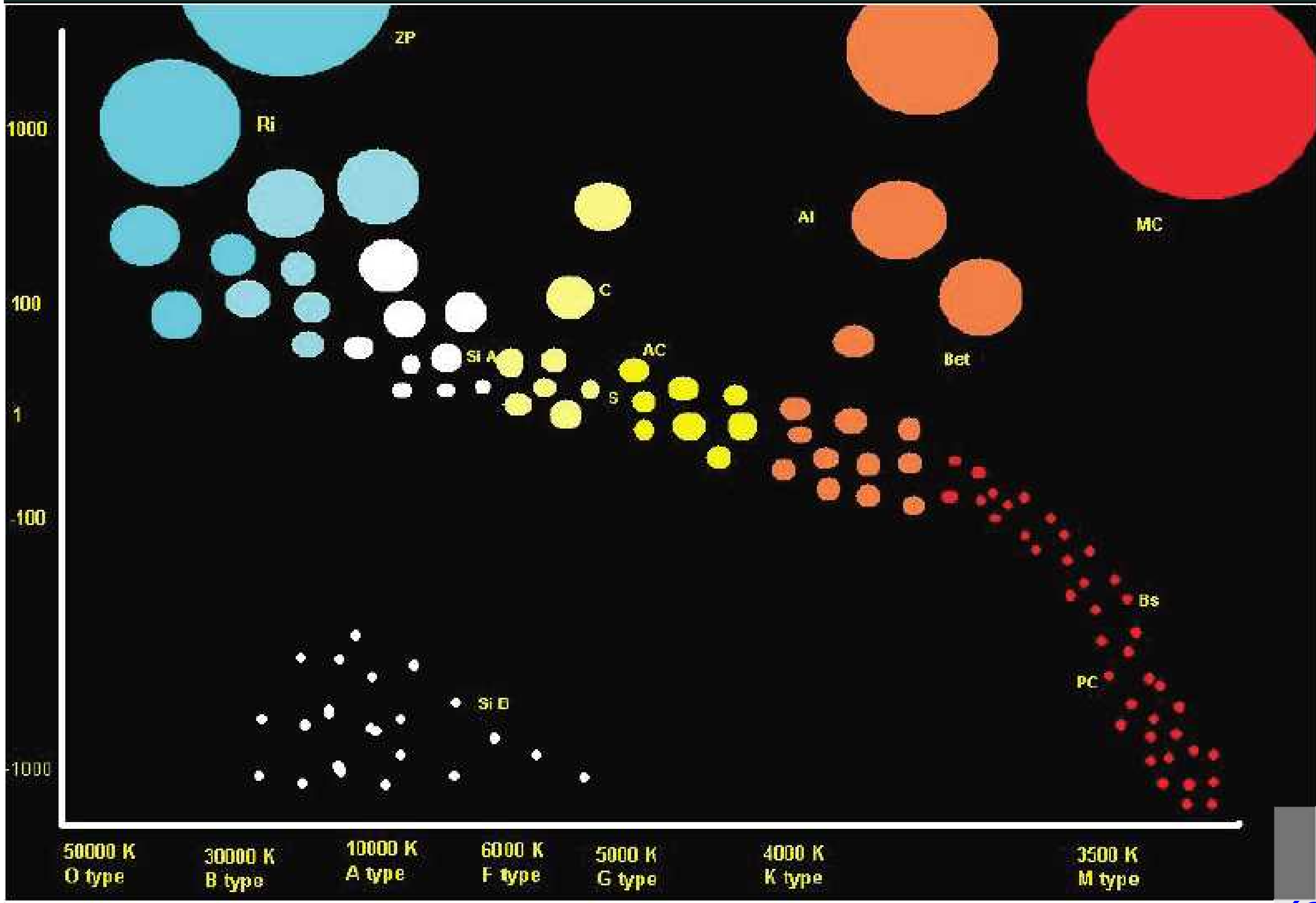
Part II. Stellar Evolution and the Milky Way Galaxy

Chapter 1. Stars: The Hertzsprung-Russell Diagram (항성: HR도)

1-1 Two-dimensional distribution of stellar parameters (별들의 2차원 분포 그림)



http://solarandspace.tripod.com/id11.html

ZP= Zeta Puppis
Ri= Rigel
SiA= Sirius A
SiB= Sirius B
C= Capella
S= Sun
AC= Alpha Centuri A
Al= Aldebaren
Bet= Betelgeuse
MC= Mu Cephi
PC= Proxima Centuri
Bs= Barnards star

김상철
(Sang Chul KIM)

Modern Astronomy

Part II. Stellar Evolution and the Milky Way Galaxy (항성진화와 우리은하)

Chapter 1. Stars: The Hertzsprung-Russell Diagram (항성: HR도)

Chapter 2. The Evolution of Stars (별의 진화)

Chapter 3. Star Deaths (별의 죽음)

Chapter 4. The Milky Way Galaxy (우리은하)

- References (참고문헌) :

  - Introductory Astronomy and Astrophysics (4th edition), Michael Zeilik & Stephen A. Gregory (1998)
  - An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996)
  - Galactic Astronomy (J. Binney & M. Merrifield, 1998)
  - An Introduction to Stellar Astrophysics (Francis LeBlanc, 2010)
  - Evolution of Stars and Stellar Populations (Maurizio Salaris & Santi Cassisi, 2005)
  - 항성내부구조 및 진화, Dina Prialnik 지음, 김용기 옮김, 2007 (An Introduction to the Theory of Stellar Structure and Evolution, 2000)

Hertzsprung-Russell Diagram

1911 Ejnar Hertzsprung (1873-1967)
Danish engineer and
amateur astronomer

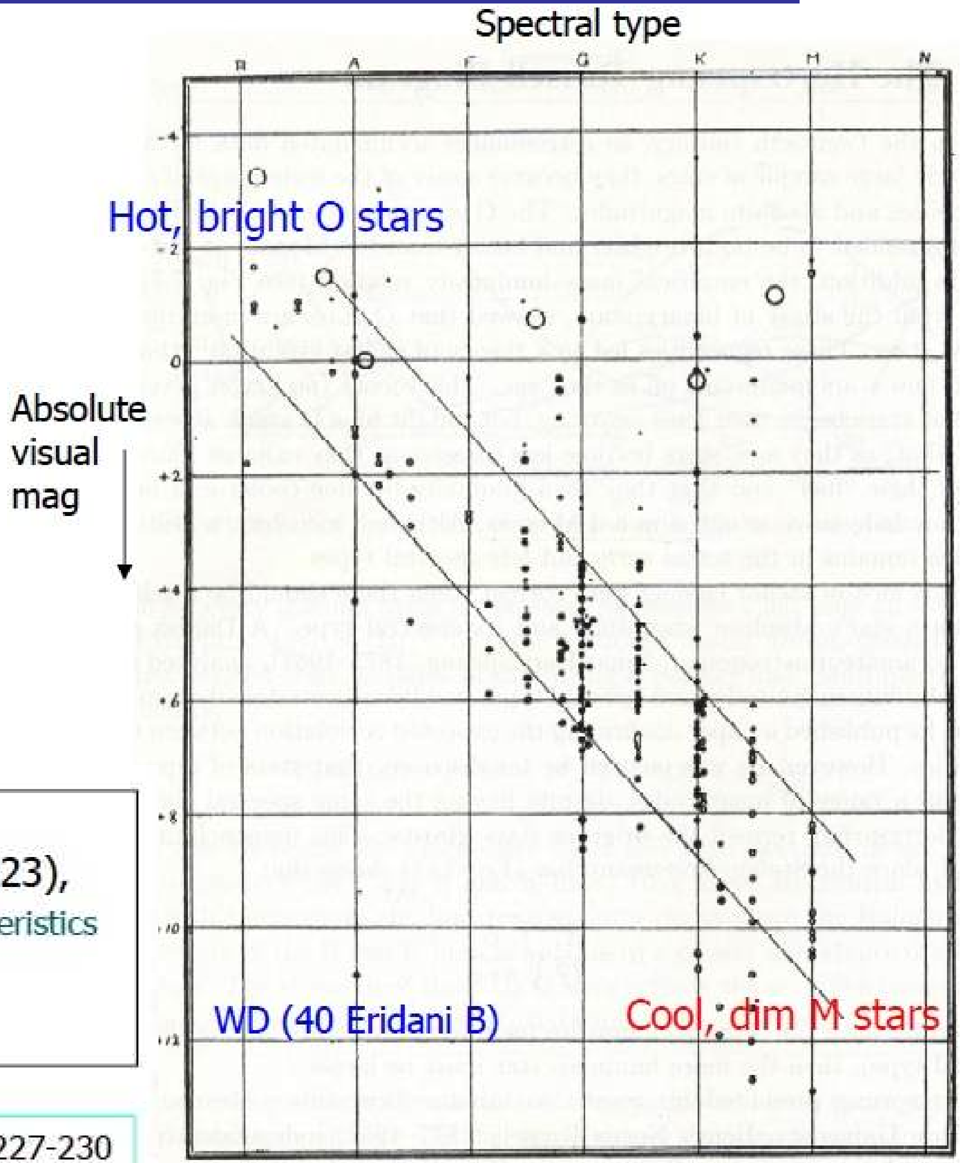
1913 Henry Norris Russell (1877-1957)
US, Princeton University
1913 – published the "diagram"

80-90% of all stars – main sequence (MS) stars

※ Bengt Strömgren (1908-1987, Danish)
: suggested the name "H-R" diagram

Fig 8.10 Henry Norris Russell's first diagram
(Russell, H. N. 1914 May 07, Nature, 93 (Number 2323), 252-258 `Relations Between the Spectra and other Characteristics of the Stars. II. Brightness and Spectral Class')
Fig. 1. > 200 stars

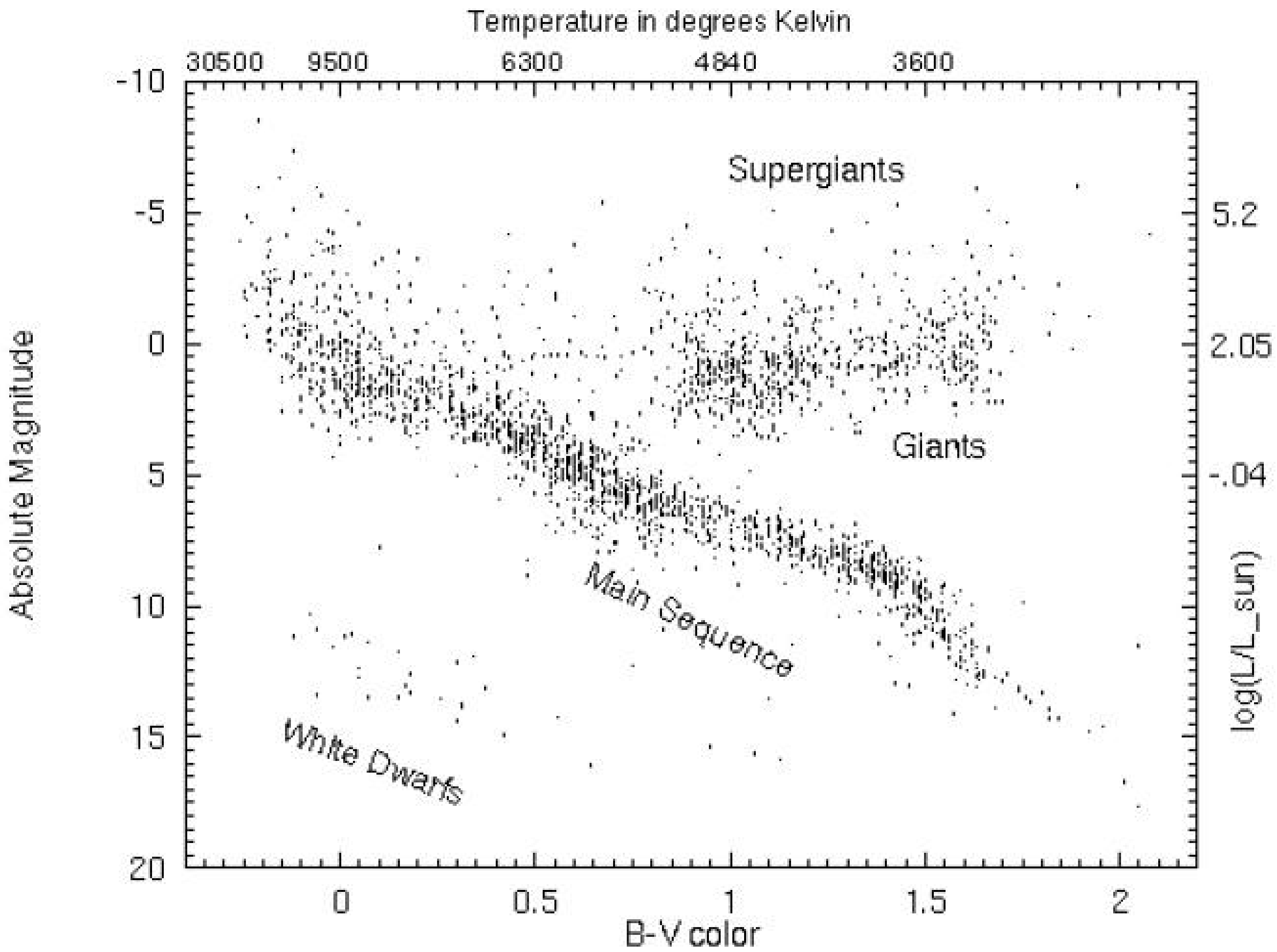
※ (Russell, H. N. 1914 April 30, Nature, 93 (Number 2322), 227-230 `Relations Between the Spectra and other Characteristics of the Stars. I. Historical')



An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 242

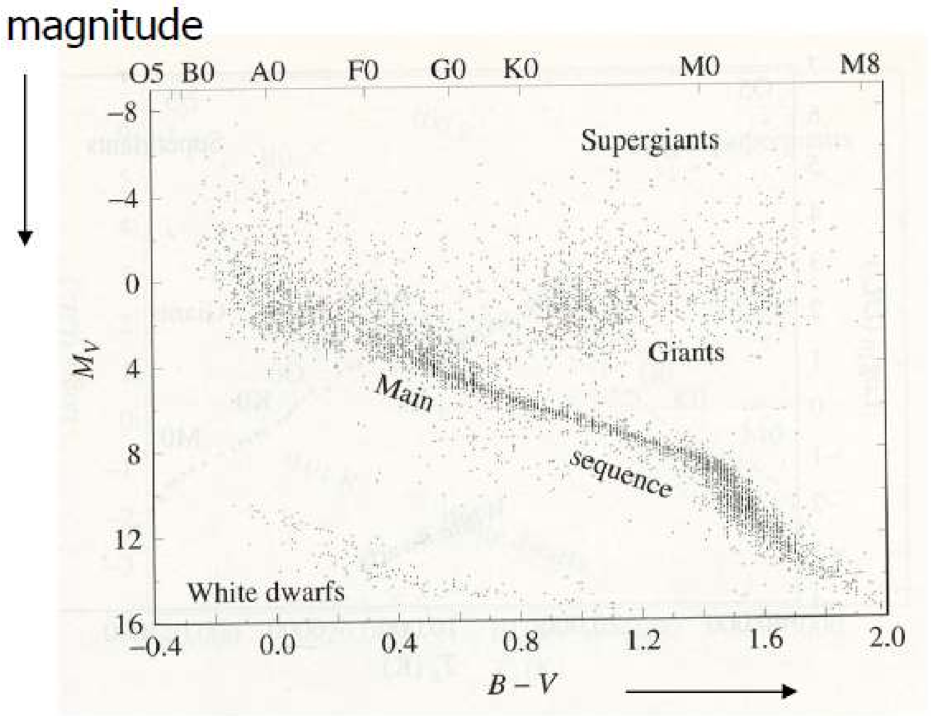
Main Sequence (MS, 주계열성)

Sequences!

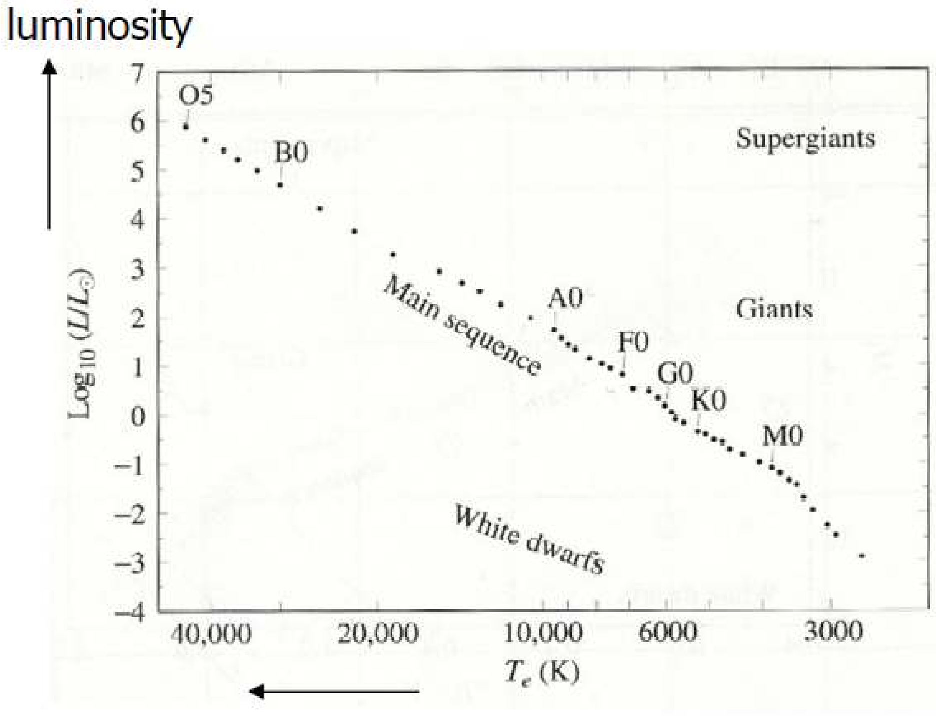


http://www.astronomynotes.com/starprop/s13.htm

Observer's vs Theoriest's H-R diagrams



Color index
(Spectral type)



Effective temperature

Fig 8.11 An observer's H-R diagram
※ MS → Sun : G2 V
Vega : A0 V

Color-Magnitude Diagram (CMD)

Fig 8.12 A theorist's H-R diagram
(log-log plot)

HR Diagram (HRD)

An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 243

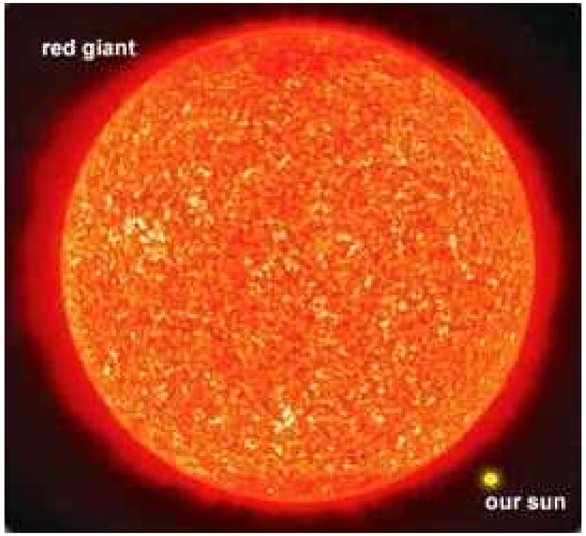
Spectral types

- O types: blue stars, usually supergiants. Very luminous and hot. rare. They have strong helium absorption lines. (e.g.) ζ (Zeta) Puppis

ζ Puppis (O4 I) – artist's rendering

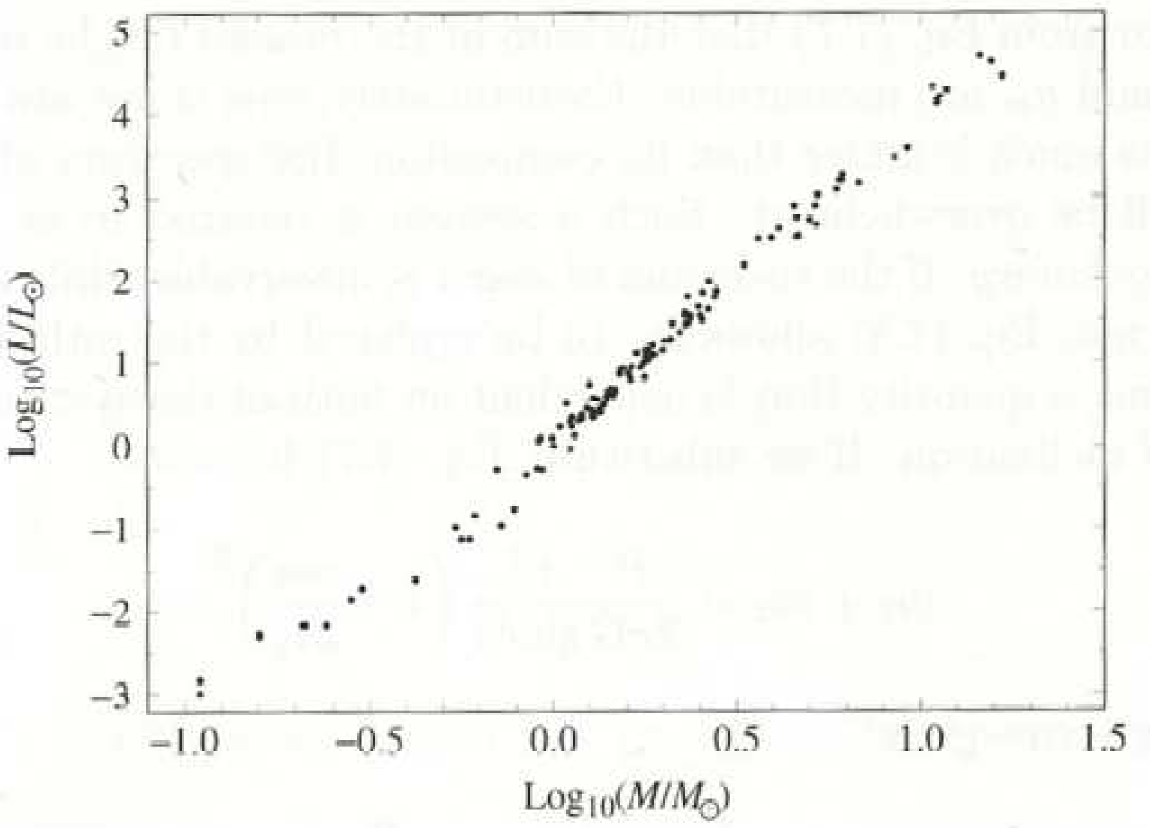
https://en.wikipedia.org/wiki/Zeta_Puppis

- B types: blue white stars. Mainly giants. They have neutral helium and hydrogen absorption lines. (e.g.) Rigel (= β Orionis)
- A types: white stars. Range from dwarfs to giants. They have huge **hydrogen absorption lines**. (e.g.) Sirius (= α CMa A)
- F types: yellow white stars, Mainly dwarfs. They have weak hydrogen and ionized calcium absorption lines. (e.g.) Procyon (= α CMi)
- G types: yellow stars, mainly dwarfs. They have strong calcium absorption lines: (e.g.) the Sun
- K types: orange stars, can exist as giants and dwarfs. Have metallic absorption lines. (e.g.) Arcturus (= α Boötis)
- M types: red stars. Exist at extremes either giants or red dwarfs. They have strong metallic absorption lines. (e.g.) Betelgeuse (= α Orionis), Proxima Centauri



https://archive.sssmediacentre.org/journals/Vol_05/01MAR07/04-SFI.htm

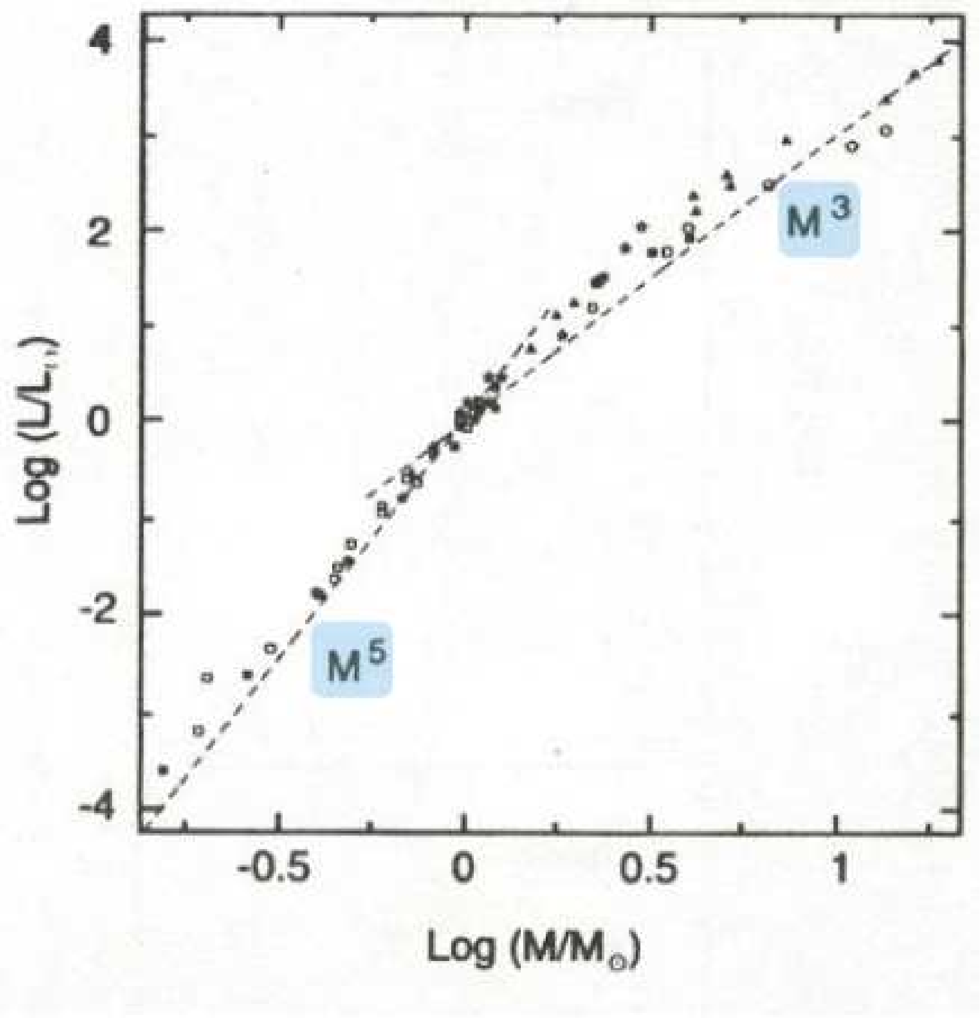
Stars → mass-luminosity relation



O stars : more luminous than M stars
→ O stars are more massive than M stars

An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 212

Stars → mass-luminosity relation

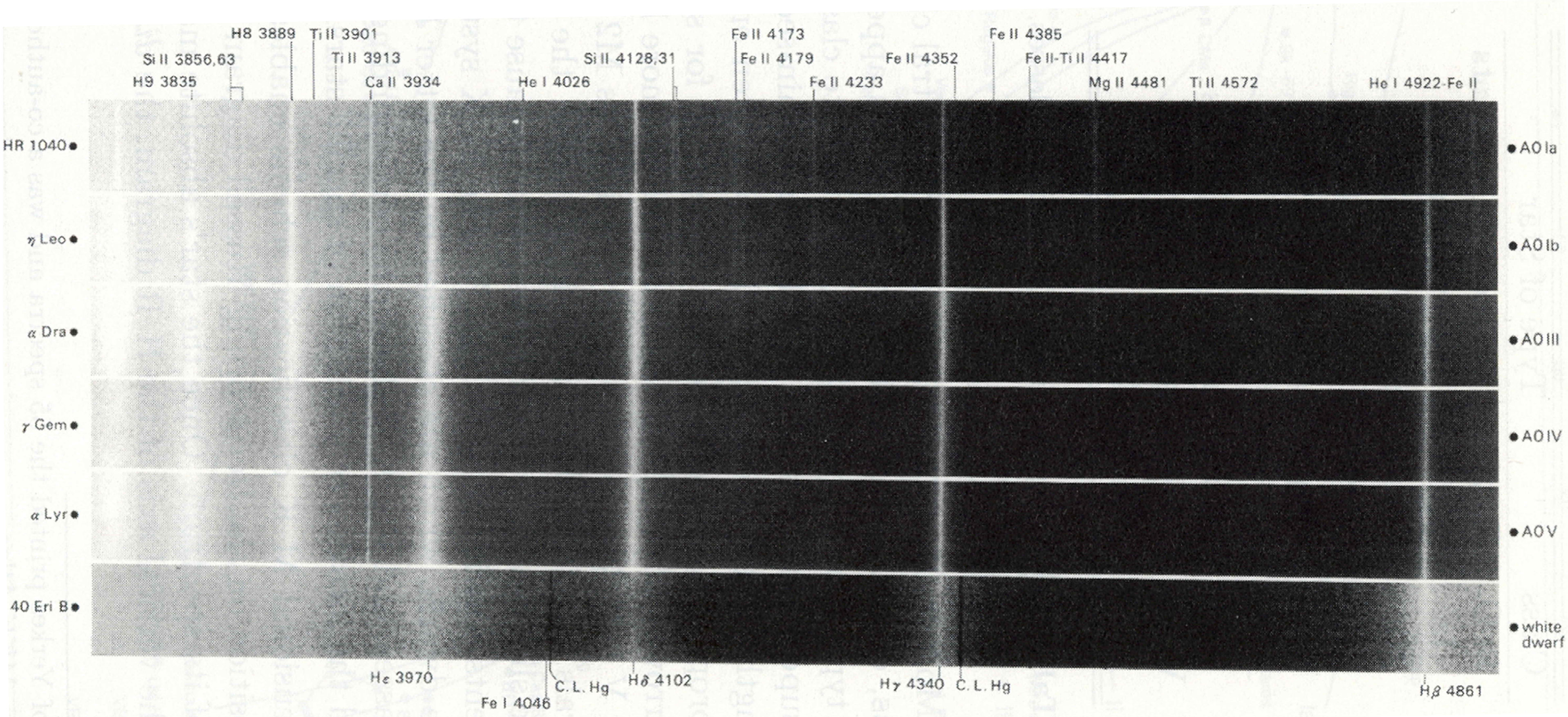


Power-law : $L \propto M^{\nu}$

$\nu = 3 - 5$

항성내부구조 및 진화, Dina Prialnik 저, 김용기 역, p. 26

Stellar spectra – hydrogen Balmer lines



More luminous stars → narrower lines

Stefan-Boltzmann equation $L = 4\pi R^2 \sigma T^4$

σ : Stefan-Boltzmann constant

$\sigma = 5.67 \times 10^{-5} \mathrm{erg\ cm^{-2}\ sec^{-1}}\ K^{-4}$

$\sigma = 5.67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$

T : same

L ∝ R^2 → less dense → fewer collisions between atoms → less broadening

An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 247

Morgan-Keenan Luminosity Classes

Class	Type of Star
Ia-O	Extreme, luminous supergiants (SGs)
Ia	Luminous SGs
Ib	Less luminous SGs
II	Bright giants
III	Normal giants
IV	Subgiants
V	Main-sequence (dwarf) stars
VI, sd	Subdwarfs
D	White dwarfs

- Same spectral type
- Same effective temperature
- Only luminosity differences ← subtle differences in the relative strengths of spectral lines

Morgan & Keenan (1973, ARA&A, 11, 29 – Spectral Classification)

An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 248

H-R diagram – luminosity classes

- Betelgeuse (=α Orionis)
  : M2 Ia (or M2 Iab) – pulsating variable
- Sun : G2 V

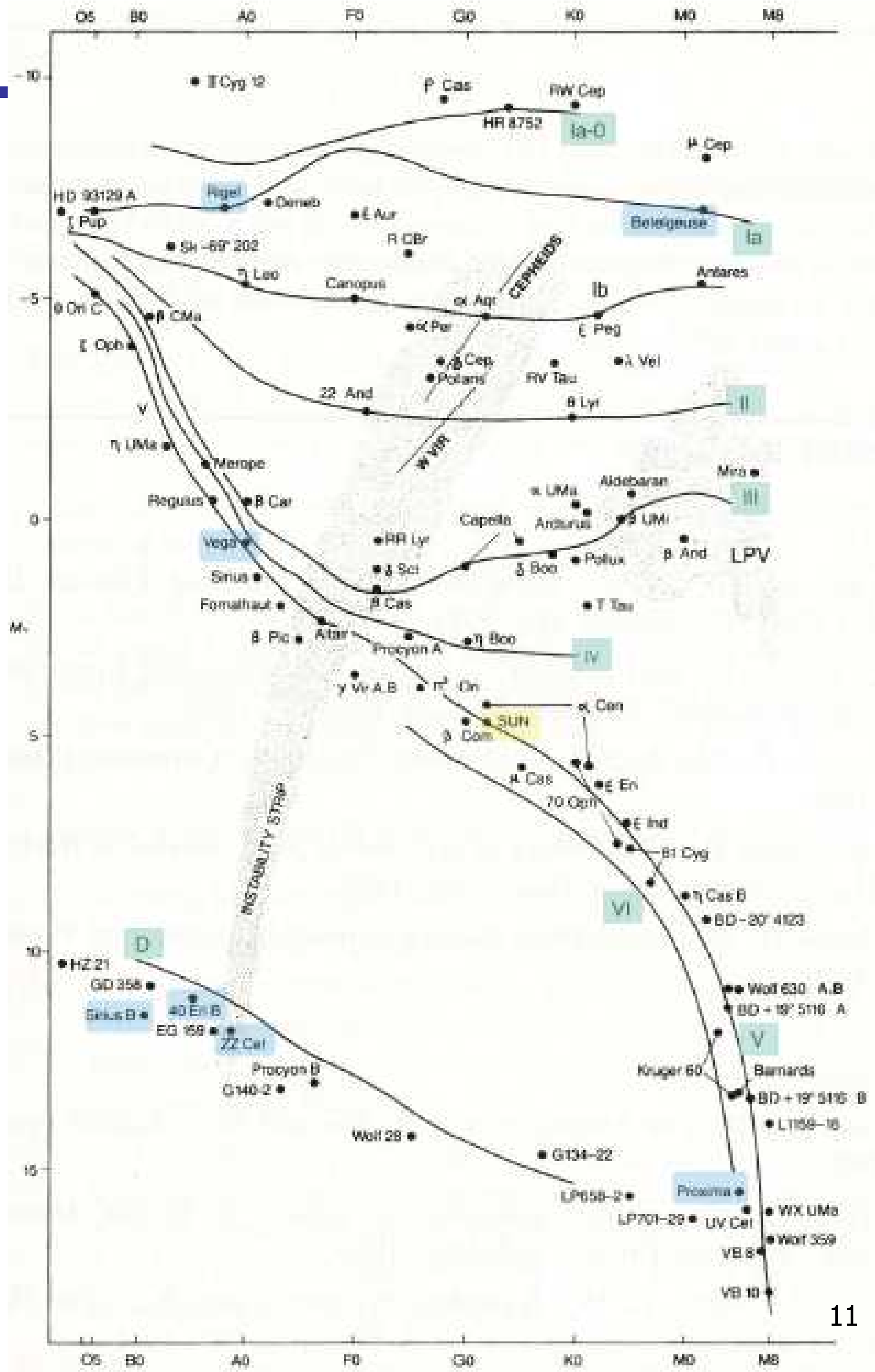
- A star's position is fixed in H-R diagram

→ (Vertical) reading of absolute mag (M_V)

→ Distance can be calculated by

$(m-M)_0 = V - M_V - A_V = 5 \log d - 5$

"spectroscopic parallax"



An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 249

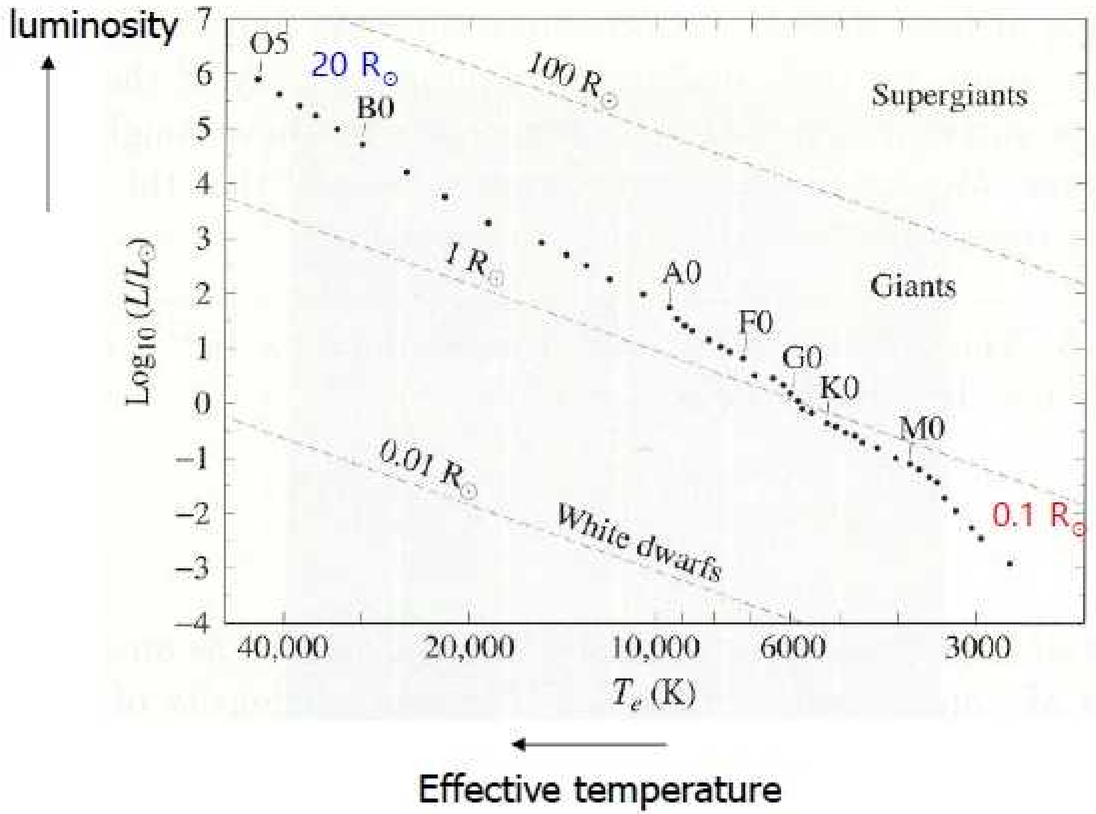
Line of constant radius

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

100 × L
→ 10 × R larger

Giant stars : 10 – 800 $R_\odot$
(e.g. Aldebaran, α Tauri : 45 $R_\odot$)

Supergiant stars
(e.g. Betelgeuse, α Orionis – pulsating variable star : 700 – 1000 $R_\odot$, P = 2070 d)



※ 1000 $R_\odot$ = 4.7 AU
※ μ Cephei : 1260 $R_\odot$ = 5.9 AU

※ Jupiter, semi-major axis a = 5.2 AU
※ Saturn, semi-major axis a = 9.5 AU

An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 245

https://www.space.com/22471-red-giant-stars.html

Vogt-Russell theorem

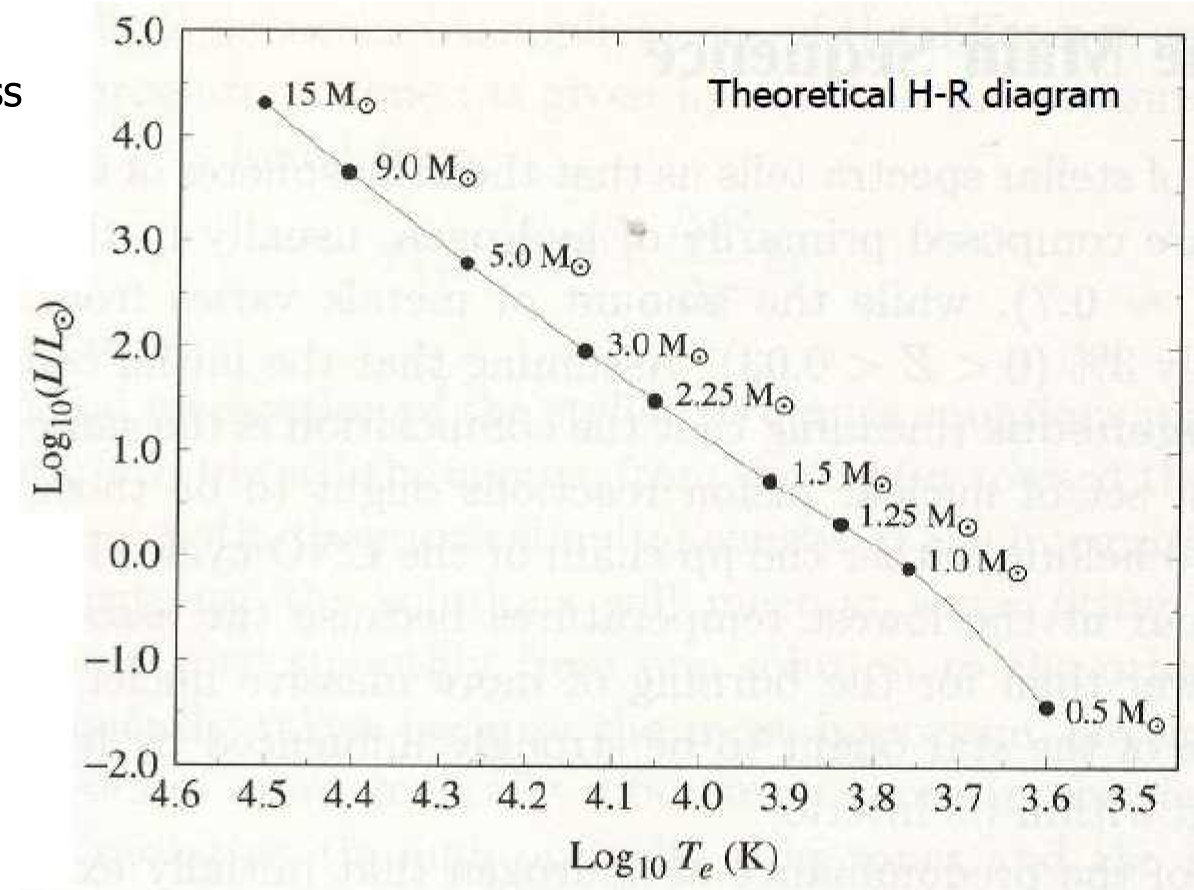
The mass and composition of a star uniquely determine its radius, luminosity, and internal structure, as well as its subsequent evolution.

An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 368

Stellar masses from models

- Theoretical models for the mass range of core H-b
  → lie along the observational MS

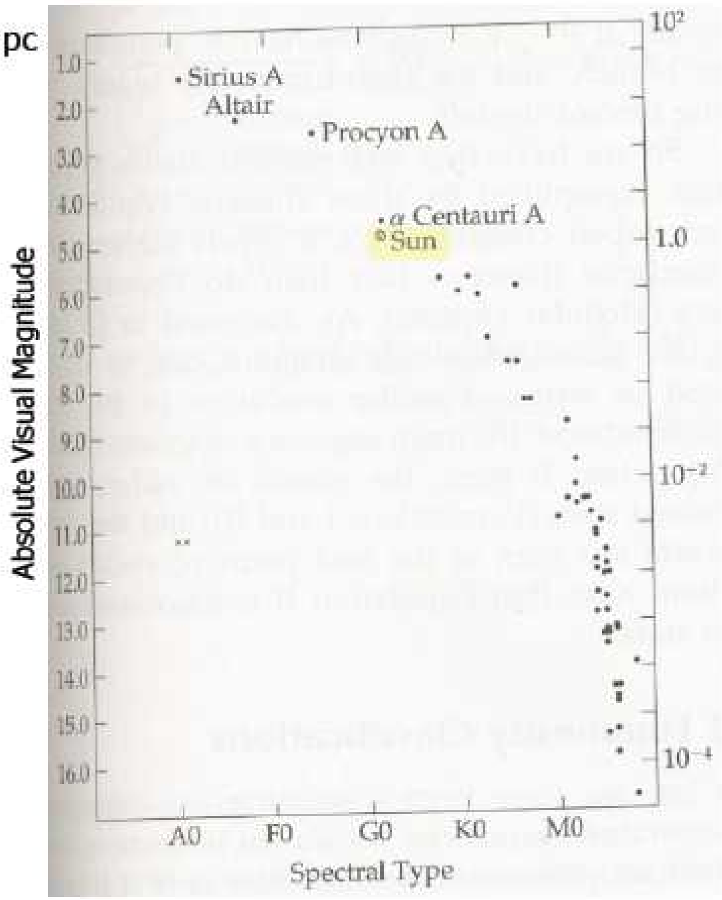
- 100 – 0.08 $M_\odot$
  → Only 3 orders of mag



An Introduction to Modern Astrophysics (2nd edition),
Bradley W. Carroll & Dale A. Ostlie (1996), p. 372

HR diagrams

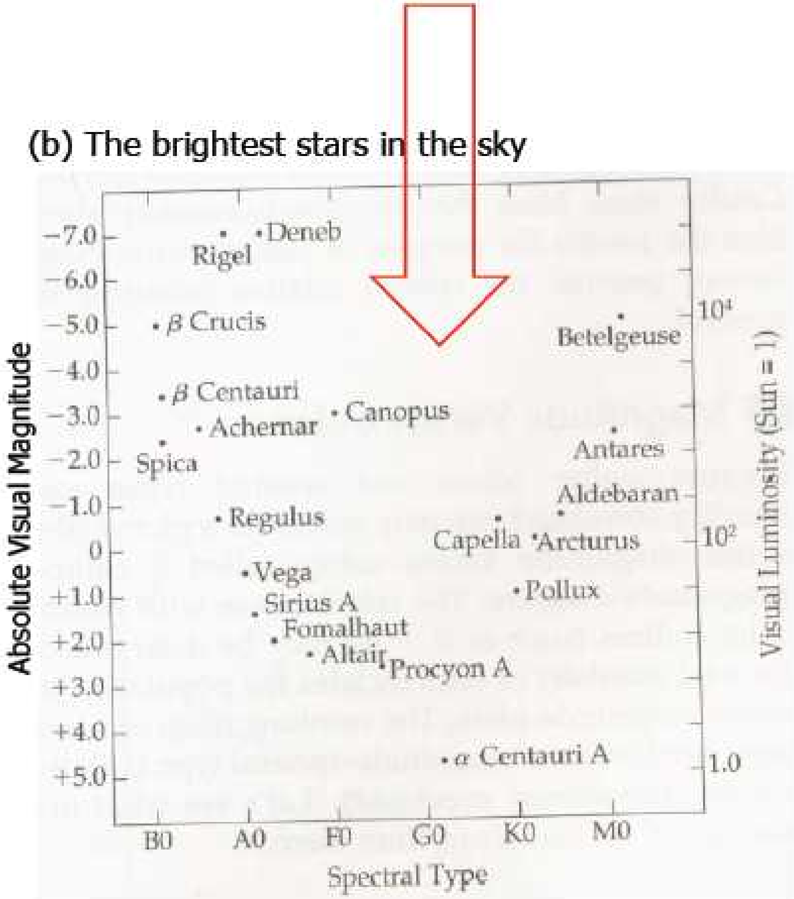
(a) Stars within 5 pc



- Most common : low-luminosity, cool (M-type) stars
- Well-defined MS + increasing number of stars toward later spectral types
- Absence of spectral classes earlier than A1 (Sirius A = α CMa A)

Hertzsprung Gap

(b) The brightest stars in the sky

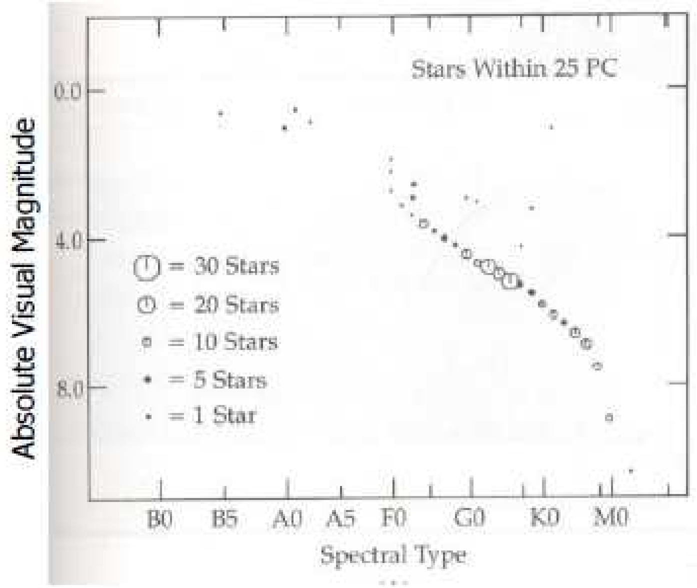


- A significant number of giants and SGs
- Several early-type MS stars

Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 259

HR diagrams

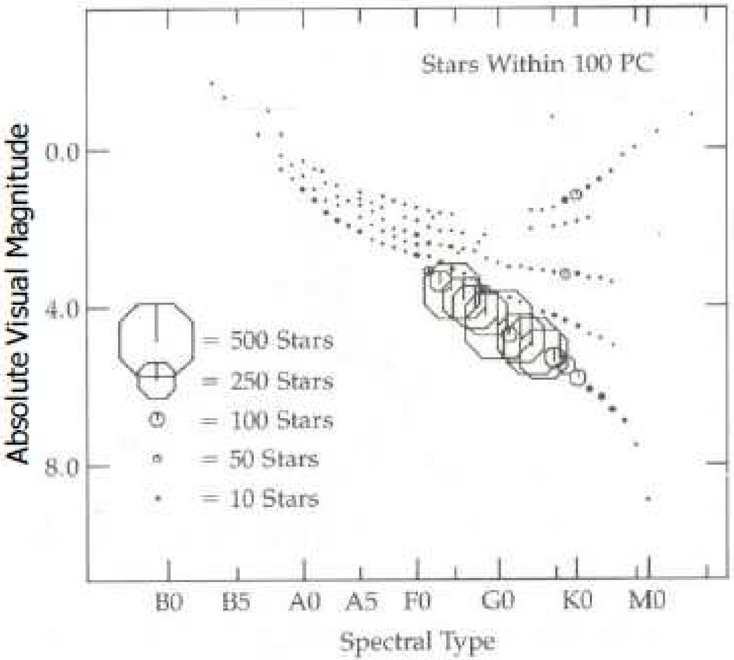
(a) Stars within 25 pc



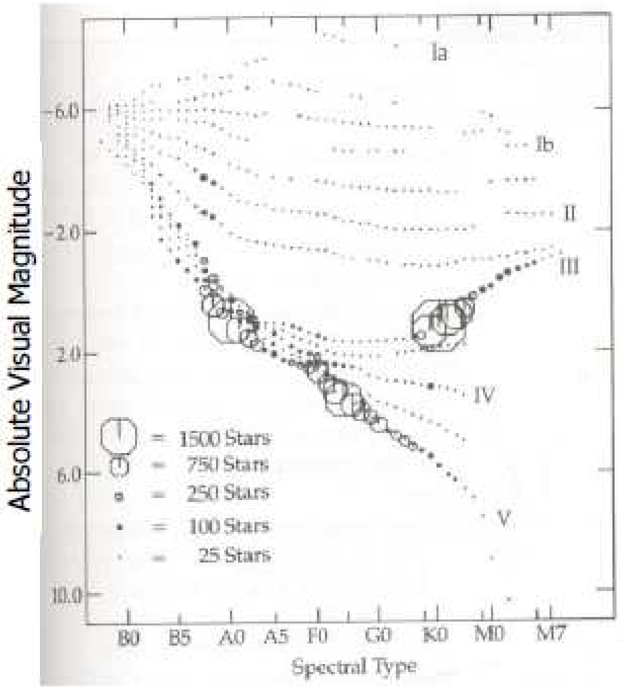
- From the Michigan Spectral Catalog
- Size ~ number of stars of that spectral type

Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 261

(b) Stars within 100 pc



(c) A sample of 36,000 stars

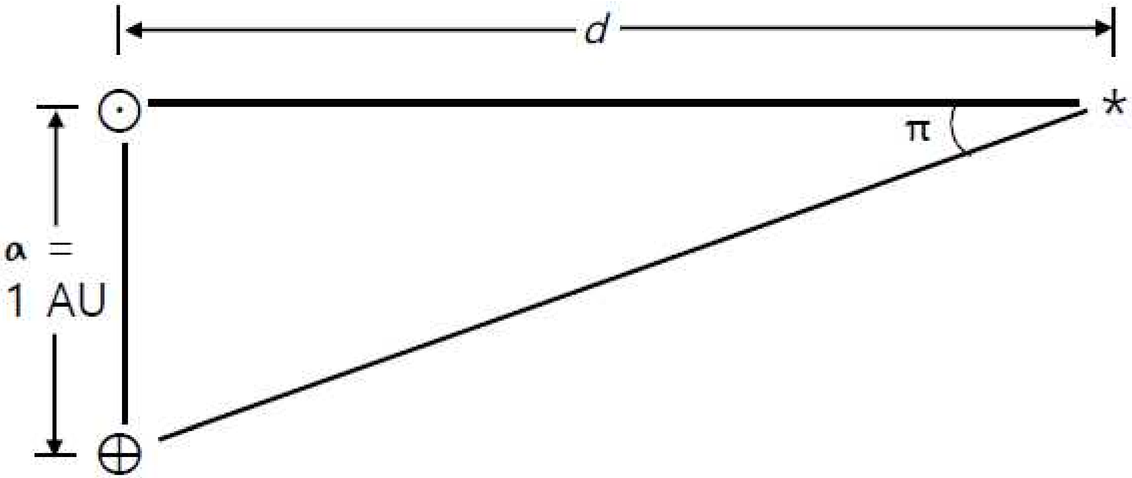


1. Stars: The Hertzsprung-Russell Diagram (항성: HR도)
1-2 Distances (거리)

http://www.centauri-dreams.org/?p=11322
http://www.centauri-dreams.org/wp-content/uploads/2010/02/light-candles.jpg

1. Trigonometric parallax (삼각시차)

- First detection (1838) :
  F. Bessel → 61 Cygni
  F. Struve → Vega (=α Lyr)



$$\pi(\mathrm{rad}) = a/d$$

- 2π (rad) = 360° → 1 rad = 57° 17′ 44.81″ = 206265″

$$\boxed{\pi'' = \frac{1}{d}}$$ (π in arcsec, d in parsec [파섹])

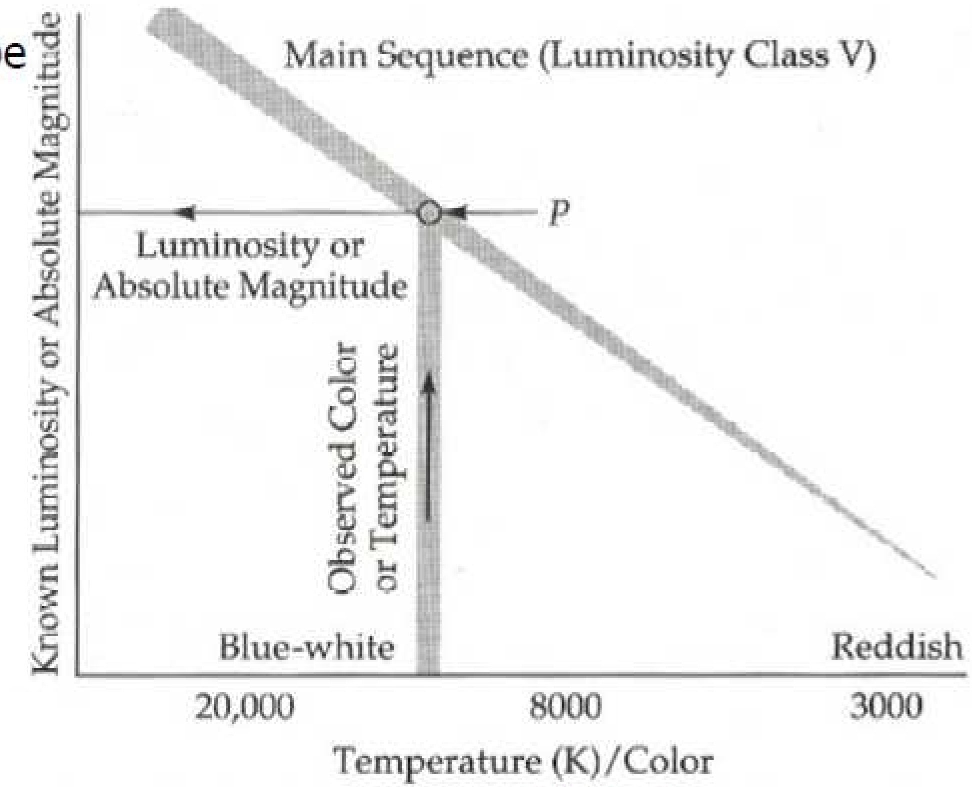
  1 pc = 3.086×10^{18} cm = 3.26 lightyears (광년)
- Largest parallax : Alpha Centauri (d=1.3 pc) → π =0.76″
- Ground-based observations → error ~ ±0.004″
  → accurate only to π =0.001″ (d ~ 100 pc)

Spectroscopic parallax – using spectral type

- A star's spectrum → determine spectral type and luminosity class

- A star's position is fixed in H-R diagram
→(Vertical) reading of absolute mag (M_V)
→Distance can be calculated by
$(m\text{-}M)_0 = V - M_V - A_V = 5 \log d - 5$
"spectroscopic parallax"

- Observational errors, scatter in the HR diagram → mag uncertainty : ± 1.0 mag
(distance error : 50%)

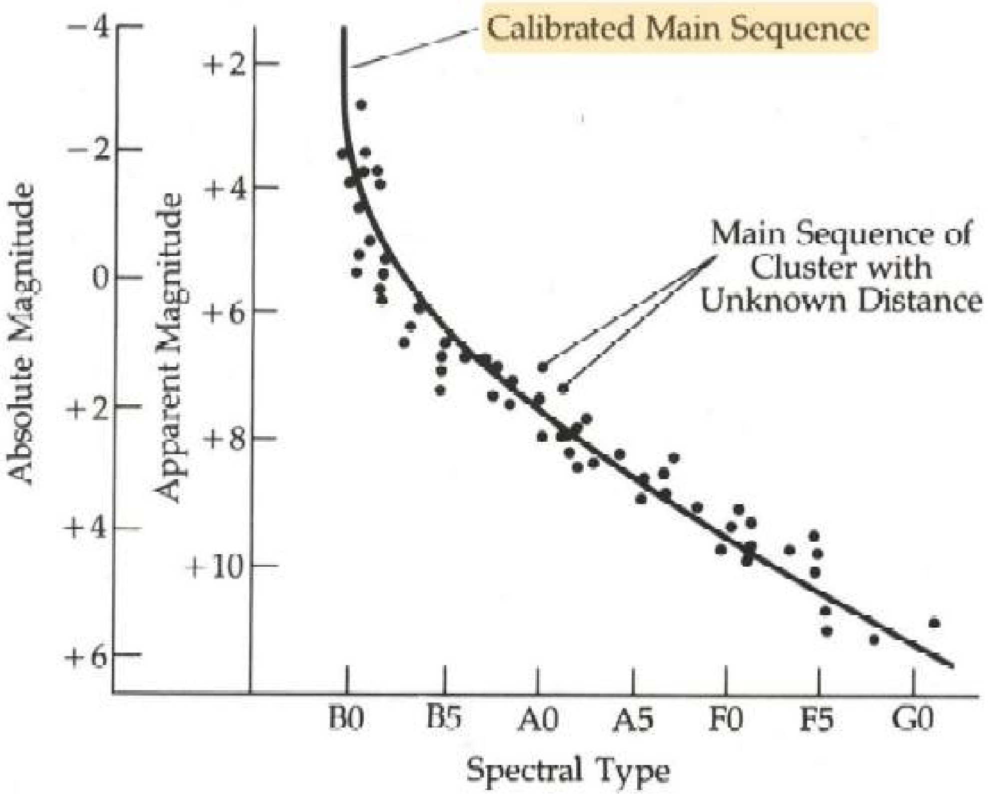


A calibrated H-R diagram

Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 266

Spectroscopic parallax – using spectral type

- For observational data of an entire star cluster : color – apparent magnitude
  → shift up and down (in magnitude)
- (test cluster apparent mag) – (calibrated absolute mag) = (m-M)
  → distance modulus
  → same for every star in the cluster
- Better accuracy than the spectroscopic parallaxes → mag uncertainty : ±0.2 mag

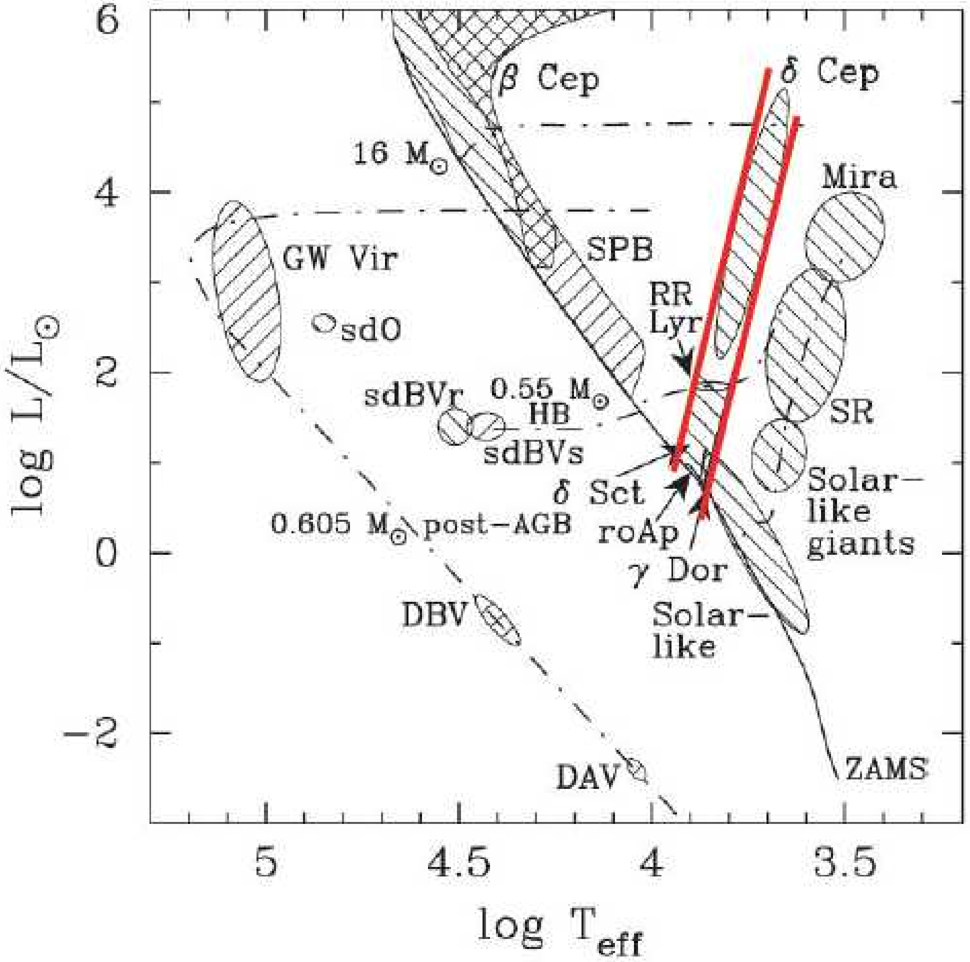


A calibrated H-R diagram

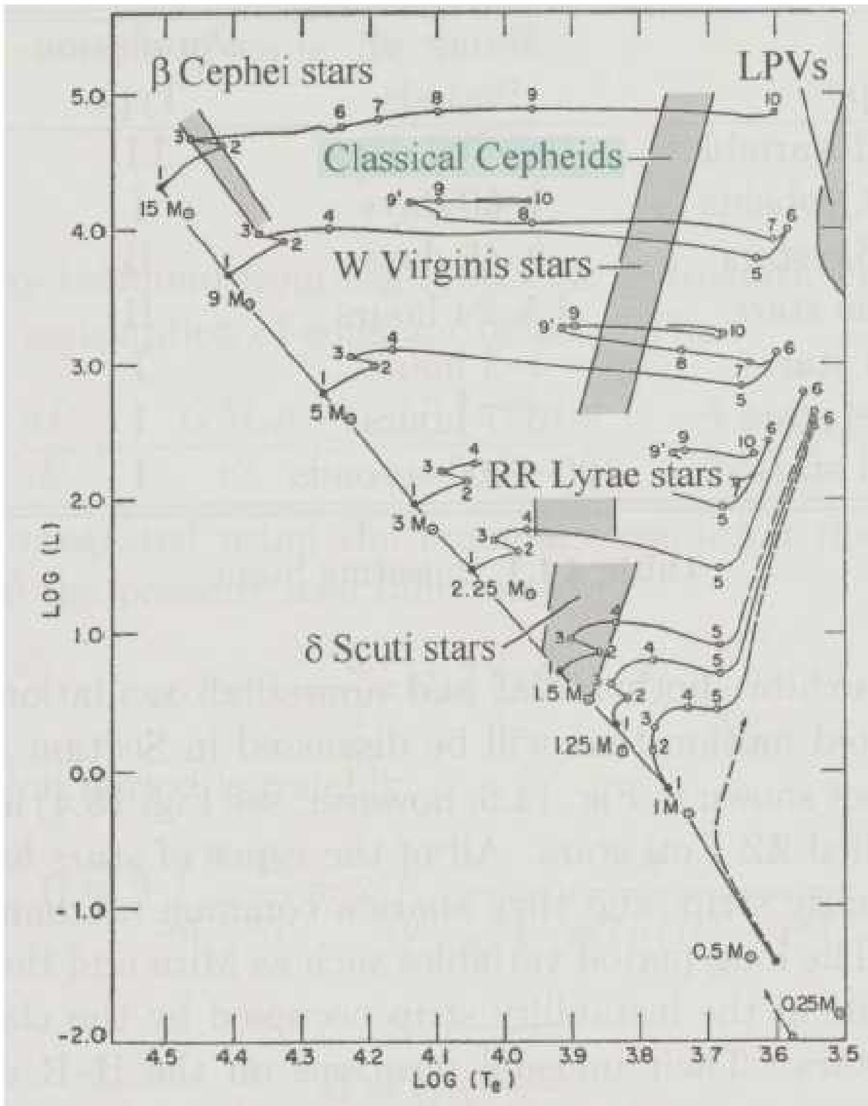
Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 266

2. Pulsating Variable Stars – Cepheids, RR Lyrae

Instability strip

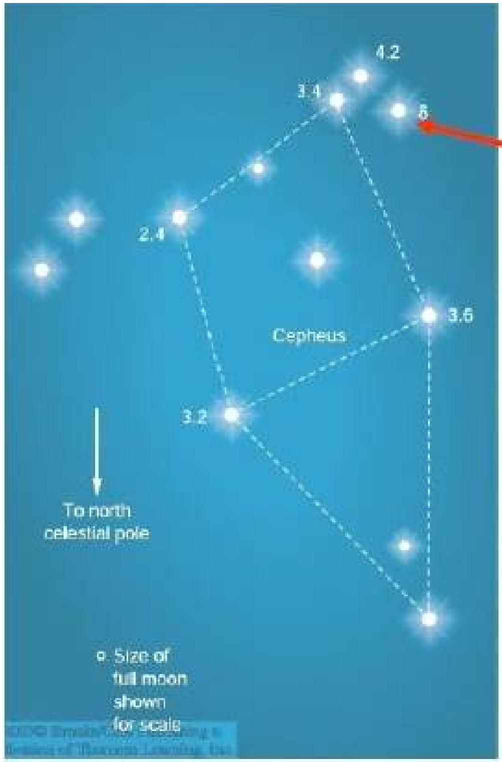


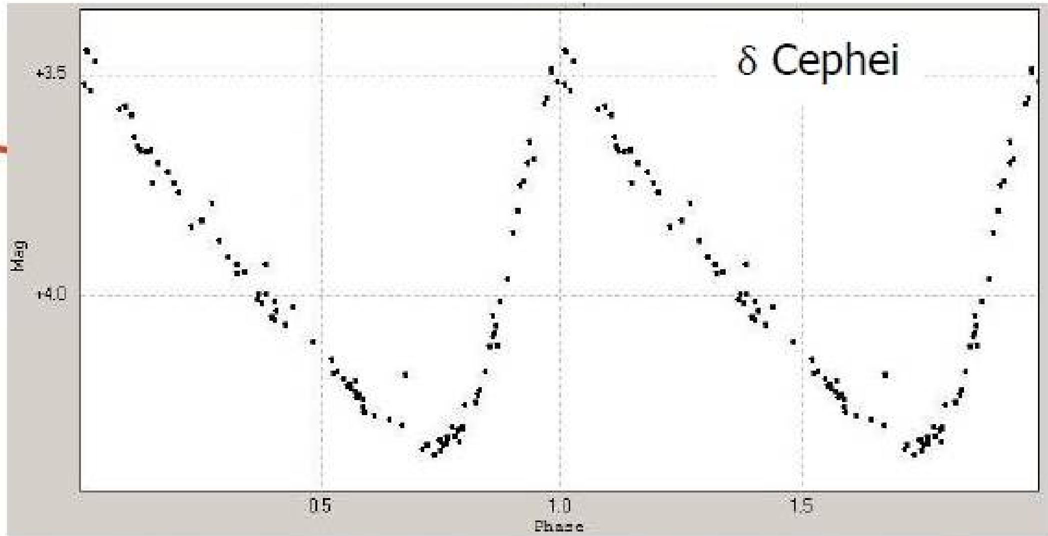
Handler (2009, MNRAS, 398, 1339) Fig 1



An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 547

Cepheid Variables – Light Curves (LCs)





P= 5.366341 d (http://earthsky.org/brightest-stars/delta-cephei-the-kings-famous-variable-star)

= δ Cepheids
= Classical Cepheids

$M_i \geq 5\ M_\odot$
(young stars)
(in spiral arms)
Age ≤ 0.1 Gyr

Galactic Astronomy (J. Binney & M. Merrifield, 1998) p. 291

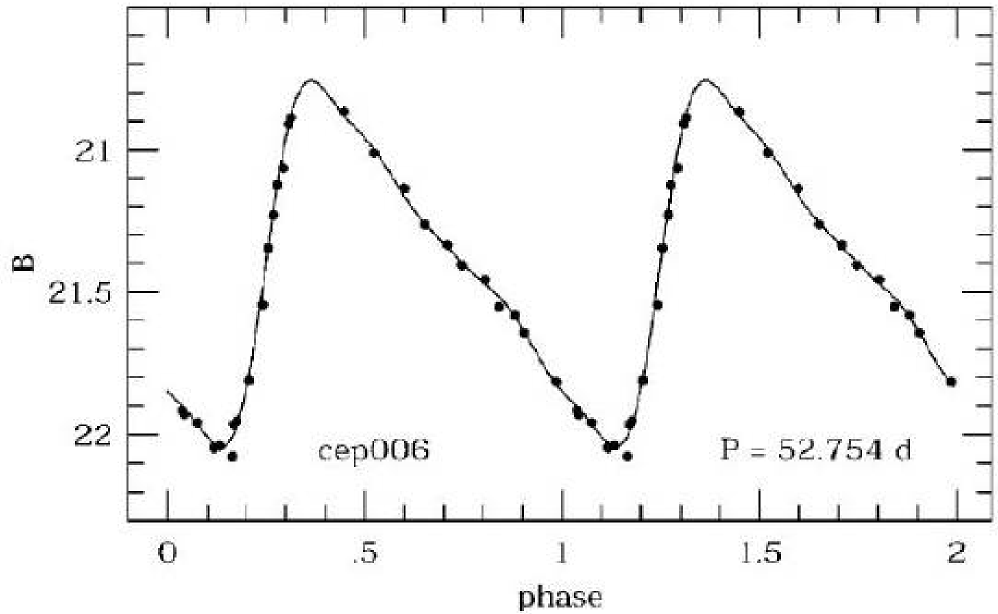
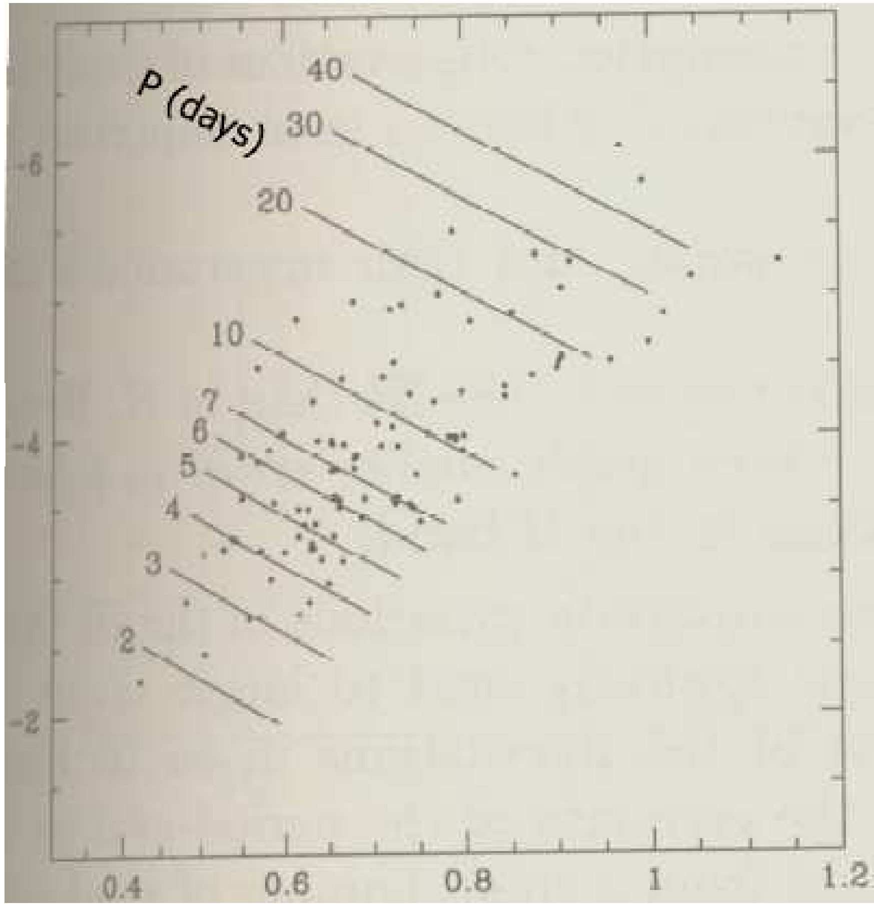


Figure 1: B light-curve of a typical Cepheid in NGC 300. The data were obtained with the ESO-MPA 2.2-m telescope and Wide Field Imager.

Gieren+01 (Messenger, 106, 15)

Cepheid Variables

Instability strip (불안정띠)



M_V

$(B\text{-}V)_0$

- Data : 98 Galactic Cepheids with well determined reddening (Fernie 1990 ApJ 354 295)
- Instability strip lines ← stellar evolution models (Chiosi+93 ApJS 86 541)

Galactic Astronomy (J. Binney & M. Merrifield, 1998) p. 291

Cepheid Variables

- Periodic (regular) variables
- Pulsation period ∝ median luminosity
- Period-Luminosity relation **(P-L relation)** : Leavitt's law
- Populations I, II - separate relations

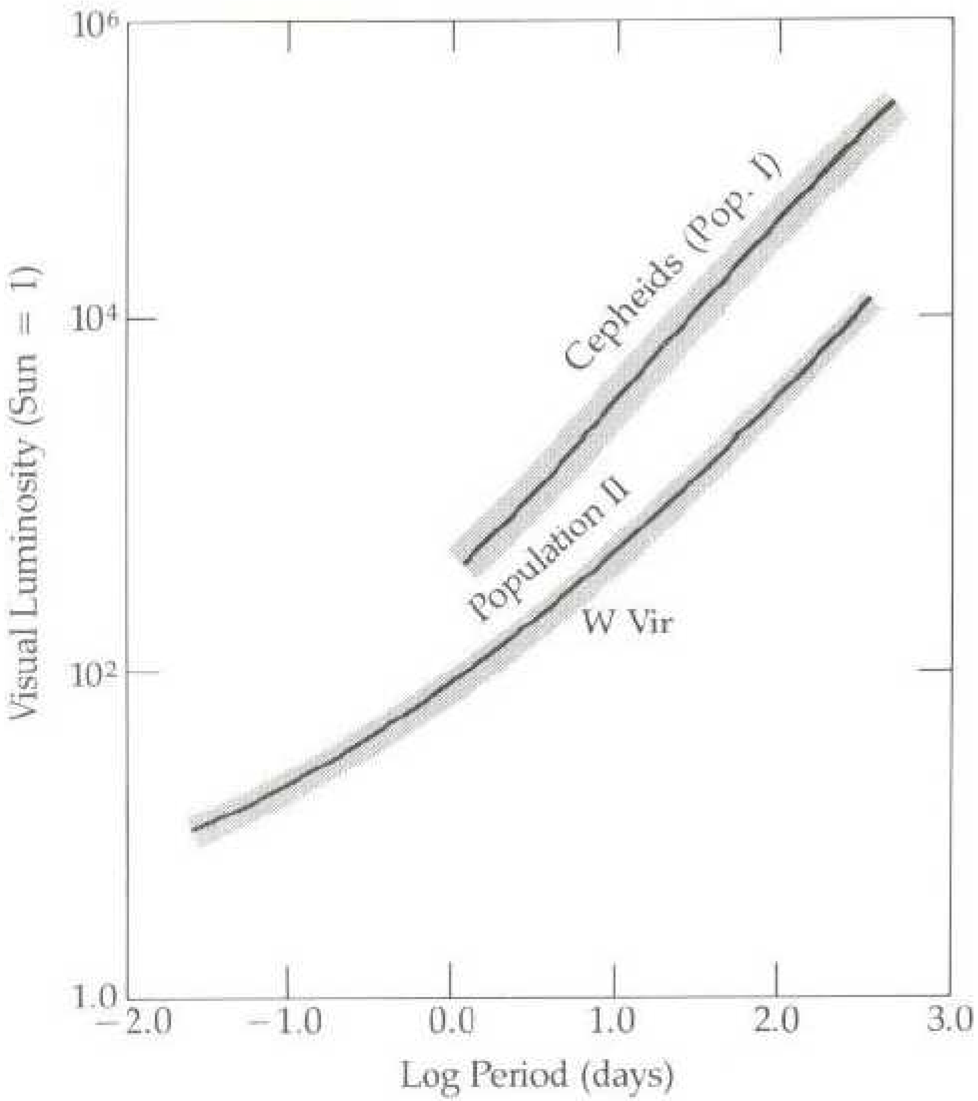
- Classical Cepheids (pop I Cepheids) : more luminous, in spiral arms, P = 1 – 50 d (5-10 d), F6 to K2

$$\langle M_V \rangle = -(2.76 \pm 0.11)\log(P/10\mathrm{d}) - 4.16 \pm 0.05$$

$$(\mathrm{scatter} \sim 0.27\ \mathrm{mag})$$

Galactic Astronomy (J. Binney & M. Merrifield, 1998, p. 292)

- W Virginis Stars (pop II Cepheids) : 4-times less luminous than classical Cepheids, in globular clusters and other population II systems, P = 2 – 45 d (12-20 d), F2 to G6



Henrietta S. Leavitt (1912, Harvard College Obs. Circ., 173, 1 'Discovery of the Cepheid PL relation')

Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 356

3. RR Lyrae stars

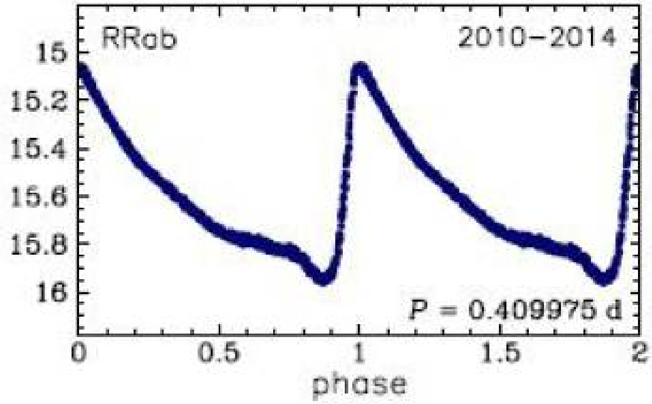
- Periodic variable stars
- P = 1.5 to 24 h (~12 h), Peak M_V ~ 0-1 mag, spectra A2 to F6
- Current mass ~ 0.8 $M_\odot$ (original MS mass ~ 1 $M_\odot$), old, relatively metal-poor
- In GCs and in low-metallicity systems (population II) – But, some have high metallicity

$$M_V(RR) = +0.71 \pm 0.12 \text{ at } \langle[\text{Fe/H}]\rangle = -1.61 \text{ for the halo (162 stars)}$$

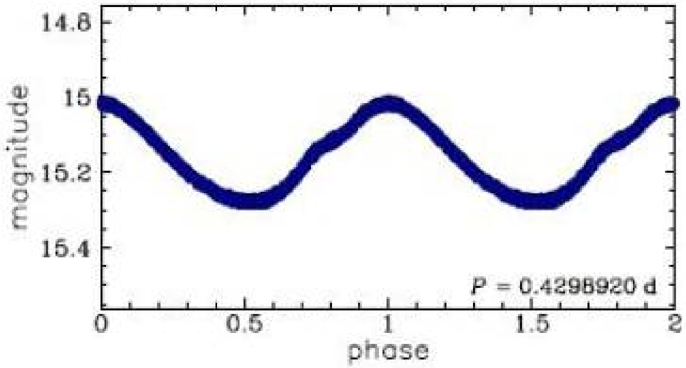
$$M_V(RR) = +0.79 \pm 0.30 \text{ at } \langle[\text{Fe/H}]\rangle = -0.76 \text{ for the thick disk (51 stars)}$$

Layden et al. (1996, AJ, 112, 2110)

RR_{ab}



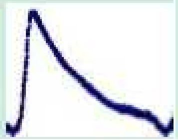
RR_c



http://ogle.astrouw.edu.pl/atlas/RR_Lyr.html

RR Lyrae classification / Oosterhoff classes

Classification : S. I. Bailey types

Bailey types	Period	Δm	Light Curve	Fraction	Location in MWG
RR_{ab}	≥0.4 d ($\langle P_{ab} \rangle$ =0.55 d)	0.5 – 1.5 mag	asymmetric light curves, steep brightness rise (fundamental mode) 	most common (91% of all observed RR Lyrae)	Halo
RR_c	≤0.4 d ($\langle P_c \rangle$ =~0.3 d)	≤0.5 mag	symmetric (more sinusoidal) (first-overtone mode) 	less common (9% of observed RR Lyrae)	old disk
RR_d			double-mode pulsators (unlike RR_{ab} and RR_c) (i.e. fundamental + first-overtone mode)	rare (<1% ~ 30% of RR Lyrae in a system)	Halo

Oosterhoff class
I : GCs with red HBs – mostly RR_{ab}, P~0.55 d
II : GCs with blue HBs – more RR_c stars + RR_{ab} stars with longer P (P~0.65 d)

Galactic Astronomy (J. Binney & M. Merrifield, 1998) p. 294
Oosterhoff, P. Th. 1939, Observatory, 62, 104

4. Tip of the red giant branch (TRGB)

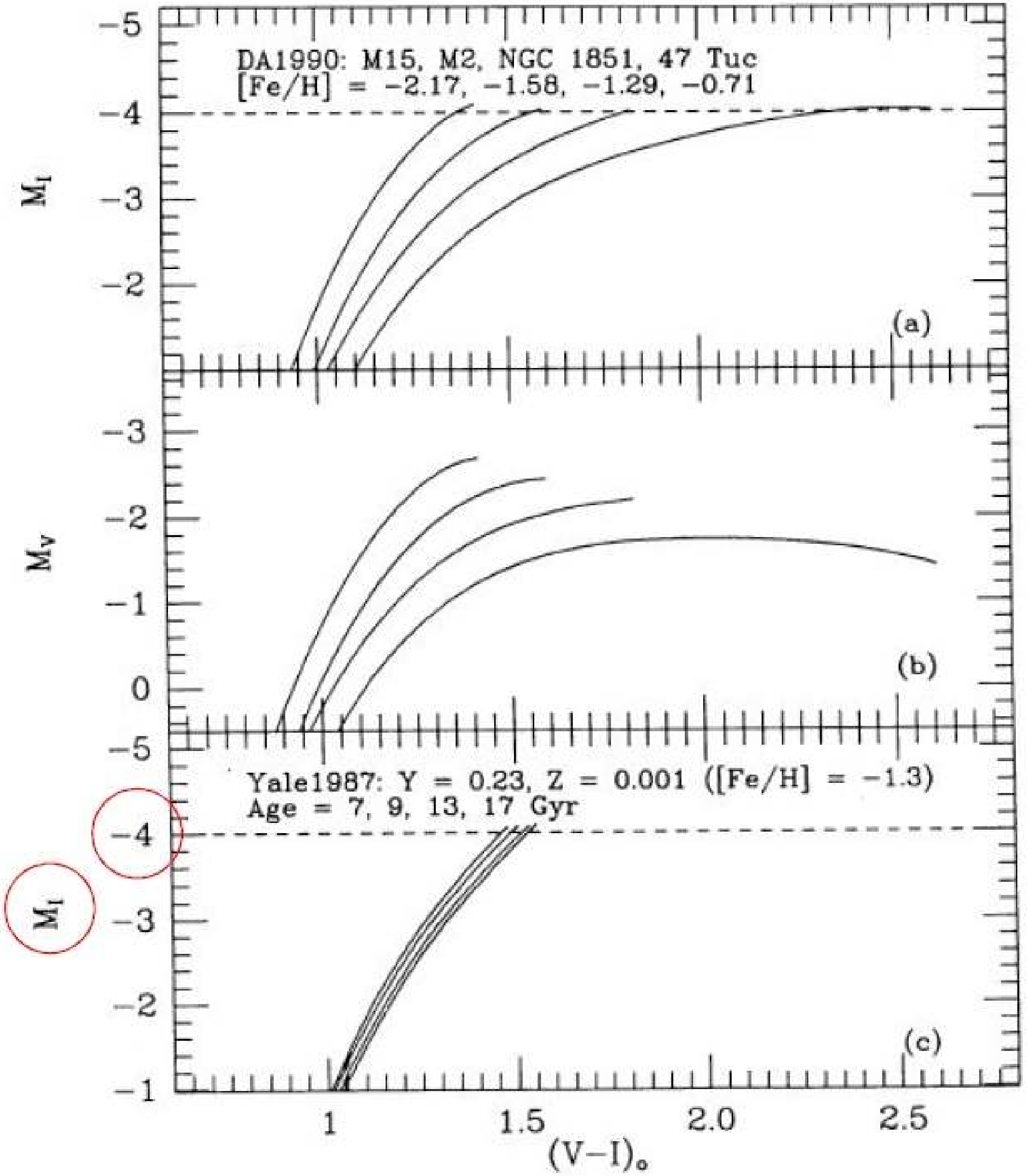


Fig. 1

Lee et al. (1993, ApJ, 417, 553)

이명균

Tip of the red giant branch (TRGB)

TABLE 1

DISTANCE ESTIMATES FOR RESOLVED GALAXIES BASED ON PRIMARY DISTANCE INDICATORS

GALAXY (1)	TYPE[a] (2)	$E(B-V)$ (3)	$(m-M)_0$ Cepheid (4)	RR Lyrae (5)	I_{TRGB} (6)	I_{TRGB} (7)	REFERENCE[b] (8)	[Fe/H][c] (9)	M_B (10)	M_V (11)
LMC	SBmII	0.10	18.50	18.28	18.42	14.6	1, 2, 3	−1.2	−17.93	−18.36
NGC 6822	ImIV–V	0.28	23.62	...	23.46	20.05	4, 4	−1.8:	−15.13	−16.42
NGC 185	dE3pec	0.19	...	24.01	23.94	20.30	5, 6	−1.2	−14.63	−15.52
NGC 147	dE5	0.17	...	24.06	24.13	20.4	7, 8	−0.9	−14.39	−15.17
IC 1613	IMV	0.02	24.42	24.27	24.27	20.25	1, 9, 10	−1.3	−14.51	−15.16
M31	SbI–II	0.08	24.44	24.36	24.44	20.55	1, 11, 12	−0.8	−20.98	−21.74
M33	Sc(s)II–III	0.10	24.63	24.71	24.70	20.95	1, 13, 12	−2.0	−18.94	−19.40
WLM	ImIV–V	0.02	24.92	...	24.81	20.85	14, 14	−1.6:	−14.28	−14.62
NGC 205	S0/dE5pec	0.035	...	24.76	24.42	20.45	15, 16	−0.8	−15.80	−16.62
NGC 3109	SmIV	0.04	25.5	...	25.45	21.55	17, 18	−1.6	−15.95	−16.25

[a] From Sandage & Tammann 1987.

[b] References: (1) Madore & Freedman 1991, (2) Walker 1988, (3) Reid & Mould 1987, (4) Lee, Freedman, & Madore 1993, (5) Saha & Hoessel 1990, (6) Lee, Freedman, & Madore 1992, 1993c; (7) Saha, Hoessel, & Mossman 1990; (8) Mould, Kristian, & Da Costa 1983; (9) Saha et al. 1992; (10) Freedman 1988; (11) Pritchet & van den Bergh 1987, 1988; (12) Mould & Kristian 1986; (13) Pritchet 1988; (14) Lee, Freedman, & Madore 1993a; (15) Mould, Kristian, & Da Costa 1984; (16) Saha, Hoessel, & Krist 1991; (17) Capaccioli, Piotto, & Bresolin 1992; (18) Lee 1993.

[c] The metallicity [Fe/H] has been determined using the color $(V-I)_{-3.5}$.

$$-2.2 < [\mathrm{Fe/H}] < -0.7 \text{ dex}$$

Lee et al. (1993, ApJ, 417, 553)

Tip of the red giant branch (TRGB)

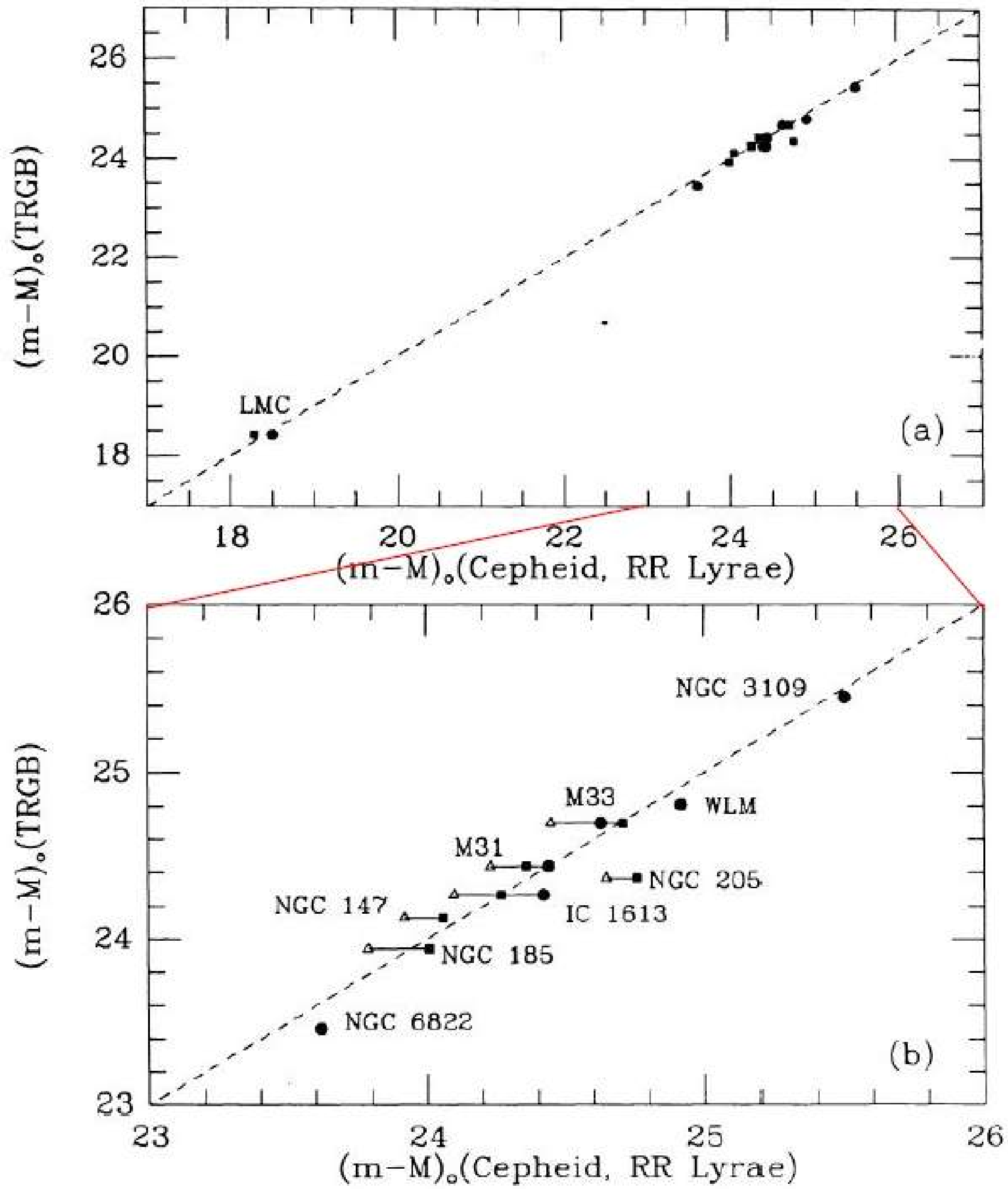


Fig. 4

Lee et al. (1993, ApJ, 417, 553)

※ Mass fractions

Mass ratios (rather than numbers of particles)

Mass fractions of hydrogen : $X \equiv \dfrac{total\ mass\ of\ hydrogen}{total\ mass\ of\ gas}$

Mass fractions of helium : $Y \equiv \dfrac{total\ mass\ of\ helium}{total\ mass\ of\ gas}$

Mass fractions of metals : $Z \equiv \dfrac{total\ mass\ of\ metals}{total\ mass\ of\ gas}$

$X + Y + Z = 1$

For stars, usually, $X \sim 0.7$, $0 < Z < 0.03$

An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 325

5. Novae (신성) – Rate of Decline

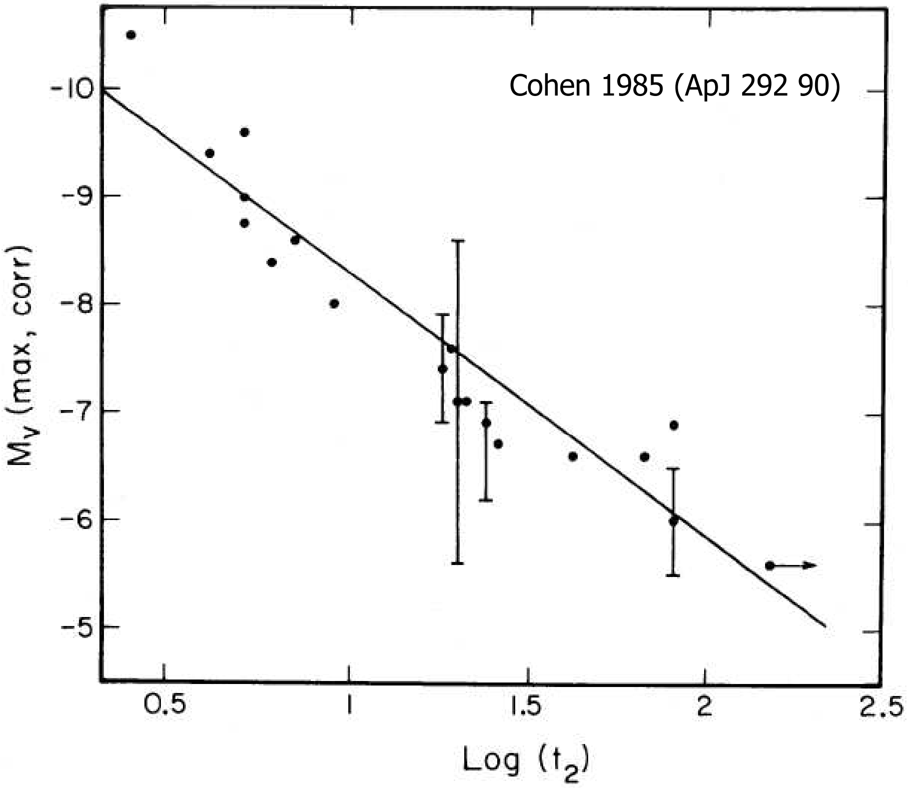
- **Peak brightness (M_V = -4.8 ~ -8.9)**
- **MMRD (Maximum Magnitude – Rate of Decline) relation**

light from faint novae decays more slowly

$$M_V(\text{max, corr}) = -10.70(\pm 0.30) + 2.41(\pm 0.23) \log t_2$$

t_2 : time that nova takes to decline in brightness by 2 mag from the maximum

Cohen 1985 (ApJ 292 90)



Galactic Astronomy (J. Binney & M. Merrifield, 1998) p. 419

5. Novae (신성) – Luminosity Function

Capaccioli+ 89 (AJ 97 1622)

L. Rosino 64 (A&A 27 498)
L. Rosino 73 (A&AS 9 347)

- Double-peak
- Sharp central minimum

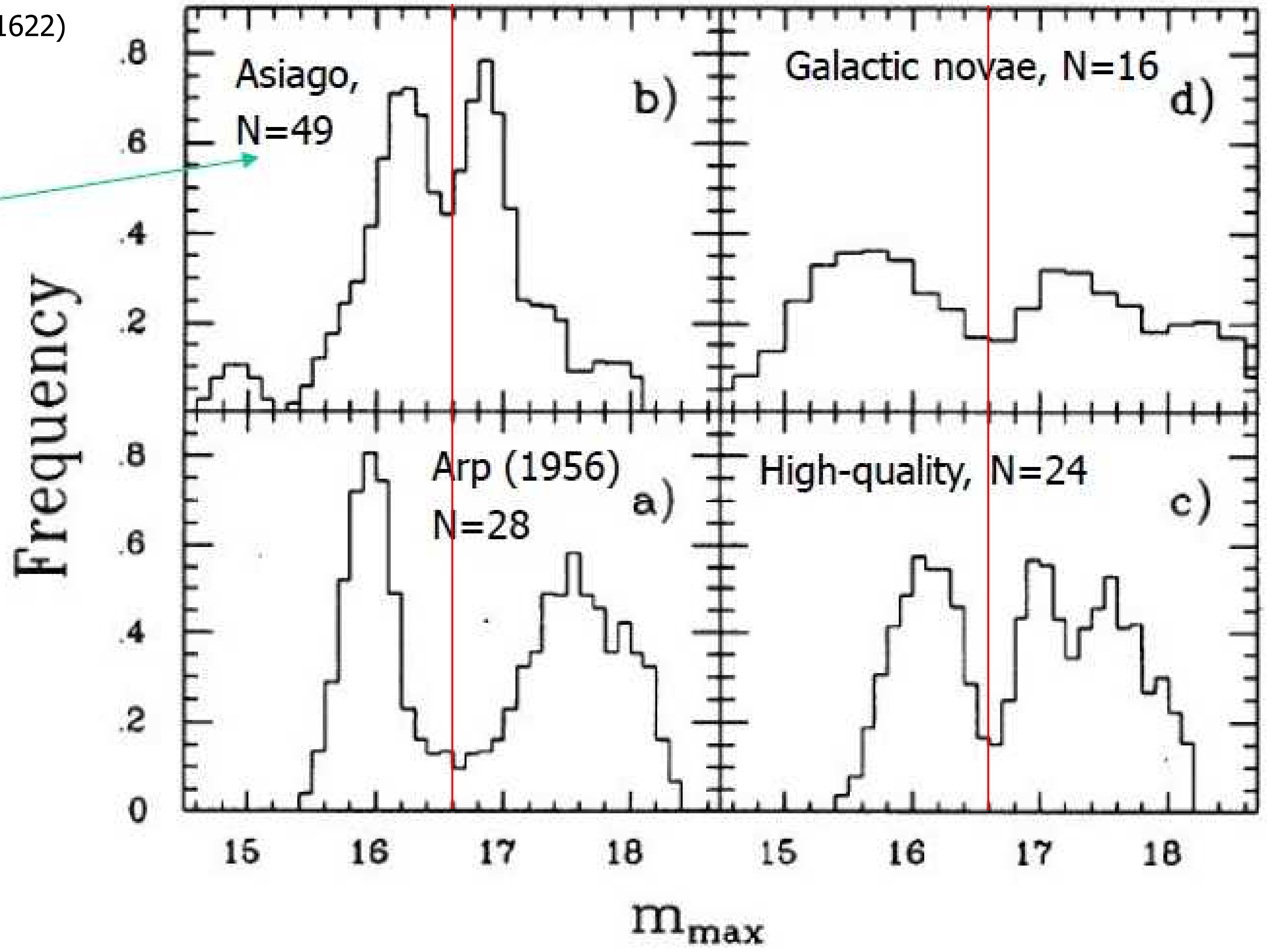


FIG. 10. Frequency distributions of magnitude at maximum for Arp (28 objects; panel a), Asiago (49; b), high-quality (24; c), and galactic (16; d) samples. All curves are computed by sampling the datasets with a running Gaussian window (step = 0.1 mag, $\sigma = 1/6$ mag for a–c, and step = 0.2 mag, $\sigma = 1/3$ mag for d), and are normalized to the same area. The magnitudes of the 16 galactic novae used here have been rescaled using an apparent distance modulus of 24.78 mag. The triple peak in the distribution of panel c is obviously due to the combination of Arp's and Asiago data.

6. Supernovae (초신성)

- Brightest objects in galaxies (M_V = -14 ~ -22)

- Typical types

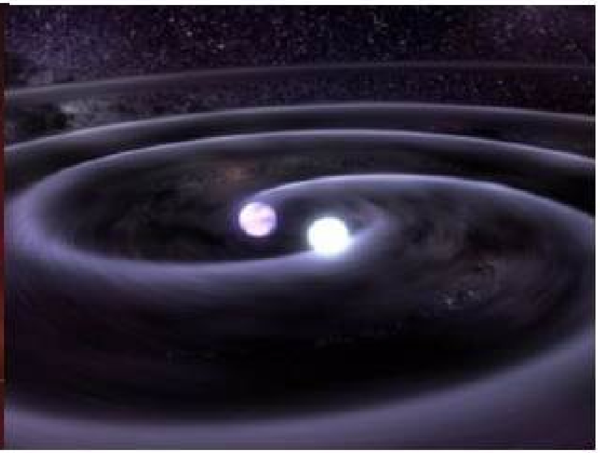
No H lines (pop II) → Type Ia

H lines (pop I) → Type II

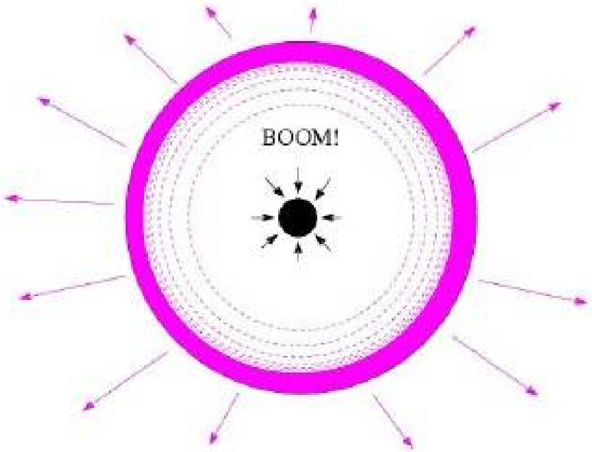
Ib

Ic

WD + Giant/MS/He *
(Single Degenerate, SD)



WD + WD
(Double Degenerate, DD)



Core collapse

SNe Ia (thermonuclear stellar explosion)
(WD originated SNe)
백색왜성 기원 초신성

CC SNe

핵붕괴 초신성

http://dujs.dartmouth.edu/2008/05/type-ia-supernovae-properties-models-and-theories-of-their-progenitor-systems
http://wwwmpa.mpa-garching.mpg.de/mpa/research/current_research/hl2013-8/hl2013-8-en.html
http://spiff.rit.edu/richmond/sdss/sn_survey/sn_survey.html

SN Ia absolute magnitude

Photometrically, SN Ia rise to maximum light in a period of approximately 20 days (Riess et al 1999b) reaching

$$\boxed{M_{\rm B} \approx M_{\rm V} \approx -19.30 \pm 0.03 + 5\log(H_0/60)} \tag{1}$$

with a dispersion of $\sigma_M \leq 0.3$ (Hamuy et al 1996b).

W. Hillebrandt & J. C.Niemeyer (2000, ARA&A, 38, 191 – Type Ia SN explosion models)

1. Stars: The Hertzsprung-Russell Diagram (항성: HR도)
1-3 Magnitudes (등급)

http://www.centauri-dreams.org/?p=11322
http://www.centauri-dreams.org/wp-content/uploads/2010/02/light-candles.jpg

1. Magnitude scale

$$\boxed{m - n = 2.5\log(\frac{l_n}{l_m})}$$

→ apparent magnitude (겉보기등급, 실시등급)

- $m > n$ ← $l_n > l_m$
- Brighter objects : numerically smaller magnitudes

Absolute magnitude, Distance modulus

- A very luminous star appears dim – if far away
- A low-luminosity star look bright – if very close

  → distance links fluxes and luminosities
- absolute magnitude (절대등급) = the magnitude to be observed if the star is placed at a distance of 10 pc from the Sun → capital M

$$\frac{L}{l} = (\frac{d}{D})^2 = (\frac{d}{10})^2$$

- M – L, m – l

$$m - M = 2.5\log(\frac{L}{l}) = 2.5\log[(\frac{d}{10})^2] = 5\log(\frac{d}{10})$$

$$\boxed{m - M = 5\log d - 5}$$

distance modulus

$$\boxed{m - M = 5\log d - 5 + A}$$

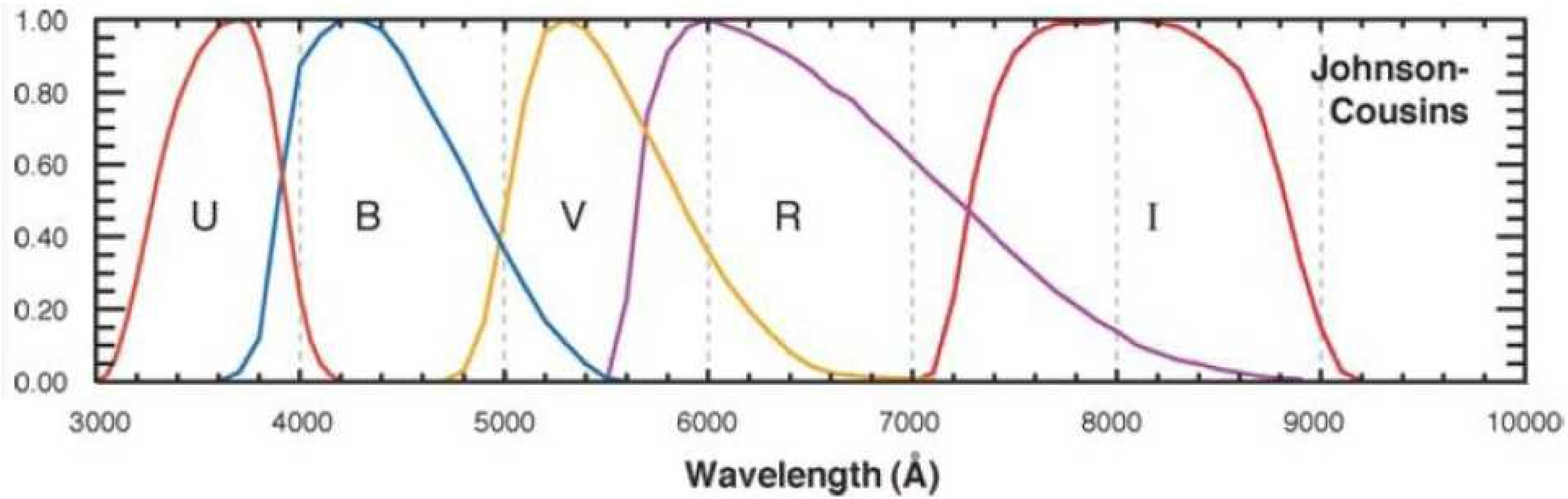
$$V - M_V = 5\log d - 5 + A_V$$

2. Photometric Filter Systems (측광계)

➢ Johnson-Cousins UBVRI System

- Originally defined by Johnson & Morgan (1953) : UBV
- Extended by Cousins (1974) : UBVRI
- Re-analyzed by Bessell (1990)

	Effective Wavelength (λ_{eff})	Bandpass ($\triangle\lambda$)
U	3663 Å	650 Å
B	4361 Å	890 Å
V	5448 Å	840 Å
R	6407 Å	1580 Å
I	7980 Å	1540 Å



Bessell (2005, ARA&A, 43, 293 – Standard photometric systems)

2. Photometric Filter Systems (측광계)

- Sloan Digital Sky Survey (SDSS) System
  - ugriz

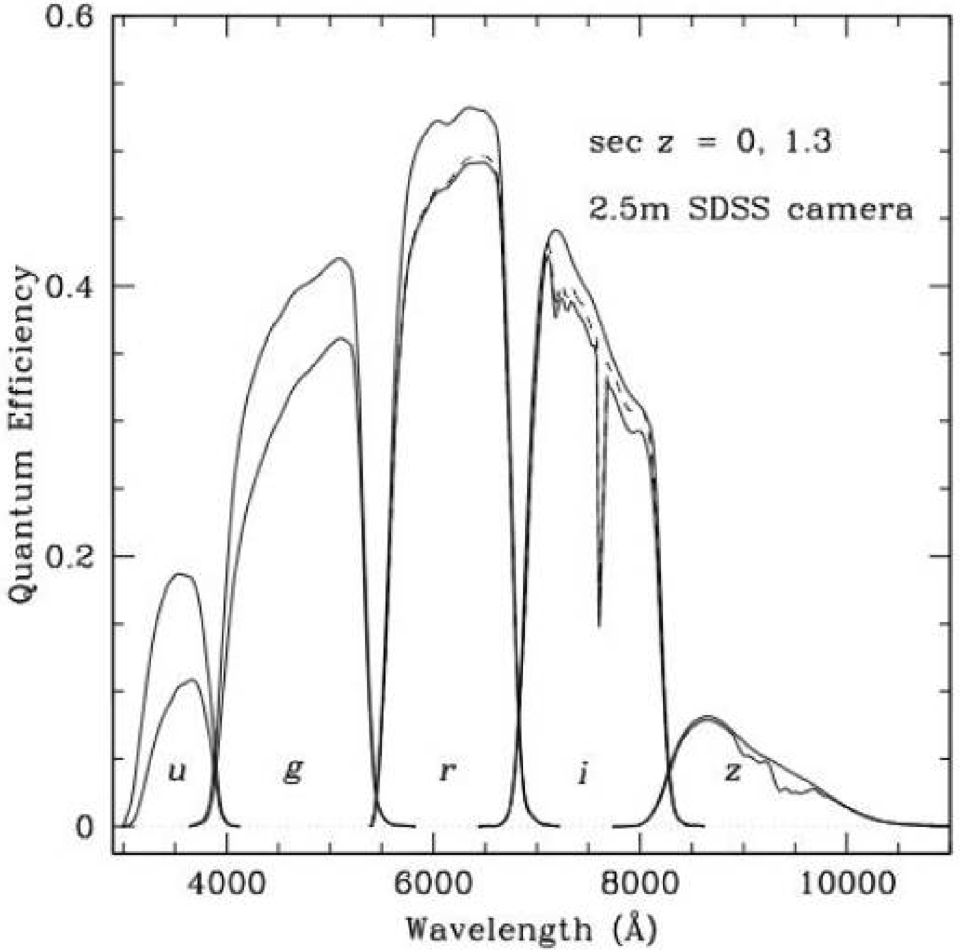


TABLE 19
SDSS FILTER PARAMETERS

Name	$\lambda_{\rm eff}$ (Å)	σ^2	FWHM (Å)	Q
u..........	3551	3.00×10^{-3}	581	0.0171
g..........	4686	7.13×10^{-3}	1262	0.0893
r..........	6166	3.13×10^{-3}	1149	0.0886
i..........	7480	2.58×10^{-3}	1237	0.0591
z..........	8932	3.18×10^{-3}	994	0.0099

C. Stoughton et al. 2002, AJ, 123, 485 (SDSS: Early Data Release)

3. Color Index (CI, 색지수, 색)

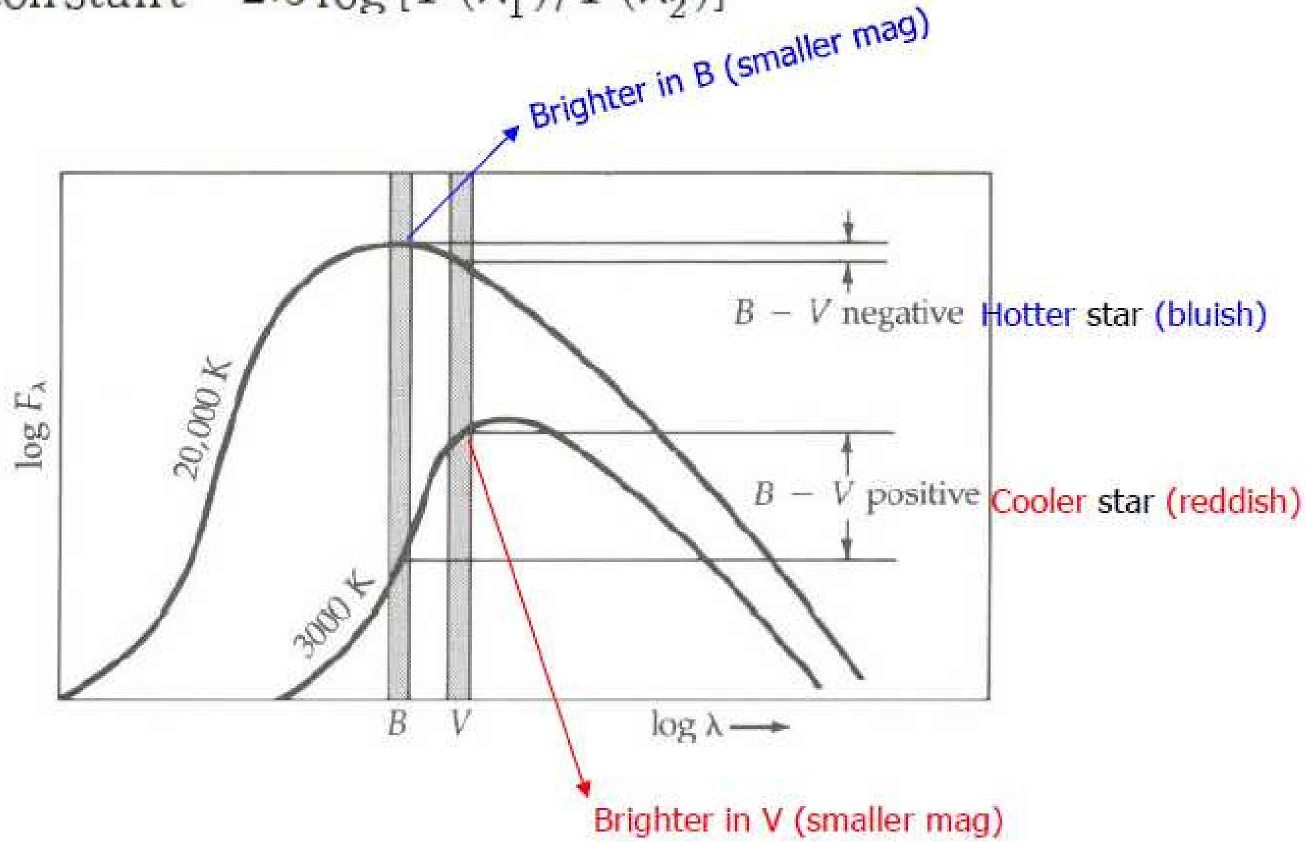
- Color index = difference between magnitudes at two different effective wavelengths

$$\mathrm{CI} = m(\lambda_1) - m(\lambda_2)$$

- Mag difference → flux ratio at the specific wavelengths involved

$$\mathrm{CI} = \mathrm{constant} - 2.5\log[F(\lambda_1)/F(\lambda_2)]$$

- Hotter stars (bluish) : negative CI
- Cooler stars (reddish) : positive CI

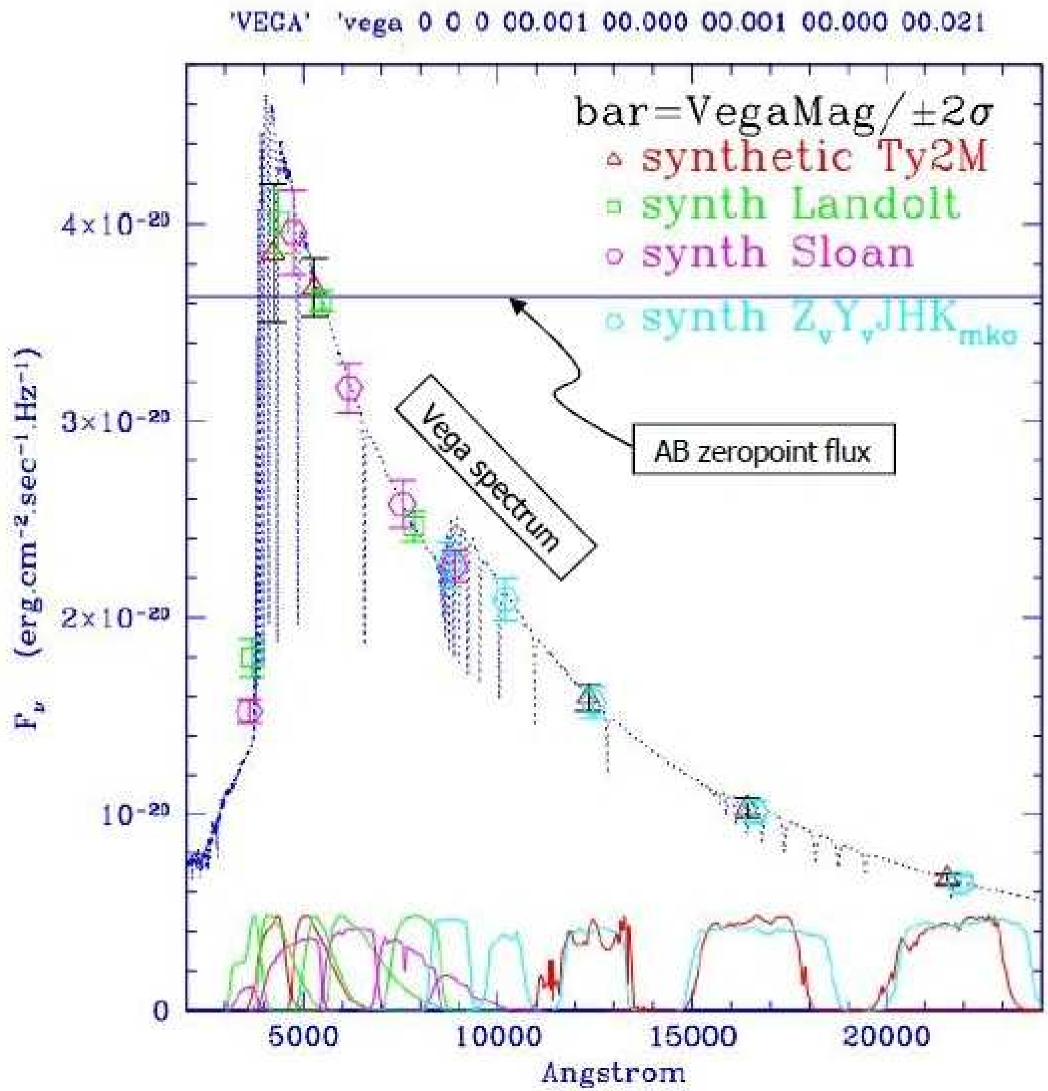


Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 229

Magnitude systems

➢ Vega magnitude system

- Vega (=α Lyr) : the primary calibrating star
- Surface temperature = 10,000 K
- CI = 0
- Zero-point was defined in terms of unreddened main-sequence (MS) stars of class A0 … with an accuracy sufficient to permit the placement of the zero-point to about 0.01 mag



Pickles & Depagne (2010 PASP 122 1437)

➢ AB magnitude system

- Magnitude zero point corresponds to a flux density of 3631 Jy (1 Jy = 1 Jansky = 10^{-26} W Hz^{-1} m^{-2} $=10^{-23}$ erg s^{-1} Hz^{-1} cm^{-2})

- Bessell (2005, ARA&A, 43, 293 – Standard photometric systems)
- Casagrande & VandenBerg (2014, MNRAS, 444, 392 – Synthetic stellar photometry. I. General considerations and new transformations for broad-band systems)

4. Color Excess, Bolometric Magnitude

- Interstellar dust grains absorb and scatter starlight → observed light appears redder than when it was emitted → interstellar reddening (성간적색화) (λ-dependent)

- Color Excess (색초과) = observed color – intrinsic color

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

- Interstellar extinction :

  $A_V \sim R \times E(B-V)$, $R = 3.0, \boxed{3.1,}\ 3.2, 3.3$

  R : total-to-selective extinction ratio

  ← Amount of interstellar medium (ISM)
  ISM composition
  Galactic longitude

- Bolometric magnitude (복사등급) : total rate of energy output at all wavelength

$$l_{bol} = \int_0^\infty l_\lambda \, d\lambda$$

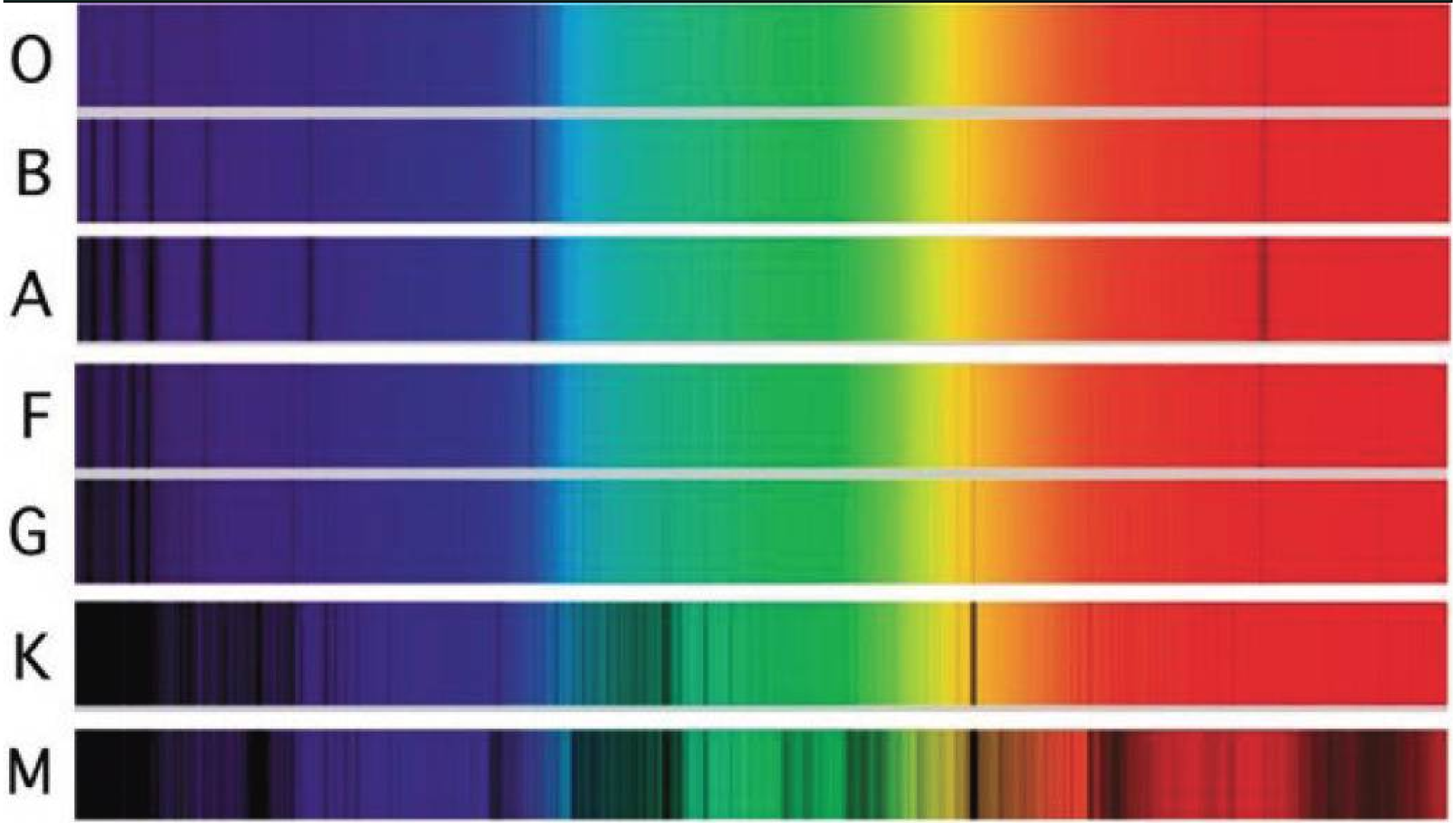
- Bolometric correction (BC, 복사보정) : difference between the bolometric and visual magnitudes

$$\mathrm{BC} = m_{\mathrm{bol}} - m_v = M_{\mathrm{bol}} - M_v = 2.5 \log\left(\frac{l_v}{l_{\mathrm{bol}}}\right)$$

for the Sun (G2) : BC = -0.07

Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 231

1. Stars: The Hertzsprung-Russell Diagram (항성: HR도)
1-4 The Classification of Stellar Spectra (별의 스펙트럼 분류)

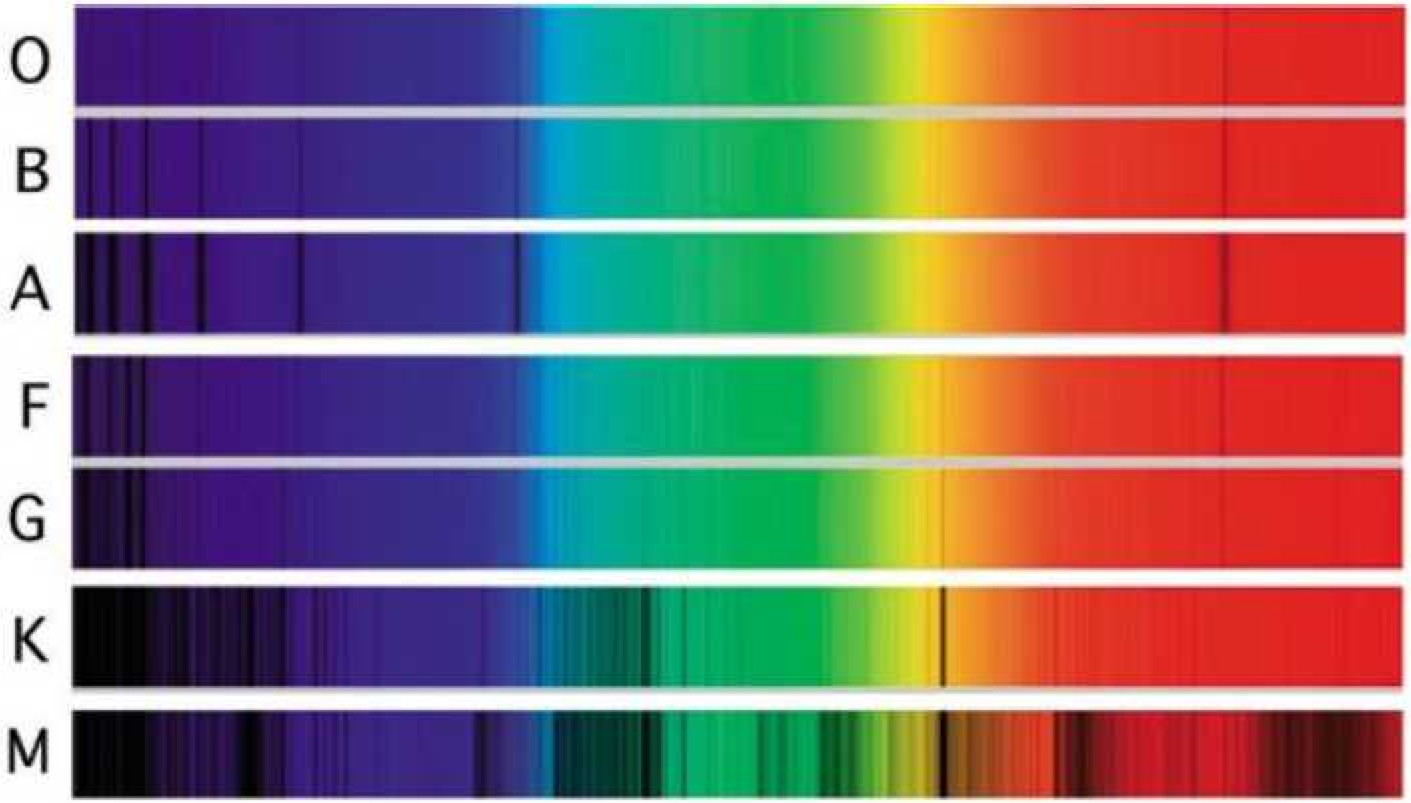


http://science.jburroughs.org/astromet/NAAP/ebs/spectraltype.html

Stellar spectra

Stars' spectra : differ depending on T and composition

Early-types (O and B) stars – few spectral lines
Late-types (K and M) stars – many spectral lines



http://science.jburroughs.org/astromet/NAAP/ebs/spectraltype.html

Spectral types

Spectral type	Stars	Spectral features	(e.g.)
O	blue stars, usually SGs, very luminous and hot, rare	**He II absorption lines** (sometimes emission: 4541, 4200Å); He I lines (4471, 4026Å) weak but increasing in strength from O5 to O9; lines from highly ionized species (e.g., C III, N III, O III, Si IV); H lines prominent but relatively weak; strong UV continuum	ζ(Zeta) Puppis (O4 I)
B	blue white stars, mainly giants	**Strong He I lines, maximum at B2**; no He II lines; **H absorption lines strengthening from B0 to B9**; lower-excitation ions (e.g., C II, O II, Mg II, Si II, Si III)	Rigel (=β Orionis, B8 Ia), ε Ori (B0 Ia)
A	White stars, dwarfs to giants	**H absorption lines maximum strength at A0** and decrease towards later types; **ionized metal lines (Fe II, Mg II, Si II) at max strength near A5**; Ca II weak and increase in strength; lines of neutral metals appear weakly	Sirius (A1 V), α Lyr (=Vega, A0 V)
F	yellow white stars, mainly dwarfs	H absorption lines weakening rapidly, **Ca II H&K absorption lines strengthen**; lines of neutral metals (Fe I, Cr I) and first ionization states of metals appear prominently	Procyon (=α CMi, F5 IV-V)
G	yellow stars, mainly dwarfs	Solar-type spectra; **Ca II absorption lines dominate (max near G2)**; neutral metal lines (Fe I, Mn I, Ca I) strengthening; ionized metal lines diminish; **G band (CH) strong**; H lines very weak	Sun (G2 V)
K	orange stars, can exist as giants and dwarfs	**Neutral metallic absorption lines dominate**; **Ca lines strong**; H lines almost gone; molecular bands (CH, CN, TiO) developing; continuum weak in blue	Arcturus (=α Boötis, K0 III), Aldebaran (=α Tau, K5 III)
M	red stars, exist at extremes either giants or red dwarfs	Strong **molecular bands, particularly TiO by M5**; **neutral metallic absorption lines** (e.g., quite strong Ca I); red continuum	Betelgeuse (=α Orionis, M2 I), Proxima Centauri (M5.5 V)

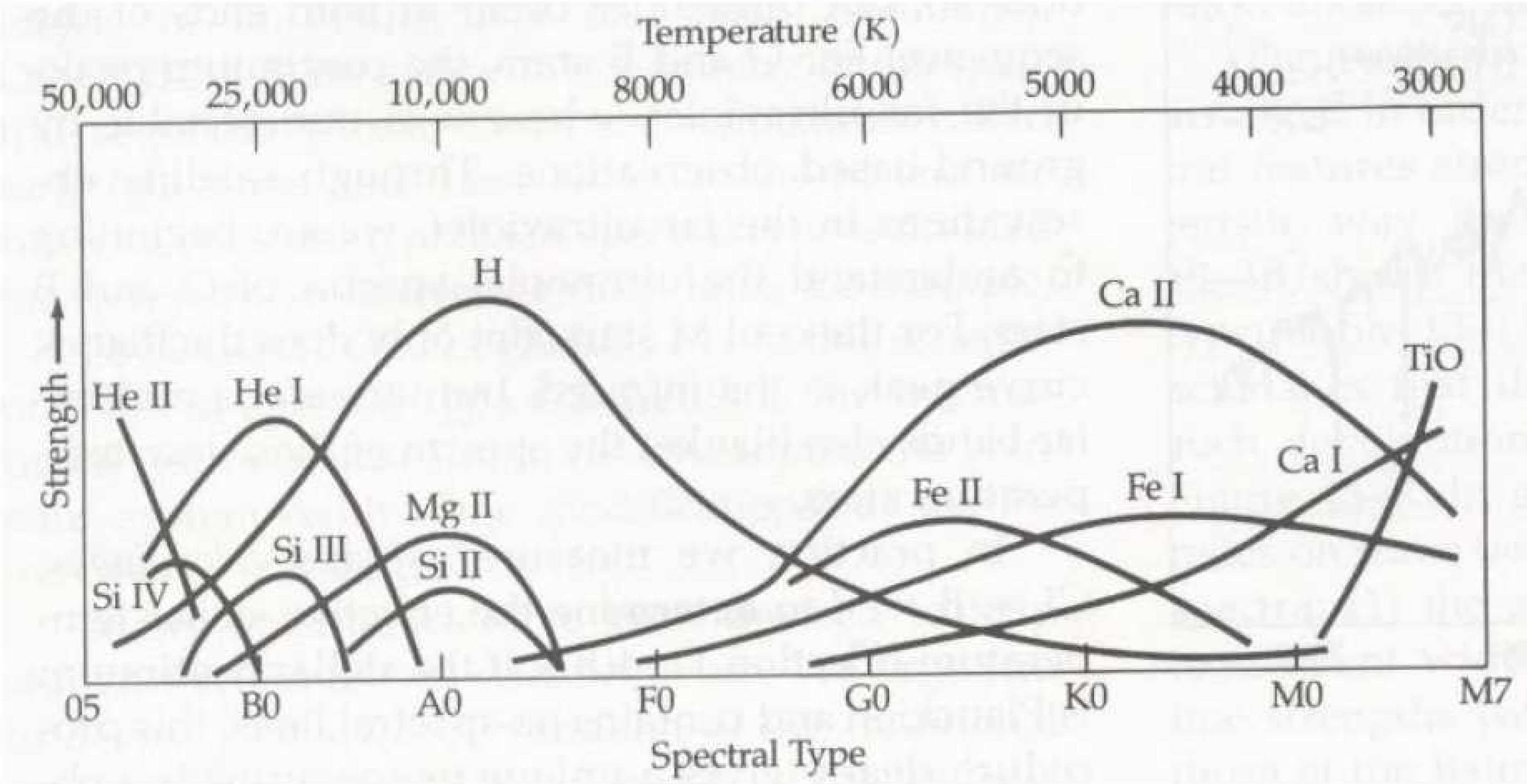
Galactic Astronomy (J. Binney & M. Merrifield, p. 92)

Introductory Astronomy & Astrophysics (Zeilik & Gregory, p. 258)

http://solarandspace.tripod.com/id11.html

Spectral types

absorption lines



Introductory Astronomy & Astrophysics (Zeilik & Gregory, p. 258)

http://solarandspace.tripod.com/id11.html

Extended spectral types

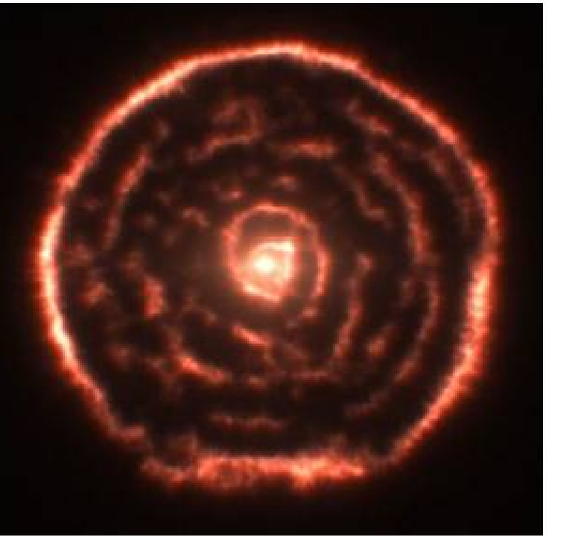
C (carbon) stars
- giant stars with similar temperatures of G, K, M stars (T = 3100 - 4600 K)
- different compositions : C is overabundant relative to O

hotter R stars (C_2, CN bands)
cooler N stars (C_2, CN, CH bands, little TiO)

S stars : giants
: molecular bands of the heavy-metal oxides ZrO, LaO, YO (instead of TiO)
: enhanced CN absorption bands
: neutral atoms strong as in K and M types

Galactic Astronomy (J. Binney & M. Merrifield, p. 92)
Introductory Astronomy & Astrophysics (Zeilik & Gregory, p. 266)

R Sculptoris : a sample C star
(Maercker+12, Nature, 490, 232)
https://en.wikipedia.org/wiki/Stellar_classification



${}_{22}Ti^{48}$: Titanium
${}_{39}Y^{89}$: Yttrium
${}_{40}Zr^{91}$: Zirconium
${}_{57}La^{139}$: Lanthanum

Extended spectral types

- Cool red dwarfs and brown dwarfs (BDs) - Infrared spectra
- BD : objects whose central temperatures never reach the critical threshold for stable thermonuclear burning (Kirkpatrick + 11 ApJS 197, 19 'The first hundred BDs discovered by the Wide-field Infrared Survey Explorer (WISE)')

- BDs cool as they age : from M to L, T, Y type

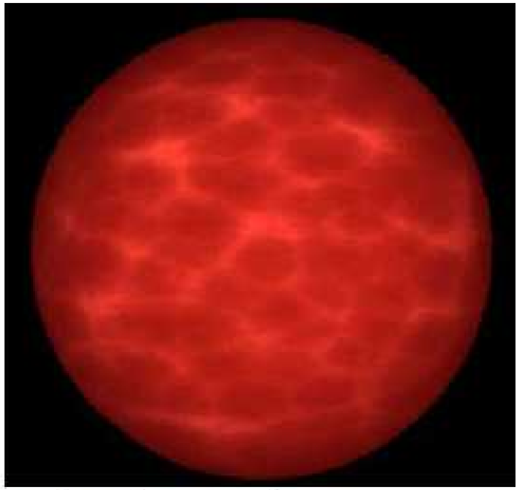
The less massive, the faster cooling

- Class L : mostly BDs with substellar mass, some stars with H-fusion

(e.g.) V838 Mon

- Temp ~1,700 K (~ 1,400 °C)
- M and L types = mixture of stars and BDs

J. D. Kirkpatrick (2005, ARA&A, 43, 195 'New spectral types L and T')



L dwarf - artist's impression

V838 Monocerotis – HST
https://en.wikipedia.org/wiki/V838_Monocerotis

https://en.wikipedia.org/wiki/Stellar_classification
http://www.nasa.gov/mission_pages/WISE/multimedia/pia14722.html

Extended spectral types

- Class T
  cool brown dwarfs
  surface T ~1,200 K (1,000 – 1,600 K)
  (~ 900 °C) (700 – 1,300 °C)
  prominent methane (CH_4) in the spectra
  ➔ "methane dwarfs"

  T dwarfs would appear reddish, or magenta, to the eye.

T dwarf - artist's impression

https://en.wikipedia.org/wiki/Stellar_classification
http://www.nasa.gov/mission_pages/WISE/multimedia/pia14720.html

Extended spectral types

- Class Y

  BDs cooler than class T

  (coldest BDs, latest classification letter)

  Cushing + 11 (ApJ, 743, 50 'The discovery of Y dwarfs using data from the Wide-field Infrared Survey Explorer (WISE)')

  Temp ~ 298 – 448 K (25 – 175 °C)

  Mass : 9 – 25 M_J

  N = 17 (2013 August)

  mostly nearby : 9 – 40 ly

  (WISE 1541-2250, d~9 ly : 7th closest star system)

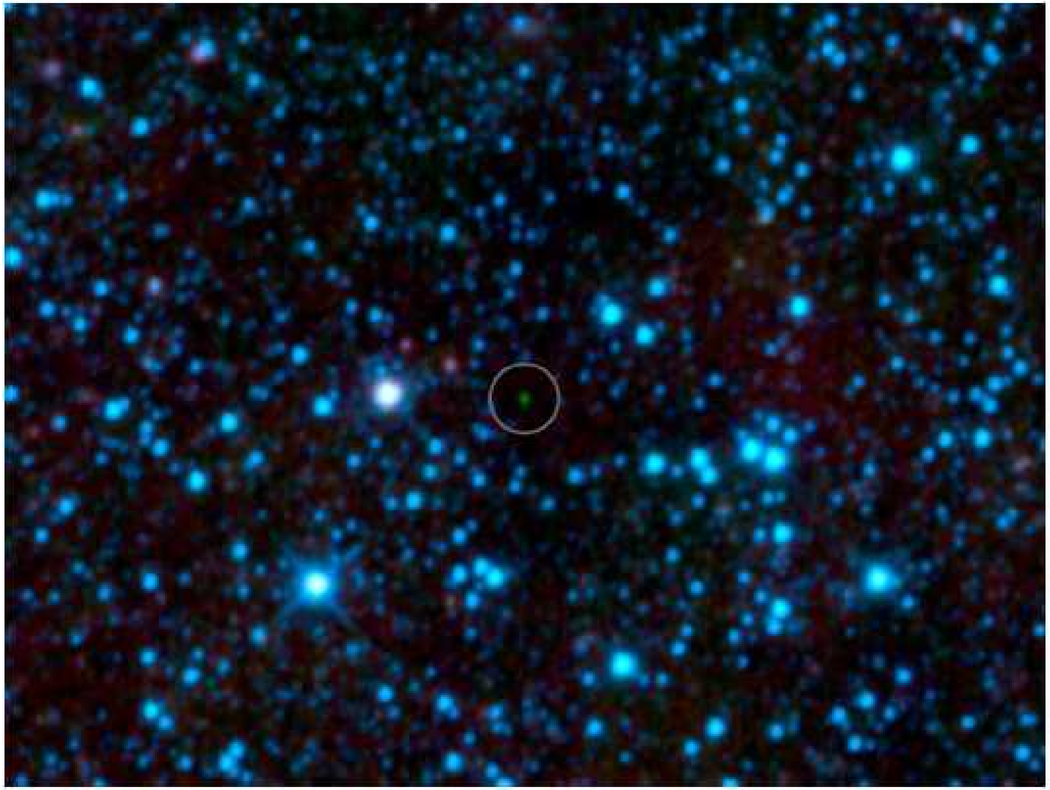
  not detected at visible wavelengths

Kirkpatrick + 13 (ApJ, 776, 128 'Discovery of the Y1 dwarf J064723.23-623235.5')

https://en.wikipedia.org/wiki/Stellar_classification
http://www.nasa.gov/mission_pages/WISE/multimedia/pia14720.html
http://science.nasa.gov/science-news/science-at-nasa/2011/23aug_coldeststars/

Extended spectral types

- WISE (Wide-field Infrared Survey Explorer) → found ~100 new BDs → 6 Y stars
- Coldest : WISE 1828+2650, T~300 K (25°C)



Y dwarf WISE 1828+2650
- artist's impression
- purple color choice : artistic reason

https://en.wikipedia.org/wiki/Stellar_classification

http://science.nasa.gov/science-news/science-at-nasa/2011/23aug_coldeststars/