Corso di Astrofisica Stellare

Gabriele Cescutti

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Lezioni

- Lunedi 11 -13

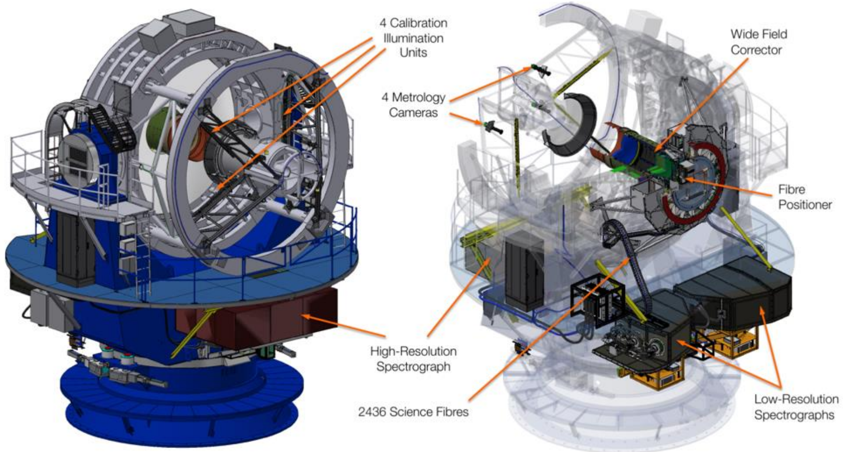
- Giovedì 13:30-15

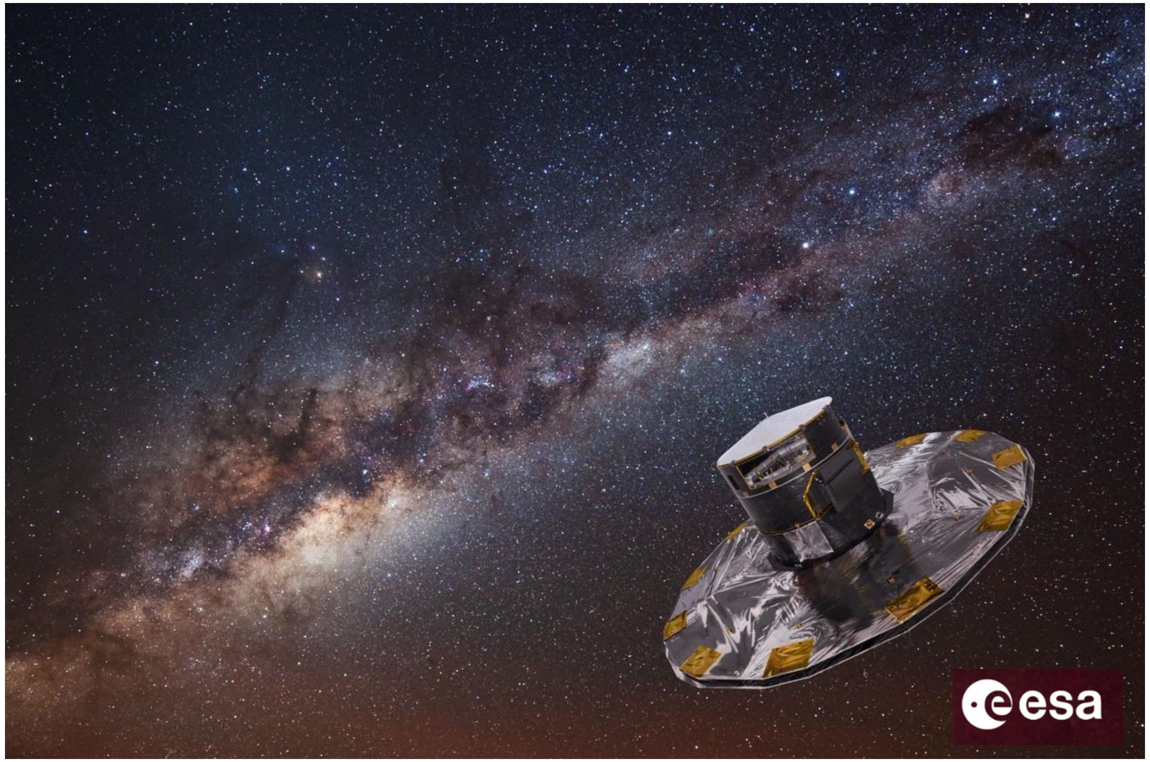
Esami

3 quesiti che spaziano sul corso (alcuni conti bisogna saperli fare)

contattarmi a gabriele.cescutti@inaf.it

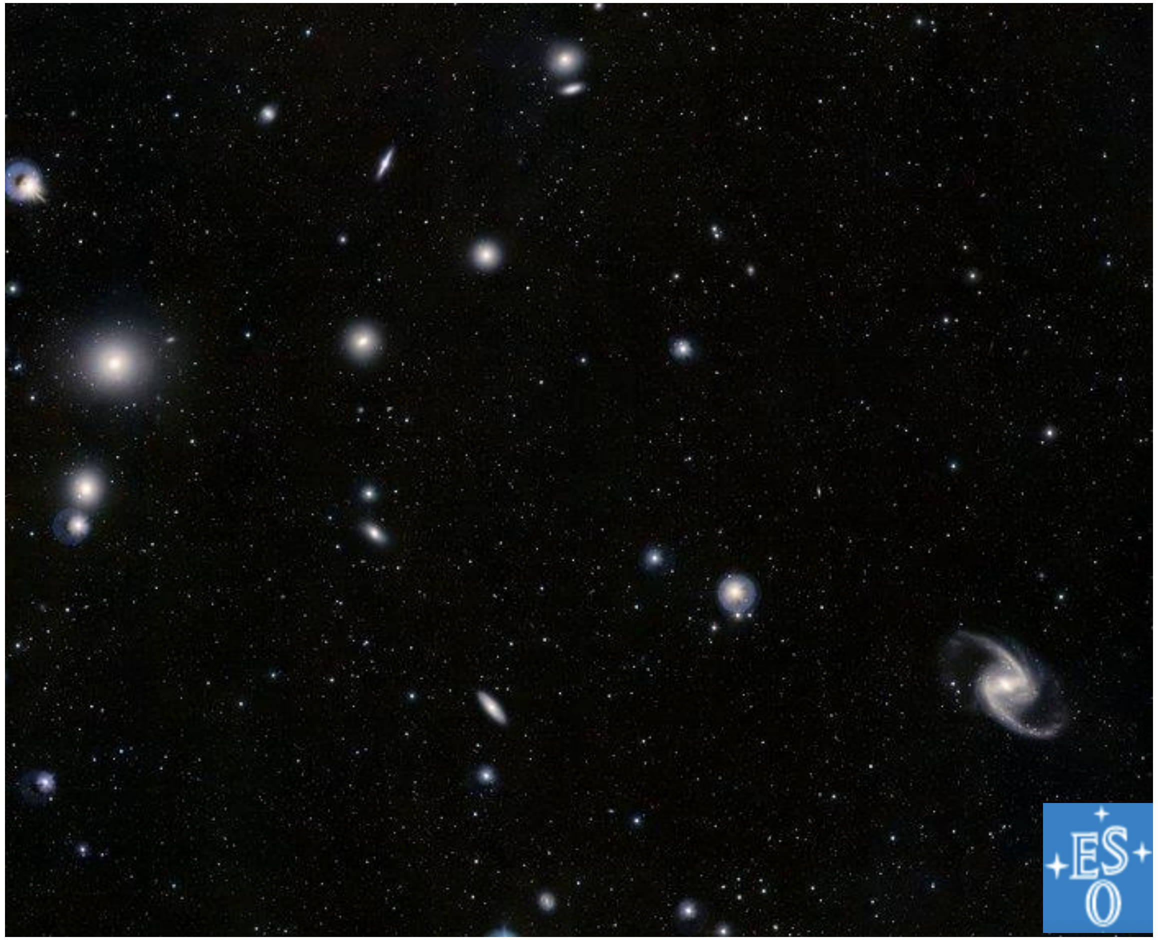
- Perché Astrofisica stellare è importante? (fondamentale!)



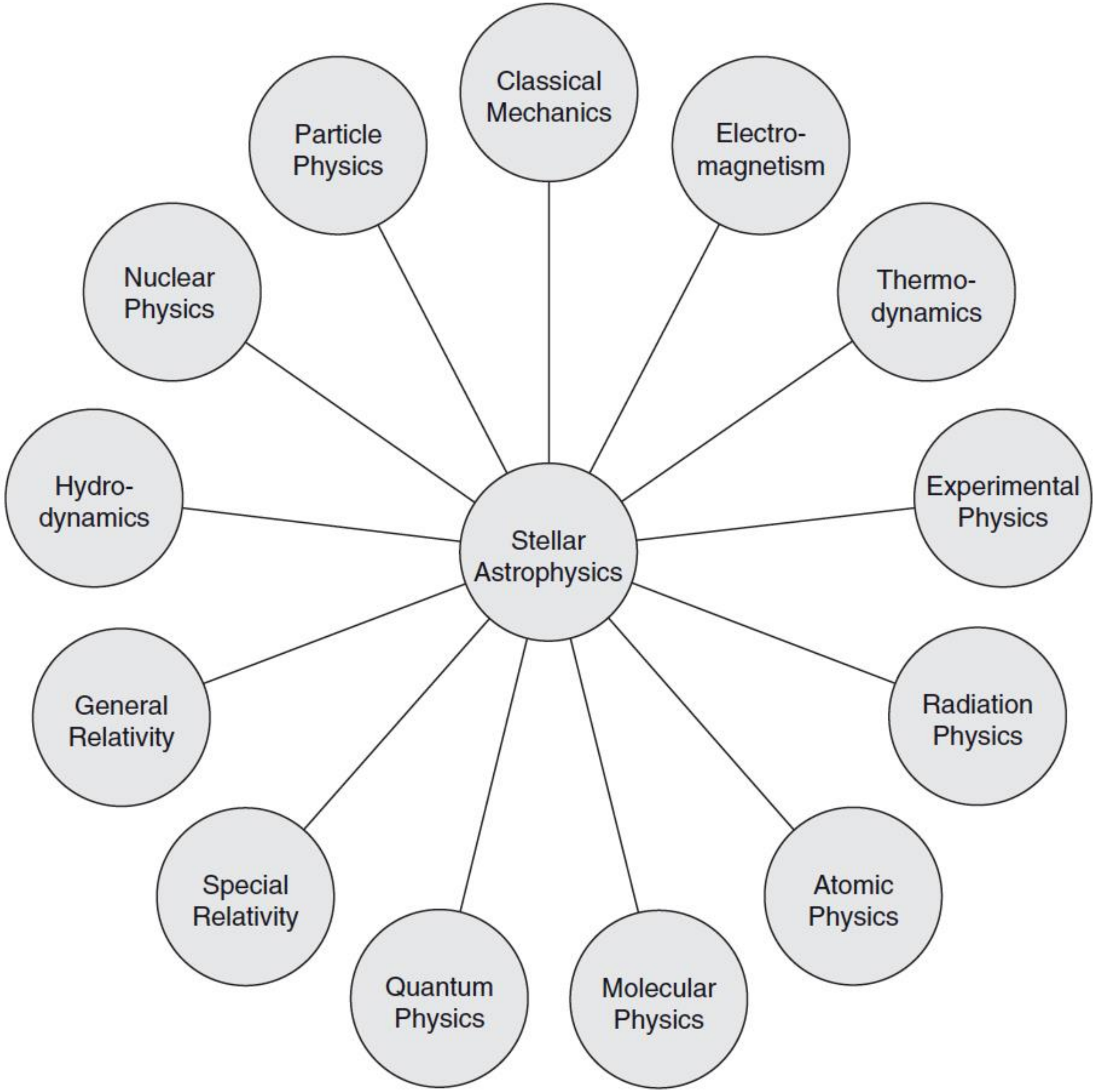


Galassie

Ammasso di Fornax



EASY?



An Introduction to
Stellar Astrophysics

FRANCIS LEBLANC
Université de Moncton, Canada

Programma ASTROFISICA STELLARE

Introduzione del corso,
Il Sole come stella tipica proprietà delle stelle

Equazioni della struttura stellare

Risoluzione equazioni della struttura stellare

Coefficiente produzione energia nucleare,
Reazioni nucleari di fusione

Elementi leggeri e nucleosintesi primordiale

Fasi di pre-sequenza stellare

Evoluzione di stelle di massa piccola ed intermedia

Evoluzione di stelle massicce

Supernovae da collasso del nucleo

Sistemi binari. Variabili cataclismatiche-Supernovae Ia

Mass loss, rotazione stellare e stelle pulsanti

Asterosismologia

Cenni di Atmosfere Stellari

Cenni di Struttura della Galassia

Evoluzione Chimica con soluzioni analitiche

Modelli di evoluzione chimica numerici

Approfondimento su modelli di stellar evolution con rotazione

Approfondimento con modelli di evoluzione stellare 3D

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} ($\sigma = ac/4$)
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

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

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} $\mathrm{Wm^{-2}K^{-4}}$)

3 independent quantities

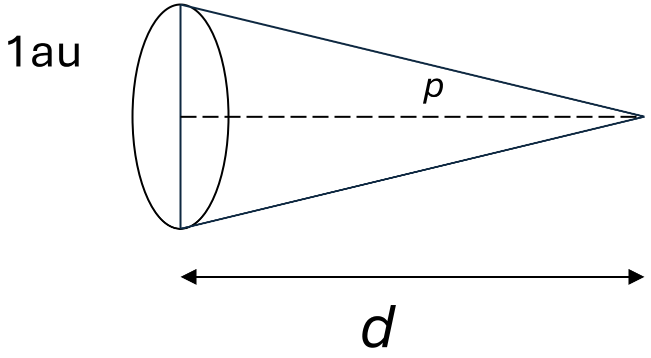
Recap Level 2/3 - definitions

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

$F = L / 4\pi d$

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

$p = 1\ \mathrm{au}/d$

$d = 1/p$ parsecs

If *p* is measured in arcsecs

SMALL DETOUR

The cosmic distance ladder

How far from the Earth to the Moon?

How far from the Earth to the Sun?

How far from the Sun to nearby stars?

How far from the Sun to distant stars?

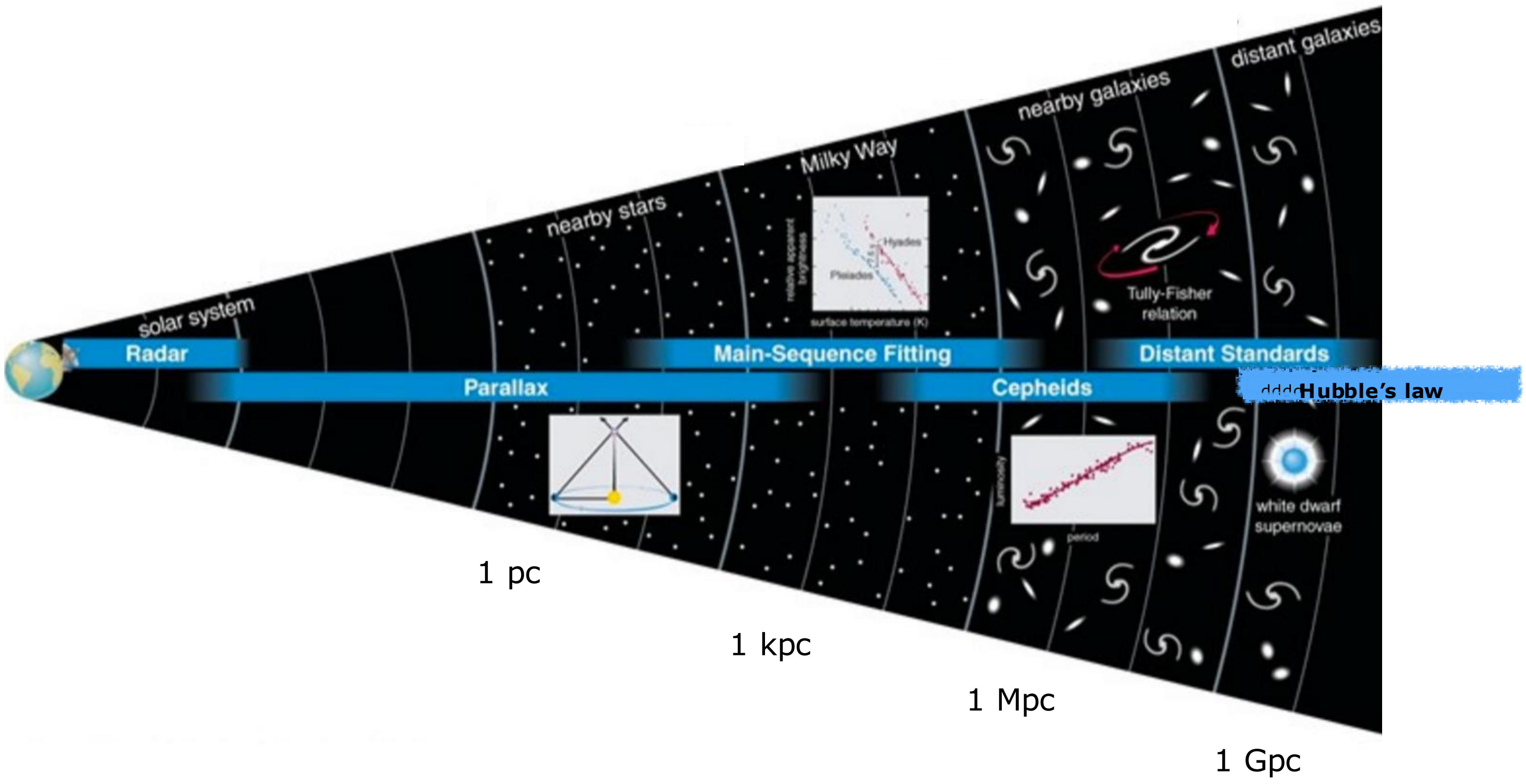
How far from the Sun to nearby galaxies?

How far from the Sun to distant galaxies?

Not a single method,

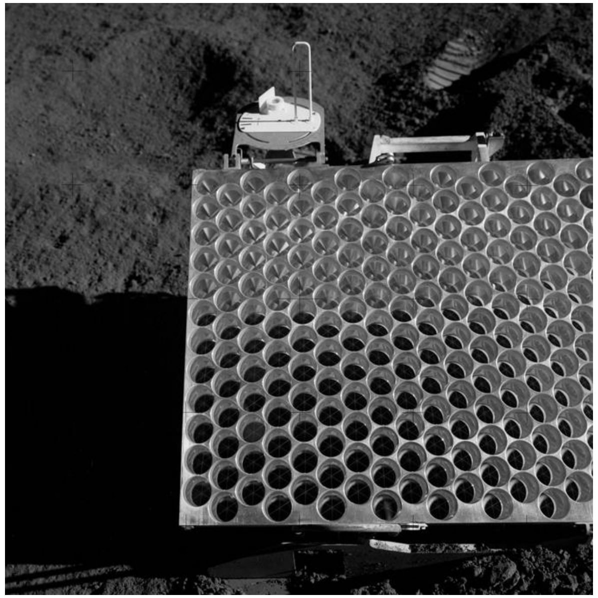
different methods should be applied!

In astronomy the distances are measured using a chain of interdependent techniques

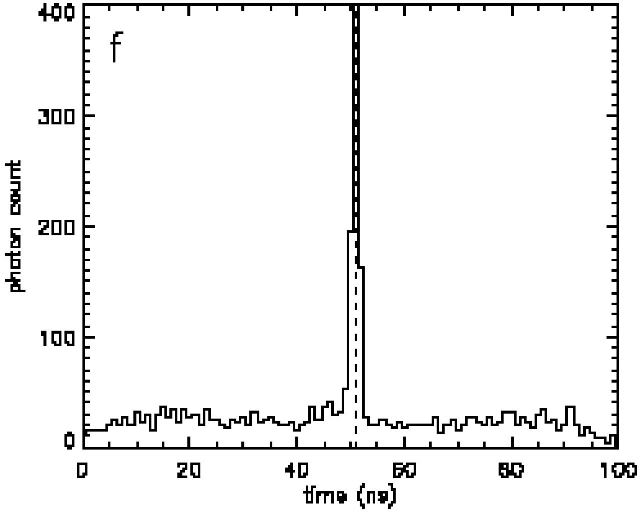


Direct method: **Laser pulse**

Using telescopes on Earth, the reflectors on the Moon, and accurate timing of laser pulses scientists can measure the distance Earth - Moon to an accuracy of a few centimetres.



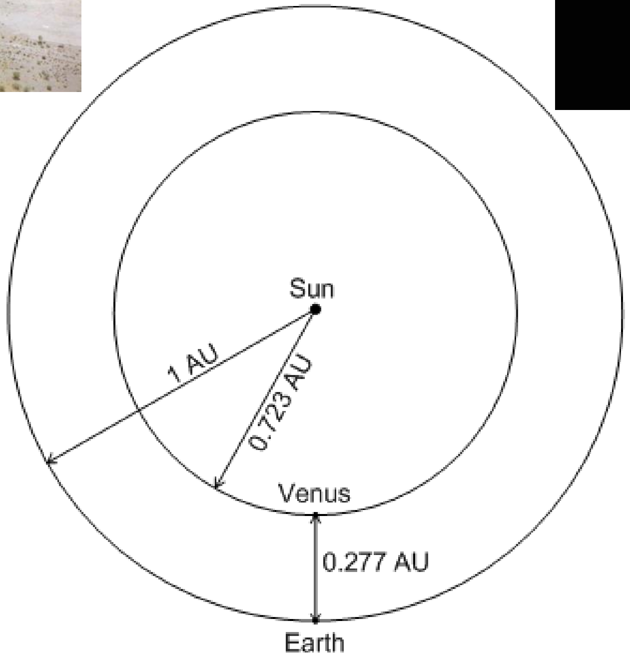
Apollo 15 Lunar Ranging Retro-Reflector .
The small circles are corner cubes, which reflect light directly back in the direction from which it came.



gate open after
~2.52s

Direct method: **Radar distance**

Since 1961, the distance to Venus can be determined directly, by radar measurements, where a series of radio waves is transmitted from Earth and is received after it bounces off Venus and comes back to Earth. By measuring the time taken for the radar echo to come back, the distance can be calculated. Once this Earth-Venus distance is known, the distance between Earth and the Sun can be calculated.



Q The time for a radar signal to make the round trip between Earth and Venus
is measured to be 276.2 seconds.
Determine the astronomical unit.

Direct method: **Stellar parallax**

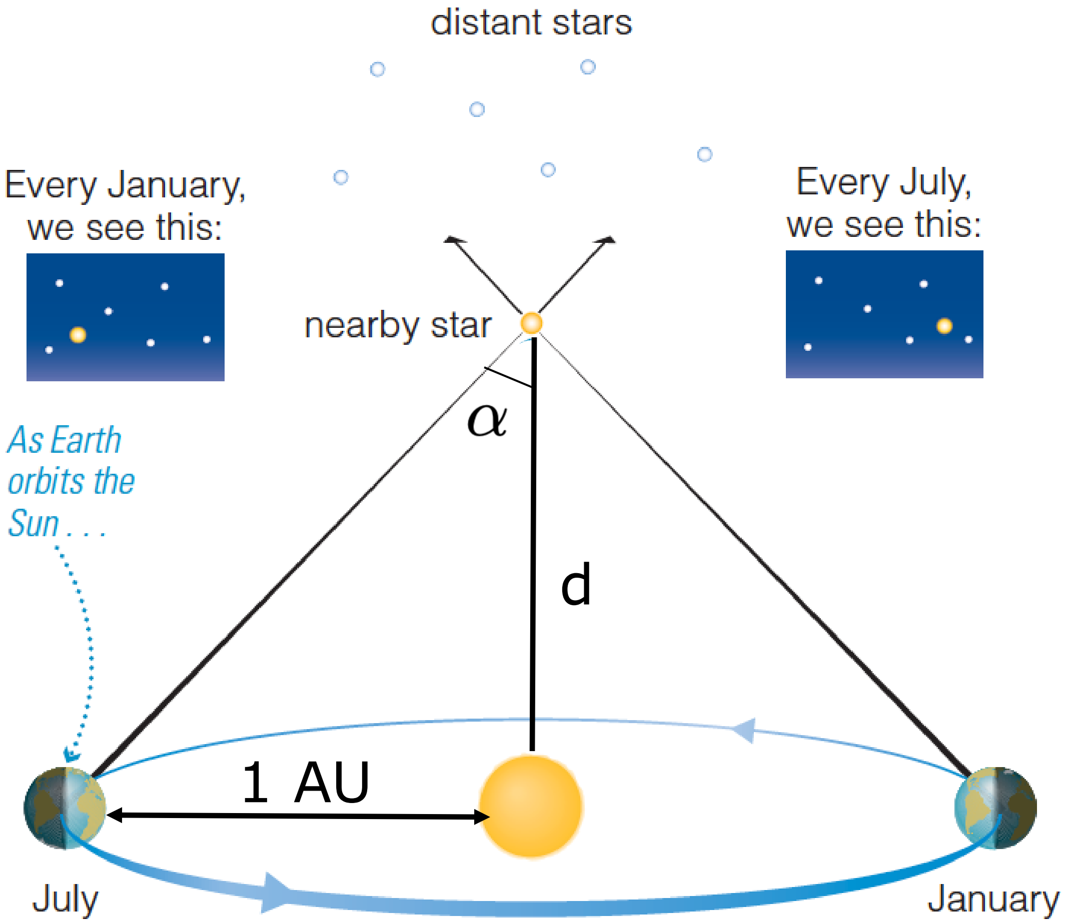
$$tan(\alpha) = \frac{AU}{d}$$

$$tan(\alpha) \sim \alpha \qquad if\ \alpha << 1"$$

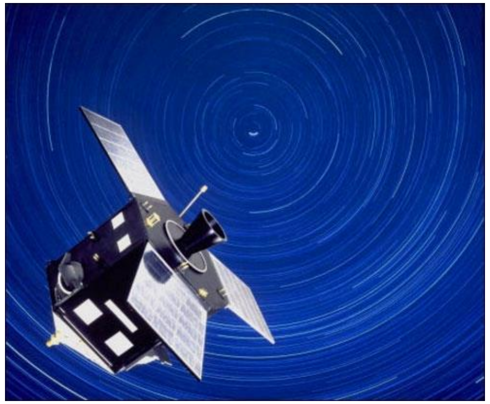
$$d(AU) = \frac{1}{\alpha(rad)}$$

Parsec (pc) is the distance at which one AU subtends an angle of one arc second. Therefore:

$$d(pc) = \frac{1}{\alpha(arcsec)}$$

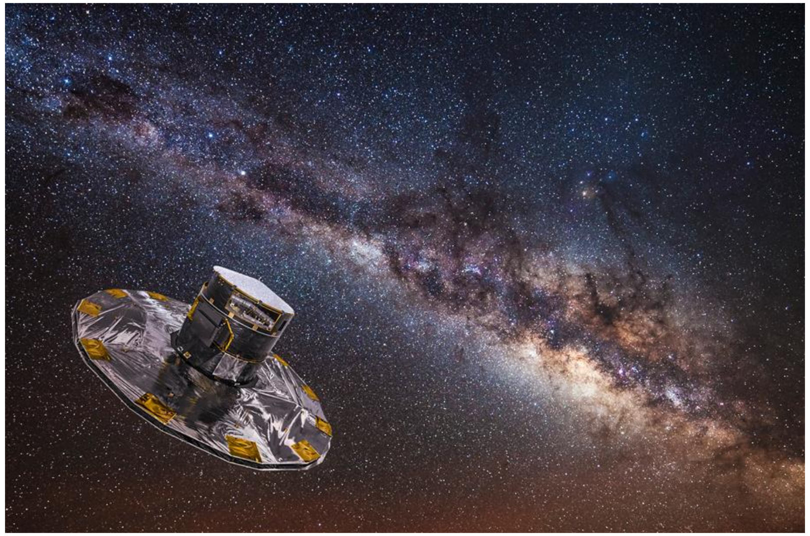


Direct method: Stellar parallax



Hypparcos satellite 1989-1993
120’000 stars with
a precision of 2 - 4 mas

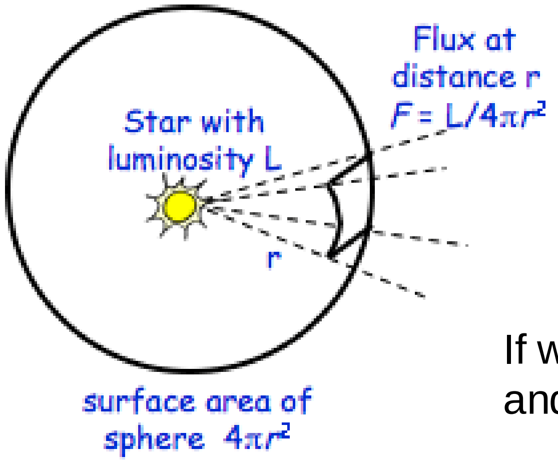
Q How far are the most distant stars measured by Hypparcos?



Gaia satellite 2013-2018
1 billion of stars(!) with
a precision up to 1 μas

Q Why always satellites?

Standard candles



L = const

$F(r) \sim 1/r^2$

F = observed flux

d = distance

If we know the Luminosity of an object
and we measure the flux from an unknown distance **d** then:

$$L = 4\pi F(d) d^2$$

therefore the unknown distance is:

$$d = \sqrt{\frac{L}{4\pi F}}$$

Indirect methods

Standard candles

In astronomy it is common the use the apparent magnitude **m:**

$$m - m_0 = -2.5\ log_{10}\left(\frac{F}{F_0}\right)$$

where F_0 and m_0 are the flux and apparent magnitude for a reference object.
If we define the absolute magnitude **M** as the apparent magnitude of an object at 10 pc then:

$$m - M = 5\ log_{10}(d) - 5$$

(Q calculate this equation from the above definitions)

Q So what is the distance of Vega, if we know that it has an apparent magnitude of +0.03 and an absolute magnitude of 0.6?

In general the problem in astronomy is that we do not know “a priori” the absolute magnitude (or luminosity) of an astronomical object.

However, there are few astronomical objects that are reasonably close to have always the same Luminosity or a Luminosity that we can predict. They are called **standard candles**,

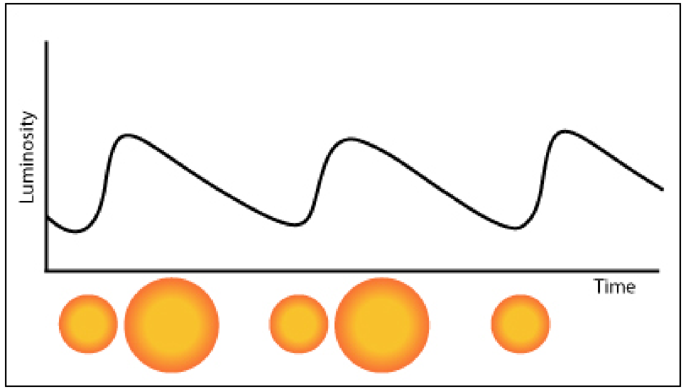
Indirect methods

Standard candles

Cepheids


Henrietta Swan Leavitt

Cepheids are bright variable stars



Henrietta Swan Leavitt in 1912 discovered an important relation between the period and the apparent magnitude of the cepheids in the Large Magellanic cloud.

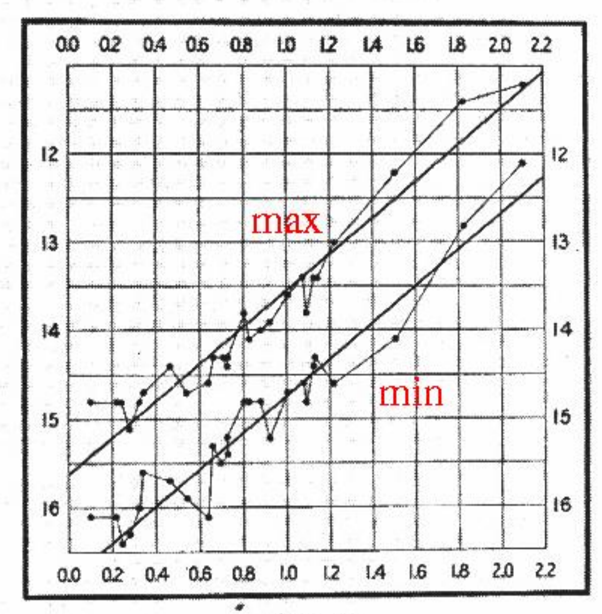


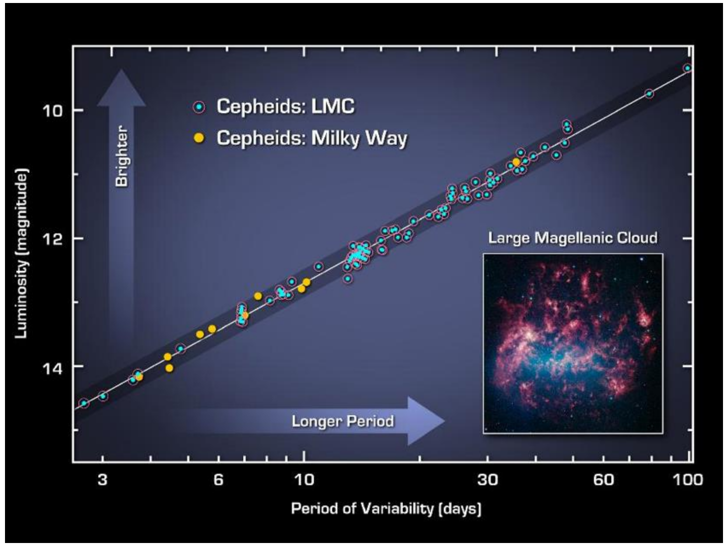
FIG. 2.

Indirect methods

Cepheids

Standard candles

The key point was that all these objects belong to the Large Magellanic cloud and therefore at (roughly) the same distance. Assuming a distance of 50 kpc for the Large Magellanic clouds, she obtained this relation:

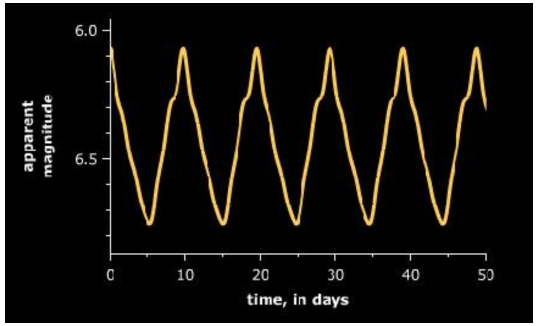


$$M = -2.87\ log_{10}P - 1.40$$

The cepheids are bright young objects and it is possible to measure them up to 10Mpc!

Thanks to this method it was possible for the first time to move from our Galaxy and explore the nearby Universe.

Q what is the distance of this cepheid if we know that it apparent magnitude is m=15?

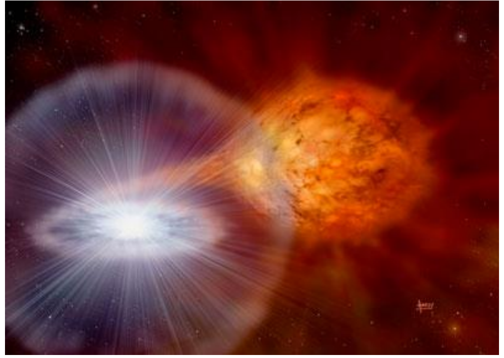


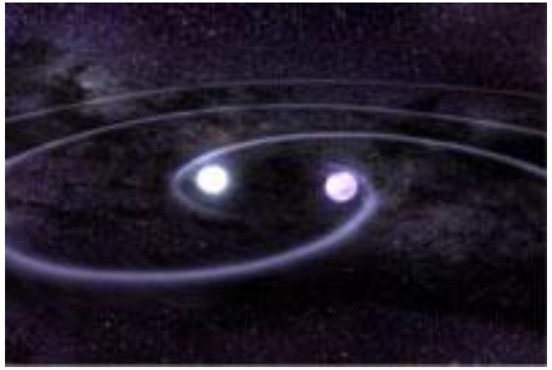
Indirect methods

Standard candles

Supernovae Ia

When a white dwarf exceeds the 1.4 Msun (Chandrasekhar mass), it becomes unstable and explodes. Two scenarios:
Mass transfer from a binary companion or Merging with another white dwarf





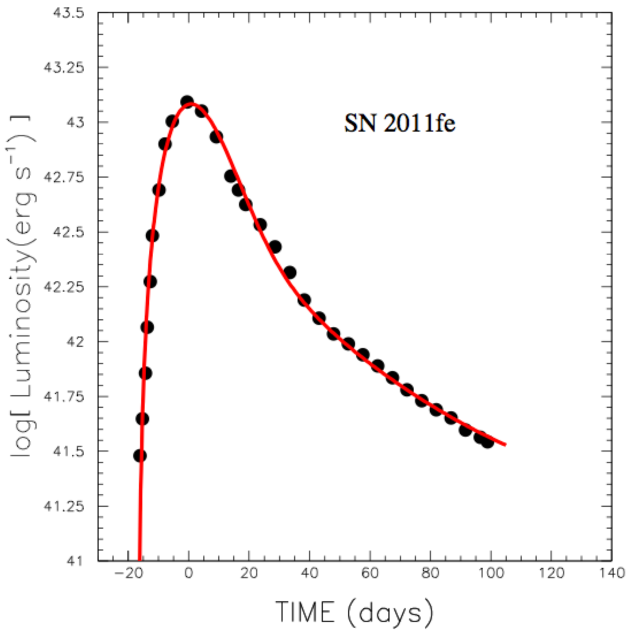
The key point is that the mechanism is always similar and it can produce in both case the same event: a Supernova Ia

Crab Nebula
the remnant of a SNIa
explosion in our Galaxies
500y ago

Indirect methods

Standard candles

Supernovae Ia

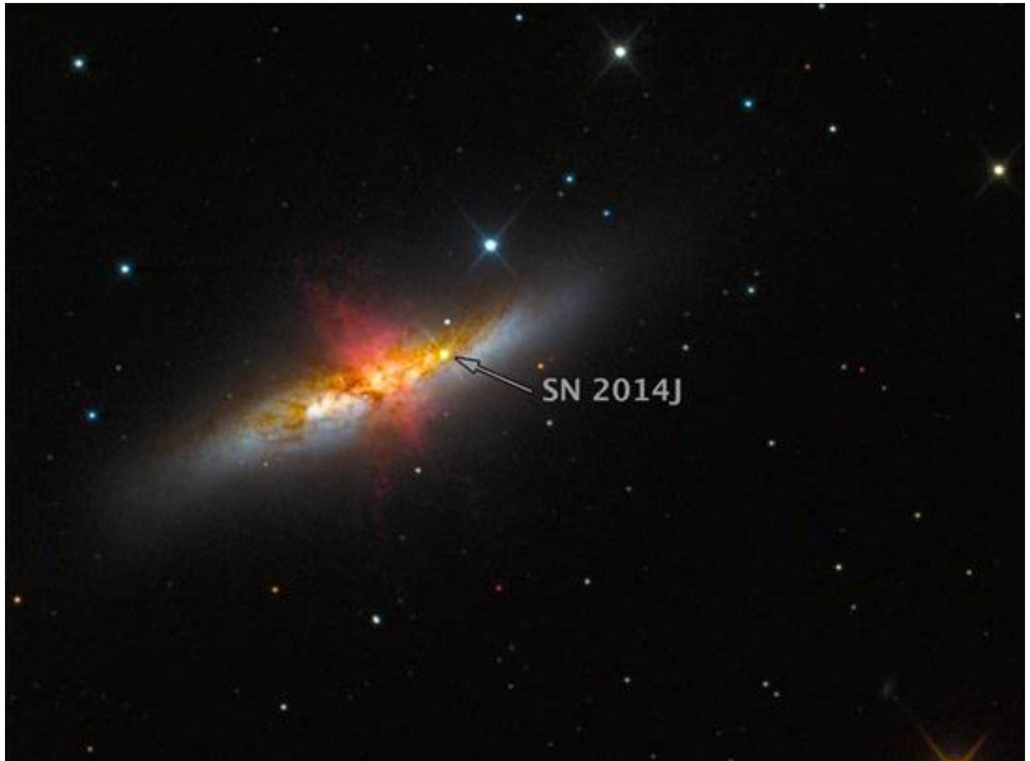


SNe Ia are generate always by the same event and therefore the peak of the luminosity for these objects is constant as well as the shape of their luminosity vs time.

Therefore, we can recognise them and because of their brightness we are able to measure distance up to a few Gpc away.

Contrary to Cepheids which are quite numerous, the SNIa are rare events.

The closest type Ia supernova recently discovered SN 2014J in the nearby galaxy M82.



Since nearest stars $d > 1$pc ; 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" difficult !

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

Hence ~100’000 stars with well measured parallax distances

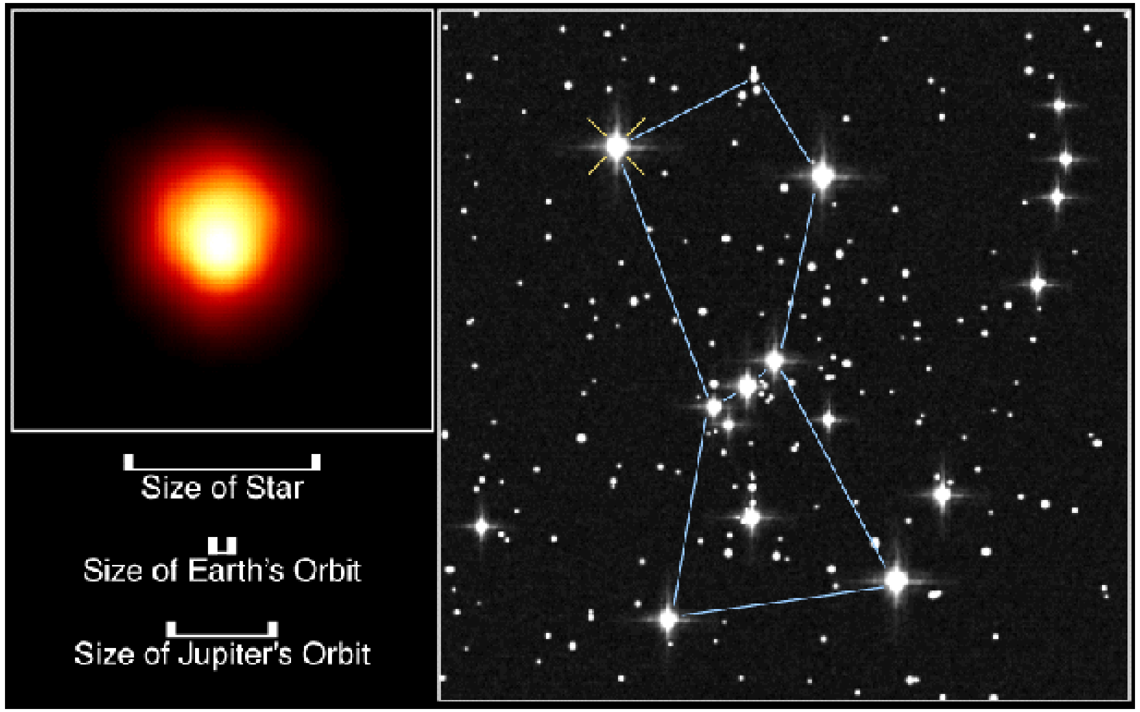
now with GAIA ⇨ 1billion!!!

Stellar radii

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

Compare with Hubble resol. of ~0.05 arcsec

→ very difficult to measure *R* directly



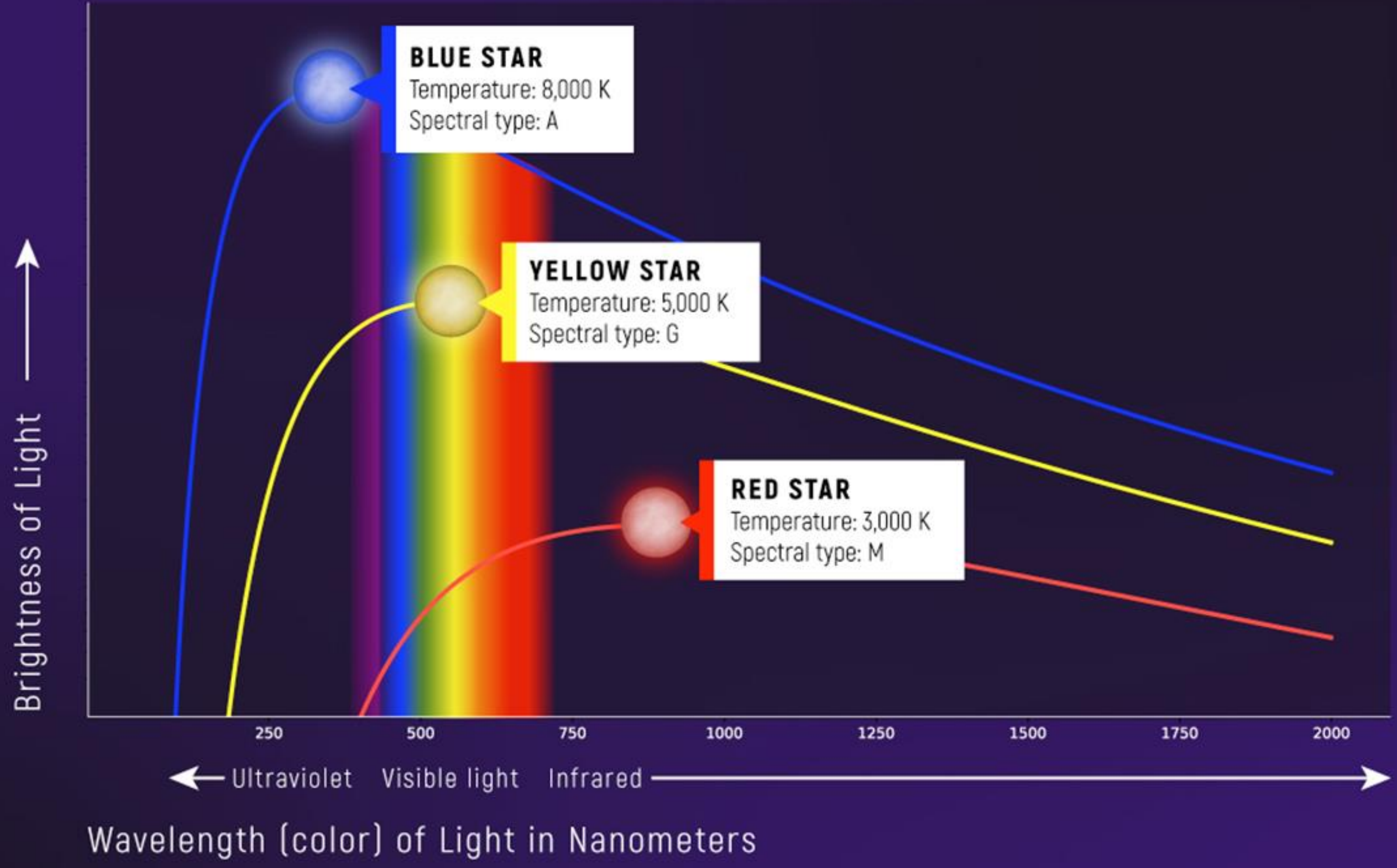
Radii of ~600 stars measured with techniques such as interferometry and eclipsing binaries.

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} $Wm^{-2}K^{-4}$)

3 independent quantities

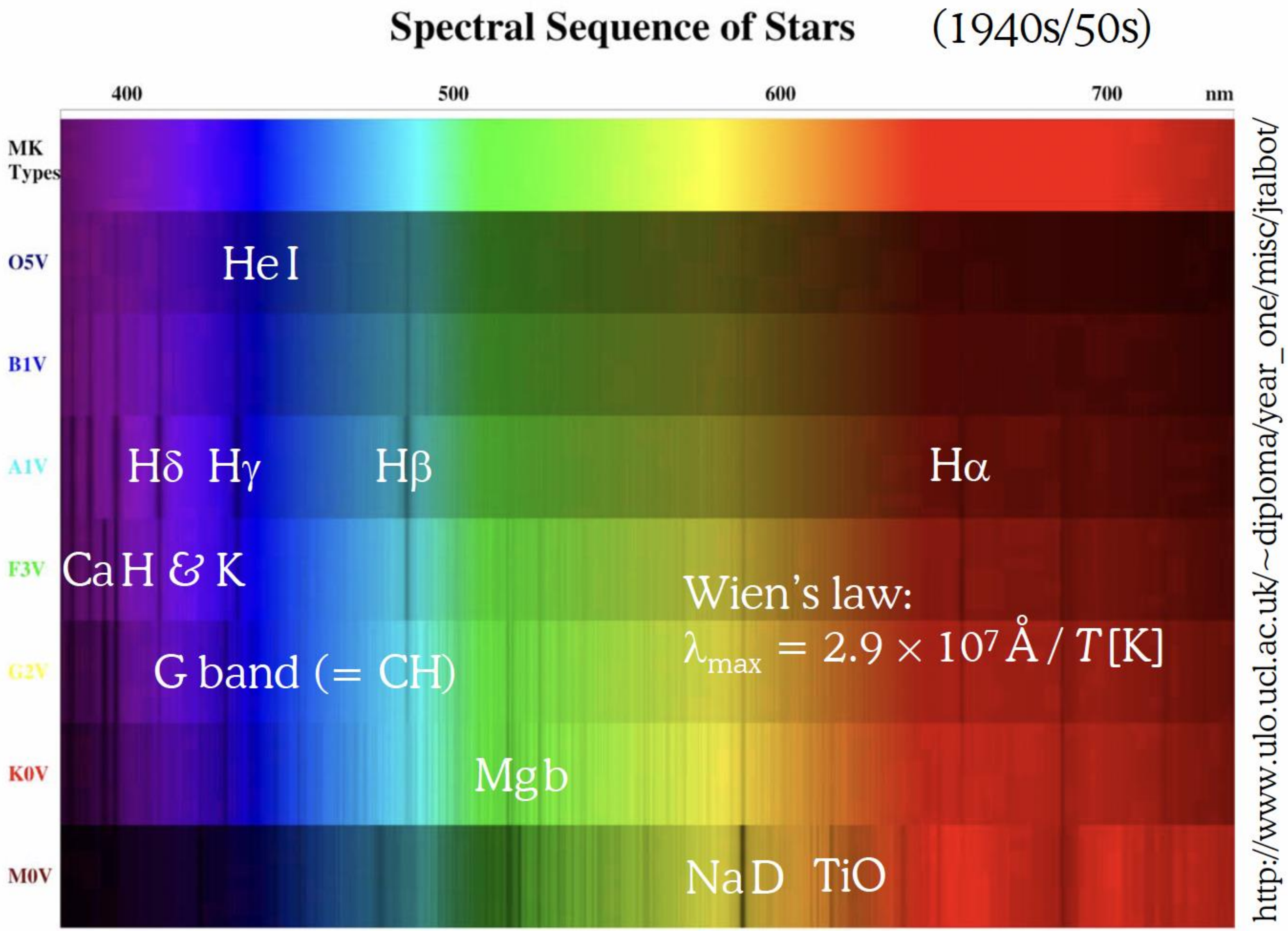

BLUE STAR
Temperature: 8,000 K
Spectral type: A
YELLOW STAR
Temperature: 5,000 K
Spectral type: G
RED STAR
Temperature: 3,000 K
Spectral type: M
Brightness of Light
250
500
750
1000
1250
1500
1750
2000
Ultraviolet
Visible light
Infrared
Wavelength (color) of Light in Nanometers

Proprietà delle stelle

Vengono classificare sulla base delle righe spettrali che predominano nel loro spettro.
La variabile fisica che determina il tipo spettrale è la **TEMPERATURA SUPERFICIALE** (più che la composizione chimica).

O B A F G K M R N S

Morgan-Keenan(-Kellman) classification



Wien's law:

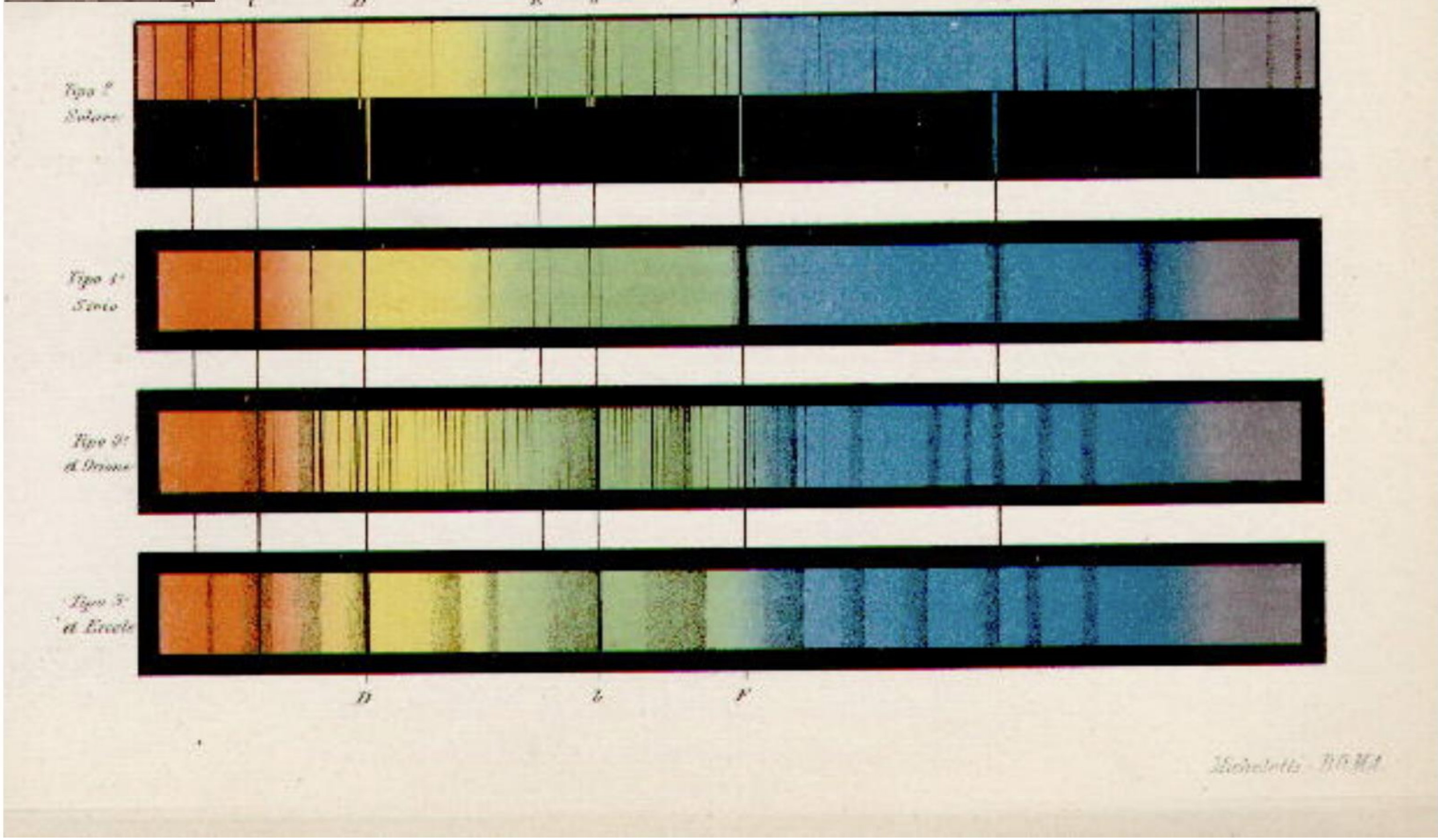
$\lambda_{max} = 2.9 \times 10^7 \text{Å} / T[\text{K}]$

http://www.ulo.ucl.ac.uk/~diploma/year_one/misc/jtalbot/

Padre Angelo Secchi

(1864) four-category scheme

TAV. III. – Tipi diversi degli spettri stellari



Ulteriore suddivisione all’interno del tipo
spettrale va da **0 a 9**
Il sole per esempio è una stella di G2 di sequenza principale.

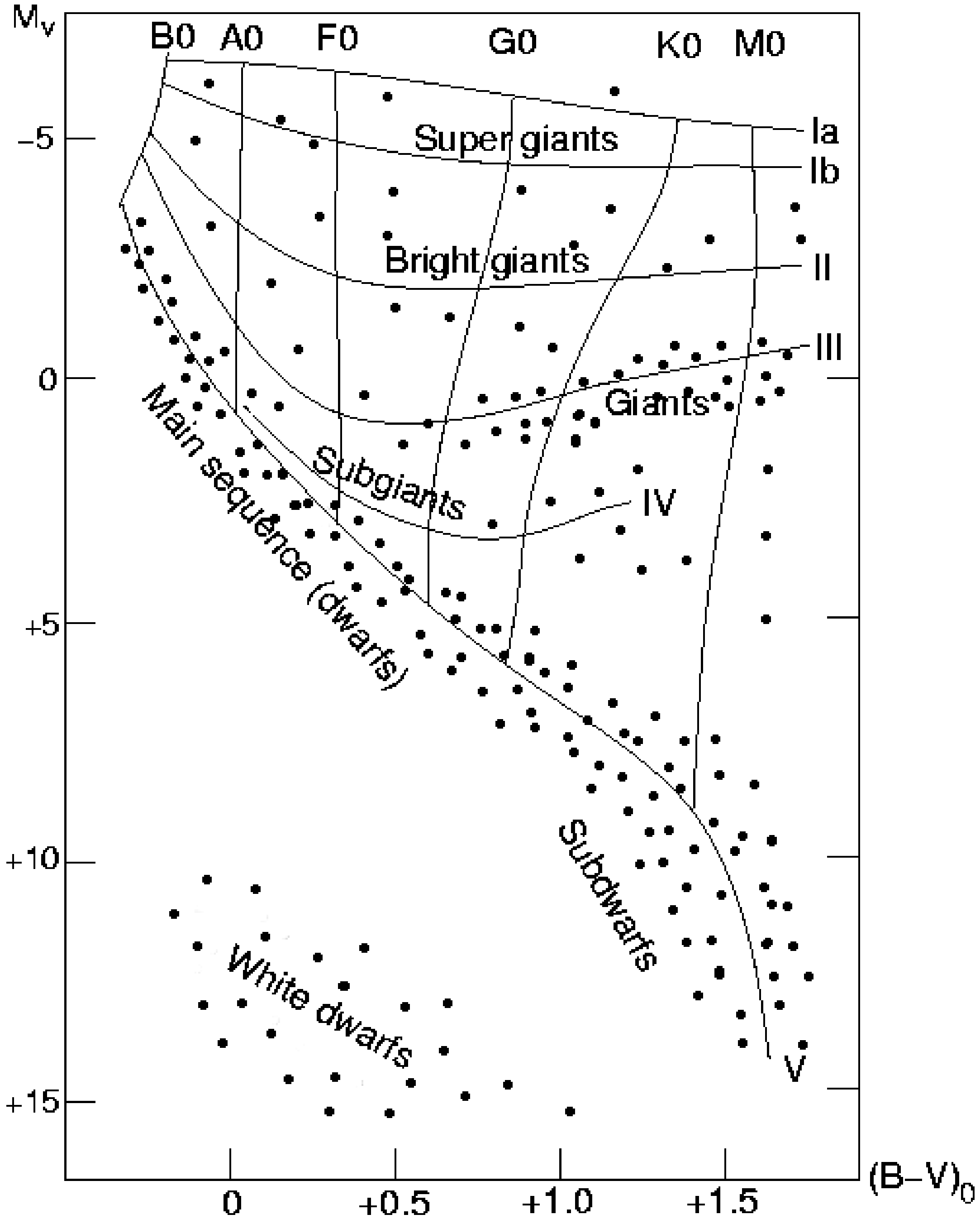
E’ possibile distinguere stelle in diverse fasi evolutive dai loro spettri (o colori)?

Le stelle irradiano come un corpo nero, quindi se due stelle hanno la stessa **temperatura superficiale (T_{eff})**
la più luminosa dev’essere quella di raggio maggiore

Stelle con raggi grandi vengono dette giganti, hanno densità minori delle stelle normali (dette nane).
Hanno anche un diverso grado di ionizzazione (influenzato dalla diversa gravità e densità superficiale) delle nane

Le righe spettrali sono diverse (vedremo perché) e quindi è possibile distinguerle anche se non sappiamo la luminosità assoluta di una stella.

In base a questo definiamo ulteriormente classi di Luminosità da **I (supergiganti) a V (nane)**


M_V
B0
A0
F0
G0
K0
M0
Super giants
Ia
Ib
Bright giants
II
III
Giants
Subgiants
IV
Main sequence (dwarfs)
Subdwarfs
White dwarfs
V
−5
0
+5
+10
+15
0
+0.5
+1.0
+1.5
(B–V)0

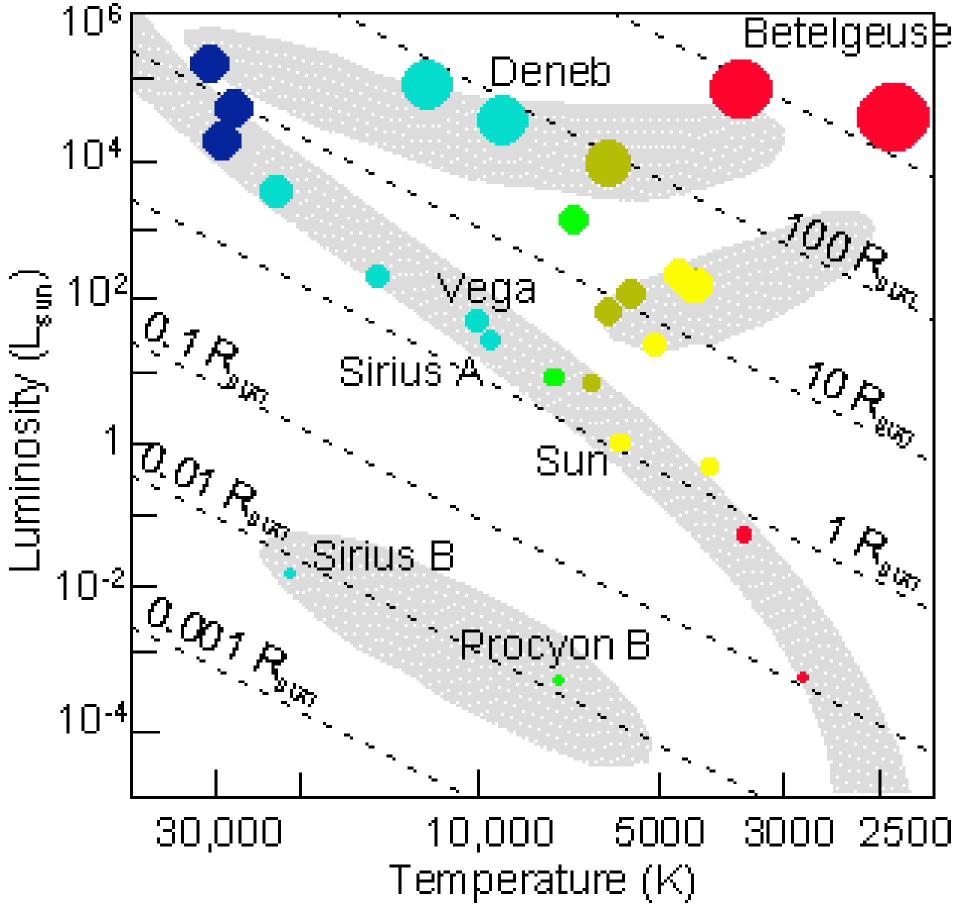
The Hertzsprung-Russell diagram

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

Two major relationships

– *L* with *T*
– *L* with *M*

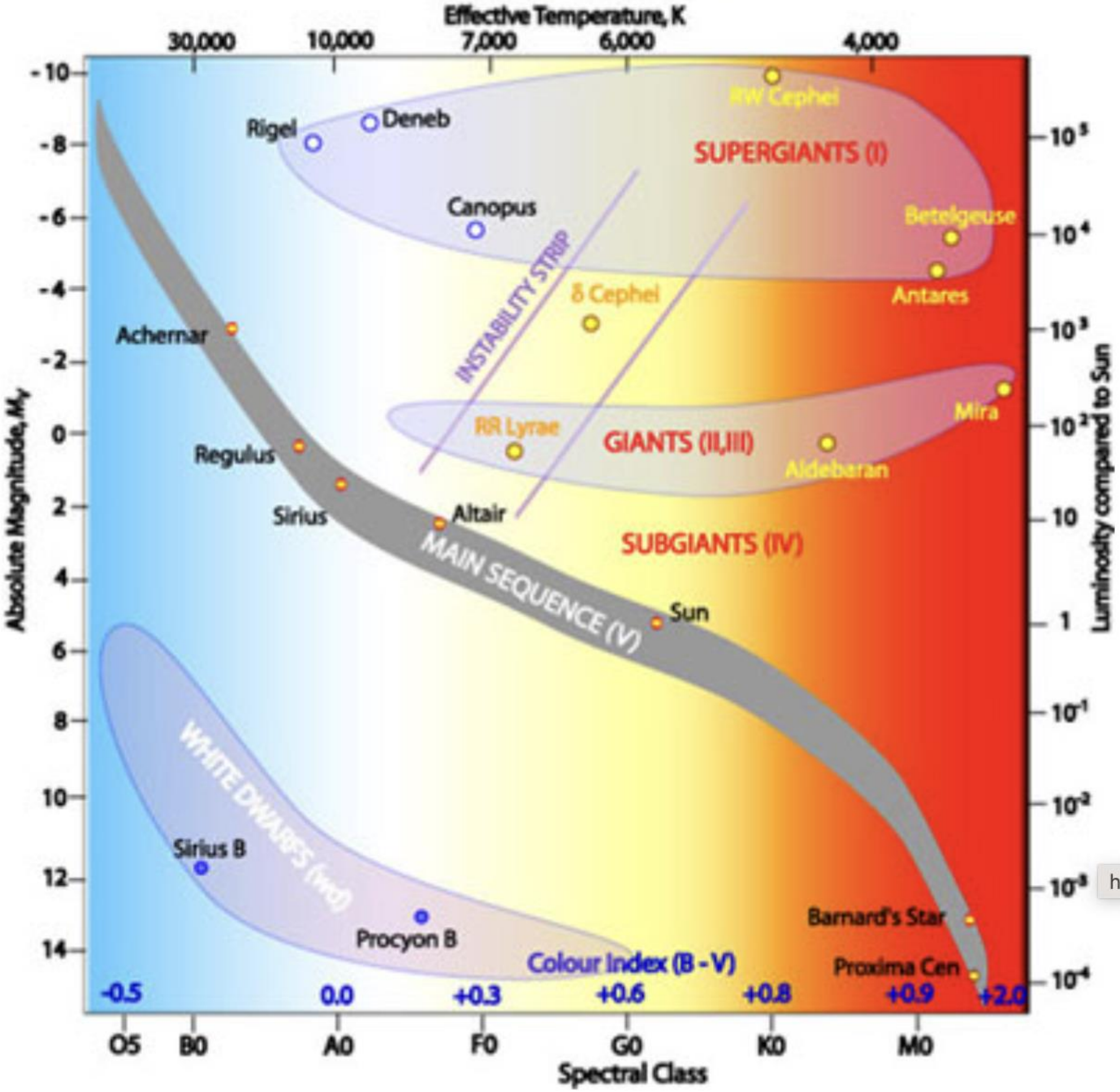
The first is known as the *Hertzsprung-Russell* (HR) diagram or the *colour-magnitude* diagram.



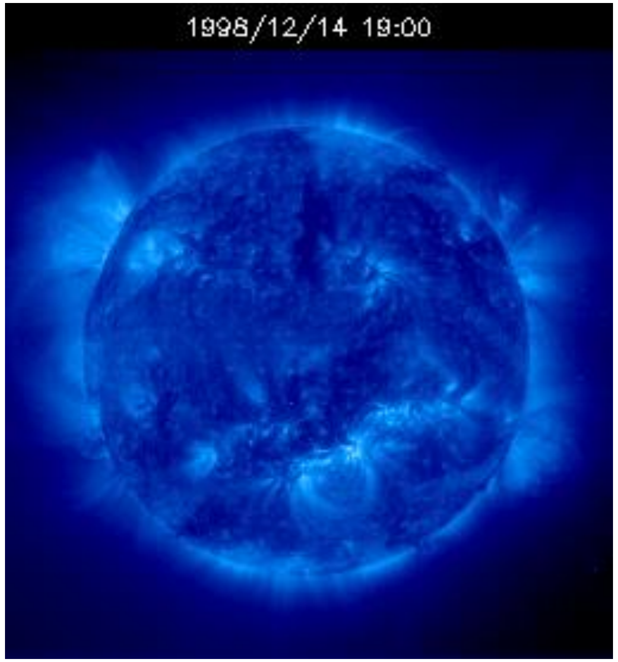
Colour Index (B-V) –0.6 0 +0.6 +2.0

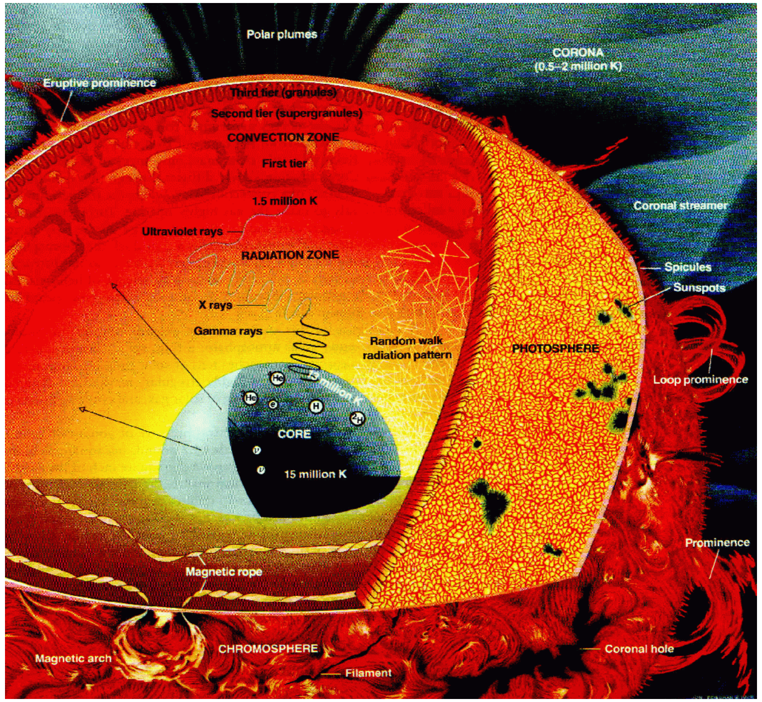
Spectral type O B A F G K M

Hertzsprung-Russell Diagram



The Sun – best studied example





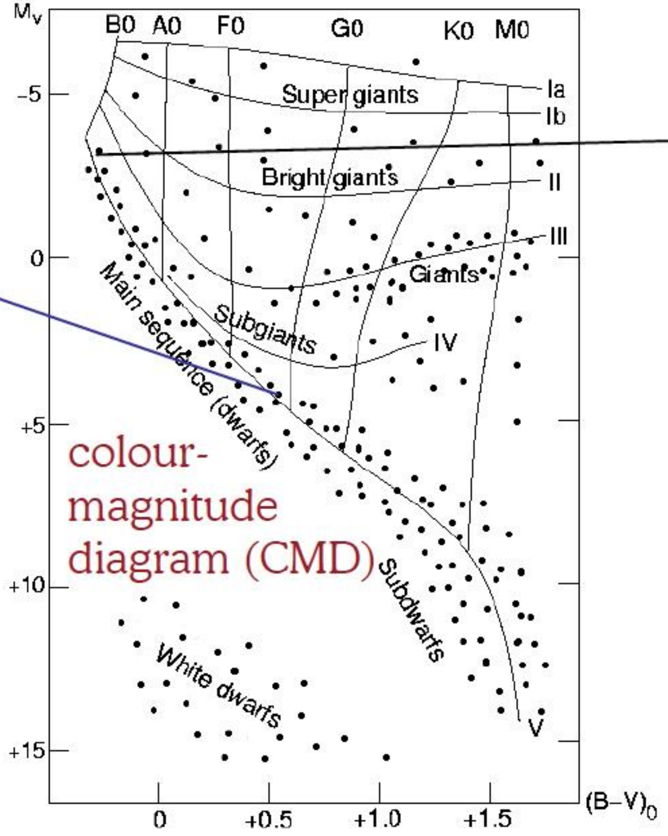
Stellar interiors not directly observable. Solar neutrinos emitted at core and detectable. Helioseismology - vibrations of solar surface can be used to probe density structure

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

The Sun

$M = 2 \times 10^{33}\ \mathrm{g} = \mathrm{M}_\odot$
$R = 7 \times 10^{10}\ \mathrm{cm} = \mathrm{R}_\odot$
$L = 4 \times 10^{33}\ \mathrm{erg/s} = \mathrm{L}_\odot$

photosphere:
$\Delta R \approx 200\ \mathrm{km} < 10^{-3}\ \mathrm{R}_\odot$
$n \approx 10^{15}\ \mathrm{cm}^{-3}$
$T \approx 6000\ \mathrm{K}$

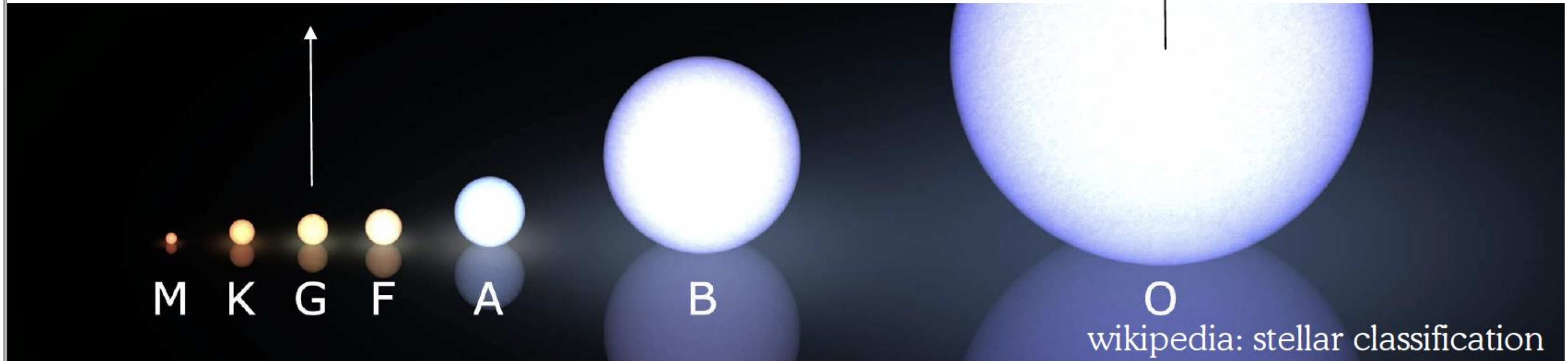


colour-magnitude diagram (CMD)

an O star

$M \sim 50\ \mathrm{M}_\odot$
$R \sim 20\ \mathrm{R}_\odot$
$L \sim 10^6\ \mathrm{L}_\odot\ (\propto M^3)$

photosphere:
$\Delta R \approx 0.1\ \mathrm{R}_\odot$
$n \approx 10^{14}\ \mathrm{cm}^{-3}$
$T \approx 40\,000\ \mathrm{K}$



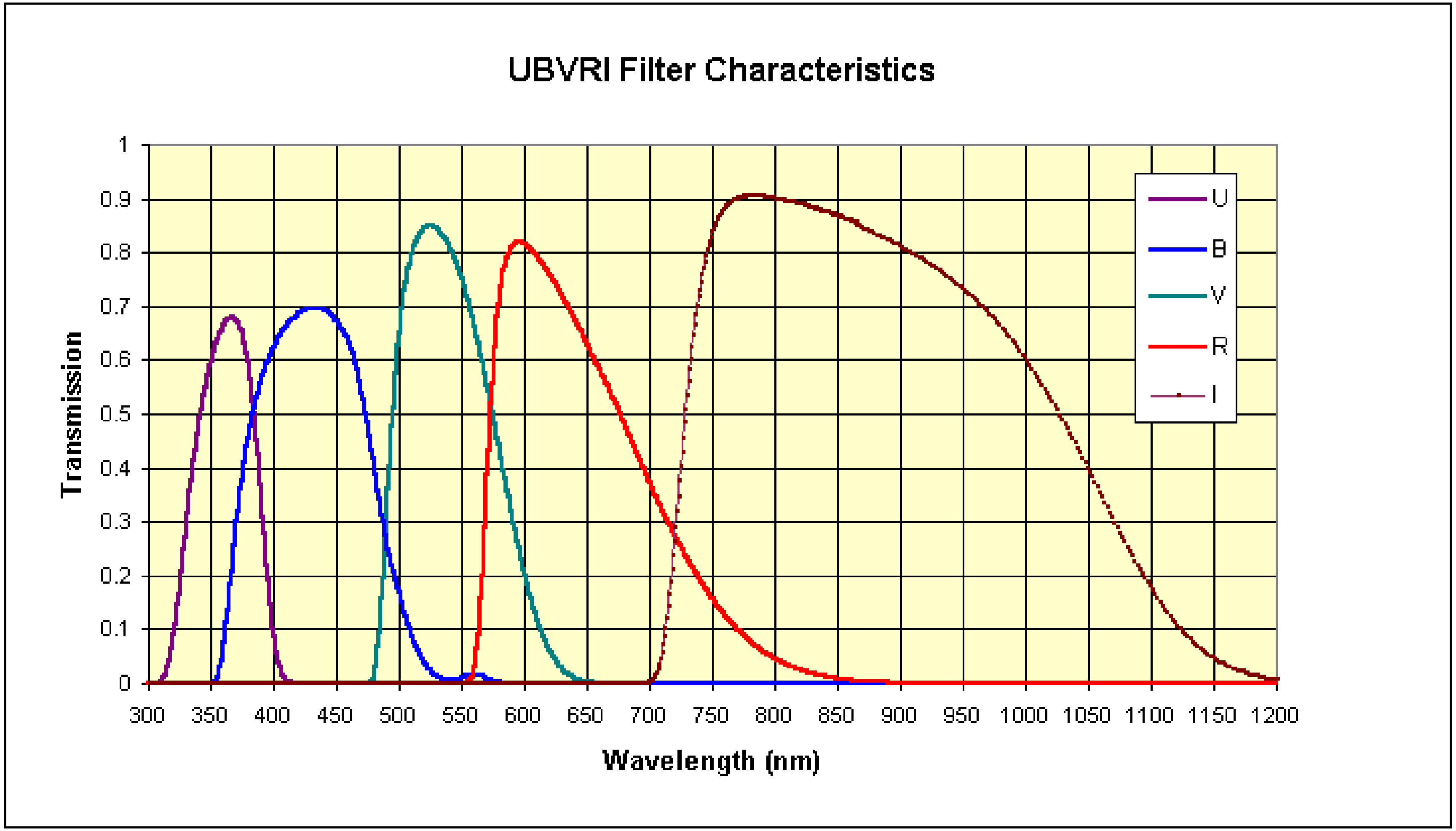
wikipedia: stellar classification

Colour-magnitude diagrams

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

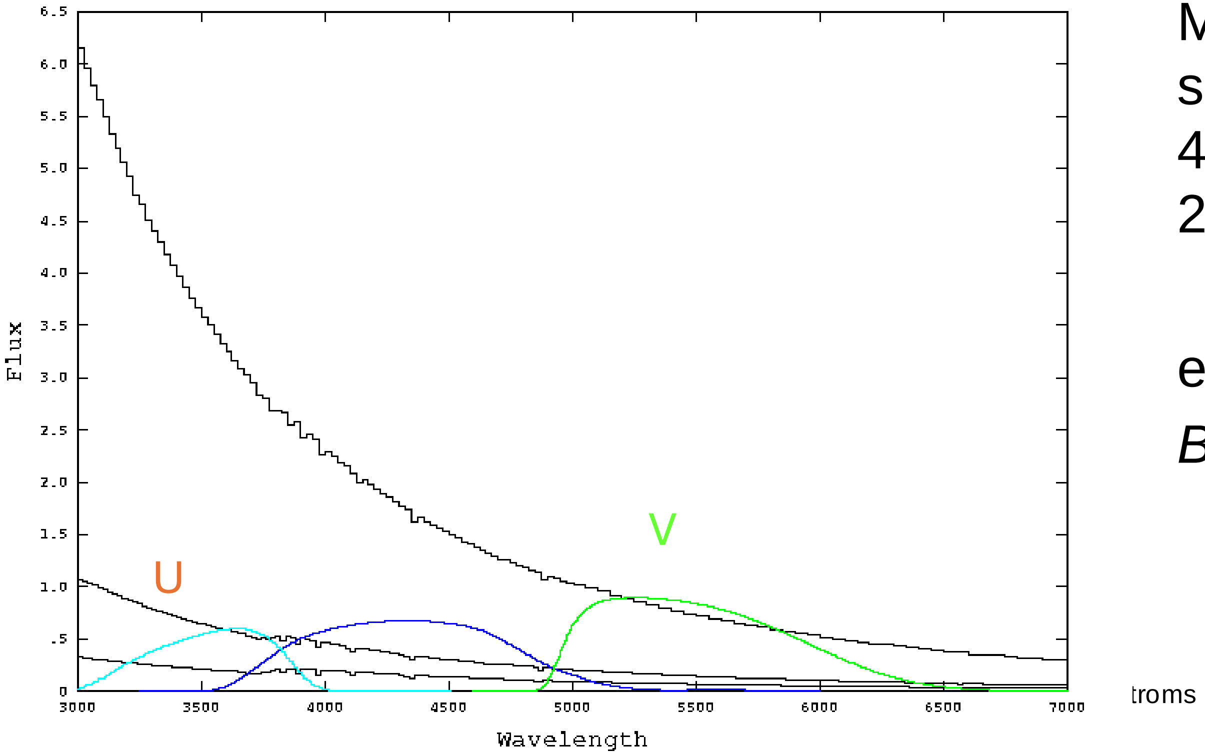
Magnitudes of stars are measured at different wavelengths: standard system is *UBVRI*

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



UBVRI Filter Characteristics
Transmission
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
Wavelength (nm)
U
B
V
R
I

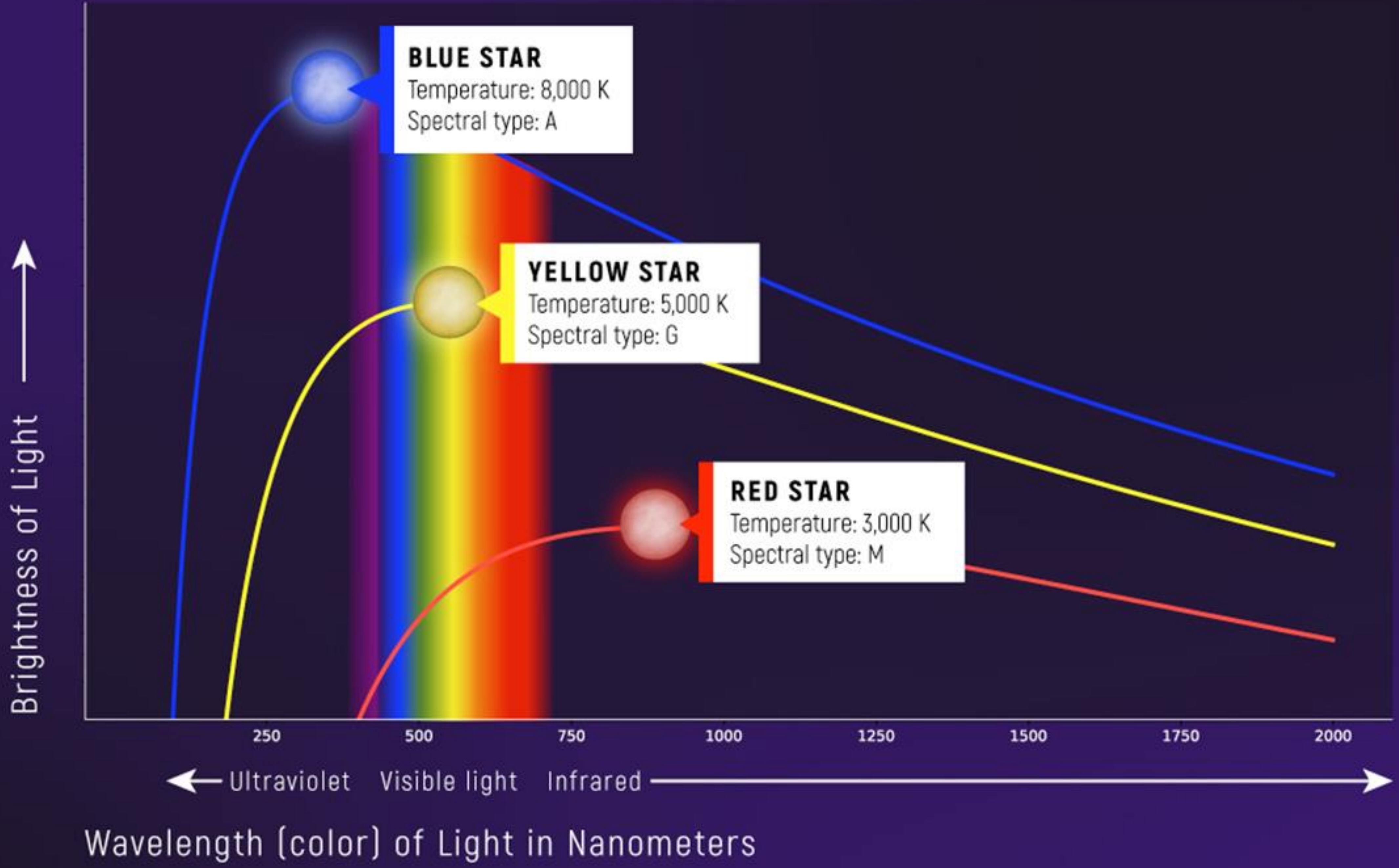
Magnitudes and Colours (see also next slides)



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

e.g.

$B\text{-}V = f(T_e)$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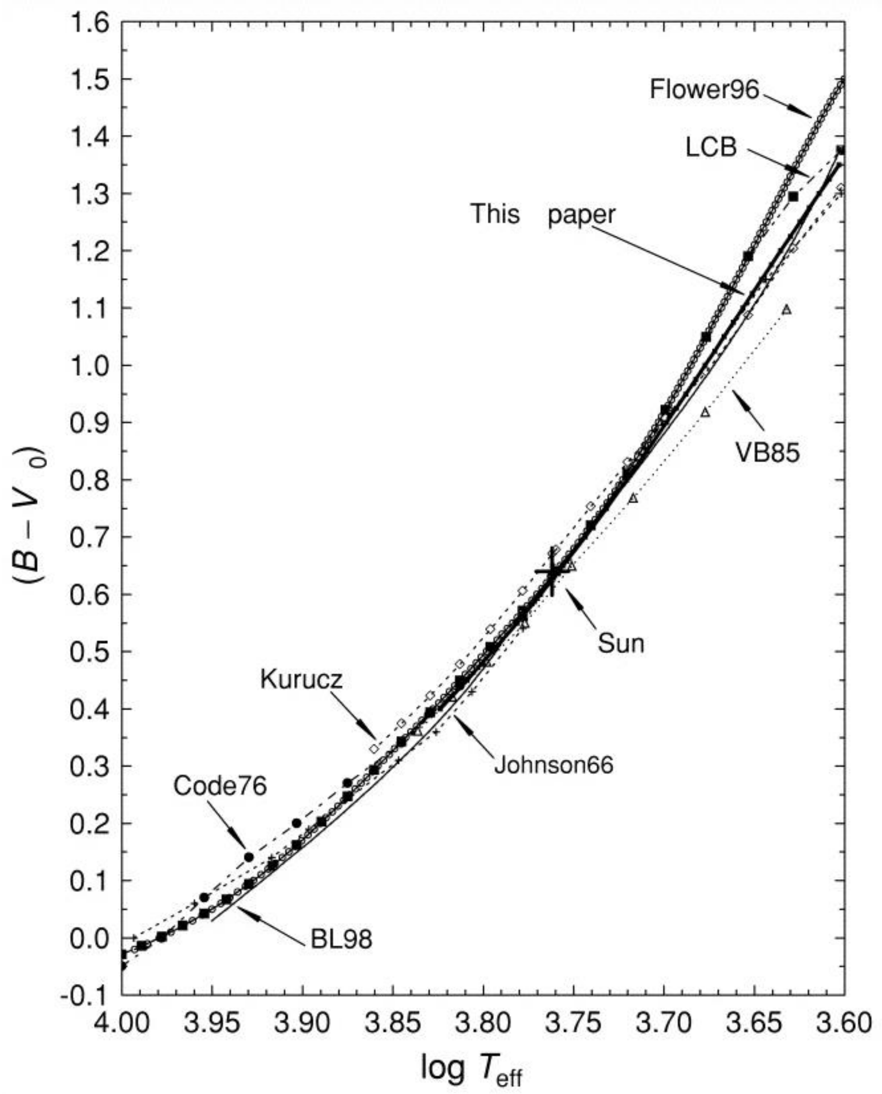
Spectral type: A
YELLOW STAR
Temperature: 5,000 K
Spectral type: G
RED STAR
Temperature: 3,000 K
Spectral type: M
Brightness of Light
250
500
750
1000
1250
1500
1750
2000
Ultraviolet
Visible light
Infrared
Wavelength (color) of Light in Nanometers



Various calibrations can be used to provide the colour relation:

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

Remember that observed

$(B\text{-}V)$ 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

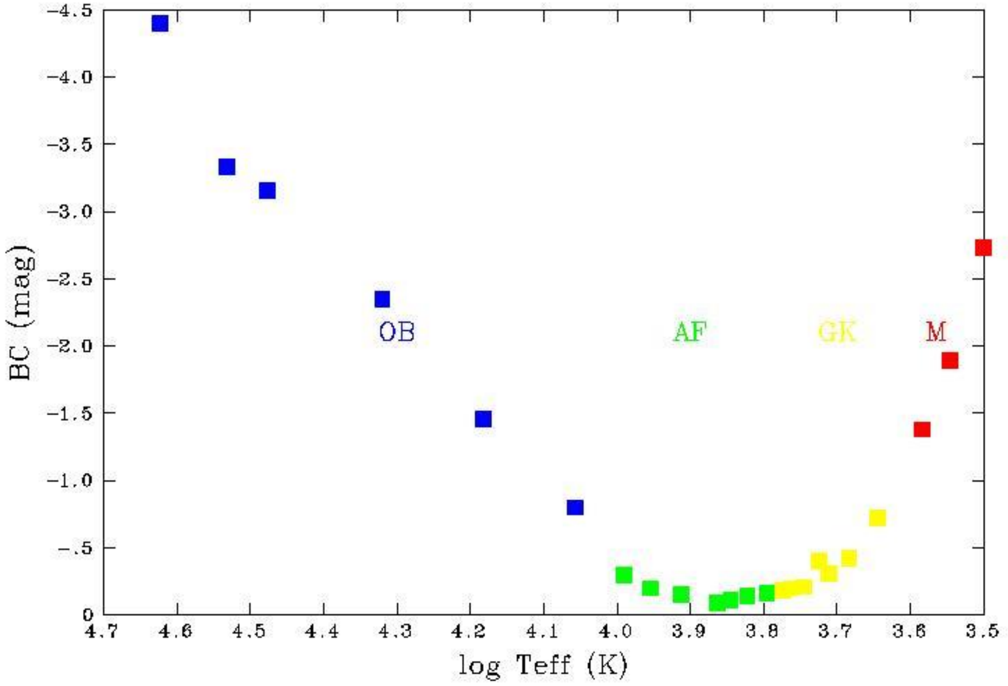
- Magnitudes are measured in some wavelength band e.g. *UBV.* To compare with theory it is more useful to determine **bolometric magnitude** – defined as absolute magnitude that would be measured by a bolometer sensitive to all wavelengths. We define the bolometric correction to be

  $BC = M_{bol} - M_v$

  Bolometric luminosity is then

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

For Main-Sequence Stars



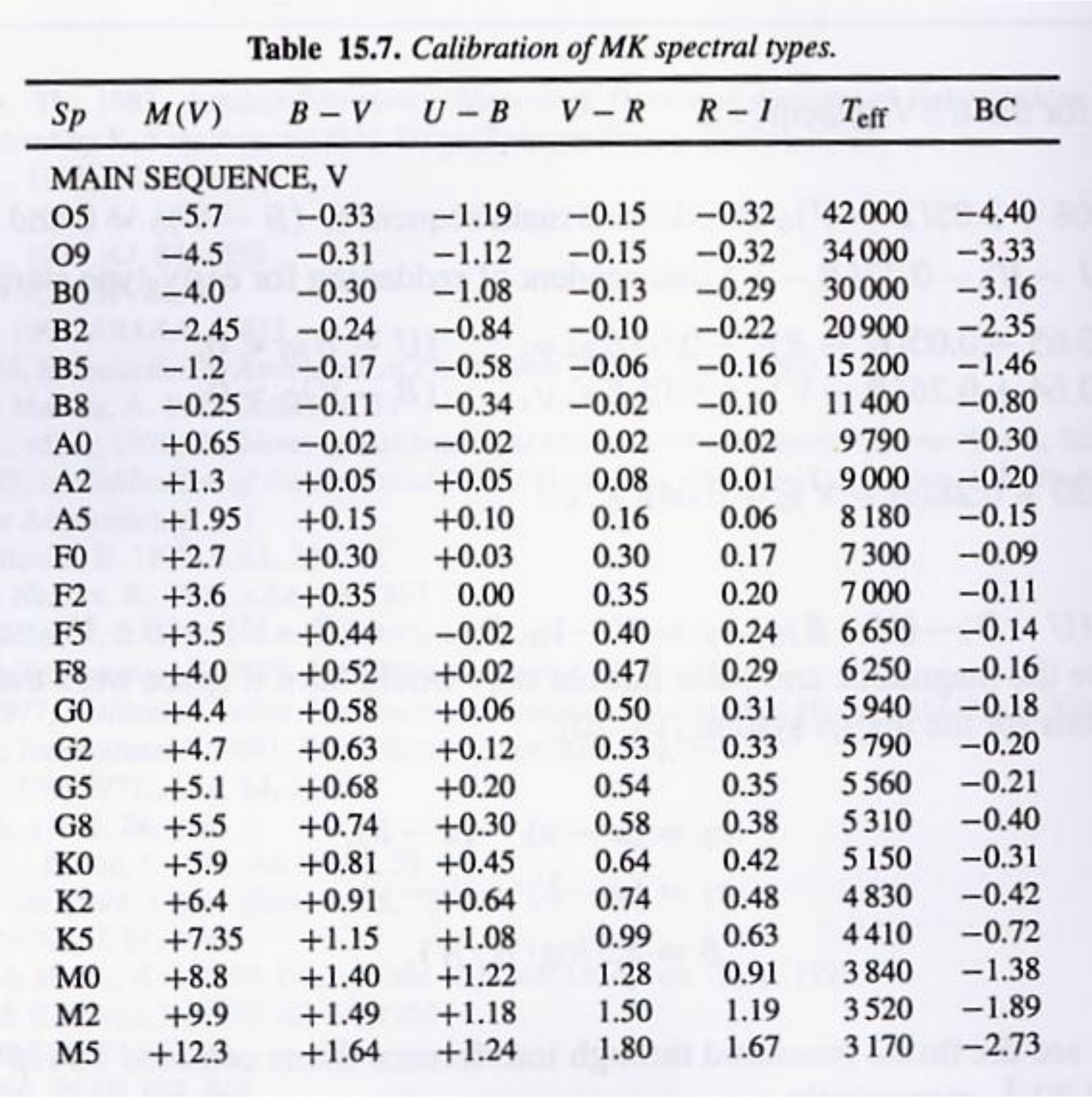


Table 15.7. *Calibration of MK spectral types.*

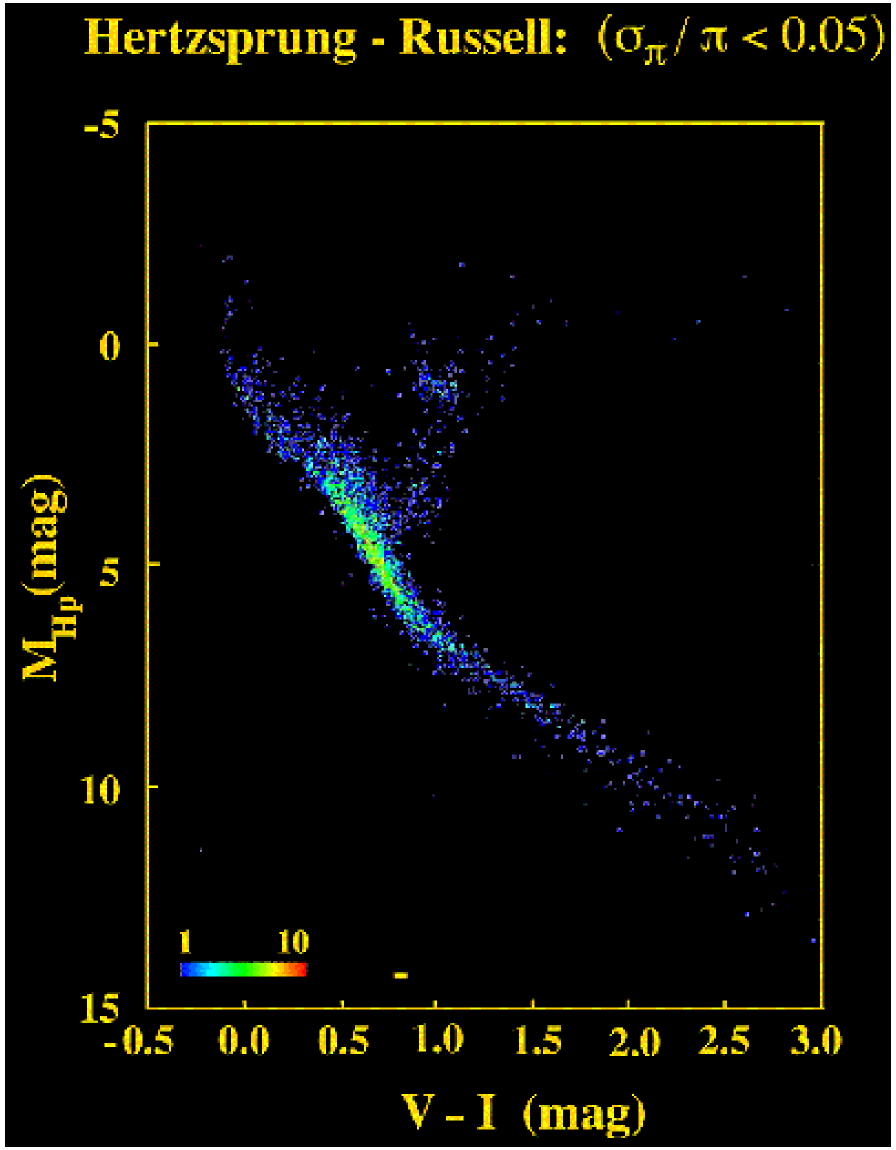
Sp	*M*(*V*)	*B* − *V*	*U* − *B*	*V* − *R*	*R* − *I*	T_{eff}	BC
MAIN SEQUENCE, V							
O5	−5.7	−0.33	−1.19	−0.15	−0.32	42 000	−4.40
O9	−4.5	−0.31	−1.12	−0.15	−0.32	34 000	−3.33
B0	−4.0	−0.30	−1.08	−0.13	−0.29	30 000	−3.16
B2	−2.45	−0.24	−0.84	−0.10	−0.22	20 900	−2.35
B5	−1.2	−0.17	−0.58	−0.06	−0.16	15 200	−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%

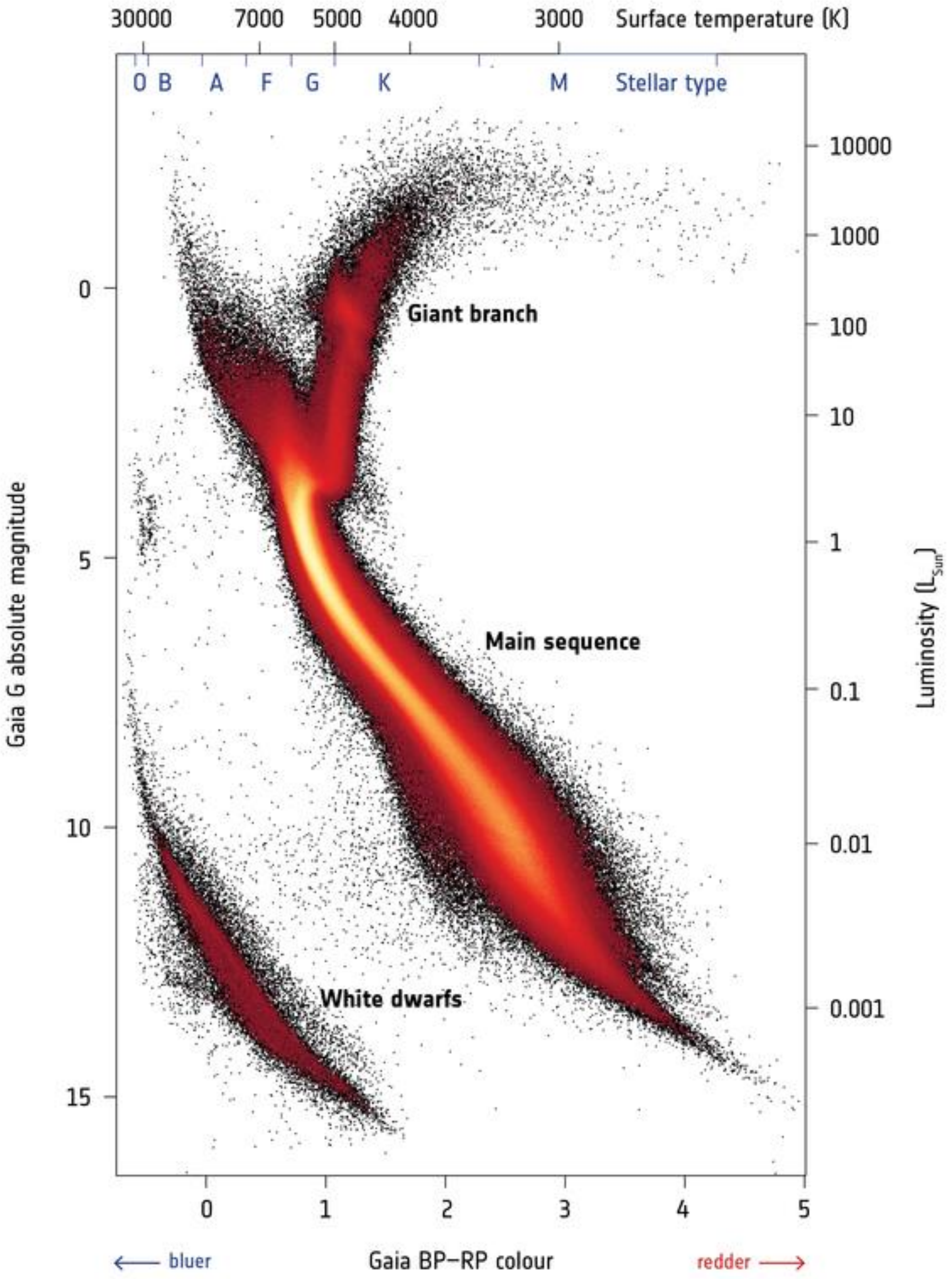


GAIA

HRD from GAIA

HR diagram for 4milions single stars from the GAIA DR3

These stars are within 1.5Kpc



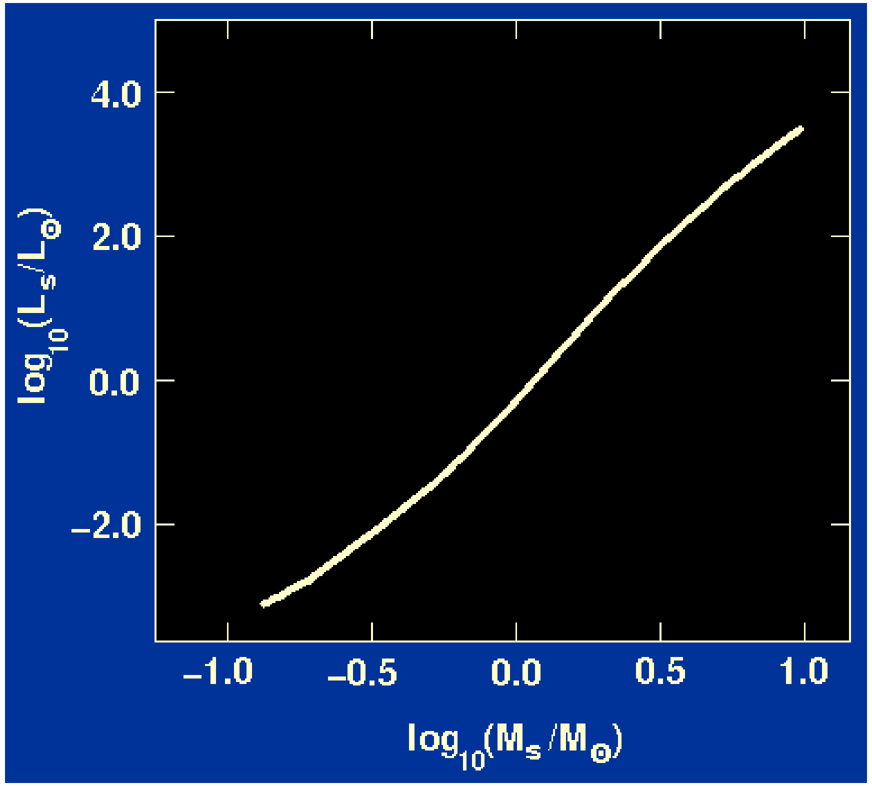
Mass-luminosity relation

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

$L \propto M^n$

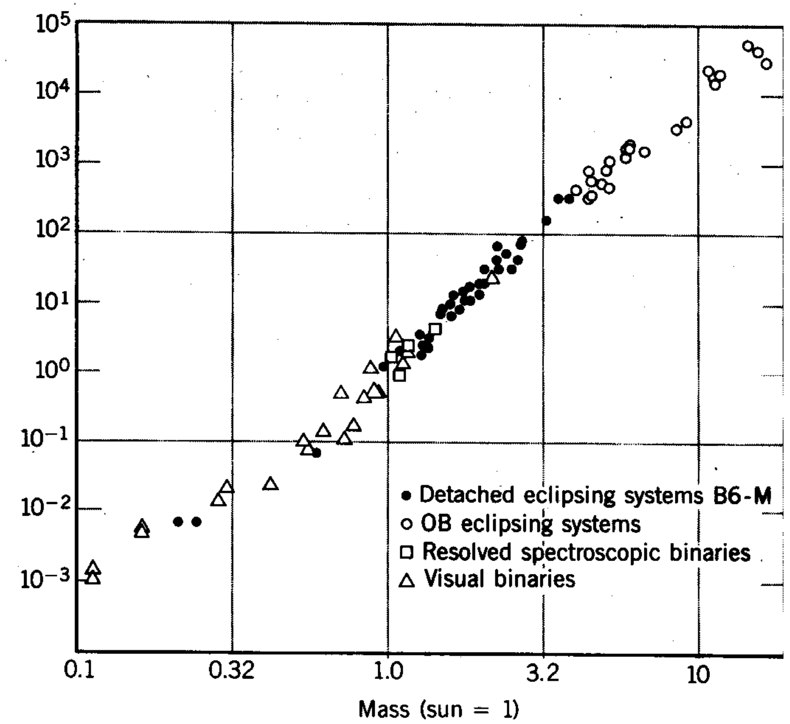
Where n=3-5. Slope changes at extremes, less steep for low and high mass stars.

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

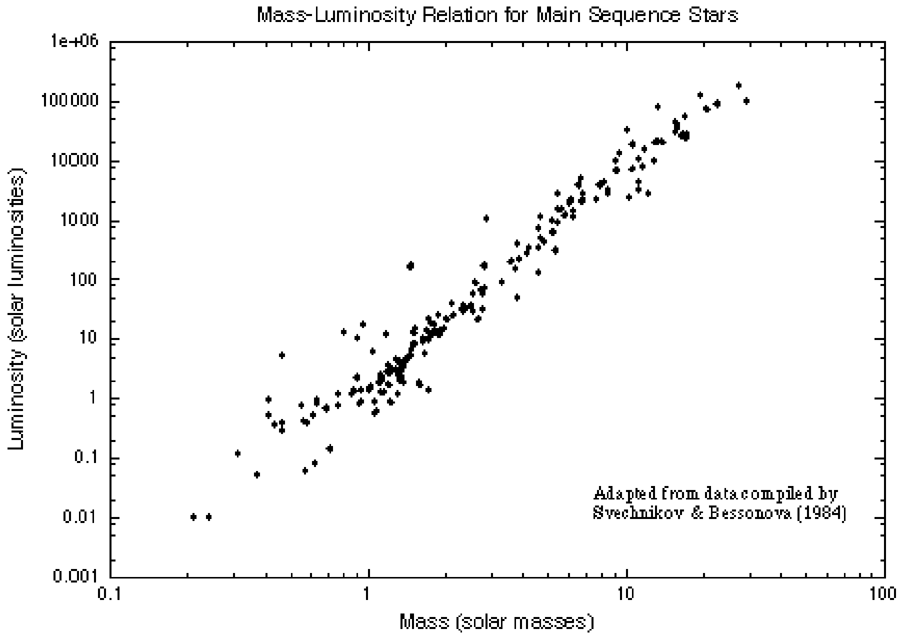


We must understand the *M-L* relation and *L*-T_e relation theoretically.

Models must reproduce observations



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



Adapted from data compiled by Svechnikov & Bessonova (1984)

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

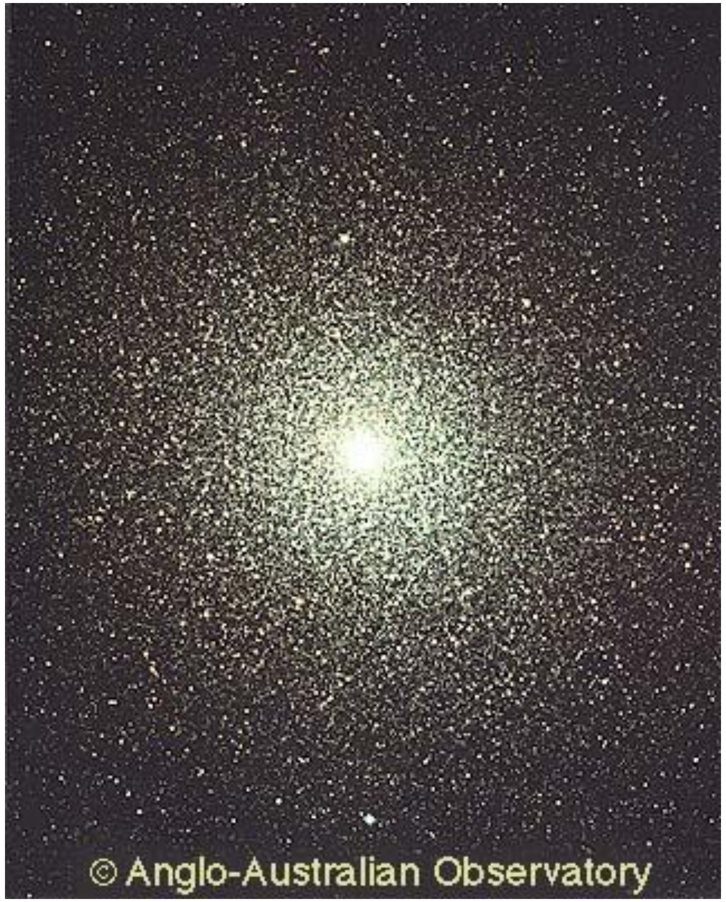
e.g. $X_{\odot} = 0.747$; $Y_{\odot} = 0.236$; $Z_{\odot} = 0.017$

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

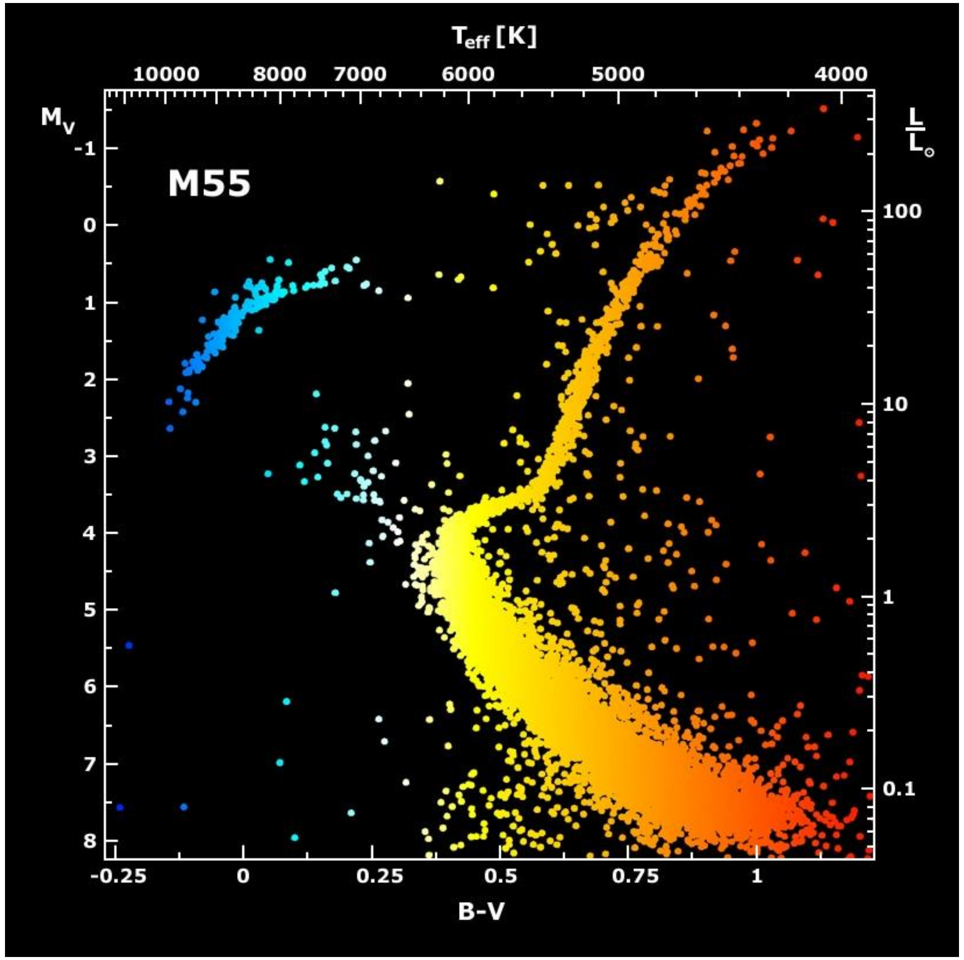
Star clusters

NGC3293 - Open cluster

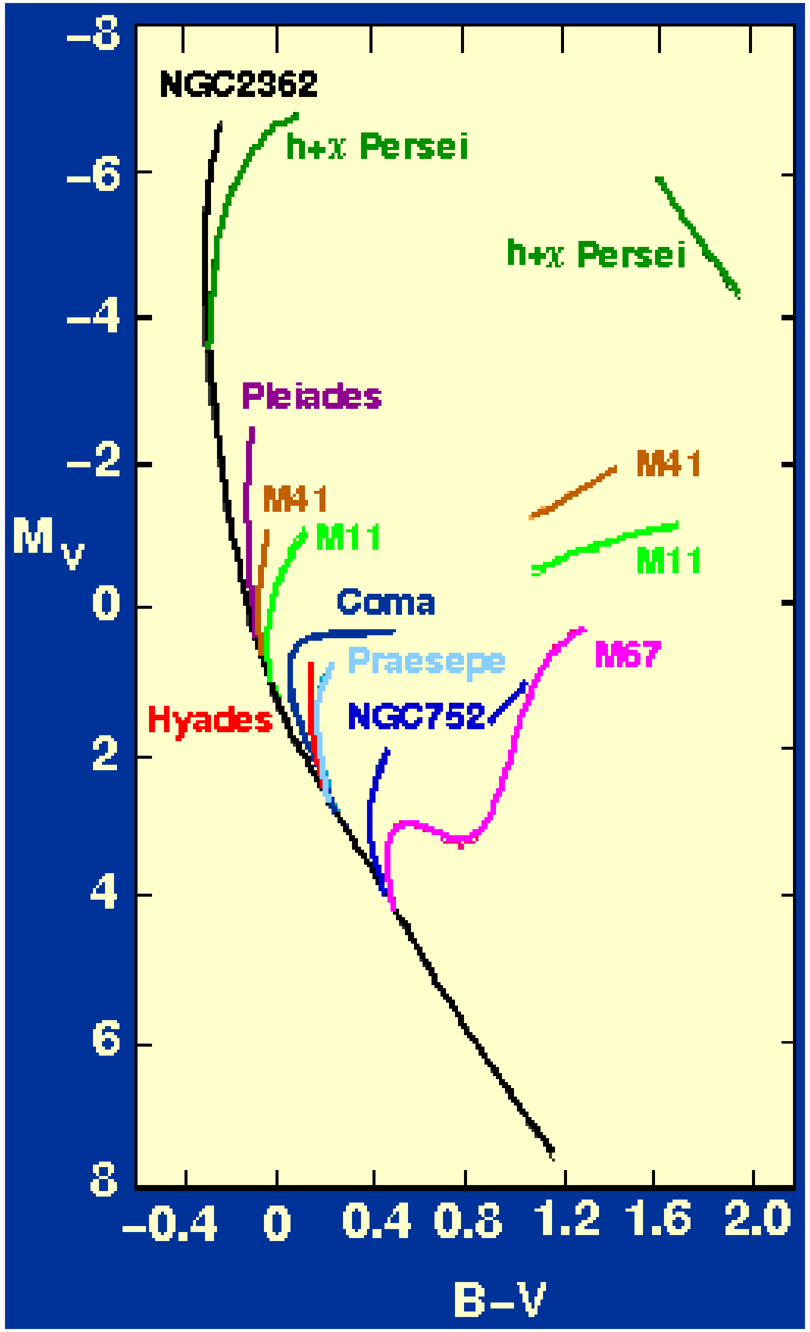


47 Tuc – Globular cluster

Globular cluster M3 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