Master I.M.A.G.2E

Imagerie et Modélisation Astrophysique et Géophysique, Espace et Environnement

Stellar structure and evolution

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Slides mainly from S. Smartt

Text books

- D. Prialnik – *An introduction to the theory of stellar structure and evolution*
- R. Taylor – *The stars: their structure and evolution*
- E. Böhm-Vitense – *Introduction to stellar astrophysics: Volume 3 stellar structure and evolution*
- R. Kippenhahn & A. Weigert – Stellar Structure and Evolution (springer-Verlag)

Learning outcomes

- Students should gain an understanding of the physical processes in stars – how they evolve and what critical parameters their evolution depends upon
- Students should be able to understand the basic physics underlying complex stellar evolution models
- Students will learn how to interpret observational characteristics of stars in terms of the underlying physical parameters

Fundamental physical constants required in this course

a	radiation density constant	7.55×10^{-16} J m^{-3} K^{-4}
c	velocity of light	3.00×10^{8} m s^{-1}
G	gravitational constant	6.67×10^{-11} N m^{2} kg^{-2}
h	Planck's constant	6.62×10^{-34} J s
k	Boltzmann's constant	1.38×10^{-23} J K^{-1}
m_e	mass of electron	9.11×10^{-31} kg
m_H	mass of hydrogen atom	1.67×10^{-27} kg
N_A	Avogardo's number	6.02×10^{23} mol^{-1}
σ	Stefan Boltzmann constant	5.67×10^{-8} W m^{-2} K^{-4} (σ = ac/4)
R	gas constant (k/m_H)	8.26×10^{3} J K^{-1} kg^{-1}
e	charge of electron	1.60×10^{-19} C
$L_\odot$	luminosity of Sun	3.86×10^{26} W
$M_\odot$	mass of Sun	1.99×10^{30} kg
$T_{eff\odot}$	effective temperature of sun	5780 K
$R_\odot$	radius of Sun	6.96×10^{8} m
Parsec	*(unit of distance)*	3.09×10^{16} m

Lecture 1: The observed properties of stars

Learning outcomes: Students will

- Recap the knowledge required from previous courses
- Understand what parameters of stars we can measure
- Appreciate the use of star clusters as laboratories for stellar astrophysics
- Begin to understand how we will constrain stellar models with hard observational evidence

Star clusters

NGC3603 from Hubble Space Telescope

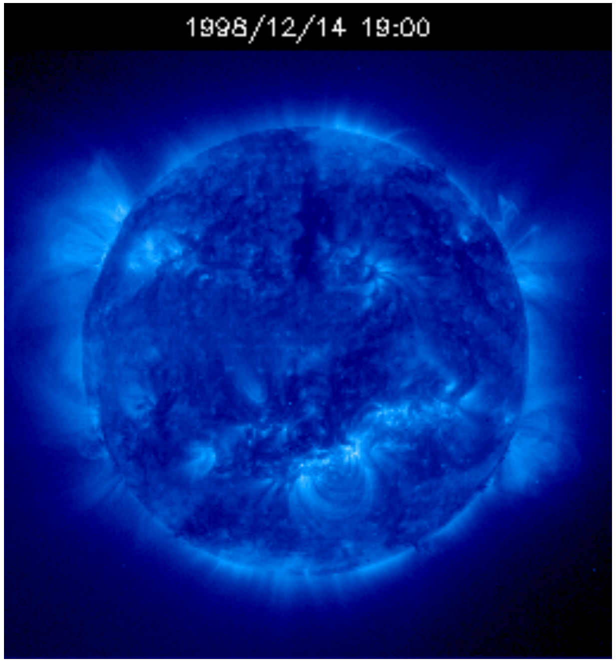
We observe star clusters

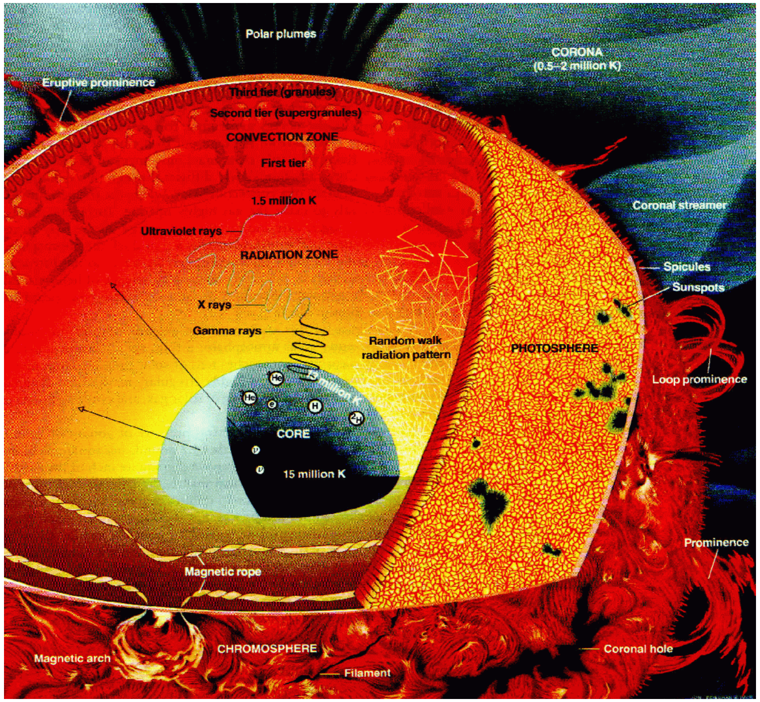
- Stars all at same distance
- Dynamically bound
- Same age
- Same initial composition

Can contain $10^3 - 10^6$ stars

Goal of this course is to understand the stellar content of such clusters

The Sun – best studied example





Stellar interiors not directly observable. Solar neutrinos emitted at core and detectable. Helioseismology - vibrations of solar surface can be used to probe density structure

Must construct models of stellar interiors – predictions of these models are tested by comparison with observed properties of individual stars

Observable properties of stars

Basic parameters to compare theory and observations:

- Mass (*M*)
- Luminosity (*L*)
  - The total energy radiated per second i.e. power (in W)

    $$L = \int_0^\infty L_\lambda d\lambda$$

- Radius (*R*)
- Effective temperature (T_e)
  - The temperature of a black body of the same radius as the star that would radiate the same amount of energy. Thus

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

    where σ is the Stefan-Boltzmann constant (5.67×10^{-8} $Wm^{-2}K^{-4}$)

$\Rightarrow$ 3 independent quantities

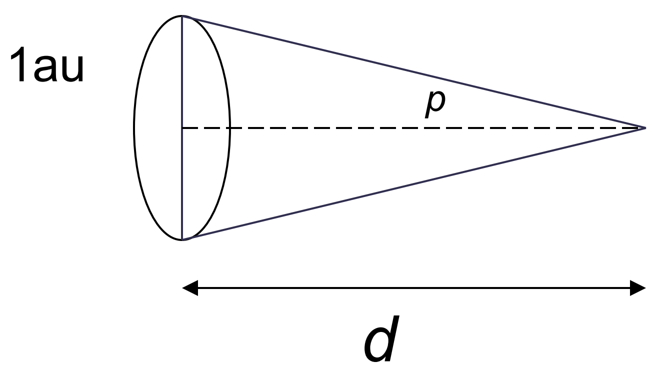
Recap Level 2/3 - definitions

Measured energy flux depends on distance to star (inverse square law)

$F = L / 4\pi d^2$

Hence if d is known then L determined

Can determine distance if we measure *parallax* - apparent stellar motion to orbit of earth around Sun.



For small angles

$p = 1$ au$/d$

$d = 1/p$ parsecs

If p is measured in arcsecs

Since nearest stars d > 1pc ; must measure p < 1 arcsec
e.g. and at d=100 pc, p= 0.01 arcsec

Telescopes on ground have resolution ~1" Hubble has resolution 0.05" $\Rightarrow$ difficult !

Hipparcos satellite measured 10^5 bright stars with δp~0.001" $\Rightarrow$ confident distances for stars with d<100 pc

Hence ~100 stars with well measured parallax distances

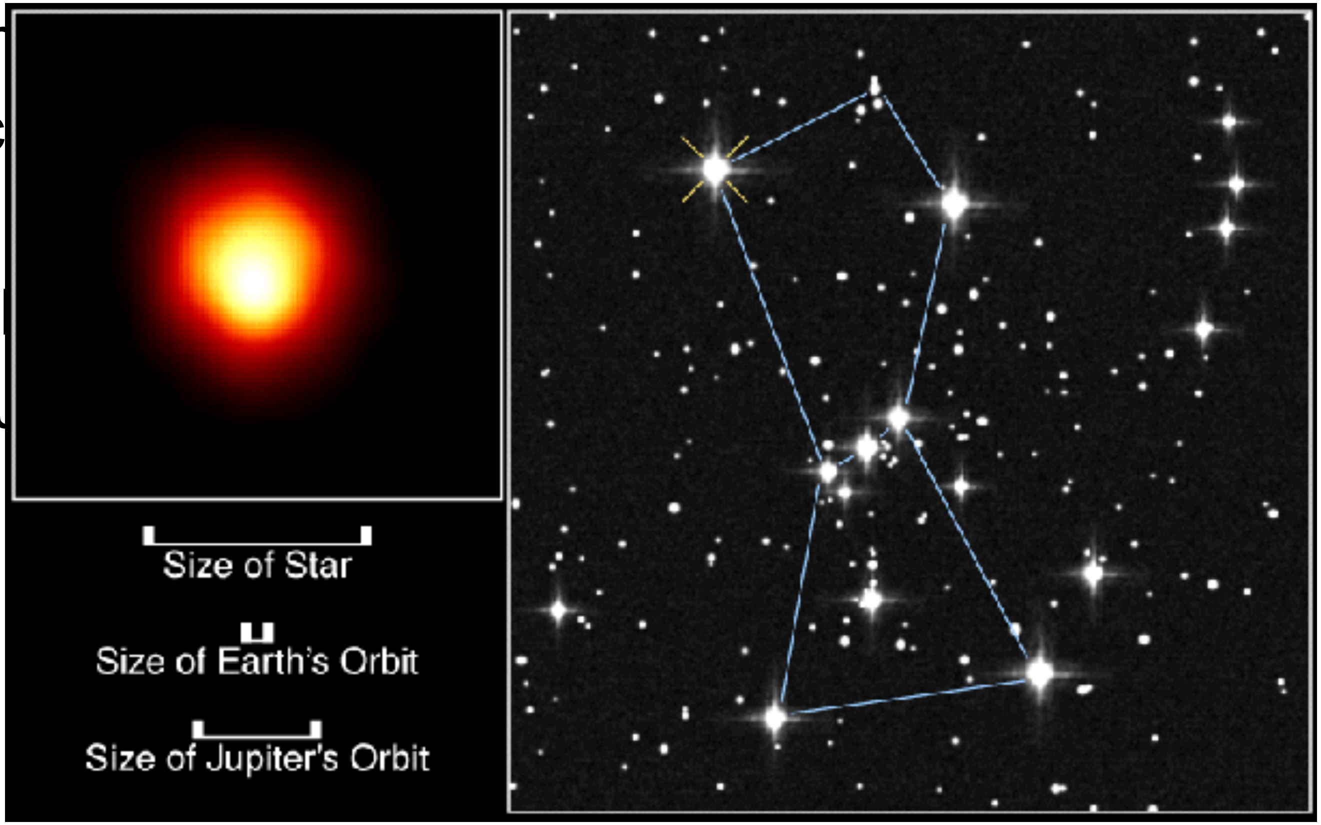
Stellar radii

Angular diam

$\theta = 2R_{\odot}/10$pc

Compare wit

$\Rightarrow$ very difficu



Radii of ~600 stars measured with techniques such as interferometry and eclipsing binaries.

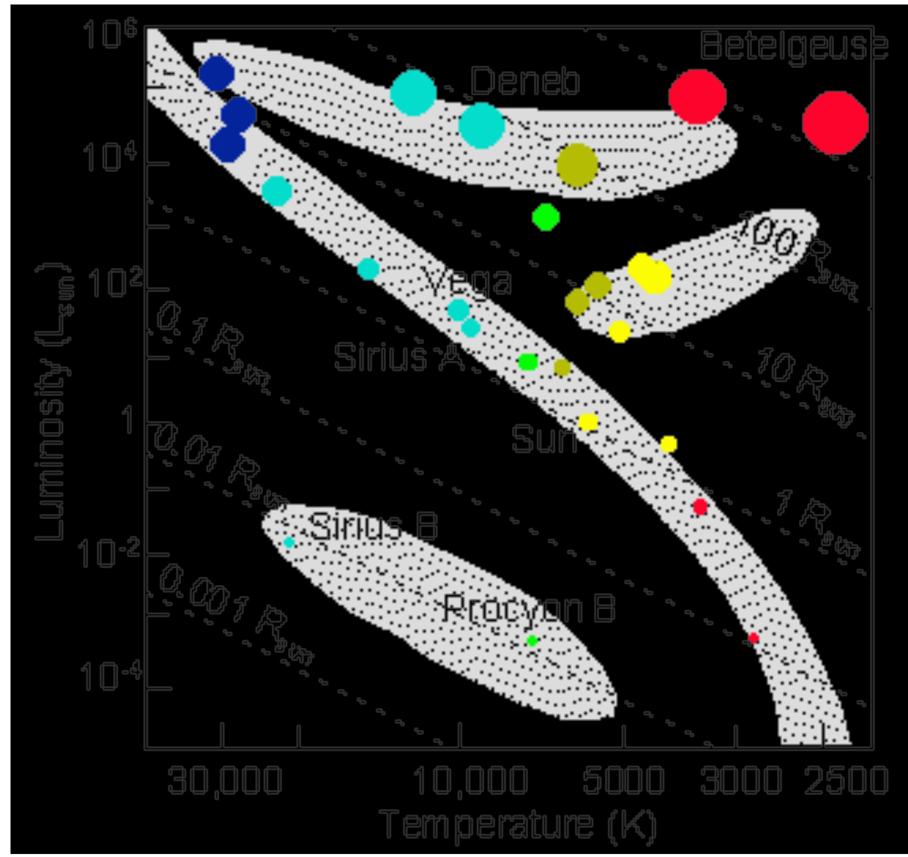
The Hertzsprung-Russell diagram

M, R, L and T_e do not vary independently.

Two major relationships – L with T

– L with M

The first is known as the *Hertzsprung-Russell* (HR) diagram or the *colour-magnitude* diagram.



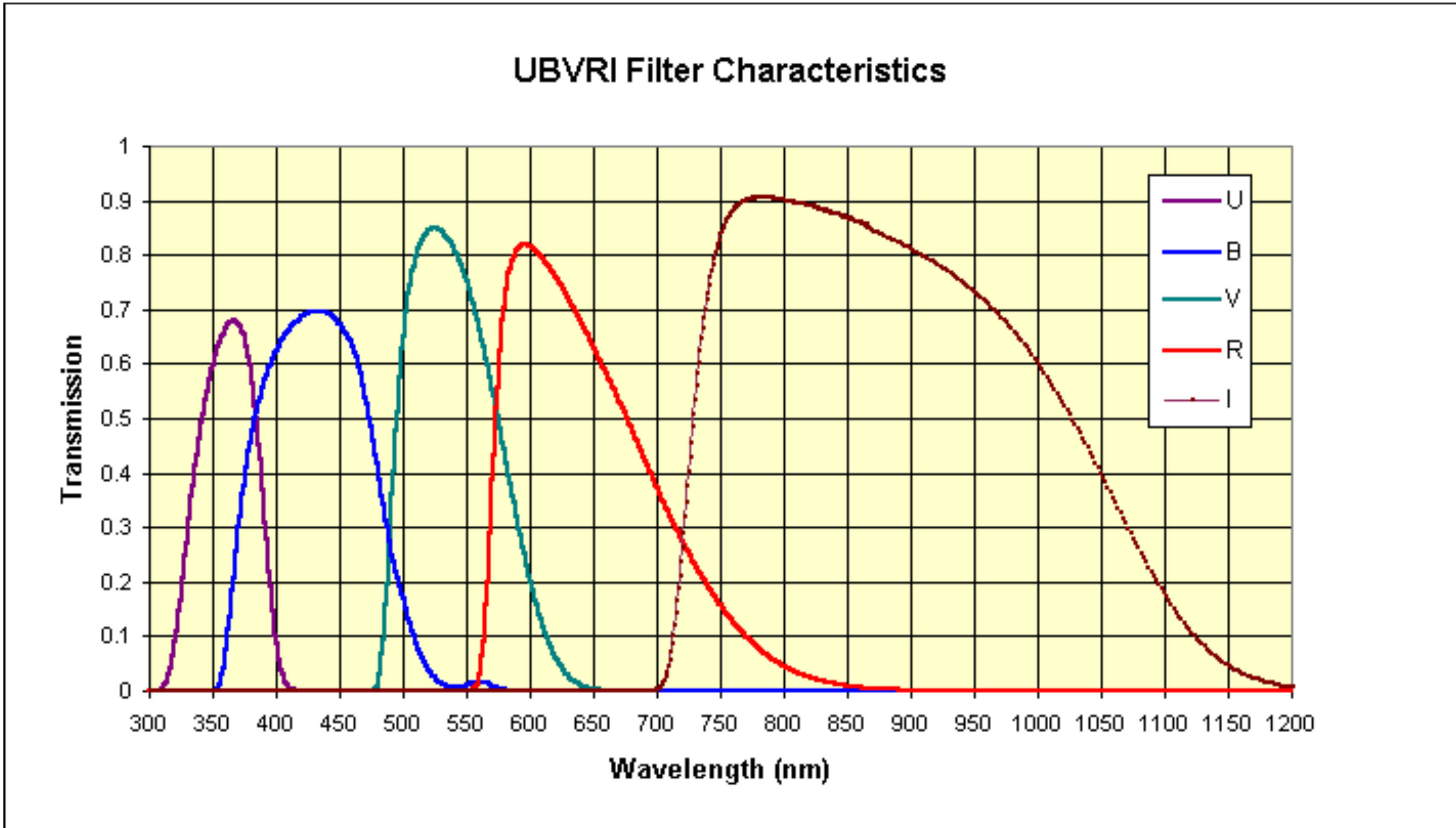
Colour Index (B-V)	–0.6		0		+0.6		+2.0
Spectral type	O	B	A	F	G	K	M

Colour-magnitude diagrams

Measuring accurate T_e for ~10^2 or 10^3 stars is intensive task – spectra needed and model atmospheres

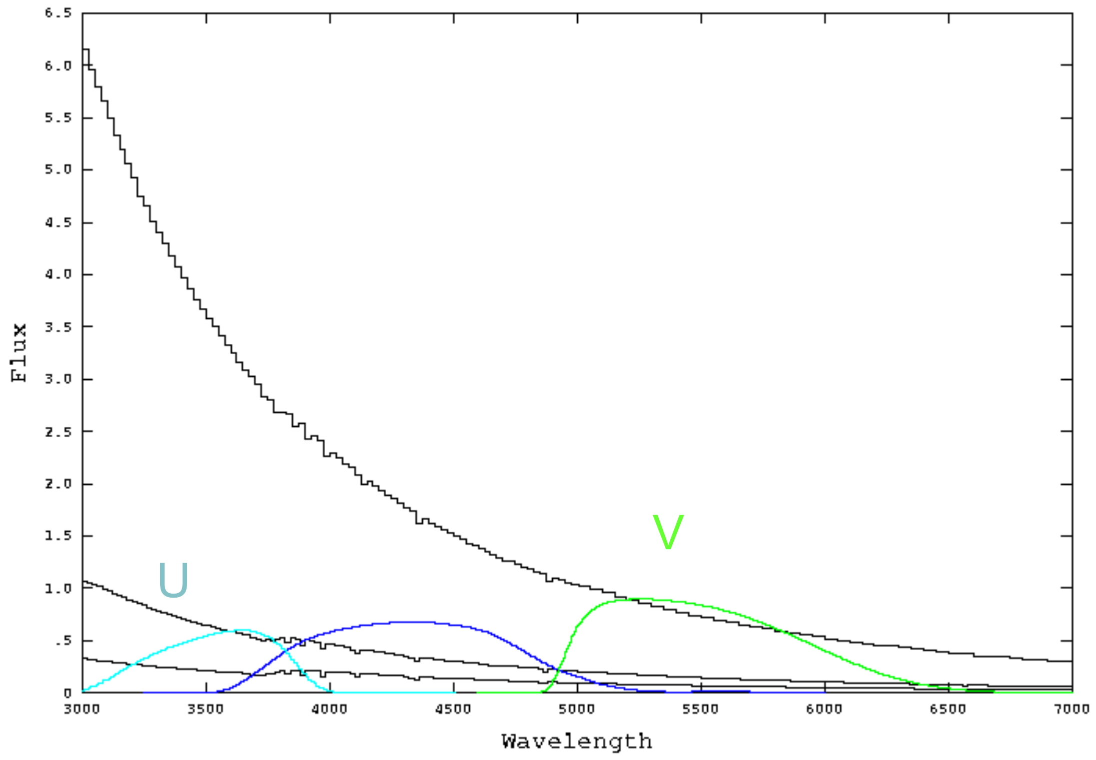
Magnitudes of stars are measured at different wavelengths: standard system is *UBVRI*

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



UBVRI Filter Characteristics
Transmission
Wavelength (nm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000 1050 1100 1150 1200
U
B
V
R
I

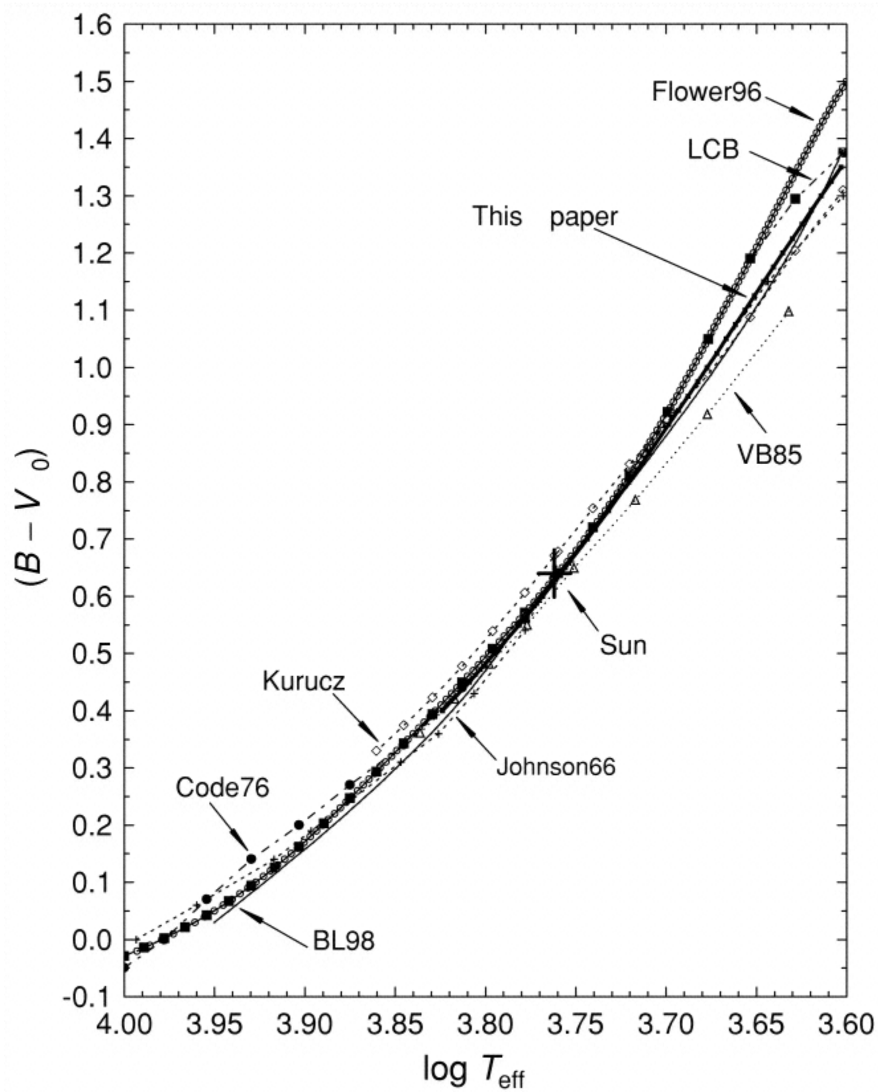
Magnitudes and Colours



Model Stellar spectra T_e = 40,000, 30,000, 20,000K

e.g.

B-V =f(T_e)



Various calibrations can be used to provide the colour relation:

$B\text{-}V = f(T_e)$

Remember that observed *(B-V)* must be corrected for interstellar extinction to $(B\text{-}V)_0$

Absolute magnitude and bolometric magnitude

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

  $m - M = 5 \log(d/10) - 5$

  where d is in pc
- Magnitudes are measured in some wavelength band e.g. *UBV.* To compare with theory it is more useful to determine **bolometric magnitude** – defined as absolute magnitude that would be measured by a bolometer sensitive to all wavelengths. We define the bolometric correction to be

  $BC = M_{bol} - M_v$

  Bolometric luminosity is then

  $M_{bol} - M_{bol}^{\odot} = -2.5 \log L/L_{\odot}$

For Main-Sequence Stars

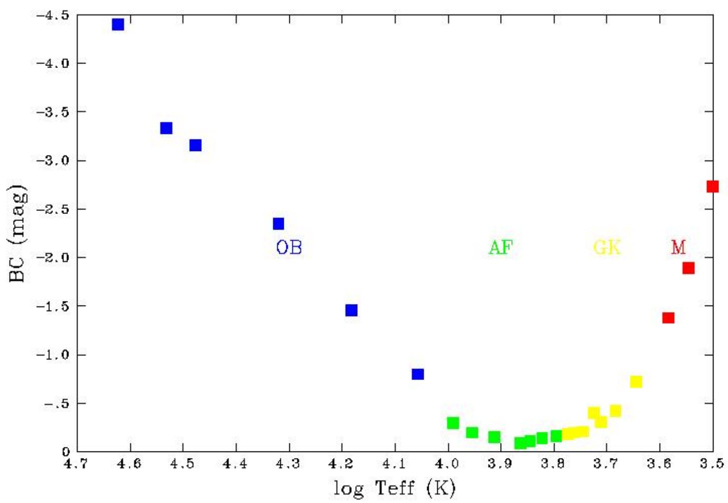


Table 15.7. *Calibration of MK spectral types.*

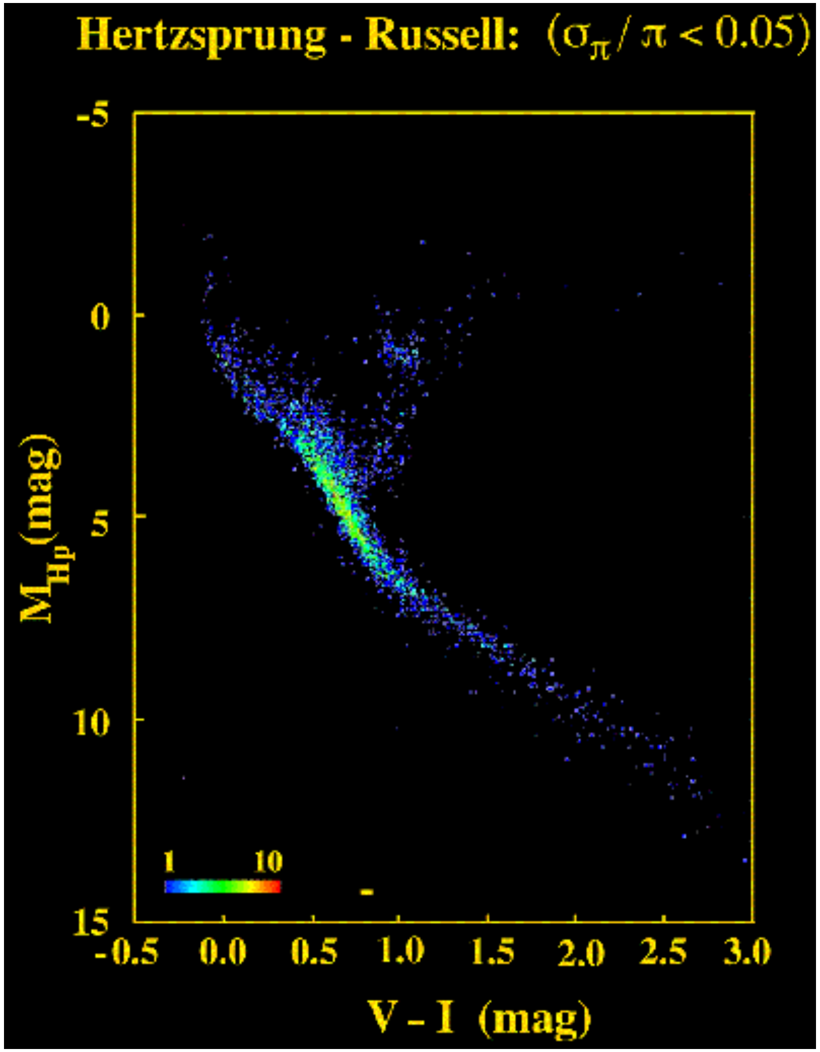
Sp	$M(V)$	$B-V$	$U-B$	$V-R$	$R-I$	T_{eff}	BC
MAIN SEQUENCE, V							
O5	−5.7	−0.33	−1.19	−0.15	−0.32	42 000	−4.40
O9	−4.5	−0.31	−1.12	−0.15	−0.32	34 000	−3.33
B0	−4.0	−0.30	−1.08	−0.13	−0.29	30 000	−3.16
B2	−2.45	−0.24	−0.84	−0.10	−0.22	20 900	−2.35
B5	−1.2	−0.17	−0.58	−0.06	−0.16	15 200	−1.46
B8	−0.25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

From Allen's Astrophysical Quantities (4th edition)

The HRD from Hipparcos

HRD from Hipparcos

HR diagram for 4477 single stars from the Hipparcos Catalogue with distance precision of better than 5%



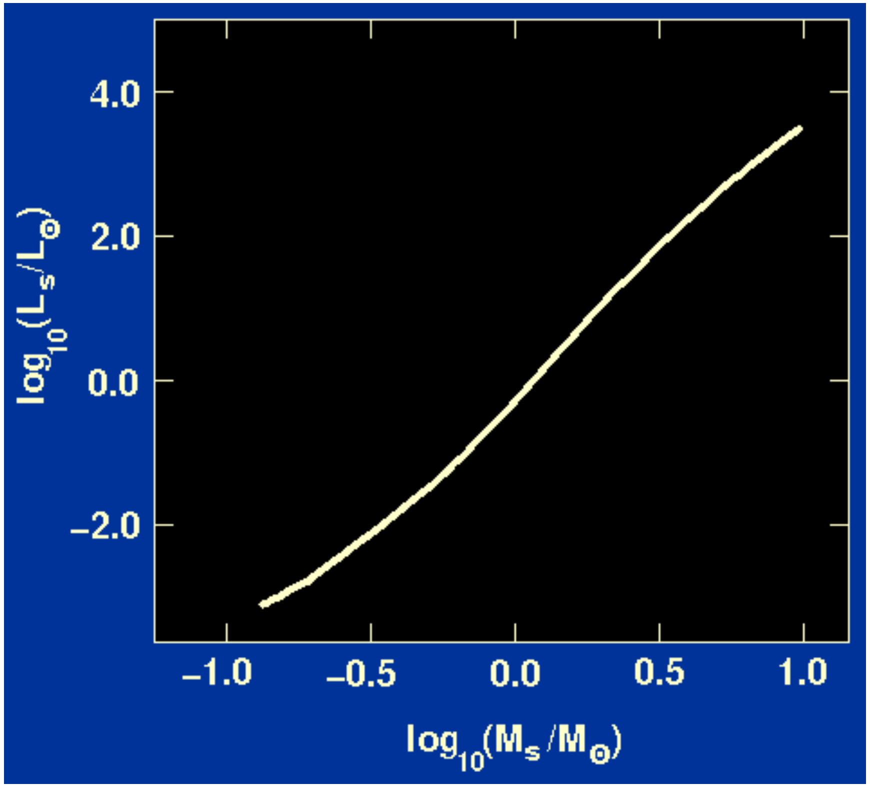
Mass-luminosity relation

For the few main-sequence stars for which masses are known, there is a *Mass-luminosity relation.*

$L \propto M^n$

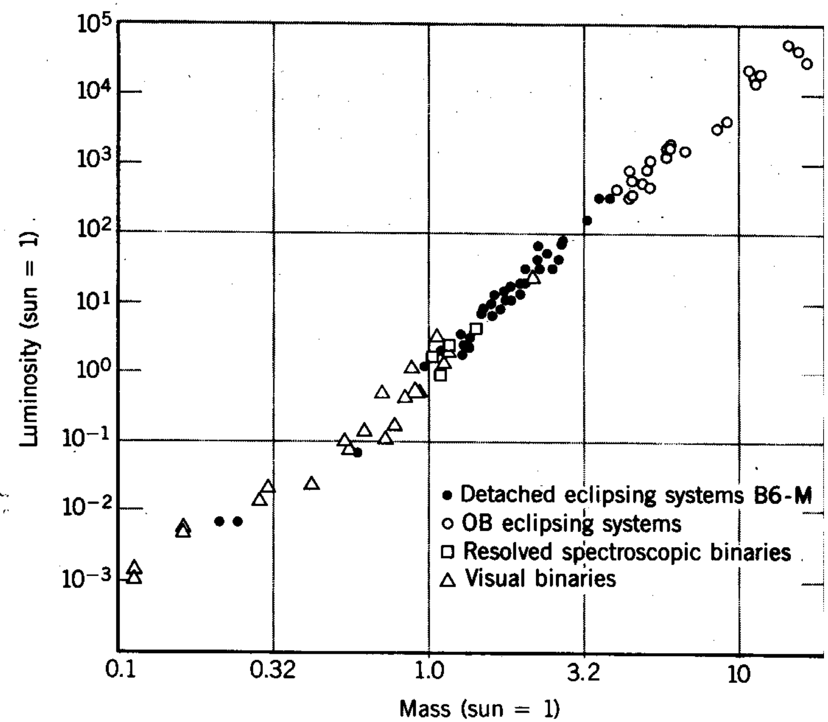
Where n=3-5. Slope changes at extremes, less steep for low and high mass stars.

This implies that the main-sequence (MS) on the HRD is a function of mass i.e. from bottom to top of main-sequence, stars increase in mass

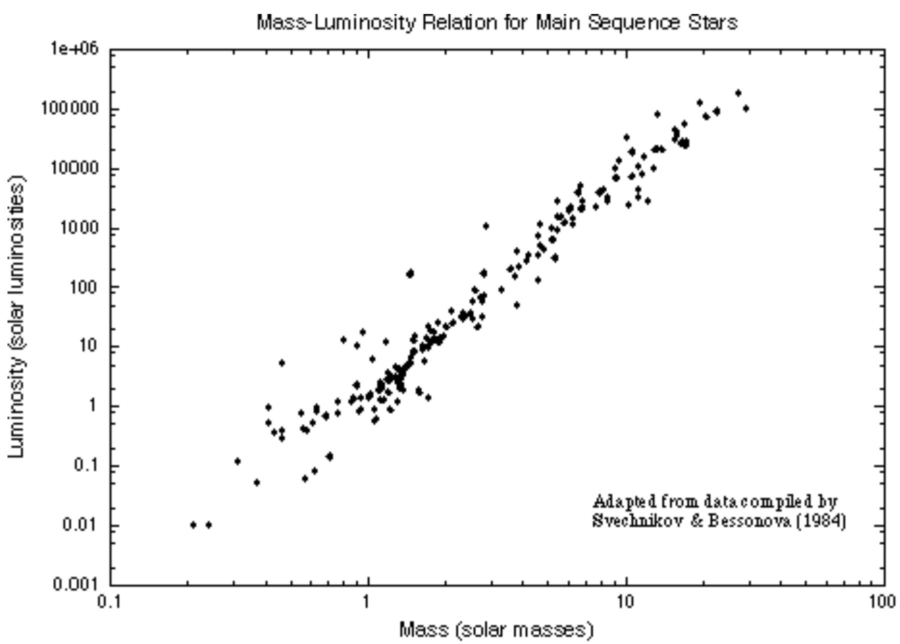


We must understand the *M-L* relation and *L-T_e* relation theoretically.

Models must reproduce observations



The mass–luminosity relation for stars, as determined from binary systems, in which the individual masses can be found.



Age and metallicity

There are two other fundamental properties of stars that we can measure – age (*t*) and chemical composition

Composition parameterised with

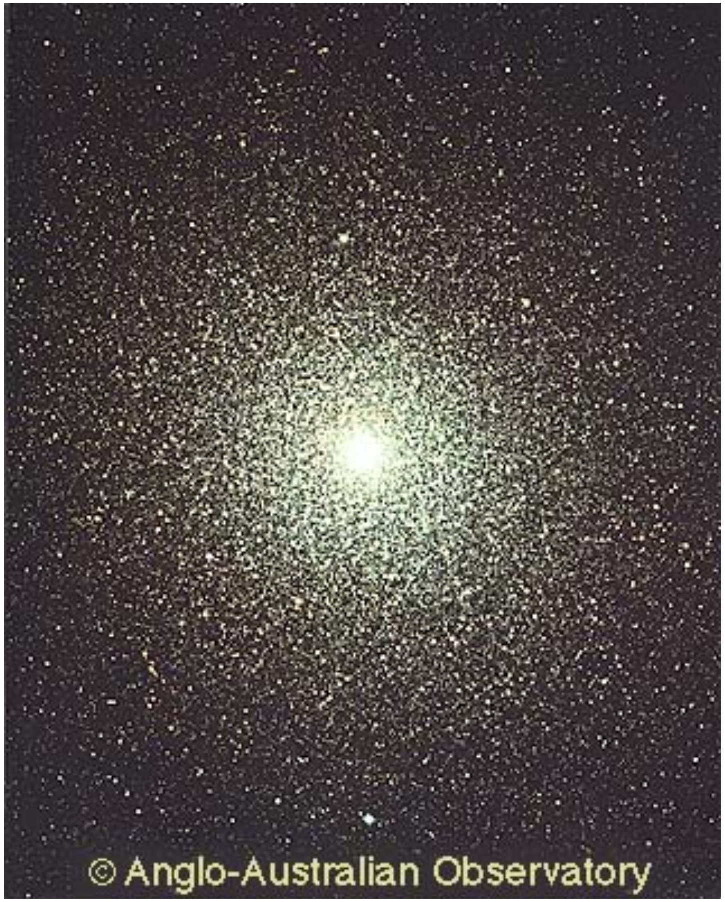
$X, Y, Z \equiv$ mass fraction of H, He and all other elements

e.g. $X_\odot = 0.747$; $Y_\odot = 0.236$; $Z_\odot = 0.017$

Note – Z often referred to as *metallicity*

Would like to studies stars of same age and chemical composition – to keep these parameters constant and determine how models reproduce the other observables

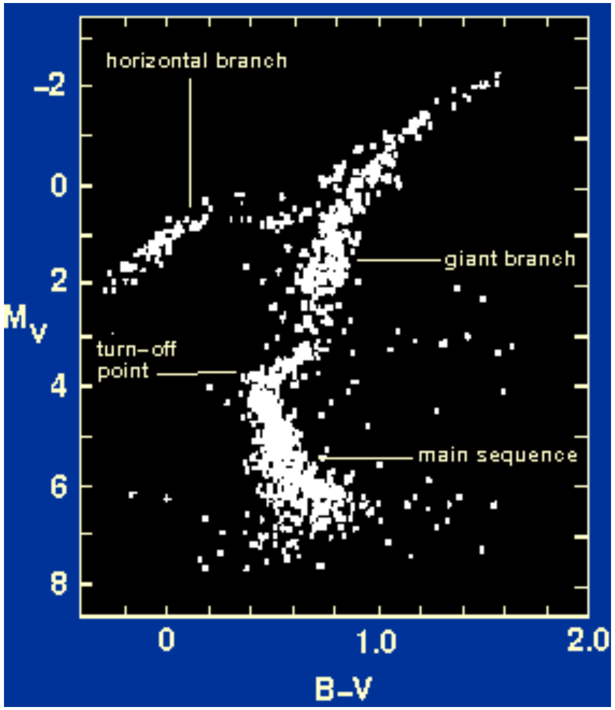
Star clusters



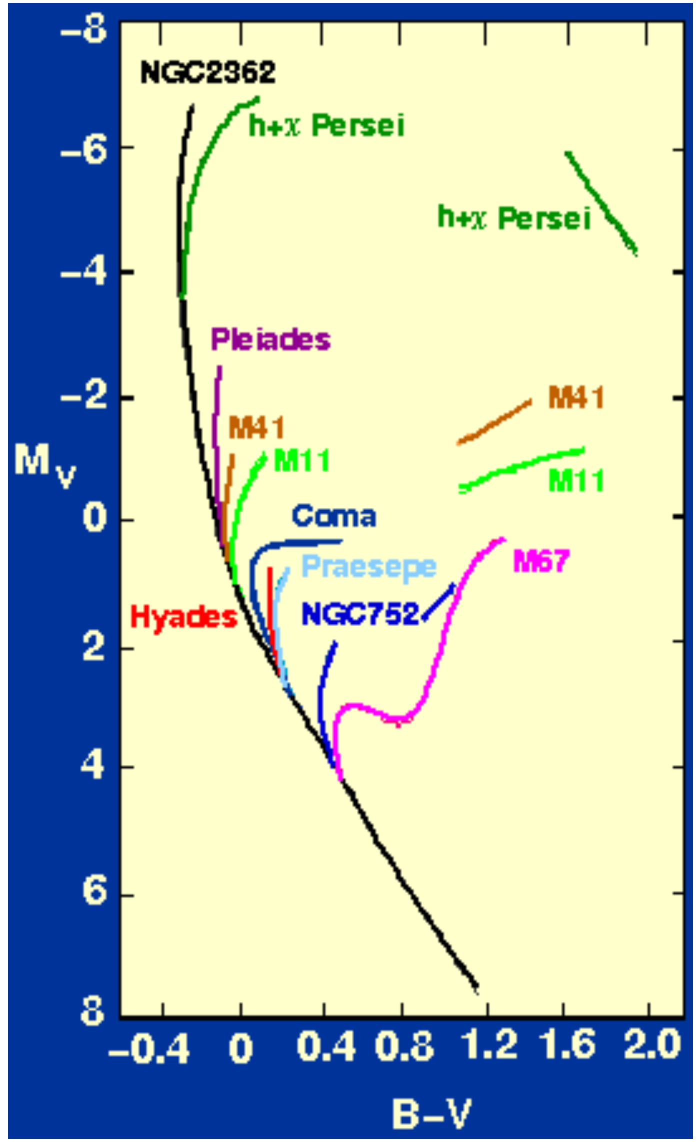
NGC3293 - Open cluster

47 Tuc – Globular cluster

Globular cluster example



Selection of Open clusters



- In clusters, *t* and *Z* must be same for all stars
- Hence differences must be due to *M*
- Stellar evolution assumes that the differences in cluster stars are due only (or mainly) to initial *M*
- Cluster HR (or colour-magnitude) diagrams are quite similar – age determines overall appearance

Globular vs. Open clusters

Globular	Open
• MS turn-off points in similar position. Giant branch joining MS • Horizontal branch from giant branch to above the MS turn-off point • Horizontal branch often populated only with variable RR Lyrae stars	• MS turn off point varies massively, faintest is consistent with globulars • Maximum luminosity of stars can get to $M_V \approx -10$ • Very massive stars found in these clusters

The differences are interpreted due to age – open clusters lie in the disk of the Milky Way and have large range of ages. The Globulars are all ancient, with the oldest tracing the earliest stages of the formation of Milky Way (~ 12×10^9 yrs)

Summary

- Four fundamental observables used to parameterise stars and compare with models *M, R, L,* T_e
- *M* and *R* can be measured directly in small numbers of stars (will cover more of this later)
- Age and chemical composition also dictate the position of stars in the HR diagram
- Stellar clusters very useful laboratories – all stars at same distance, same *t*, and initial *Z*
- We will develop models to attempt to reproduce the *M, R, L,* T_e relationships and understand HR diagrams