Stellar Atmosphere and Structure
“Stars”

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

Stellar Atmosphere and Structure ---

Instructor: Professor Wen-Ping Chen

Class Time: Thursday 2 to 5 pm

Classroom: Room 914; online

Office: S4, Room 906

Office Hours: Please check my schedule posted on my door

This course covers the interior structures and atmospheres of stars. We will discuss the important physical processes governing the stability of a star ("stellar structure") and how emerging photons interact with the stellar atmosphere that we observe to derive the stellar parameters. We will deal with the "static" stellar properties, but not the formation processes or how these properties evolve with time, i.e., stellar evolution, which will be the subjects of the subsequent course in the next semester.

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

In addition to the midterm (30% grade) and final (30%) exams, there will be homework assignments, plus in-class exercises and perhaps projects (40%).

For numerical modeling of atmospheres or interiors --- at least for some of the homework problems --- simple computer coding is required.

. Stellar Observational Properties; Gas Properties

. Radiative Transfer
  Blackbody Radiation
  Emission, Absorption, and Source Function
  Equation of Transfer and its Solutions/Approximations

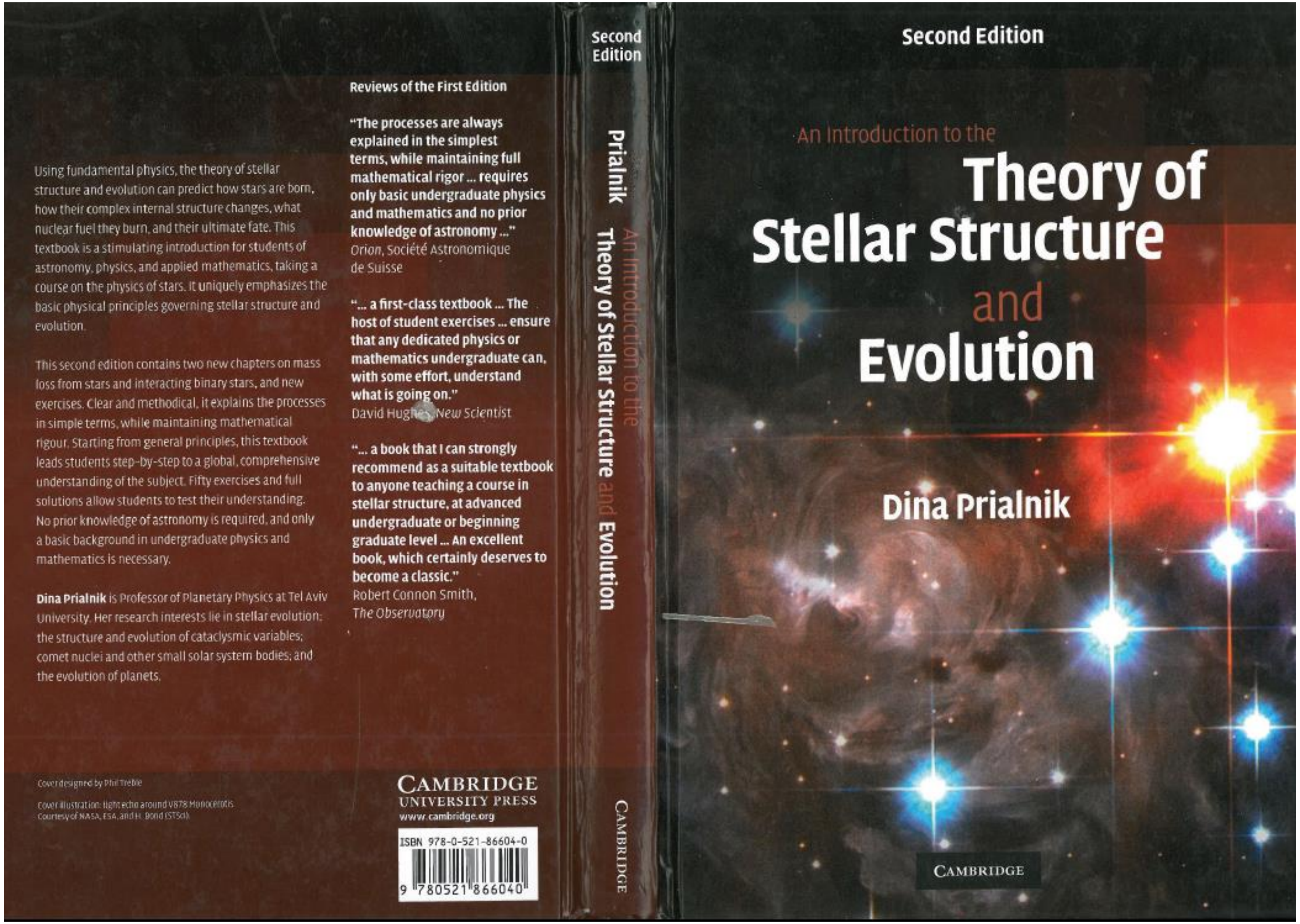
. Stellar Atmospheres
  Opacities (Kramers, Rosseland)
  Equations of State
  Absorption and Spectral Lines
  Line Formation

. Stellar Interiors
  Hydrostatic Equilibrium
  Mass Distribution
  Lane-Emden Equation
  Radiative, Thermal, and Convective Equilibrium
  Energy Generation; Thermonuclear Reactions
  (Degenerate Matter)

References

- ✓ ***The Internal Constitution of the Stars,*** Arthur S. Eddington, 1926, 1988 reprint, Cambridge U Press
- ✓ ***An Introduction to the Study of Stellar Structure,*** S. Chandrasekhar, 1939, 1967, Dover
- ✓ ***Principles of Stellar Evolution and Nucleosynthesis,*** Donald Clayton, 1968, 1983, U. Chicago Press
- ✓ ***Introduction to Stellar Atmospheres and Interiors***, Eva Novotny, 1973, Oxford U Press, an old but very comprehensive book on the subject
- ✓ ***Stellar Atmospheres,*** Dimitri Mihalas, 1978, W. H. Freeman & Company
- ✓ ***The Fundamentals of Stellar Astrophysics,*** George W. Collins, 1989, Freeman
- ✓ ***Stellar Structure and Evolution***, R. Kippenhahn & W. Weigert, 1990, Springer-Verlag
- ✓ ***Stellar Structure and Evolution***, 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***, Erika Bohm-Vitense, 1992, Cambridge
- ✓ ***The Observation and Analysis of Stellar Photospheres,*** David Gray, 1992, Cambridge U Press
- ✓ ***The Stars,*** Evry Scharzman and Françoise Praderie, 1993, Springer-Verlag, translated by A. R. King
- ✓ ***Compendium of Practical Astronomy, Vol 2, Stars and Stellar Systems,*** G. D. Roth (ed), 1993, Springer-Verlag

- ✓ ***恆星大氣物理,*** 汪珍如、區欽岳, 1993, 高等教育出版社
- ✓ ***The Physics of Stars***, A. C. Phillips, 1994, John Wiley & Sons
- ✓ ***The Stars: Their Structure and Evolution***, R. J. Tayler, 1994, Cambridge
- ✓ ***Supernovae and Nucleosynthesis,*** David Arnett, 1996, Princeton
- ✓ ***Advanced Stellar Astrophysics,*** William K. Rose, 1998, Cambridge
- ✓ ***Theoretical Astrophysics, Vol II*: Stars and Stellar Systems,** Padmanabhan, T., a hefty, mathematical 3 volume set; a comprehensive coverage of basic astrophysical processes in vol. 1, stars in vol. 2, and galaxies and cosmology in vol. 3, 2001, Cambridge
- ✓ ***Stars and Stellar Evolution,*** K. S. De Boer & W. Seggewiss, Ed., 2008, EDP Science
- ✓ ***Stellar Physics, 2: Stellar Evolution and Stability,*** Bisnovatyi-Kogan, 2nd Ed., 2010, Springer (translated from Russian)
- ✓ ***Theory of stellar Atmospheres***, Ivan Hubeny & Demitri Mihalas, 2015, Princeton U Press
- ✓ ***The Structure and Evolution of Stars,*** J. J. Eldridge & Chrostopher A. Tout, 2019, World Scientific
- ✓ ***Stars and Stellar Processes,*** Mike Guidry, 2019, Cambridge



Using fundamental physics, the theory of stellar structure and evolution can predict how stars are born, how their complex internal structure changes, what nuclear fuel they burn, and their ultimate fate. This textbook is a stimulating introduction for students of astronomy, physics, and applied mathematics, taking a course on the physics of stars. It uniquely emphasizes the basic physical principles governing stellar structure and evolution.

This second edition contains two new chapters on mass loss from stars and interacting binary stars, and new exercises. Clear and methodical, it explains the processes in simple terms, while maintaining mathematical rigour. Starting from general principles, this textbook leads students step-by-step to a global, comprehensive understanding of the subject. Fifty exercises and full solutions allow students to test their understanding. No prior knowledge of astronomy is required, and only a basic background in undergraduate physics and mathematics is necessary.

Dina Prialnik is Professor of Planetary Physics at Tel Aviv University. Her research interests lie in stellar evolution; the structure and evolution of cataclysmic variables; comet nuclei and other small solar system bodies; and the evolution of planets.

Reviews of the First Edition

"The processes are always explained in the simplest terms, while maintaining full mathematical rigor ... requires only basic undergraduate physics and mathematics and no prior knowledge of astronomy ..."
Orion, Société Astronomique de Suisse

"... a first-class textbook ... The host of student exercises ... ensure that any dedicated physics or mathematics undergraduate can, with some effort, understand what is going on."
David Hughes, *New Scientist*

"... a book that I can strongly recommend as a suitable textbook to anyone teaching a course in stellar structure, at advanced undergraduate or beginning graduate level ... An excellent book, which certainly deserves to become a classic."
Robert Connon Smith, *The Observatory*

Cover designed by Phil Treble

Cover illustration: light echo around V838 Monocerotis.
Courtesy of NASA, ESA, and H. Bond (STScI).

CAMBRIDGE
UNIVERSITY PRESS
www.cambridge.org

ISBN 978-0-521-86604-0

Second Edition

Prialnik

An Introduction to the Theory of Stellar Structure and Evolution

CAMBRIDGE

Second Edition

An Introduction to the

Theory of Stellar Structure and Evolution

Dina Prialnik

CAMBRIDGE

Digital copy available on the internet

Contents

Class Schedule 2023 Fall

#	Date	
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03	09/28	Holiday eve
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08	11/02	
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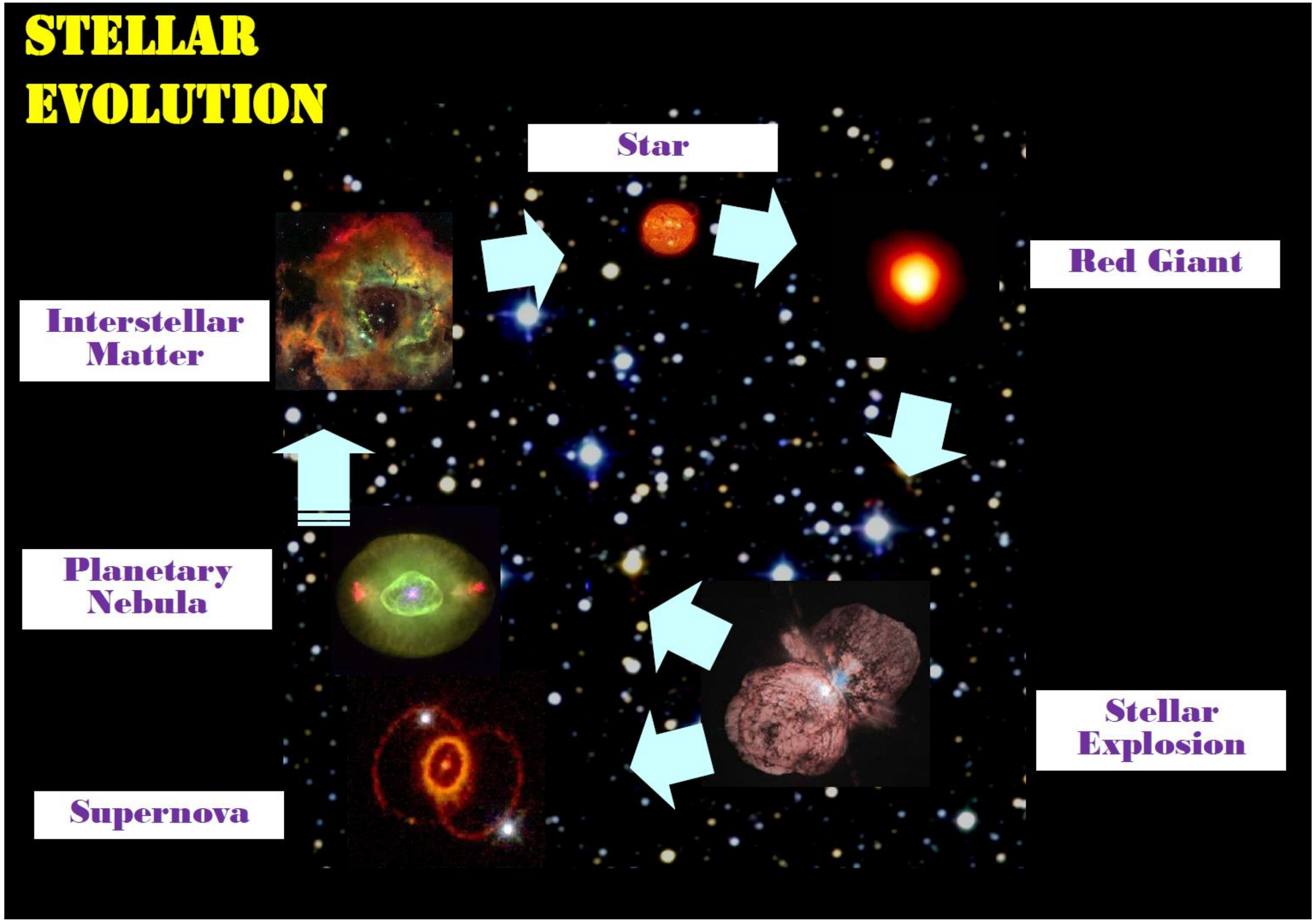
15	12/21	
16	**12/28**	Final Exam
17	01/04	Exam review
18	01/11	Supple. materials

Stellar structure:

stability; balance of forces



Stellar evolution:

temporal changes of structure

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

Frequently used fundamental constants

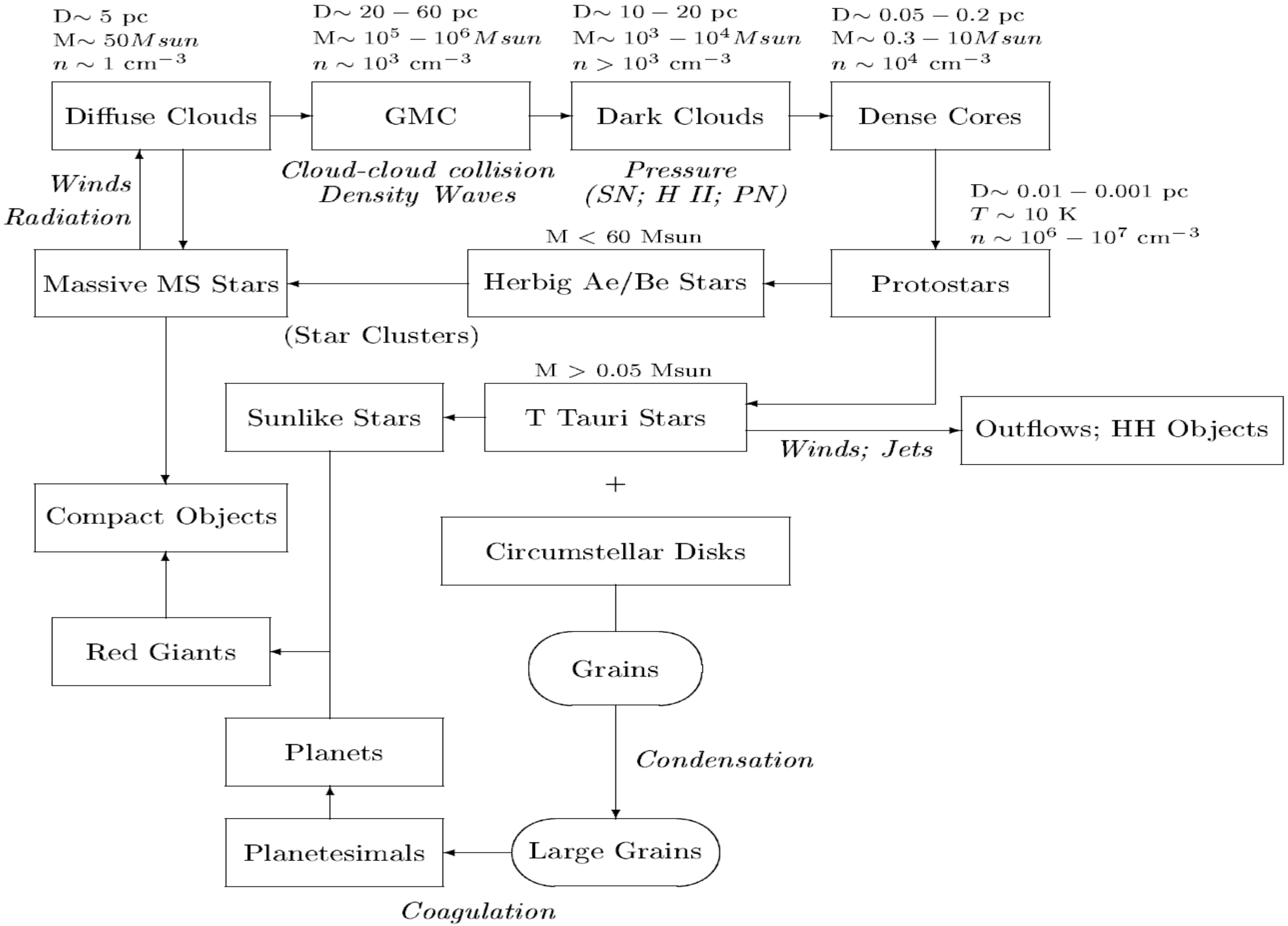
Physical

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

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 (observed)
$T_{c,\odot}$	Solar Central temperature	1.6×10^{7} K (theoretical)
$R_\odot$	Solar radius	6.96×10^{8} m
$m_\odot$	apparent mag of Sun	-26.7 mag (V)
$M_\odot$	absolute mag of Sun	$+4.8$ mag (V)
θ	apparent size of Sun	32’
$<\rho>$	mean density of Sun	$1.4\ \mathrm{g\ cm^{-3}}$
$(B-V)_\odot$	color of the Sun	0.6 mag
Parsec	unit of distance	3.09×10^{16} m



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

Diffuse Clouds

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

GMC

Cloud-cloud collision
Density Waves

D~ $10 - 20$ pc
M~ $10^3 - 10^4 M sun$
$n > 10^3$ cm^{-3}

Dark Clouds

Pressure
(SN; H II; PN)

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

Dense Cores

Winds
Radiation

Massive MS Stars

M $<$ 60 Msun

Herbig Ae/Be Stars

(Star Clusters)

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

Protostars

M $>$ 0.05 Msun

Sunlike Stars

T Tauri Stars

Winds; Jets

Outflows; HH Objects

Compact Objects

+

Circumstellar Disks

Red Giants

Grains

Condensation

Planets

Planetesimals

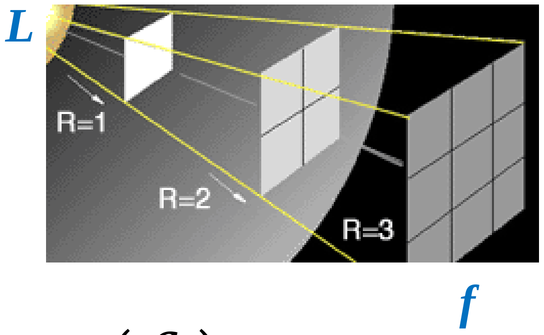
Large Grains

Coagulation

Galactic Ecology

Properties of Stars

Brightness



- **Luminosity** [erg s^{-1}] ***L*** = bolometric luminosity = power
- **Spectral luminosity** [erg $s^{-1}\mu m^{-1}$] $\boldsymbol{L_\lambda}$
- **Flux** [erg s^{-1} cm^{-2}] ***f***
- **Flux density** [erg s^{-1} cm^{-2} μm^{-1}] $\boldsymbol{f_\lambda}$ ***or*** $\boldsymbol{f_\nu}$
- $$\begin{aligned} 1 \text{ Jansky (Jy)} &= 10^{-23}\ [\text{erg s}^{-1}\ \text{cm}^{-2}\ \text{Hz}^{-1}] \\ &= 10^{-26}\ [\text{W m}^{-2}\ \text{Hz}^{-1}] \\ &= 10^{-7}\ [\text{photons}\ \ \text{m}^{-2}\ \text{s}^{-1}\ (\lambda/d\lambda)] \end{aligned}$$
- **Brightness/intensity** [erg s^{-1} cm^{-2} sr^{-1}] ***B***
- **Specific intensity** [erg s^{-1} $cm^{-2}sr^{-1}$ Hz^{-1}] $\boldsymbol{I_\nu}$
- **Energy density** [erg cm^{-3}] ***u*** = (4 π/c) J
- **Mean intensity** ***J*** = (1/4π) $\int I\, d\Omega$

$$\mathrm{d}\lambda = -\left(\frac{c}{\nu^2}\right)\mathrm{d}\nu$$

$$f_\nu = \left(\frac{\lambda^2}{c}\right) f_\lambda$$

$$f(m_V = 0) = 3640 \text{ Jy}$$

Solar radio astronomers
use the solar flux unit
1 s.f.u.= 10^4 Jy

Pay attention to the subscript and unit.

Magnitude $m_1 - m_2 = 2.5 \log \left(I_2/I_1\right)$

100 times the intensity → 5 mag difference
The brighter the intensity, the smaller the magnitude value

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

- The Vega system: 0.0 mag (latest ~0.3 mag) at every Johnson band

$$m_{\rm V}^{\odot} = -26.74 \text{ mag}$$

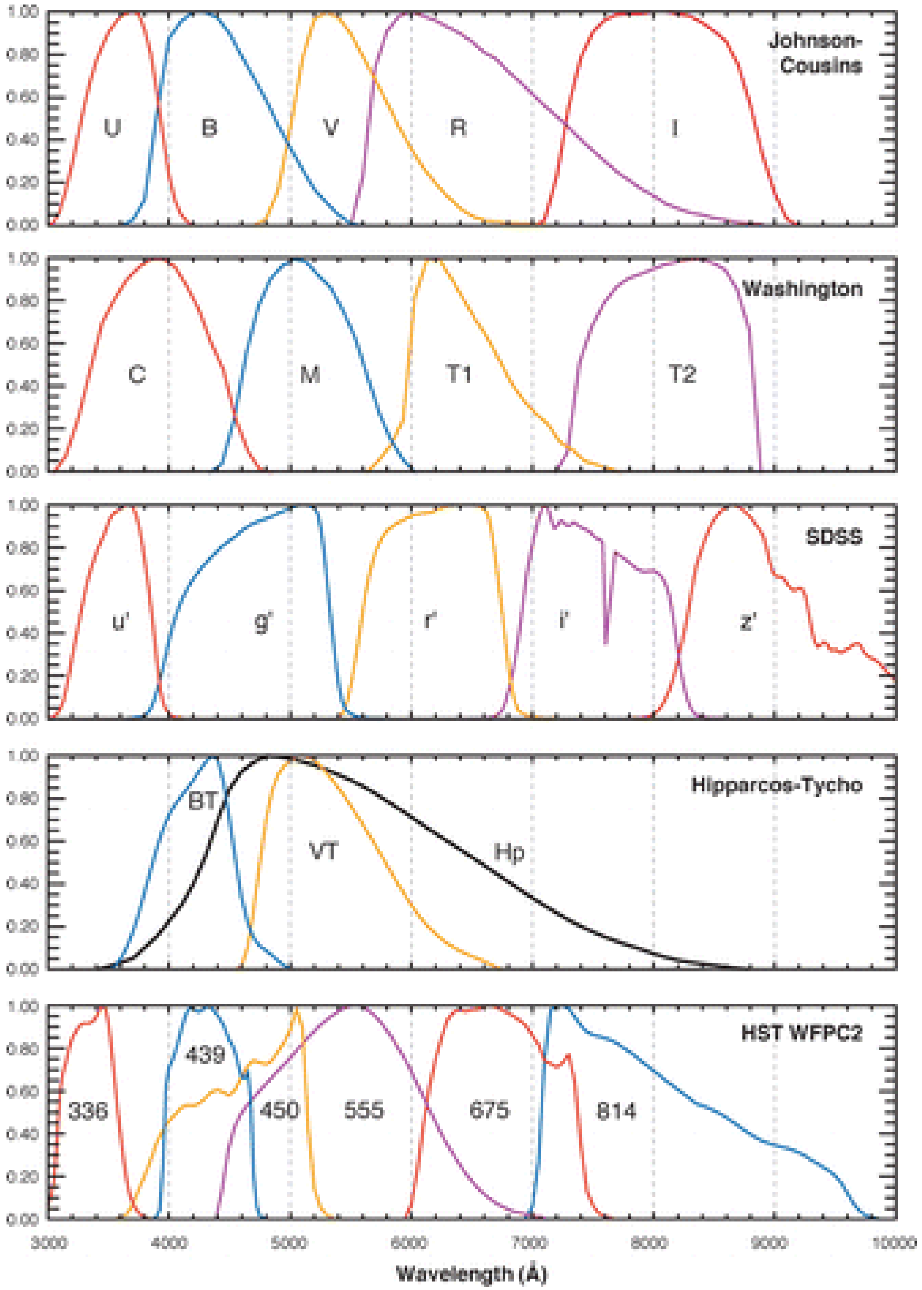
- Gunn system: no Vega; use F subdwarfs as standards (metal poor so with smooth spectra), e.g., BD + 17 4708

- The AB system: $\boxed{m_{\rm AB} = -2.5 \log_{10}\left(\frac{f_\nu}{3631 \text{ Jy}}\right) = -2.5 \log_{10}(f_\nu/\text{Jy}) + 8.90}$

or $= -2.5 \log_{10}(f_\nu\ [\text{erg s}^{-1}\text{ cm}^{-2}\text{ Hz}^{-1}]) - 48.60$

- STMAG system: used for HST photometry

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



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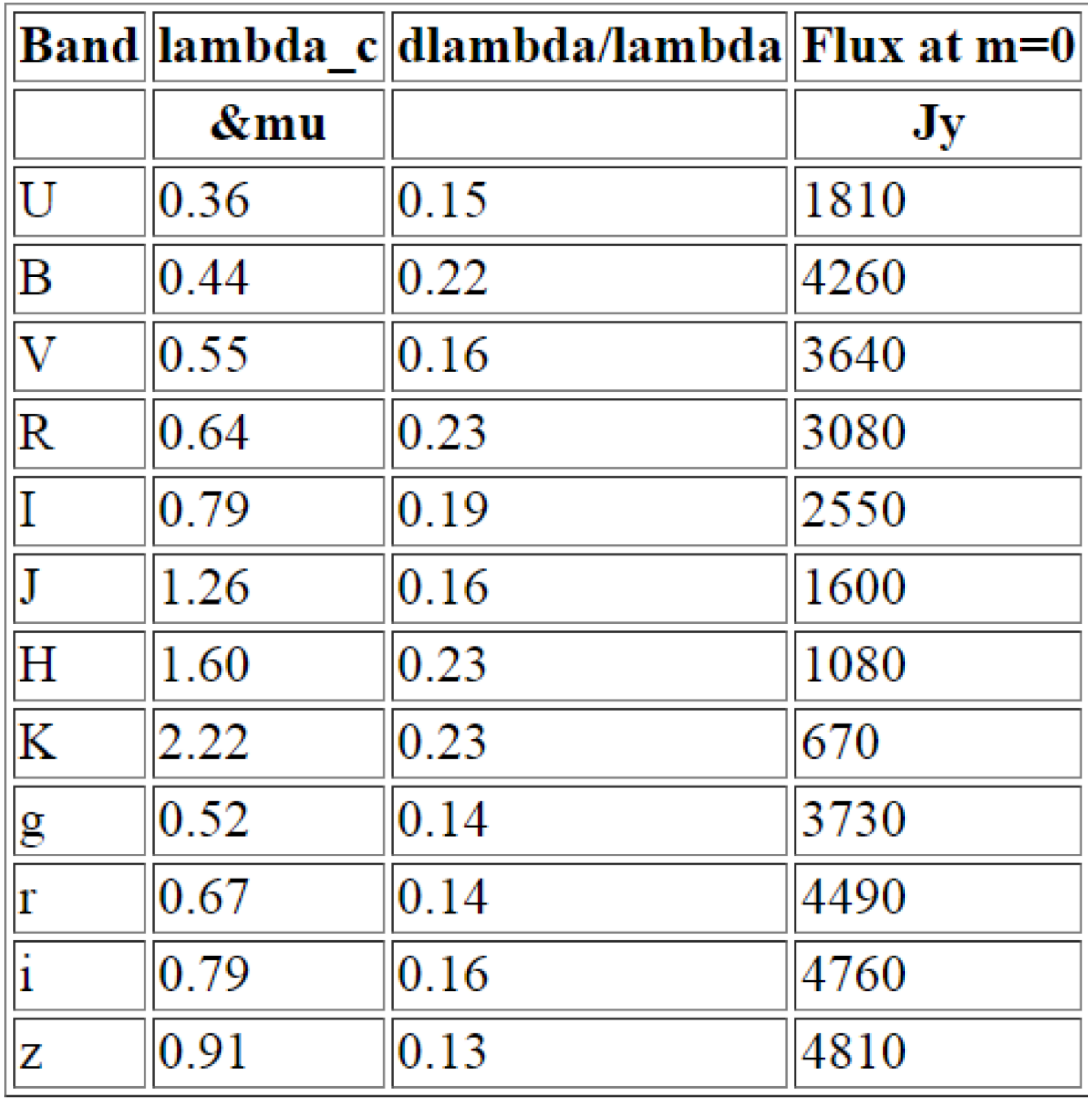
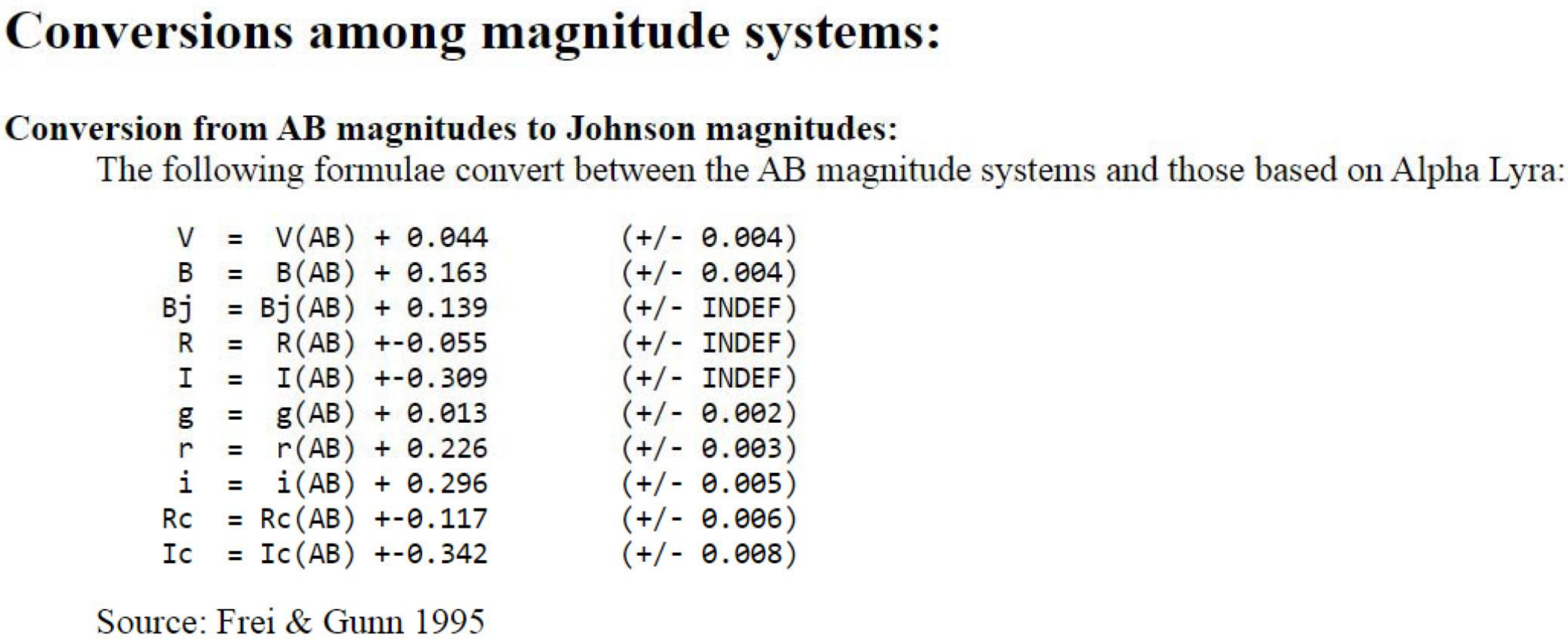
Annu. Rev. Astron. Astrophys. 43: 293–336



Band	lambda_c	dlambda/lambda	Flux at m=0
	&mu		Jy
U	0.36	0.15	1810
B	0.44	0.22	4260
V	0.55	0.16	3640
R	0.64	0.23	3080
I	0.79	0.19	2550
J	1.26	0.16	1600
H	1.60	0.23	1080
K	2.22	0.23	670
g	0.52	0.14	3730
r	0.67	0.14	4490
i	0.79	0.16	4760
z	0.91	0.13	4810

https://lweb.cfa.harvard.edu/~dfabricant/huchra/ay145/mags.html



Conversions among magnitude systems:

Conversion from AB magnitudes to Johnson magnitudes:

The following formulae convert between the AB magnitude systems and those based on Alpha Lyra:

```
 V  =  V(AB) + 0.044        (+/- 0.004)
 B  =  B(AB) + 0.163        (+/- 0.004)
Bj  = Bj(AB) + 0.139        (+/- INDEF)
 R  =  R(AB) +-0.055        (+/- INDEF)
 I  =  I(AB) +-0.309        (+/- INDEF)
 g  =  g(AB) + 0.013        (+/- 0.002)
 r  =  r(AB) + 0.226        (+/- 0.003)
 i  =  i(AB) + 0.296        (+/- 0.005)
Rc  = Rc(AB) +-0.117        (+/- 0.006)
Ic  = Ic(AB) +-0.342        (+/- 0.008)
```

Source: Frei & Gunn 1995

https://lweb.cfa.harvard.edu/~dfabricant/huchra/ay145/mags.html

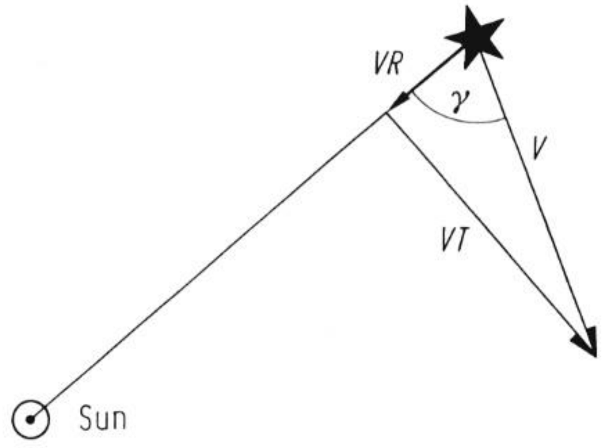
Specific Intensity I_ν or simply “intensity”, or “brightness”, is the amount of radiation energy per unit frequency interval at υ per unit time interval per unit area per unit solid angle passing into the specified direction at a position P.

$$I_\upsilon(\theta) = \lim_{\substack{\Delta\upsilon\to 0 \\ \Delta t\to 0 \\ \Delta\sigma\to 0 \\ \Delta\omega\to 0}} \frac{\Delta E_\nu}{\Delta\upsilon\, \Delta t\, \Delta\sigma\, \Delta\omega\, \cos\theta}$$

In cgs unit, I_υ [ergs $\mathrm{s^{-1}\ Hz^{-1}\ cm^{-2}\ sr^{-1}}$]

Because $\Delta\omega \rightarrow 0$, the energy does not diverge. The intensity is independent of the distance from the source (i.e., light ray).

Motion



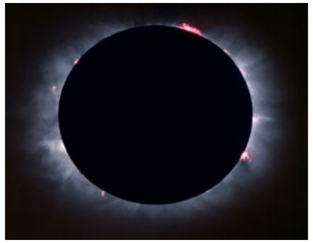
Velocity components:
radial velocity V_R, and tangential V_{T}

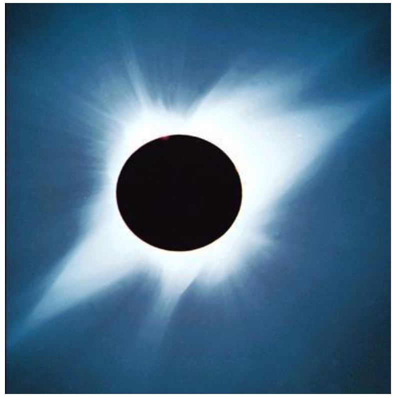
Proper motion (apparent angular motion in the sky), μ_α and μ_δ, e.g., mas per year along RA and Decl.

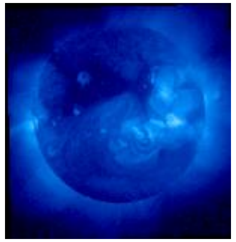
V_{T} is a function of distance given (μ_α, μ_δ)

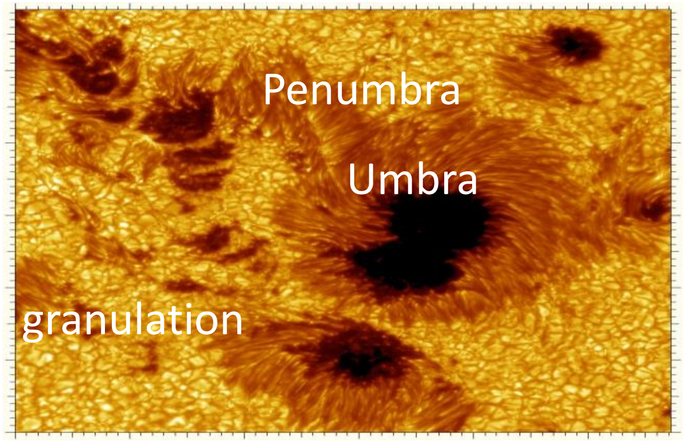
V_R is distance independent (to the first order, a long distance reduces the signal hence the accuracy).

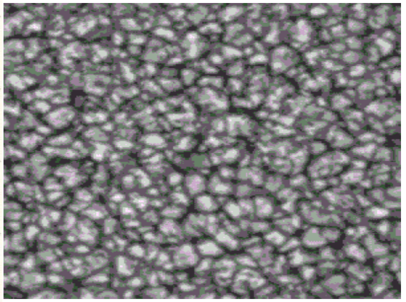
Our Sun ---- the best studied star

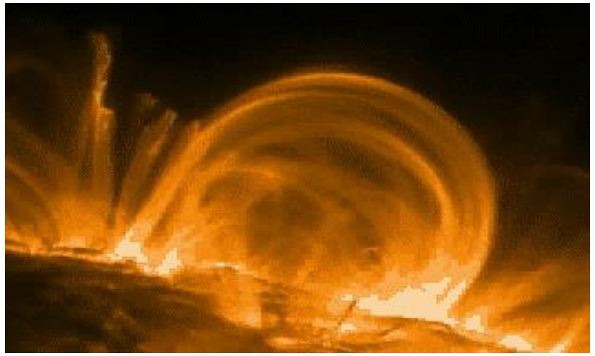


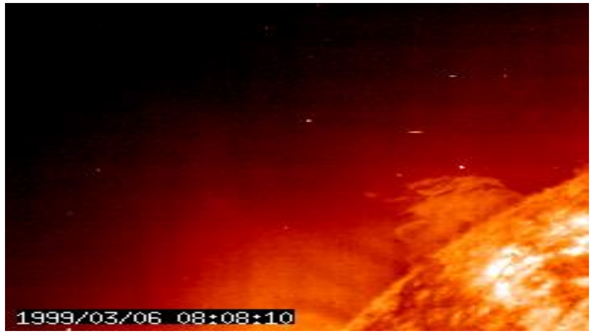


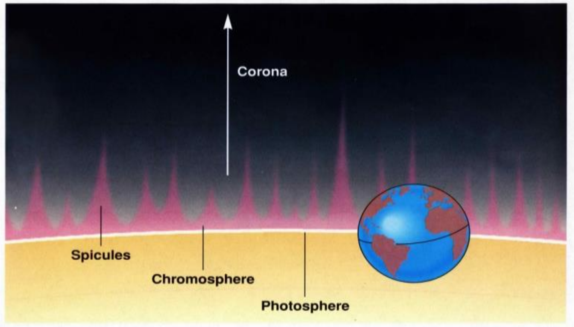




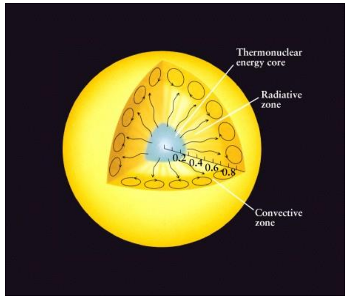


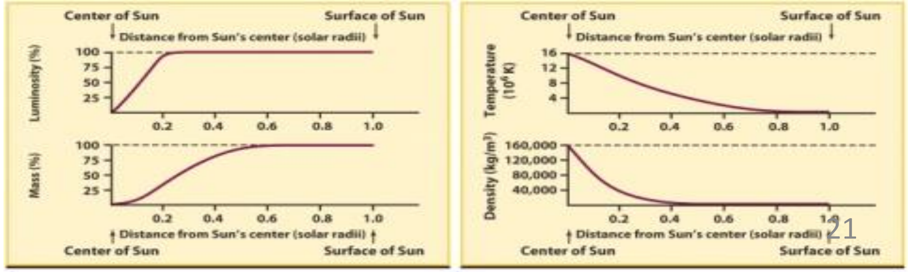


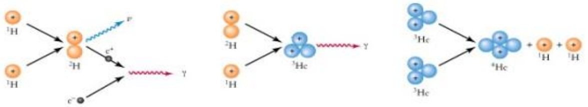




Cross section of photosphere.







Physical properties of stars

Basic parameters to compare between theories and observations

◆ Mass (M)

◆ Luminosity (L)

◆ Radius/size (R)

◆ Effective temperature (T_e) $L = 4\pi R^2 \sigma T_e^4$

◆ Distance → measured flux $F = L/4\pi d^2$

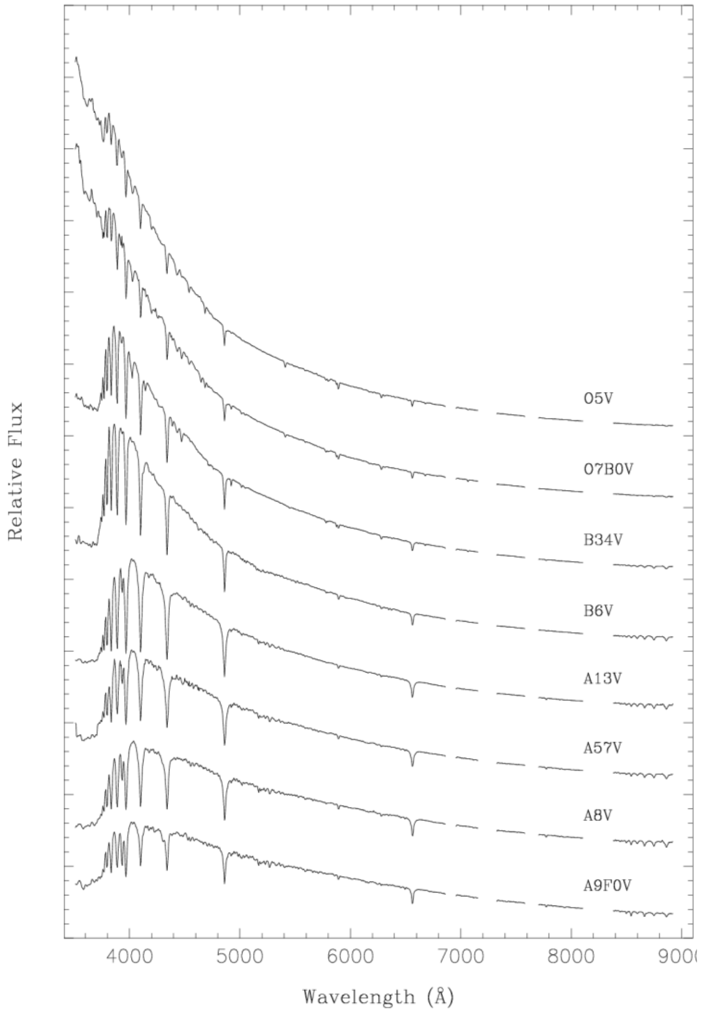
M, R, L and T_e not independent

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

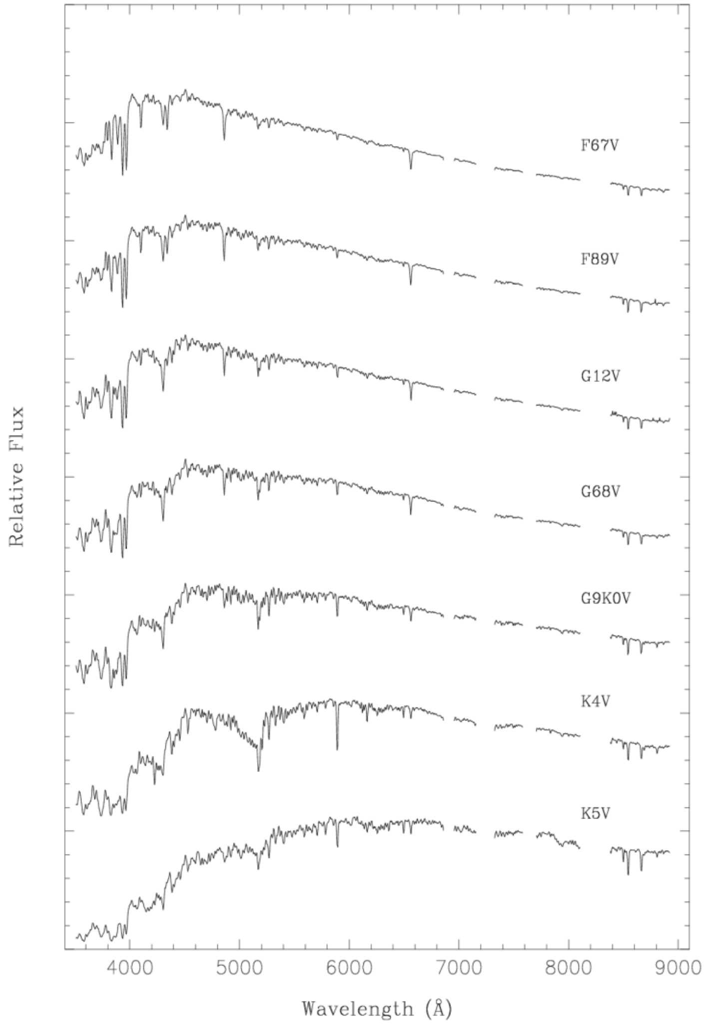
- L and M → mass-luminosity relation

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

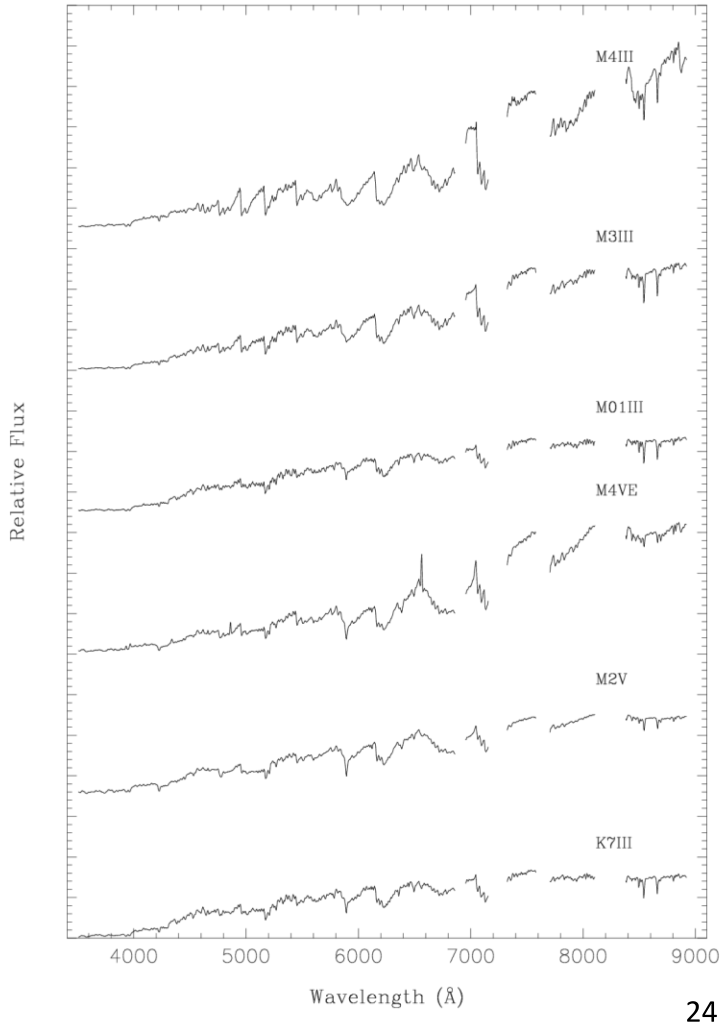
Hot stars --- peaked at short wavelengths (UV); mainly He lines, some H lines

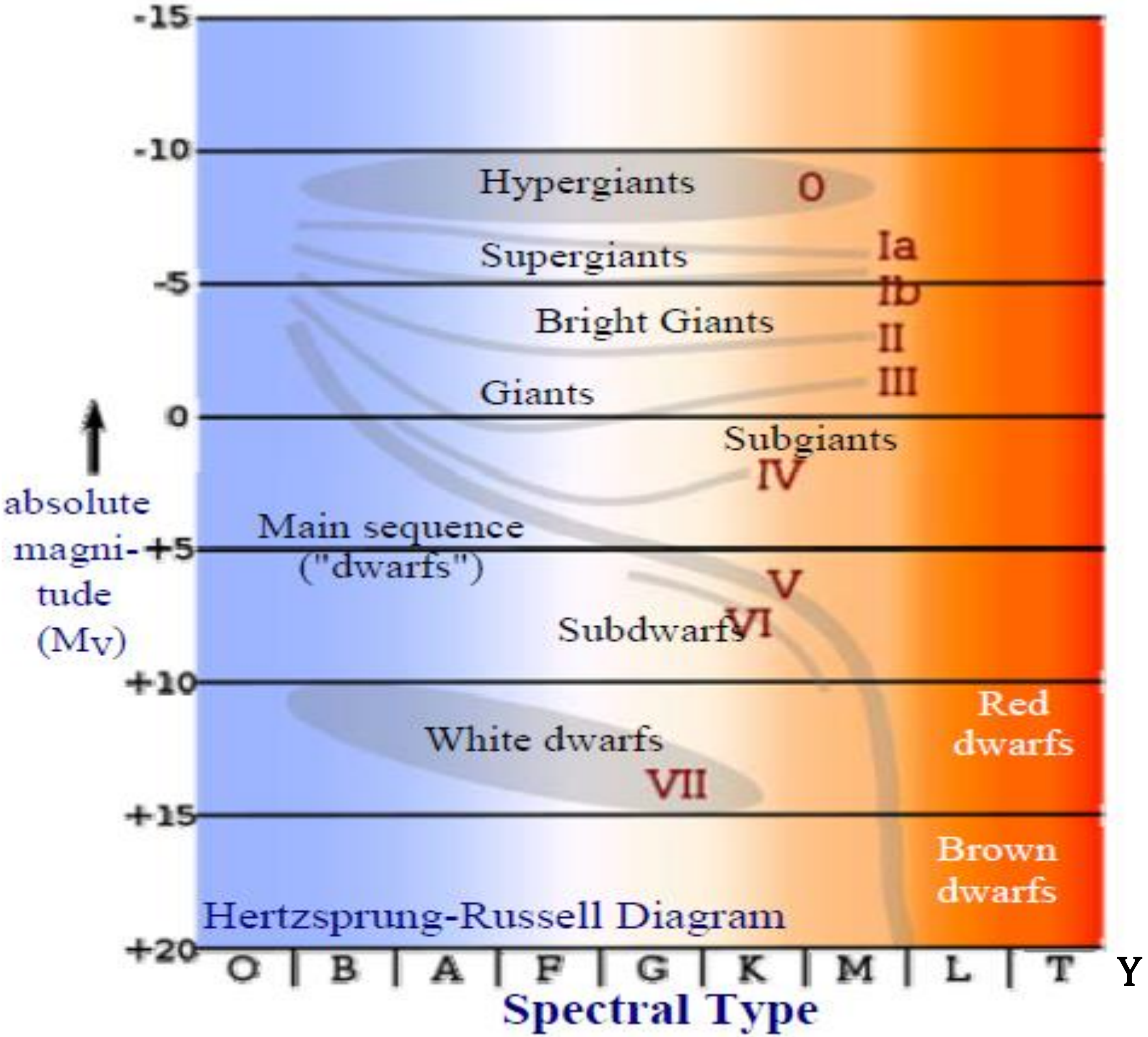


Warm stars --- peaked in the visible wavelengths; H lines prominent



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





Stars:

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

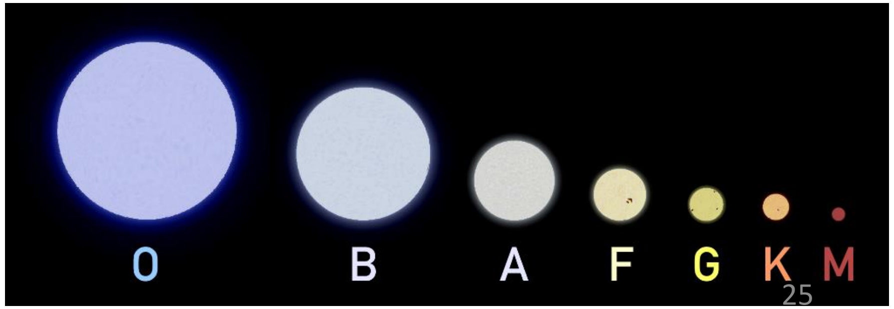
Brown Dwarfs:

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

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

Planet-mass Objects:

$M < 13\,\mathcal{M}_J$



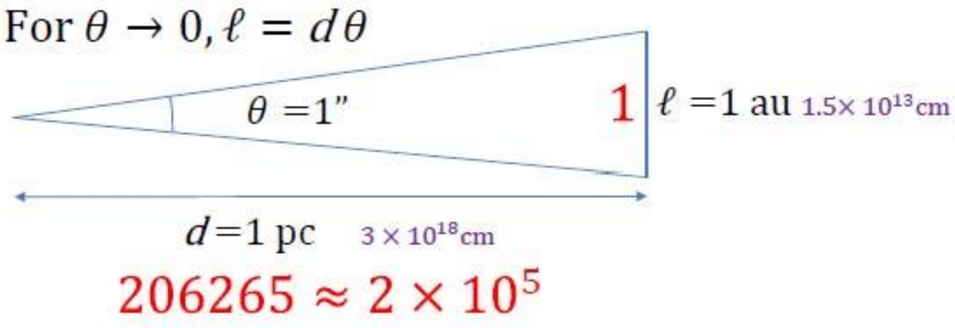
To measure the stellar **distance**

Directly by trigonometric **parallax**

◆ Nearest stars $d > 1$ pc → $p < 1''$

◆ For a star at $d = 100$ pc, $p = 0.01''$

◆ Ground-based observations limited to angular resolution ~1“; *HST* has 0.05”, JWST?



For $\theta \to 0, \ell = d\theta$

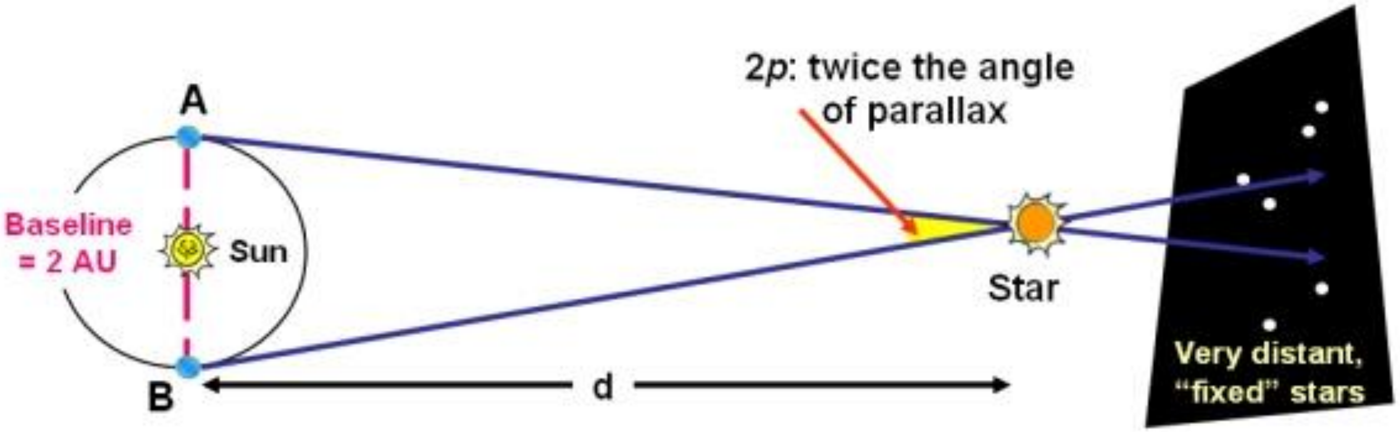
$\theta = 1''$

1

$\ell = 1$ au 1.5×10^{13} cm

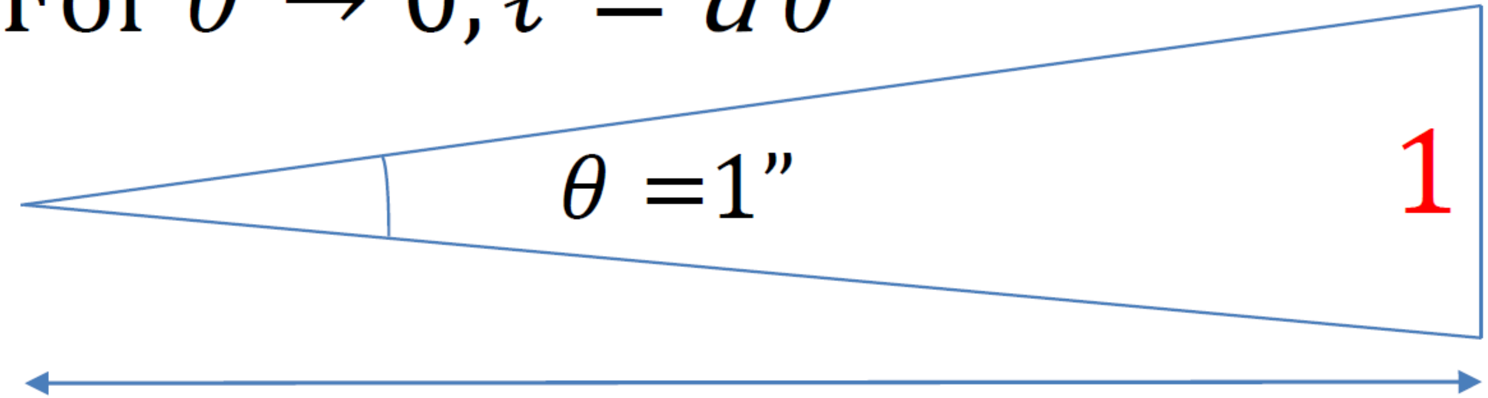
$d = 1$ pc 3×10^{18} cm

$206265 \approx 2\times 10^5$



http://astronomy.swin.edu.au/cosmos/T/Trigonometric+Parallax

For $\theta \to 0, \ell = d\theta$



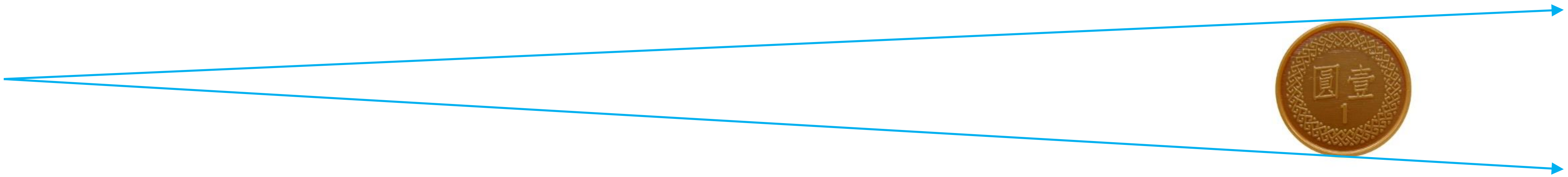
θ =1”

1

ℓ =1 au 1.5×10^{13}cm

d=1 pc 3×10^{18}cm

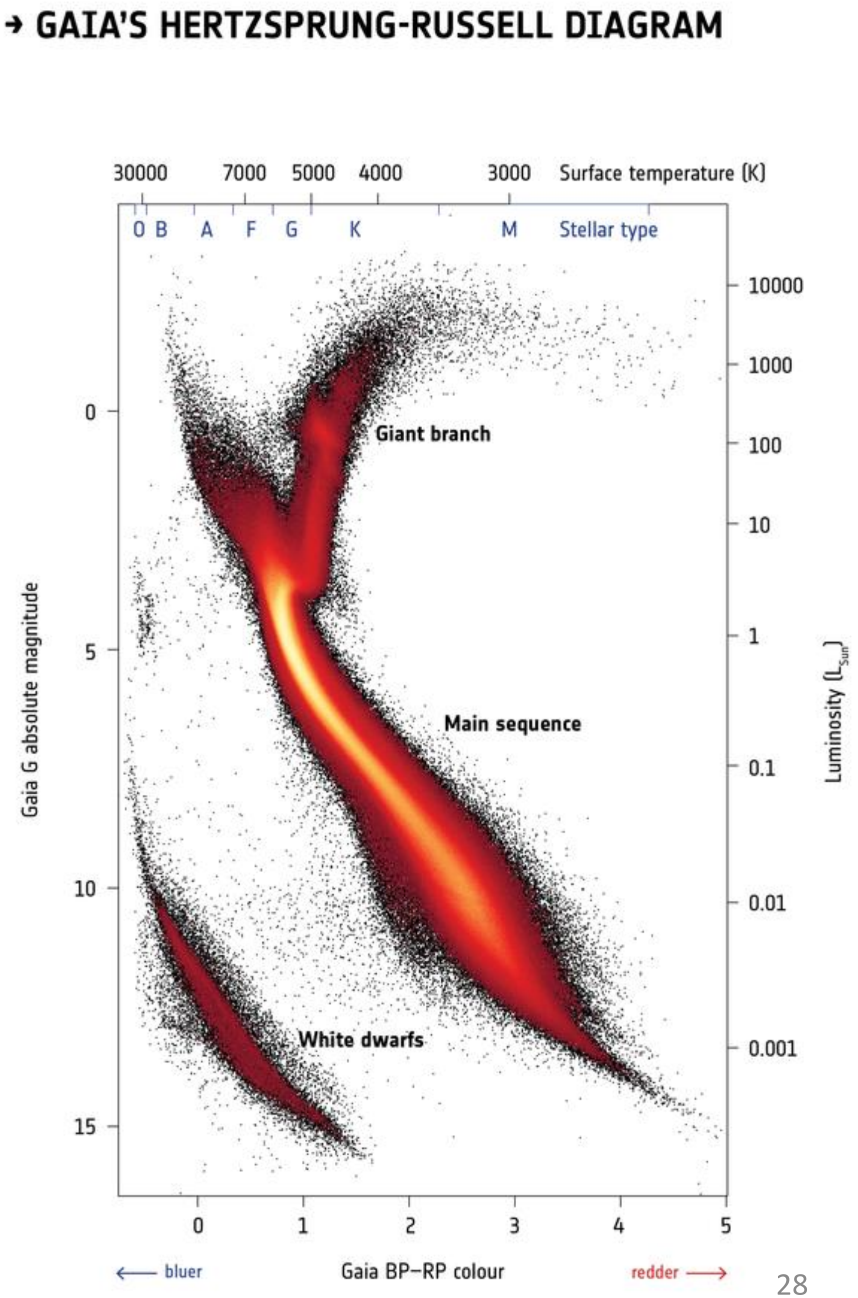
$$206265 \approx 2 \times 10^5$$



4 km

2 cm

- *Gaia* is a space telescope to measure accurate astrometry (i.e., position), 20 microarcsecond (μas) at 15 mag and 200 μas at 20 mag, of 10^9 stars (1% of the Milky Way galaxy).
- With multi-epoch (~70) data, this affords parallax (distance), and space motion information of a star.
- Accurate photometry is also provided.



Otherwise, the distance is estimated

- **Spectroscopic parallax**: Stars with the same spectra are assumed to have identical set of physical parameters. 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

$$m_\lambda - M_\lambda = 5 \log d_{\mathrm{pc}} - 5 + A_\lambda(d)$$

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

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

- The apparent magnitude is a measure of the relative observed flux density of a celestial object with a filter

$$m_\lambda = -2.5 \log\left(\frac{f_\lambda}{f_{\lambda,0}}\right)$$

A larger mag value → fainter
Flux ratio of 100 → magnitude difference of 5
For the same object, flux drops with distance squared

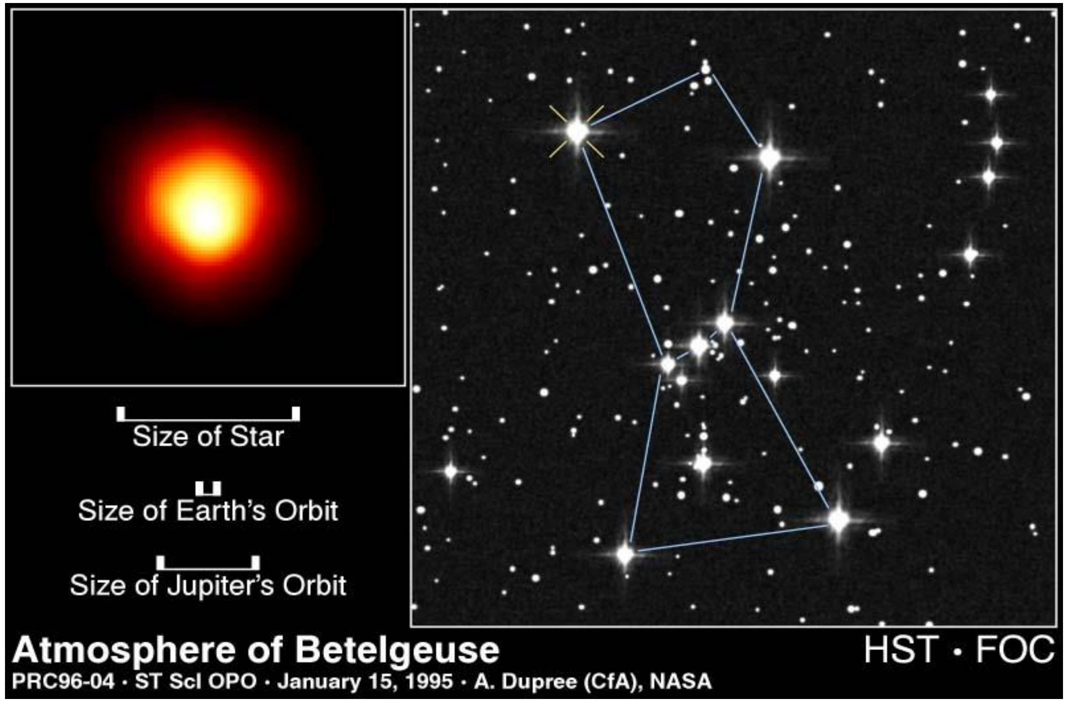
$$m_{d1} - m_{d2} = 5 \log\left(\frac{d2}{d1}\right)$$

- The absolute magnitude is a measure of the intrinsic (absolute) brightness of a celestial object. It is defined numerically as the apparent magnitude of an object that would have if it were viewed from a distance of 10 parsecs.

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

To measure the stellar **size**

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

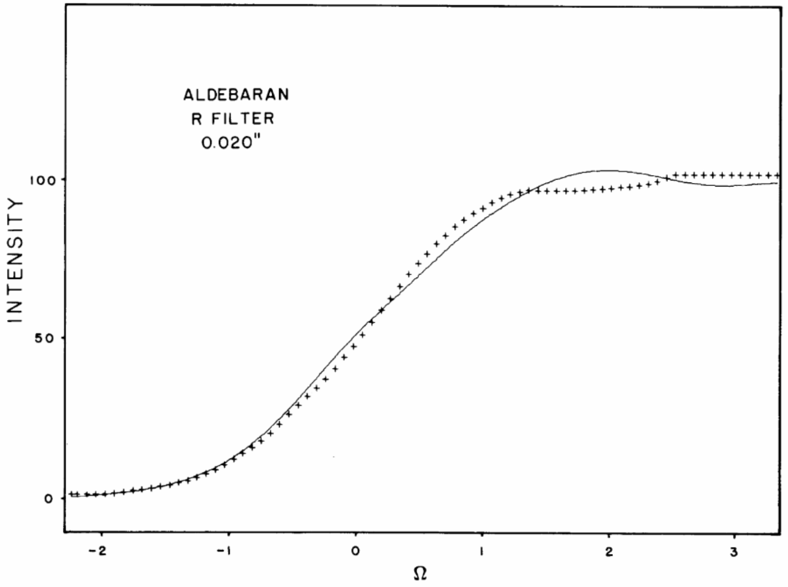


FIG. 1.—A comparison of the (*crosses*) observed points and the (*line*) theoretical pattern for the Aldebaran λ = 7460 Å record with $\theta = 0''.020$.

Lunar occultation

Beaver & Eitter (1979)

Optical interferometery, e.g.,
CHARA array (6 × 1 m, $\theta \approx 200$ μas)

White et al (2013)

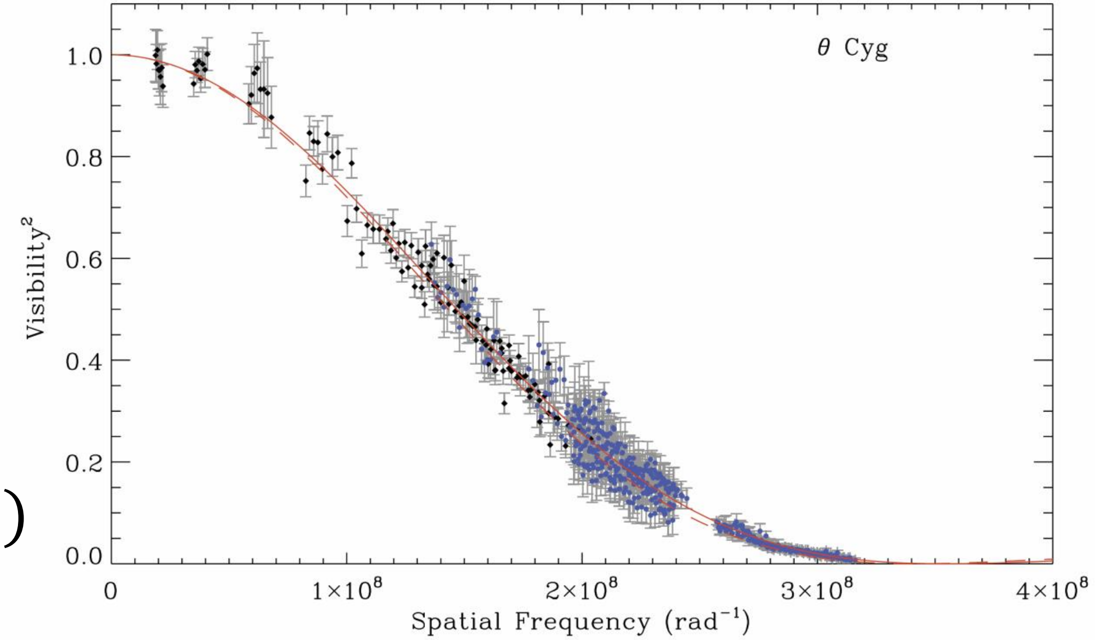
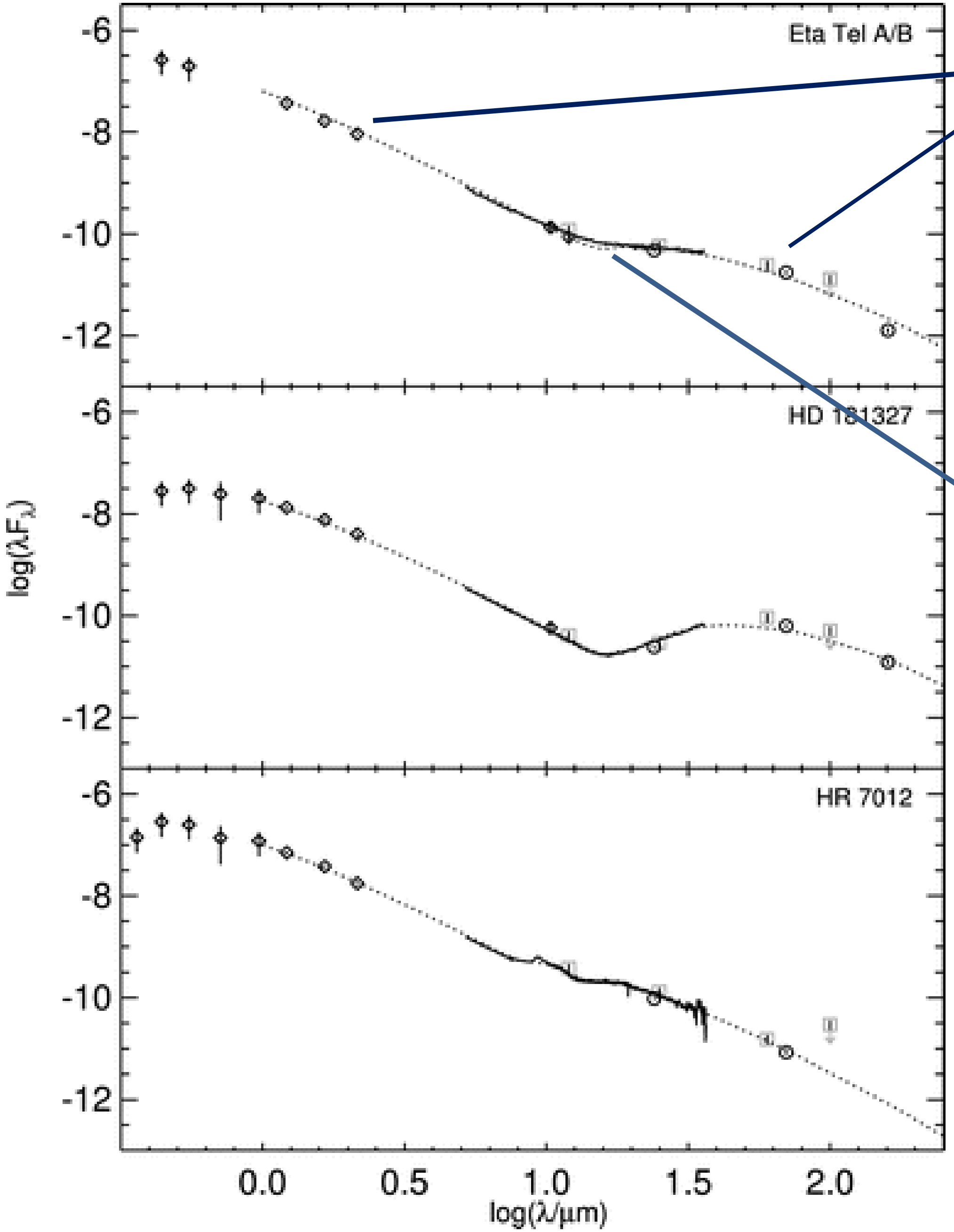


Figure 1. Squared visibility versus spatial frequency for θ Cyg for PAVO (blue circles) and MIRC (black diamonds) data. The red lines show the fitted limb-darkened model to the combined data. The solid line is for $\mu = 0.47 \pm 0.04$ (PAVO) while the dashed line is for $\mu = 0.21 \pm 0.03$ (MIRC).

To measure the stellar temperature

- What is $T_{\rm eff}$? What is the "surface" of a star?
- What is T anyway? Temperature is ill-defined, often defined by other physical quantities through an equation, i.e., a physical law, e.g., by radiation (blackbody, brightness, color), by particles (excitation, ionization, kinetic, electron), by 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*
- There are many photometric systems, using broad bands, intermediate bands, special bands, at optical or infrared wavelengths, etc.

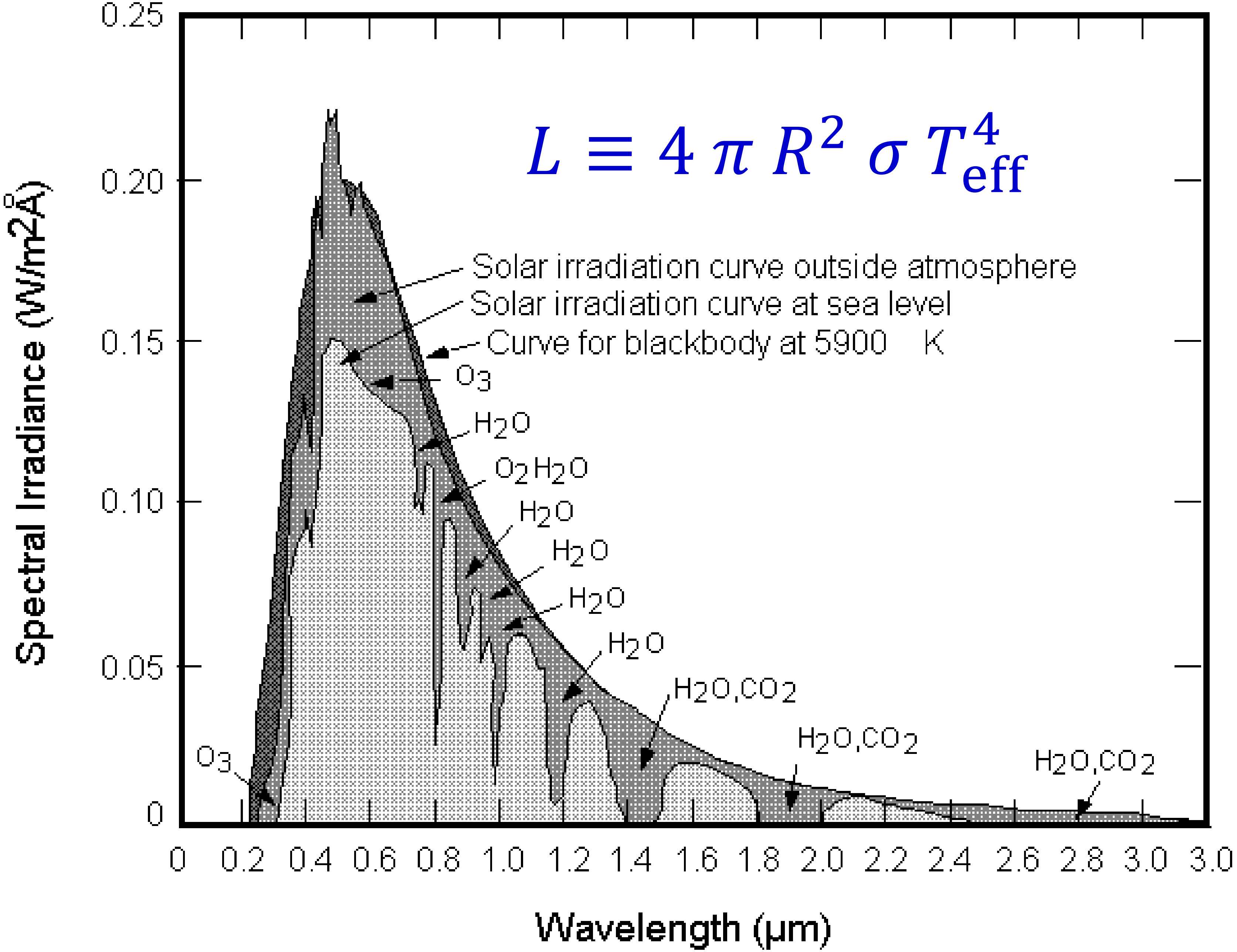
Band	U	B	V	R	I
λ/nm	365	445	551	658	806
$\Delta\lambda$/nm	66	94	88	138	149



Photometric data through
a spectral filter

Spectroscopic data

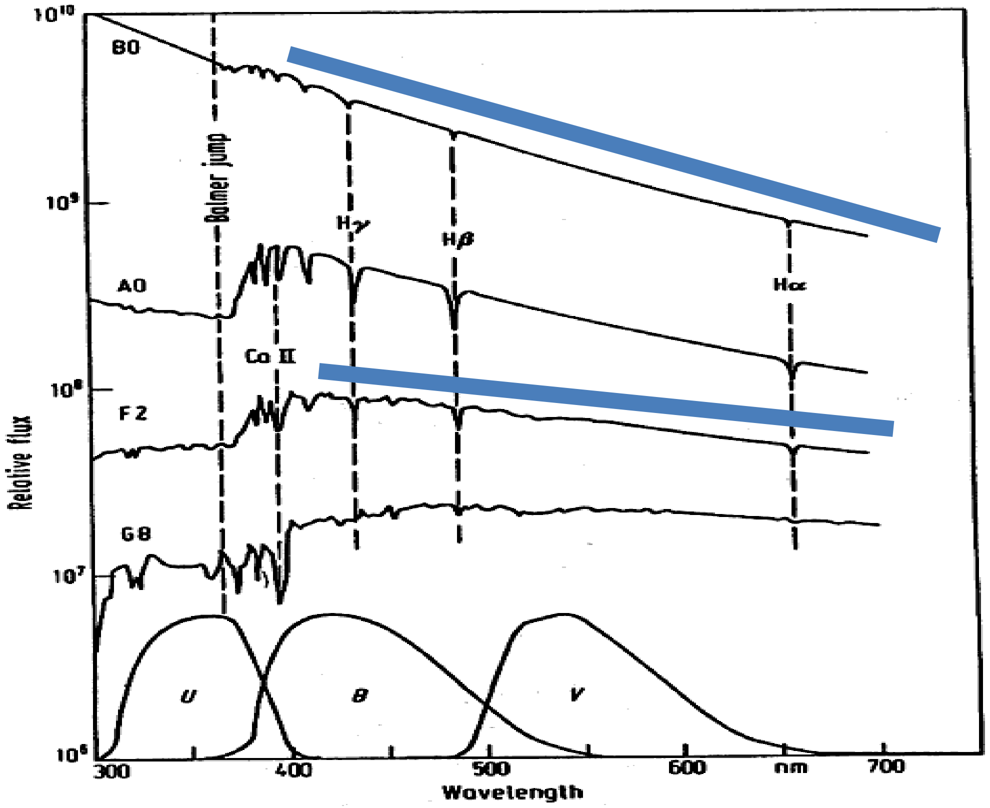
http://coolwiki.ipac.caltech.edu/index.php/SED_plots_introduction



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

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.



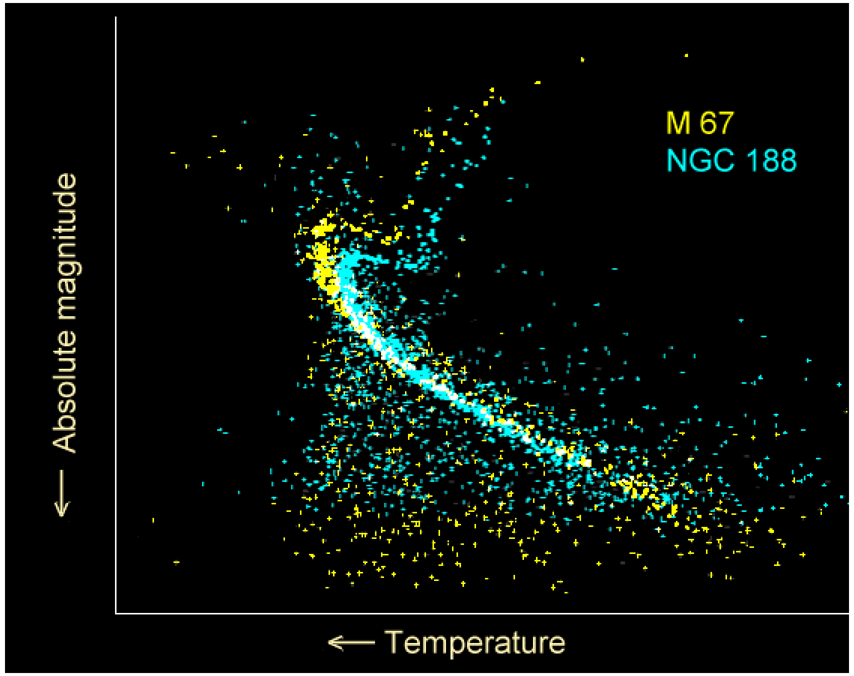
An unreddened O-type star $(B-V) = -0.3$

A late M-type star has $(B-V) = +1.65$

For the Sun, $(B-V)_{\odot} = +0.656 \pm 0.005$

Hertzsprung-Russell (HR) Diagram
(theory)

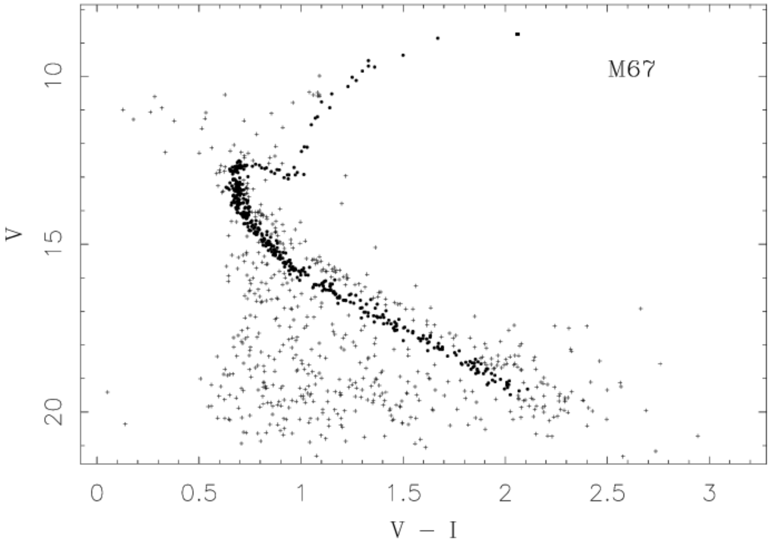
Brightness (Luminosity or Absolute Magnitude)



Spectral Type or surface Temperature

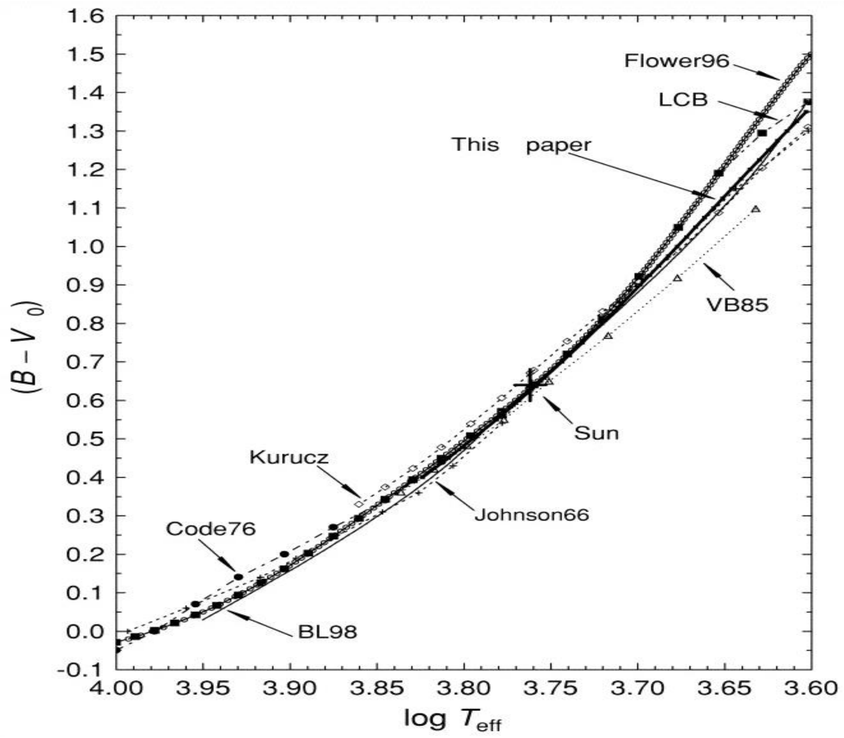
Color-Magnitude Diagram (CMD)
(observation, a proxy of the HRD)

Apparent or Absolute Magnitude



“Color” ($m_1 - m_2$)

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



Color Excess

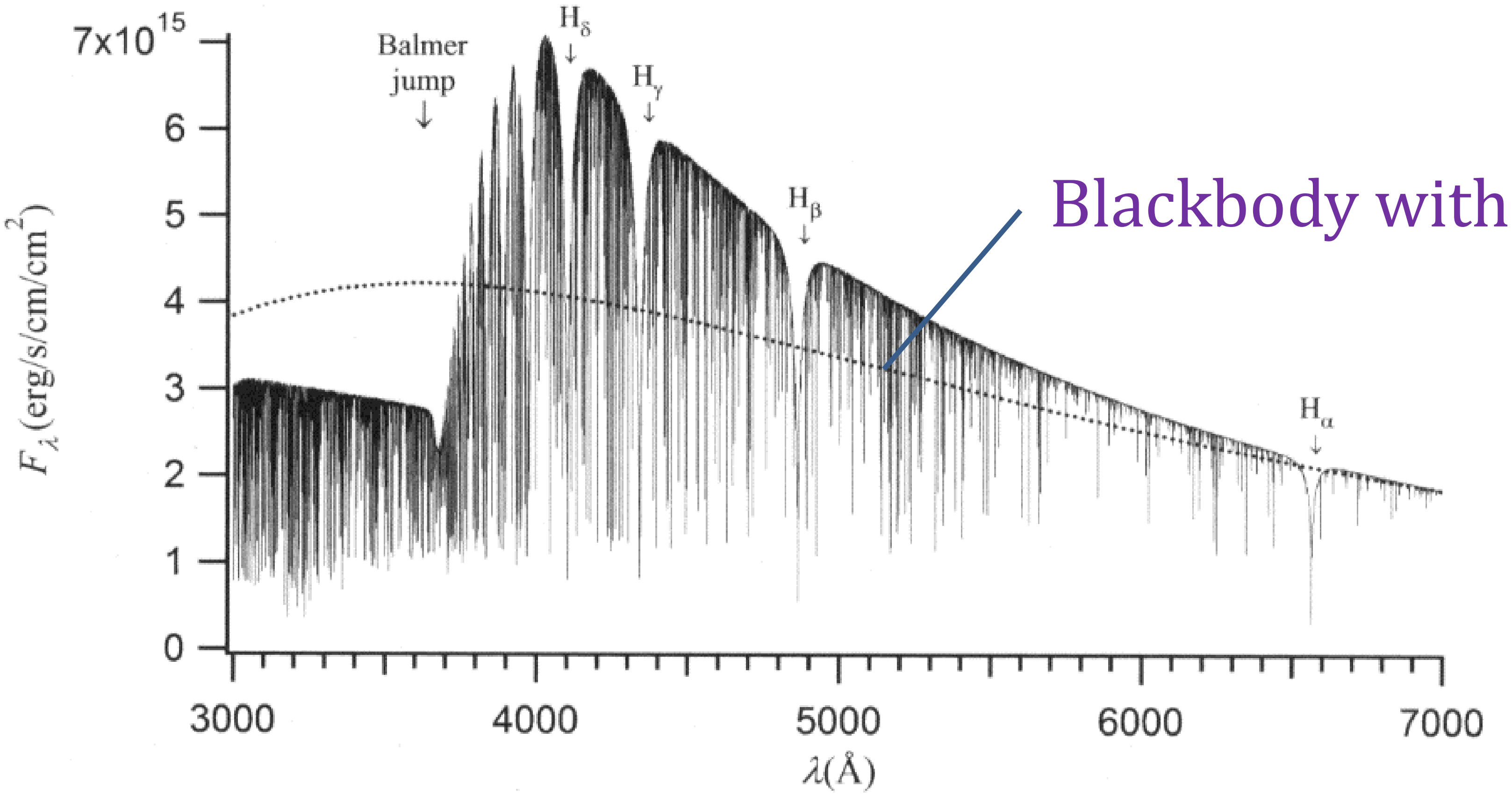
$$E_{B-V} = (B-V)_{\text{observed}} - (B-V)_{\text{intrinsic}}$$

$$= (B-V) - (B-V)_0$$

The Kurucz (Kurucz & Castelli) grids of model atmospheres

http://kurucz.harvard.edu/grids.html

http://wwwuser.oats.inaf.it/castelli/



Blackbody with T=8000 K

Figure 1.8 Theoretical monochromatic flux emerging form an A type star with $T_{\mathrm{eff}} = 8000\,\mathrm{K}$. 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 $T = 8000\,\mathrm{K}$ (dotted curve) is also shown.

LeBlanc

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

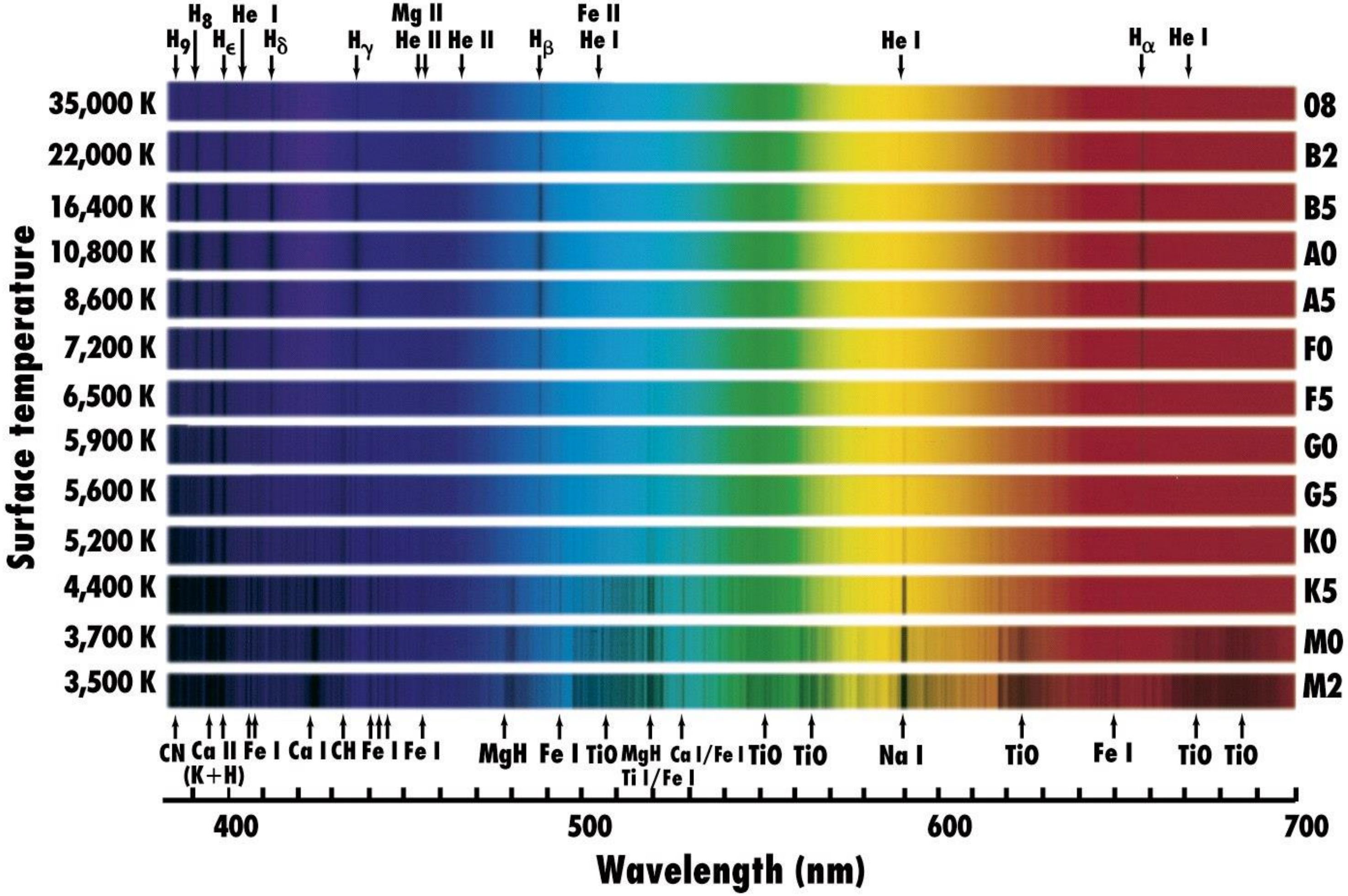
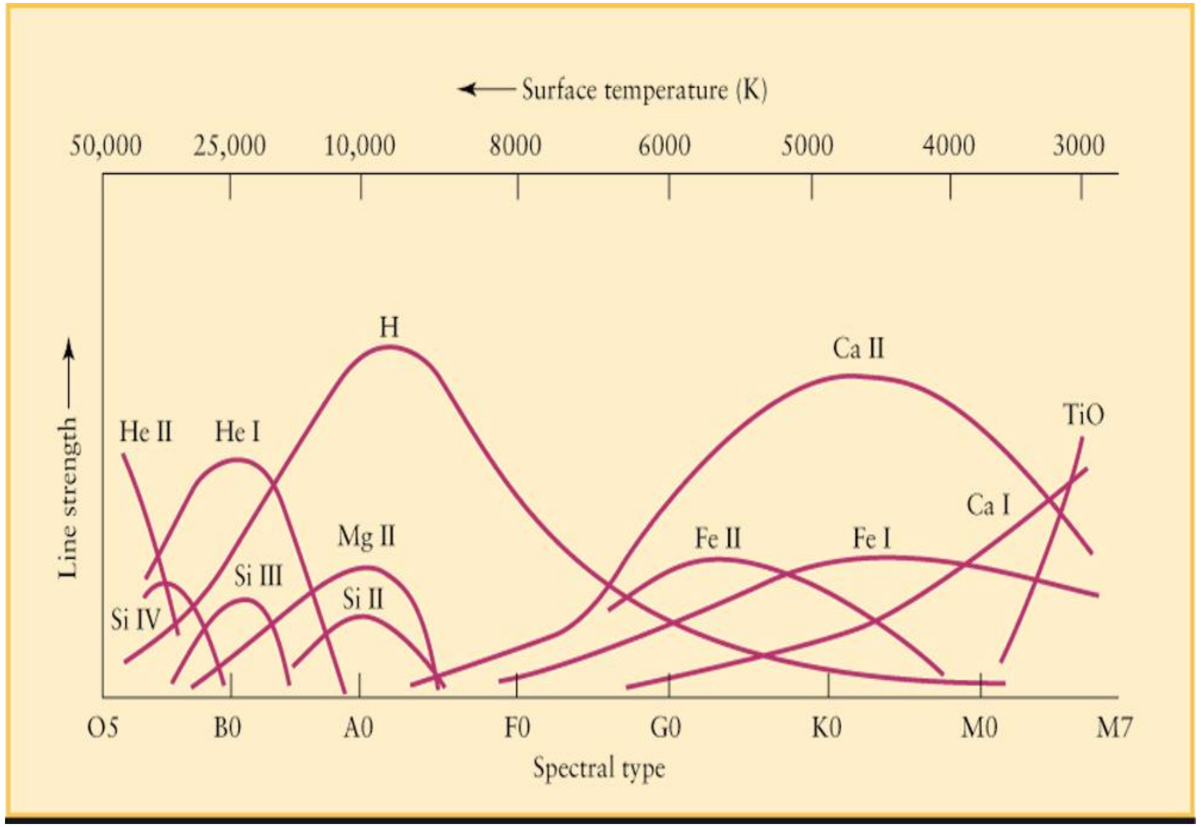


Figure 11-5
Discovering the Universe, Seventh Edition

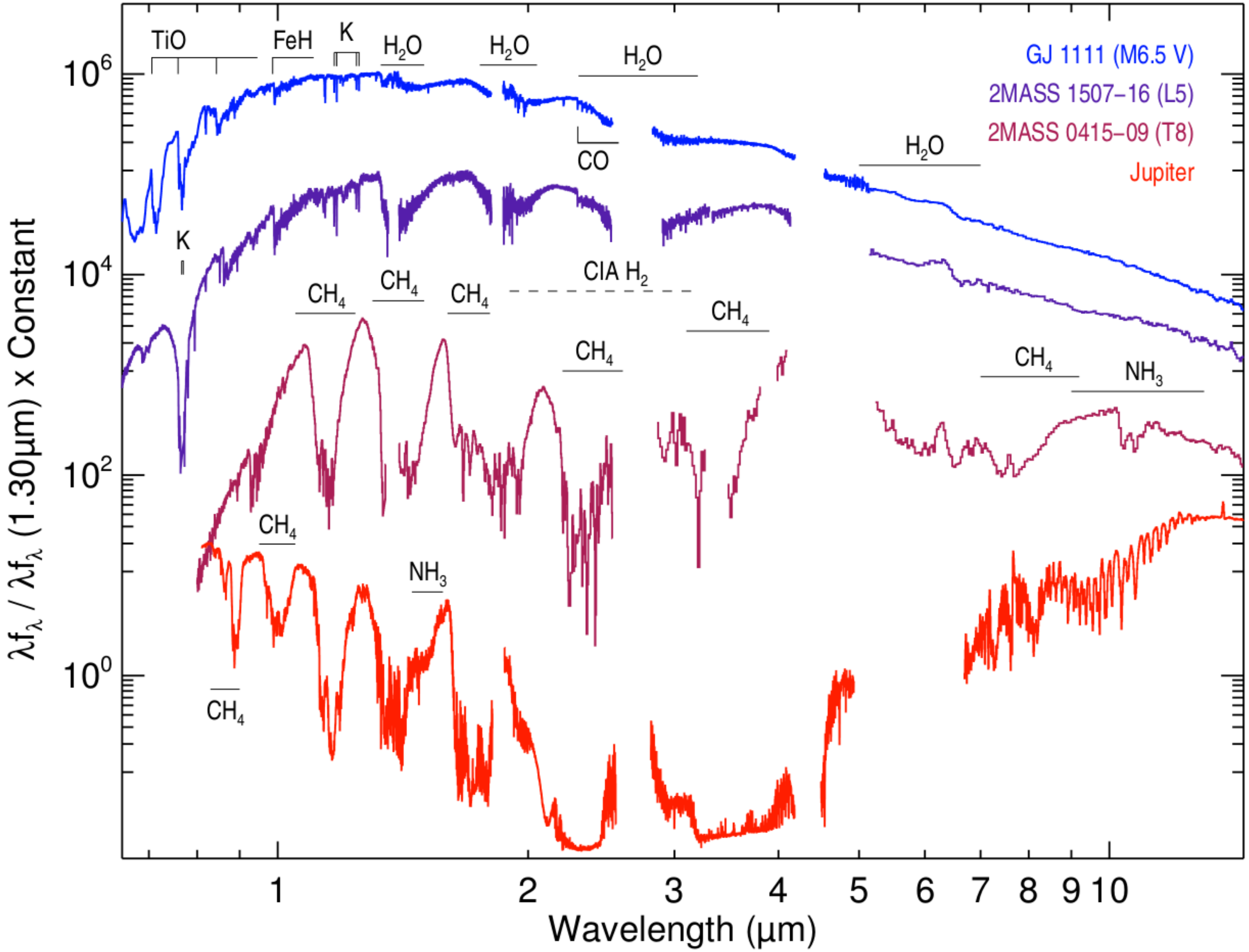
Line ratios → Temperature



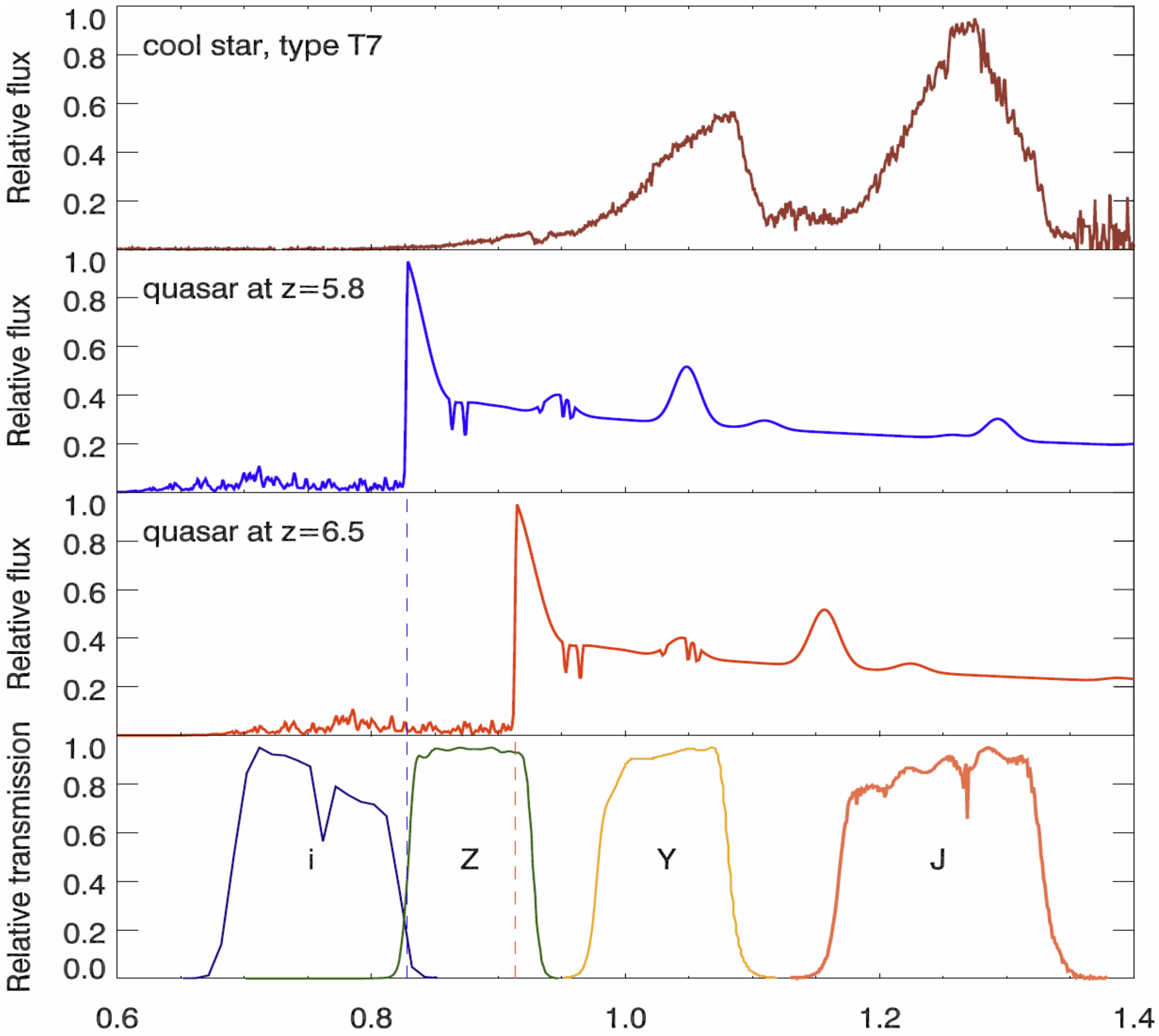
I --- neutral atoms; II --- ionized once; III --- ionized twice; …

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

Brown dwarfs and Planetary Objects

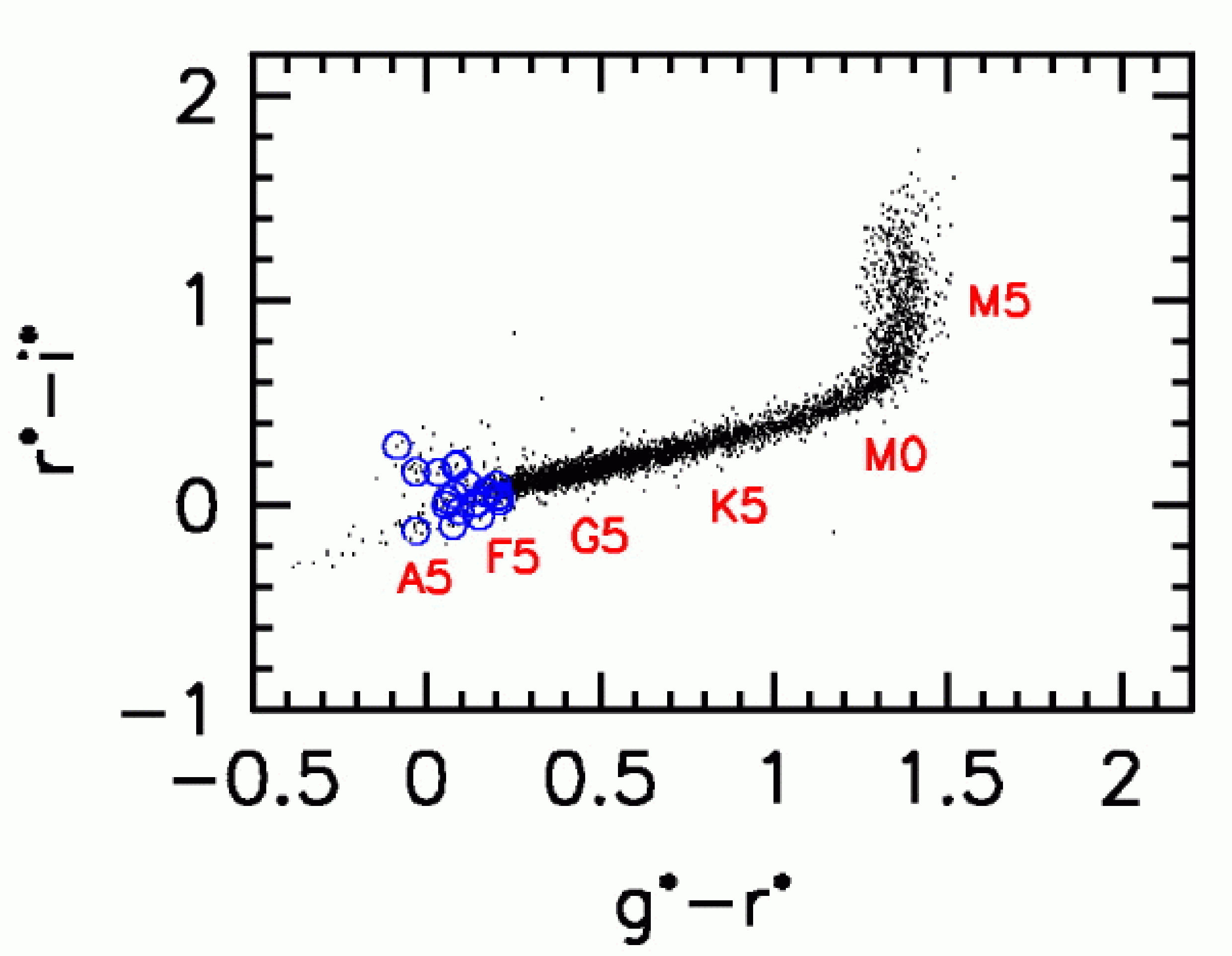


http://www.exoclimes.com/paper-outlines/exoplanets-and-brown-dwarfs-ii/



Using imaging photometry (time saving) to trace spectral features

One of the SDSS color-color diagrams



http://spiff.rit.edu/classes/phys440/lectures/color/sdss_color_color_b.gif

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

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

$$M_{\rm V}^{\odot} = +4.83 \text{ mag} \quad m_{\rm V}^{\odot} = -26.74 \text{ mag}$$

But there is extinction … $\boxed{m_\lambda - M_\lambda = 5\log(d_{\rm pc}) - 5 + A_\lambda}$ $d_{\rm pc} = 1/p''$

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

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

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

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

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

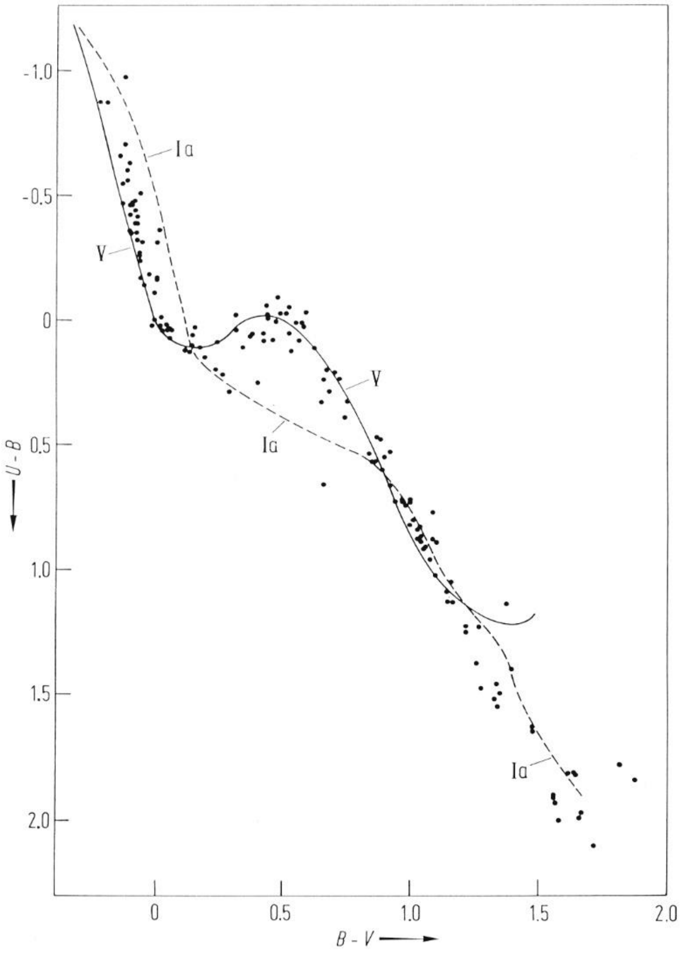
Total energy flux of the Sun received immediately outside the Earth atmosphere ($d = 1$ au)

$$f_\odot = 1.3608(5) \times 10^6 \, [\mathrm{erg\ s^{-1}\ cm^{-2}}]$$
$$= \ 1.3608 \, [\mathrm{kW/m^2}] \text{ (solar “constant”)}$$

- ✓ Including radiation at all frequency
- ✓ Varied $< 0.2\%$ in the past 400 years; varying duing 11-year sunspot cycles
- ✓ Much lower billions of years ago (*why?*)

Two-Color Diagrams

$(U - B)$ versus $(U - B)$



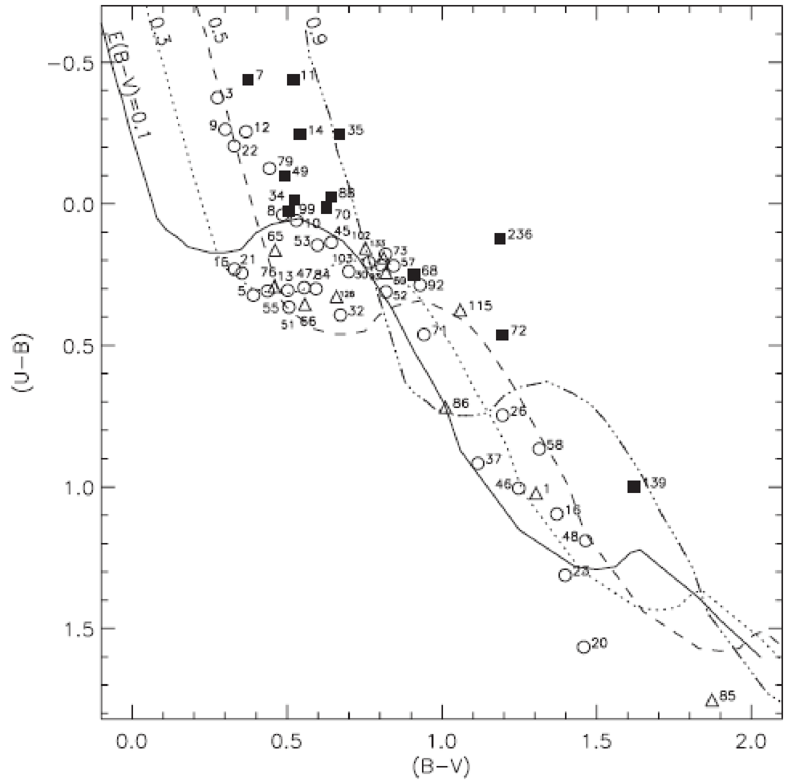
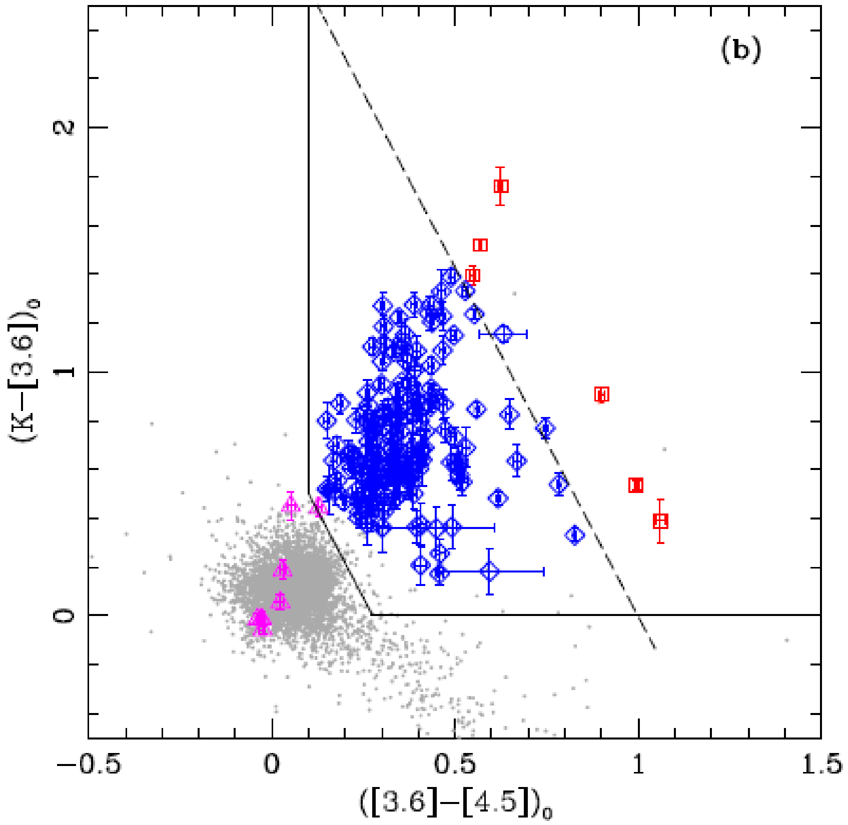


Figure 8. $(U - B)$ vs. $(B - V)$ TCD of the stars with polarimetric data. The symbols are the same as in Figure 7. The ZAMS from Schmidt-Kaler (1982) is shifted along a normal reddening vector with a slope of $E(U - B)/E(B - V) = 0.72$. The TCD shows a variable reddening in the cluster region with $E(B - V)_{\min} \sim 0.5$ mag and $E(B - V)_{\max} \sim 0.9$ mag.

Pandey+13



Spitzer/IRAC and 2MASS color-color diagram for the sources (black dots) in IC 1805. Class I sources are shown with red squares and Class II with blue diamonds. Magenta triangles mark the transition disk candidates.

Panwar+17

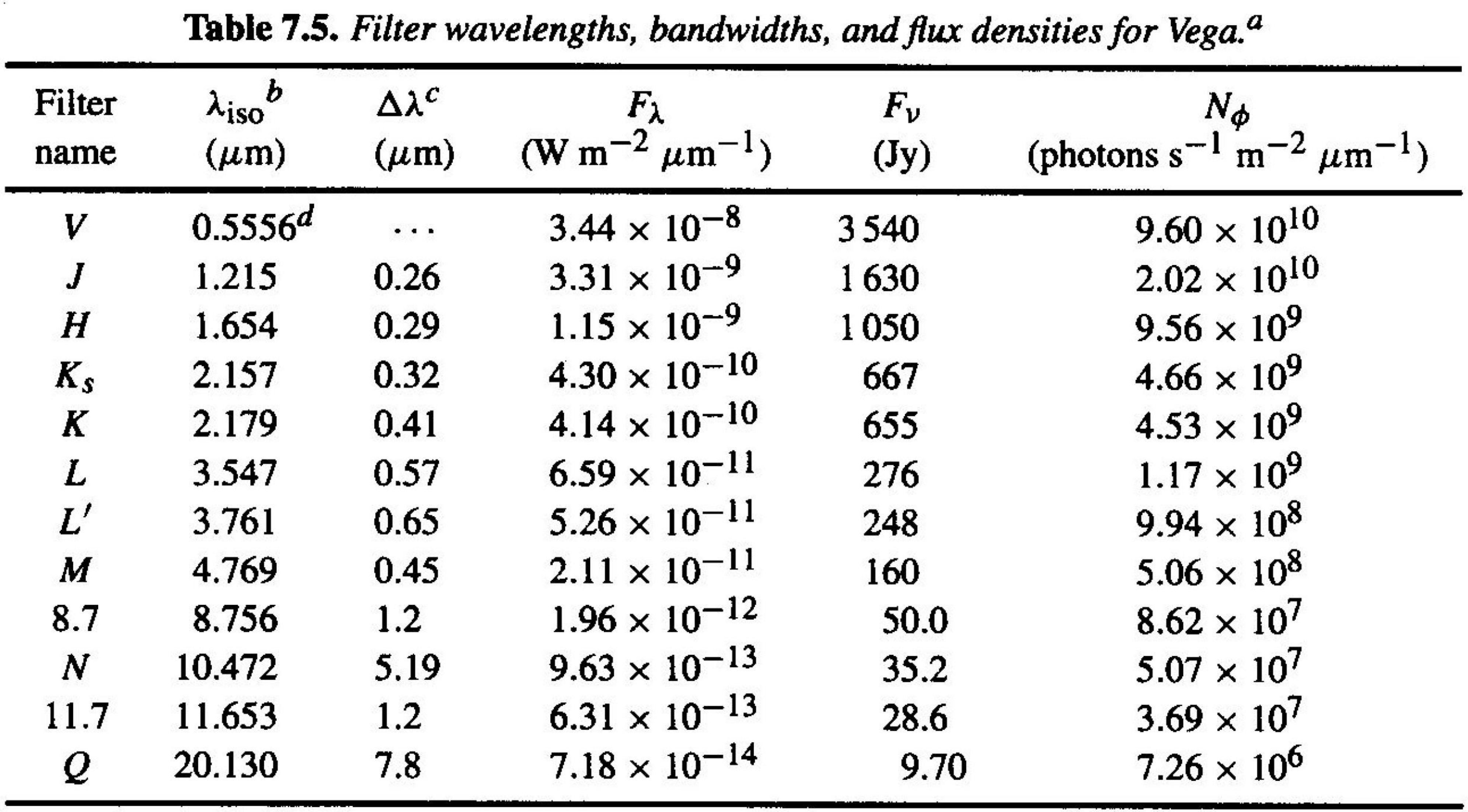


Table 7.5. *Filter wavelengths, bandwidths, and flux densities for Vega.*[a]

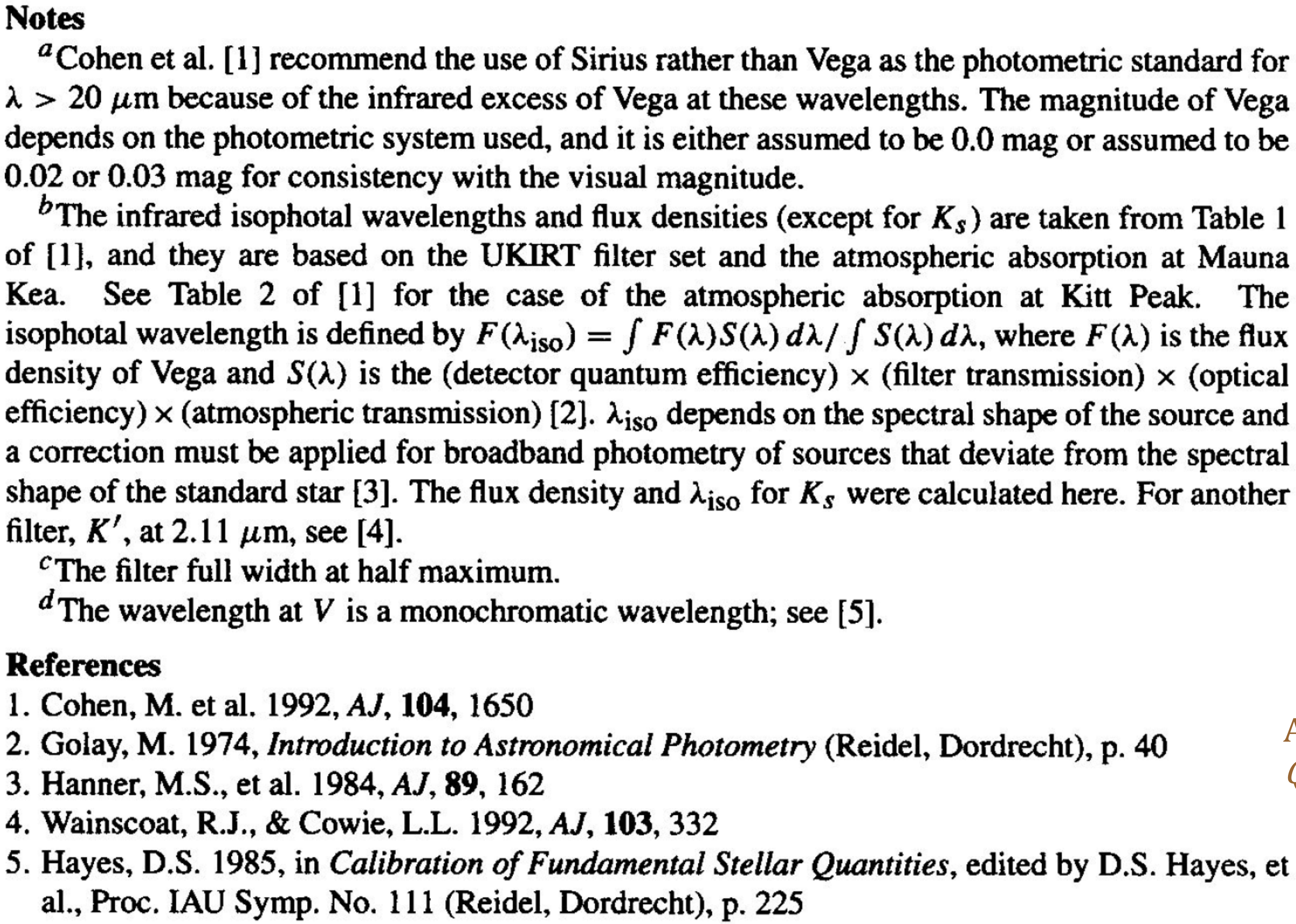
Filter name	λ_{iso}[b] (μm)	$\Delta\lambda$[c] (μm)	F_λ (W m^{-2} μm^{-1})	F_ν (Jy)	N_ϕ (photons s^{-1} m^{-2} μm^{-1})
V	0.5556[d]	...	3.44×10^{-8}	3 540	9.60×10^{10}
J	1.215	0.26	3.31×10^{-9}	1 630	2.02×10^{10}
H	1.654	0.29	1.15×10^{-9}	1 050	9.56×10^{9}
K_s	2.157	0.32	4.30×10^{-10}	667	4.66×10^{9}
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}

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

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 $F(\lambda_{\rm iso}) = \int F(\lambda)S(\lambda)\,d\lambda / \int S(\lambda)\,d\lambda$, where $F(\lambda)$ is the flux density of Vega and $S(\lambda)$ is the (detector quantum efficiency) × (filter transmission) × (optical efficiency) × (atmospheric transmission) [2]. $\lambda_{\rm iso}$ 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 $\lambda_{\rm iso}$ 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

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

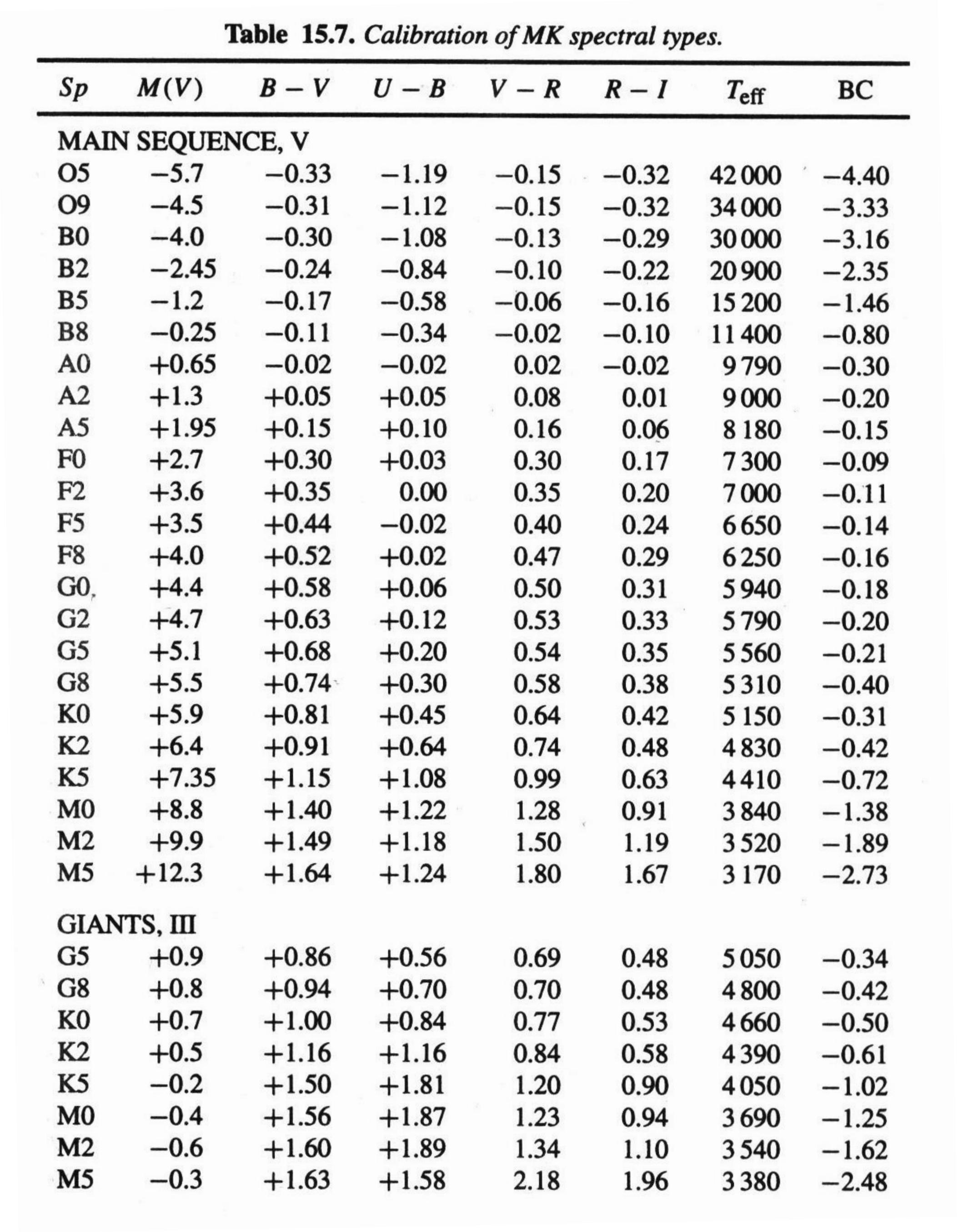


Table 15.7. *Calibration of MK spectral types.*

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

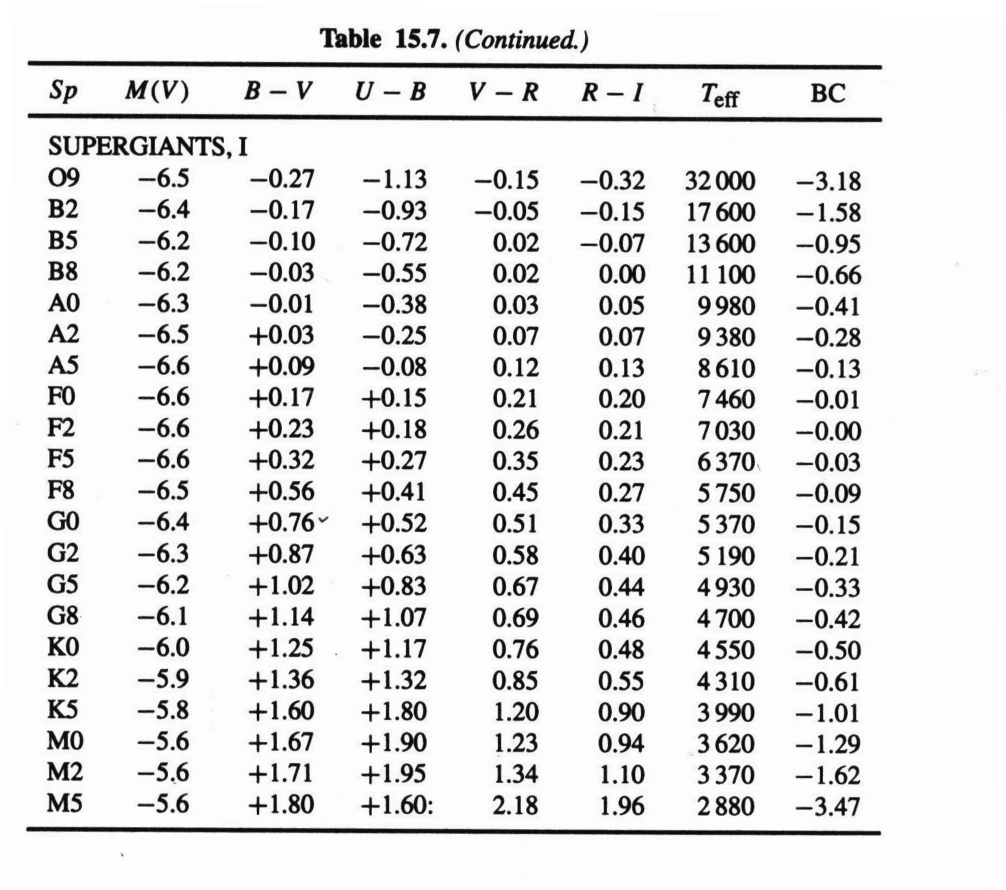


Table 15.7. *(Continued.)*

Sp	*M*(*V*)	*B* − *V*	*U* − *B*	*V* − *R*	*R* − *I*	$T_{\rm eff}$	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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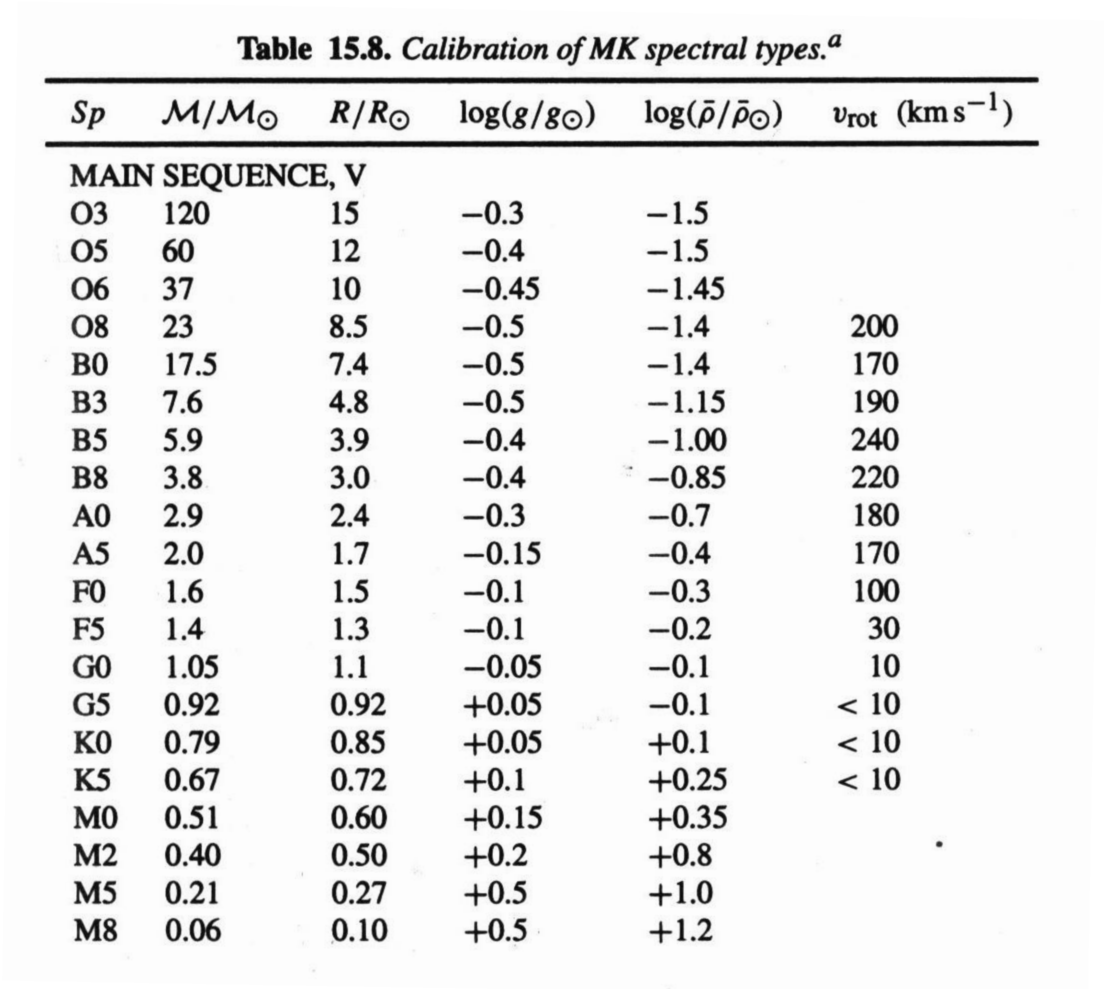

Table 15.8. *Calibration of MK spectral types.*[a]

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

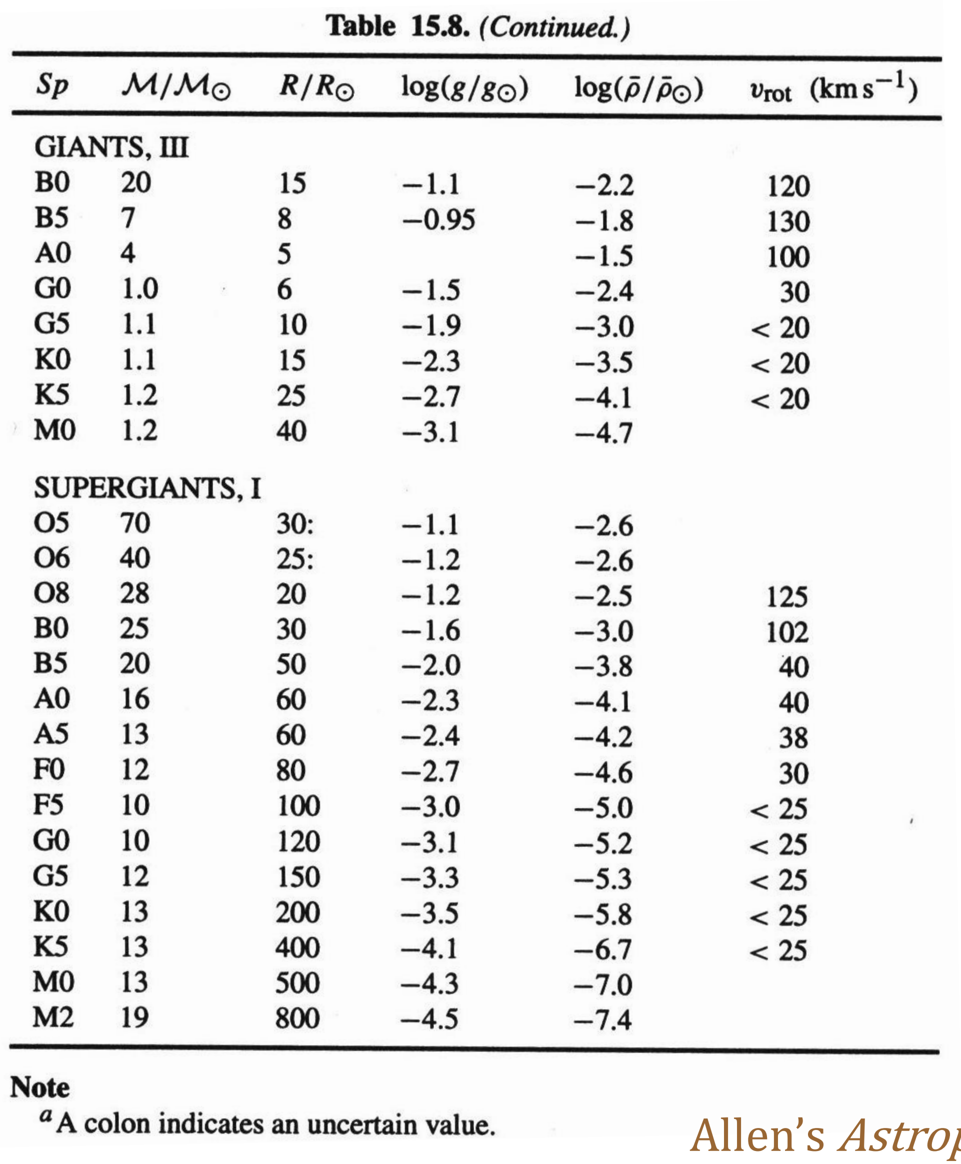

Table 15.8. *(Continued.)*

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.

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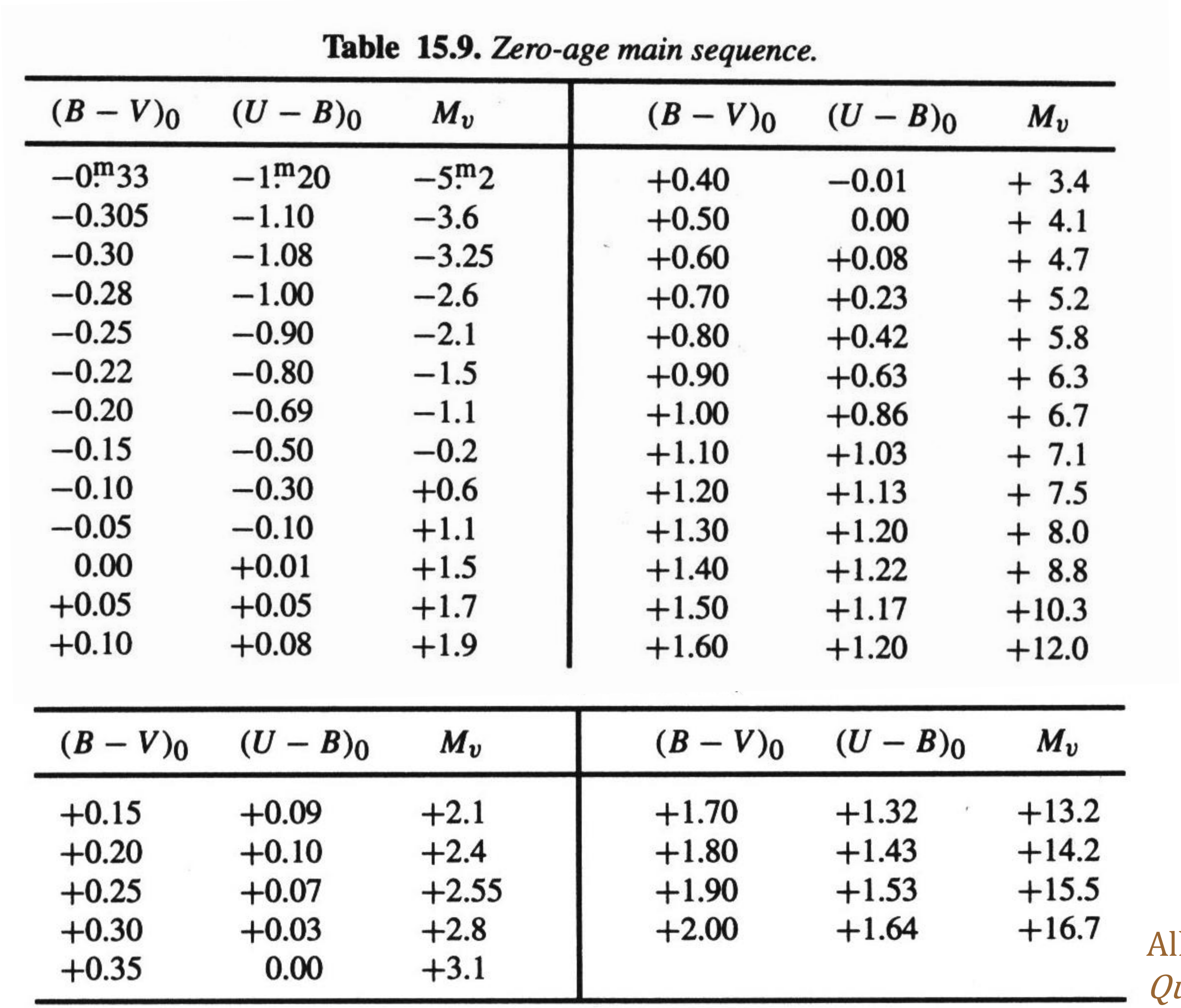
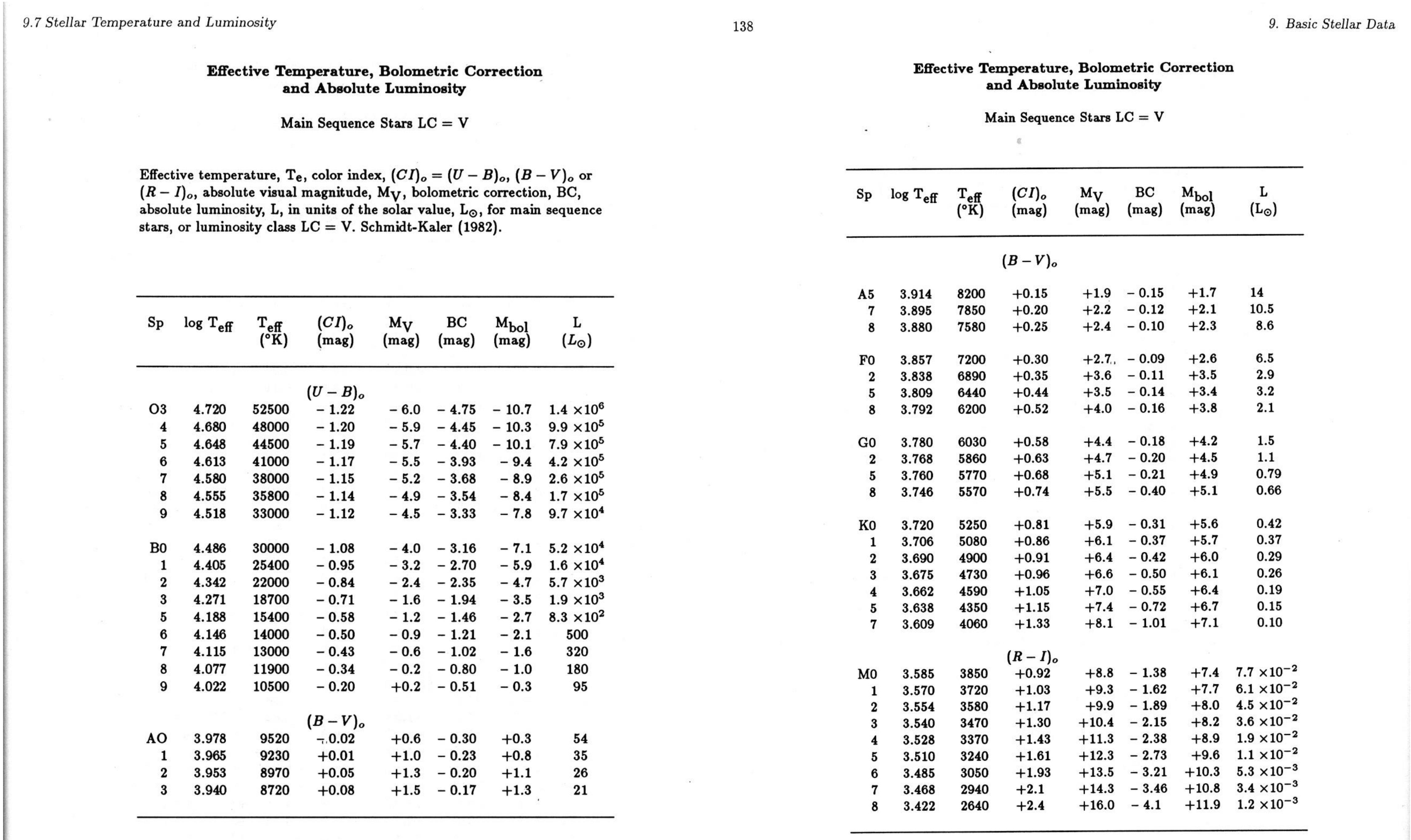


Table 15.9. *Zero-age main sequence.*

$(B-V)_0$	$(U-B)_0$	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)



Effective Temperature, Bolometric Correction and Absolute Luminosity

Main Sequence Stars LC = V

Effective temperature, T_e, color index, $(CI)_o = (U-B)_o$, $(B-V)_o$ or $(R-I)_o$, absolute visual magnitude, M_V, bolometric correction, BC, absolute luminosity, L, in units of the solar value, $L_\odot$, for main sequence stars, or luminosity class LC = V. Schmidt-Kaler (1982).

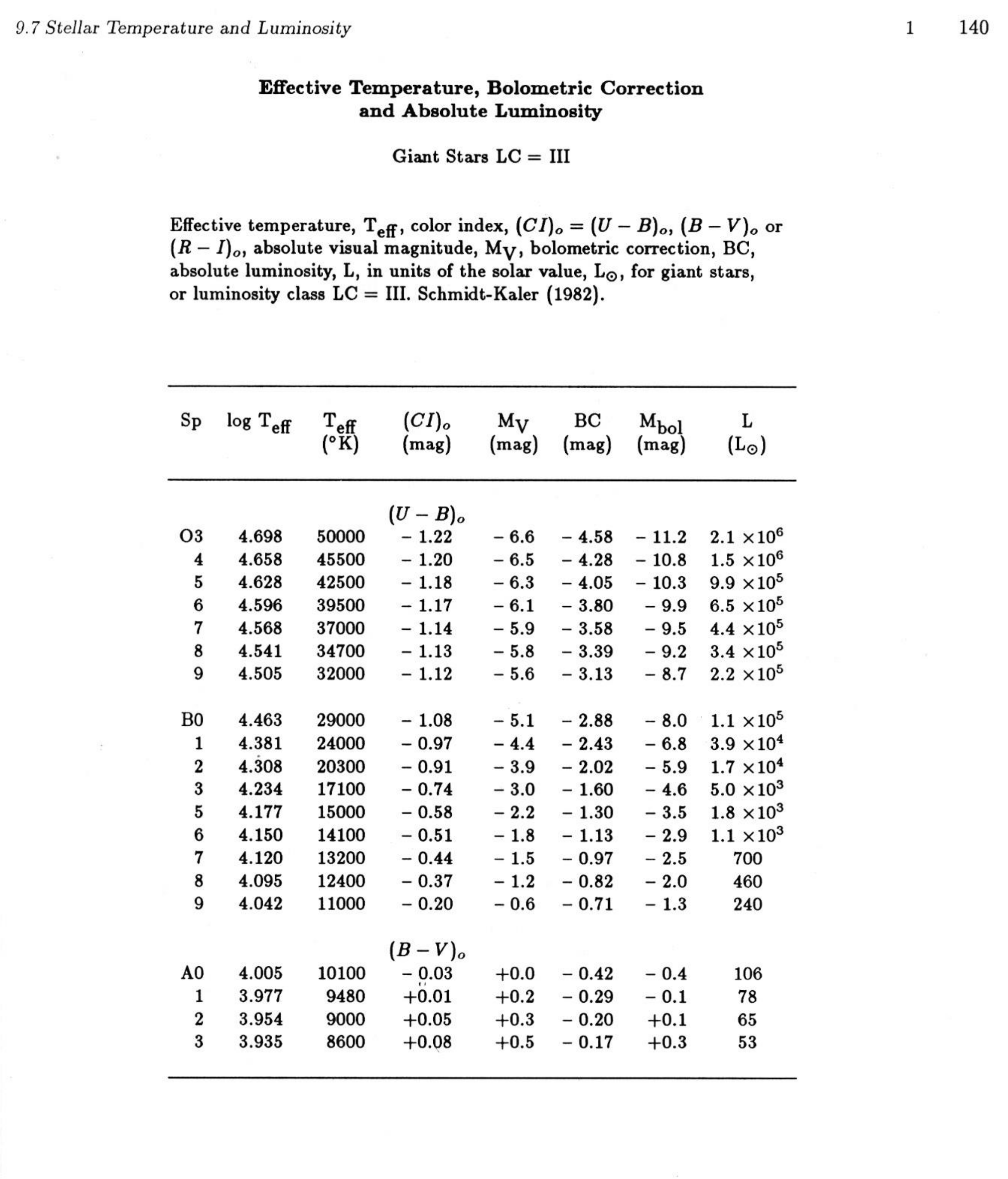
Sp	log T_{eff}	T_{eff} (°K)	$(CI)_o$ (mag)	M_V (mag)	BC (mag)	M_{bol} (mag)	L ($L_\odot$)
			$(U-B)_o$				
O3	4.720	52500	− 1.22	− 6.0	− 4.75	− 10.7	1.4×10^6
4	4.680	48000	− 1.20	− 5.9	− 4.45	− 10.3	9.9×10^5
5	4.648	44500	− 1.19	− 5.7	− 4.40	− 10.1	7.9×10^5
6	4.613	41000	− 1.17	− 5.5	− 3.93	− 9.4	4.2×10^5
7	4.580	38000	− 1.15	− 5.2	− 3.68	− 8.9	2.6×10^5
8	4.555	35800	− 1.14	− 4.9	− 3.54	− 8.4	1.7×10^5
9	4.518	33000	− 1.12	− 4.5	− 3.33	− 7.8	9.7×10^4
B0	4.486	30000	− 1.08	− 4.0	− 3.16	− 7.1	5.2×10^4
1	4.405	25400	− 0.95	− 3.2	− 2.70	− 5.9	1.6×10^4
2	4.342	22000	− 0.84	− 2.4	− 2.35	− 4.7	5.7×10^3
3	4.271	18700	− 0.71	− 1.6	− 1.94	− 3.5	1.9×10^3
5	4.188	15400	− 0.58	− 1.2	− 1.46	− 2.7	8.3×10^2
6	4.146	14000	− 0.50	− 0.9	− 1.21	− 2.1	500
7	4.115	13000	− 0.43	− 0.6	− 1.02	− 1.6	320
8	4.077	11900	− 0.34	− 0.2	− 0.80	− 1.0	180
9	4.022	10500	− 0.20	+0.2	− 0.51	− 0.3	95
			$(B-V)_o$				
AO	3.978	9520	− 0.02	+0.6	− 0.30	+0.3	54
1	3.965	9230	+0.01	+1.0	− 0.23	+0.8	35
2	3.953	8970	+0.05	+1.3	− 0.20	+1.1	26
3	3.940	8720	+0.08	+1.5	− 0.17	+1.3	21

Effective Temperature, Bolometric Correction and Absolute Luminosity

Main Sequence Stars LC = V

Sp	log T_{eff}	T_{eff} (°K)	$(CI)_o$ (mag)	M_V (mag)	BC (mag)	M_{bol} (mag)	L ($L_\odot$)
			$(B-V)_o$				
A5	3.914	8200	+0.15	+1.9	− 0.15	+1.7	14
7	3.895	7850	+0.20	+2.2	− 0.12	+2.1	10.5
8	3.880	7580	+0.25	+2.4	− 0.10	+2.3	8.6
F0	3.857	7200	+0.30	+2.7	− 0.09	+2.6	6.5
2	3.838	6890	+0.35	+3.6	− 0.11	+3.5	2.9
5	3.809	6440	+0.44	+3.5	− 0.14	+3.4	3.2
8	3.792	6200	+0.52	+4.0	− 0.16	+3.8	2.1
G0	3.780	6030	+0.58	+4.4	− 0.18	+4.2	1.5
2	3.768	5860	+0.63	+4.7	− 0.20	+4.5	1.1
5	3.760	5770	+0.68	+5.1	− 0.21	+4.9	0.79
8	3.746	5570	+0.74	+5.5	− 0.40	+5.1	0.66
K0	3.720	5250	+0.81	+5.9	− 0.31	+5.6	0.42
1	3.706	5080	+0.86	+6.1	− 0.37	+5.7	0.37
2	3.690	4900	+0.91	+6.4	− 0.42	+6.0	0.29
3	3.675	4730	+0.96	+6.6	− 0.50	+6.1	0.26
4	3.662	4590	+1.05	+7.0	− 0.55	+6.4	0.19
5	3.638	4350	+1.15	+7.4	− 0.72	+6.7	0.15
7	3.609	4060	+1.33	+8.1	− 1.01	+7.1	0.10
			$(R-I)_o$				
M0	3.585	3850	+0.92	+8.8	− 1.38	+7.4	7.7×10^{-2}
1	3.570	3720	+1.03	+9.3	− 1.62	+7.7	6.1×10^{-2}
2	3.554	3580	+1.17	+9.9	− 1.89	+8.0	4.5×10^{-2}
3	3.540	3470	+1.30	+10.4	− 2.15	+8.2	3.6×10^{-2}
4	3.528	3370	+1.43	+11.3	− 2.38	+8.9	1.9×10^{-2}
5	3.510	3240	+1.61	+12.3	− 2.73	+9.6	1.1×10^{-2}
6	3.485	3050	+1.93	+13.5	− 3.21	+10.3	5.3×10^{-3}
7	3.468	2940	+2.1	+14.3	− 3.46	+10.8	3.4×10^{-3}
8	3.422	2640	+2.4	+16.0	− 4.1	+11.9	1.2×10^{-3}

Lang “*Astrophysical Data: Planets and Stars*” (1992)

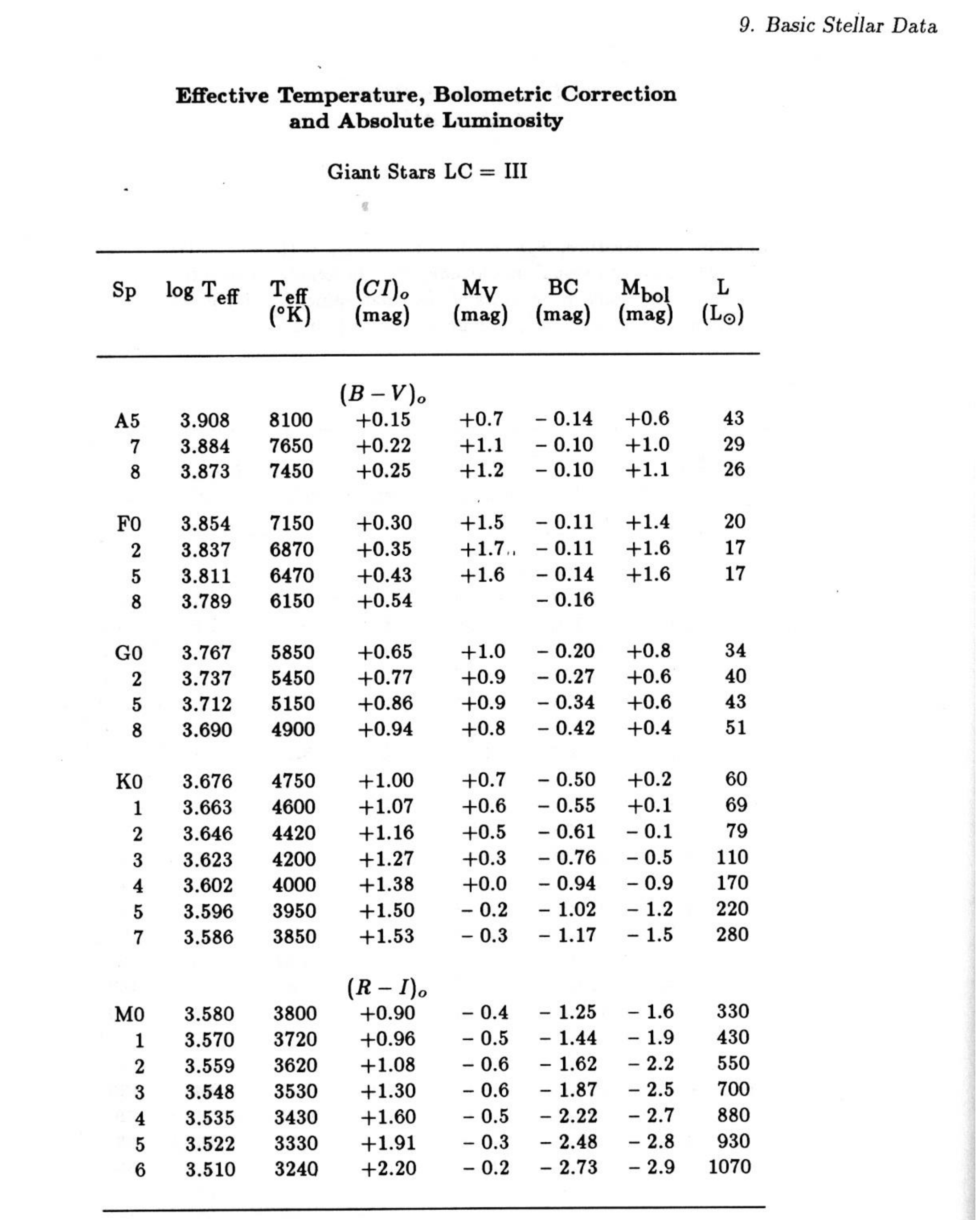


Effective Temperature, Bolometric Correction and Absolute Luminosity

Giant Stars LC = III

Effective temperature, T_{eff}, color index, $(CI)_o = (U-B)_o$, $(B-V)_o$ or $(R-I)_o$, absolute visual magnitude, M_V, bolometric correction, BC, absolute luminosity, L, in units of the solar value, $L_\odot$, for giant stars, or luminosity class LC = III. Schmidt-Kaler (1982).

Sp	log T_{eff}	T_{eff} (°K)	$(CI)_o$ (mag)	M_V (mag)	BC (mag)	M_{bol} (mag)	L ($L_\odot$)
			$(U-B)_o$				
O3	4.698	50000	− 1.22	− 6.6	− 4.58	− 11.2	2.1×10^6
4	4.658	45500	− 1.20	− 6.5	− 4.28	− 10.8	1.5×10^6
5	4.628	42500	− 1.18	− 6.3	− 4.05	− 10.3	9.9×10^5
6	4.596	39500	− 1.17	− 6.1	− 3.80	− 9.9	6.5×10^5
7	4.568	37000	− 1.14	− 5.9	− 3.58	− 9.5	4.4×10^5
8	4.541	34700	− 1.13	− 5.8	− 3.39	− 9.2	3.4×10^5
9	4.505	32000	− 1.12	− 5.6	− 3.13	− 8.7	2.2×10^5
B0	4.463	29000	− 1.08	− 5.1	− 2.88	− 8.0	1.1×10^5
1	4.381	24000	− 0.97	− 4.4	− 2.43	− 6.8	3.9×10^4
2	4.308	20300	− 0.91	− 3.9	− 2.02	− 5.9	1.7×10^4
3	4.234	17100	− 0.74	− 3.0	− 1.60	− 4.6	5.0×10^3
5	4.177	15000	− 0.58	− 2.2	− 1.30	− 3.5	1.8×10^3
6	4.150	14100	− 0.51	− 1.8	− 1.13	− 2.9	1.1×10^3
7	4.120	13200	− 0.44	− 1.5	− 0.97	− 2.5	700
8	4.095	12400	− 0.37	− 1.2	− 0.82	− 2.0	460
9	4.042	11000	− 0.20	− 0.6	− 0.71	− 1.3	240
			$(B-V)_o$				
A0	4.005	10100	− 0.03	+0.0	− 0.42	− 0.4	106
1	3.977	9480	+0.01	+0.2	− 0.29	− 0.1	78
2	3.954	9000	+0.05	+0.3	− 0.20	+0.1	65
3	3.935	8600	+0.08	+0.5	− 0.17	+0.3	53

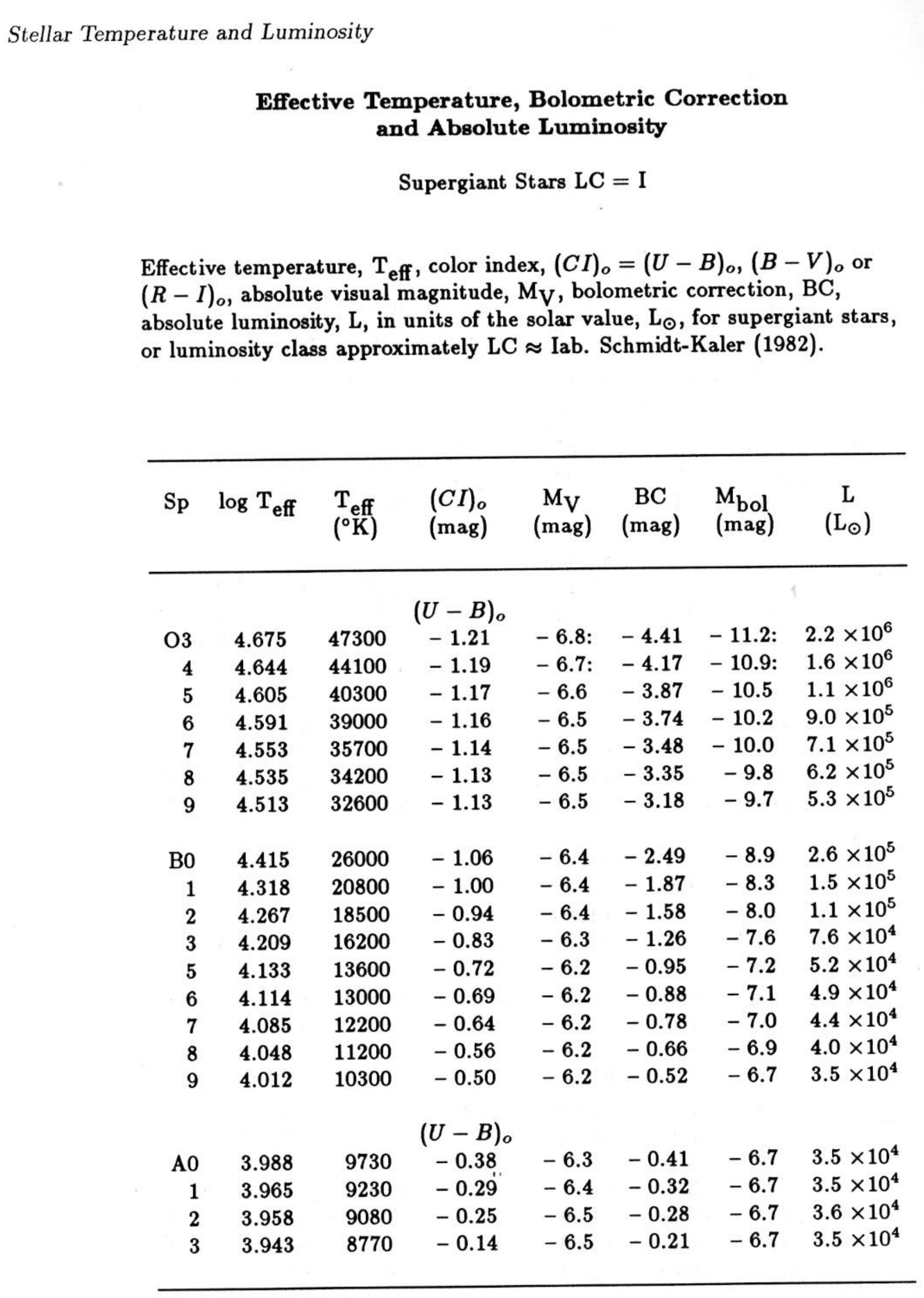


Effective Temperature, Bolometric Correction and Absolute Luminosity

Giant Stars LC = III

Sp	log T_{eff}	T_{eff} (°K)	$(CI)_o$ (mag)	M_V (mag)	BC (mag)	M_{bol} (mag)	L ($L_\odot$)
			$(B-V)_o$				
A5	3.908	8100	+0.15	+0.7	− 0.14	+0.6	43
7	3.884	7650	+0.22	+1.1	− 0.10	+1.0	29
8	3.873	7450	+0.25	+1.2	− 0.10	+1.1	26
F0	3.854	7150	+0.30	+1.5	− 0.11	+1.4	20
2	3.837	6870	+0.35	+1.7	− 0.11	+1.6	17
5	3.811	6470	+0.43	+1.6	− 0.14	+1.6	17
8	3.789	6150	+0.54		− 0.16		
G0	3.767	5850	+0.65	+1.0	− 0.20	+0.8	34
2	3.737	5450	+0.77	+0.9	− 0.27	+0.6	40
5	3.712	5150	+0.86	+0.9	− 0.34	+0.6	43
8	3.690	4900	+0.94	+0.8	− 0.42	+0.4	51
K0	3.676	4750	+1.00	+0.7	− 0.50	+0.2	60
1	3.663	4600	+1.07	+0.6	− 0.55	+0.1	69
2	3.646	4420	+1.16	+0.5	− 0.61	− 0.1	79
3	3.623	4200	+1.27	+0.3	− 0.76	− 0.5	110
4	3.602	4000	+1.38	+0.0	− 0.94	− 0.9	170
5	3.596	3950	+1.50	− 0.2	− 1.02	− 1.2	220
7	3.586	3850	+1.53	− 0.3	− 1.17	− 1.5	280
			$(R-I)_o$				
M0	3.580	3800	+0.90	− 0.4	− 1.25	− 1.6	330
1	3.570	3720	+0.96	− 0.5	− 1.44	− 1.9	430
2	3.559	3620	+1.08	− 0.6	− 1.62	− 2.2	550
3	3.548	3530	+1.30	− 0.6	− 1.87	− 2.5	700
4	3.535	3430	+1.60	− 0.5	− 2.22	− 2.7	880
5	3.522	3330	+1.91	− 0.3	− 2.48	− 2.8	930
6	3.510	3240	+2.20	− 0.2	− 2.73	− 2.9	1070

Lang "*Astrophysical Data: Planets and Stars*" (1992)

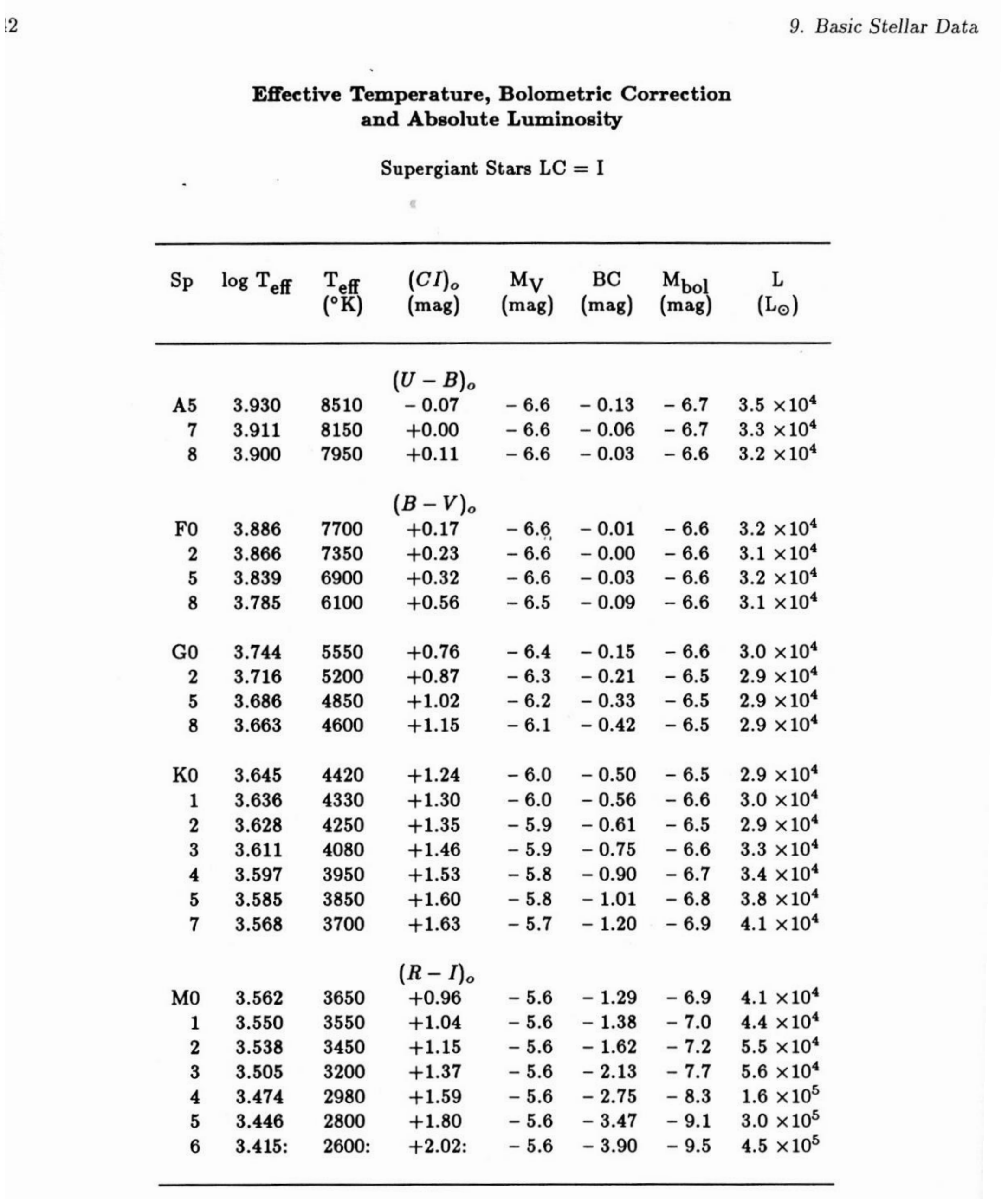


Effective Temperature, Bolometric Correction and Absolute Luminosity

Supergiant Stars LC = I

Effective temperature, T_{eff}, color index, $(CI)_o = (U-B)_o$, $(B-V)_o$ or $(R-I)_o$, absolute visual magnitude, M_V, bolometric correction, BC, absolute luminosity, L, in units of the solar value, $L_\odot$, for supergiant stars, or luminosity class approximately LC ≈ Iab. Schmidt-Kaler (1982).

Sp	log T_{eff}	T_{eff} (°K)	$(CI)_o$ (mag)	M_V (mag)	BC (mag)	M_{bol} (mag)	L ($L_\odot$)
			$(U-B)_o$				
O3	4.675	47300	– 1.21	– 6.8:	– 4.41	– 11.2:	2.2×10^6
4	4.644	44100	– 1.19	– 6.7:	– 4.17	– 10.9:	1.6×10^6
5	4.605	40300	– 1.17	– 6.6	– 3.87	– 10.5	1.1×10^6
6	4.591	39000	– 1.16	– 6.5	– 3.74	– 10.2	9.0×10^5
7	4.553	35700	– 1.14	– 6.5	– 3.48	– 10.0	7.1×10^5
8	4.535	34200	– 1.13	– 6.5	– 3.35	– 9.8	6.2×10^5
9	4.513	32600	– 1.13	– 6.5	– 3.18	– 9.7	5.3×10^5
B0	4.415	26000	– 1.06	– 6.4	– 2.49	– 8.9	2.6×10^5
1	4.318	20800	– 1.00	– 6.4	– 1.87	– 8.3	1.5×10^5
2	4.267	18500	– 0.94	– 6.4	– 1.58	– 8.0	1.1×10^5
3	4.209	16200	– 0.83	– 6.3	– 1.26	– 7.6	7.6×10^4
5	4.133	13600	– 0.72	– 6.2	– 0.95	– 7.2	5.2×10^4
6	4.114	13000	– 0.69	– 6.2	– 0.88	– 7.1	4.9×10^4
7	4.085	12200	– 0.64	– 6.2	– 0.78	– 7.0	4.4×10^4
8	4.048	11200	– 0.56	– 6.2	– 0.66	– 6.9	4.0×10^4
9	4.012	10300	– 0.50	– 6.2	– 0.52	– 6.7	3.5×10^4
			$(U-B)_o$				
A0	3.988	9730	– 0.38	– 6.3	– 0.41	– 6.7	3.5×10^4
1	3.965	9230	– 0.29	– 6.4	– 0.32	– 6.7	3.5×10^4
2	3.958	9080	– 0.25	– 6.5	– 0.28	– 6.7	3.6×10^4
3	3.943	8770	– 0.14	– 6.5	– 0.21	– 6.7	3.5×10^4



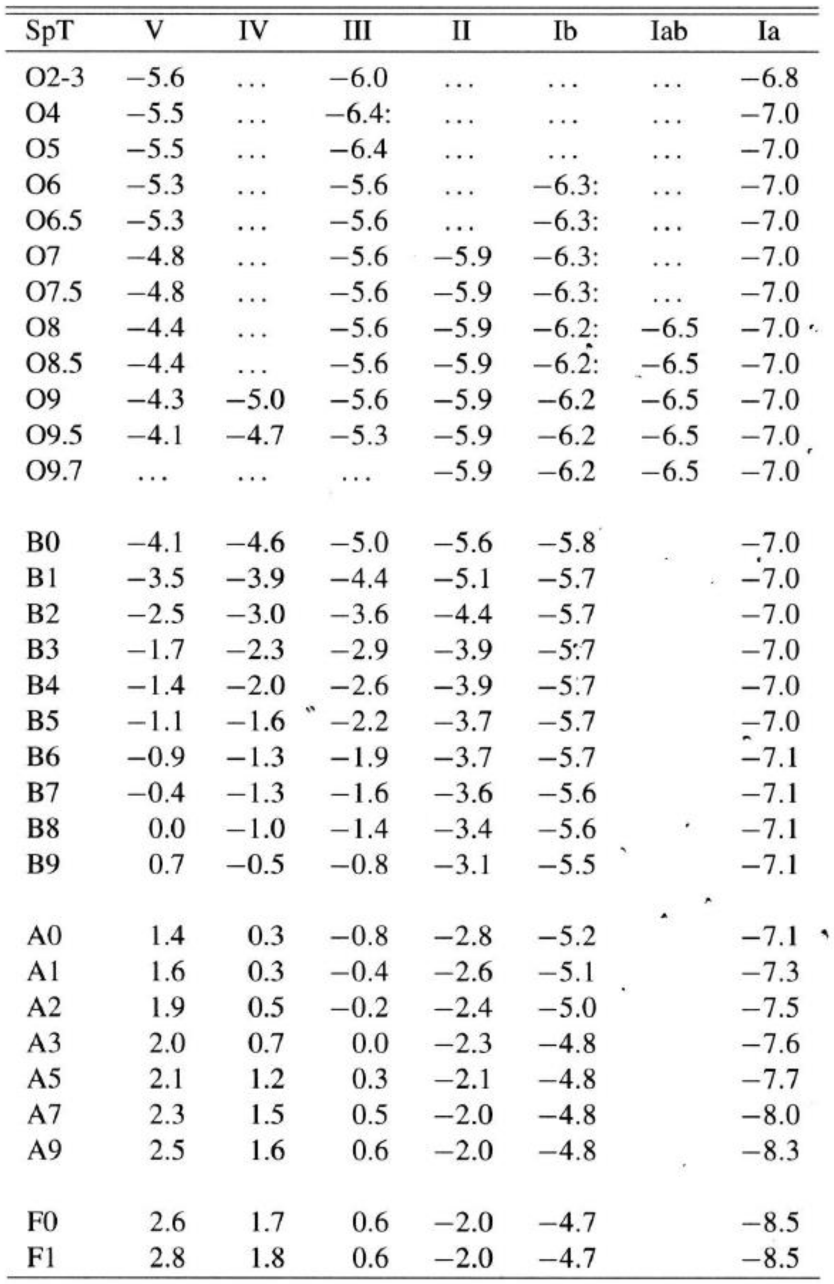
Effective Temperature, Bolometric Correction and Absolute Luminosity

Supergiant Stars LC = I

Sp	log T_{eff}	T_{eff} (°K)	$(CI)_o$ (mag)	M_V (mag)	BC (mag)	M_{bol} (mag)	L ($L_\odot$)
			$(U-B)_o$				
A5	3.930	8510	– 0.07	– 6.6	– 0.13	– 6.7	3.5×10^4
7	3.911	8150	+0.00	– 6.6	– 0.06	– 6.7	3.3×10^4
8	3.900	7950	+0.11	– 6.6	– 0.03	– 6.6	3.2×10^4
			$(B-V)_o$				
F0	3.886	7700	+0.17	– 6.6	– 0.01	– 6.6	3.2×10^4
2	3.866	7350	+0.23	– 6.6	– 0.00	– 6.6	3.1×10^4
5	3.839	6900	+0.32	– 6.6	– 0.03	– 6.6	3.2×10^4
8	3.785	6100	+0.56	– 6.5	– 0.09	– 6.6	3.1×10^4
G0	3.744	5550	+0.76	– 6.4	– 0.15	– 6.6	3.0×10^4
2	3.716	5200	+0.87	– 6.3	– 0.21	– 6.5	2.9×10^4
5	3.686	4850	+1.02	– 6.2	– 0.33	– 6.5	2.9×10^4
8	3.663	4600	+1.15	– 6.1	– 0.42	– 6.5	2.9×10^4
K0	3.645	4420	+1.24	– 6.0	– 0.50	– 6.5	2.9×10^4
1	3.636	4330	+1.30	– 6.0	– 0.56	– 6.6	3.0×10^4
2	3.628	4250	+1.35	– 5.9	– 0.61	– 6.5	2.9×10^4
3	3.611	4080	+1.46	– 5.9	– 0.75	– 6.6	3.3×10^4
4	3.597	3950	+1.53	– 5.8	– 0.90	– 6.7	3.4×10^4
5	3.585	3850	+1.60	– 5.8	– 1.01	– 6.8	3.8×10^4
7	3.568	3700	+1.63	– 5.7	– 1.20	– 6.9	4.1×10^4
			$(R-I)_o$				
M0	3.562	3650	+0.96	– 5.6	– 1.29	– 6.9	4.1×10^4
1	3.550	3550	+1.04	– 5.6	– 1.38	– 7.0	4.4×10^4
2	3.538	3450	+1.15	– 5.6	– 1.62	– 7.2	5.5×10^4
3	3.505	3200	+1.37	– 5.6	– 2.13	– 7.7	5.6×10^4
4	3.474	2980	+1.59	– 5.6	– 2.75	– 8.3	1.6×10^5
5	3.446	2800	+1.80	– 5.6	– 3.47	– 9.1	3.0×10^5
6	3.415:	2600:	+2.02:	– 5.6	– 3.90	– 9.5	4.5×10^5

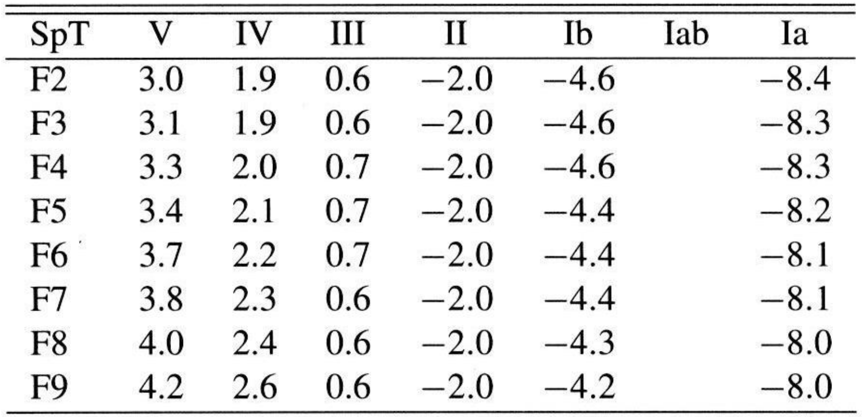
Lang "*Astrophysical Data: Planets and Stars*" (1992)

Table B.1 Averaged Absolute Visual Magnitude Calibration for the Early-type Stars



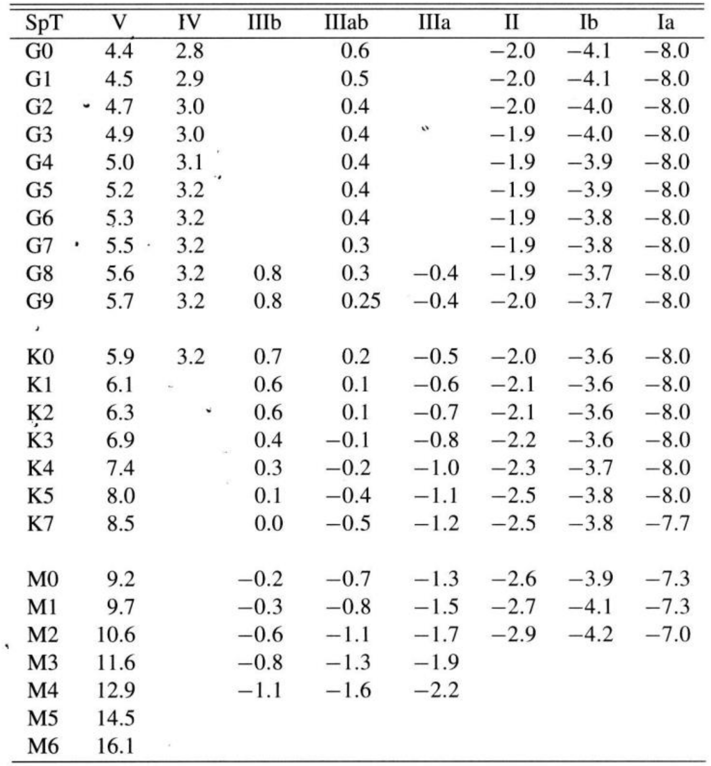
SpT	V	IV	III	II	Ib	Iab	Ia
O2-3	−5.6	. . .	−6.0	. . .	. . .	. . .	−6.8
O4	−5.5	. . .	−6.4:	. . .	. . .	. . .	−7.0
O5	−5.5	. . .	−6.4	. . .	. . .	. . .	−7.0
O6	−5.3	. . .	−5.6	. . .	−6.3:	. . .	−7.0
O6.5	−5.3	. . .	−5.6	. . .	−6.3:	. . .	−7.0
O7	−4.8	. . .	−5.6	−5.9	−6.3:	. . .	−7.0
O7.5	−4.8	. . .	−5.6	−5.9	−6.3:	. . .	−7.0
O8	−4.4	. . .	−5.6	−5.9	−6.2:	−6.5	−7.0
O8.5	−4.4	. . .	−5.6	−5.9	−6.2:	−6.5	−7.0
O9	−4.3	−5.0	−5.6	−5.9	−6.2	−6.5	−7.0
O9.5	−4.1	−4.7	−5.3	−5.9	−6.2	−6.5	−7.0
O9.7	. . .	. . .	. . .	−5.9	−6.2	−6.5	−7.0
B0	−4.1	−4.6	−5.0	−5.6	−5.8		−7.0
B1	−3.5	−3.9	−4.4	−5.1	−5.7		−7.0
B2	−2.5	−3.0	−3.6	−4.4	−5.7		−7.0
B3	−1.7	−2.3	−2.9	−3.9	−5.7		−7.0
B4	−1.4	−2.0	−2.6	−3.9	−5.7		−7.0
B5	−1.1	−1.6	−2.2	−3.7	−5.7		−7.0
B6	−0.9	−1.3	−1.9	−3.7	−5.7		−7.1
B7	−0.4	−1.3	−1.6	−3.6	−5.6		−7.1
B8	0.0	−1.0	−1.4	−3.4	−5.6		−7.1
B9	0.7	−0.5	−0.8	−3.1	−5.5		−7.1
A0	1.4	0.3	−0.8	−2.8	−5.2		−7.1
A1	1.6	0.3	−0.4	−2.6	−5.1		−7.3
A2	1.9	0.5	−0.2	−2.4	−5.0		−7.5
A3	2.0	0.7	0.0	−2.3	−4.8		−7.6
A5	2.1	1.2	0.3	−2.1	−4.8		−7.7
A7	2.3	1.5	0.5	−2.0	−4.8		−8.0
A9	2.5	1.6	0.6	−2.0	−4.8		−8.3
F0	2.6	1.7	0.6	−2.0	−4.7		−8.5
F1	2.8	1.8	0.6	−2.0	−4.7		−8.5

Table B.1 Continued



SpT	V	IV	III	II	Ib	Iab	Ia
F2	3.0	1.9	0.6	−2.0	−4.6		−8.4
F3	3.1	1.9	0.6	−2.0	−4.6		−8.3
F4	3.3	2.0	0.7	−2.0	−4.6		−8.3
F5	3.4	2.1	0.7	−2.0	−4.4		−8.2
F6	3.7	2.2	0.7	−2.0	−4.4		−8.1
F7	3.8	2.3	0.6	−2.0	−4.4		−8.1
F8	4.0	2.4	0.6	−2.0	−4.3		−8.0
F9	4.2	2.6	0.6	−2.0	−4.2		−8.0

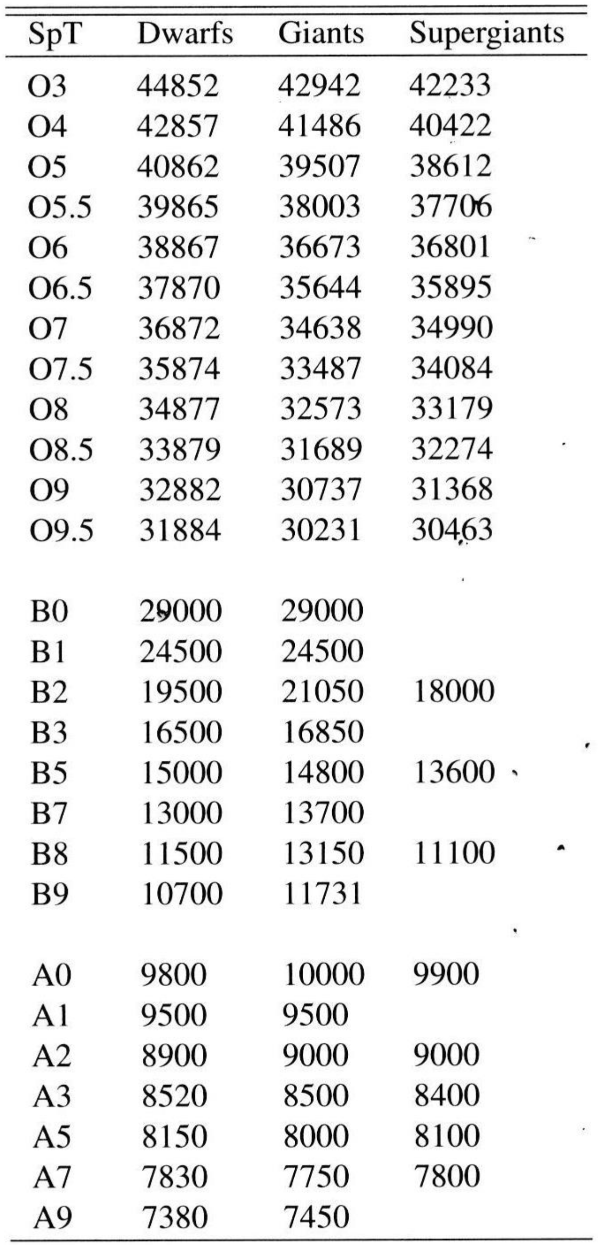
Table B.2 Averaged Absolute Visual Magnitude Calibration for the Late-type Stars



SpT	V	IV	IIIb	IIIab	IIIa	II	Ib	Ia
G0	4.4	2.8		0.6		−2.0	−4.1	−8.0
G1	4.5	2.9		0.5		−2.0	−4.1	−8.0
G2	4.7	3.0		0.4		−2.0	−4.0	−8.0
G3	4.9	3.0		0.4		−1.9	−4.0	−8.0
G4	5.0	3.1		0.4		−1.9	−3.9	−8.0
G5	5.2	3.2		0.4		−1.9	−3.9	−8.0
G6	5.3	3.2		0.4		−1.9	−3.8	−8.0
G7	5.5	3.2		0.3		−1.9	−3.8	−8.0
G8	5.6	3.2	0.8	0.3	−0.4	−1.9	−3.7	−8.0
G9	5.7	3.2	0.8	0.25	−0.4	−2.0	−3.7	−8.0
K0	5.9	3.2	0.7	0.2	−0.5	−2.0	−3.6	−8.0
K1	6.1		0.6	0.1	−0.6	−2.1	−3.6	−8.0
K2	6.3		0.6	0.1	−0.7	−2.1	−3.6	−8.0
K3	6.9		0.4	−0.1	−0.8	−2.2	−3.6	−8.0
K4	7.4		0.3	−0.2	−1.0	−2.3	−3.7	−8.0
K5	8.0		0.1	−0.4	−1.1	−2.5	−3.8	−8.0
K7	8.5		0.0	−0.5	−1.2	−2.5	−3.8	−7.7
M0	9.2		−0.2	−0.7	−1.3	−2.6	−3.9	−7.3
M1	9.7		−0.3	−0.8	−1.5	−2.7	−4.1	−7.3
M2	10.6		−0.6	−1.1	−1.7	−2.9	−4.2	−7.0
M3	11.6		−0.8	−1.3	−1.9			
M4	12.9		−1.1	−1.6	−2.2			
M5	14.5							
M6	16.1							

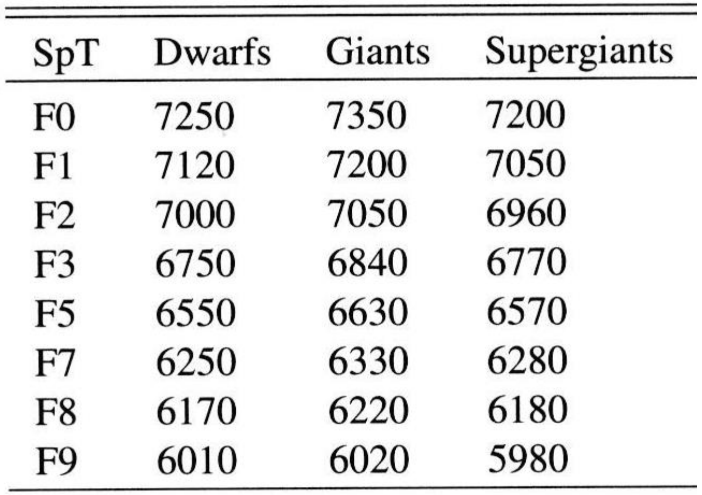
Gray

Table B.3 Effective Temperature (K) Calibration for the Early-type Stars



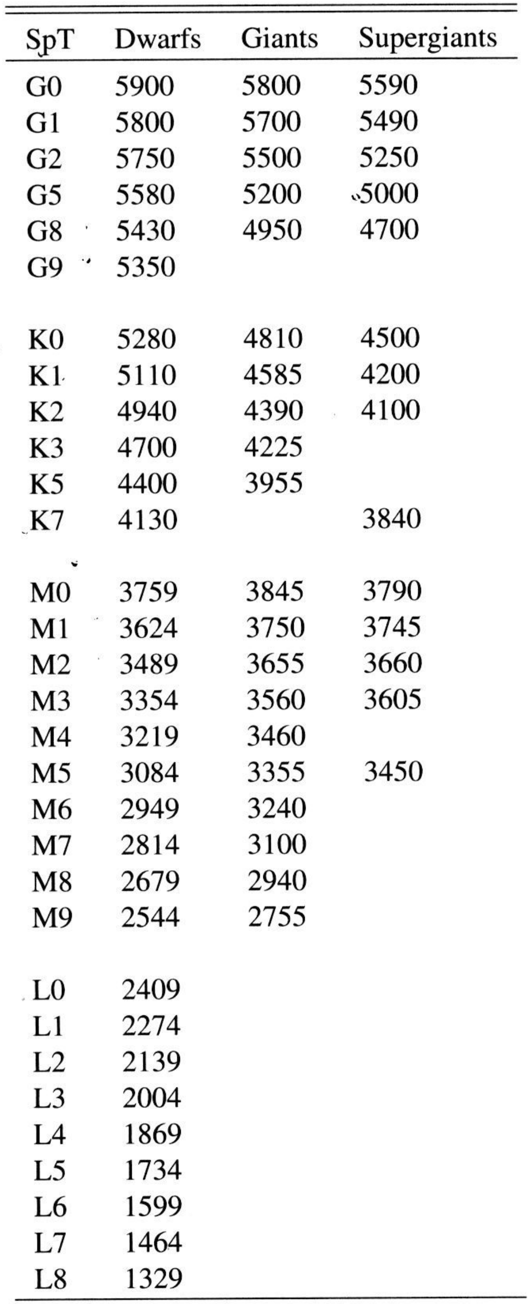
SpT	Dwarfs	Giants	Supergiants
O3	44852	42942	42233
O4	42857	41486	40422
O5	40862	39507	38612
O5.5	39865	38003	37706
O6	38867	36673	36801
O6.5	37870	35644	35895
O7	36872	34638	34990
O7.5	35874	33487	34084
O8	34877	32573	33179
O8.5	33879	31689	32274
O9	32882	30737	31368
O9.5	31884	30231	30463
B0	29000	29000	
B1	24500	24500	
B2	19500	21050	18000
B3	16500	16850	
B5	15000	14800	13600
B7	13000	13700	
B8	11500	13150	11100
B9	10700	11731	
A0	9800	10000	9900
A1	9500	9500	
A2	8900	9000	9000
A3	8520	8500	8400
A5	8150	8000	8100
A7	7830	7750	7800
A9	7380	7450	

Table B.3 Continued

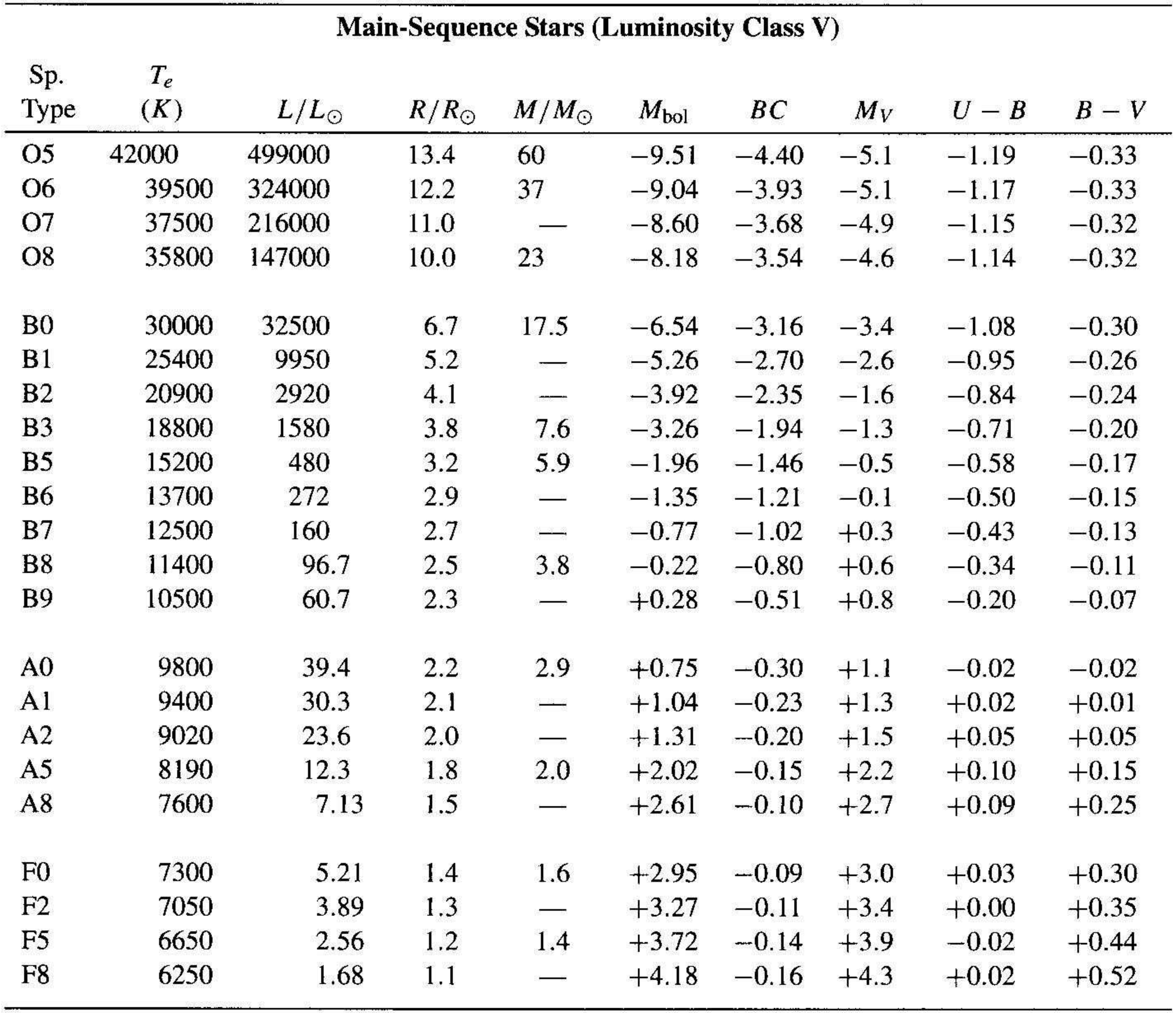


SpT	Dwarfs	Giants	Supergiants
F0	7250	7350	7200
F1	7120	7200	7050
F2	7000	7050	6960
F3	6750	6840	6770
F5	6550	6630	6570
F7	6250	6330	6280
F8	6170	6220	6180
F9	6010	6020	5980

Table B.4 Effective Temperature (K) Calibration for the Late-type Stars



SpT	Dwarfs	Giants	Supergiants
G0	5900	5800	5590
G1	5800	5700	5490
G2	5750	5500	5250
G5	5580	5200	5000
G8	5430	4950	4700
G9	5350		
K0	5280	4810	4500
K1	5110	4585	4200
K2	4940	4390	4100
K3	4700	4225	
K5	4400	3955	
K7	4130		3840
M0	3759	3845	3790
M1	3624	3750	3745
M2	3489	3655	3660
M3	3354	3560	3605
M4	3219	3460	
M5	3084	3355	3450
M6	2949	3240	
M7	2814	3100	
M8	2679	2940	
M9	2544	2755	
L0	2409		
L1	2274		
L2	2139		
L3	2004		
L4	1869		
L5	1734		
L6	1599		
L7	1464		
L8	1329		



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

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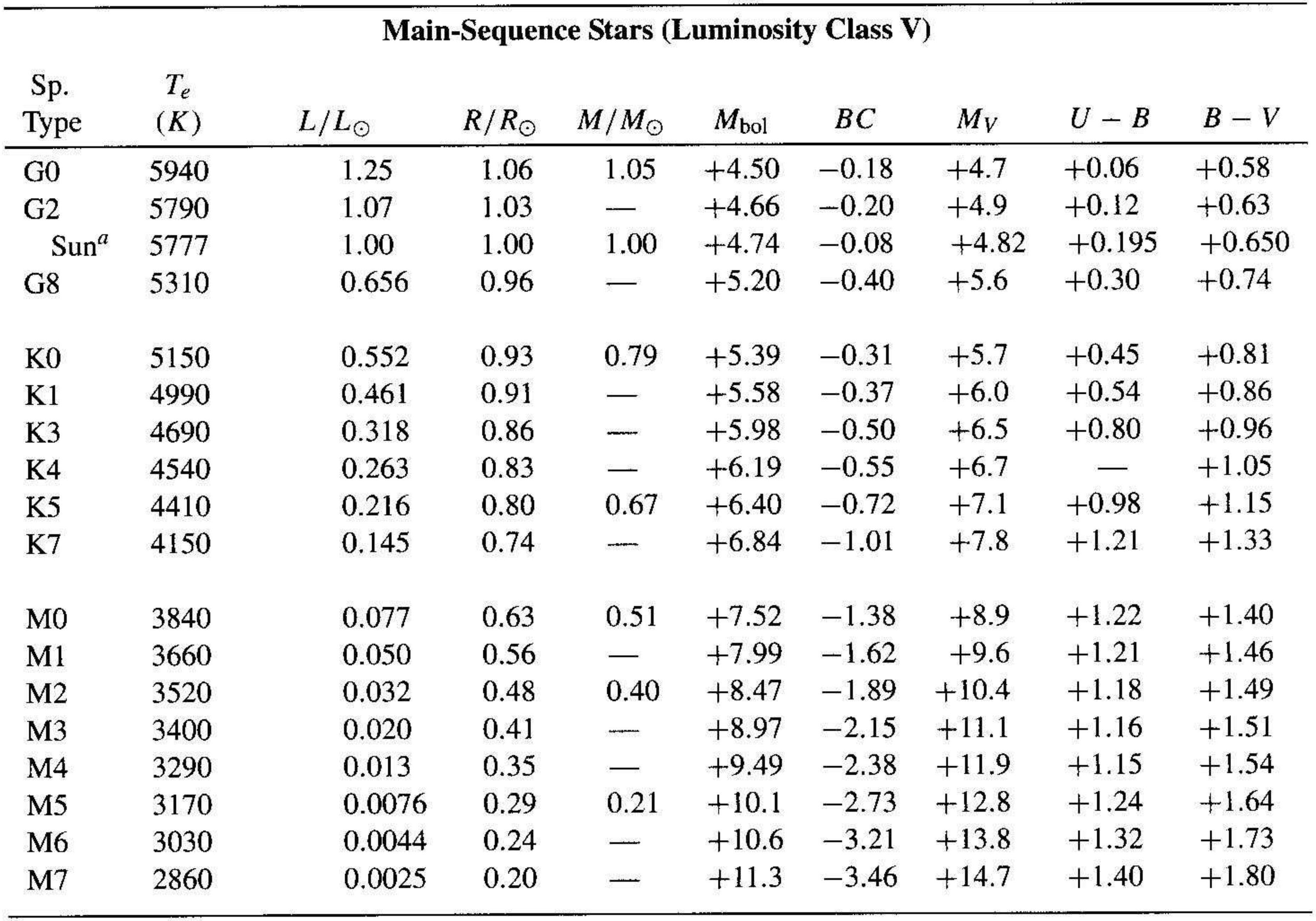

Main-Sequence Stars (Luminosity Class V)

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

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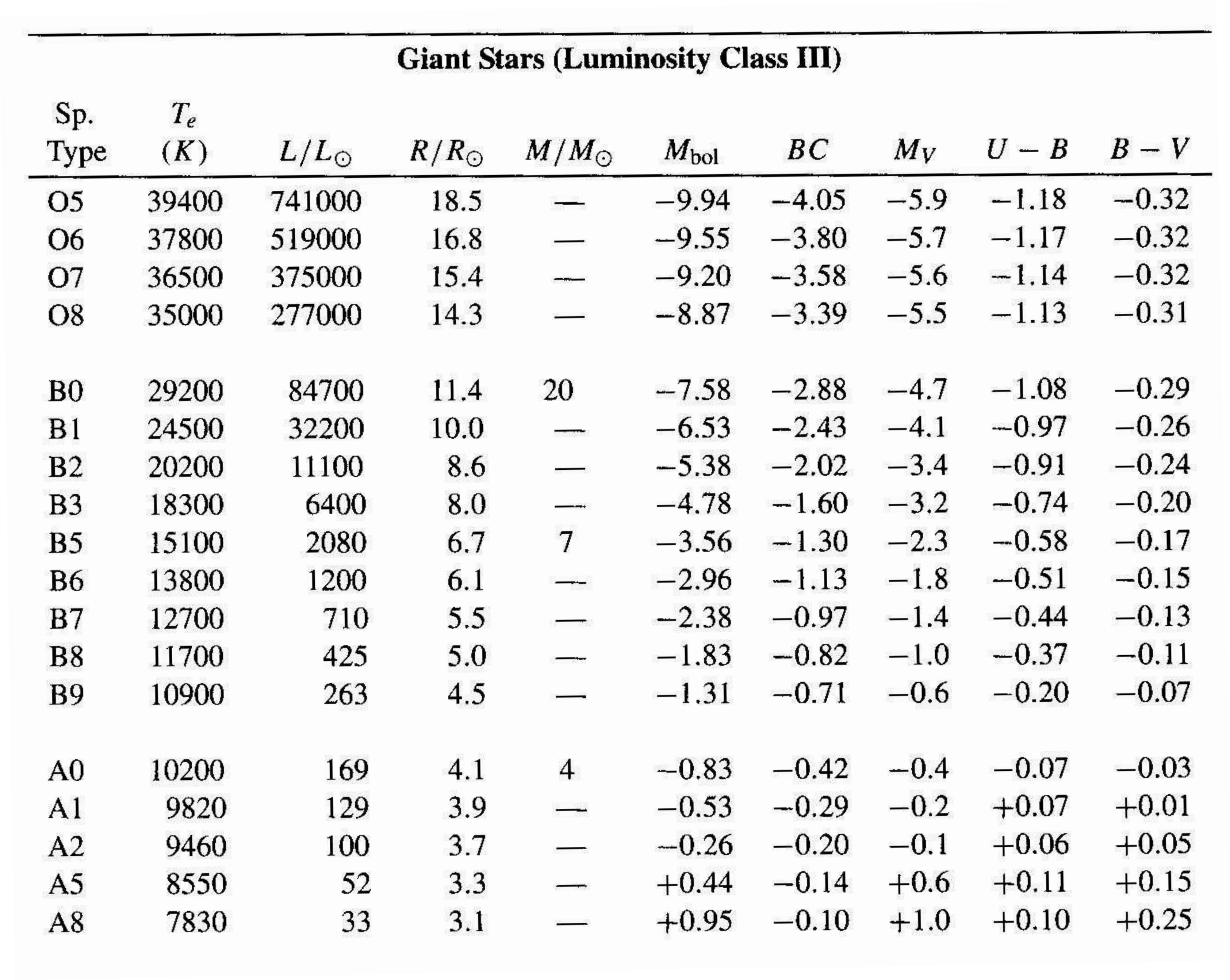

Giant Stars (Luminosity Class III)

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

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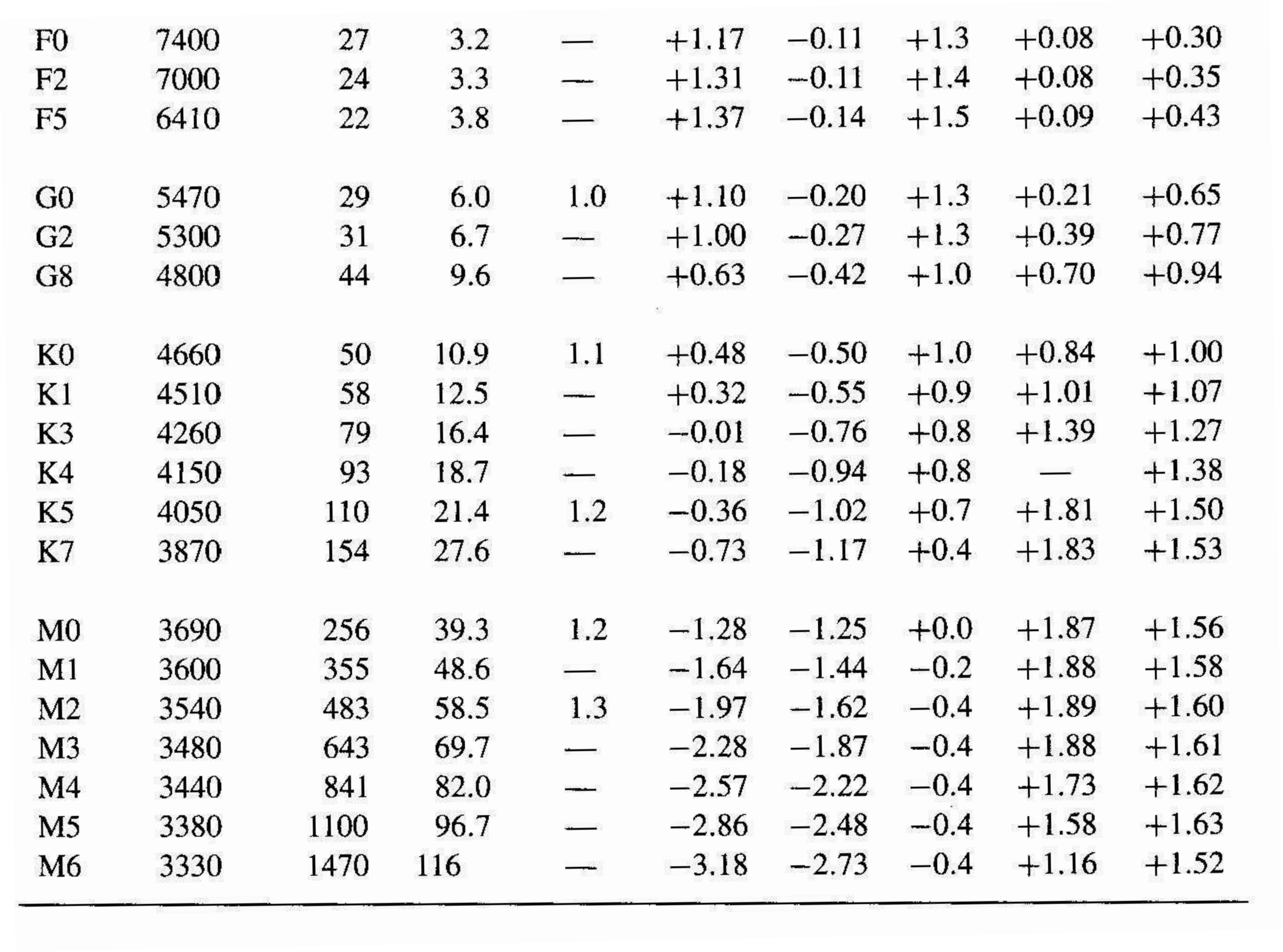
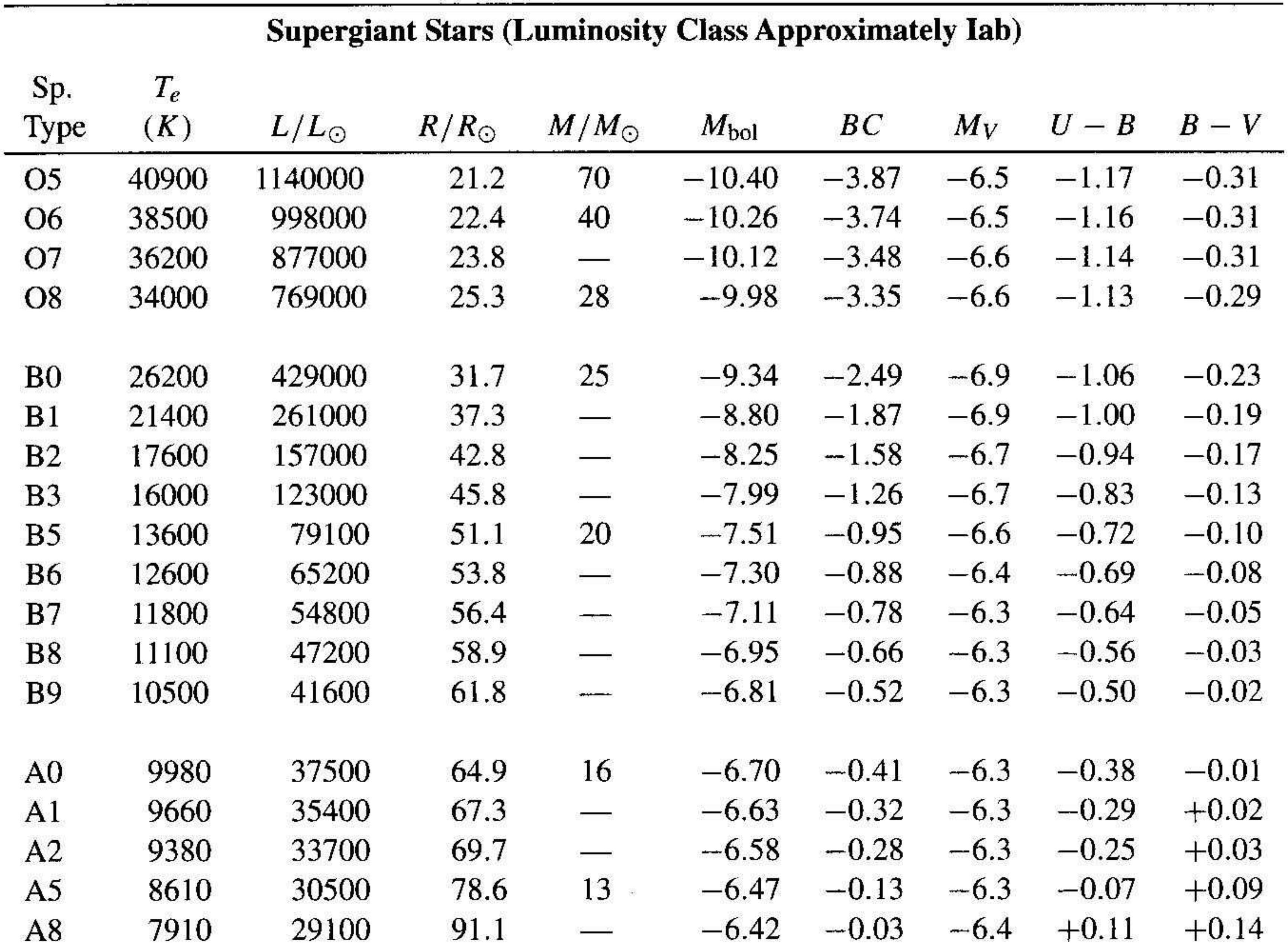


F0	7400	27	3.2	—	+1.17	−0.11	+1.3	+0.08	+0.30
F2	7000	24	3.3	—	+1.31	−0.11	+1.4	+0.08	+0.35
F5	6410	22	3.8	—	+1.37	−0.14	+1.5	+0.09	+0.43
G0	5470	29	6.0	1.0	+1.10	−0.20	+1.3	+0.21	+0.65
G2	5300	31	6.7	—	+1.00	−0.27	+1.3	+0.39	+0.77
G8	4800	44	9.6	—	+0.63	−0.42	+1.0	+0.70	+0.94
K0	4660	50	10.9	1.1	+0.48	−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

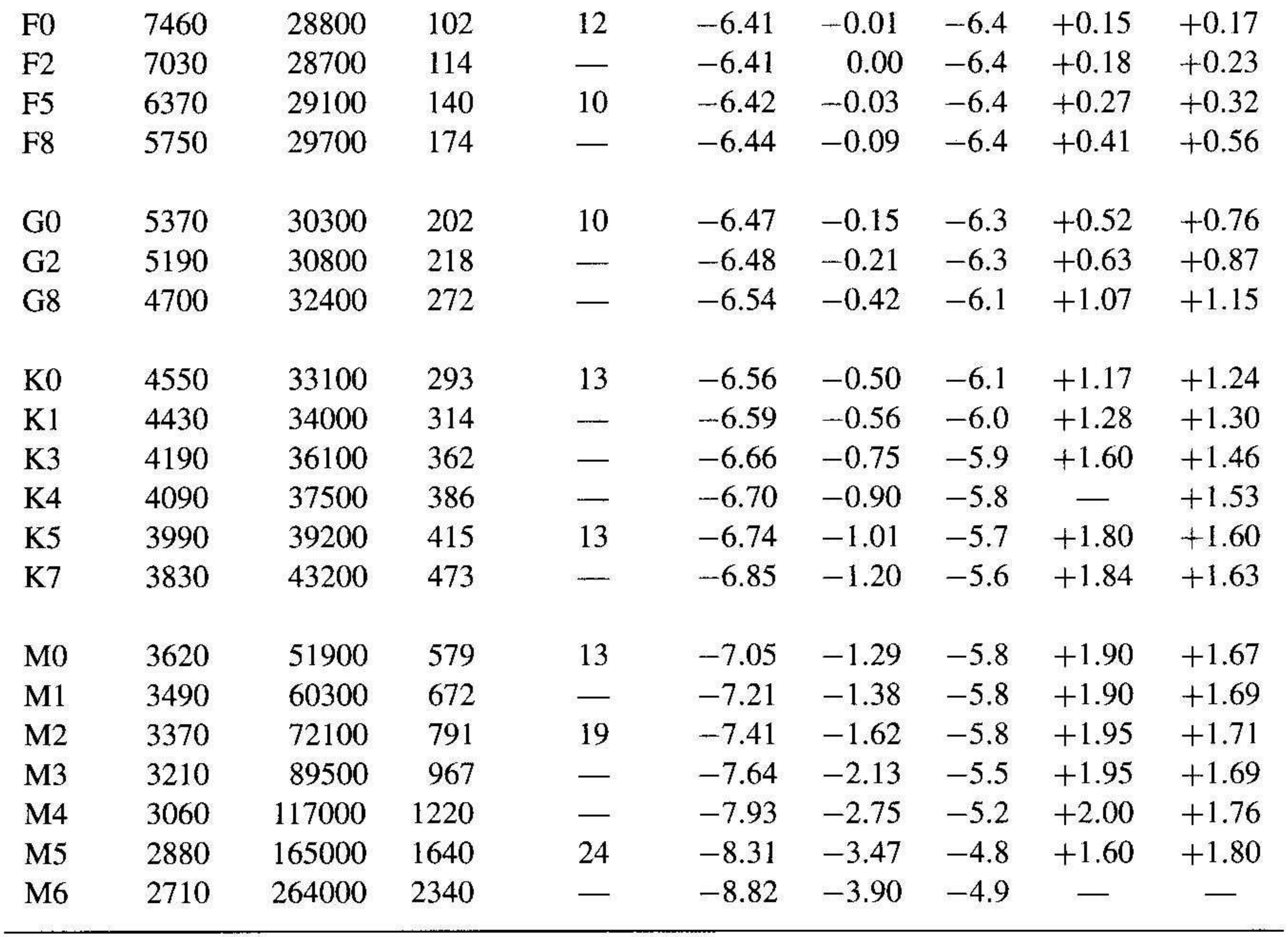
Carroll & Ostelie



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

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**

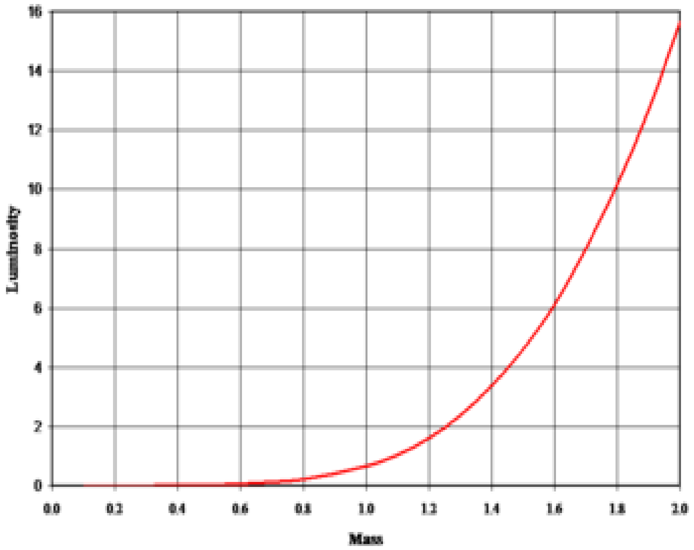
- Stellar mass difficult to measure; direct measurements, except the Sun, only by binary systems *(but uncertain even for these)*

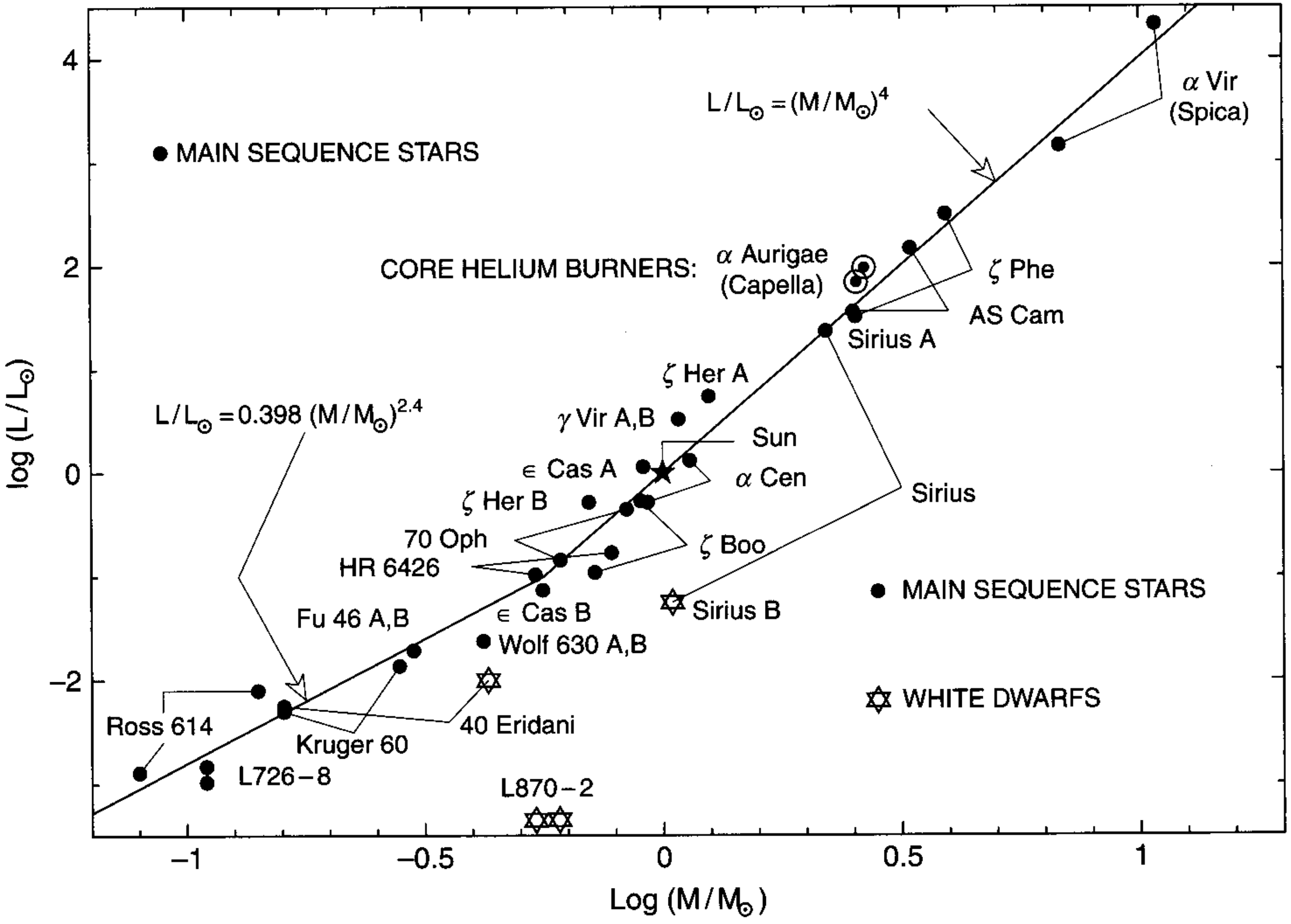
  Binary mass function $f = \frac{M_2^3 \sin^3 i}{(M_1+M_2)^2}$ c.f., **initial mass function**

- Then one gets the **mass-luminosity relation** $L \propto M^{\alpha}$ where the slope $\alpha =$ 3 to 5, depending on the mass range

- The main-sequence (MS) is a sequence of stellar mass; under the condition of hydrostatic equilibrium

- Why are lower mass stars cooler on the surface and fainter in luminosity?





$$M_{\max} \sim 120\ M_\odot$$
$$M_{\min} \sim 0.08\ M_\odot$$
$$L_{\max} \sim 10^{+6}\ L_\odot$$
$$L_{\min} \sim 10^{-4}\ L_\odot$$

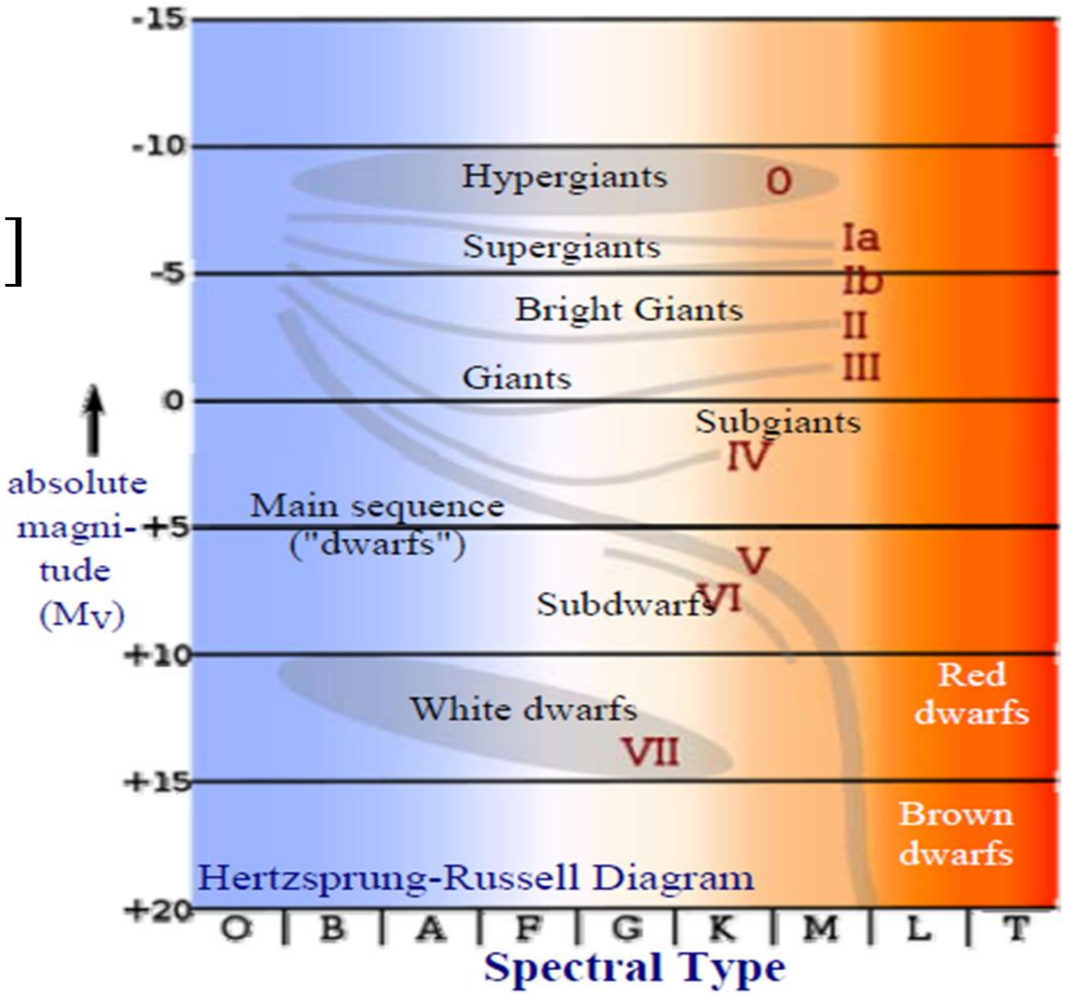
Luminosity versus mass for a selection of stars in binaries

Iben (2013)

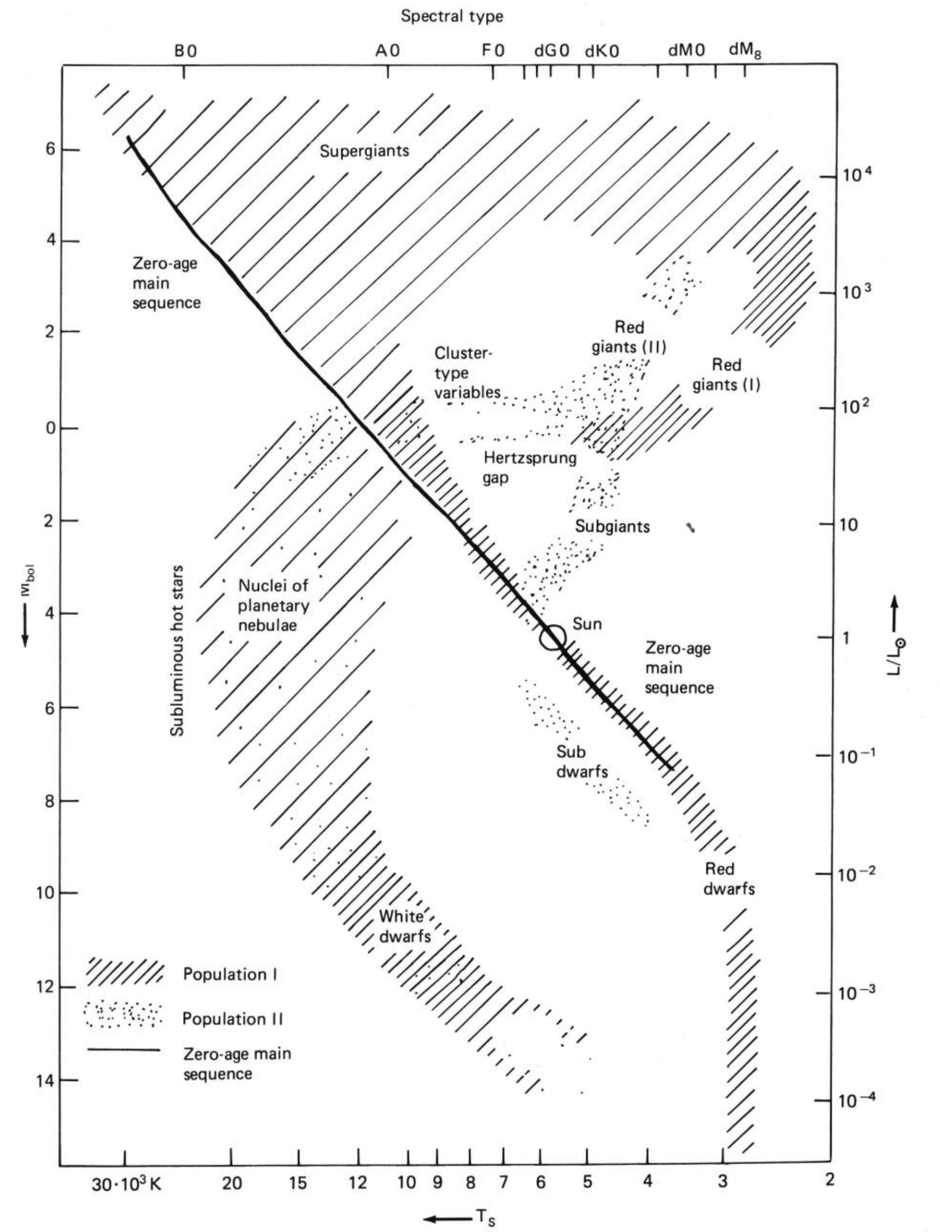
Luminosity class and **surface gravity**

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

- Betelgeuse … (M2 I) $\log g \approx -0.6$ [cgs]
- Jupiter … $\log g = +3.4$
- Sun (G2 V) … $\log g = +4.44$
- $G\ell$ 229B … (T6.5) $\log g \approx +5$
- Sirius B… (WD) $\log g \approx +8$



What is the surface gravity of the Earth?



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”

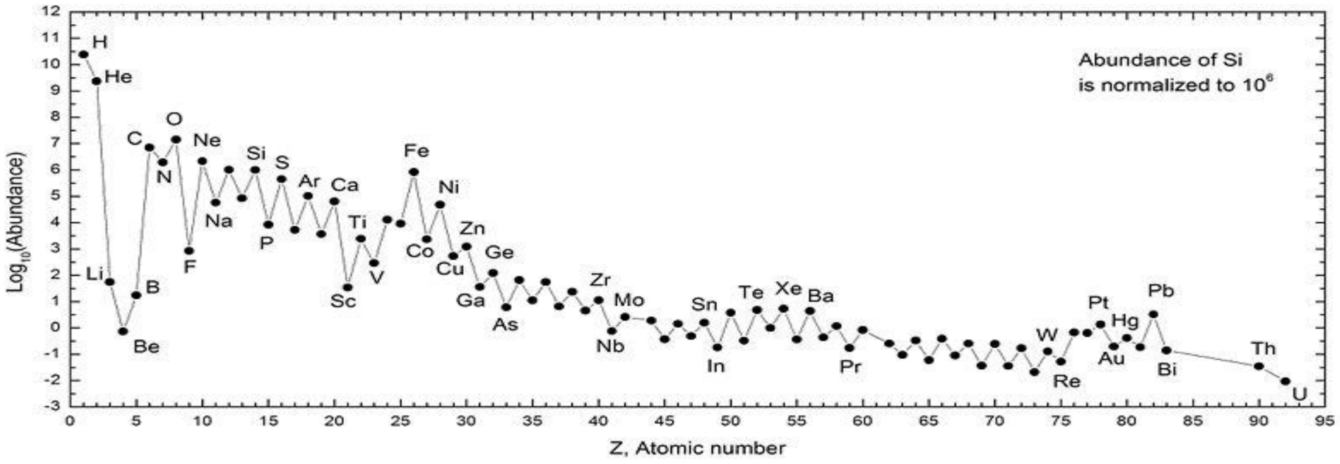
To measure the stellar abundance

- ◆ By spectroscopy
- ◆ Stellar composition (X, Y, Z) = mass fraction of H, of He, and of all the rest 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?*

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

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

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



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

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

“Metals”: by astronomers to mean “complex” elements, i.e., any element other than H or He (primodial).

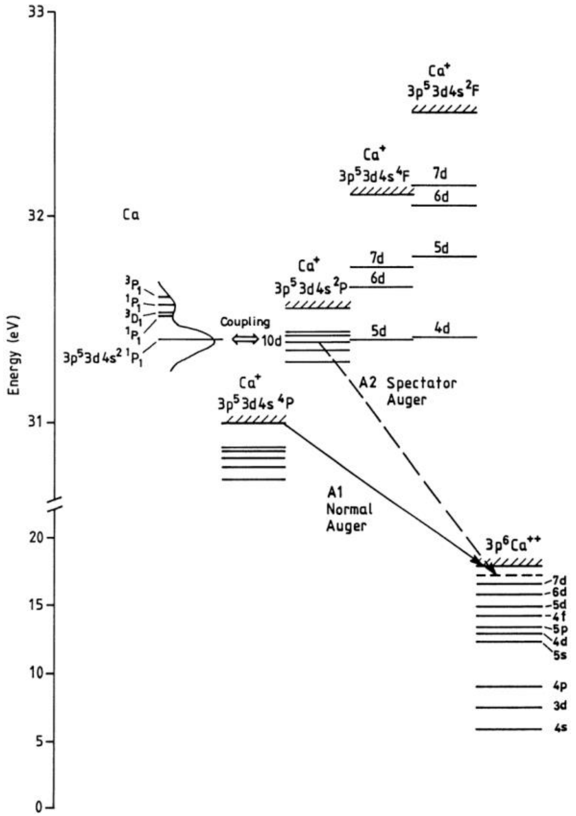
For H ($Z = 1$) it requires $\sim$10 eV to from the ground level to the first excited state; needs $>$ 13.6 eV to free (ionize) the electron.

For He (Z =2), it is even more difficult; ionization potential of 24.6 eV (once) or 54.4 eV (twice).

Metals have many electrons. It is easier to excite or ionize the outer layer of electrons (a few eV), e.g., $E_{\rm ion}^{\rm Ca\,I}$ =6.1 eV; $E_{\rm ion}^{\rm Fe\,I}$ =7.9 eV

“Metals” are hence efficient coolants, affecting ISM and stellar structure.

“Metallicity”: the amount of metals (e.g., Fe, Mg, Ca) relative to H.

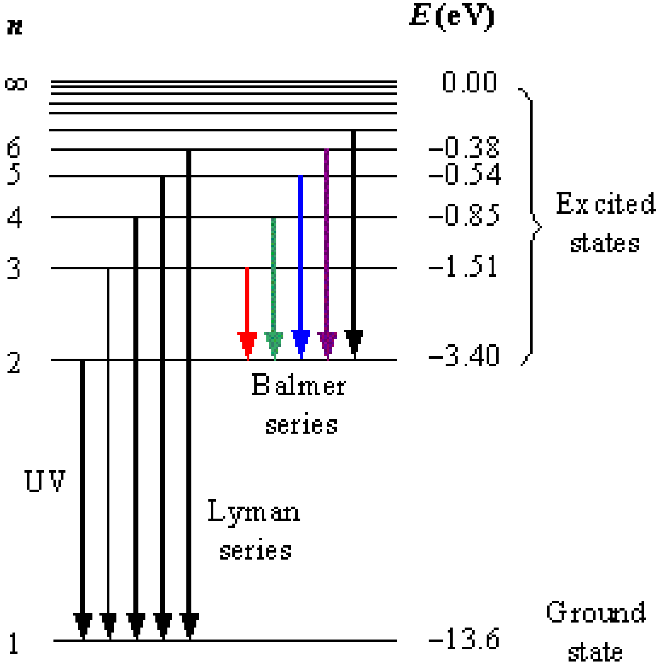


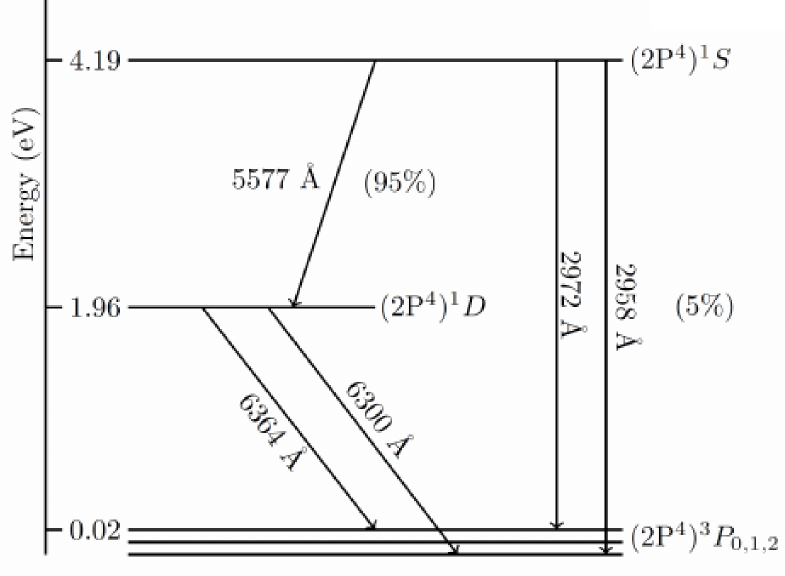
Effects of Metallicity

‘Metals’. i.e., elements other than H and He, are efficient coolants.

Collisional excitation
→ dominates cooling process in H I and H II ISM

Metals = low-lying levels





ResearchGate

Given the same mass, a metal poorer star is bluer and brighter.

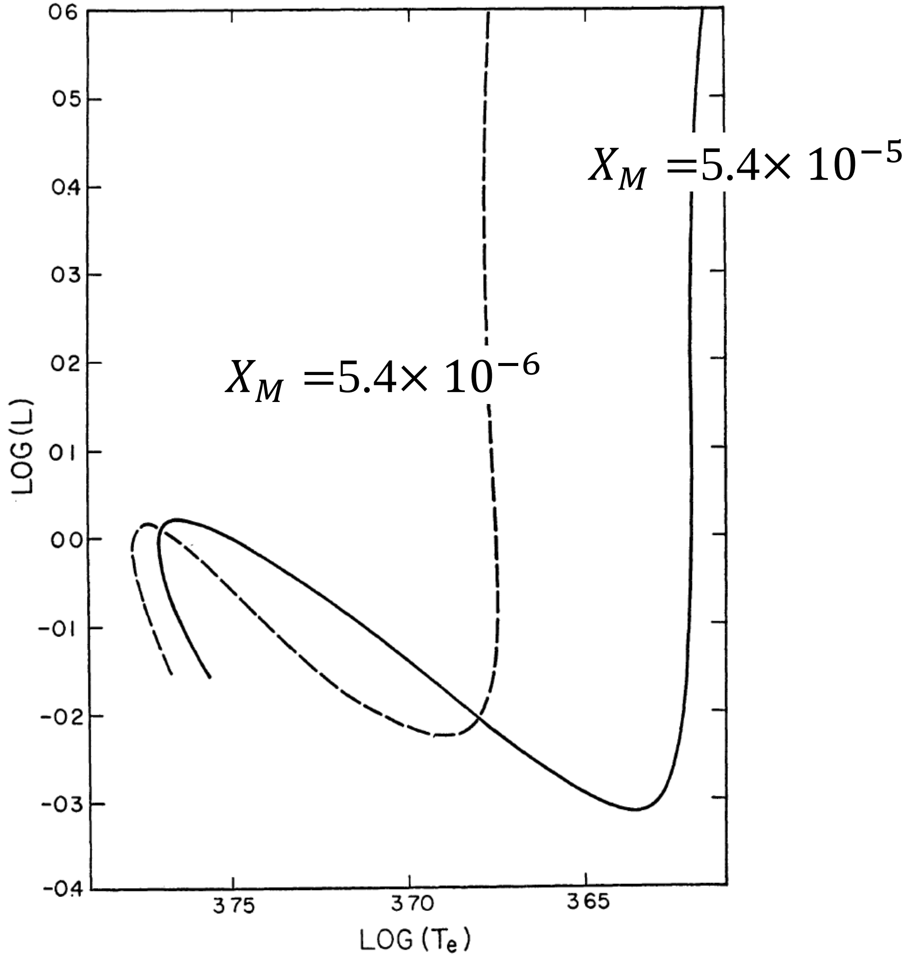
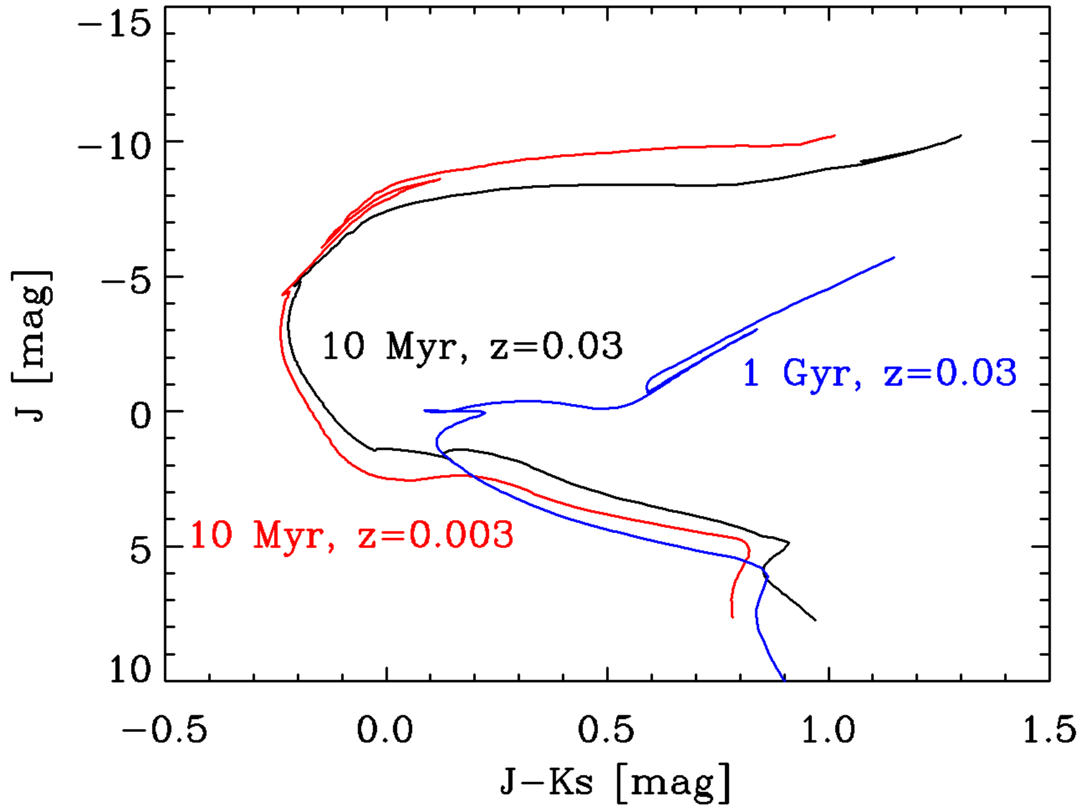


Fig. 1.—Paths in the theoretical Hertzsprung-Russell diagram for $M = M_\odot$. Luminosity in units of $L_\odot = 3.86 \times 10^{33}$ erg/sec and surface temperature T_e in units of ° K. Solid curve constructed using a mass fraction of metals with 7.5-eV ionization potential, $X_M = 5.4 \times 10^{-5}$. Dashed curve constructed with $X_M = 5.4 \times 10^{-6}$.

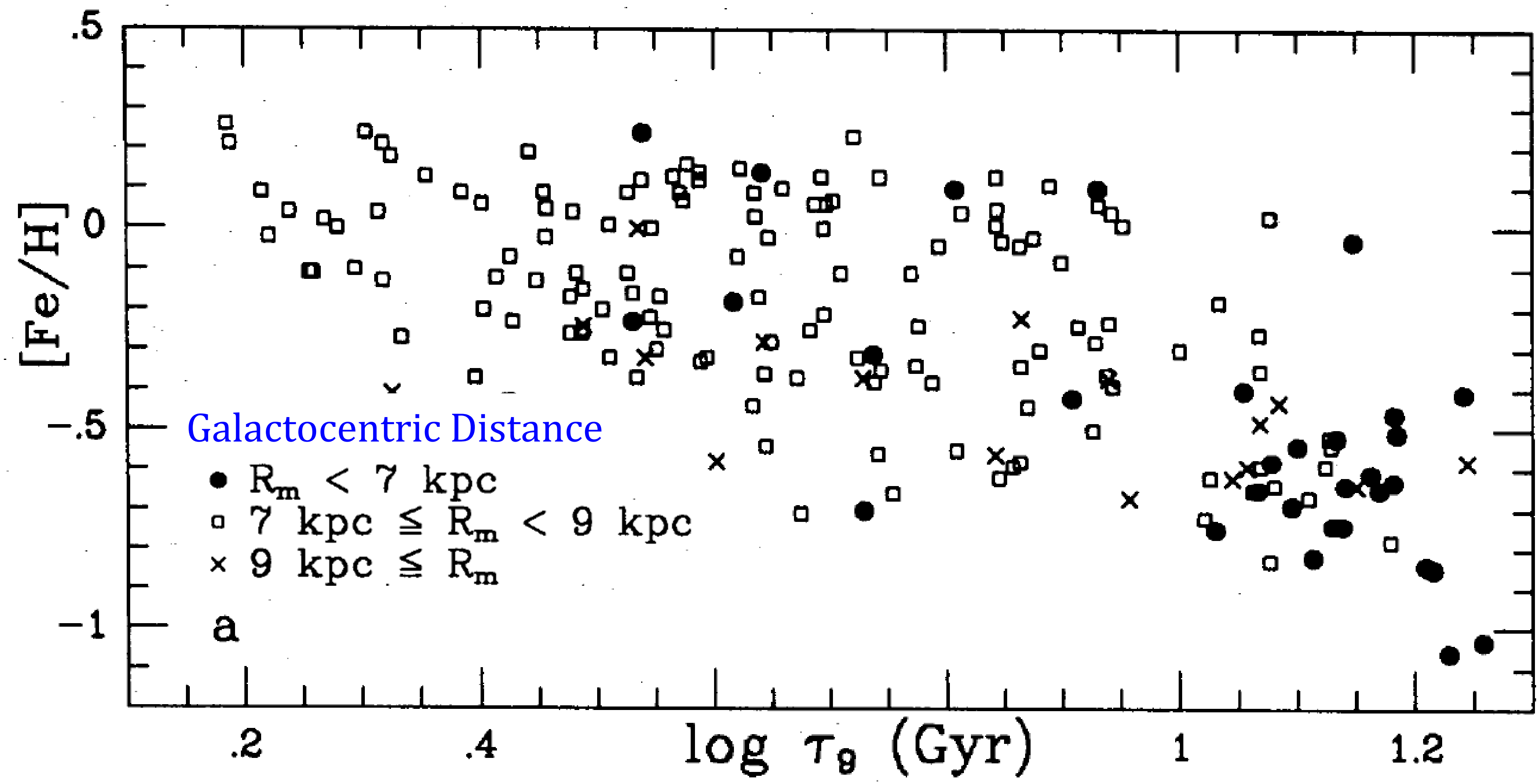
Iben (1965)

A metal poorer cluster has an overall bluer sequence.



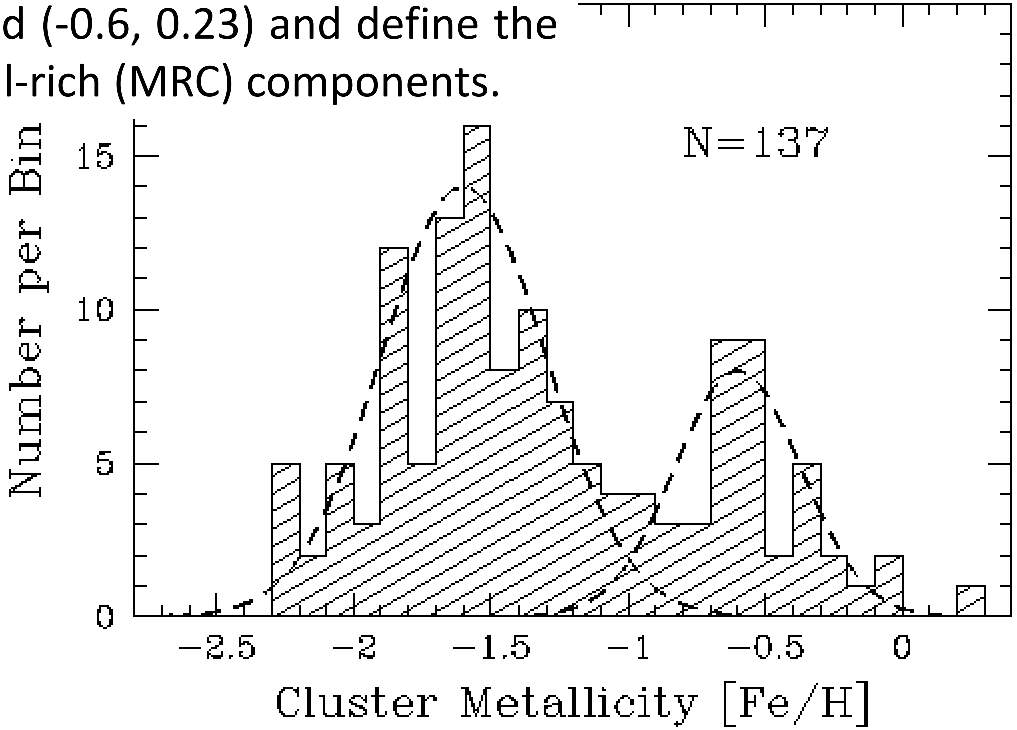
A younger cluster retains a longer upper MS, and even contains some PMS stars.

Younger stars tend to be metal-richer. 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)

The two Gaussian curves have means and standard deviations of (-1.6, 0.30) and (-0.6, 0.23) and define the metal-poor (MPC) and metal-rich (MRC) components.



https://ned.ipac.caltech.edu/level5/Harris2/Harris1.html

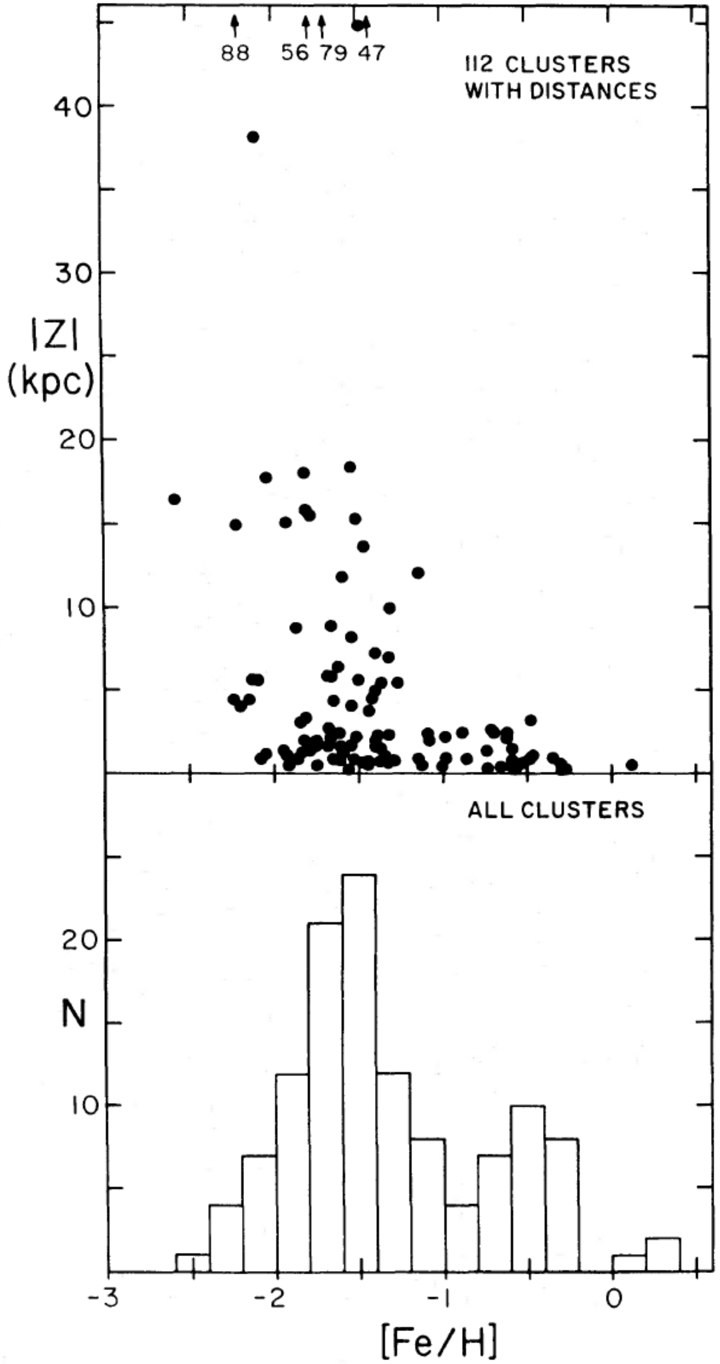


FIG. 1.—In the upper diagram, $|Z|$ is plotted against [Fe/H] for the 112 globular clusters of known distance. Notice that there are no clusters in the zone $20 \lesssim |Z| \lesssim 37$ kpc and that the $|Z|$ distribution changes suddenly at $[\mathrm{Fe/H}] \approx -1$. The lower diagram is a histogram of the values of [Fe/H] for all 121 clusters in Table 1. Notice that the valley in the distribution over [Fe/H] occurs at the same value as the sudden change in the $|Z|$ distribution.

To measure the stellar age

- ◆ Very tricky for single stars. 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

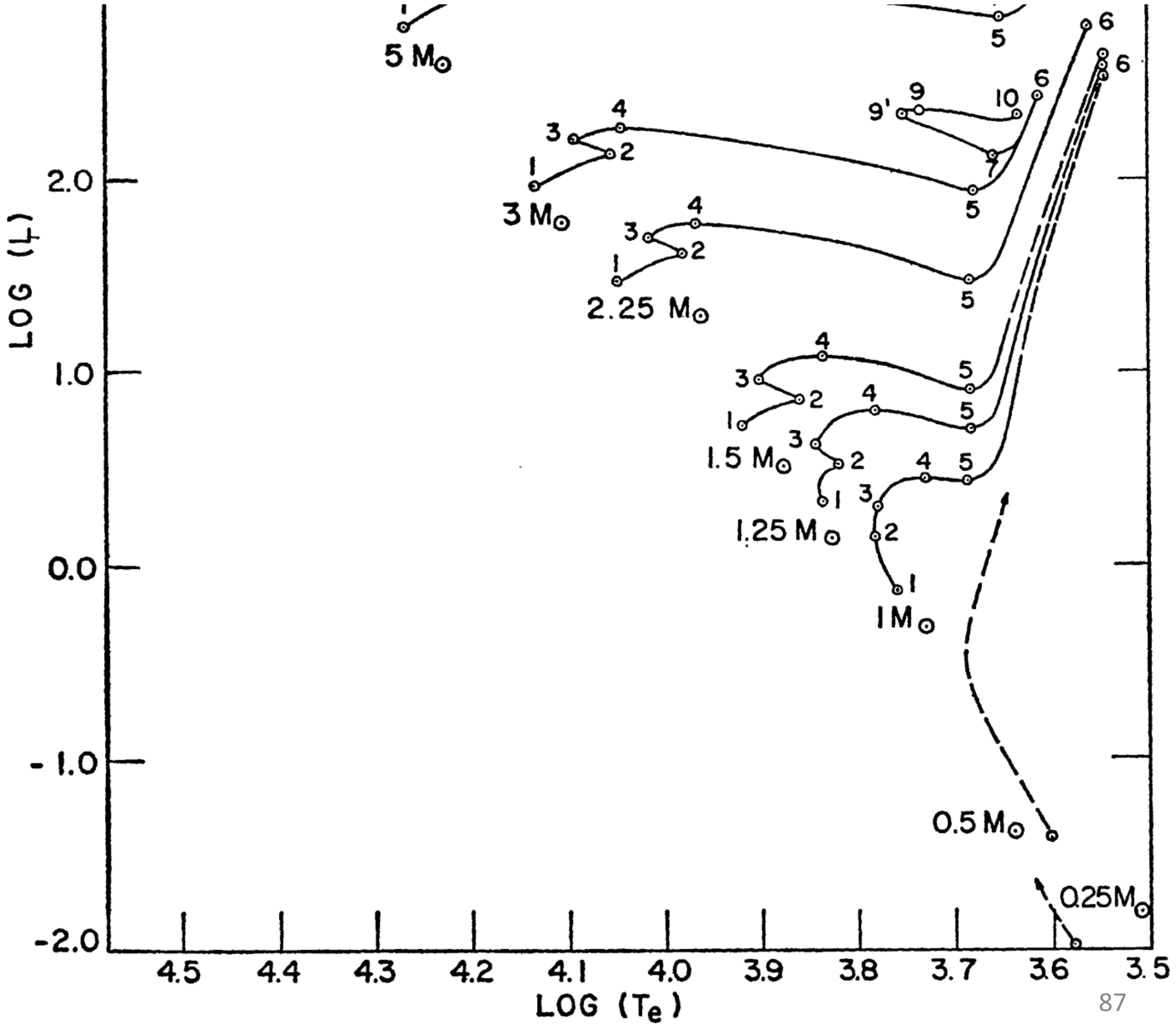
  … hence subject to large uncertainties

References:

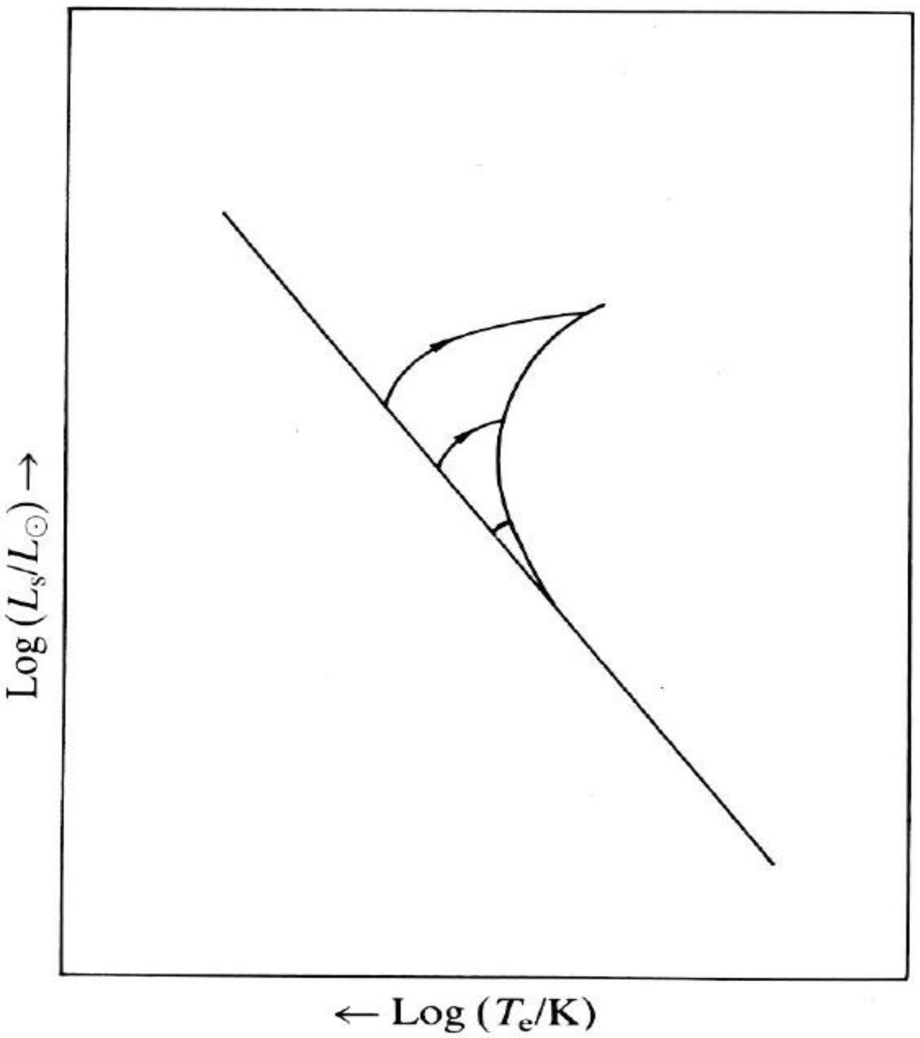
Edvardsson et al., 1993, A&A, 275, 101
Nordström et al., 2004, A&A, 418, 989

Stellar evolutionary models (tracks)

1-2 main sequence
2-3 overall contraction
3-4 H <u>thick</u> shell burning
5-6 H <u>thin</u> shell burning
6-7 red giant
7-10 core He burning
8-9 envelope contraction



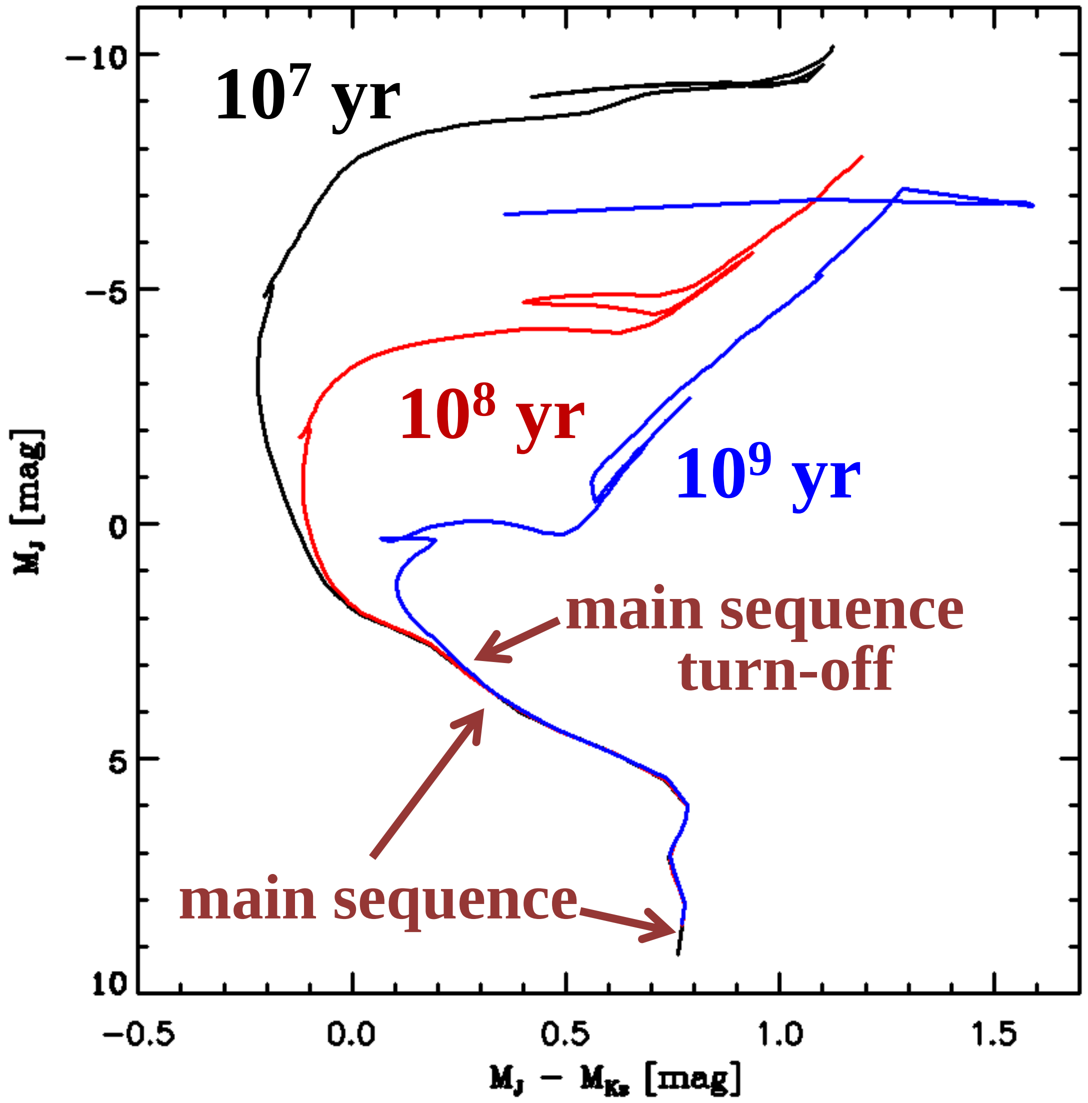
To Determine the Age of a Star Cluster

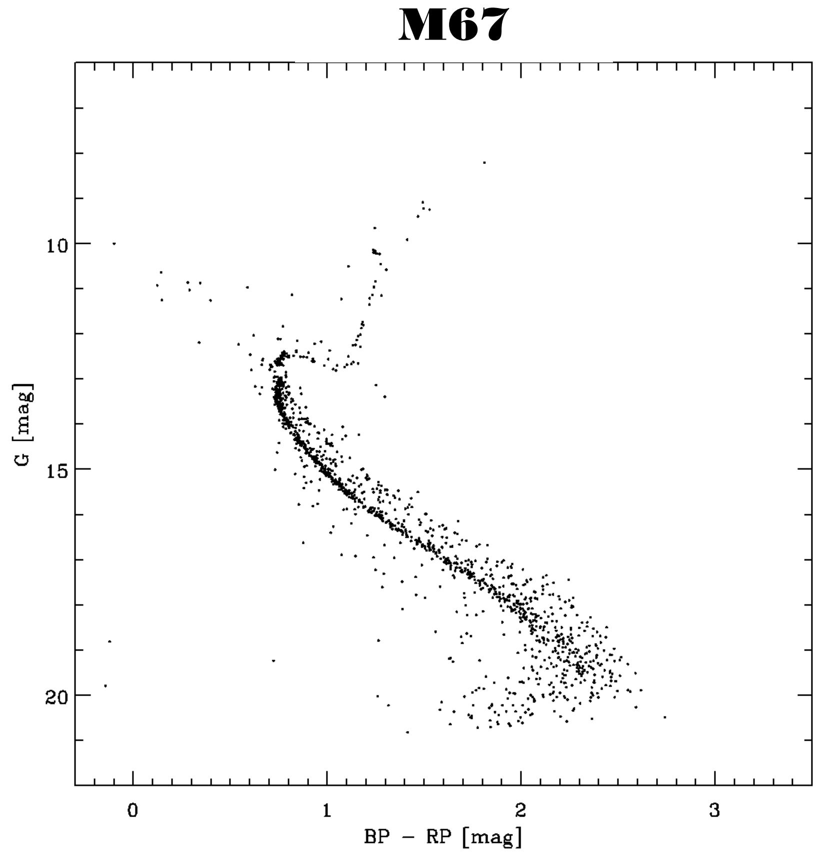


As a cluster (its member stars) ages, massive stars leave the MS first and evolve to the post-main sequence phase, then progressively followed by lower-mass members. Only lower-mass stars still remain on the MS.

The MS is “peeled off” from the top (upper MS) down.

Theoretical isochrones





Age of the cluster

= the main sequence lifetime of stars at the MSTO

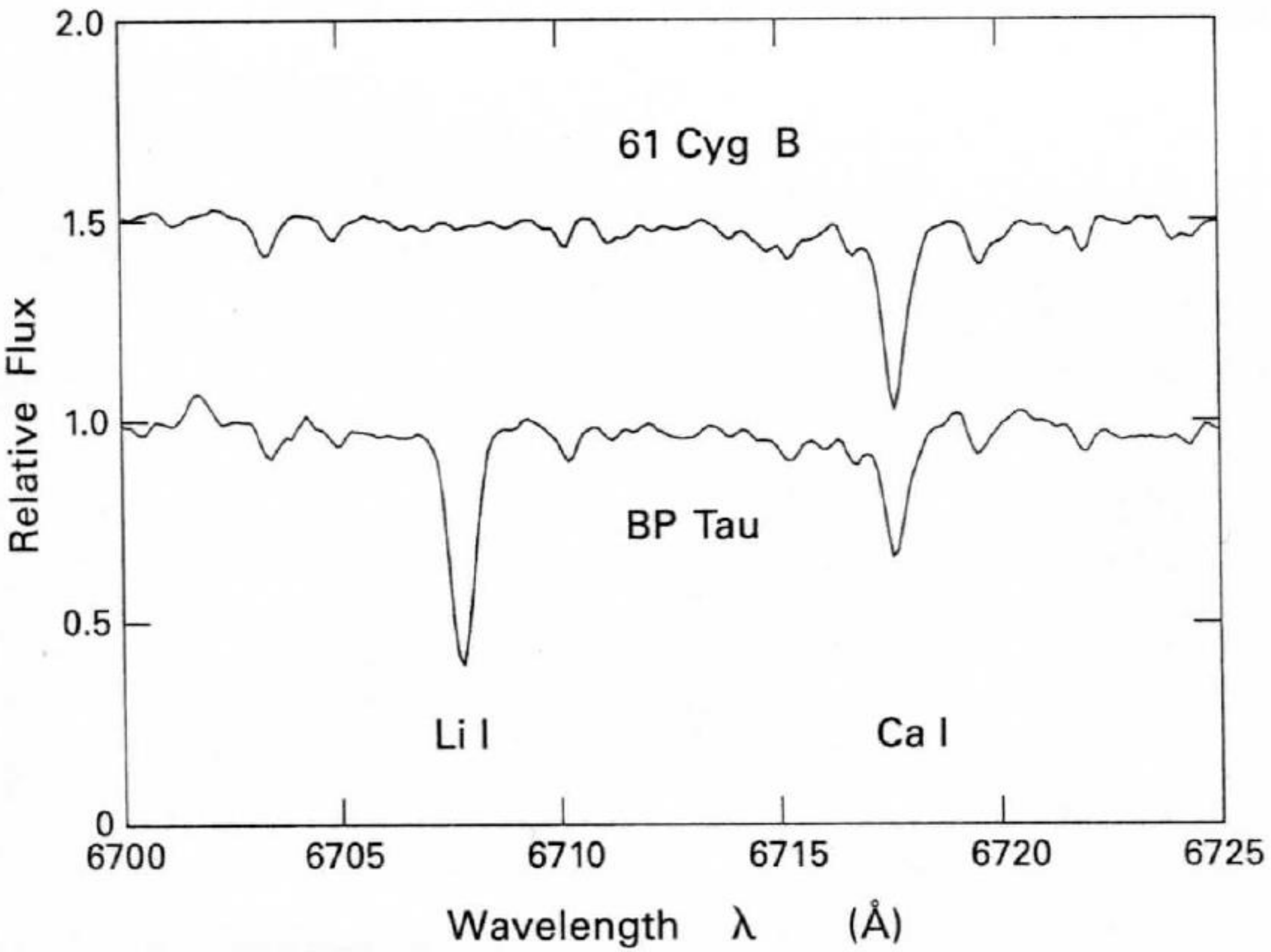
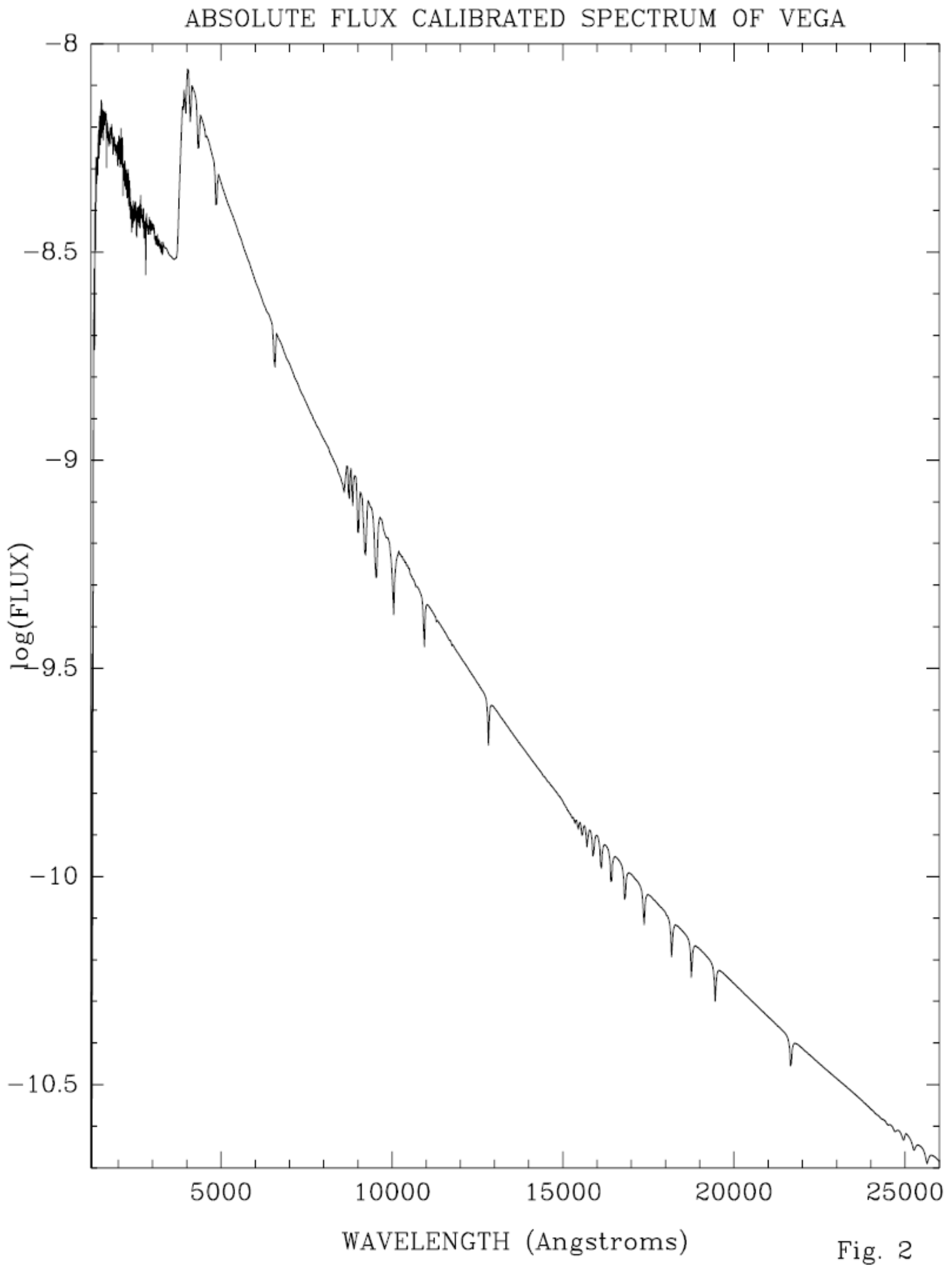


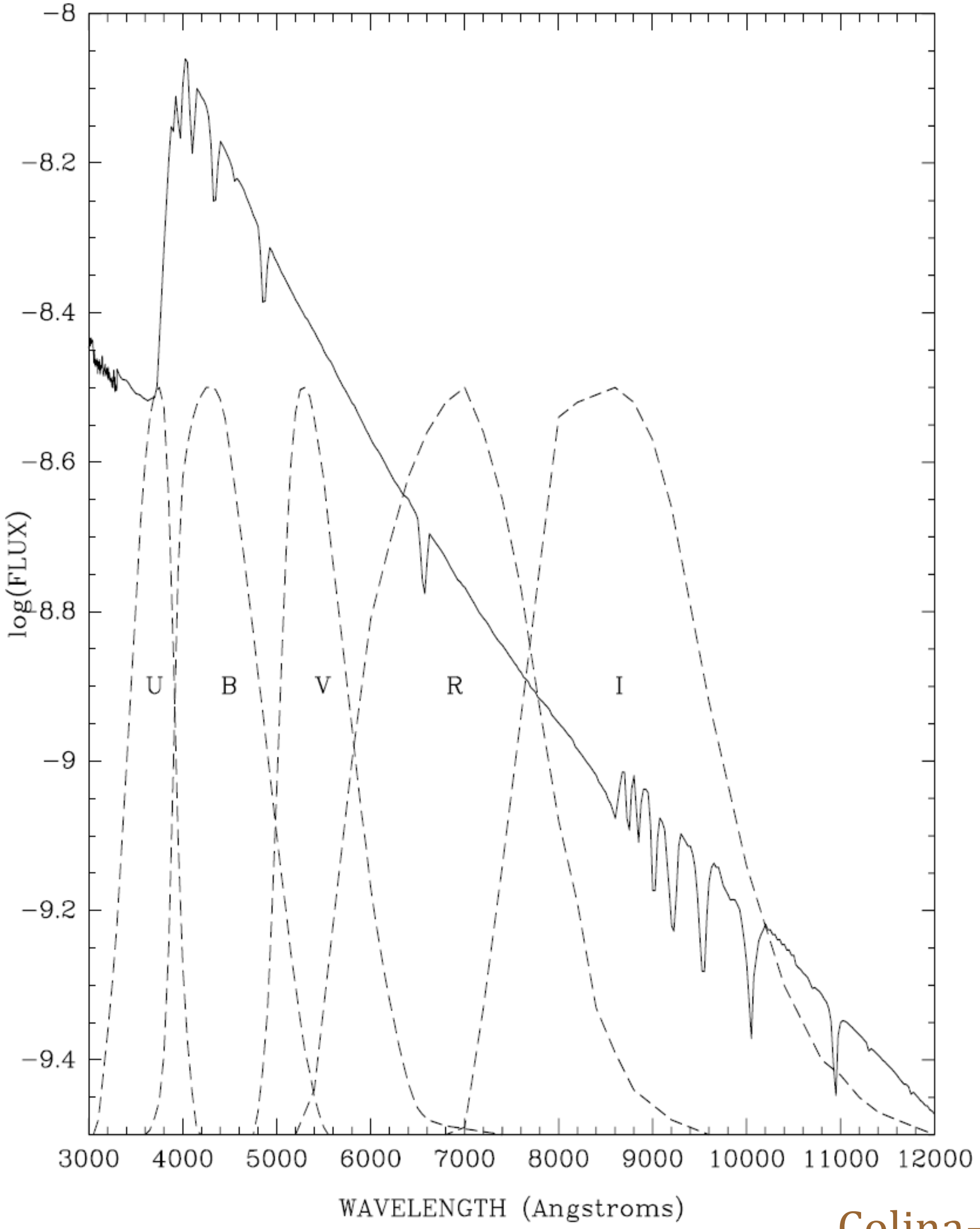
Figure 16.9 Lithium absorption in a pre-main-sequence star. Shown is a portion of the optical spectrum of BP Tau, a T Tauri star of spectral type K7, corresponding to an effective temperature of 4000 K. Also shown, for comparison, is a main-sequence star of the same spectral type, 61 Cyg B. Only in the 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

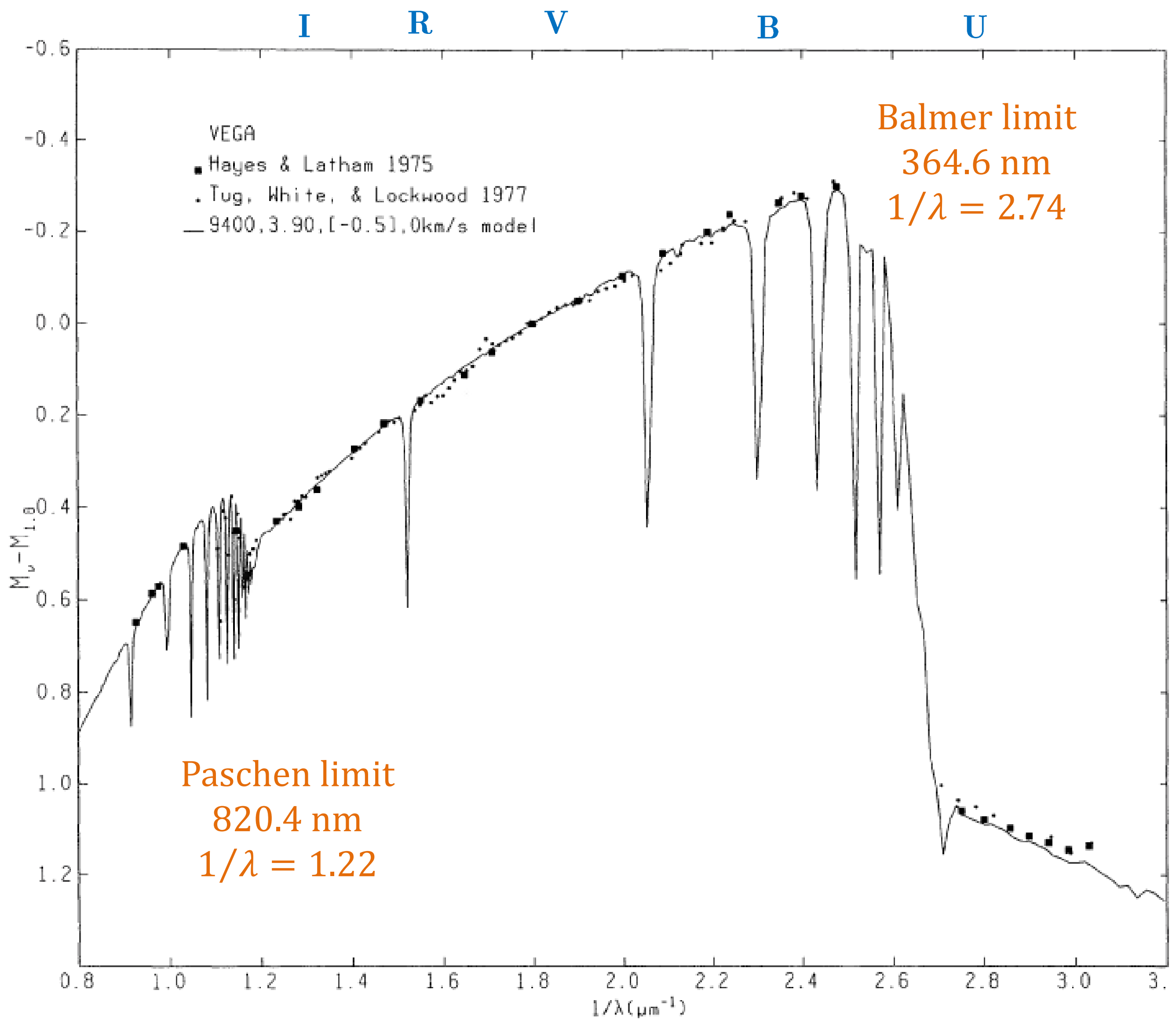
A PMS (young) star shows Li absorption.

Stahler


ABSOLUTE FLUX CALIBRATED SPECTRUM OF VEGA
−8
−8.5
−9
−9.5
−10
−10.5
log(FLUX)
5000
10000
15000
20000
25000
WAVELENGTH (Angstroms)
Fig. 2


−8
−8.2
−8.4
−8.6
−8.8
−9
−9.2
−9.4
log(FLUX)
U
B
V
R
I
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
WAVELENGTH (Angstroms)

Colina+96



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

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

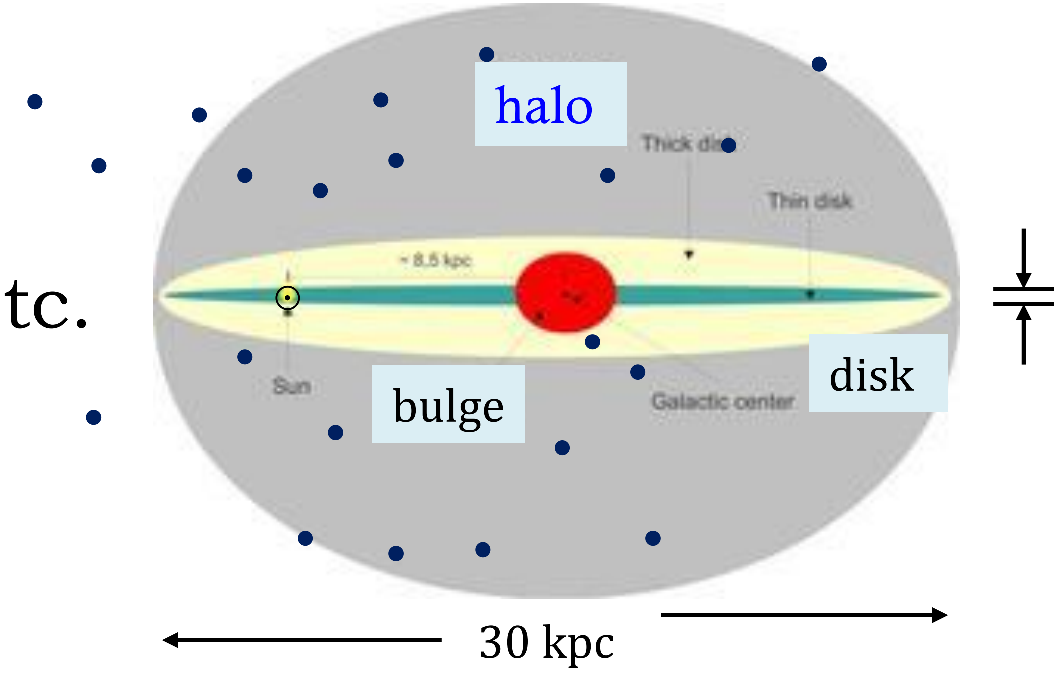
FIG. 1. Kurucz's (1991a) new model for Vega compared with a series of independent UV-optical measurements, specifically those by Hayes & Latham (1985) and by Tug *et al.* (1977).

Cohen+92

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

MW galaxy

Stars, ISM, CRs,
B, dark matter, etc.



- ✓ YSOs, gas/dust 100 pc
- ✓ Old thin disk 300 pc
- ✓ Thick disk 2000 pc

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	