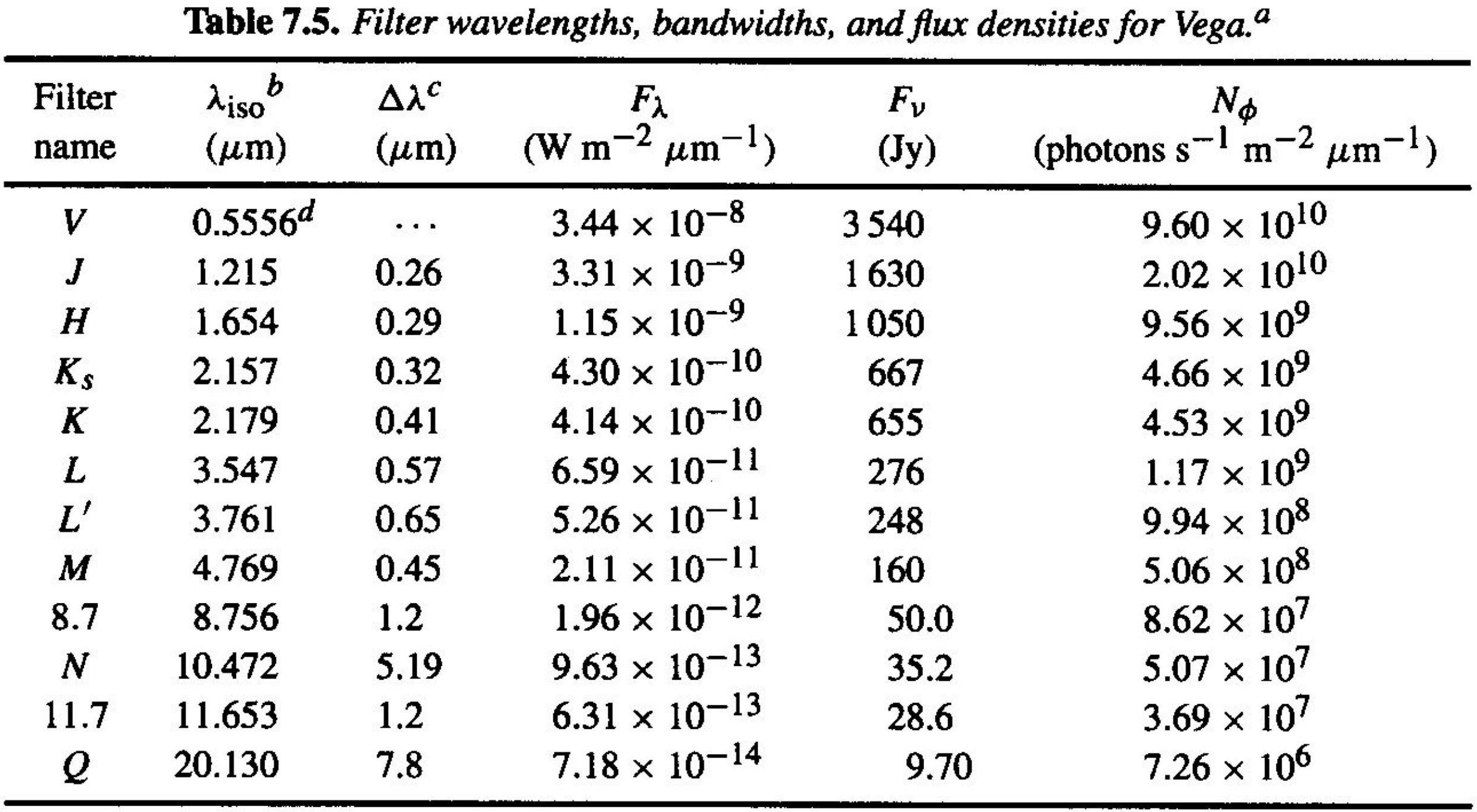

Table 7.5. *Filter wavelengths, bandwidths, and flux densities for Vega.*[a]

Filter name	$\lambda_{\rm iso}$[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}

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

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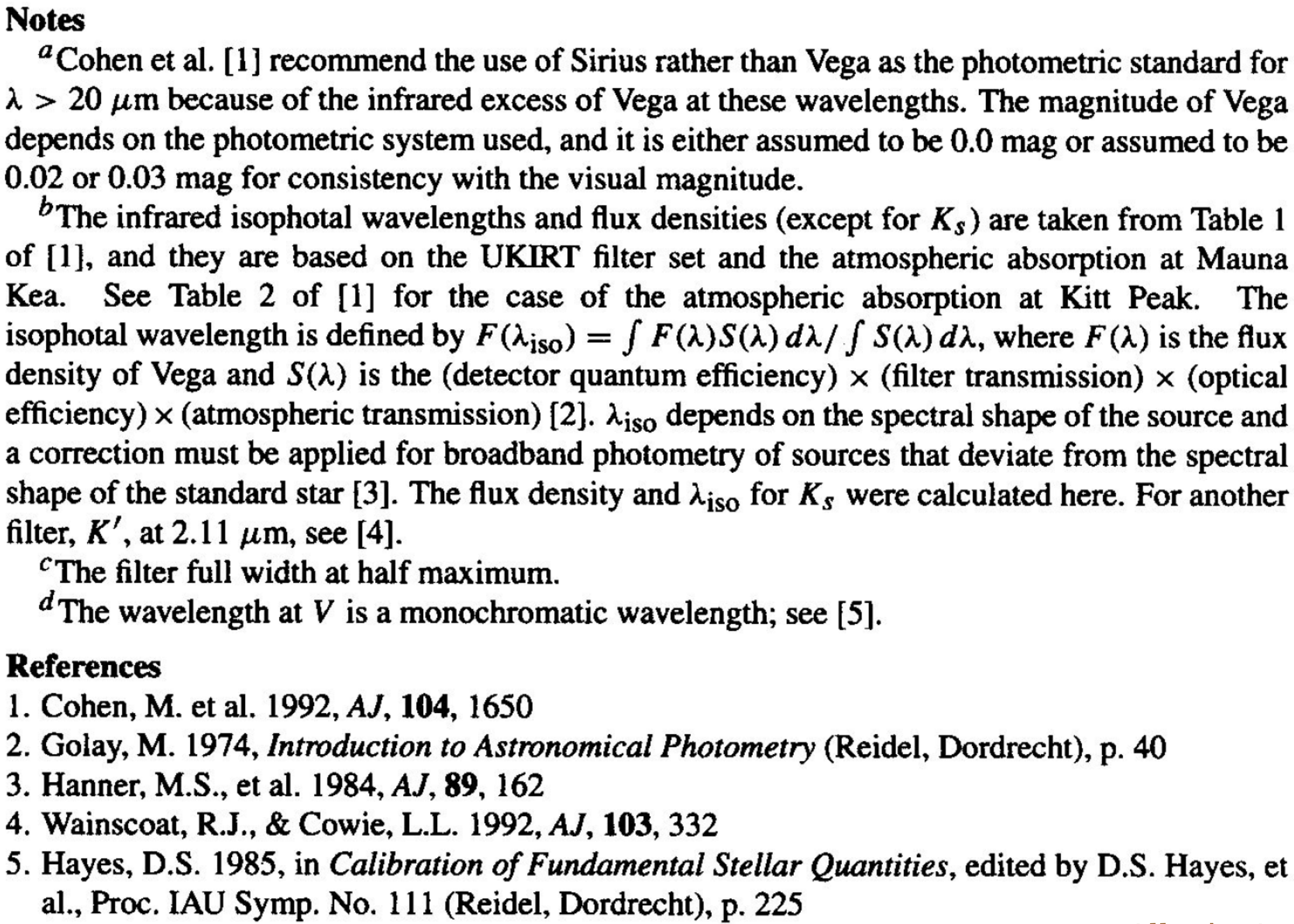
Band	λ_0	$d\lambda/\lambda$	f_ν (m=0)	Reference
	μm		Jy	
U	0.36	0.15	1810	Bessel (1979)
B	0.44	0.22	4260	Bessel (1979)
V	0.55	0.16	3640	Bessel (1979)
R	0.64	0.23	3080	Bessel (1979)
I	0.79	0.19	2550	Bessel (1979)
J	1.26	0.16	1600	Campins, Reike, & Lebovsky (1985)
H	1.60	0.23	1080	Campins, Reike, & Lebovsky (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 $F(\lambda_{\text{iso}}) = \int F(\lambda)S(\lambda)\,d\lambda / \int S(\lambda)\,d\lambda$, 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

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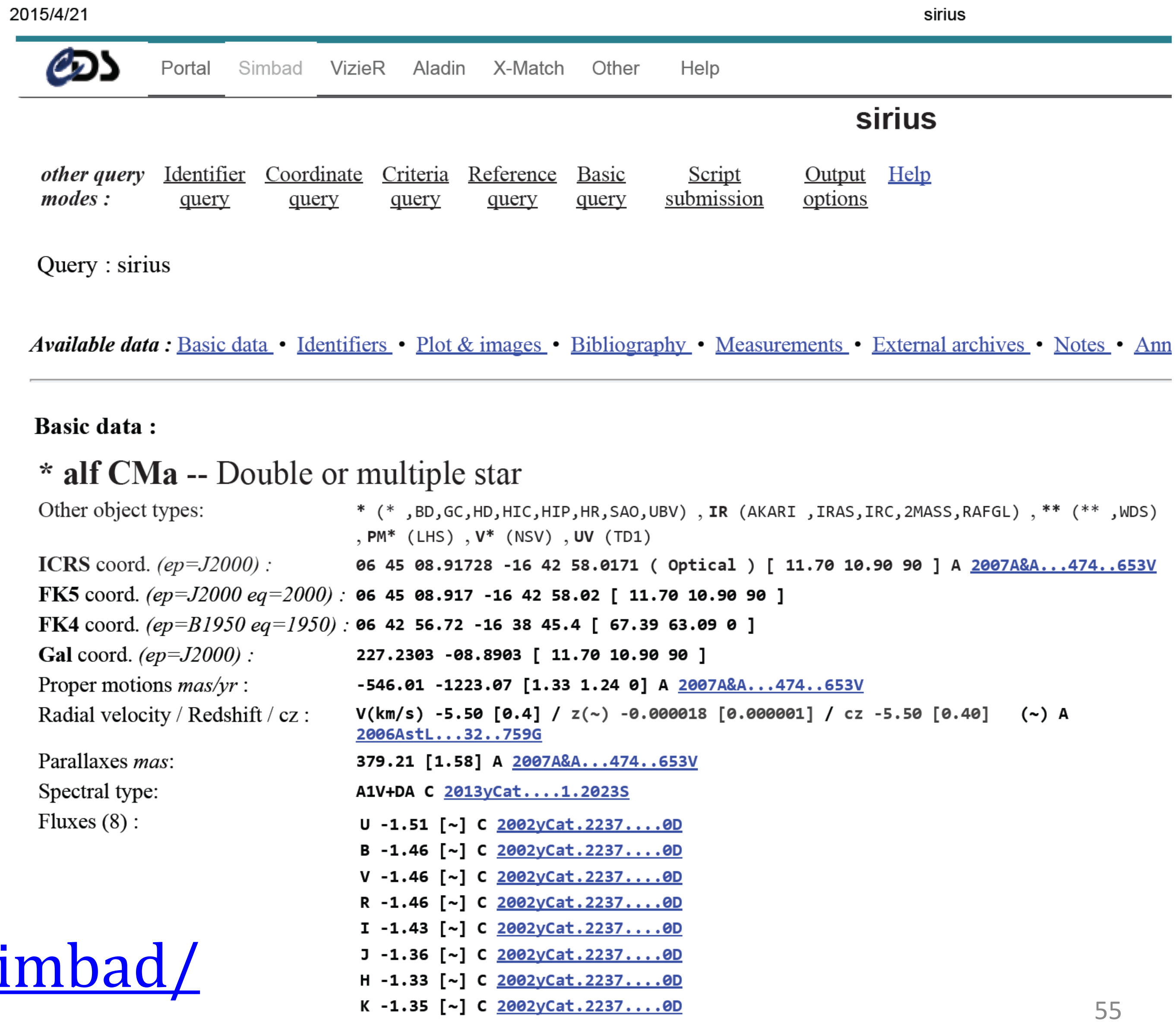
Exercise

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 $0.379''/\mathrm{yr}$.

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?

SIMBAD Astronomical Database



2015/4/21 sirius

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`

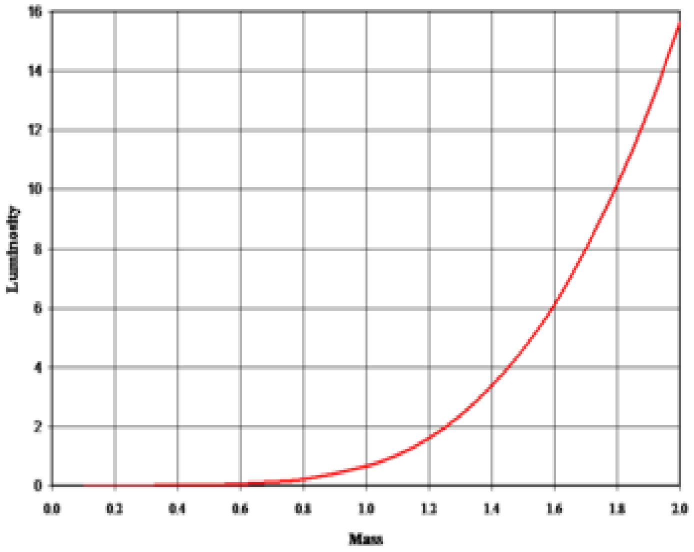
Fluxes (8) :	`U -1.51 [~] C 2002yCat.2237....0D`
	`B -1.46 [~] C 2002yCat.2237....0D`
	`V -1.46 [~] C 2002yCat.2237....0D`
	`R -1.46 [~] C 2002yCat.2237....0D`
	`I -1.43 [~] C 2002yCat.2237....0D`
	`J -1.36 [~] C 2002yCat.2237....0D`
	`H -1.33 [~] C 2002yCat.2237....0D`
	`K -1.35 [~] C 2002yCat.2237....0D`

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

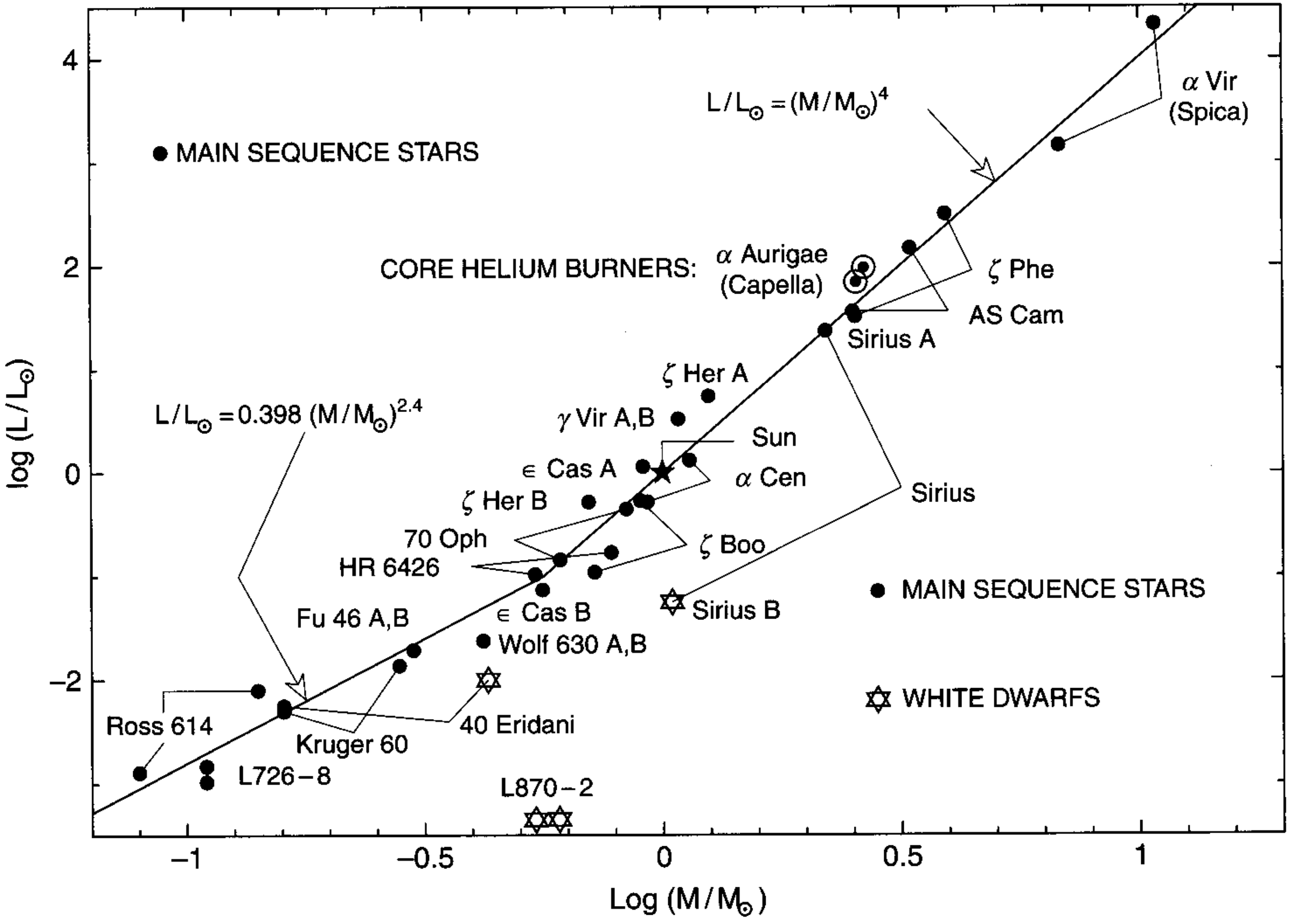
To measure the stellar mass

- 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?



$M_{\max} \sim 120\ M_\odot$
$M_{\min} \sim 0.008\ M_\odot$
$L_{\max} \sim 10^{+6}\ L_\odot$
$L_{\min} \sim 10^{-4}\ L_\odot$



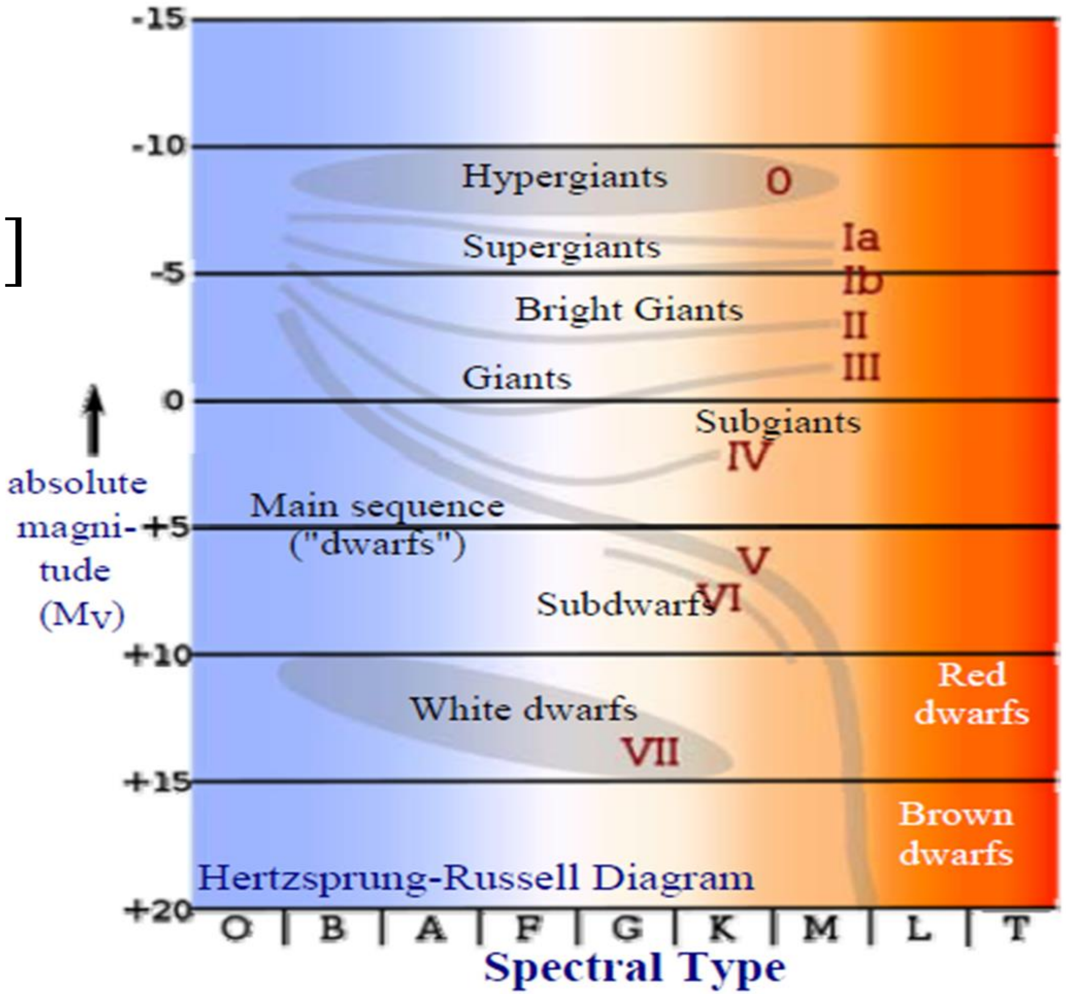
Luminosity versus mass for a selection of stars in binaries

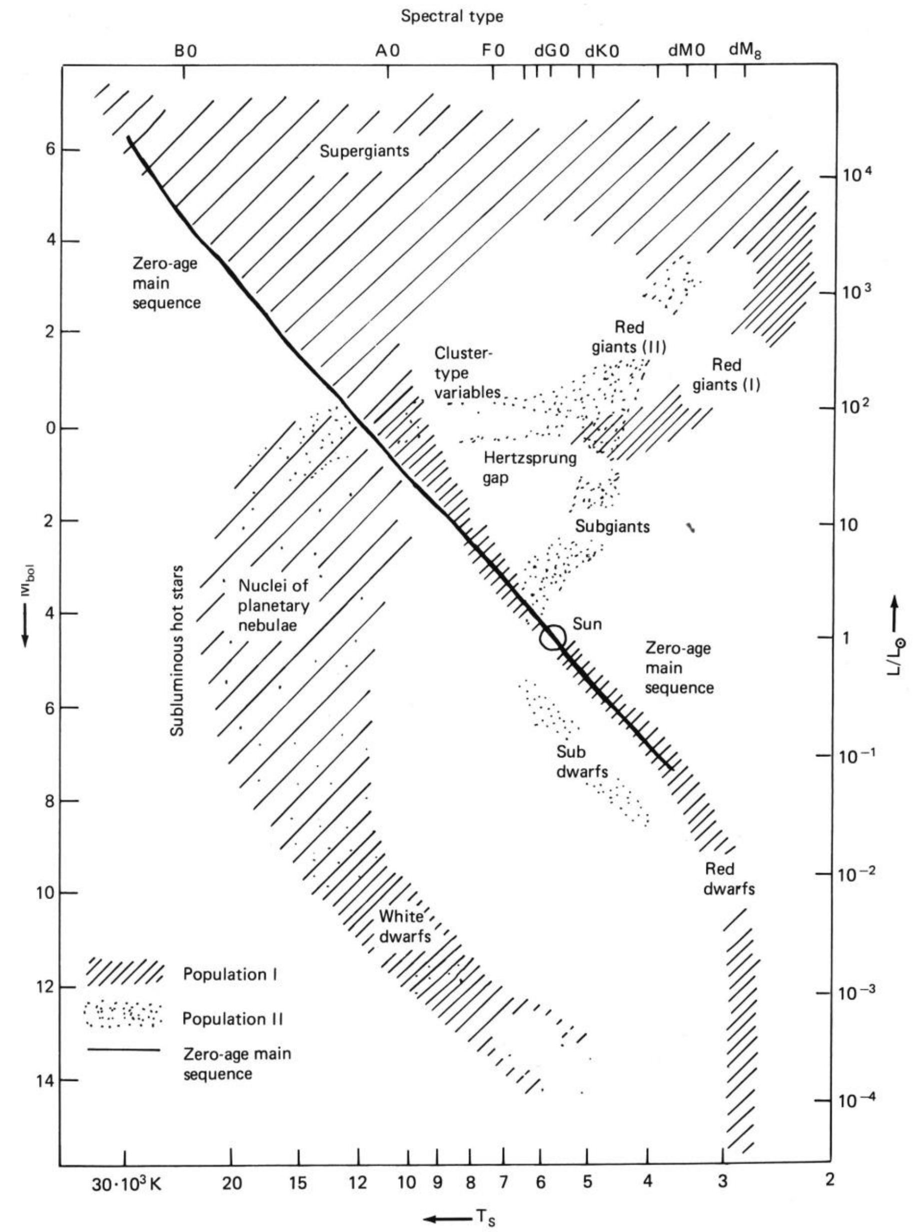
Iben (2013)

Luminosity class and surface gravity

$$\log g \;= \log \mathrm{GM/R^2}$$

- Betelgeuse … (M2 I) $\log g \;\approx -0.6$ [cgs]
- Jupiter … $\log g \;= 3.4$
- Sun (G2 V) … $\log g \;= 4.44$
- $\mathrm{G}\ell 229\mathrm{B}$ … (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

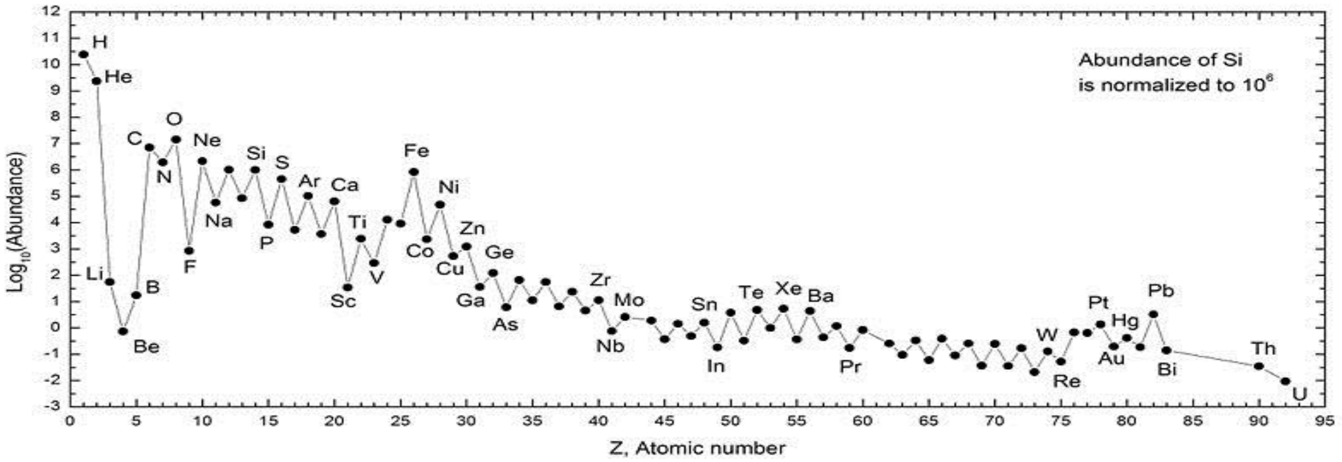
- By spectroscopy
- Stellar composition $X, Y, Z =$ mass fraction of H, He and all other elements ("metals") Z: *metallicity* $X+Y+Z=1$
- Solar abundance: $X_{\odot} = 0.747$; $Y_{\odot} = 0.236$; $Z_{\odot} = 0.017$
- One often compares the iron abundance of a star to that of the sun. Iron is not the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

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

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

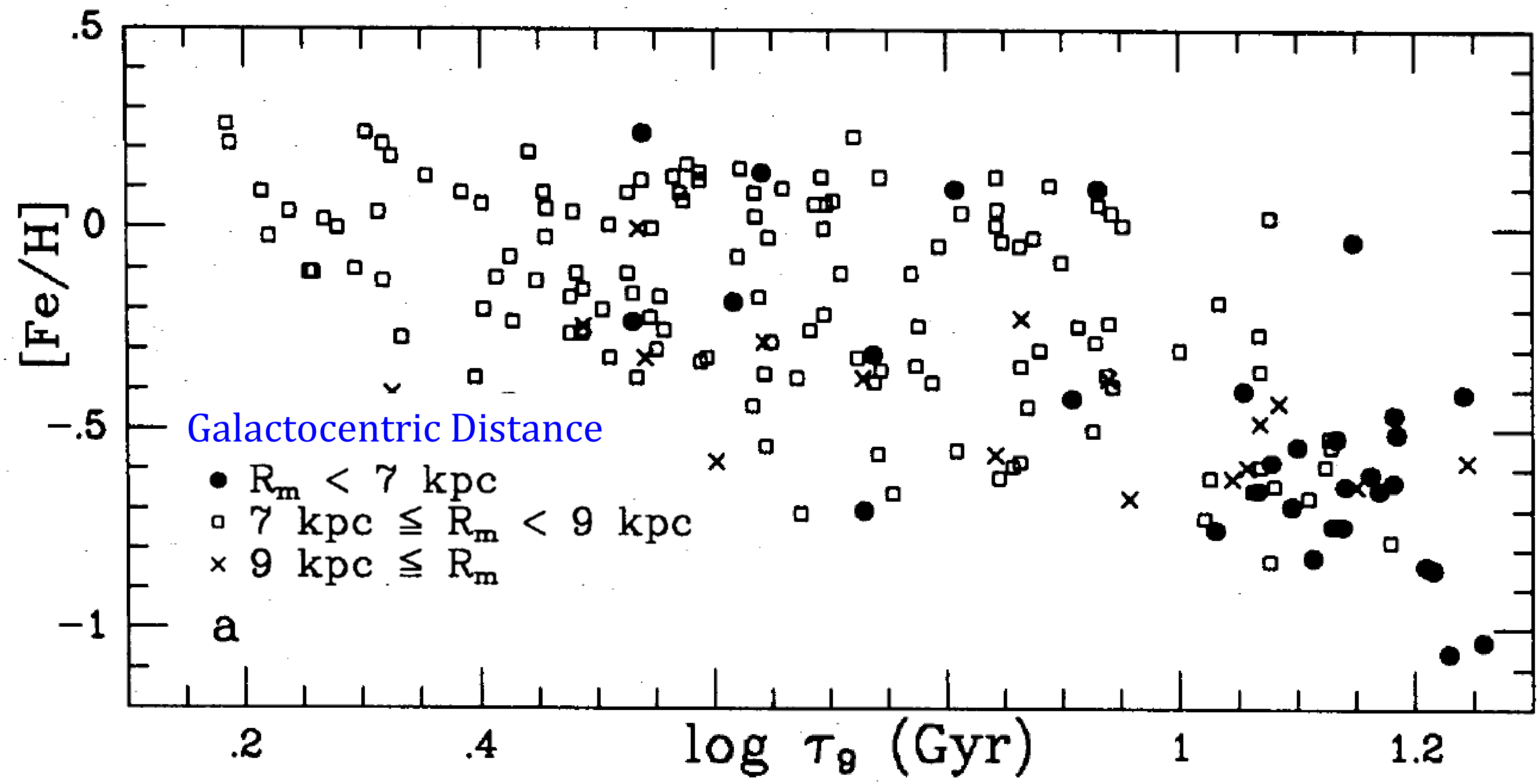
i.e., 1 iron atom for 20,000 H atoms

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

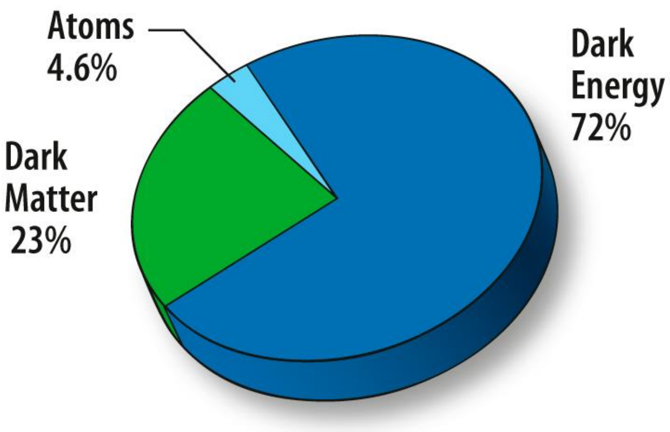


Data from: Katharina Lodders (2003) ApJ, 591, 1220

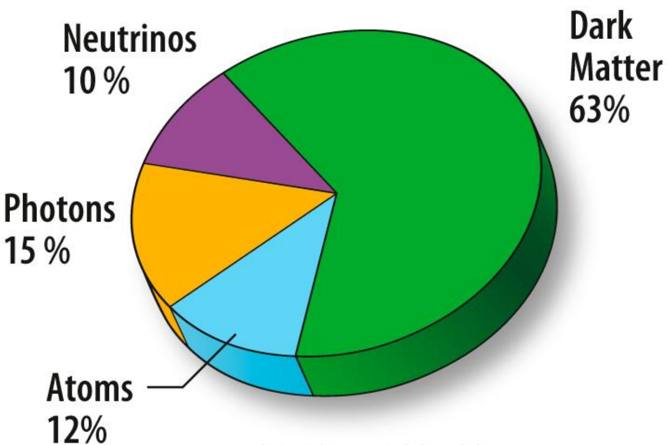
Younger stars tend to be more metal-rich. Stars older than 10 Gyr almost all have [Fe/H] $\lesssim -0.5$; stars younger than 5 Gyr have [Fe/H] $\gtrsim -0.5$.



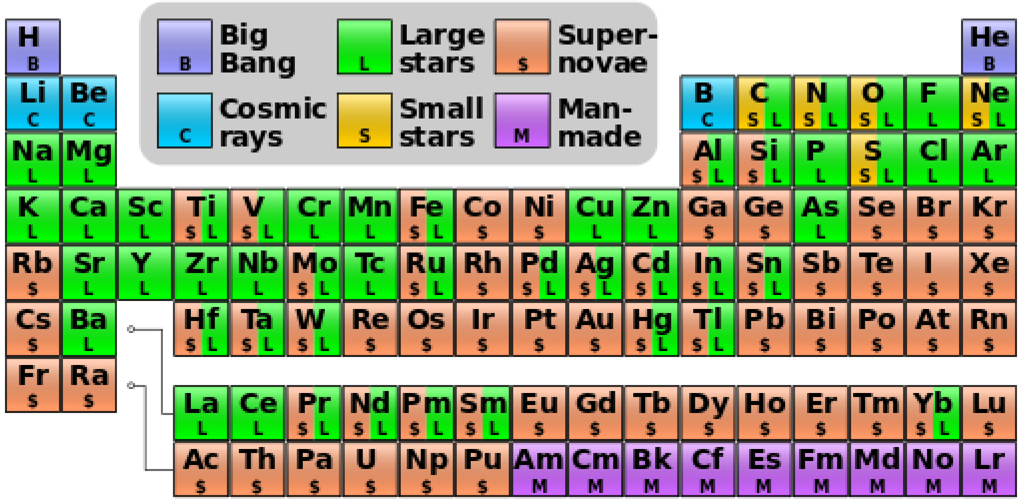
Edvardsson et al. (1993)



TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)



B Big Bang
L Large stars
S Super-novae
C Cosmic rays
S Small stars
M Man-made

H B																	He B
Li C	Be C											B C	C S L	N S L	O S L	F L	Ne S L
Na L	Mg L											Al S L	Si S L	P L	S S L	Cl L	Ar L
K L	Ca L	Sc L	Ti S L	V S L	Cr L	Mn L	Fe S L	Co S	Ni S	Cu L	Zn L	Ga S	Ge S	As L	Se S	Br S	Kr S
Rb S	Sr L	Y L	Zr L	Nb L	Mo S L	Tc L	Ru S L	Rh S	Pd S L	Ag S L	Cd S L	In S L	Sn S L	Sb S	Te S	I S	Xe S
Cs S	Ba L		Hf S L	Ta S L	W S L	Re S	Os S	Ir S	Pt S	Au S	Hg S L	Tl S L	Pb S	Bi S	Po S	At S	Rn S
Fr S	Ra S																
			La L	Ce L	Pr S L	Nd S L	Pm S L	Sm S L	Eu S	Gd S	Tb S	Dy S	Ho S	Er S	Tm S	Yb S L	Lu S
			Ac S	Th S	Pa S	U S	Np S	Pu S	Am M	Cm M	Bk M	Cf M	Es M	Fm M	Md M	No M	Lr M

Cosmic element factories --- the Big Bang, stellar nucleosynthesis, and supernova explosion

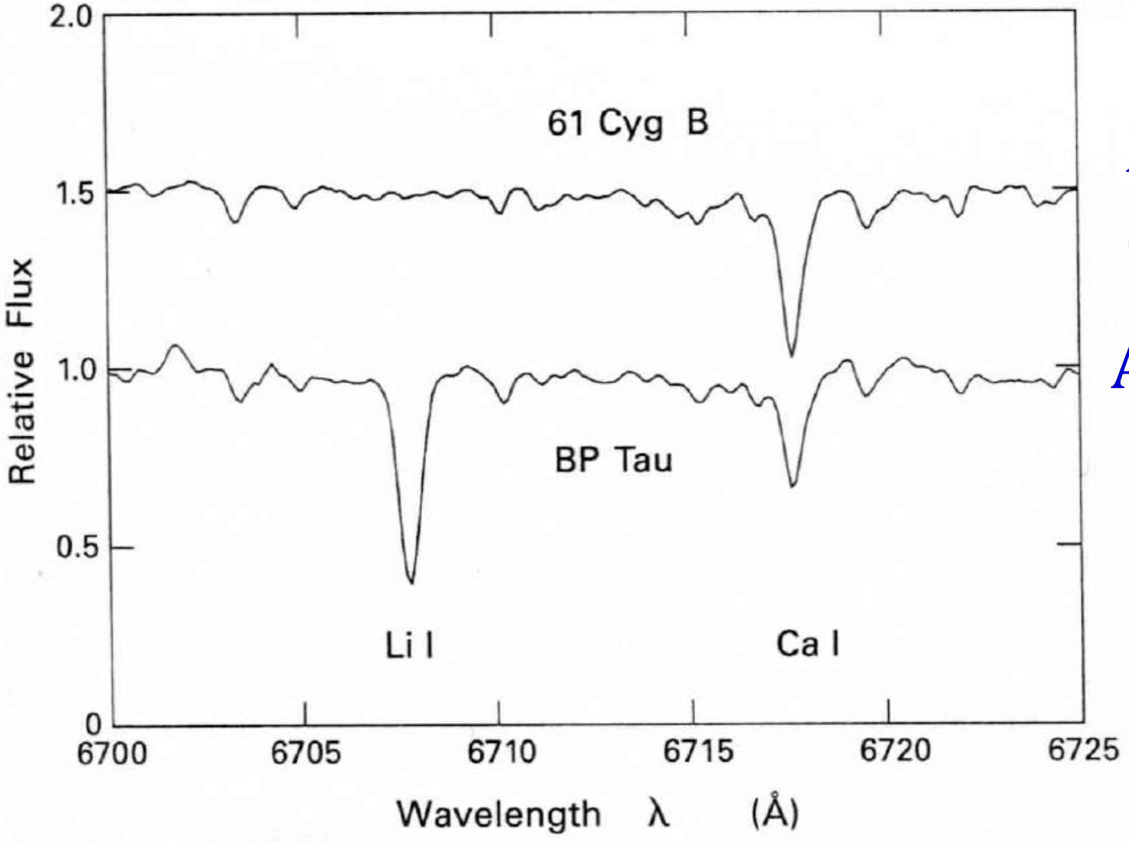
http://en.wikipedia.org/wiki/Abundance_of_the_chemical_elements

To measure the stellar age

- ◆ Very tricky. Often one relies on measurements of M_V, $T_{\rm eff}$, [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



An MS star of the same spectral type

A PMS (young) star

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.

Stahler

Stellar Formation and Evolution

Problem Set #170307, due in two weeks

1. A globular cluster has a total of 10^5 stars; 100 of them have Mv=0.0 mag and the rest have Mv=+5.0 mag. What is the integrated visual magnitude of the cluster?

2. An F0 star at a distance of 25 pc is measured to have an apparent V magnitude of 7.5 mag. Determine for the star its V-band absolute magnitude, distance modulus, bolometric apparent and absolute magnitudes, and luminosity. The star later was resolved to be a pair of stars with a magnitude difference of 3.0. Drive the apparent magnitude of each component star.

3. A star of mass M and a homogeneous composition assumes a density of a radial dependence, $\rho(r) = \rho_0 (1 - r/R_0)$, where ρ_0 is the central density, and R_0 is the radius of the star. (a) Find $m(r)$. (b) Find the relation between M and R_0. (c) Derive and plot the pressure as a function of radius. (d) What is the central temperature?

4. (a) What is the spectral type of the star Vega? What is its expected surface temperature? (b) List the brightness of the star Vega from optical (UBVRI) to near-infrared (JHKL) to mid- and far-infrared wavelengths (12, 25, 60 and 100 microns). (c) Plot its spectral-energy distribution and compare with that of a blackbody radiating with the surface temperature.

ABSOLUTE FLUX CALIBRATED SPECTRUM OF VEGA

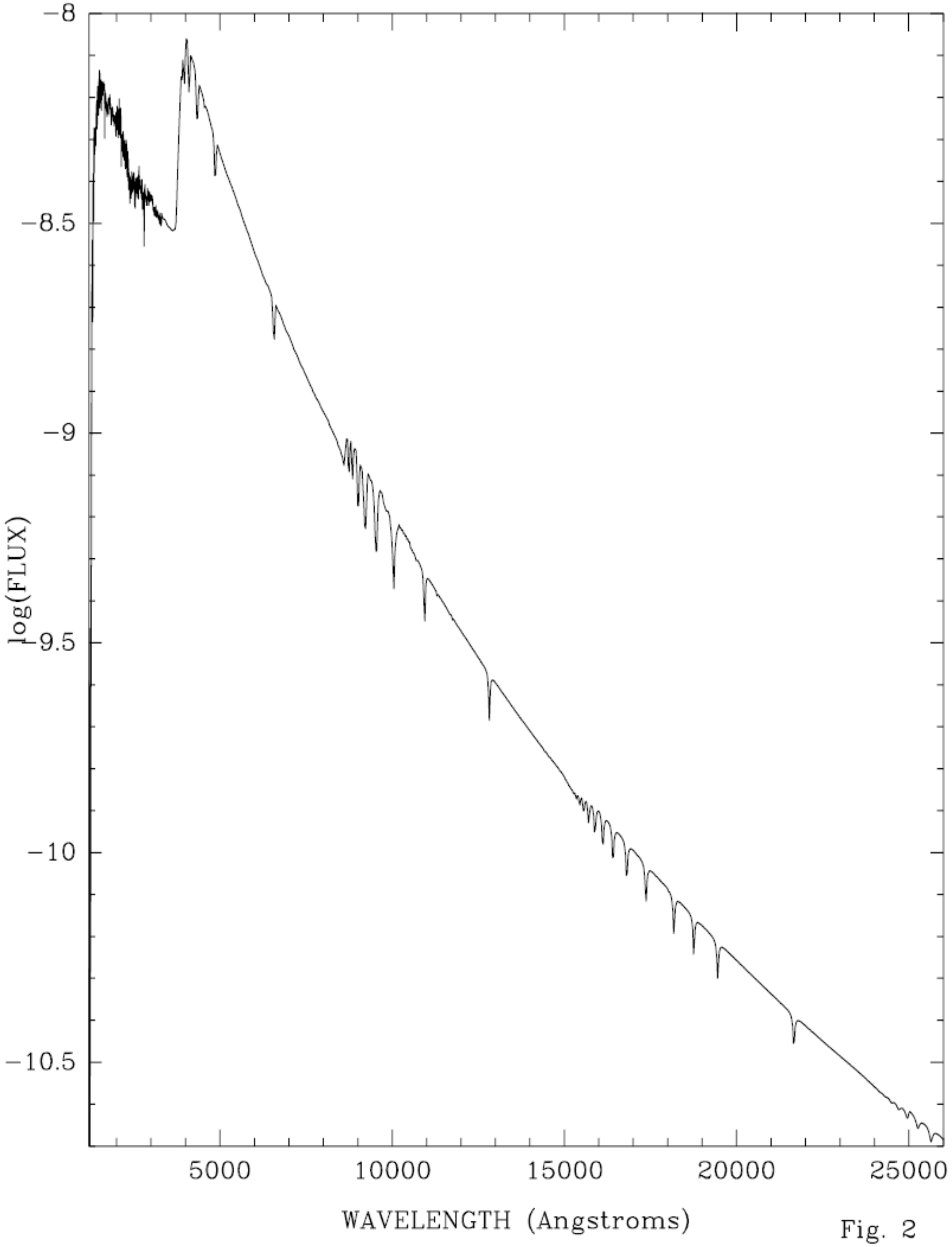
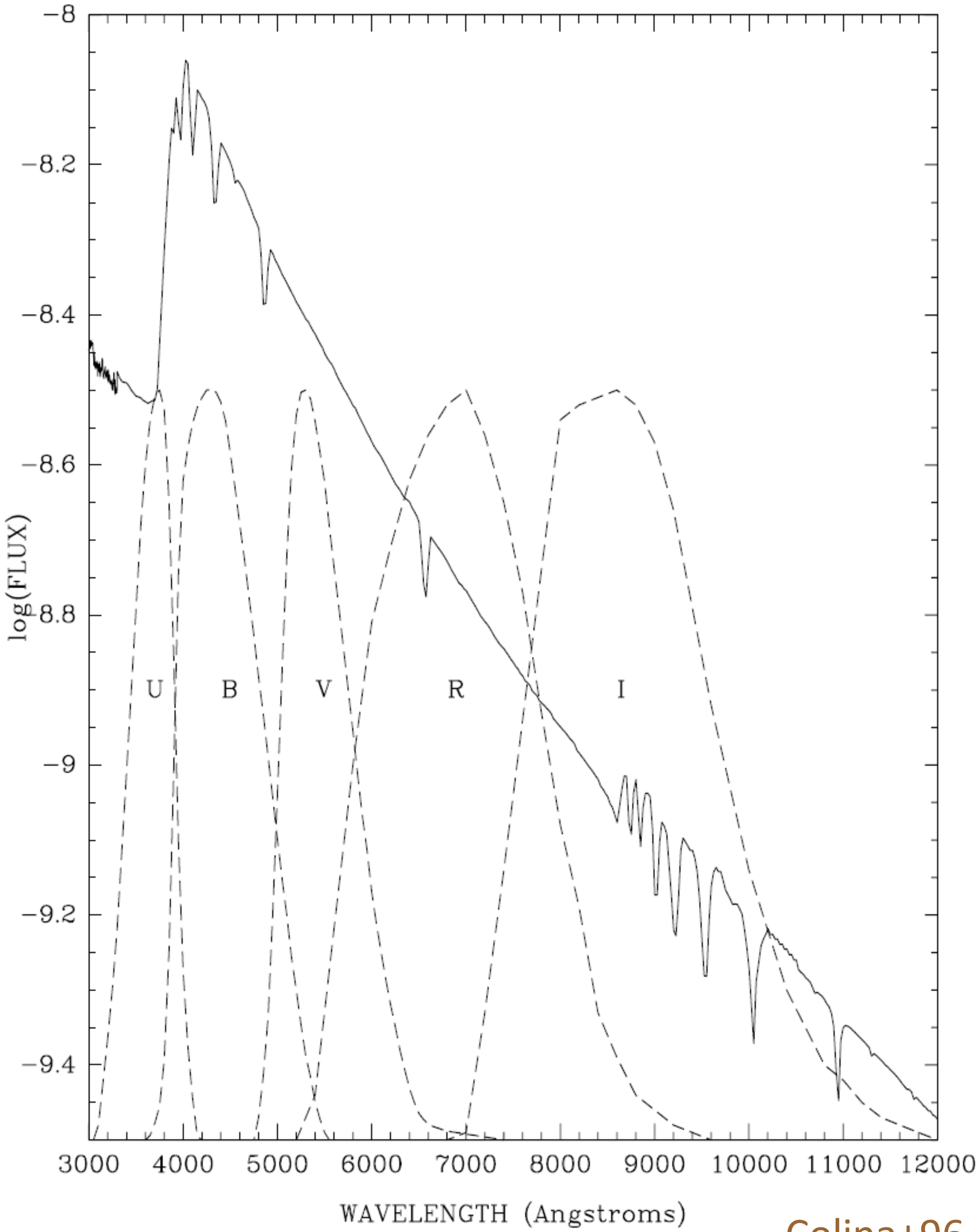
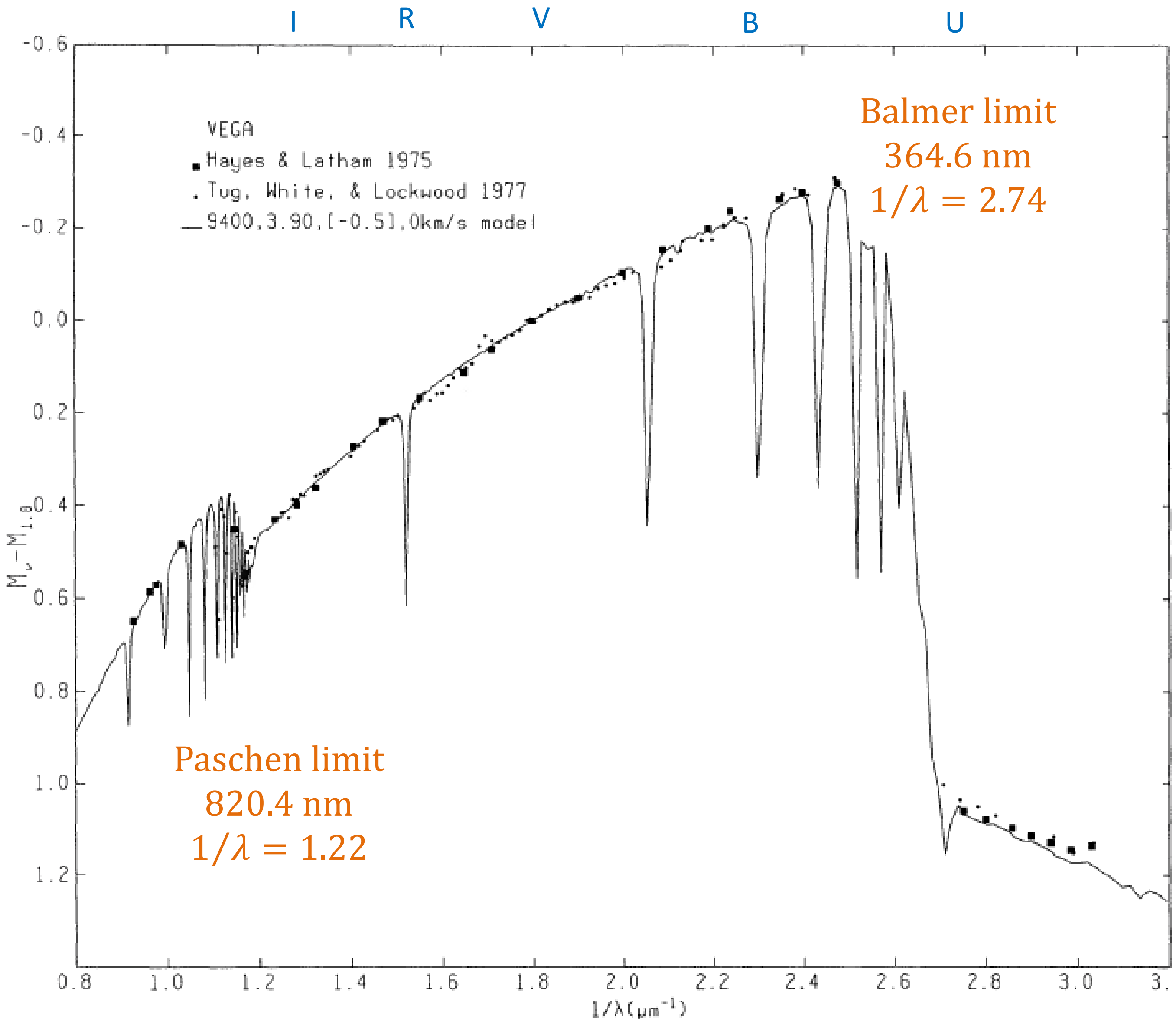


Fig. 2



Colina+96



Balmer limit
364.6 nm
$1/\lambda = 2.74$

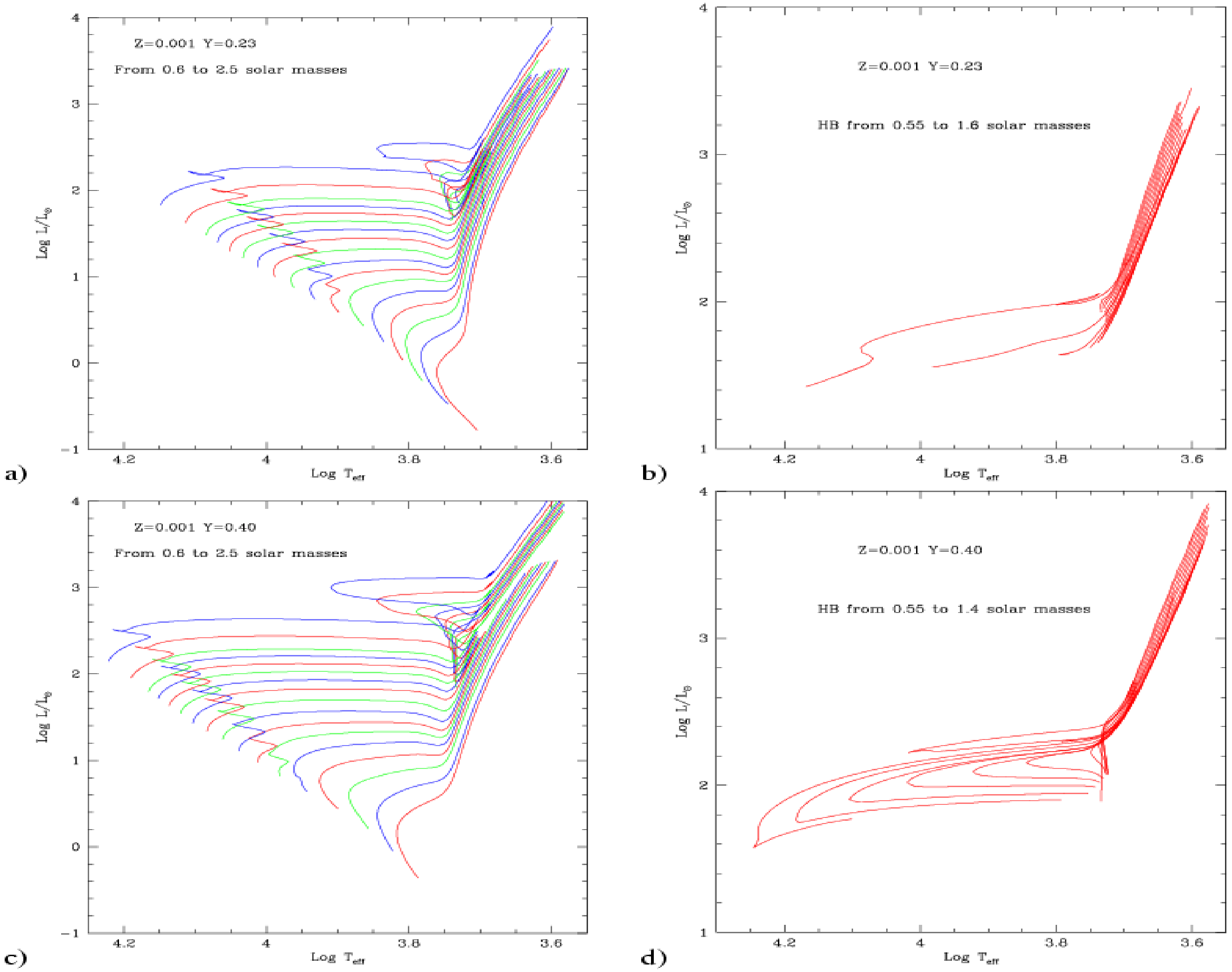
Paschen limit
820.4 nm
$1/\lambda = 1.22$

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)

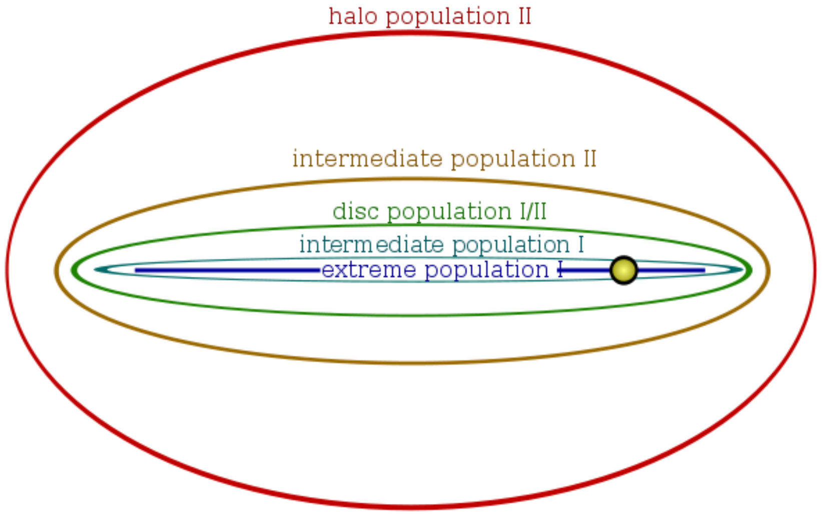


Bertelli et al, 2008, A&A, 484, 815

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

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

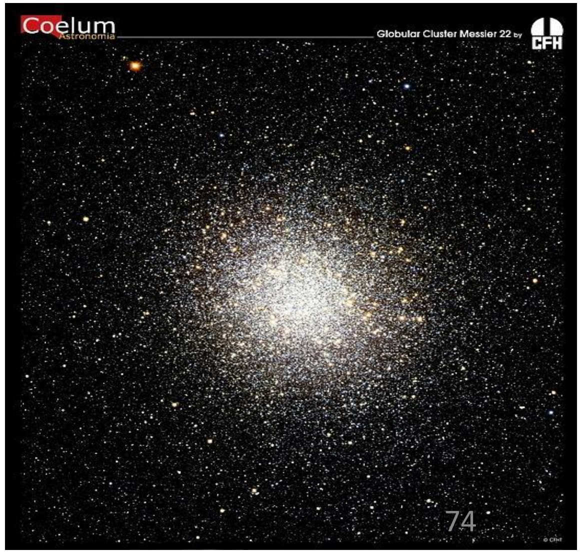
Star clusters are good laboratories to study stellar evolution, because member stars in a star cluster

- are (almost) of the same age;
- are (almost) at the same distance;
- evolve in the same Galactic environments;
- have the same chemical composition;
- are dynamical bound.

Two distinct classes:

- ✓**globular clusters** (100+ in the MW)
- ✓**open clusters** (a few 10^3 known in the MW)

How do these two classes differ in terms of shape, size, spatial distribution, number of member stars, and stellar population?



Open Clusters

10^2 to 10^3 member stars; $\sim$10 pc across; loosely bound; open shape;
young population I;
located mainly in spiral arms;
$>$1000 open clusters known in the MW

Globular Clusters

10^5 to 10^6 member stars; up to 100 pc across; tightly bound;
centrally concentrated;
spherical shape; old population II;
located in the Galactic halo;
200 globular clusters known in the MW

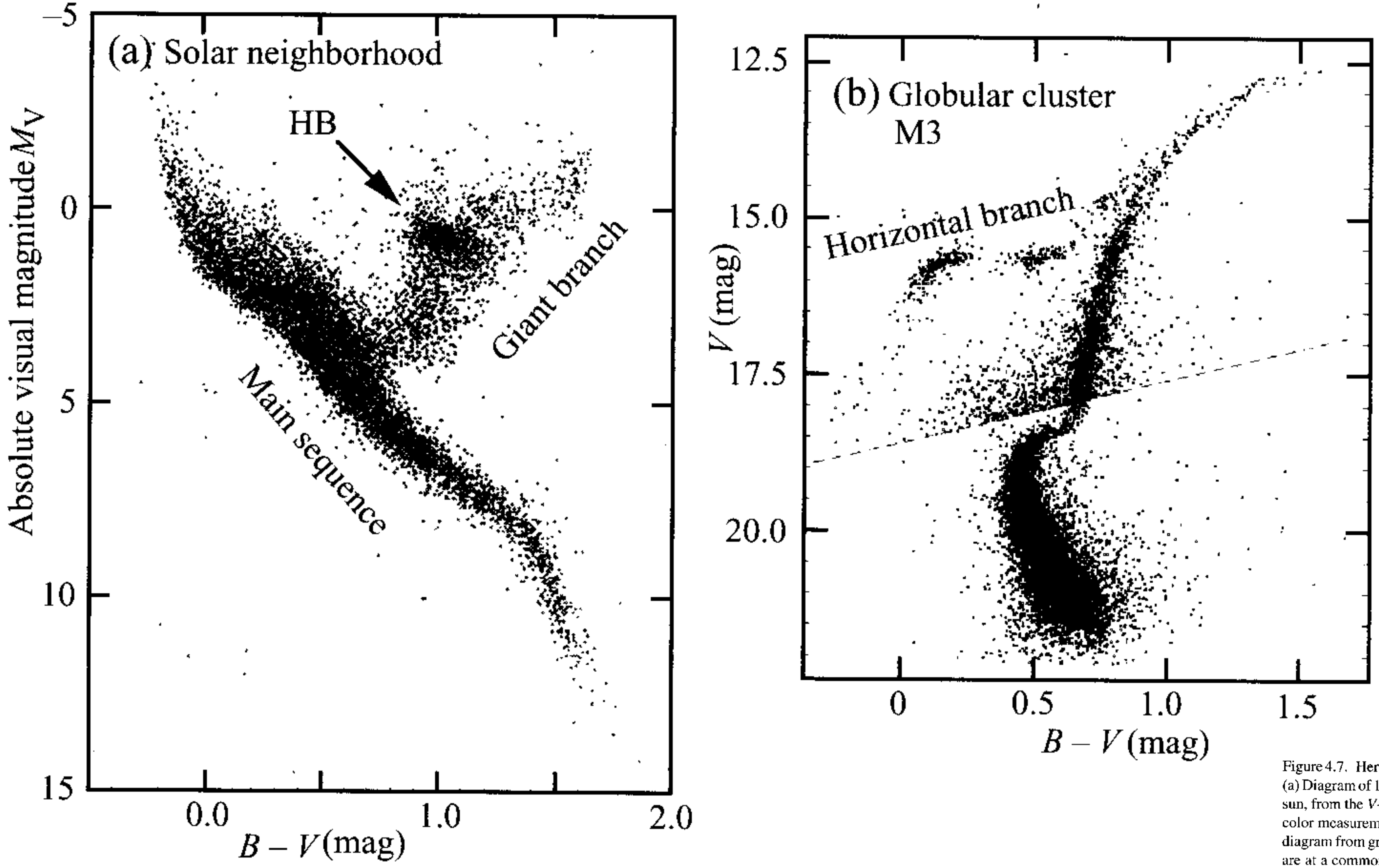
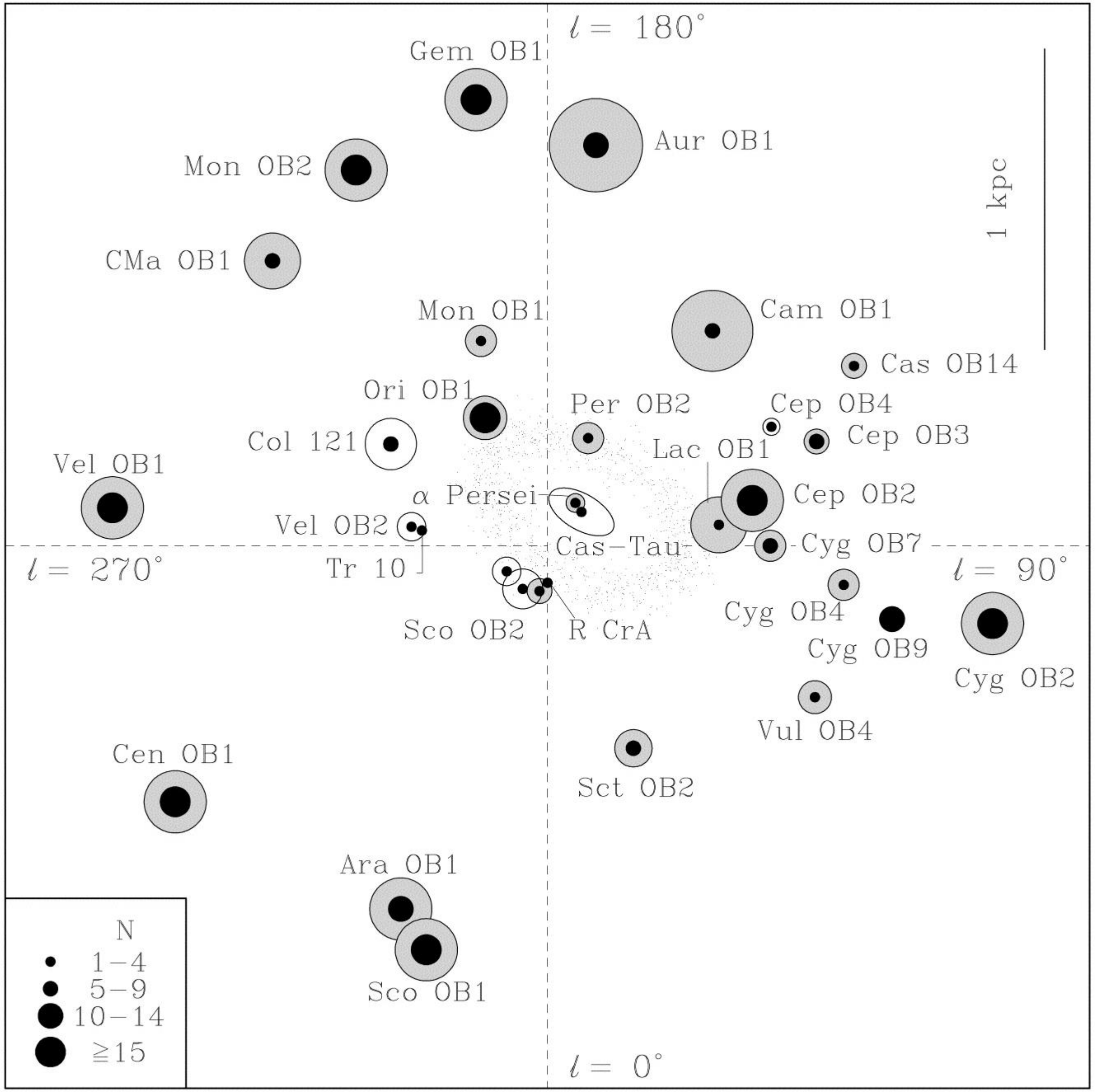


Figure 4.7. Hertzsprung–Russell color-magnitude diagrams for two very different samples of stars. (a) Diagram of 16 631 stars of various ages and various distances that are within about 330 LY of the sun, from the V-band and parallax distance measures by the Hipparcos satellite and ground-based color measurements. Horizontal-branch (HB) stars overlie the giant branch. (b) Color-magnitude diagram from ground-based studies of ~12 200 stars in globular cluster M3. The stars in the cluster are at a common distance of ~32 000 LY, and thus apparent magnitudes suffice for the ordinate of this H-R diagram. The stars are mostly of the common age of ~12 Gyr. The data come in two distinct samples. A deep photographic sample yields most of the stars in the diagram both above and below the diagonal line. Short exposures with a charge-coupled device (CCD) camera provide fluxes for the rarer brighter stars plotted only above the dashed line representing $B = 18.6$. The scatter just above the diagonal line is mostly due to increased uncertainty at the fainter end of the CCD sample. The distance modulus of M3 is 14.93. Thus, $M_V = 0$ in (a) corresponds to $V = 14.93$ in (b). Note the absence of bright main-sequence stars in M3 and also the well-defined horizontal branch. [(a) ESA SP-1200, Hipparcos catalog (1997) in J. Kovalevsky, *ARAA* **36**, 121 (1998); (b) F. Ferraro *et al.*, *A&A* **320**, 757 (1997); photographic data from R. Buonanno *et al.*, *A&A* **290**, 69 (1994)]

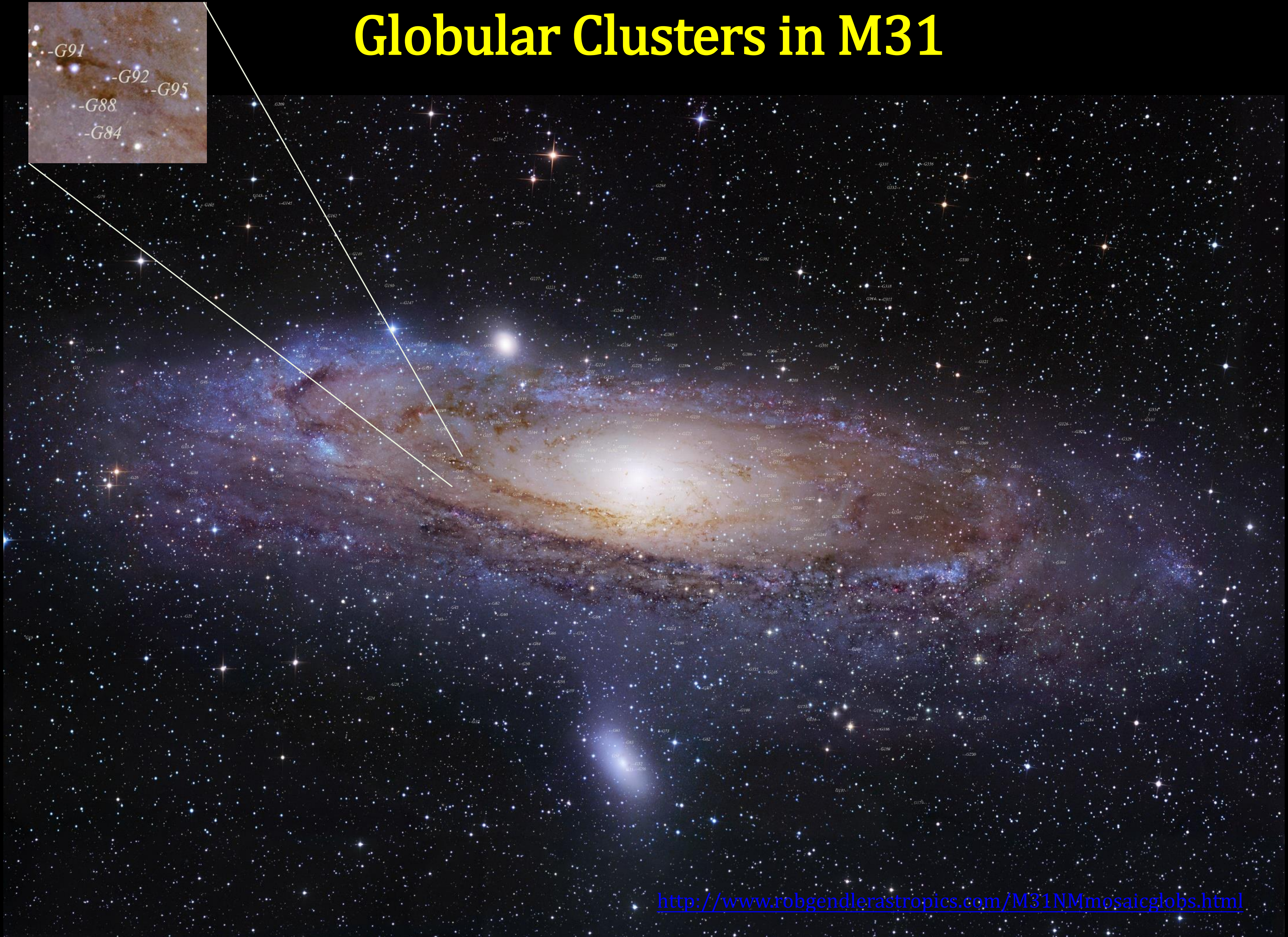
Bradt “Astrophysics Processes”

OB associations in the solar neighborhood



De Zeeuw +1999

Globular Clusters in M31



http://www.robgendlerastropics.com/M31NMmosaicglobs.html