STARS - S03

Wladimir (Wlad) Lyra
Brian Levine

AMNH After-School Program

AMERICAN MUSEUM OF NATURAL HISTORY

From last class

Logarithms convert multiplications into additions
Useful when dealing with numbers that span a large range (many orders of magnitude)

$$\boxed{\log xy = \log x + \log y} \iff 10^n 10^m = 10^{n+m}$$

or 100 in brightness

with the square of the distance

Parallax: apparent movement of a star as the Earth moves around its orbit
Parsec: distance where the parallax angle is one arcsec = 3.26 ly

Absolute magnitude: Magnitude from the standard distance of 10 parsecs

Black body (thermal) radiation: a property of nature, every body with a temperature emits thermal radiation.

Steffan-Boltzmann law: thermal radiation is a strong function of temperature

Wien's law: peak wavelength is uniquely determined by temperature

Luminosity is a function of radius and a strong function of temperature

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Magnitude scale: A reverse scale
Logarithmic: 5 magnitudes mean a factor 100 in brightness

Physical brightness is called Flux, falls with the square of the dista

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Small (or negative) - Bright

Absolute magn ndard distance of 10

Big magnitude – Dim

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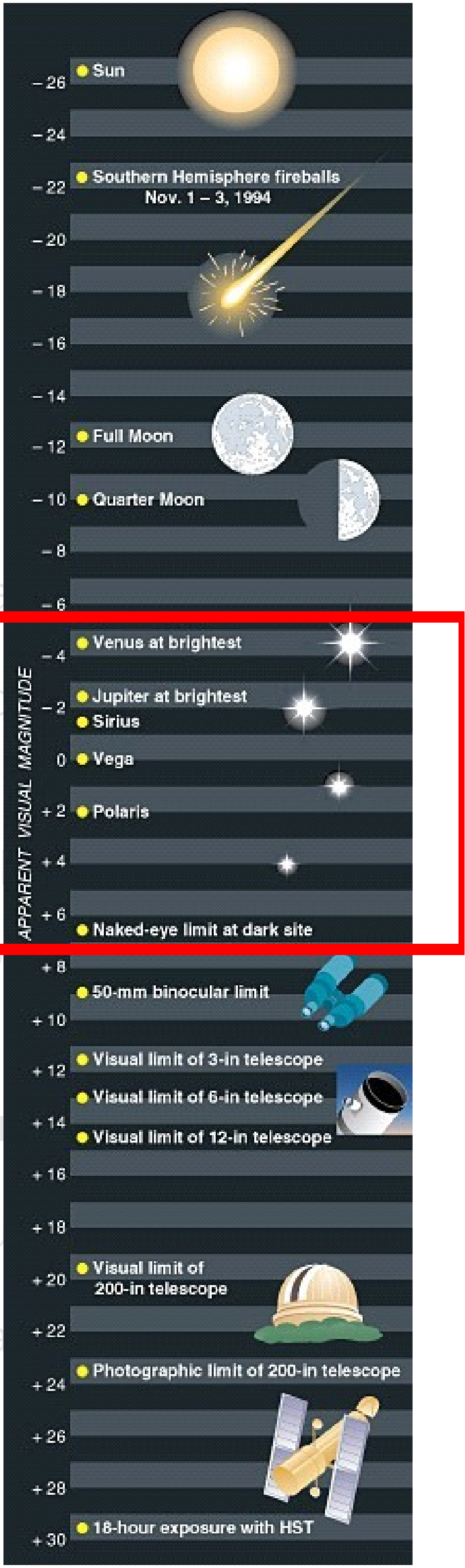

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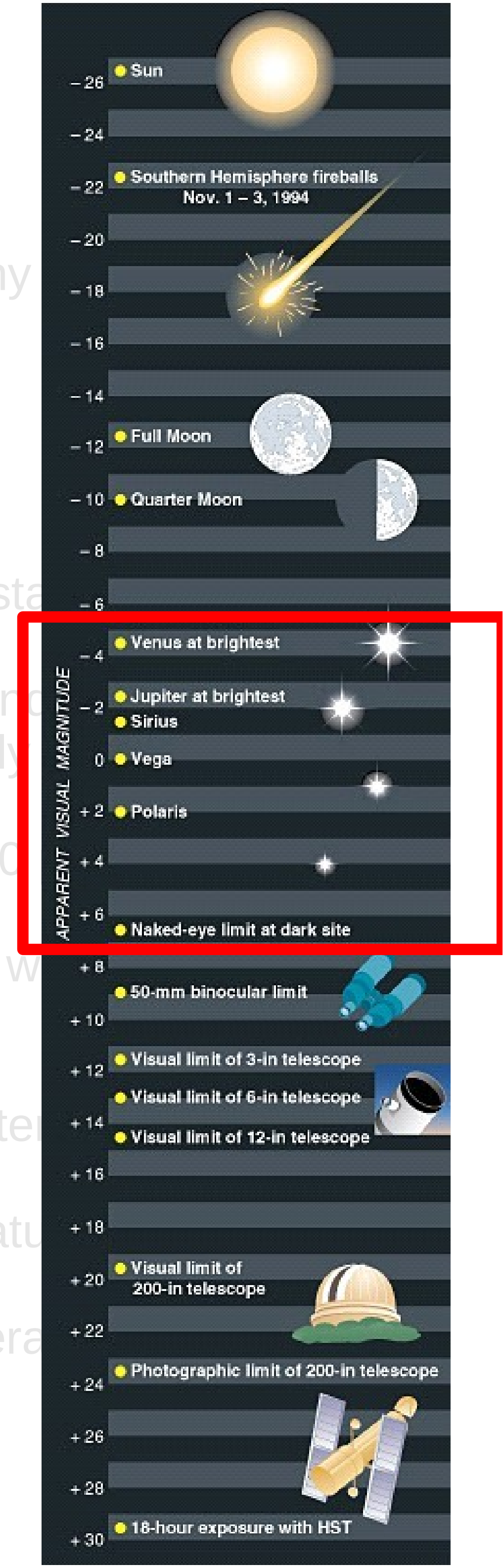
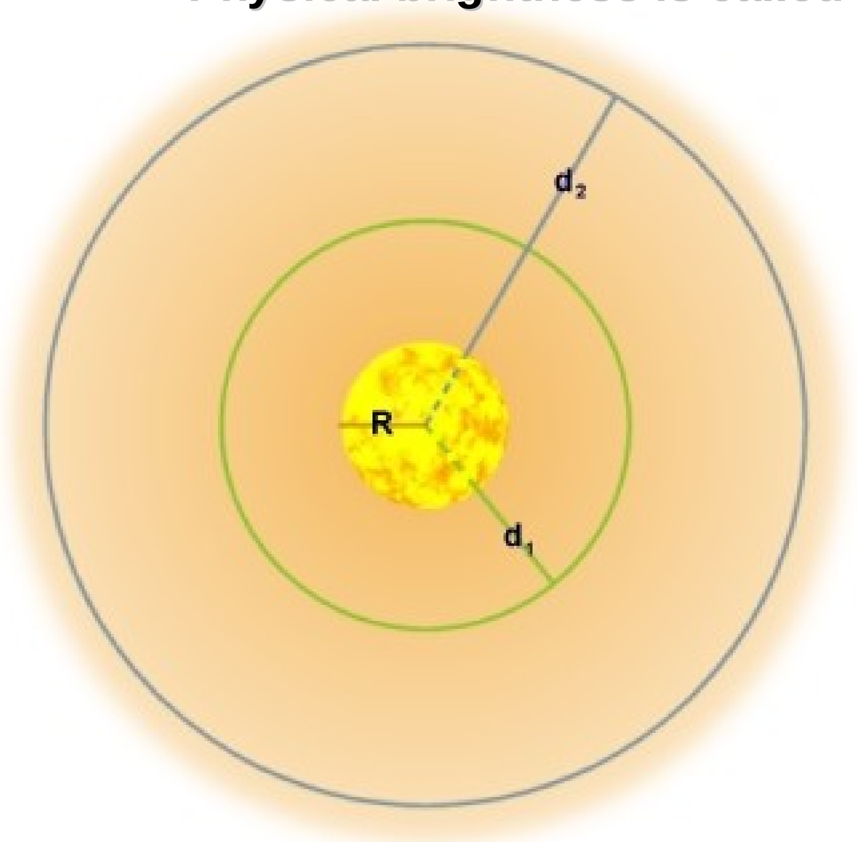


From last class

$$\text{Flux} = \frac{\text{Energy}}{\text{Time * Area}}$$

Physical brightness is called Flux, falls with the square of the distance



$$\boxed{F(r) \propto 1/r^2}$$

From last class

Parallax: apparent movement of a star as the Earth moves around its orbit

Parsec: distance where the parallax angle is one arcsec = 3.26 ly

Logarithms convert
Useful when dealing
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Magnitude scale: A
Logarithmic: 5 magn

Physical brightness

Parallax: apparent
Parsec: distance w

Absolute magnitude

Black body (therma
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Steffan-Boltzmann l

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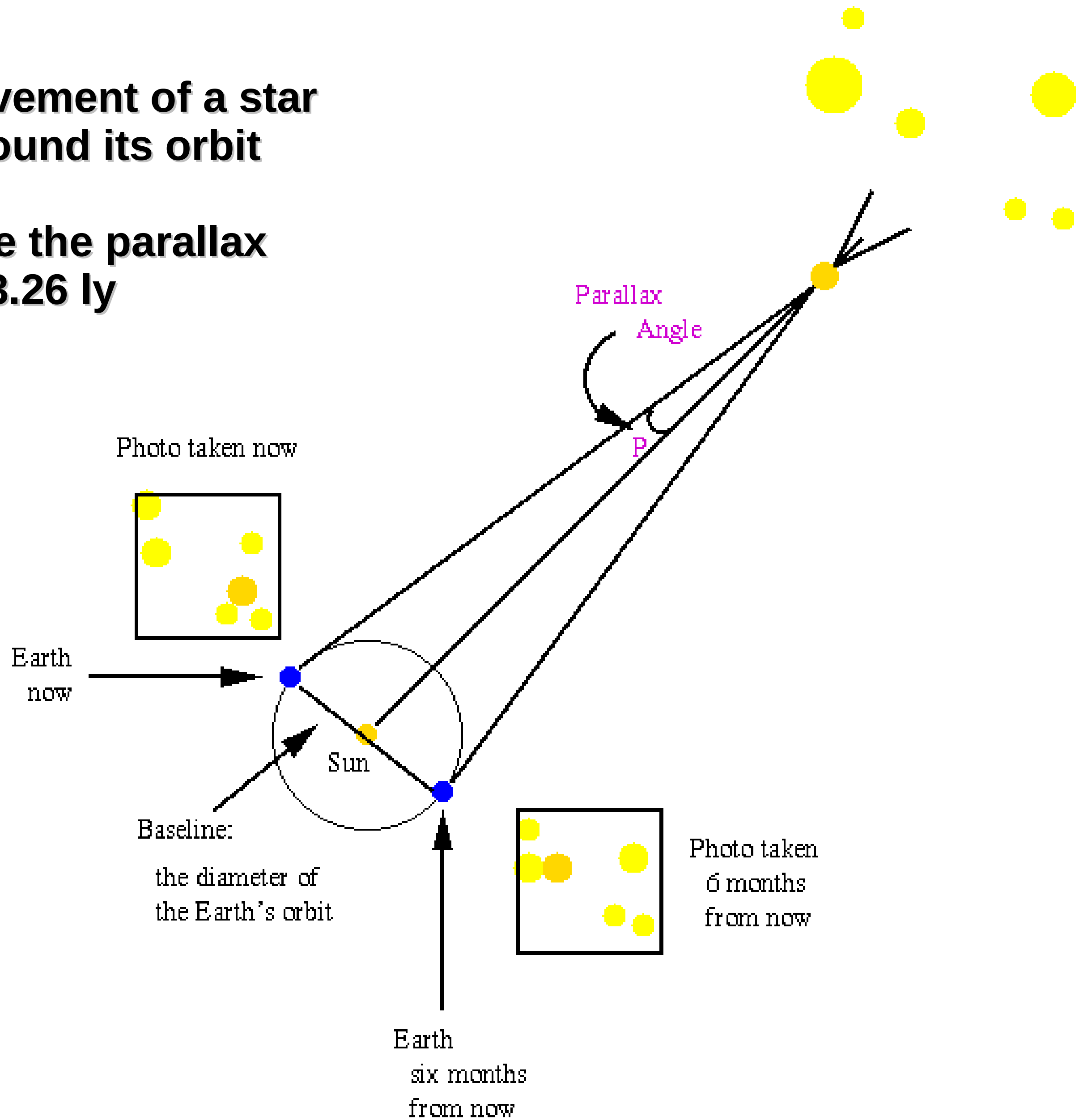
Luminosity is a func



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Apparent magnitude

The magnitude of a star as we see it.

Absolute magnitude

The magnitude a star would have if placed 10 pc away

Magnitude scale: A reverse scale
Logarithmic: 5 magnitudes mean a factor 100 in brightness

$$m = -2.5\log\left(\frac{L}{4\pi d^2}\right) + C$$

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Absolute magnitude: Magnitude from the standard distance of 10 parsecs

Black body (thermal) radiation: a property of nature, every body with a
temperature emit

$$d(pc) = 10^{0.2(m-M)+1}$$

Steffan-Boltzman ... ction of temperature

Wien's law: peak wav ... d by temperature

$$\mu = m - M$$

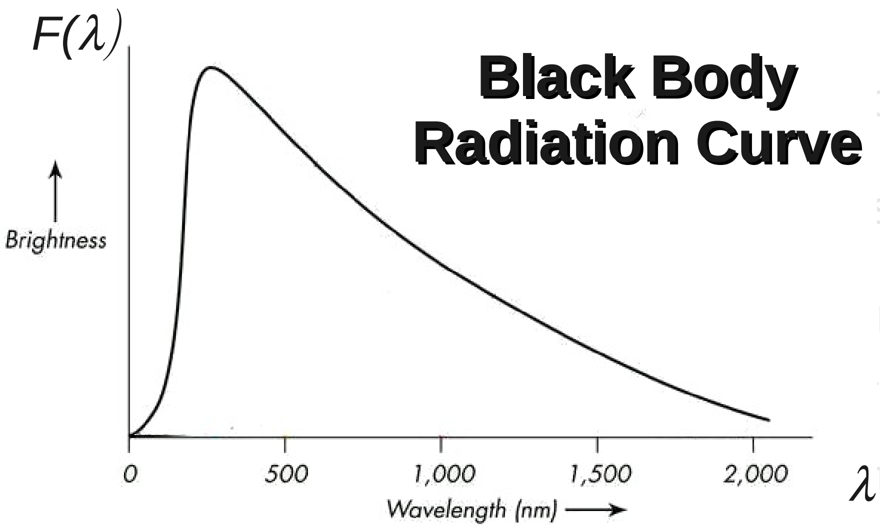
Distance modulus

Luminosity is a functi ... ion of temperature

From last class

) additions
at span a large range (many orders of

ctor 100 in brightness



$$\boxed{I(\nu) = \frac{2h\nu^2}{c^2}\frac{h\nu}{e^{h\nu/kT}-1}}$$

the standard distance of 10 parsecs

Black body (thermal) radiation: a property of nature, every body with a non-zero temperature emits thermal radiation.

Steffan-Boltzmann law: thermal radiation is a strong function of temperature

Wien's law: peak wavelength is uniquely determined by temperature

Luminosity is a function of radius and a strong function of temperature

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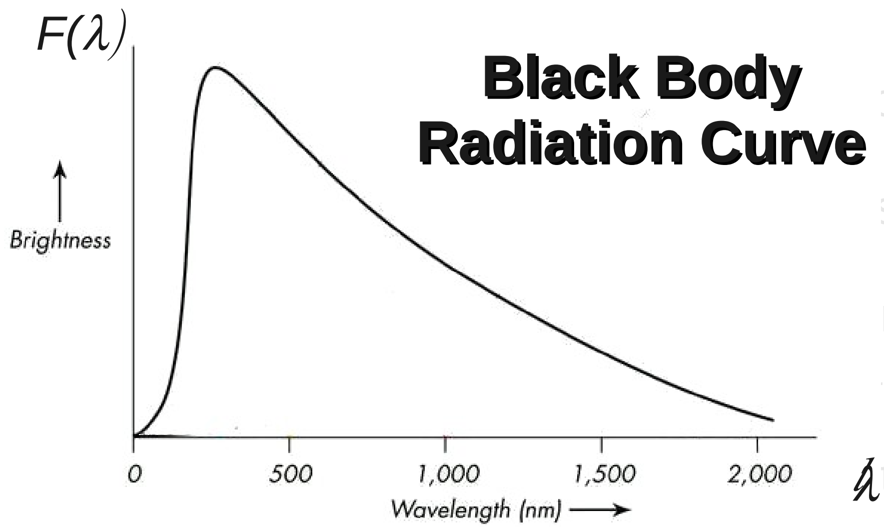

ctor 10

$$\boxed{F_R = \sigma T^4}$$

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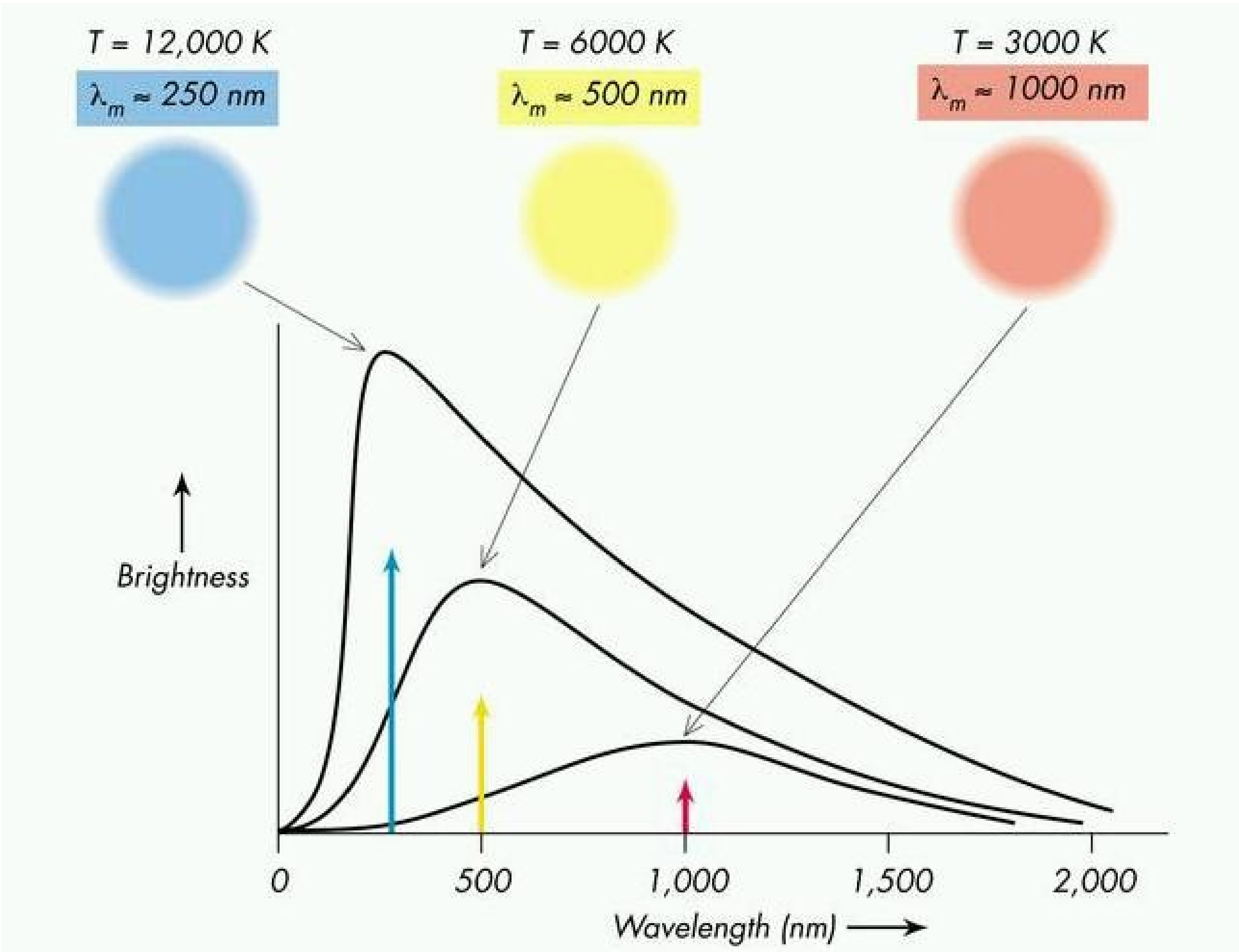
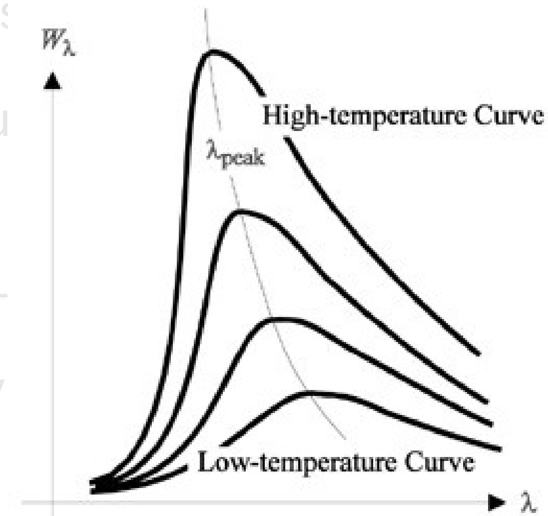


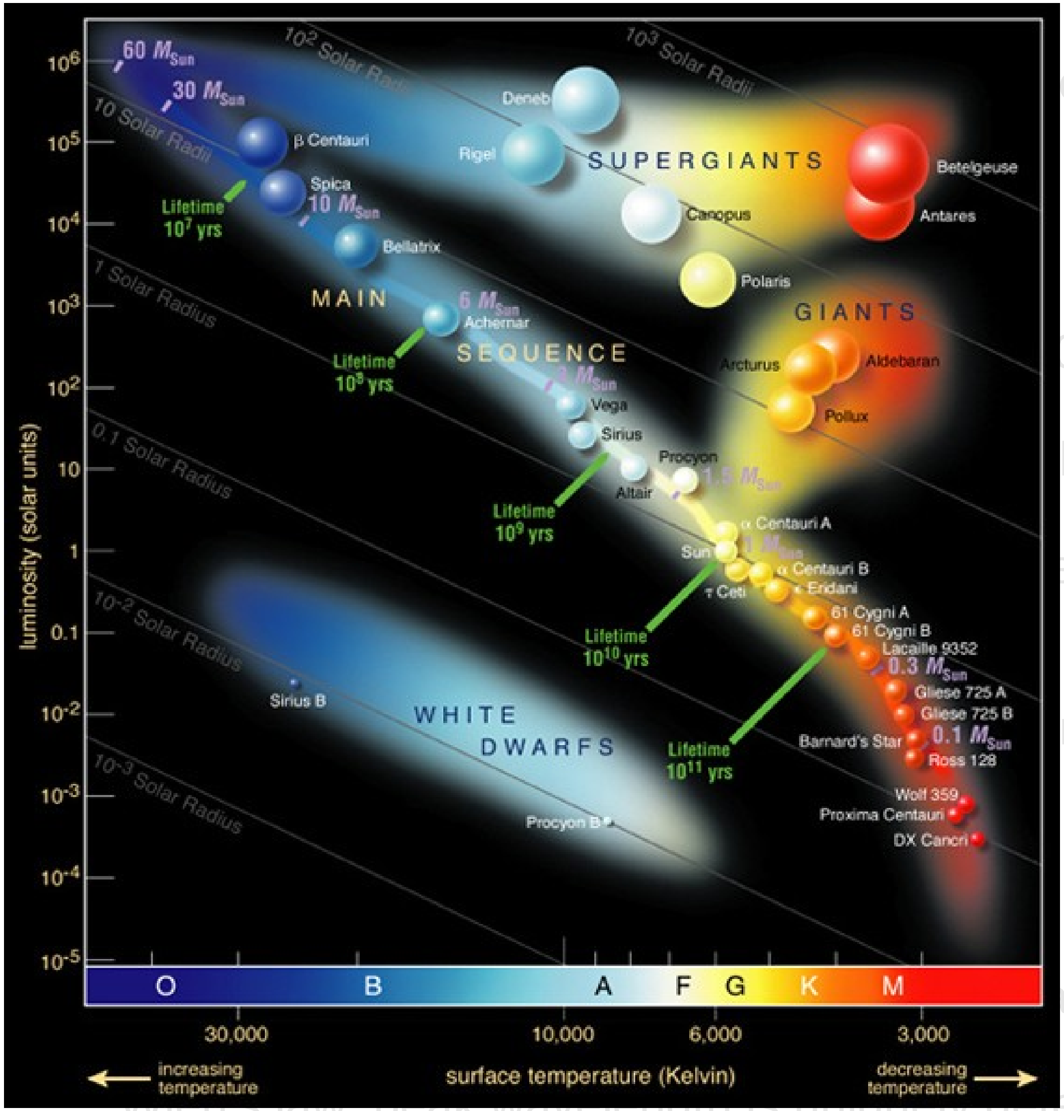


Wien's displacement law: peak wavelength is uniquely determined by temperature

Luminosity is a function of radius and a strong function of temperature

$$\lambda_{max} T = const = 2.898 \times 10^{-3}\, m\, K$$

From last class



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

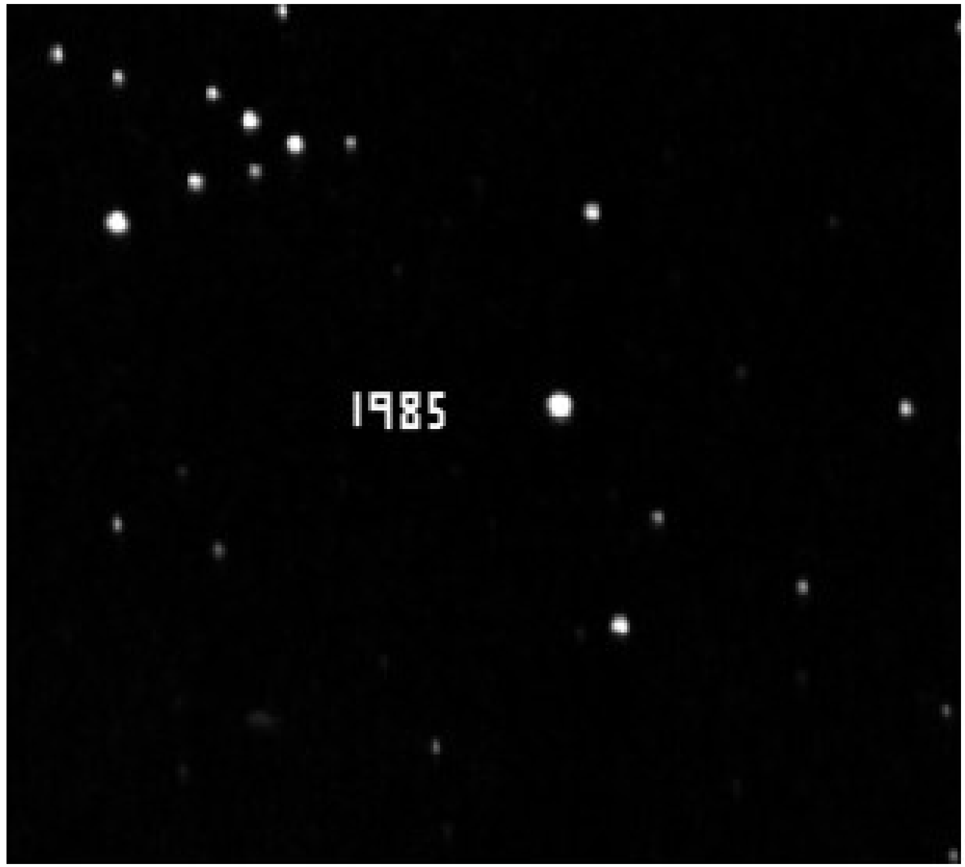
$$\lambda_{max} T = const = 2.898 \times 10^{-3}\, m\, K$$

Luminosity is a function of radius and a strong function of temperature
The wavelength of peak brightness goes bluer as the temperature rises

Outline

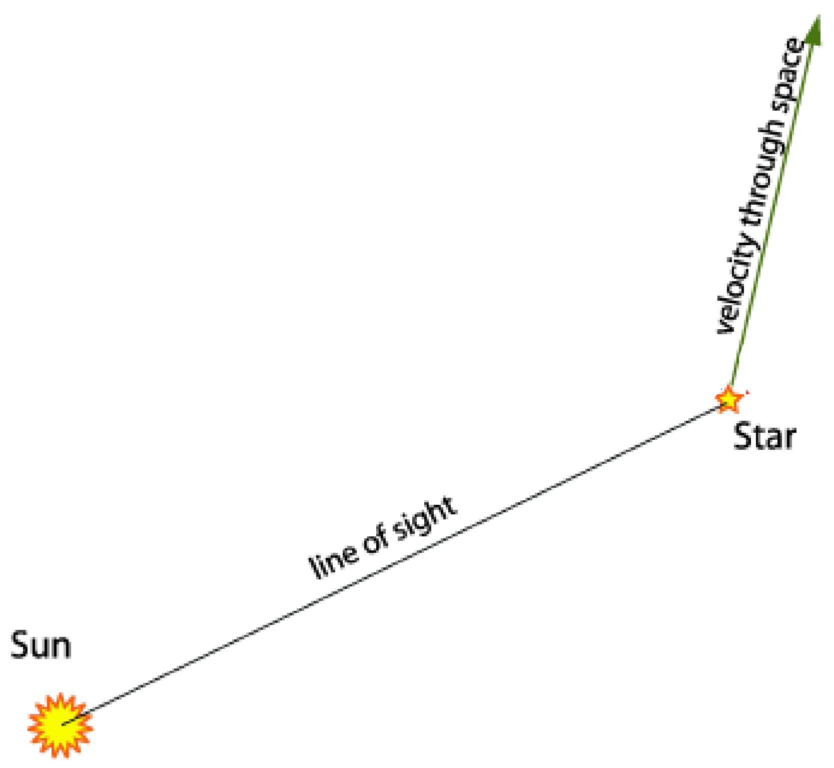
- **Proper motion**
- **Stellar distances and the Distance Scale**
    - Trigonometric Parallax
    - Main Sequence fitting
    - Eclipsing Binaries
    - Standard Candles
        - RR Lyrae
        - Cepheids
        - Supernovae Ia
- **Spectroscopy**
    - The three laws of Kirchhoff
    - Hydrogen lines
    - Chemical abundances
- **Photometry**
    - UBVRI system of magnitudes
    - Photometric colors
    - Color-magnitude diagram

Stars move through space

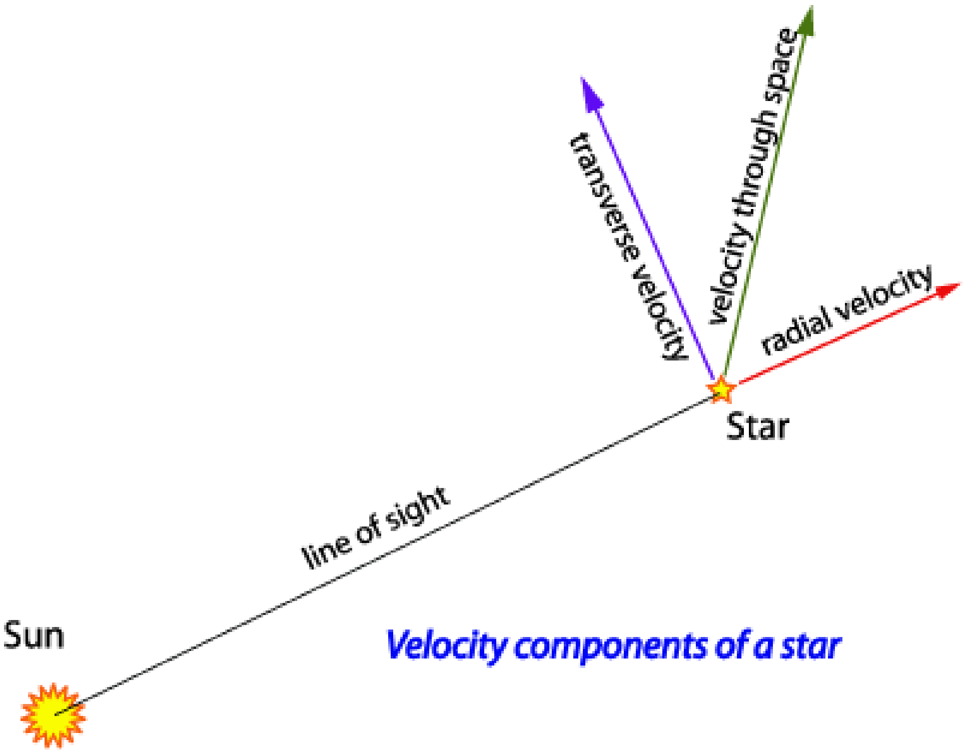


Barnard's Star

Cool, but how do we measure that?

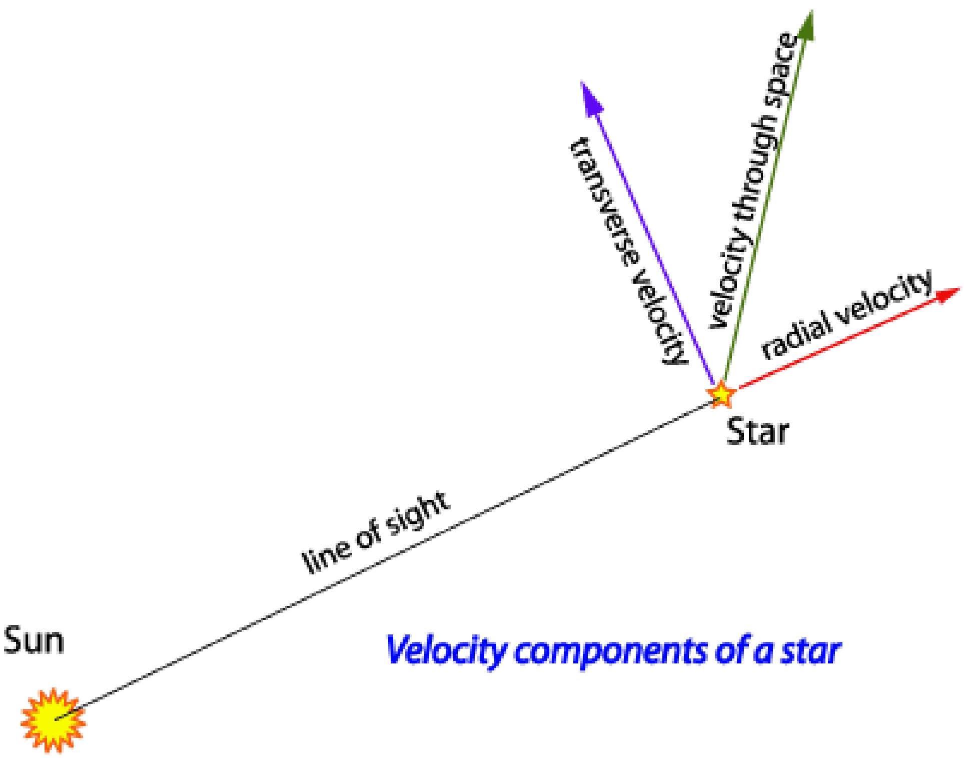


Stellar velocity components



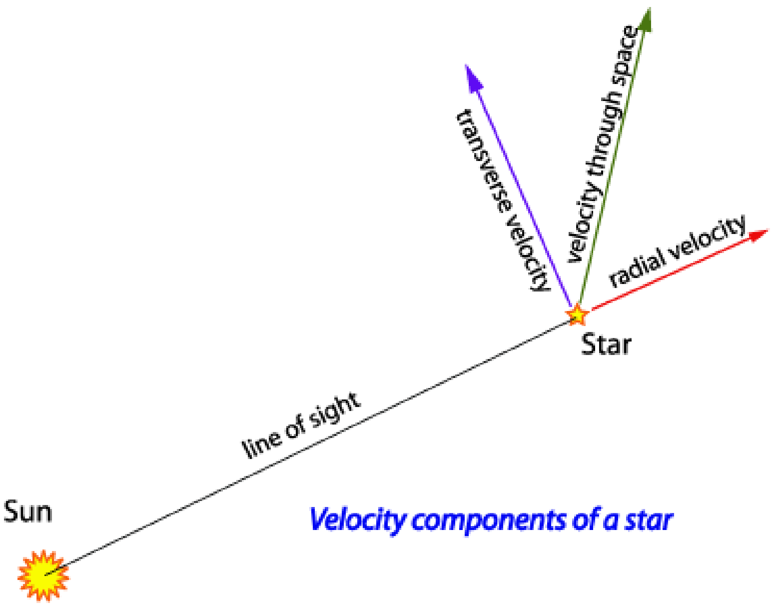
Velocity components of a star

Stellar velocity components



We see the ***transverse velocity*** as a star's "***proper motion***", which changes its position in the sky.

Stellar Motions

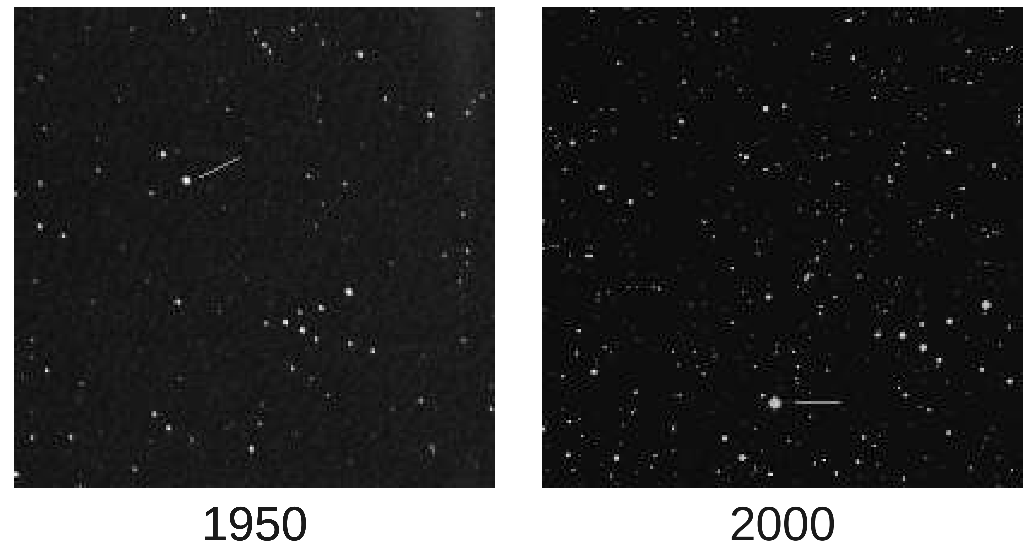


Velocity components of a star

***Proper motion** is measured in* ***arcsec per year**.*

Typical proper motion: 0.1 "/yr

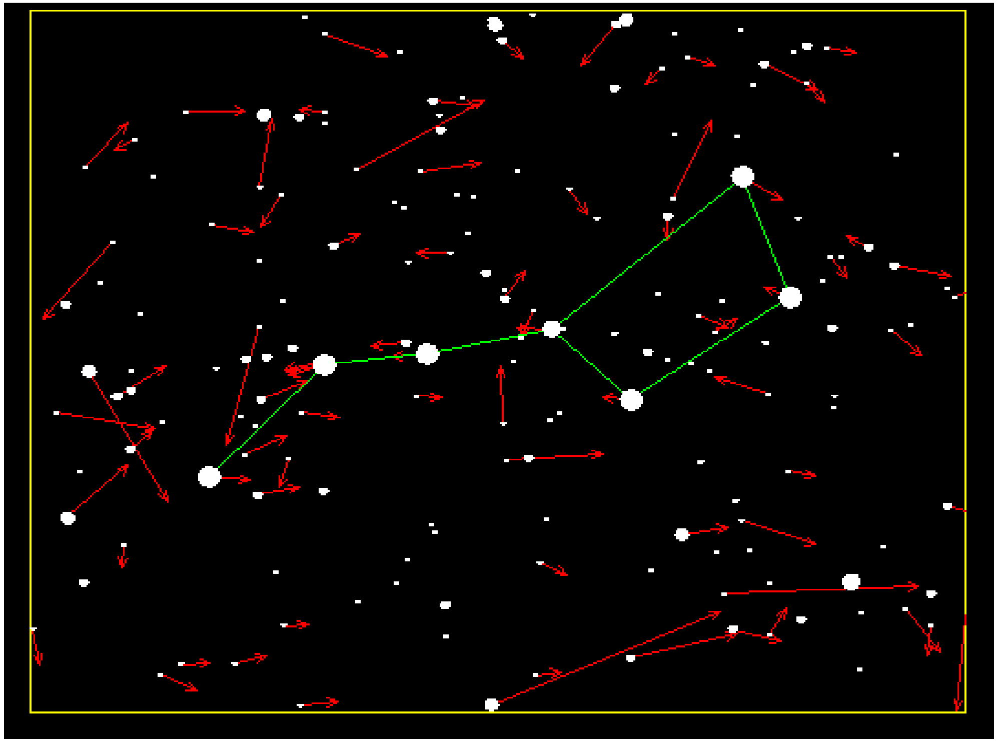
Barnard's star



Largest proper motion - **10.3 "/yr**
(crosses half the moon in a human lifetime)

Stellar Motions

Proper motions of stars at the vicinity of the Big Dipper



Constellations change over time

Stellar Motions

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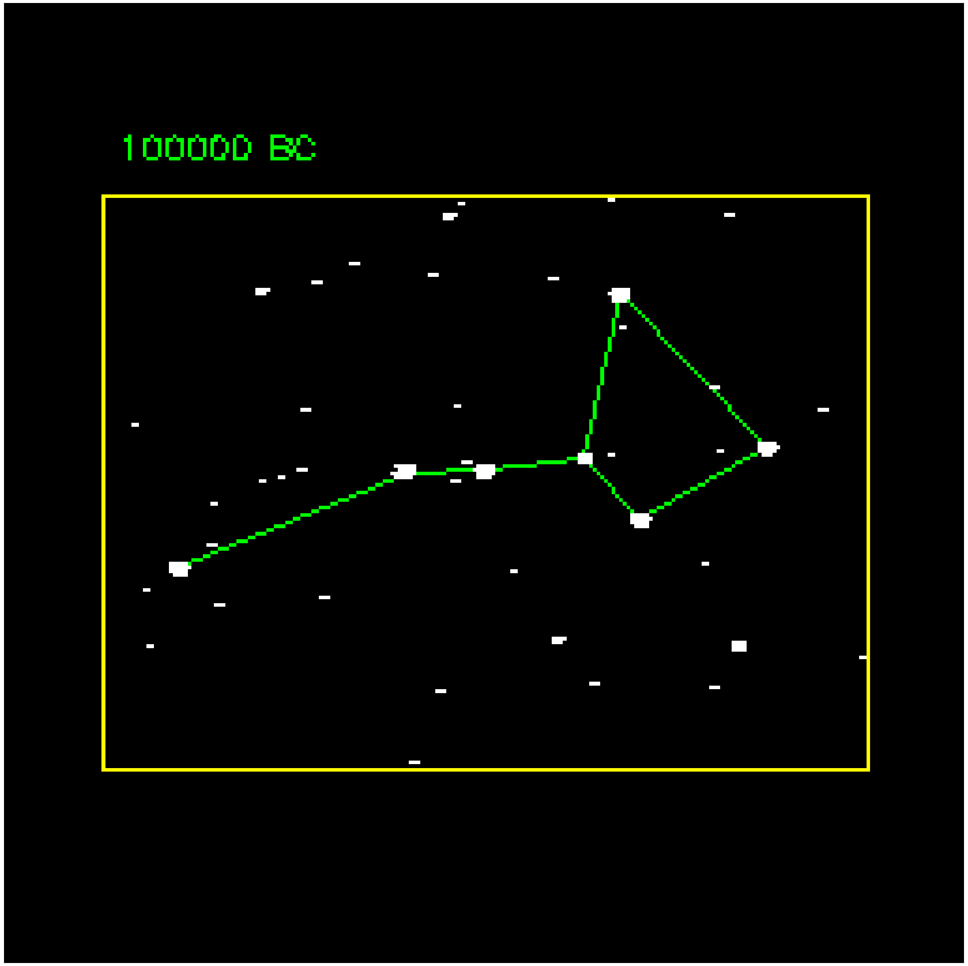
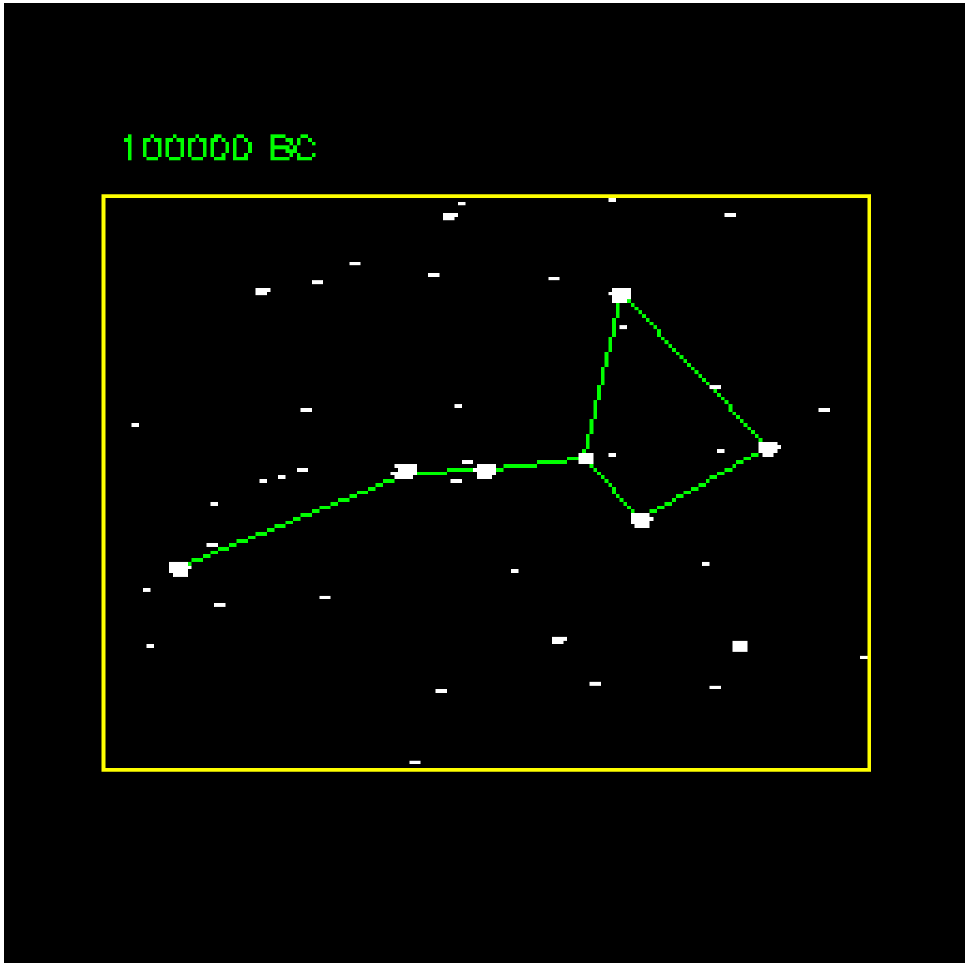


Stellar Motions

Constellations change over time



Stellar Distances

D=10 pc

Apparent magnitude

The magnitude of a star as we see it.

$$m = -2.5 \log\left(\frac{L}{4\pi d^2}\right) + C$$

Absolute magnitude

The magnitude a star would have if placed 10 pc away

$$M = -2.5 \log\left(\frac{L}{4\pi D^2}\right) + C$$

$$m - M = 5 \log d - 5$$

$$d(pc) = 10^{0.2(m-M)+1}$$

Absolute Magnitude $\Longleftrightarrow$ **Distance**

If only it was that simple...

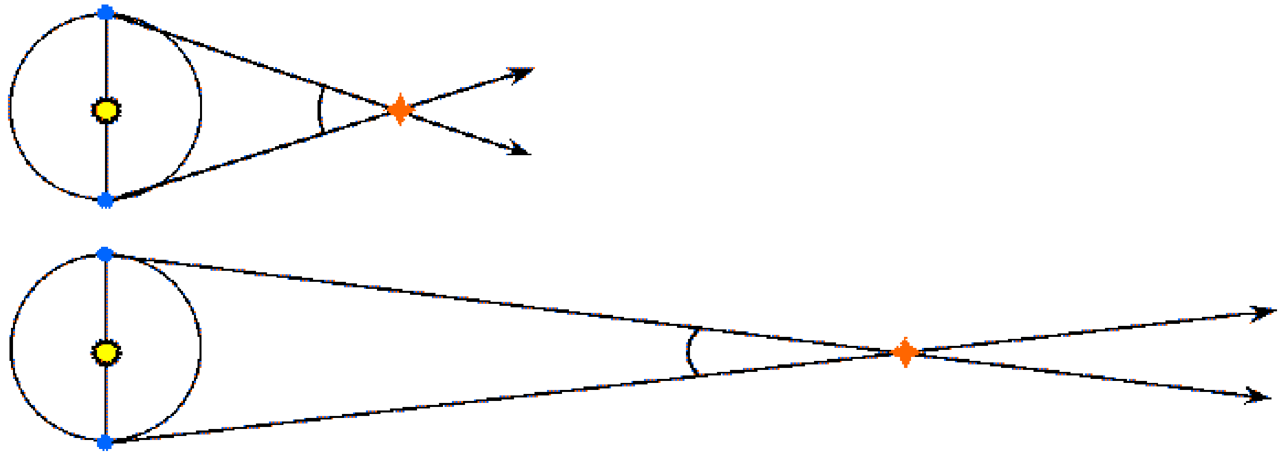
If only it was that simple...

In practice, ***distances*** and ***luminosities*** are among the ***hardest quantities to measure*** in Astronomy...

Stellar Distances

Heliocentric (trigonometric) parallax

Best method, but gets increasingly harder as distance increases (p = 1/*d*)



Largest parallax – Proxima Centauri (0.78")

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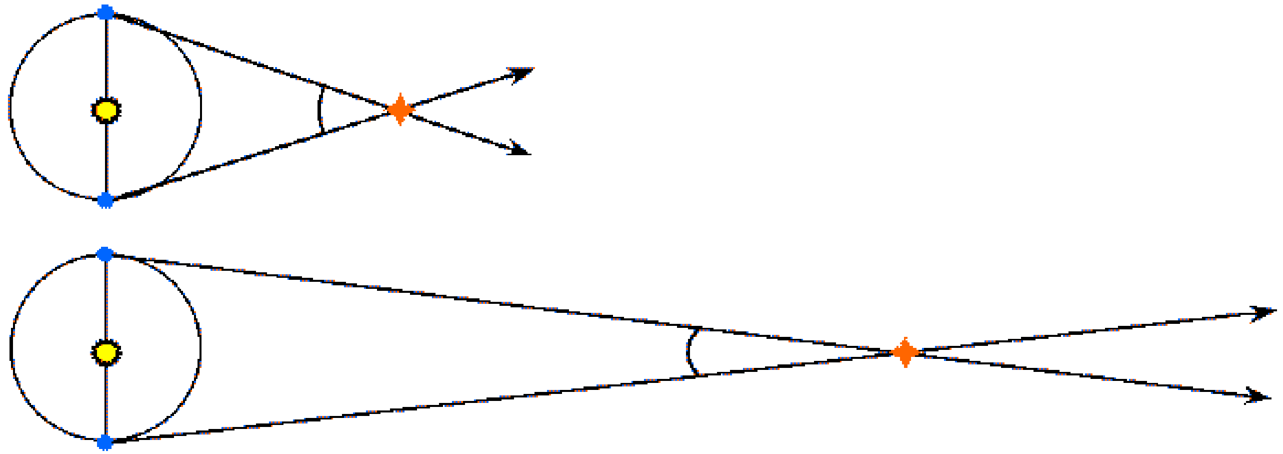

Largest parallax – Proxima Centauri (0.78")

2 cm seen from 5 km away
(a dime seen from one end of the Central Park to the other)

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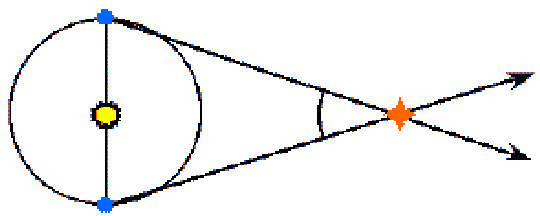

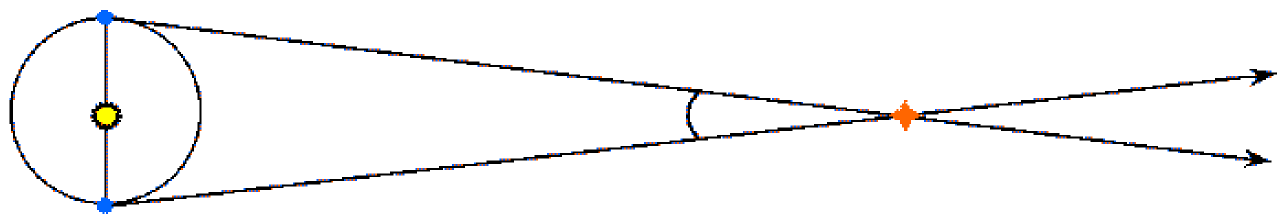

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Definitely doable!

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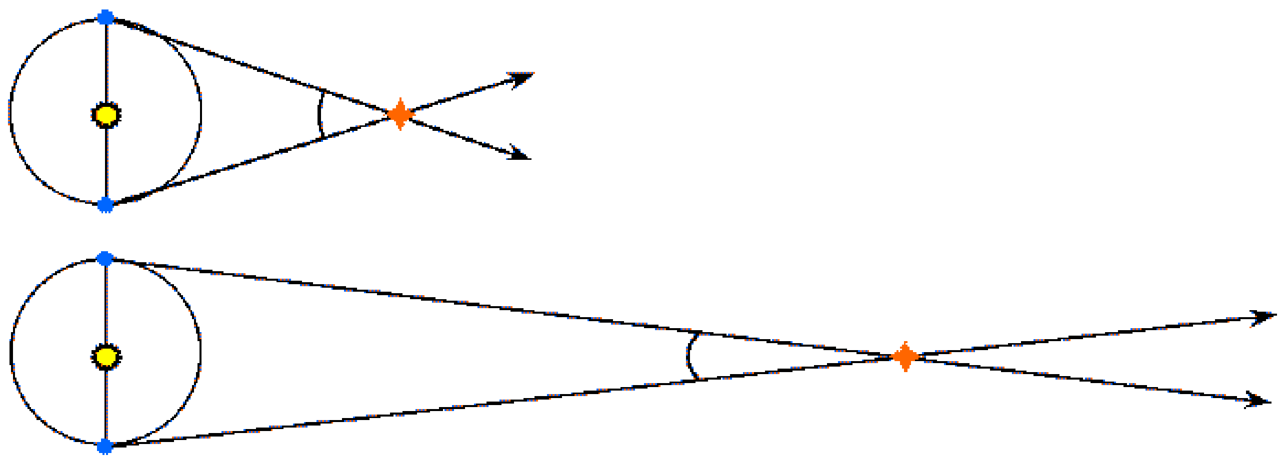

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The **limit** is ***one miliarcsecond***, or **1000 pc** of distance.

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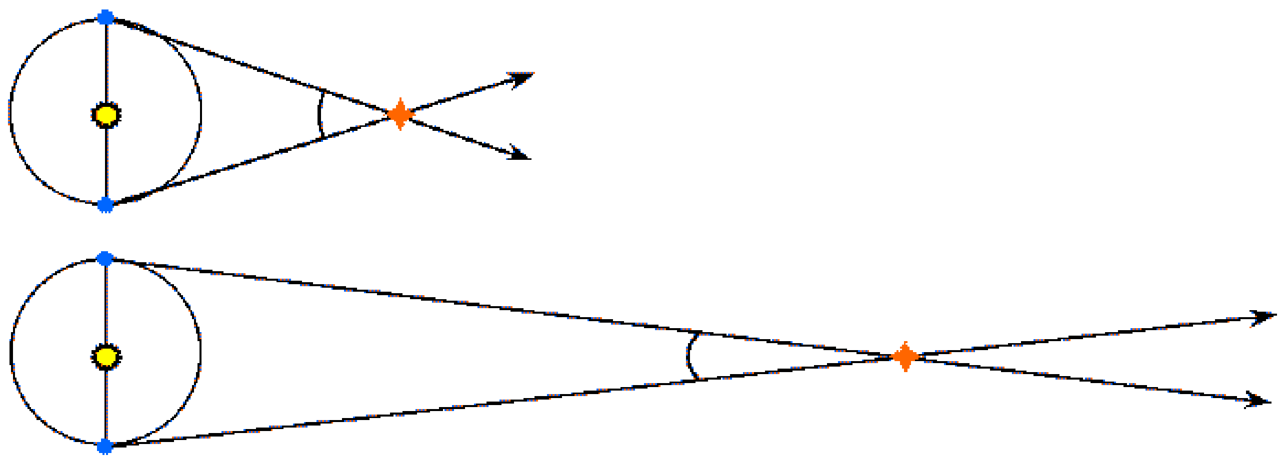


Largest parallax – Proxima Centauri (0.78")

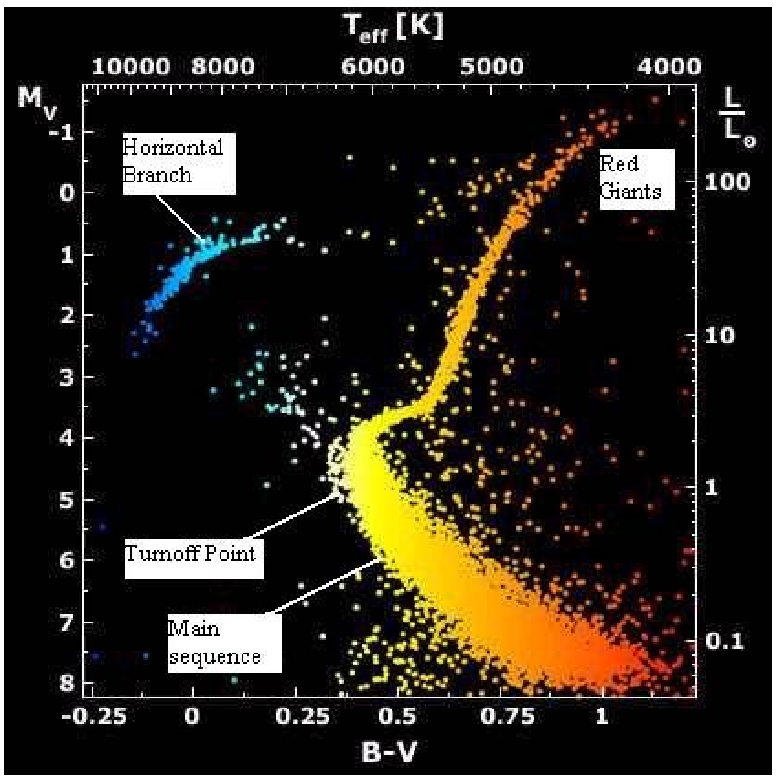
2 cm seen from 5 km away
(a dime seen from one end of the Central Park to the other)
Definitely doable!

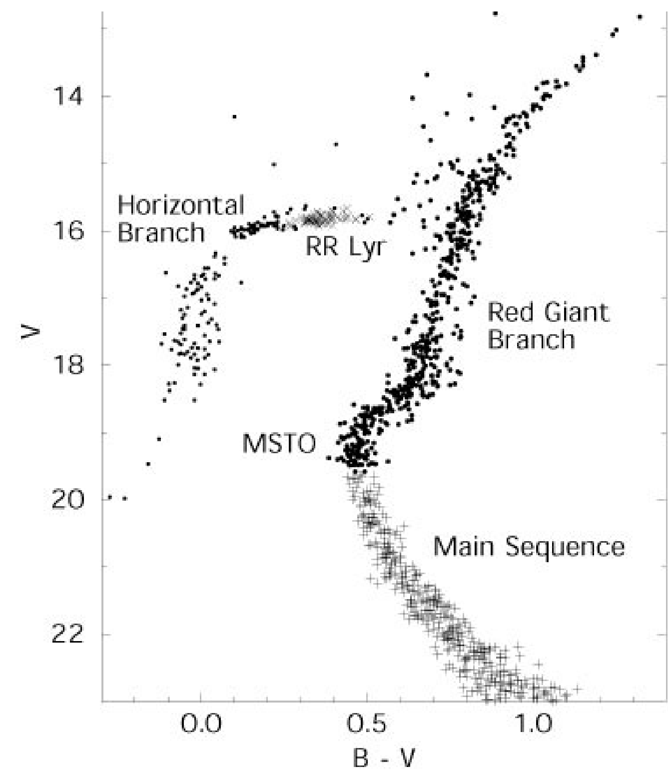
The **limit** is ***one miliarcsecond***, or **1000 pc** of distance.
(a dime in New York seen from California)

Stellar Distances

Main Sequence (HR Diagram) fitting

We know the absolute luminosity of the main sequence





Calibrated (or from model)

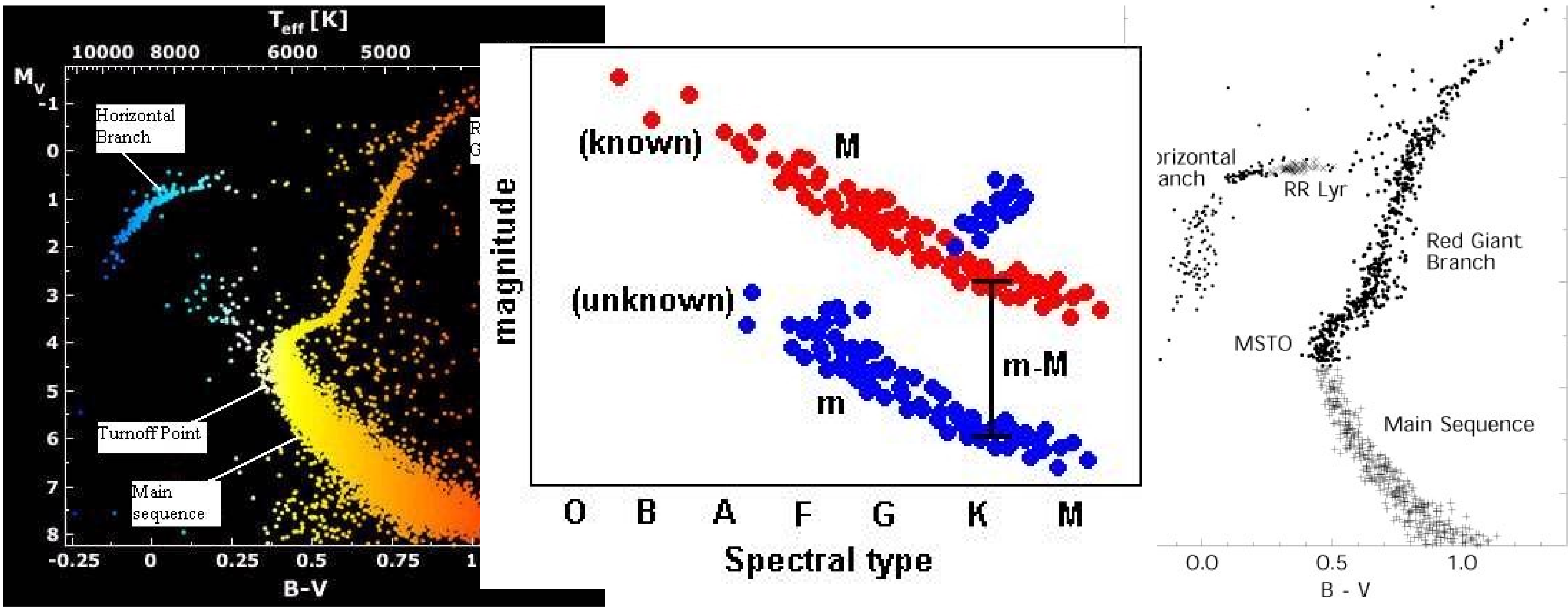
Observed

Stellar Distances

Main Sequence (HR Diagram) fitting

We know the absolute luminosity of the main sequence

Slide the observed sequence and you get the distance modulus!



Calibrated (or from model)

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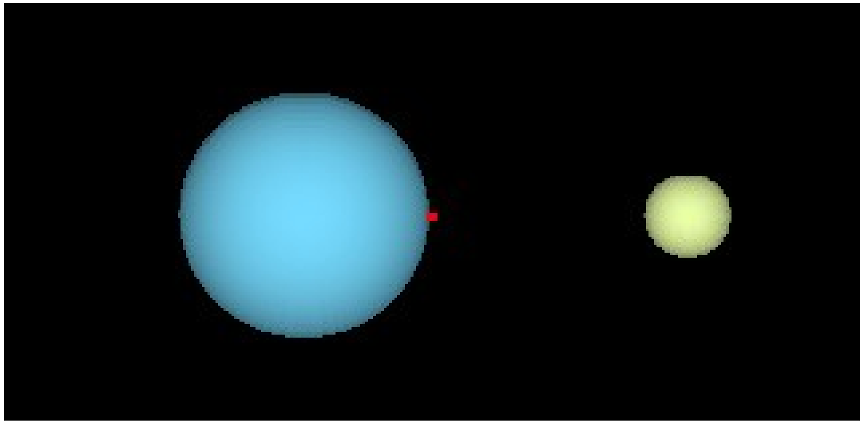
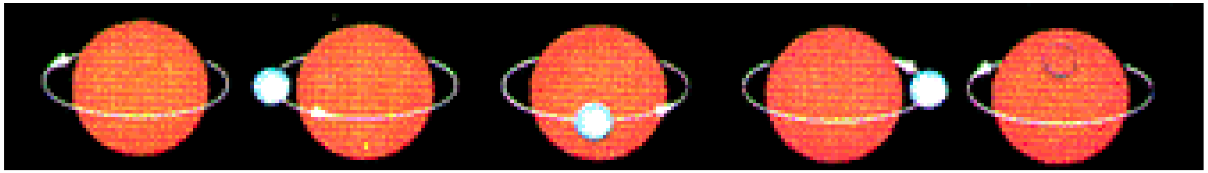
Stellar Distances

Eclipsing binaries



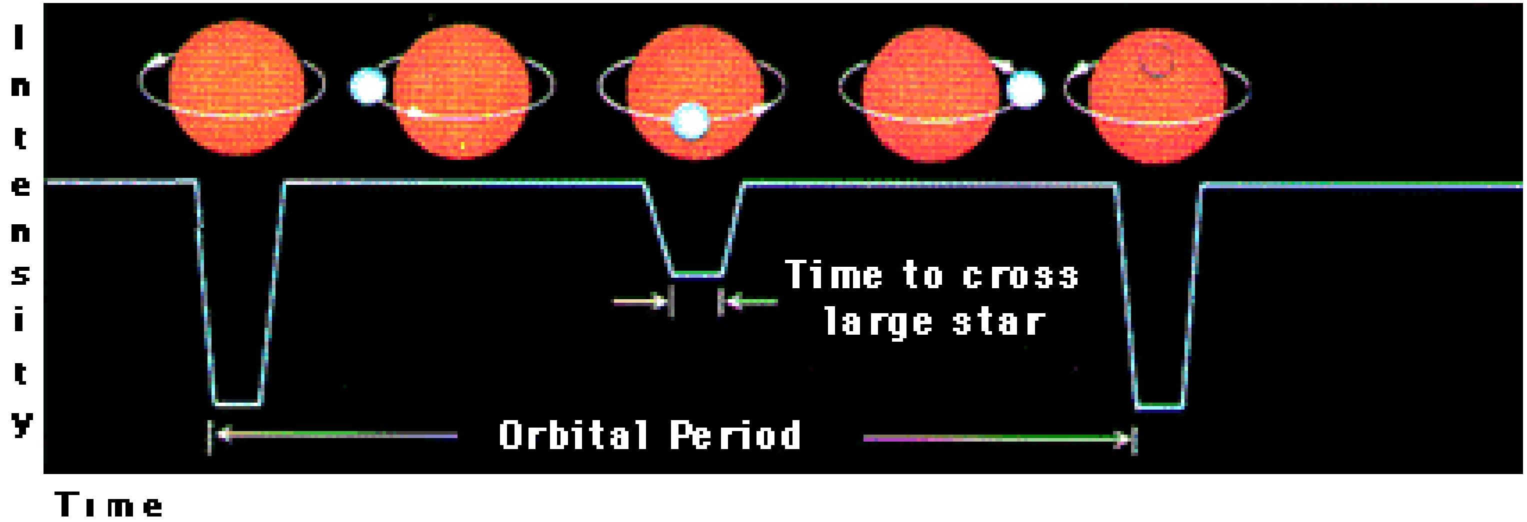
Stellar Distances

Eclipsing binaries



Stellar Distances

Eclipsing binaries



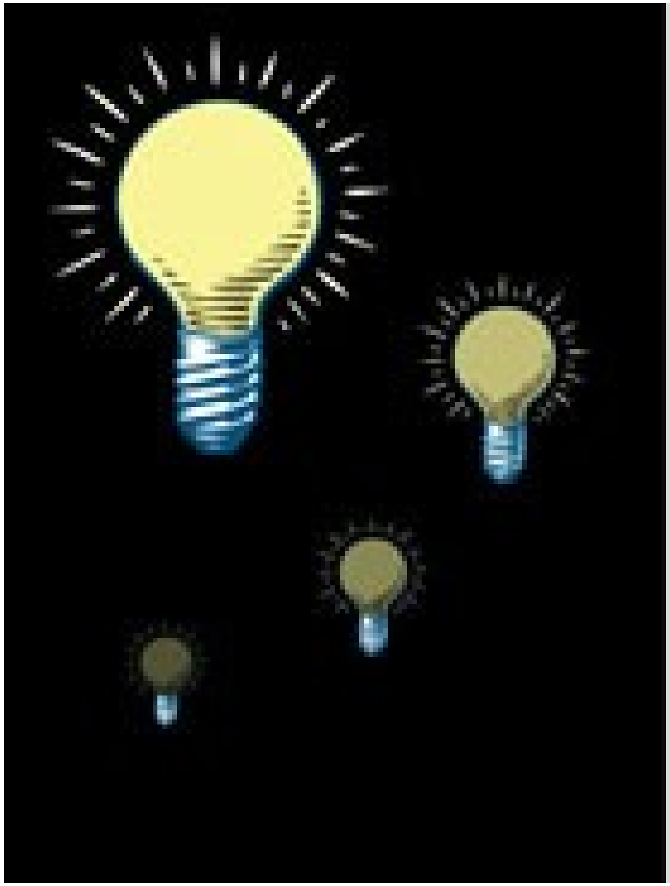
The ***duration of the eclipse*** enables the determination of the ***radii*** of the stars

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

Stellar Distances

Standard Candles

Standard candles are objects that have known luminosity.



RR Lyrae variables
Mean absolute magnitude M = 0.75

Cepheid variables
Absolute magnitude up to M = - 7

Supernovae Type Ia
Absolute magnitude M = -19.3

Stellar Distances

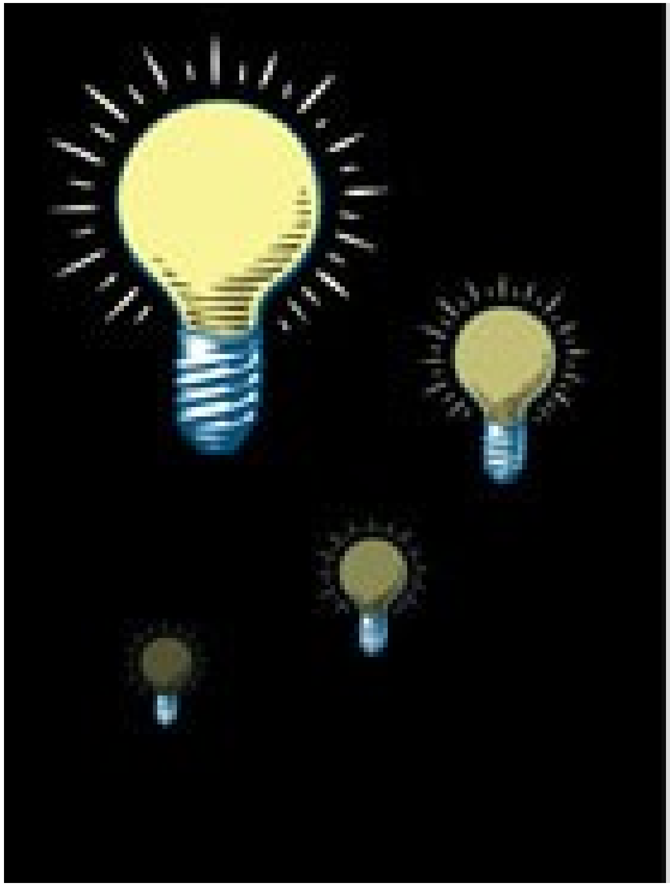
Standard Candles

Standard candles are
objects that have known luminosity.

RR Lyrae variables
Mean absolute magnitude M = 0.75
Galactic distances

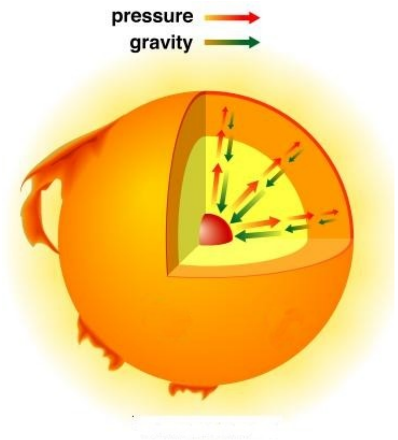
Cepheid variables
Absolute magnitude up to M = - 7
Nearby galaxies (30 Mpc)

Supernovae Type Ia
Absolute magnitude M = -19.3
Cosmological distances



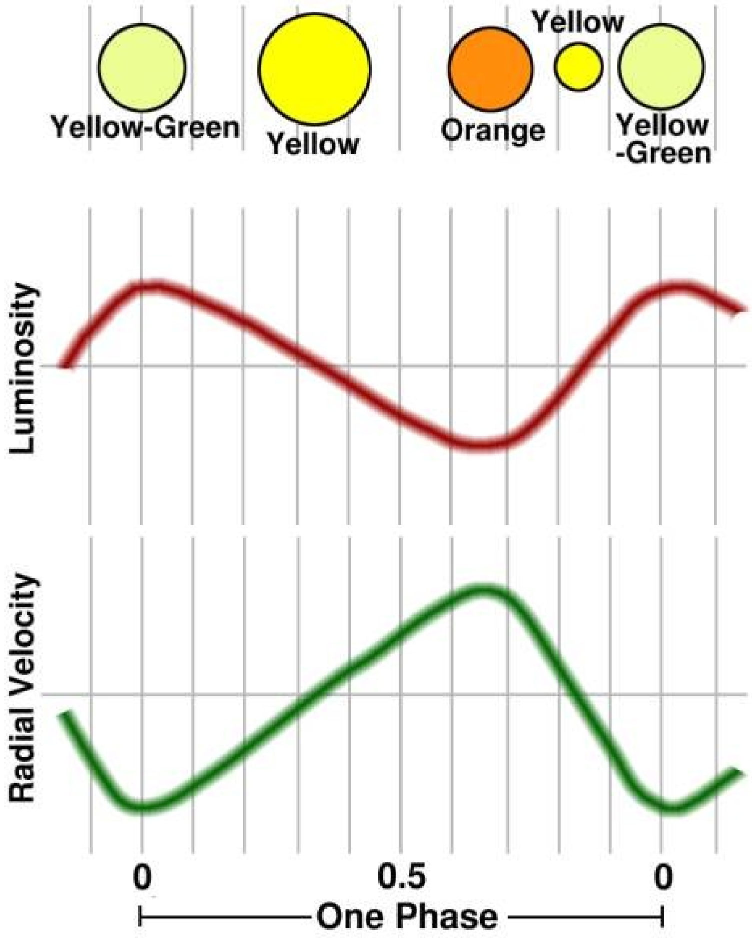
Stellar Distances

Standard Candles

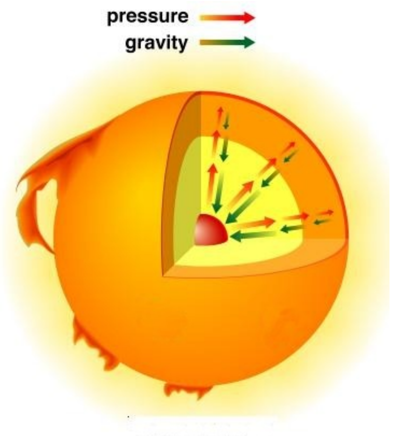


RR Lyrae and **Cepheid** variables
are ***pulsating stars***

Periodic imbalance of pressure and gravity



Stellar Distances



Standard Candles

RR Lyrae and **Cepheid** variables
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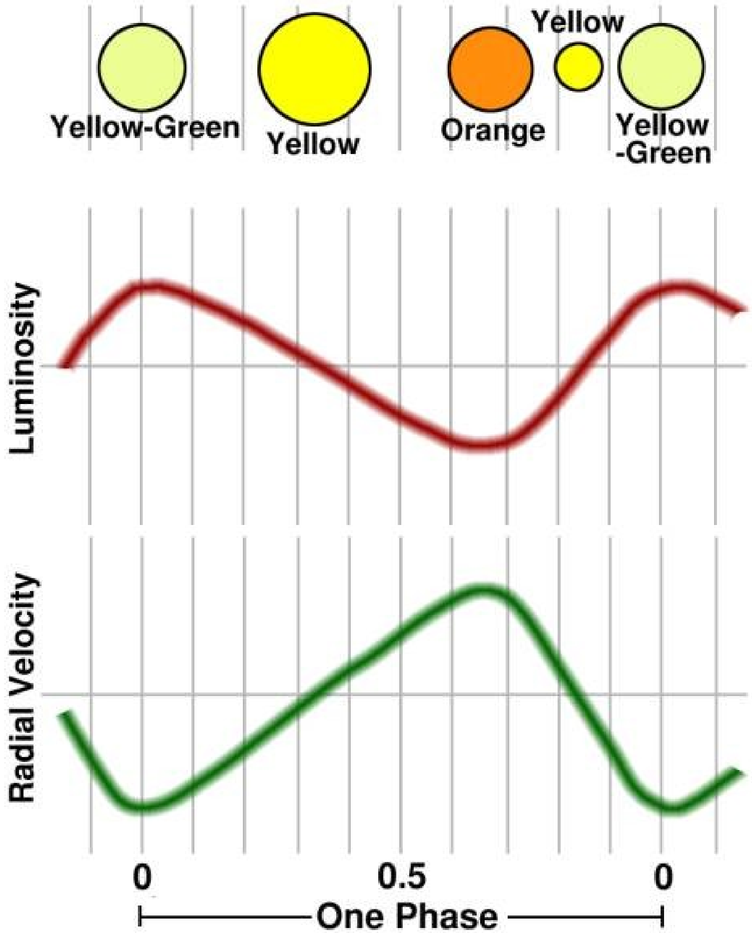
Periodic imbalance of pressure and gravity

1. The ***pulsation*** has ***gravity*** as a restoring force



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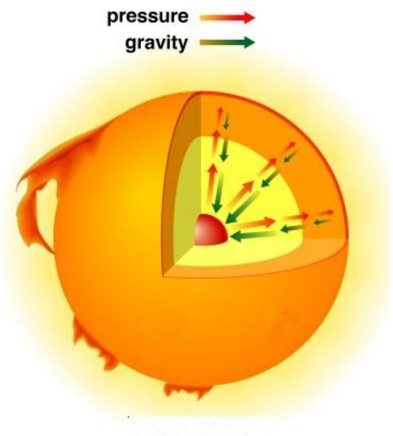

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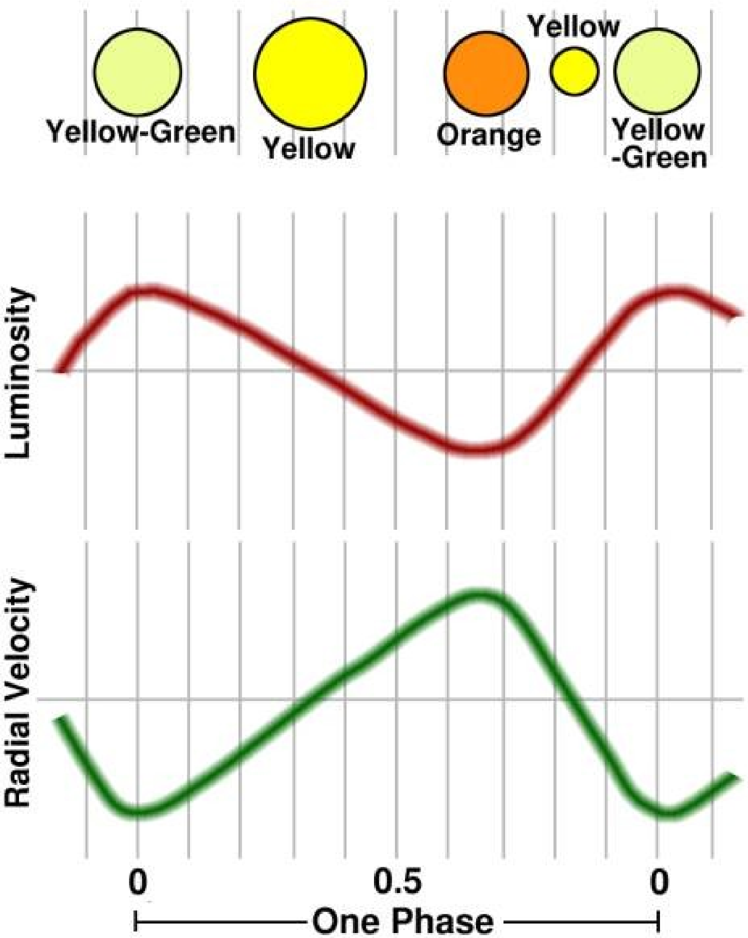
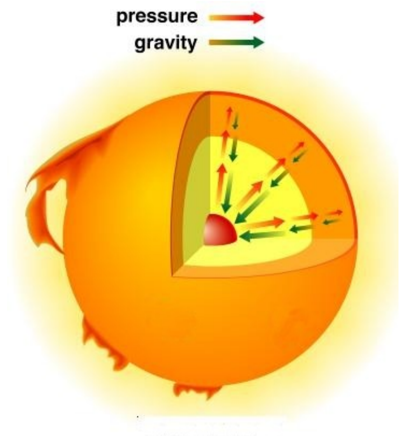


1. The ***pulsation*** has ***gravity*** as a restoring force

2. ***Gravity*** is determined by the ***mass***

Stellar Distances



Standard Candles

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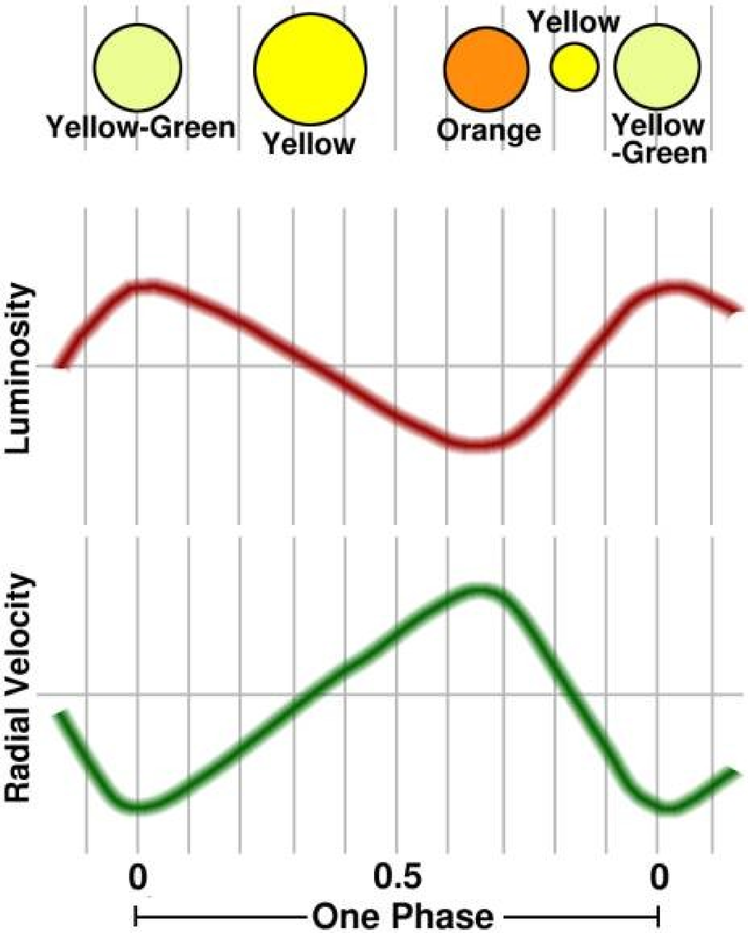
Periodic imbalance of pressure and gravity

1. The ***pulsation*** has ***gravity*** as a restoring force

2. ***Gravity*** is determined by the ***mass***

3. Thus the ***period of pulsation*** depends on the ***mass***



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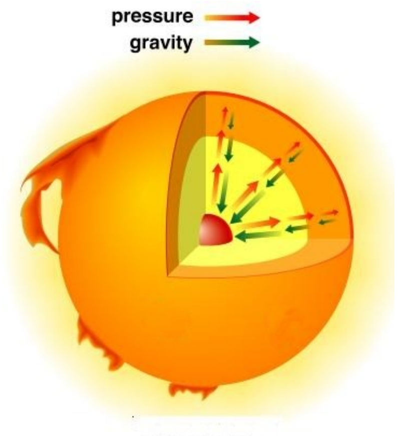

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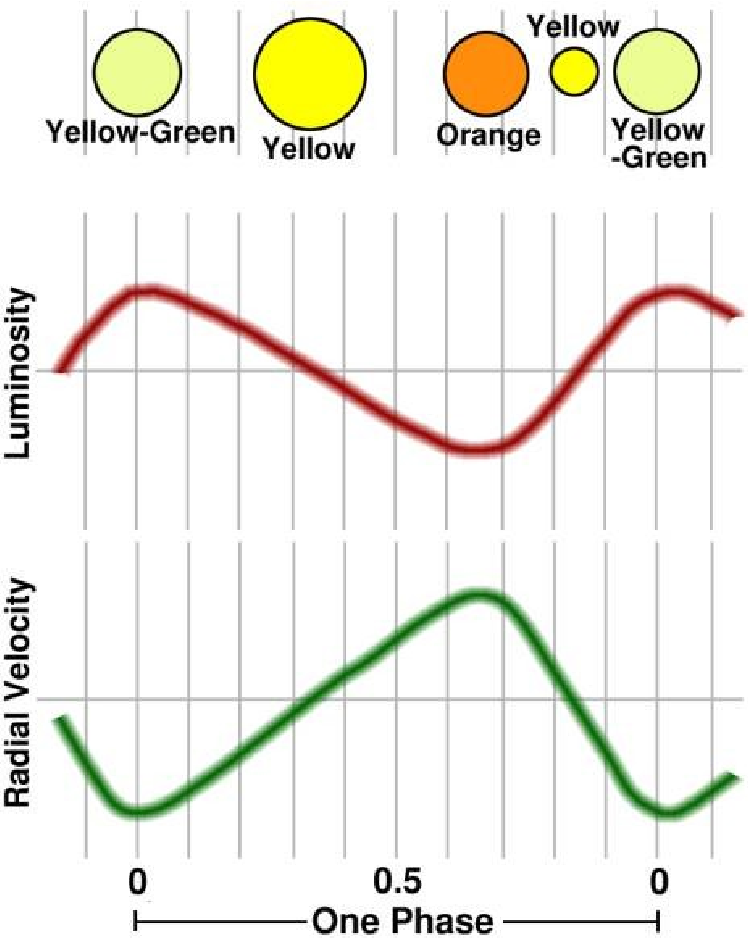

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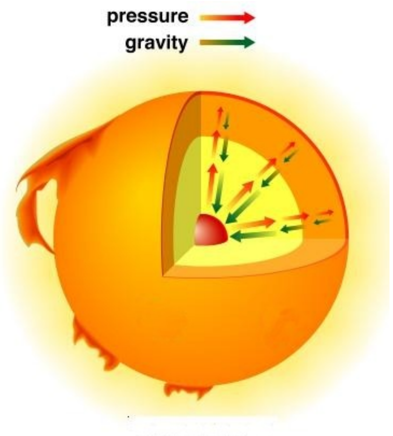
4. ***Mass*** determines the energy production rate at the stellar core, therefore, the ***luminosity***.

Stellar Distances



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2. ***Gravity*** is determined by the ***mass***

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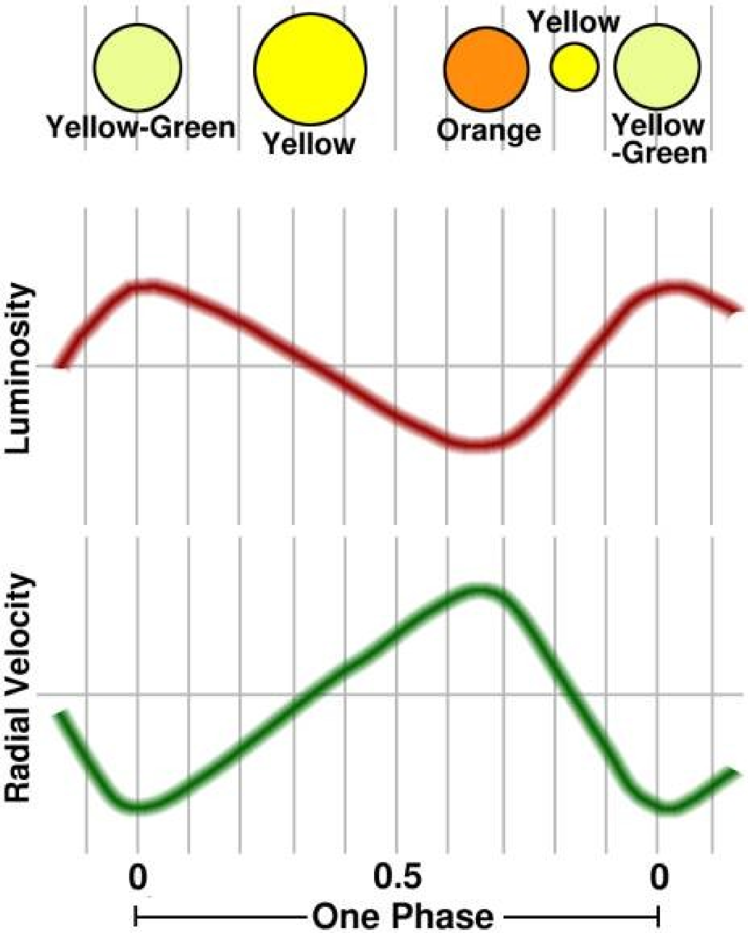
5. There should be a ***period-luminosity*** relation!



Stellar Distances

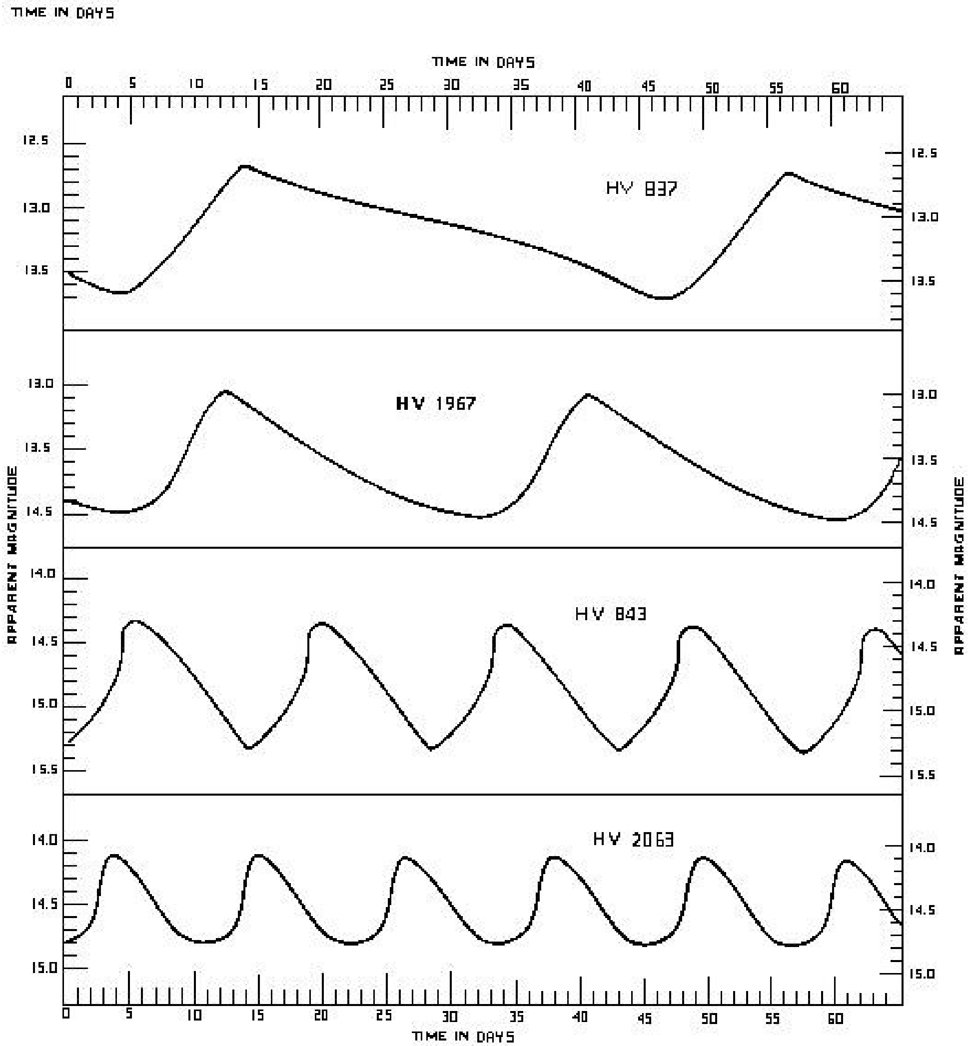
Henrietta Leavitt

Standard Candles

The Cepheid Period-Luminosity Relationship

Bright

Dim

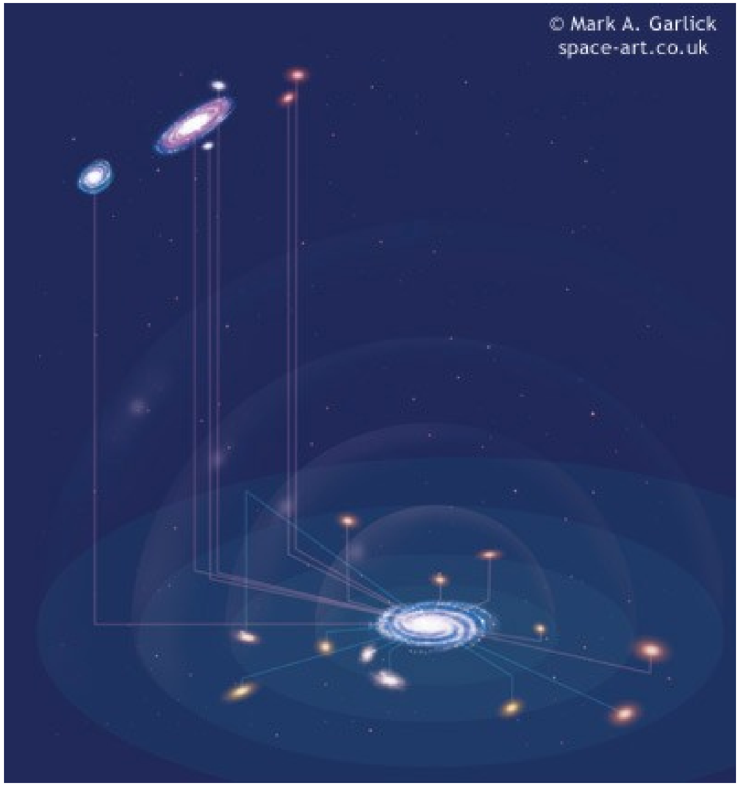


Long period

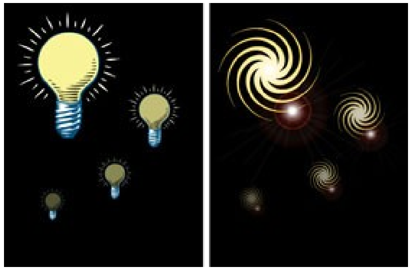
Short period

Distance to the Triangulum Galaxy

Cepheid variable	850 +/- 40 kpc
HRD fitting	794 +/- 23 kpc
Eclipsing Binaries	861 +/- 28 kpc

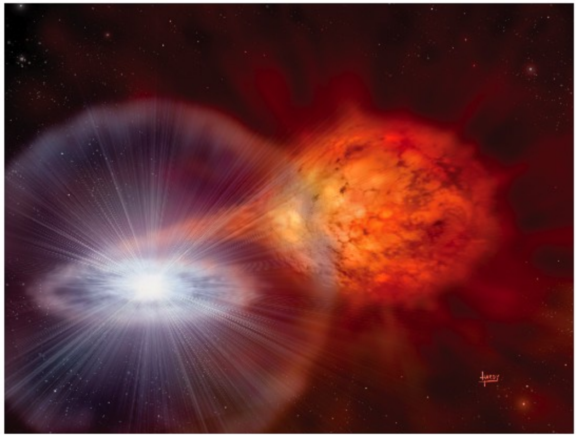


Stellar Distances



Standard Candles

A Supernova Type Ia
is the thermonuclear explosion
of an accreting white dwarf

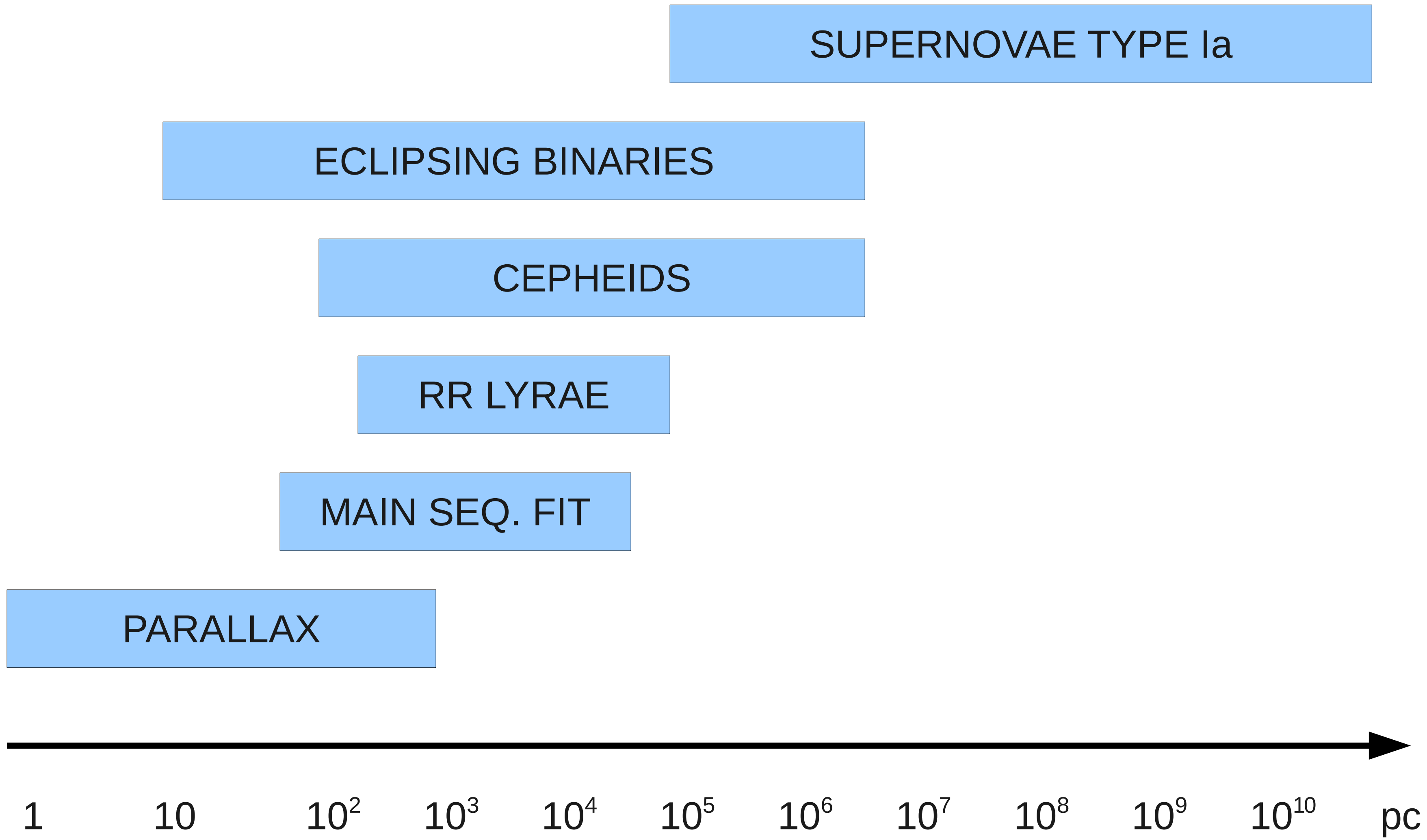


Because they always go
at the **same mass**,
the explosion has always
the **same luminosity**

10^{51} ergs

Stellar Distances

The Cosmic Distance Ladder



Let's summarize

Proper motion: movement of stars in the sky. Typical 0.1”/yr. Barnard's star 10”/yr.

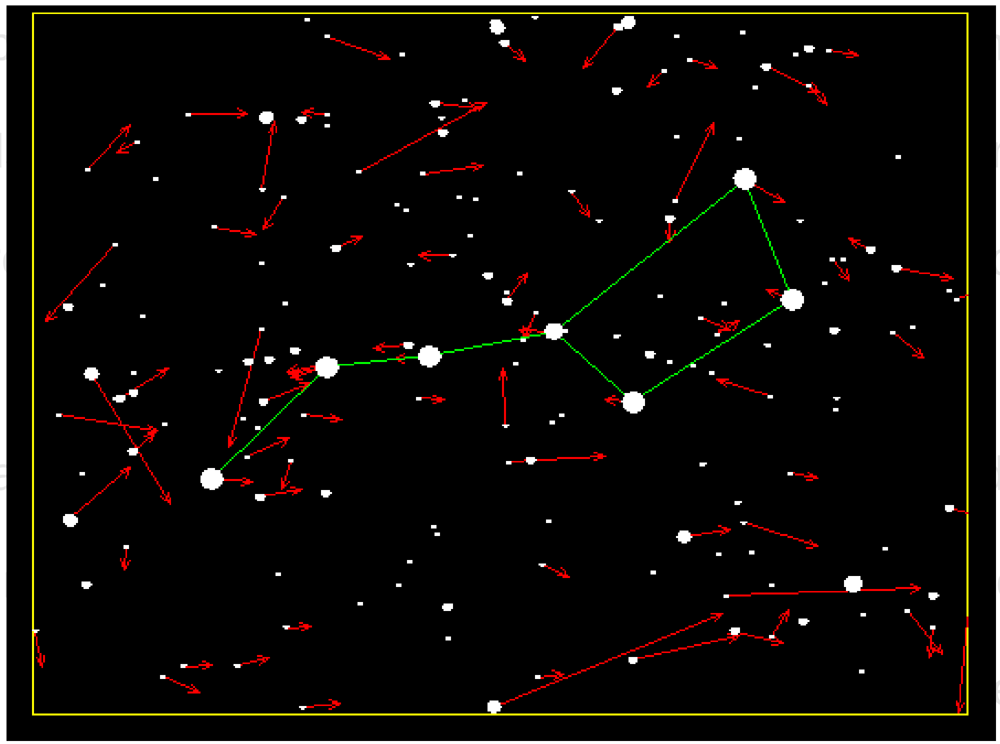
Distance is hard to measure. Parallaxes only work up to 1000 pc.

Beyond that we n ... standard candles.

Eclipsing b ... osity via

Cepheid ... relation

Type Ia Supernovae ar ... osmological distances



Stellar spectra a ... l by colder gas

Spectral li ... ormation

Five ... es.

Magnitude difference = color. A measurement of temperature.

Spectroscopy = individual accuracy. Photometry = large number statistics.
Tens of thousands of stars can be automatedly measured in a single frame.

CMD is the photometrically equivalent to the HR diagram.

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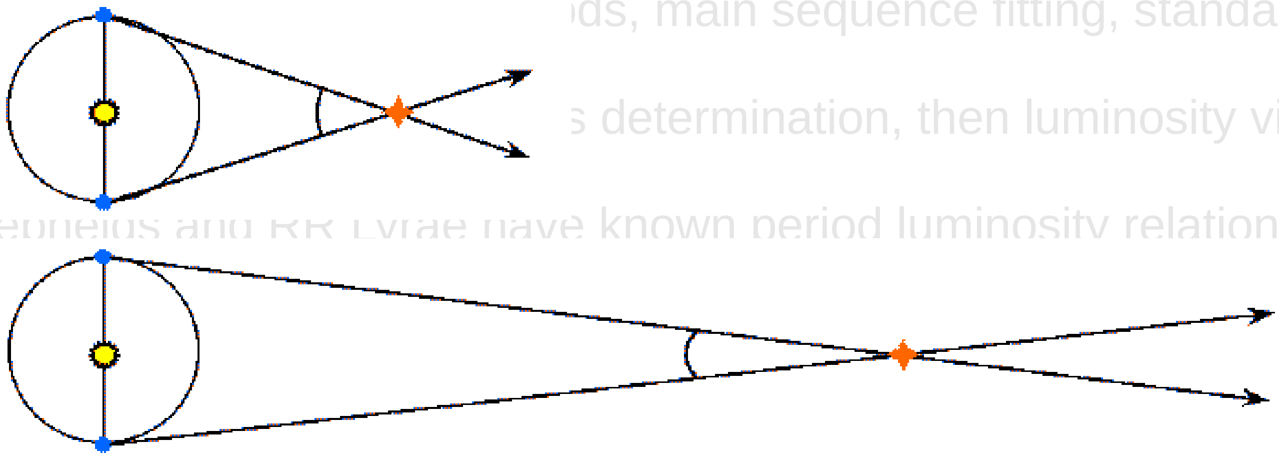

Ec … s determination, then luminosity via

Cepheids and RR Lyrae have known period luminosity relation

Type Ia Superno … gical distances

Stellar spectra are absorption spectra, thus hot source covered by colder gas

Spectral lines are chemical fingerprints, and a mine of information

Five photometric passbands UBVRI. Five magnitudes.

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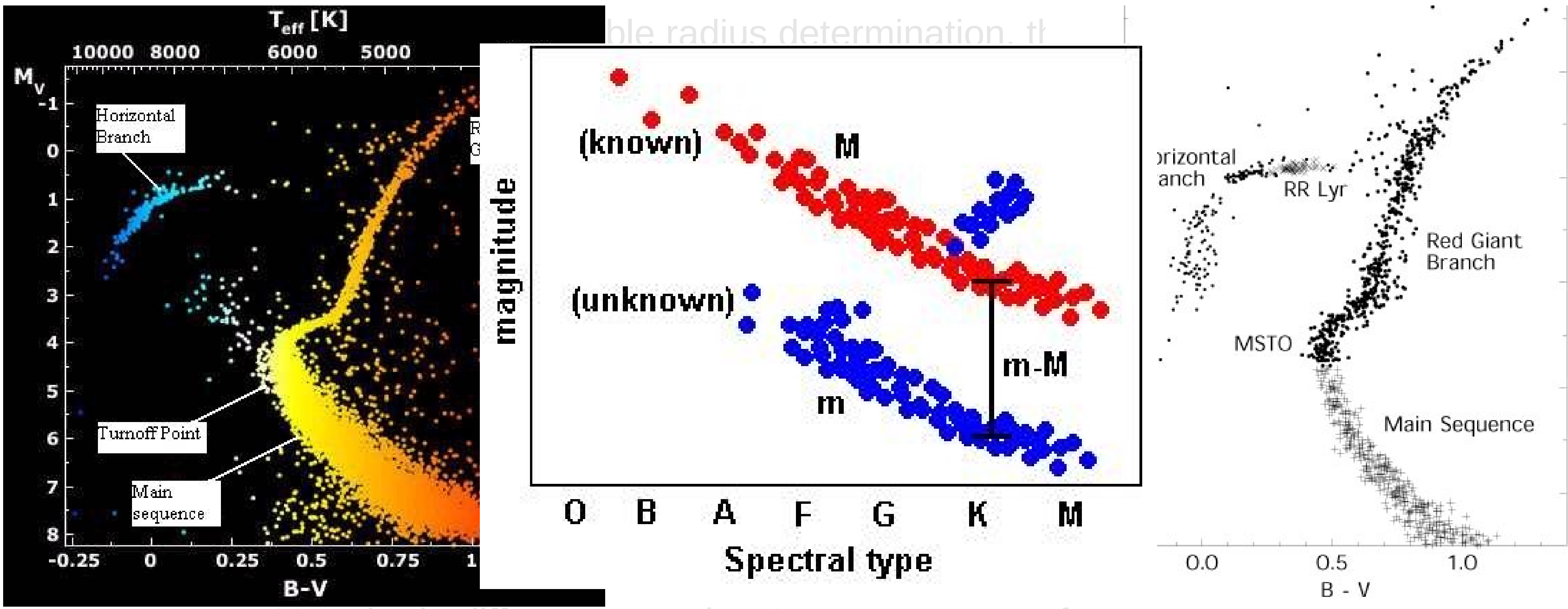

Magnitude difference = color. A measurement of temperature.

Calibrated (or from model) Observed

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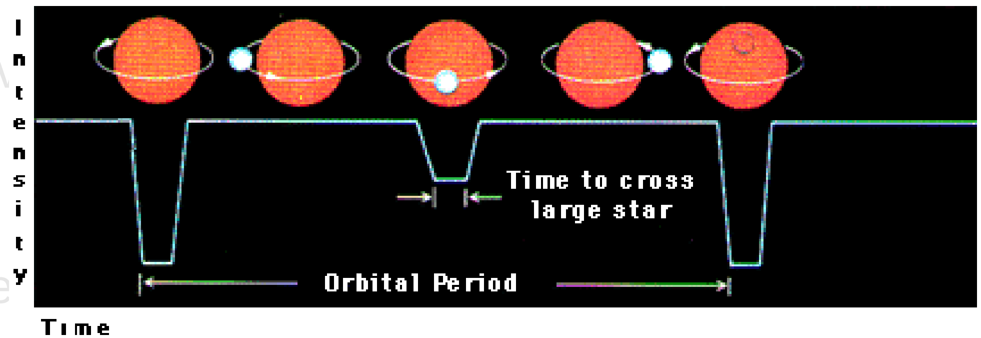
Eclipsing binaries enable radius determination, thus luminosity via $L=4\pi R^2\sigma T^4$

Cepheids and RR Lyrae have known period luminosity relation



Type Ia Supernovae are v… …smological distances

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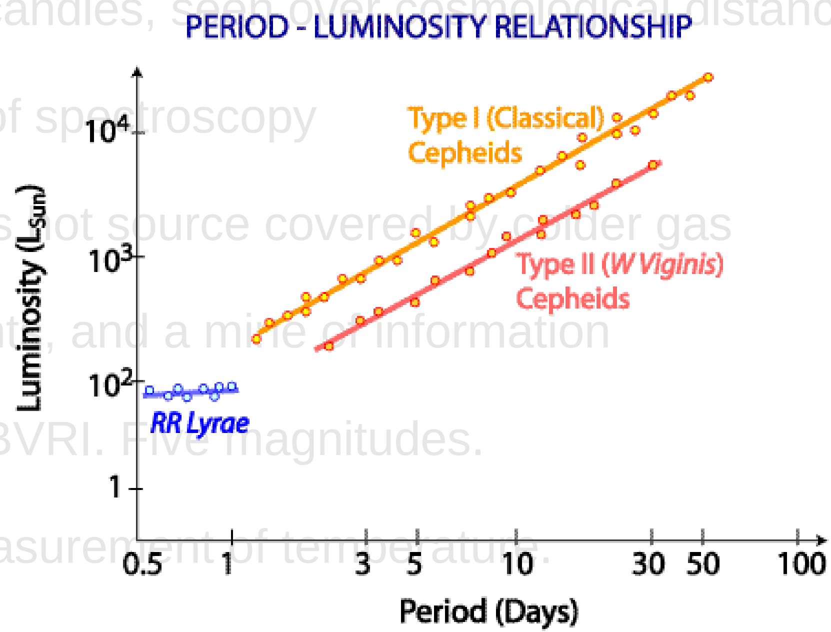

Kirchhoff's three laws of spectroscopy

Stellar spectra are absorption spectra, thus hot source covered by colder gas

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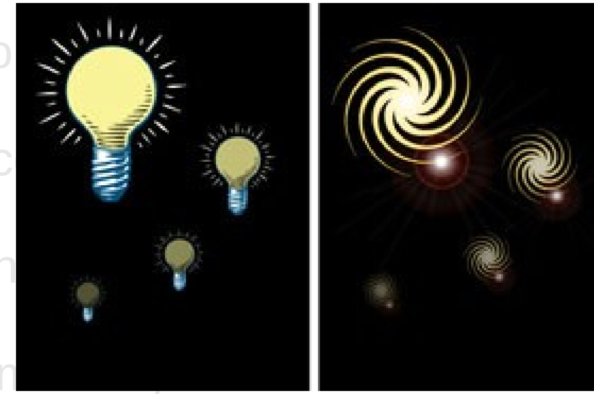

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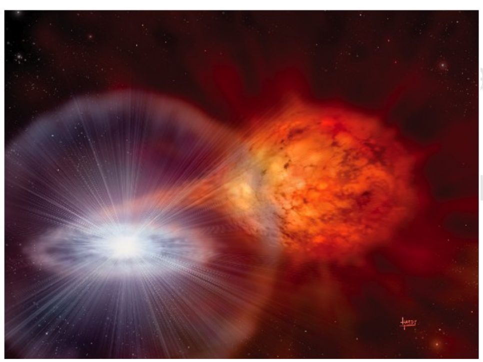

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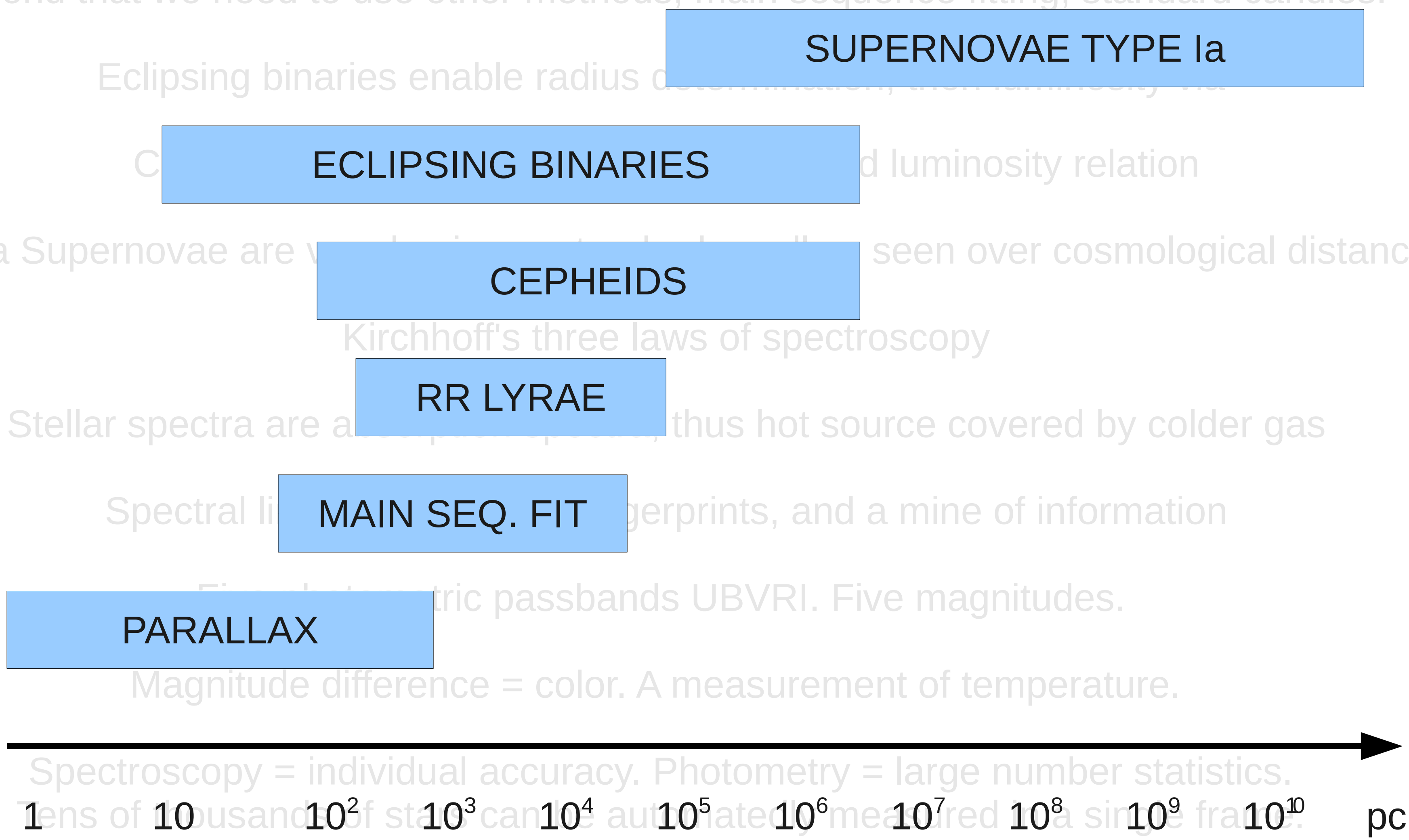


What are some differences between the nearby stars and the brightest stars we see?

$$m - M = -5 + 5\log d$$

$$\boxed{d(pc) = 10^{0.2(m-M)+1}}$$

$$\mu = m - M$$

Distance modulus

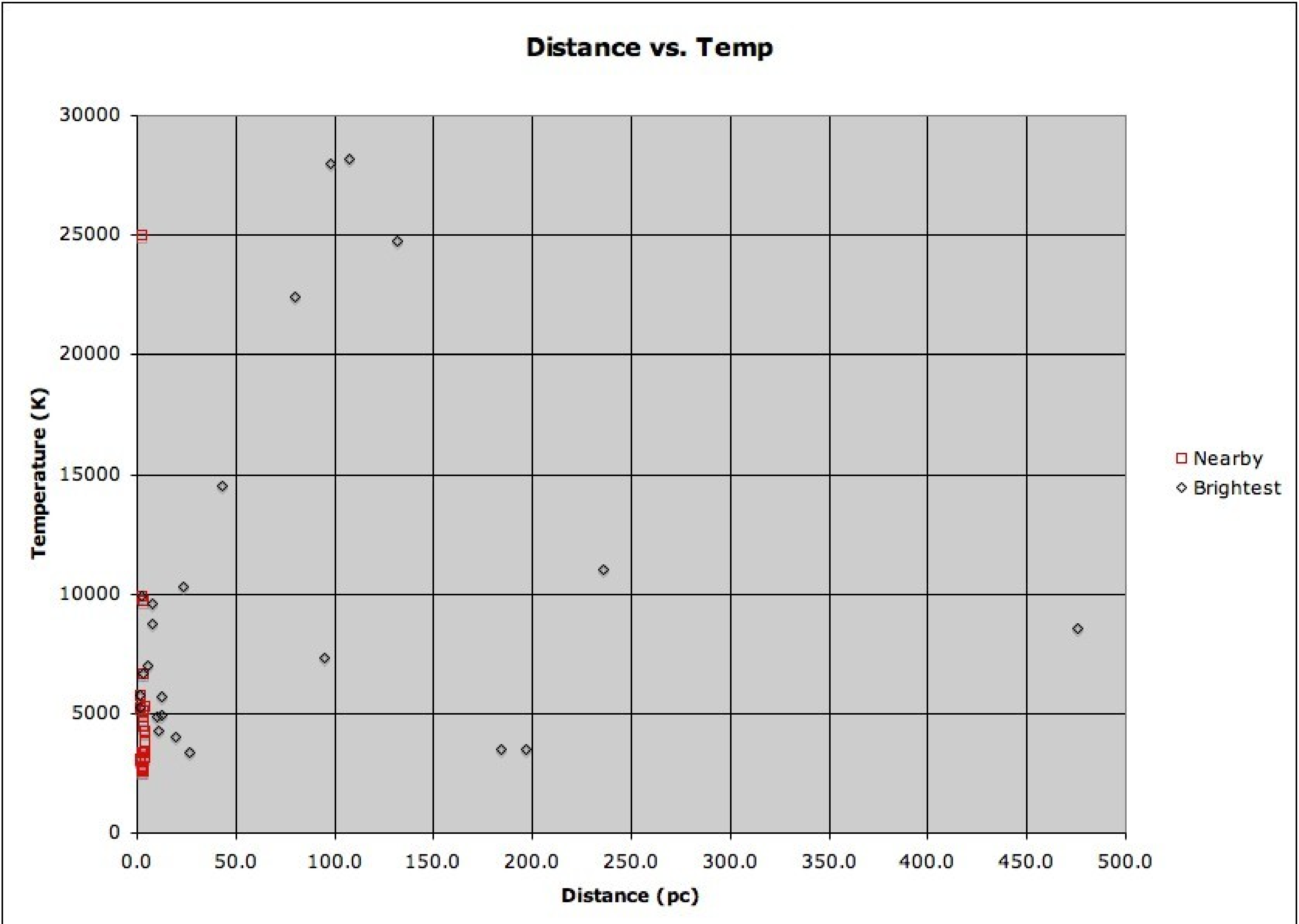
1 – From your graph, make a general statement about the temperatures of the closest stars, and of the brightest stars

2 – Which stars, closest/brightest, have higher luminosities? How can you tell?

3 - In general, what spectral types (OBAFGKM) are the nearby stars?

4 – In general, what spectral types are the brightest stars?

5 – Explain how some of the brightest stars have low temperatures and are quite far away. In other words, why are they so bright?

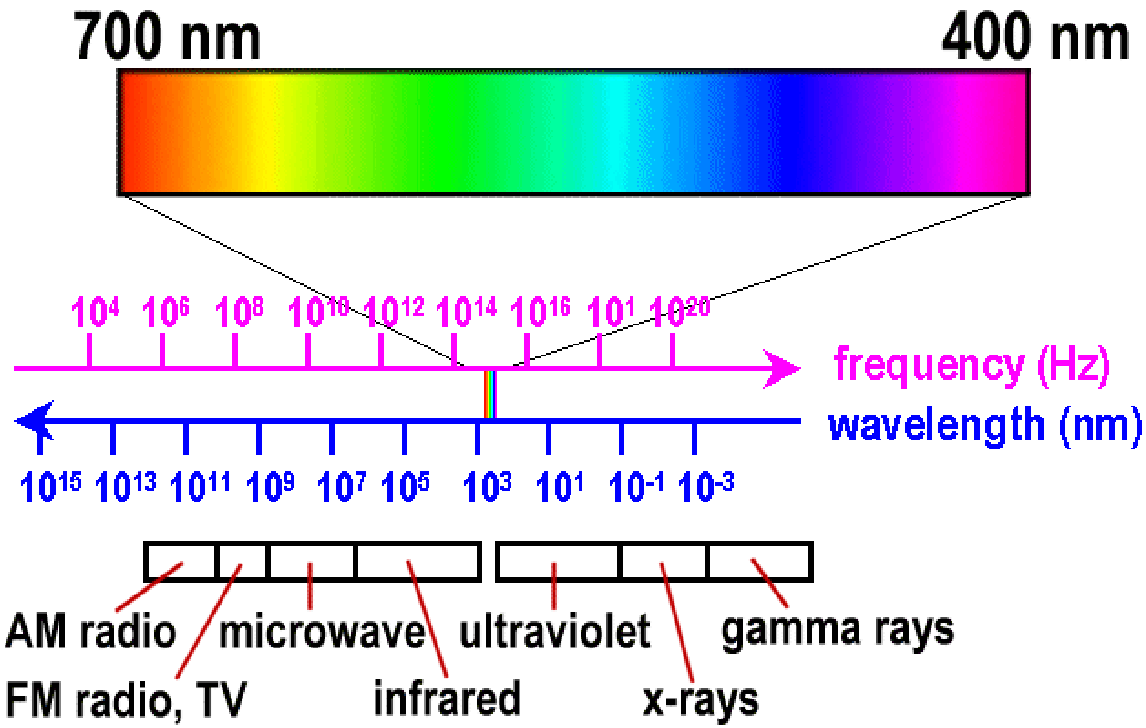

Distance vs. Temp
Temperature (K)
30000
25000
20000
15000
10000
5000
0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
Distance (pc)
Nearby
Brightest

Spectroscopy

Information we get from stars

Direction of the radiation	***Astrometry***
Amount of radiation	***Photometry***
Spectral distribution of the radiation	***Spectroscopy***

The electromagnetic spectrum



Spectroscopy

Information we get from stars

Direction of the radiation	***Astrometry***
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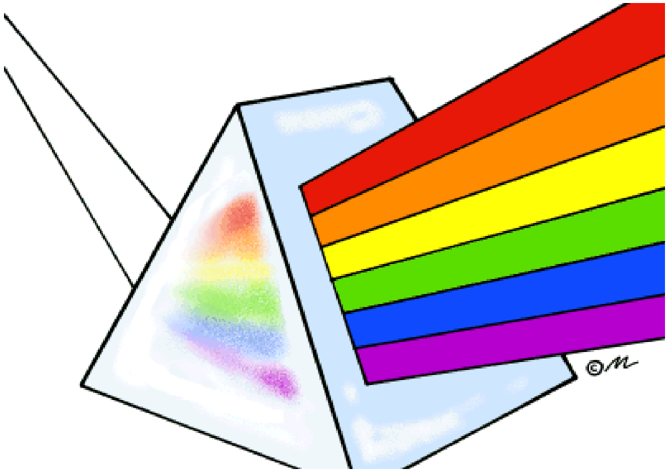
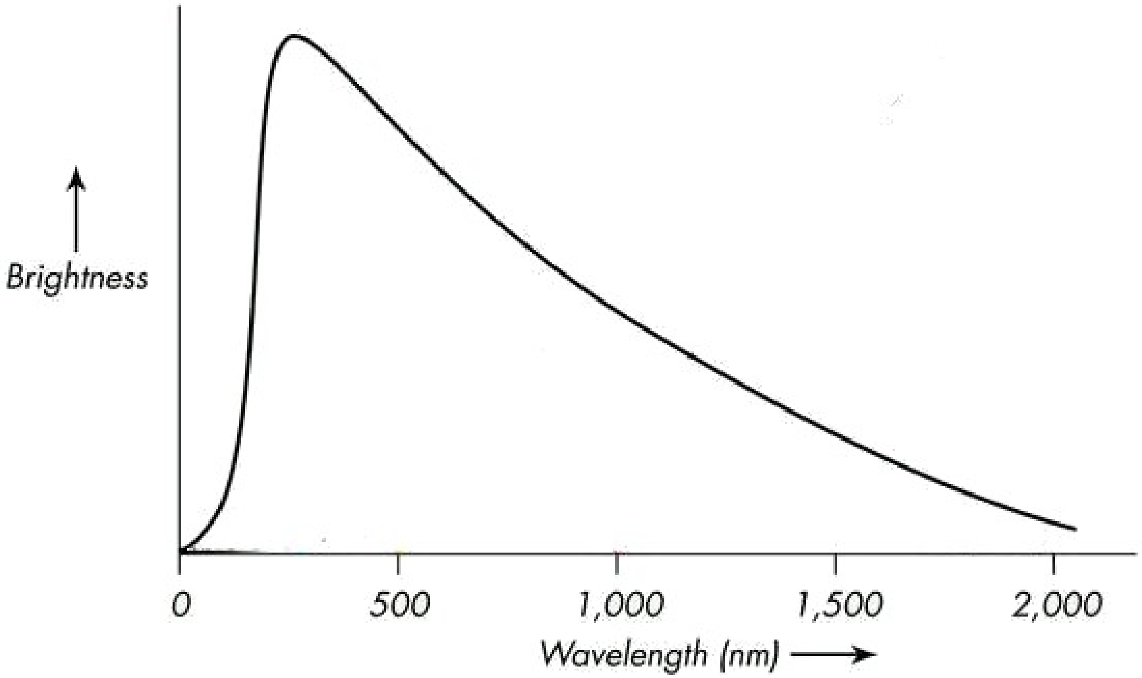
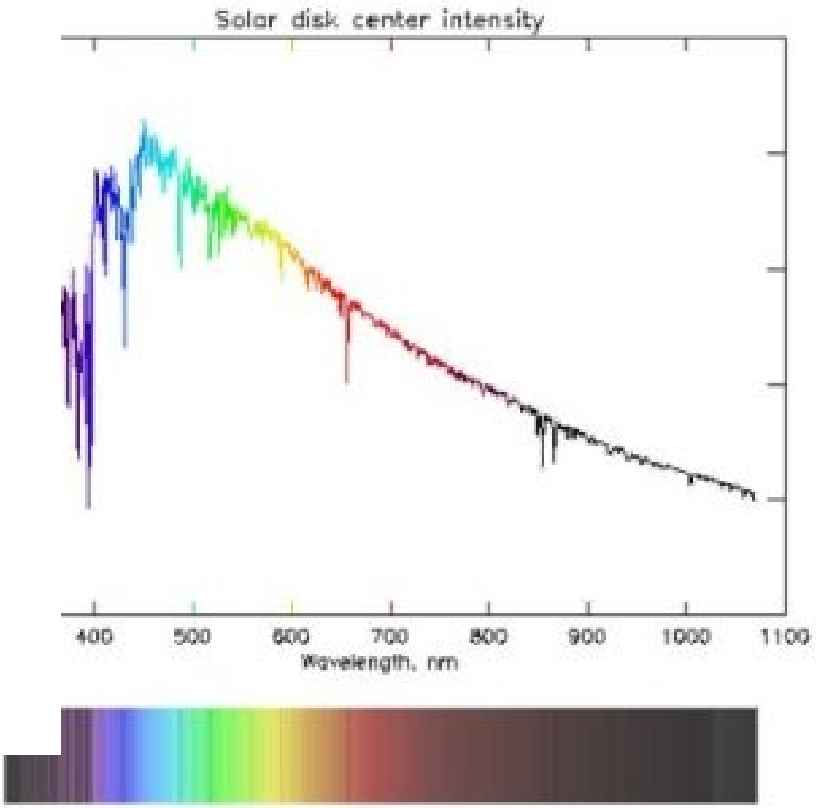
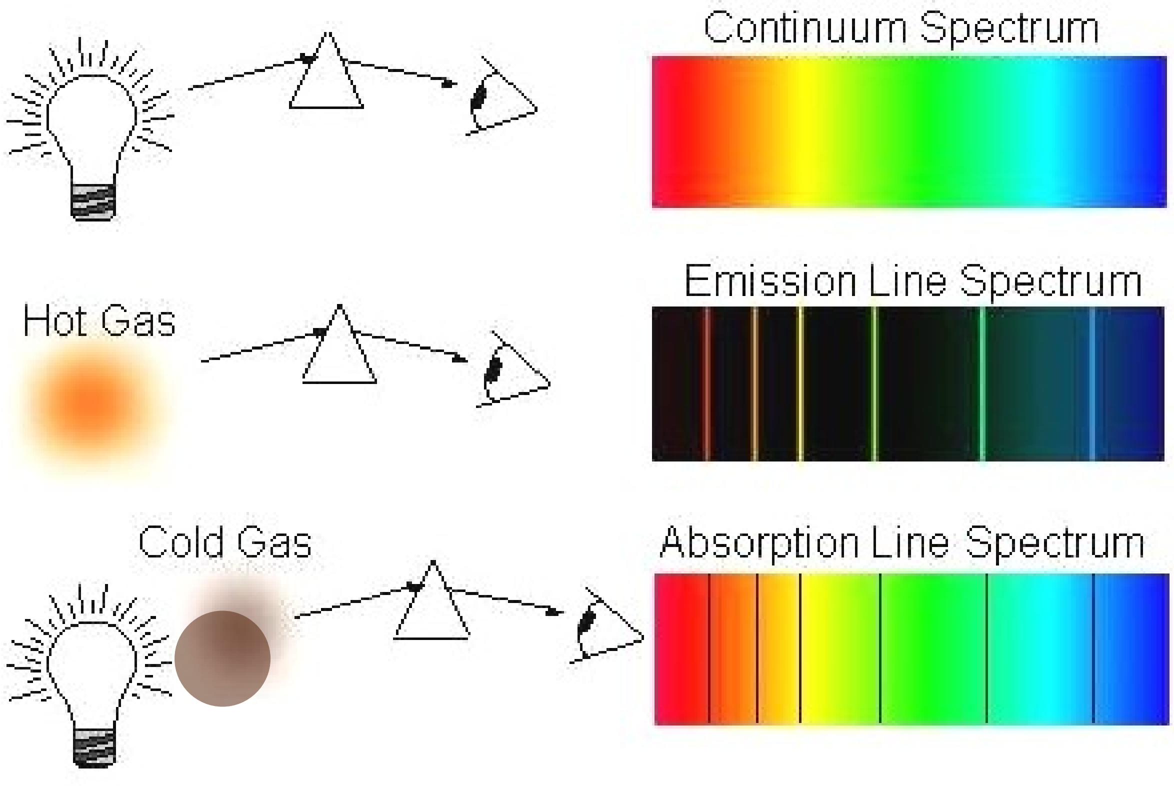






Spectroscopy

Spectral lines – Kirchhoff's three empirical laws of spectroscopy



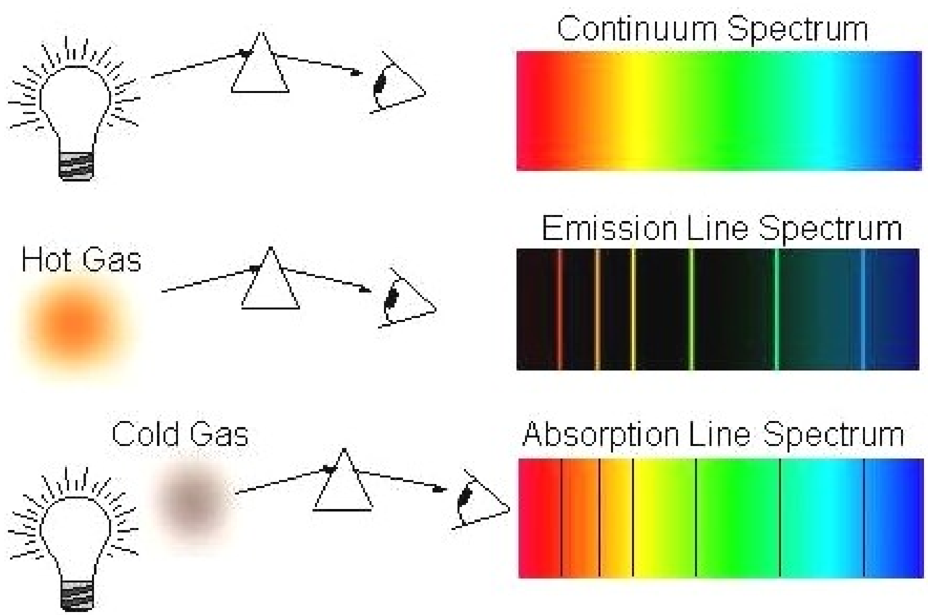
A hot solid or a hot dense gas produces a continuum spectrum.

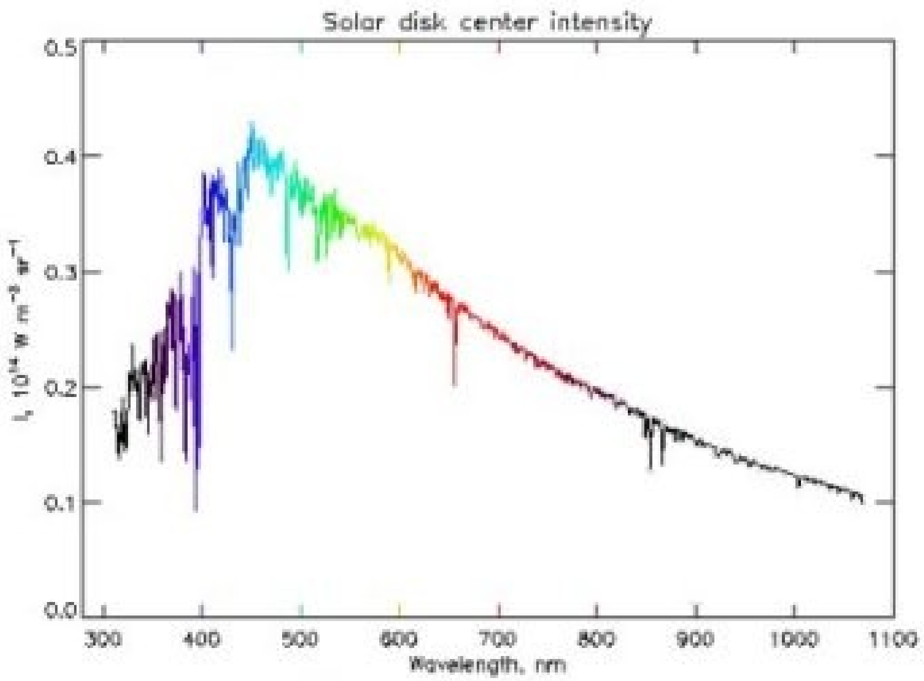
A hot low-density gas produces an emission-line spectrum.

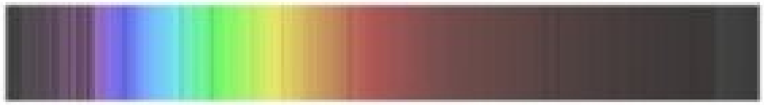
A continuos source viewed through a cold gas produces an absorption-line spectrum.

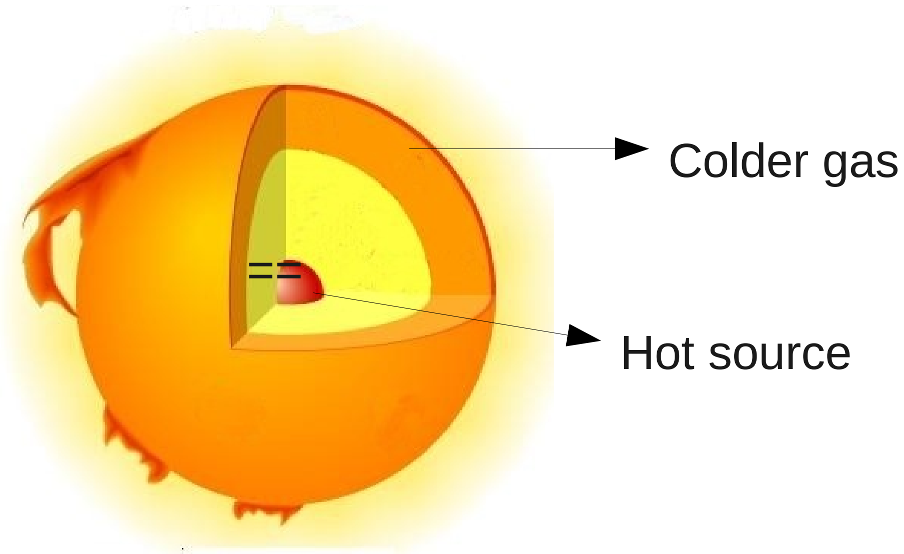
Spectroscopy

Spectral lines – Kirchhoff's three empirical laws of spectroscopy



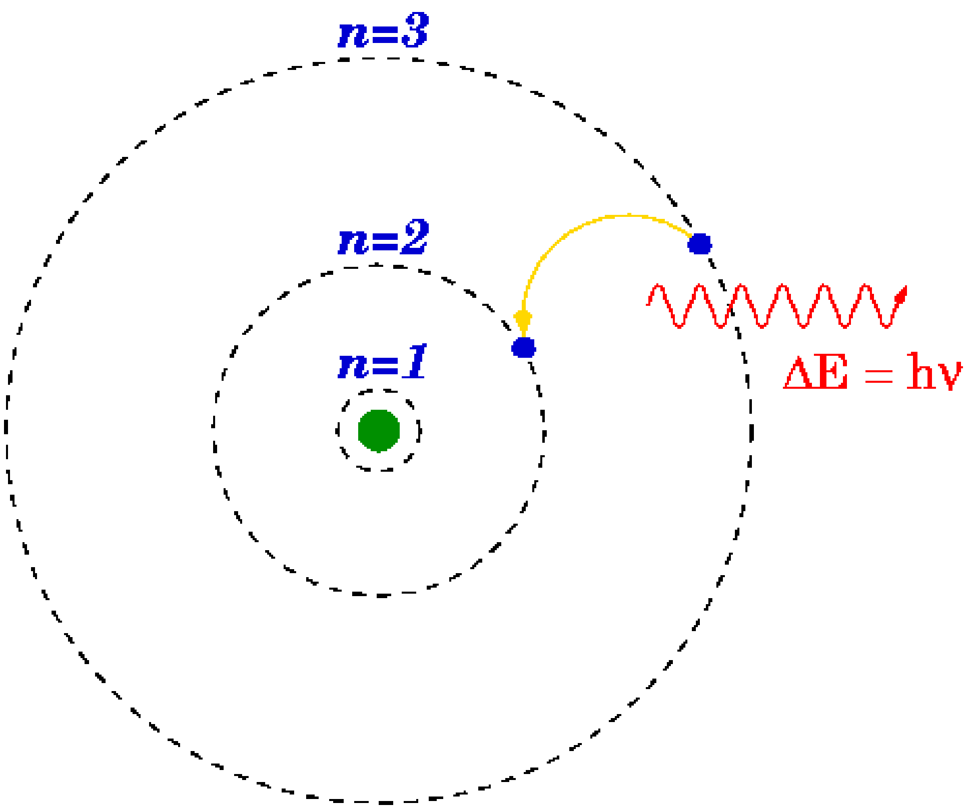


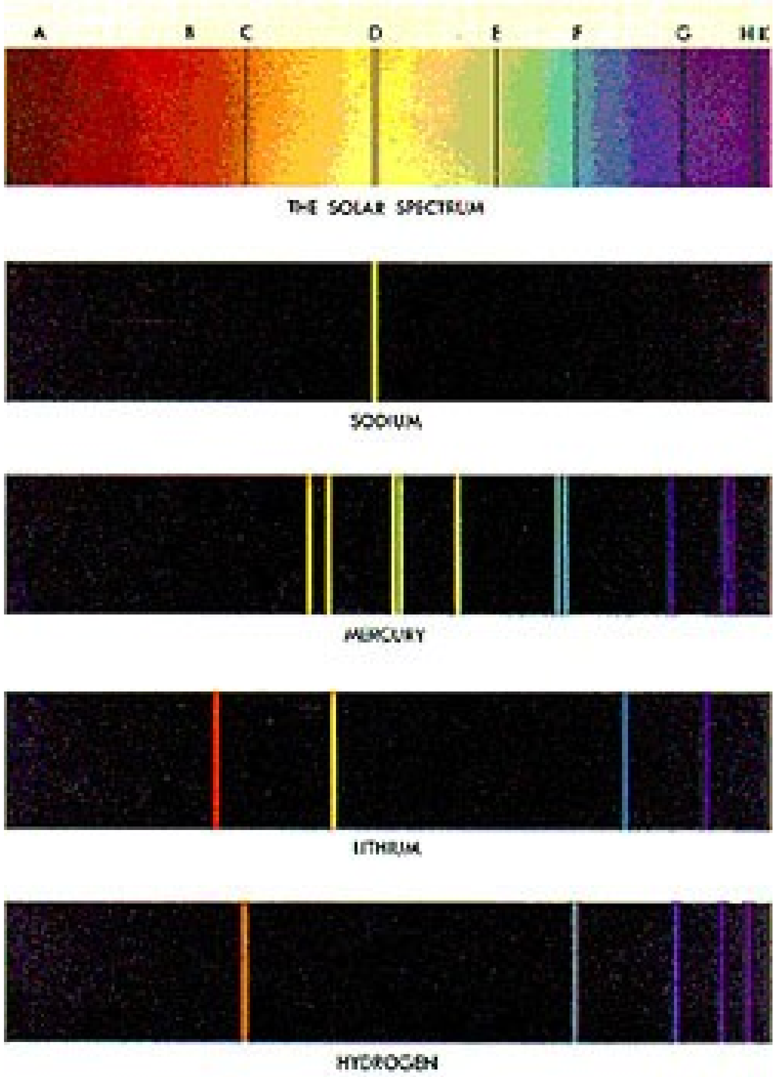




Spectroscopy

Spectral lines are chemical signatures

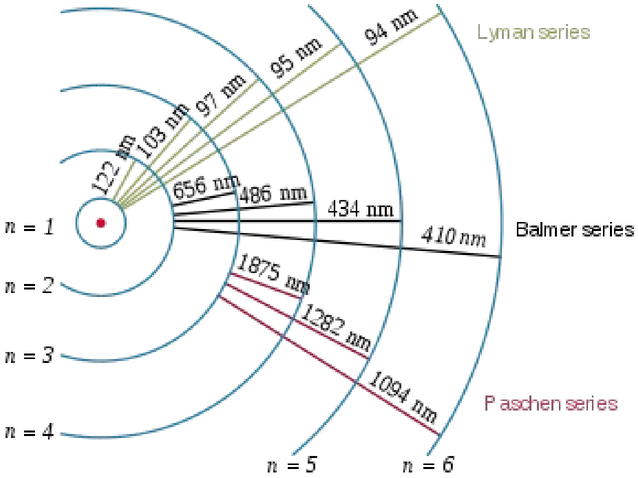


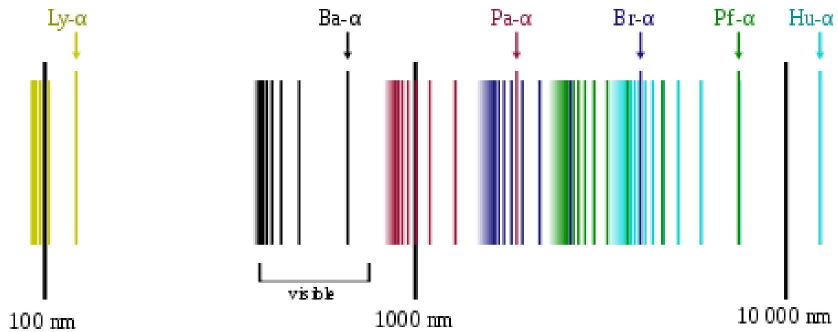


Different elements have different energy levels,
Thus different spectral lines

Spectroscopy

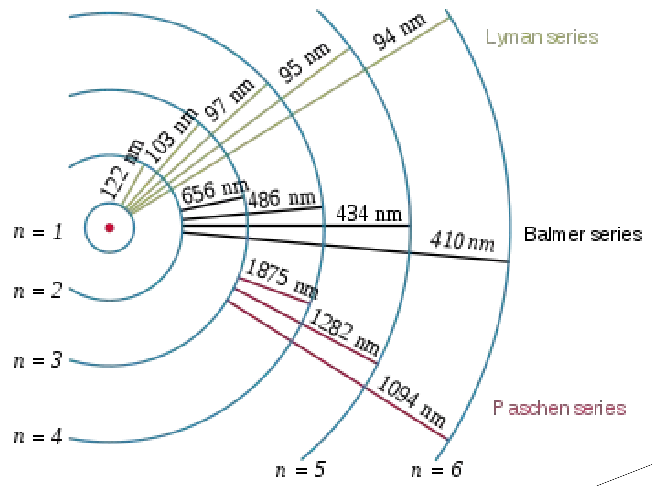
The hydrogen spectrum

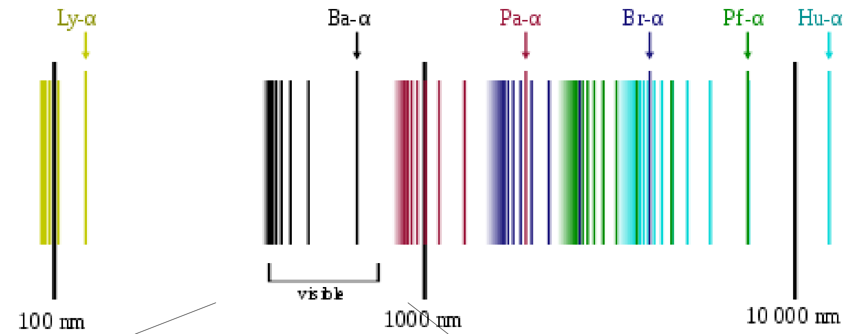




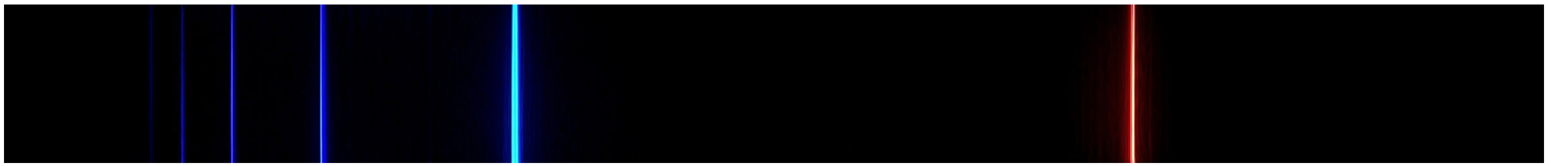
Spectroscopy

The hydrogen spectrum





The Balmer series (*n*=2) is in the visible range

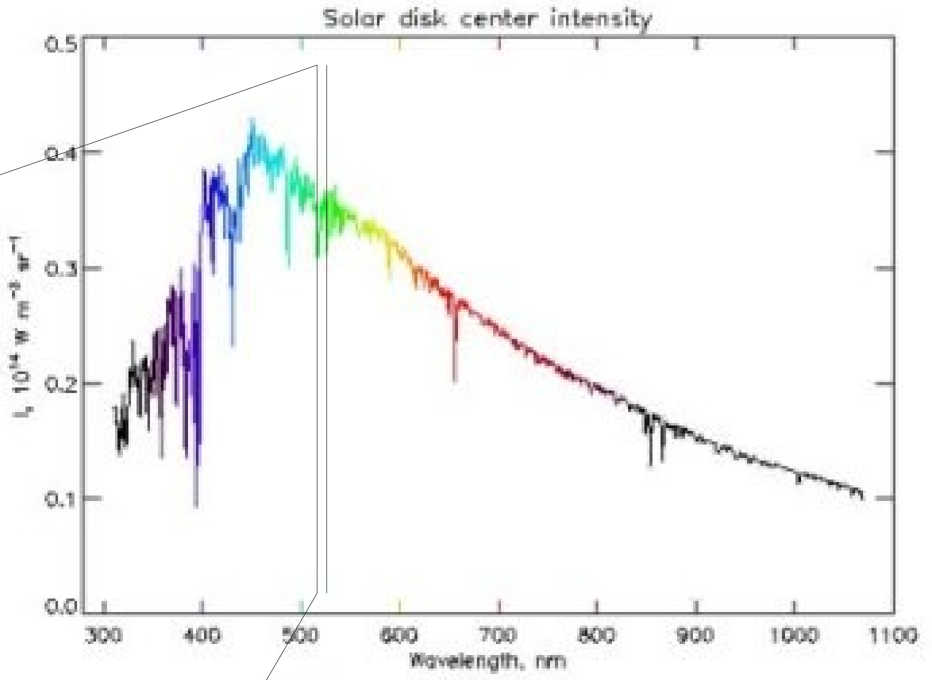


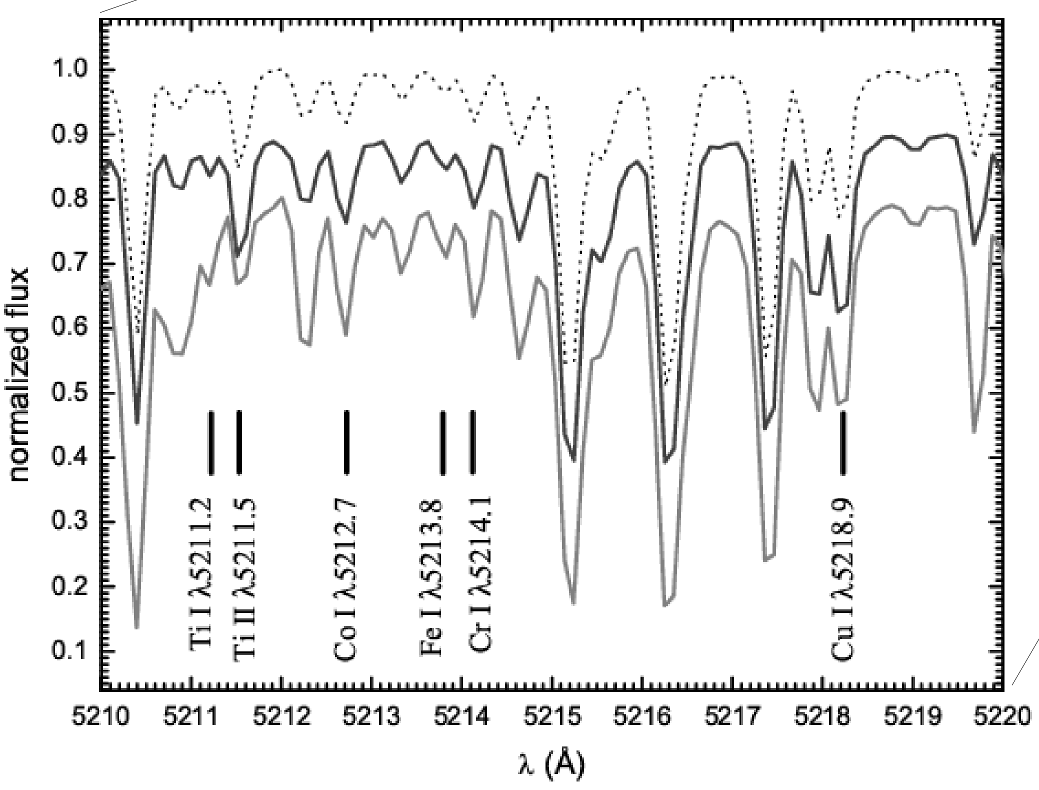
Line	He Hd Hg	Hb	Ha	
Wavelength	434nm	486nm	656nm	

Spectroscopy

Spectroscopy is very accurate

We can measure line positions to an accuracy of *mili-Ångströms (mÅ)*.





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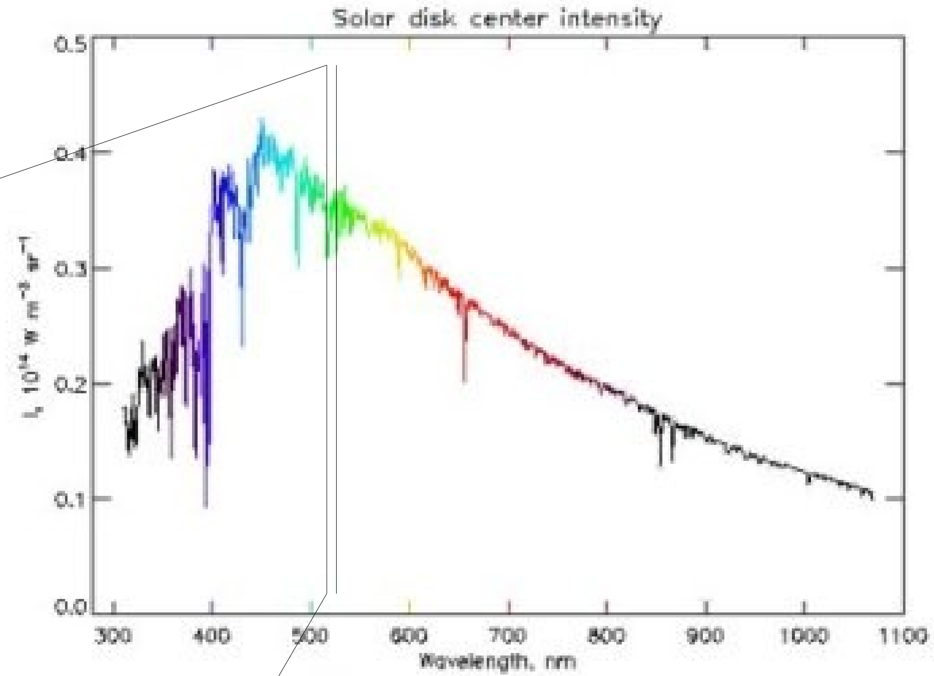
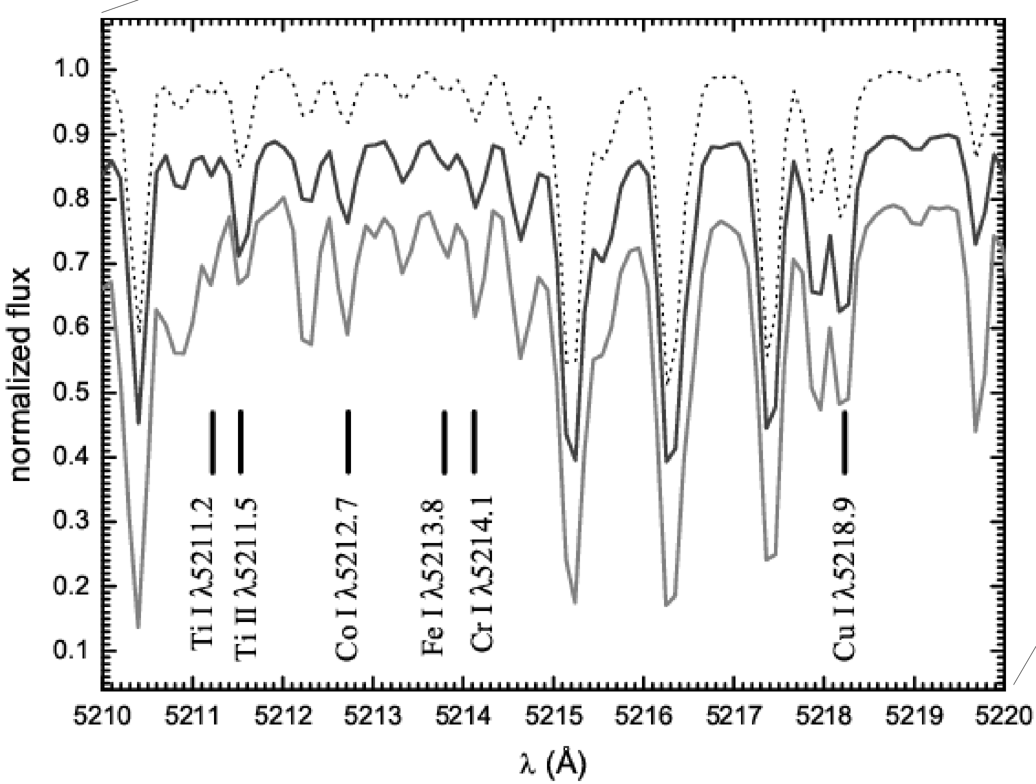




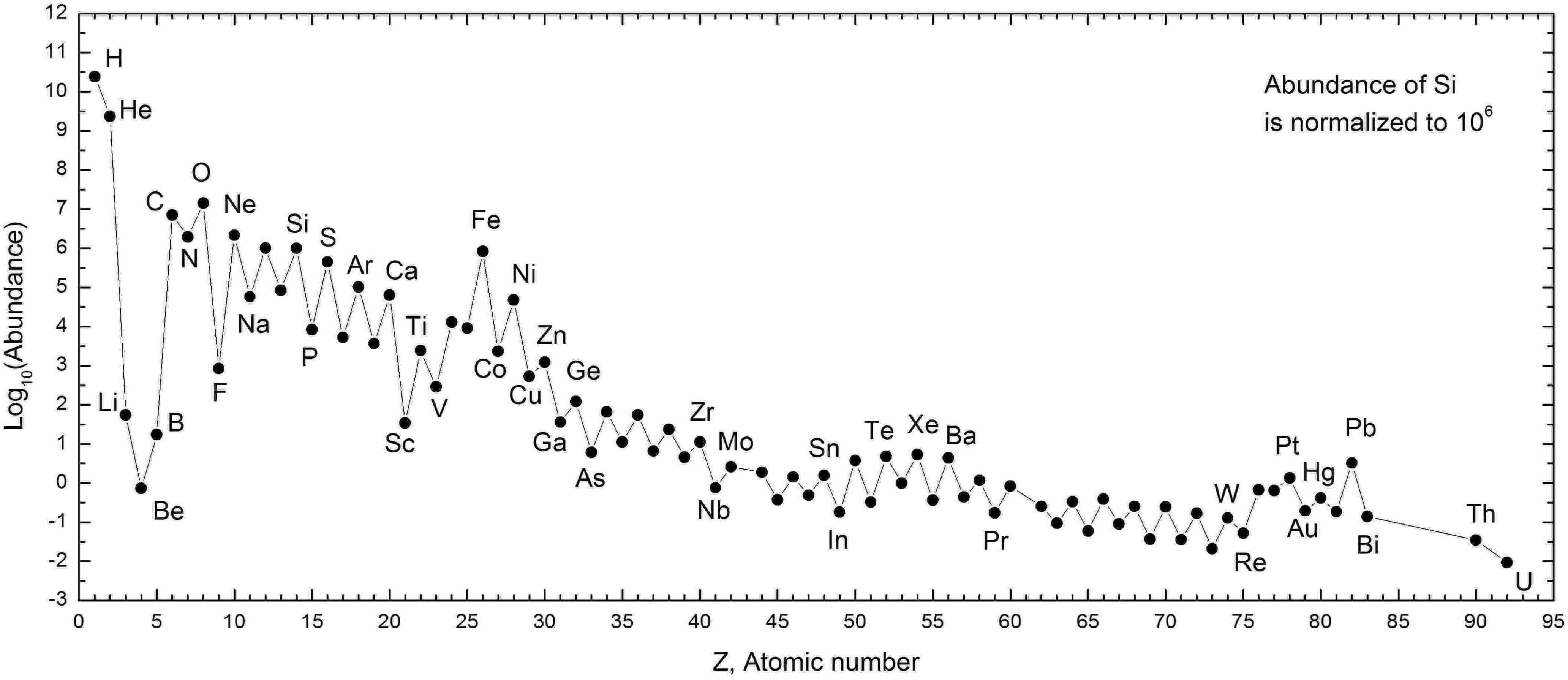
Ångström

$1\text{Å} = 10^{-10}$ m

$= 10^{-1}$ nm

Spectroscopy

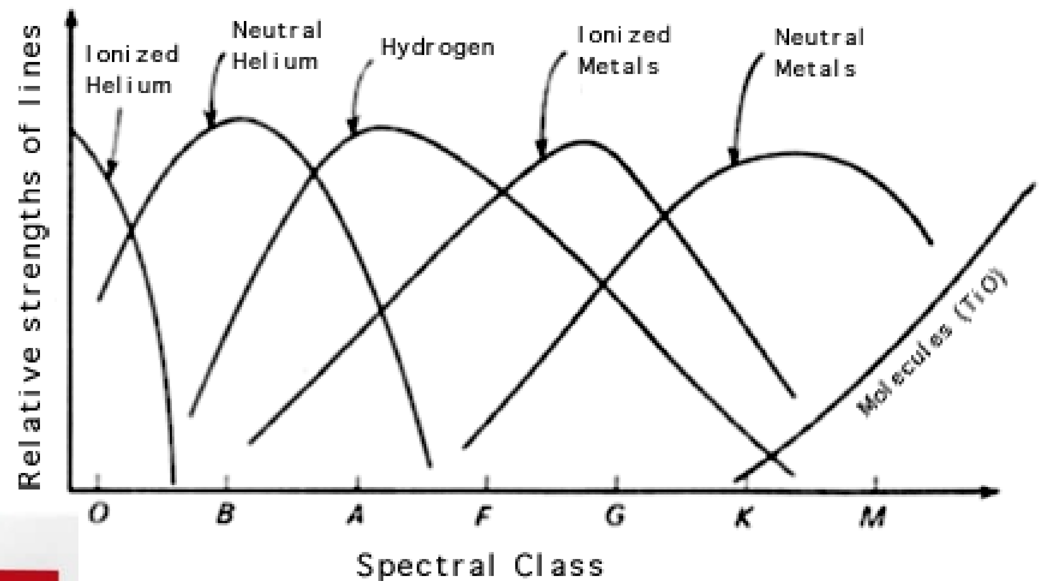
The chemical composition of the Sun

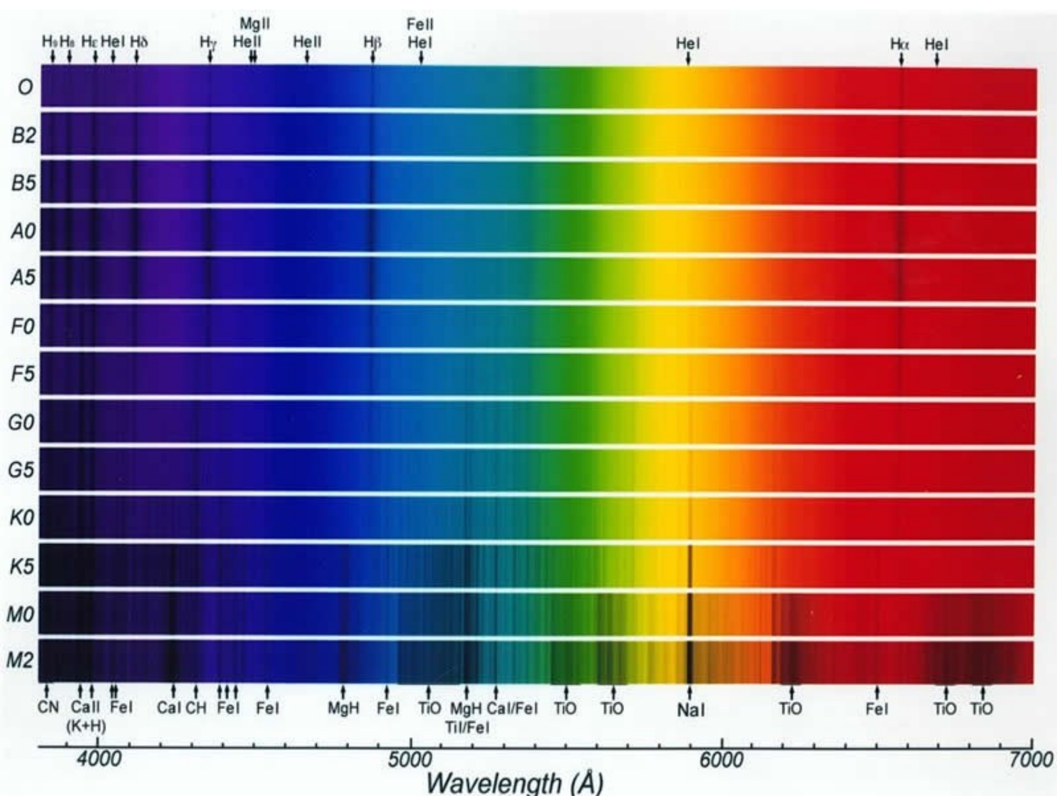


Spectroscopy

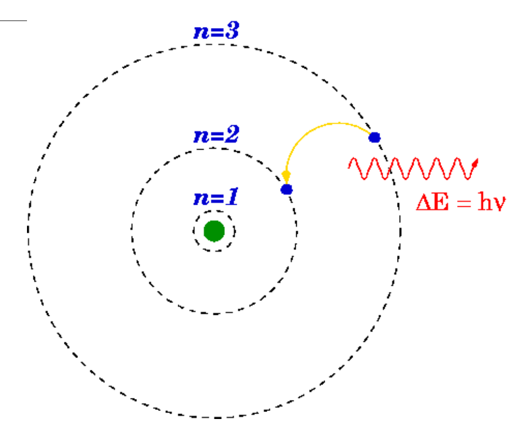
The strength of spectral lines enables a measurement of the stellar temperature

Excitation-ionization sequence



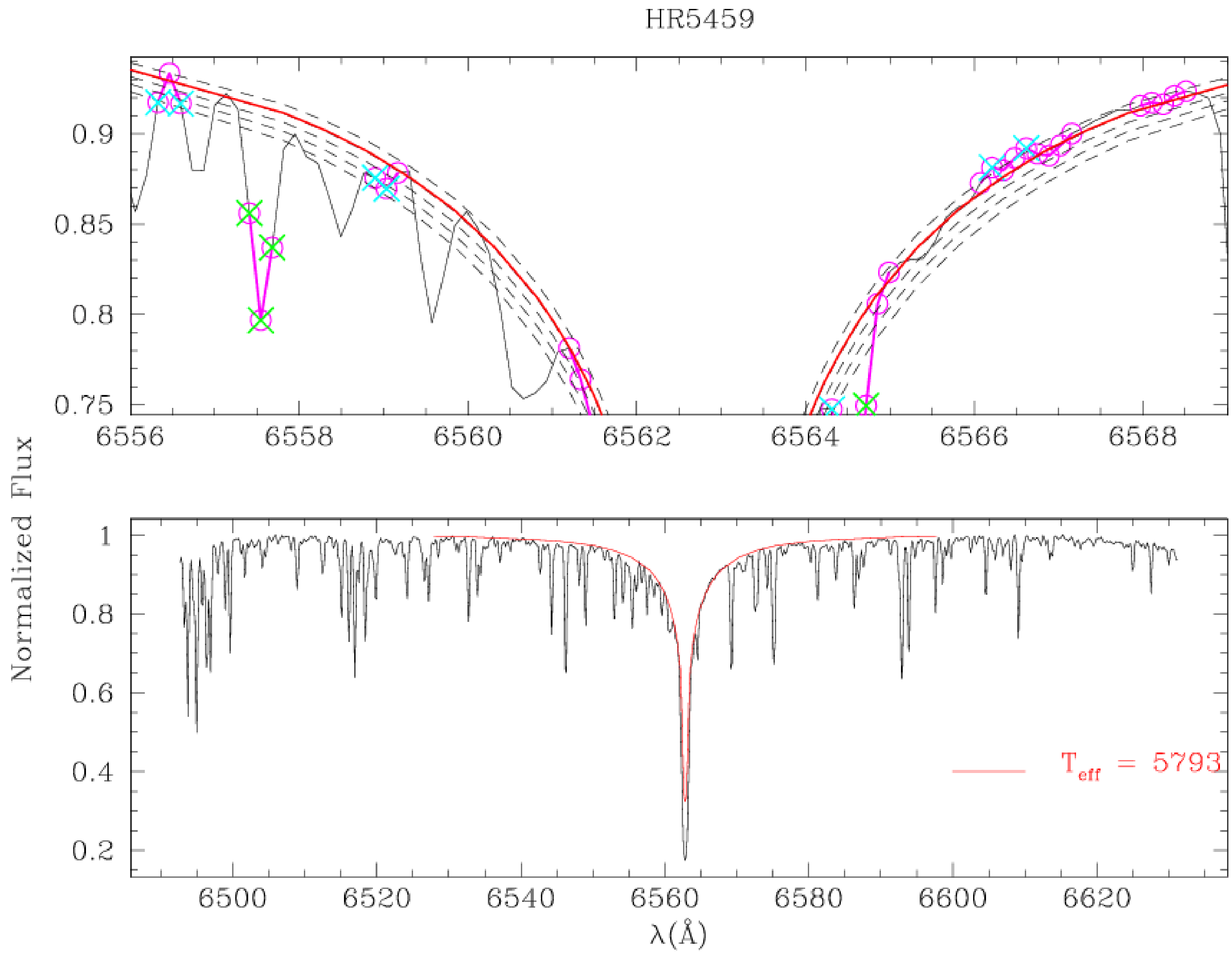


Resulting lines

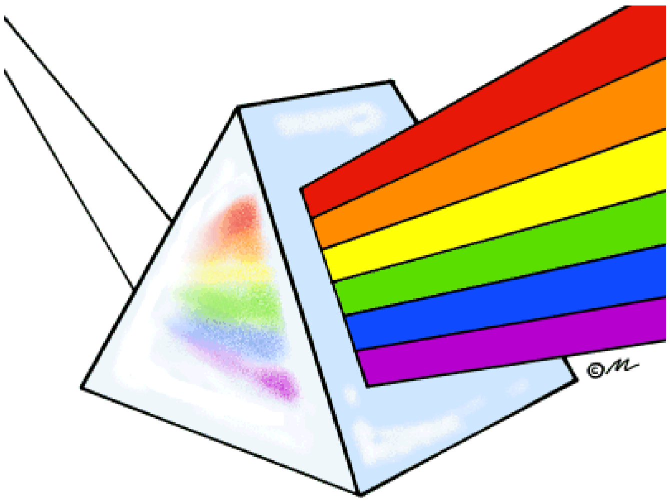


Spectroscopy

Measuring temperatures by the wings of Ha

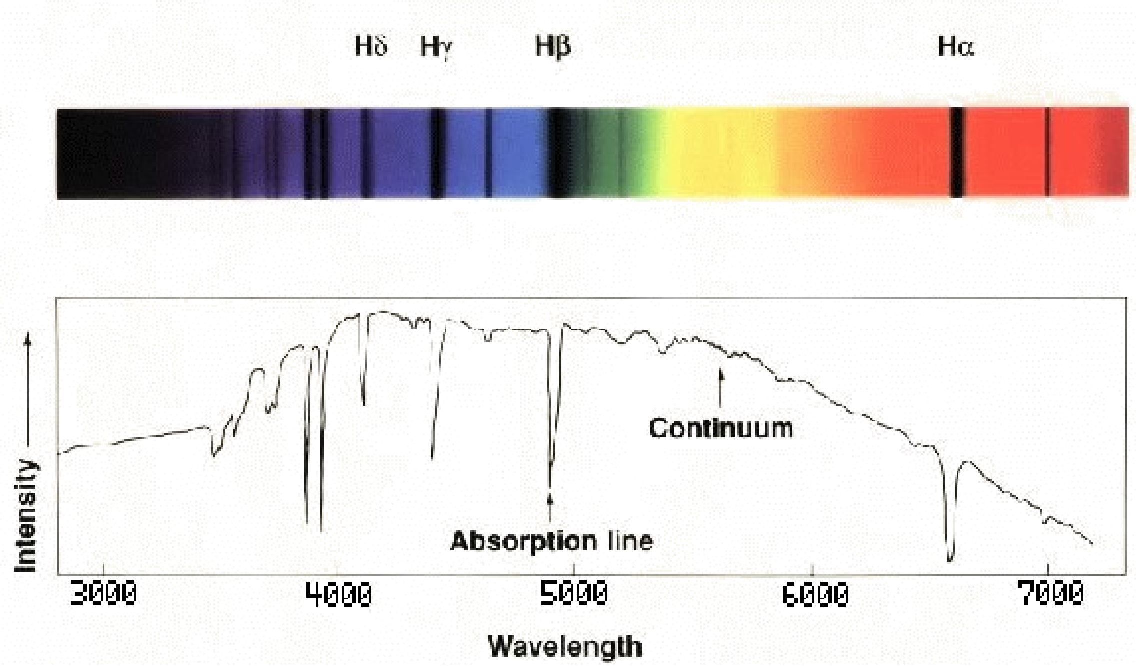


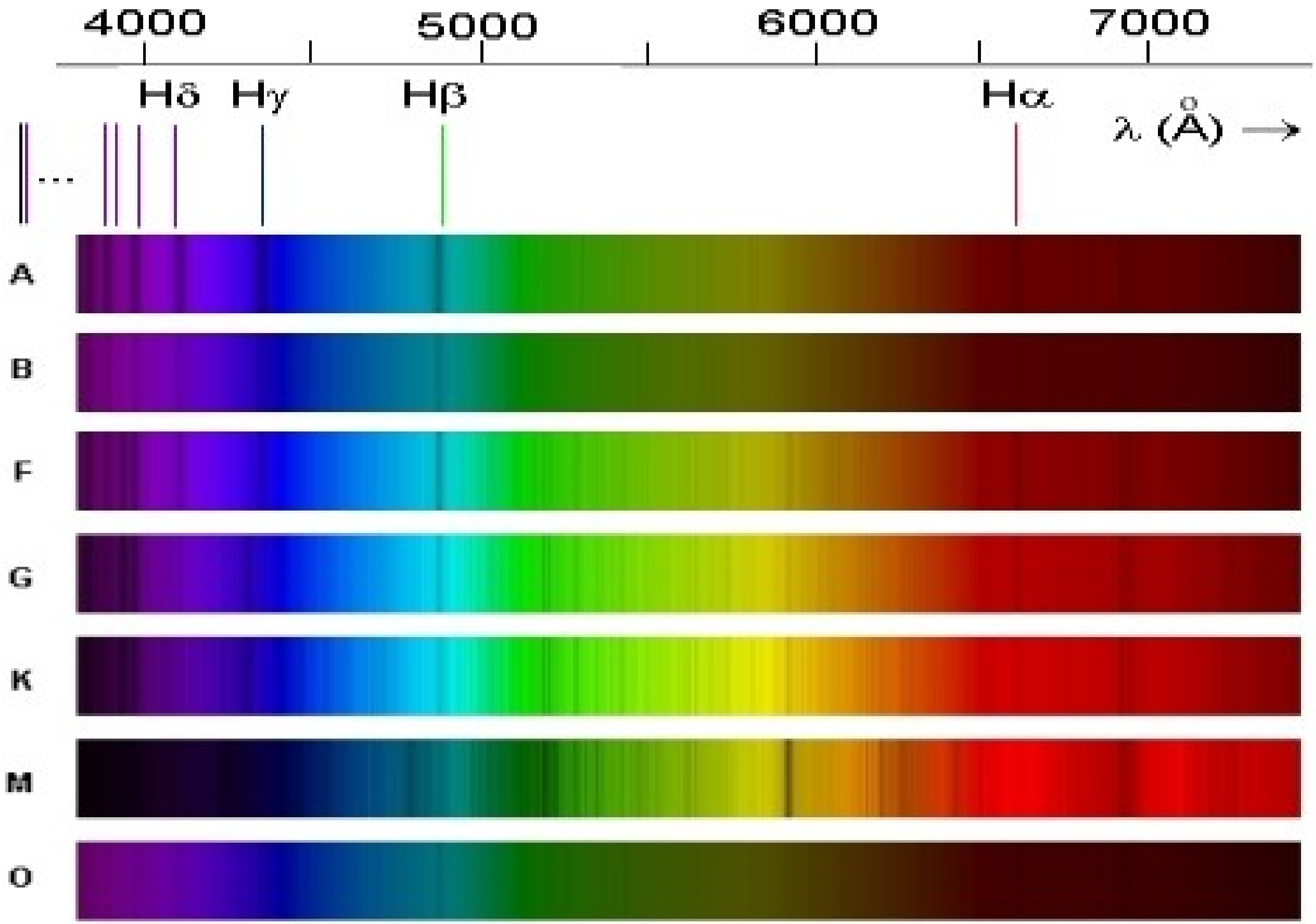
Why OBAFGKM? A little history of spectral classification



A prism decomposes
white light into a spectrum

Absorption lines!





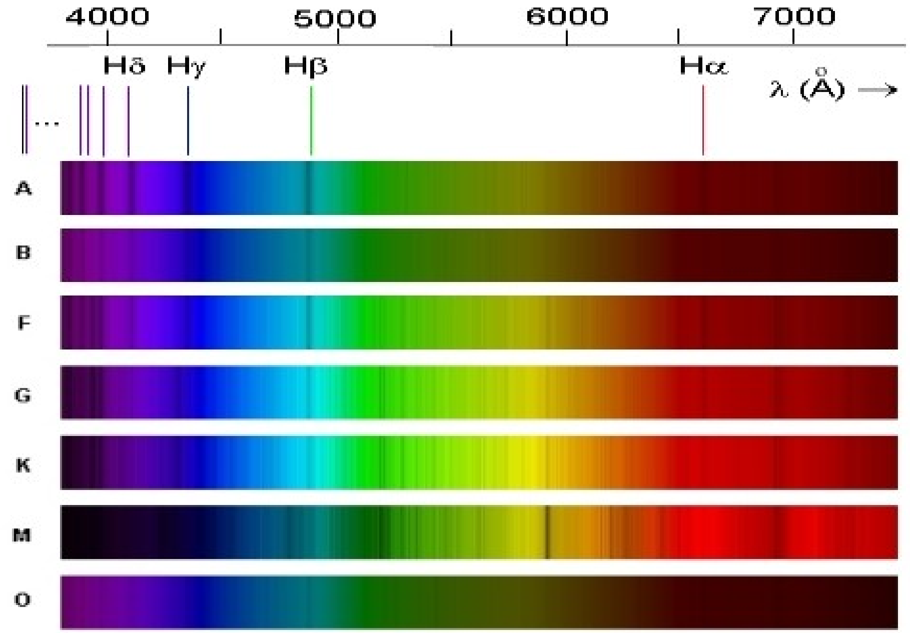
The hydrogen Balmer spectrum is visible for most stars. And astronomers catagorized stars according to the strength of the hydrogen absorption lines in the spectrum in the late 19th century.

1860s – **Antonio Secchi** classifies the stars based on the width of Hα, giving roman numerals I-IV.

1890s - **Williamina Fleming** uses fine details and replaces the Roman numerals with letters A-N

1900s – **Annie Jump Cannon** recognizes that the sequence is almost a **temperature sequence** (from color and shape of the spectrum), but O and B were misplaced. She makes a true temperature sequence by ordering the types as **OBAFGKM** and also invents the mnemonics.

1925 – **Cecilia Paynes** uses Megh Saha's ionization theory to accurately describe the sequence as an **excitation-ionization sequence determined by temperature**. It was described as the *most brilliant thesis ever written in Astronomy*.



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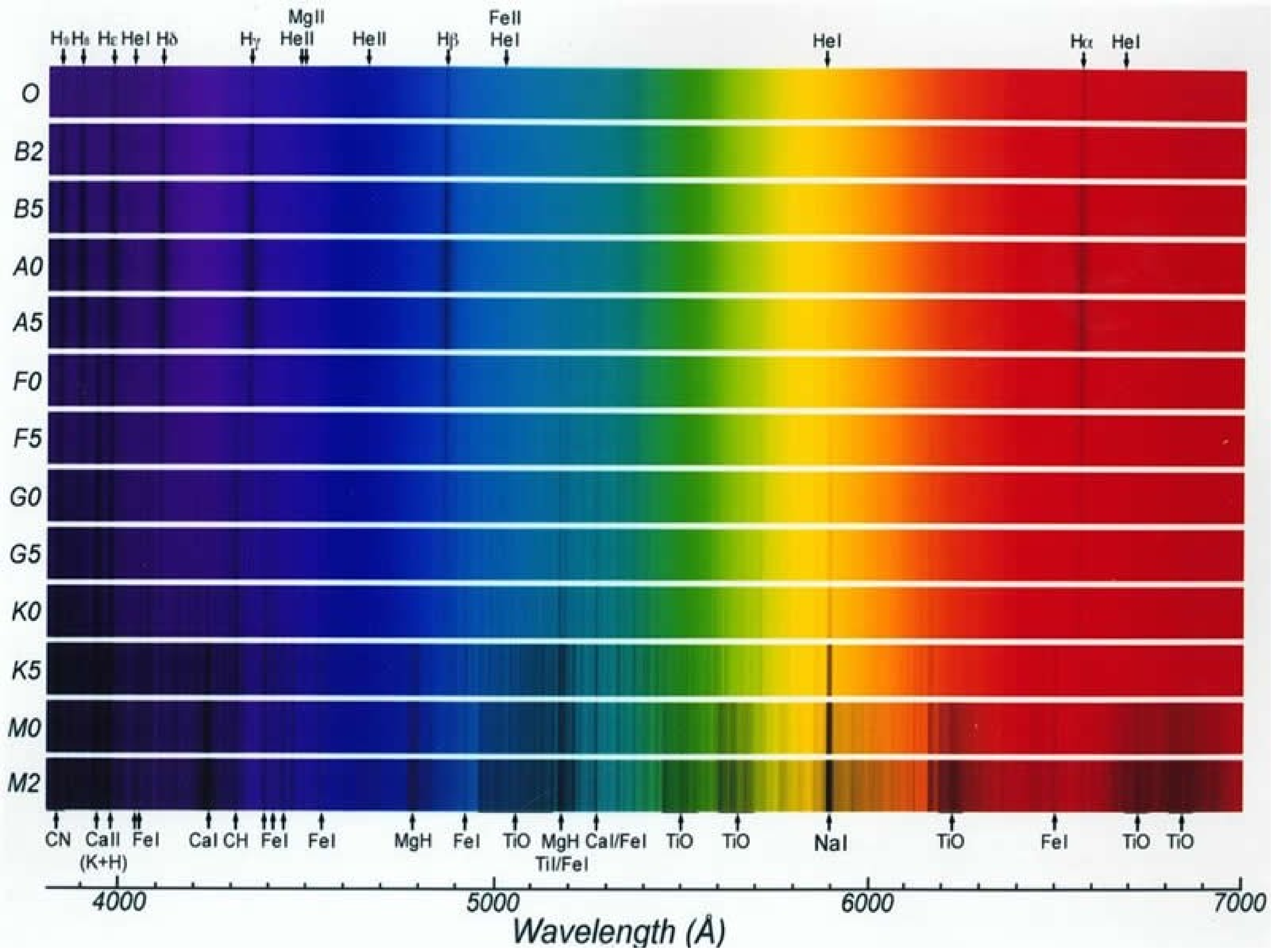
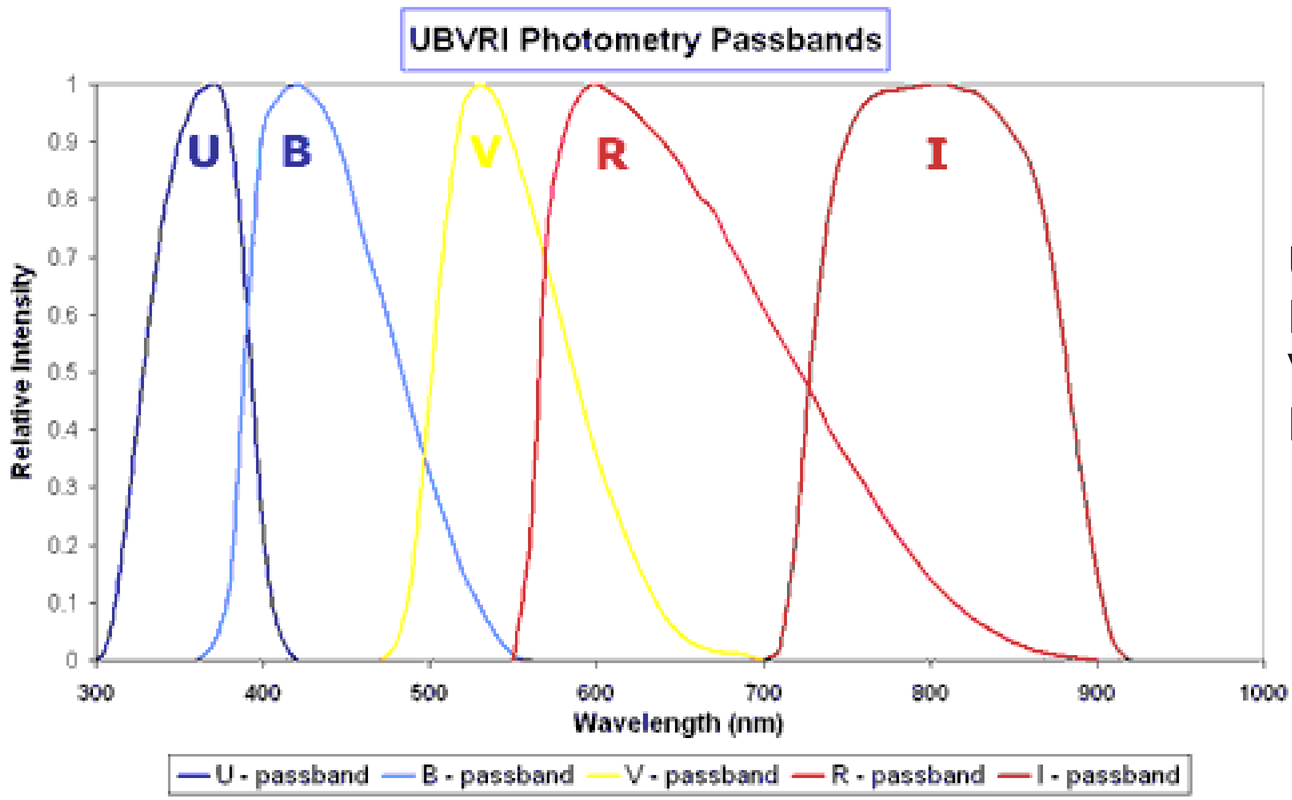


Hε HeI Hδ Hγ
MgII
HeII
HeII
Hβ
FeII
HeI
HeI
Hα
HeI
O
B2
B5
A0
A5
F0
F5
G0
G5
K0
K5
M0
M2
CN
CaII
(K+H)
FeI
CaI
CH
FeI
FeI
MgH
FeI
TiO
MgH
TiI/FeI
CaI/FeI
TiO
TiO
NaI
TiO
FeI
TiO
TiO
4000
5000
6000
7000
Wavelength (Å)

Photometry

The UBVRI system – 5 little quantities that carry a lot of information



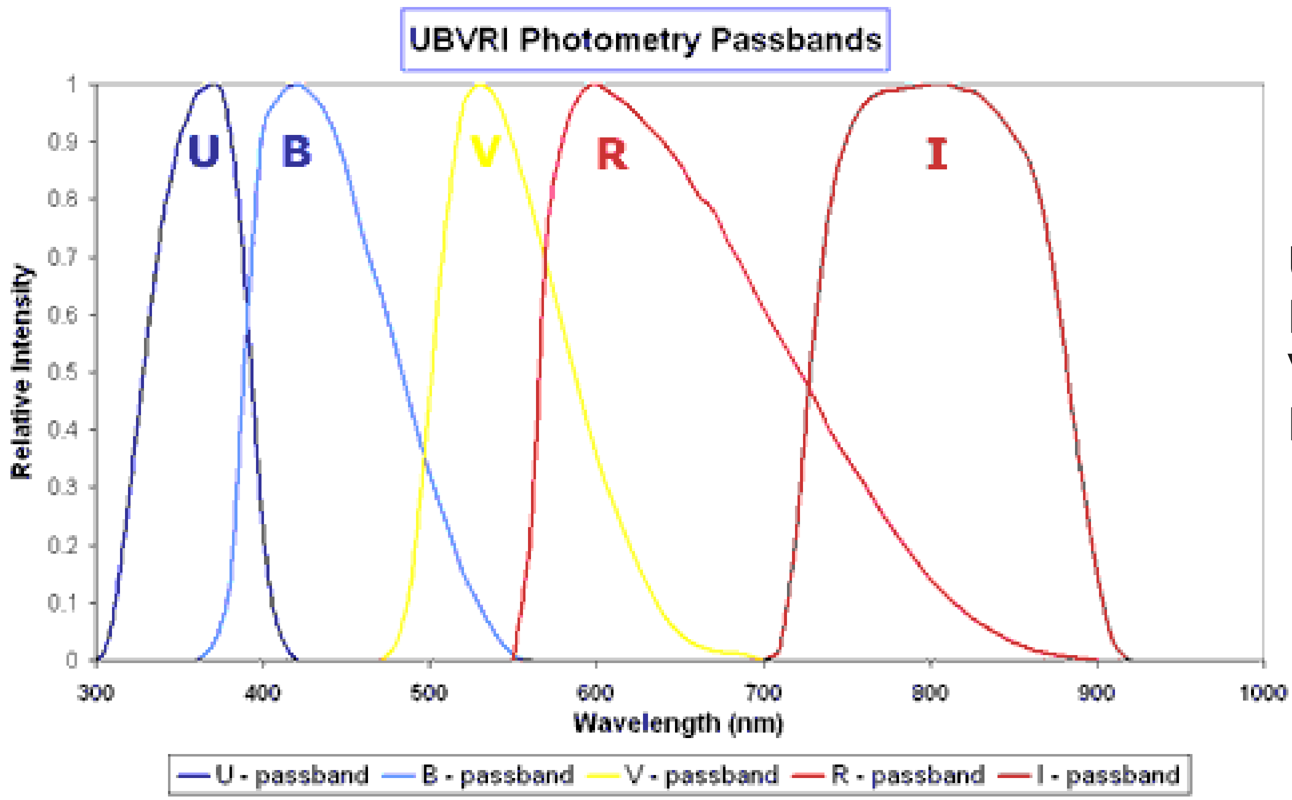
Ultraviolet
Blue
Visible
Red
Infrared

These are magnitudes!

M_U M_B M_V M_R M_I

Photometry

The UBVRI system – 5 little quantities that carry a lot of information



Ultraviolet
Blue
Visible
Red
Infrared

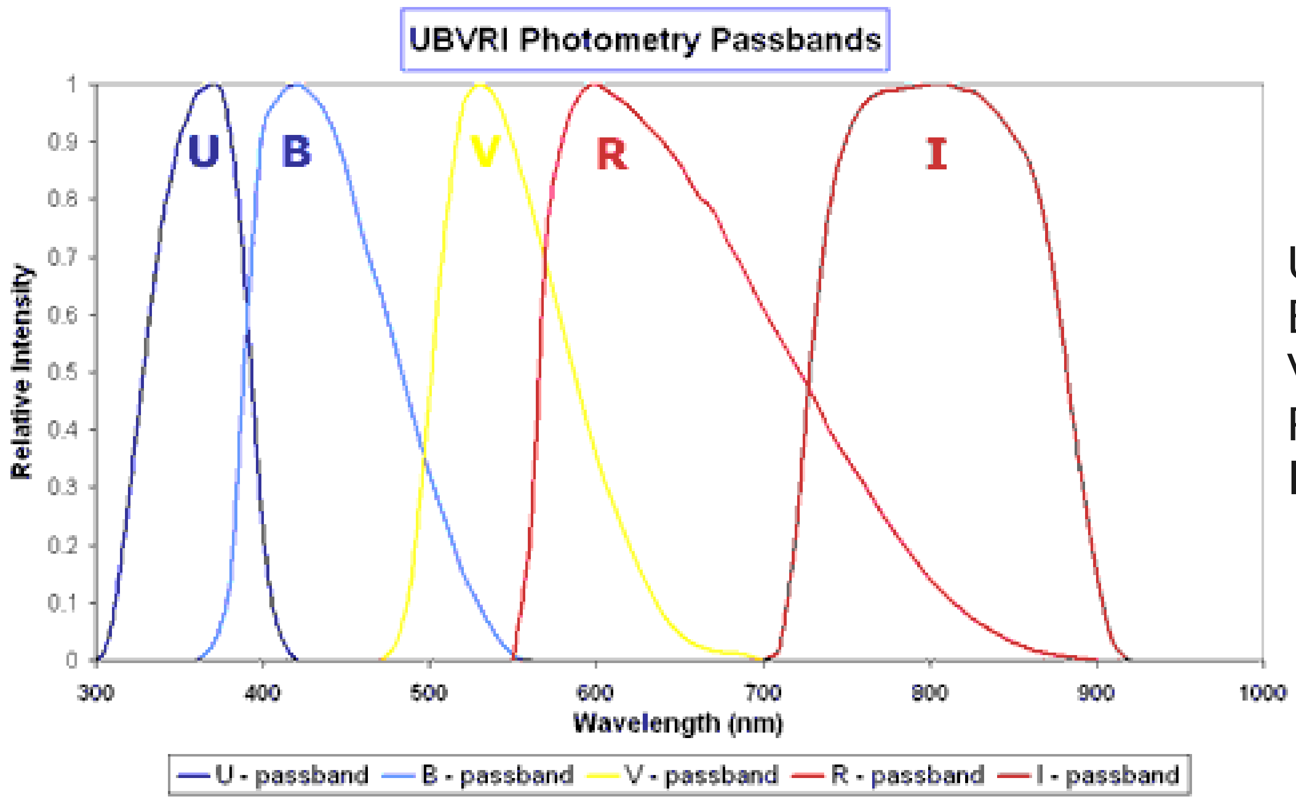
These are magnitudes!

$M_U \ M_B \ M_V \ M_R \ M_I$

When you ask an astronomer for a magnitude, you have to specify the waveband.

Photometry

The UBVRI system – 5 little quantities that carry a lot of information



Ultraviolet
Blue
Visible
Red
Infrared

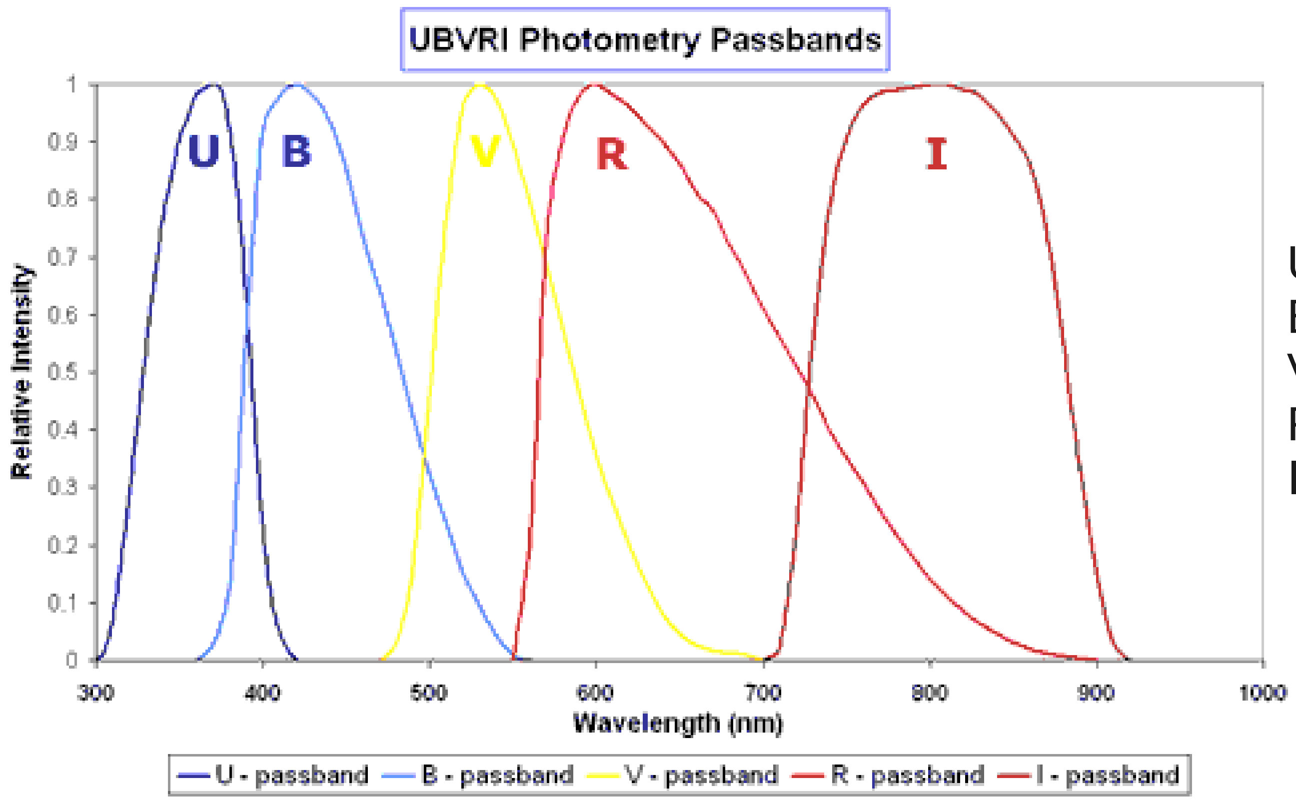
These are magnitudes!

$M_U \; M_B \; M_V \; M_R \; M_I$

Bolometric Magnitude

Photometry

The UBVRI system – 5 little quantities that carry a lot of information



Ultraviolet
Blue
Visible
Red
Infrared

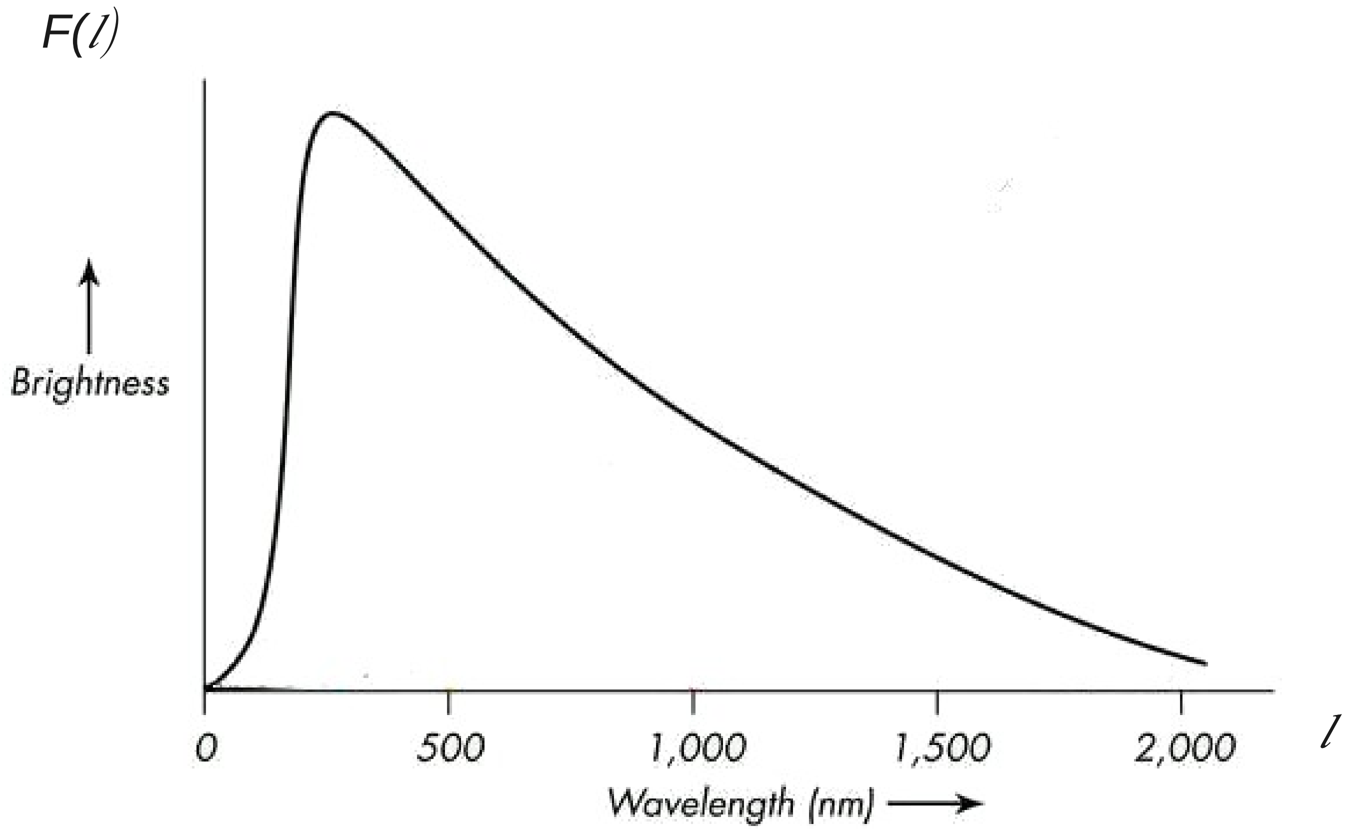
These are magnitudes!

$M_U\ M_B\ M_V\ M_R\ M_I$

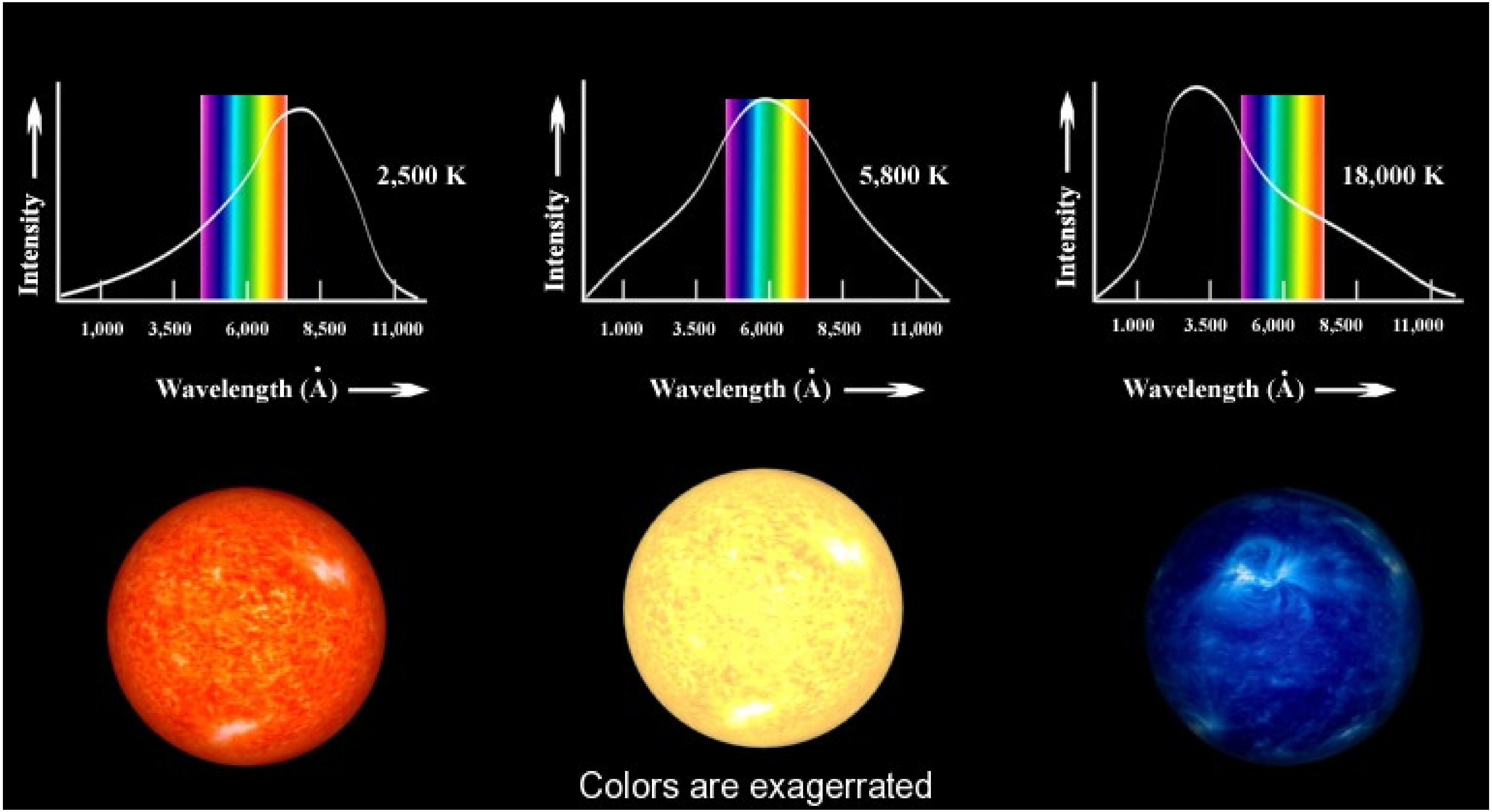
Bolometric Magnitude = In all wavelengths

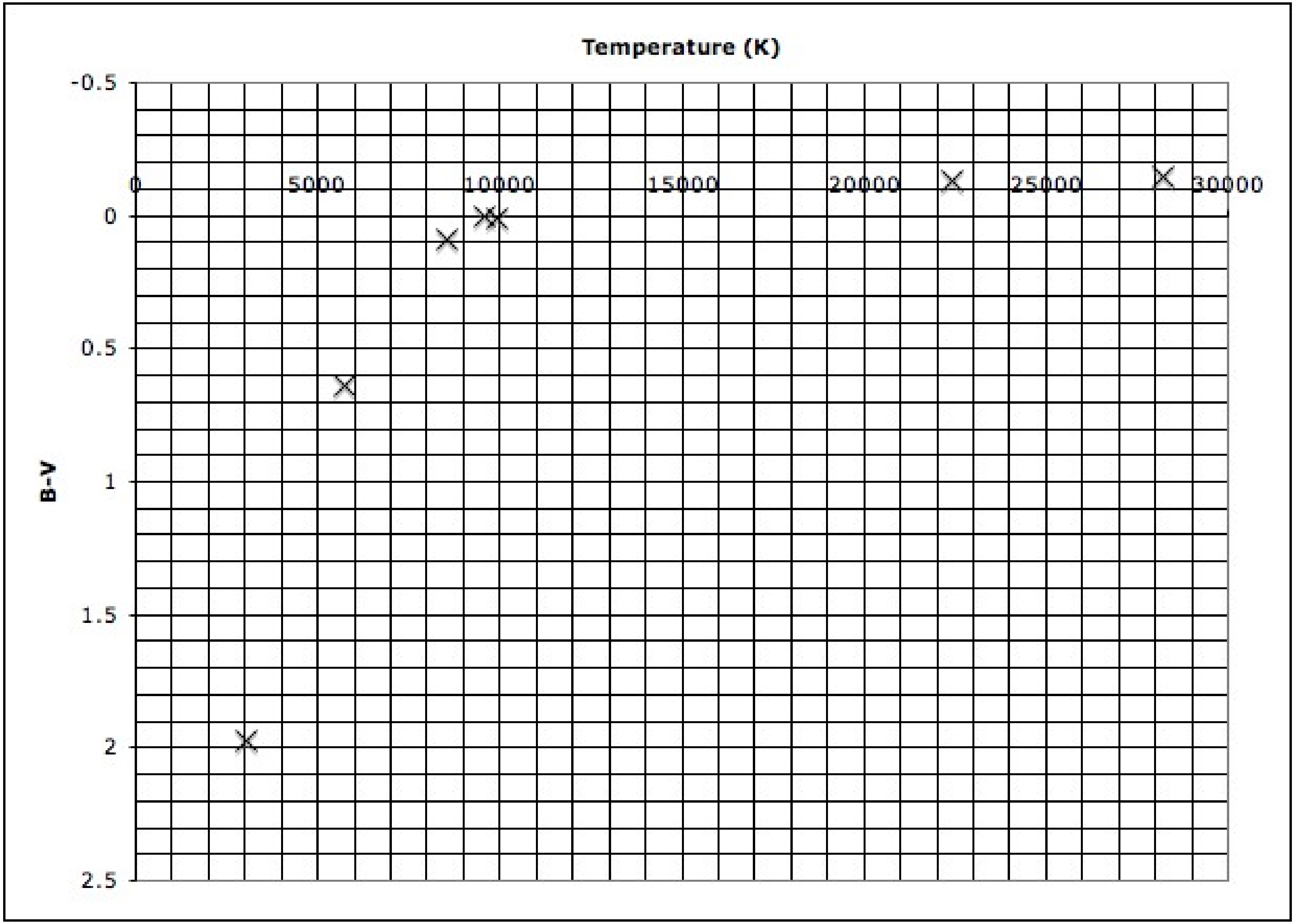
*(*integrated over the whole electromagnetic spectrum, from radio to gamma rays*)*

The Black Body radiation curve again



Color as a measurement of temperature

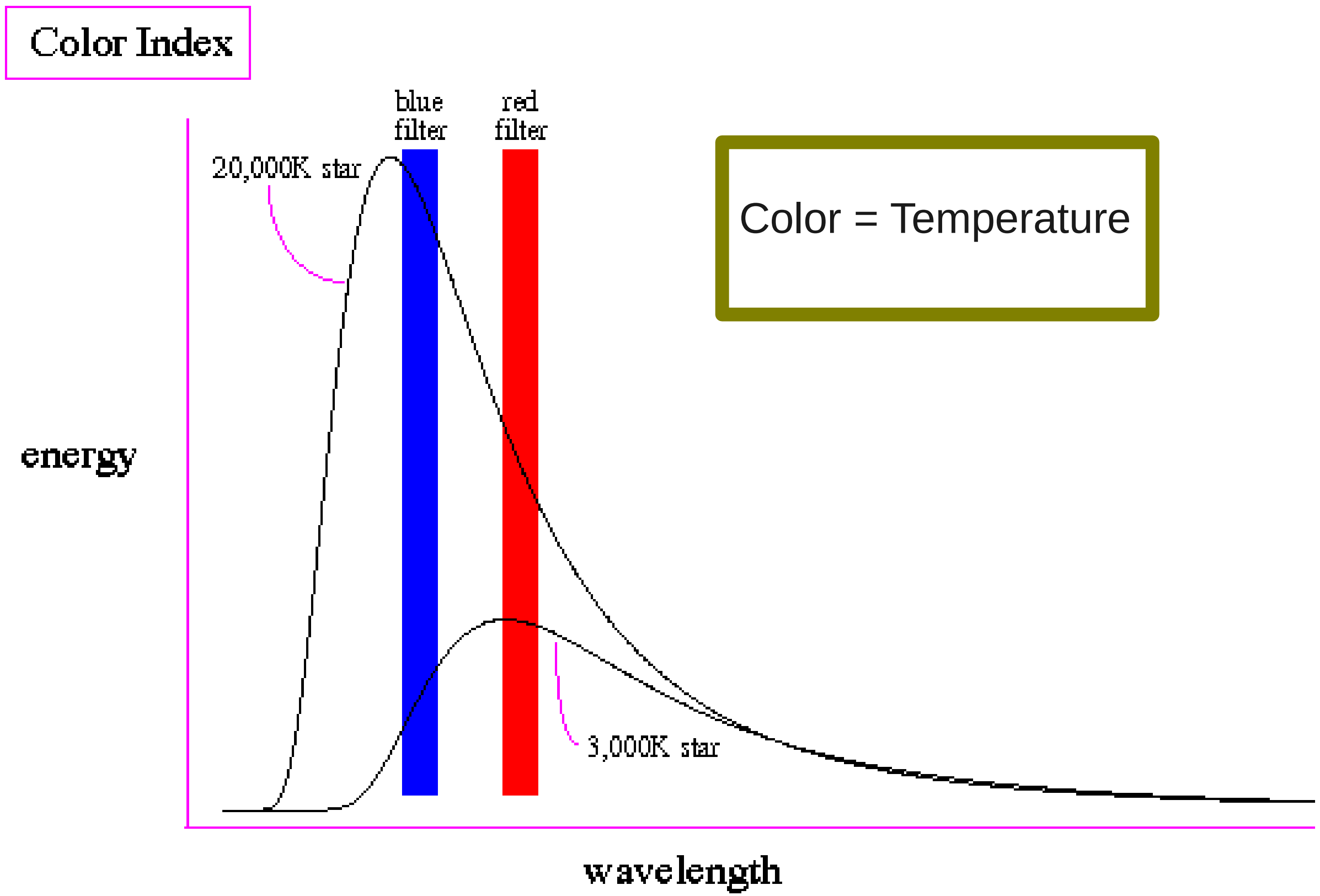




Temperature (K)
0
5000
10000
15000
20000
25000
30000
-0.5
0
0.5
1
1.5
2
2.5
B-V

Photometry

Color: Magnitude difference between filters. Eg. *B-V, U-B, V-I, B-R*



Color = Temperature

Color is a measurement of the **slope** of the Black Body radiation curve
And therefore of temperature!

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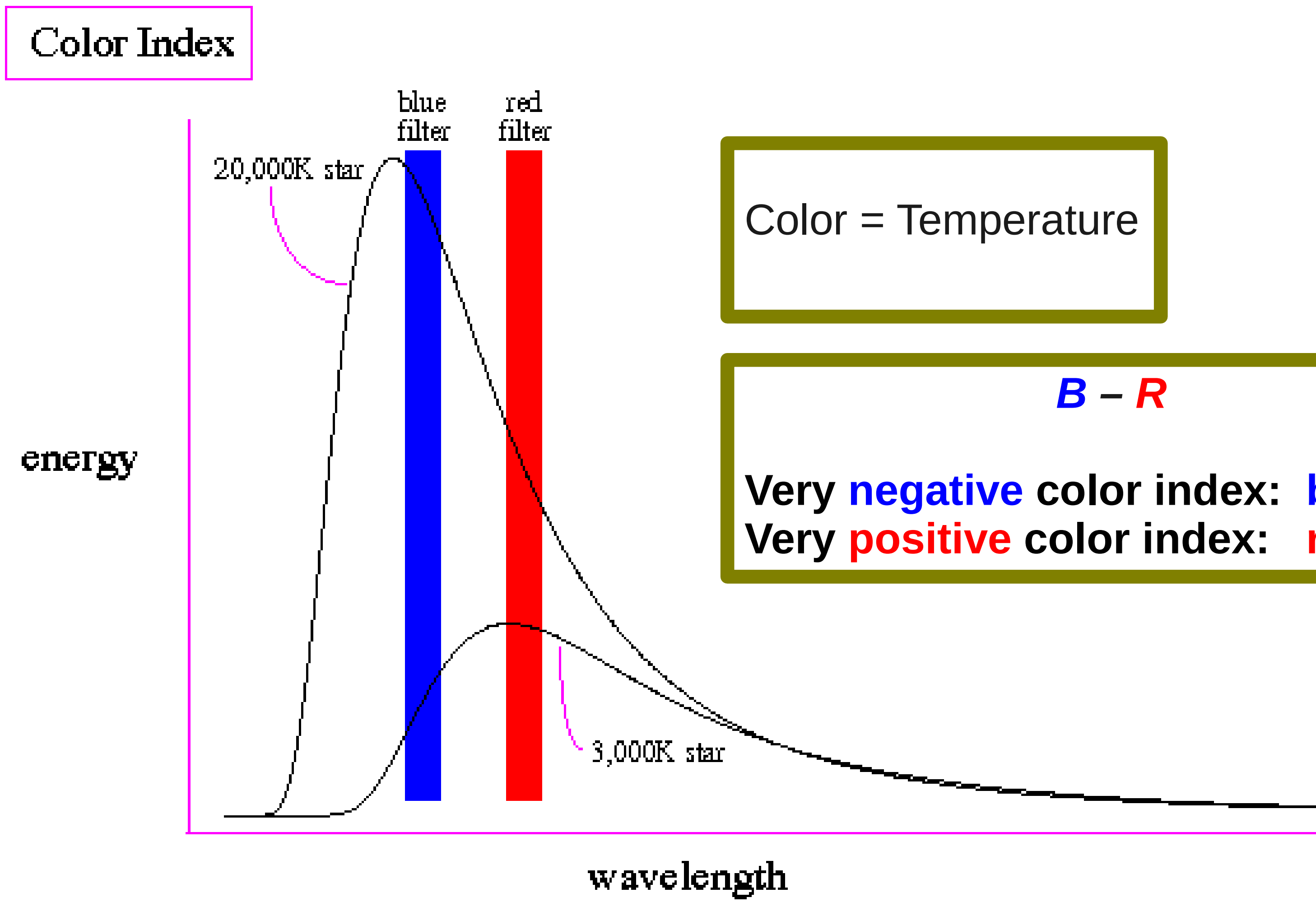


Color = Temperature

B* – *R

Very negative color index: blue
Very positive color index: red

Color is a measurement of the **slope** of the Black Body radiation curve
And therefore of temperature!

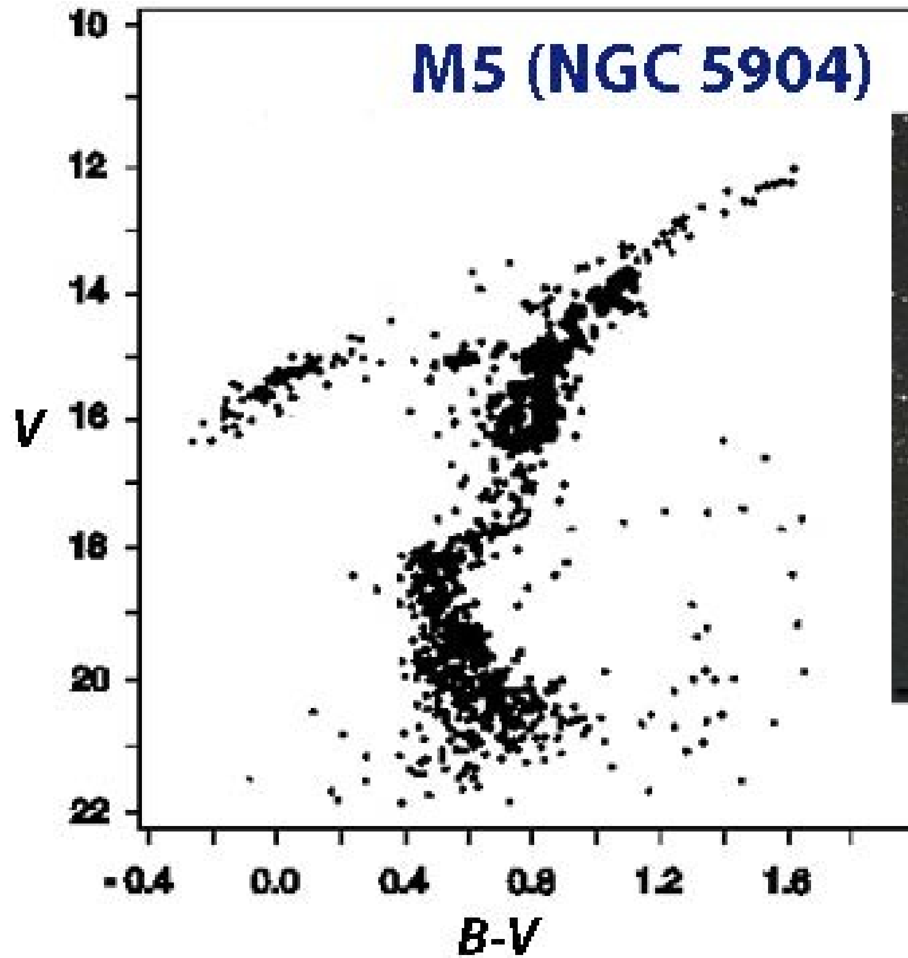
Photometry

Photometry of a single star is a lot less accurate than spectroscopy of a single star

The **main advantage** of photometry over spectroscopy is that
one can easily measure a statistically significant sample of stars.

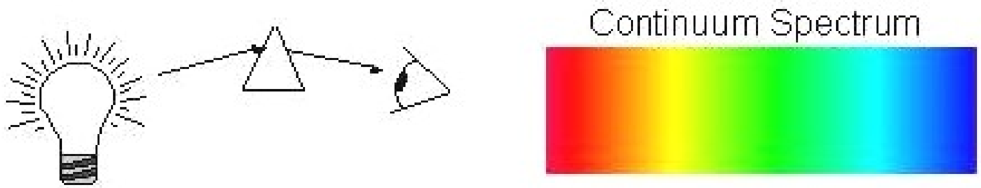
Application: Clusters
Instead of a HR diagram, we can do a **Color-Magnitude diagram** (CMD)

- A cluster has $>10^4$ stars
- Impractical to do a spectral analysis of every star to get temperatures
- But... we can do photometry of a whole field in one go!

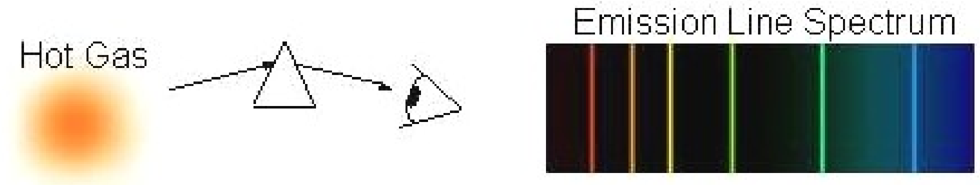


Let's summarize

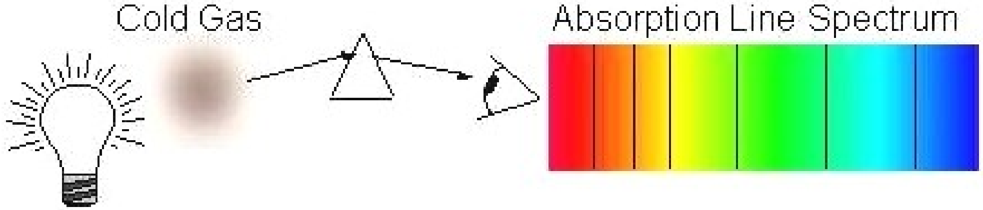
Kirchhoff's three empirical laws of spectroscopy



A hot solid or a hot dense gas produces a continuum spectrum.



A hot low-density gas produces an emission-line spectrum.



A continuos source viewed through a cold gas produces an absorption-line spectrum.

Let's summarize

Kirchhoff's three laws of spectroscopy

Stellar spectra are absorption spectra, thus hot source covered by colder gas

Spectral lines are chemical fingerprints, a

otometric passbands UBVRI

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ndividual accuracy. Photomet

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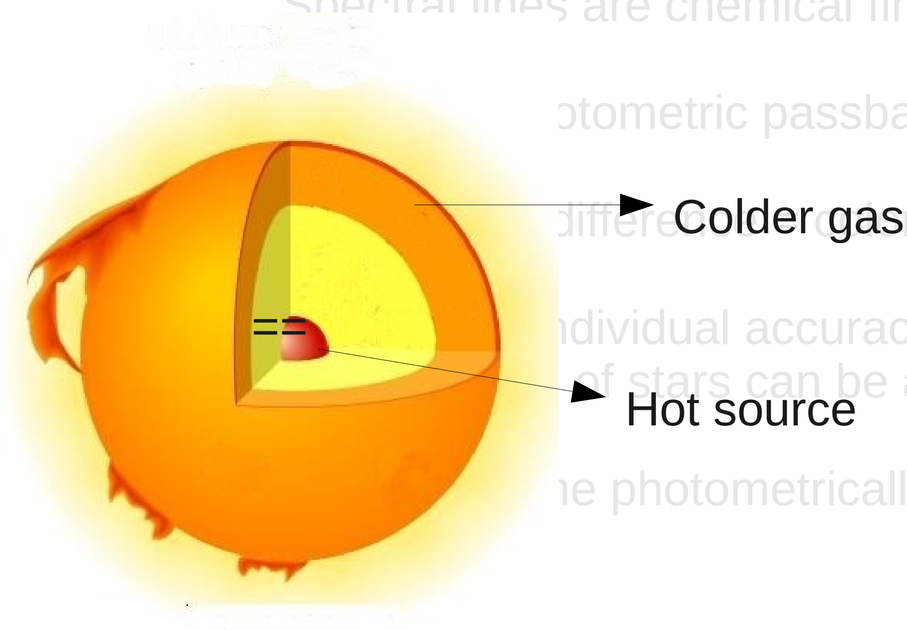

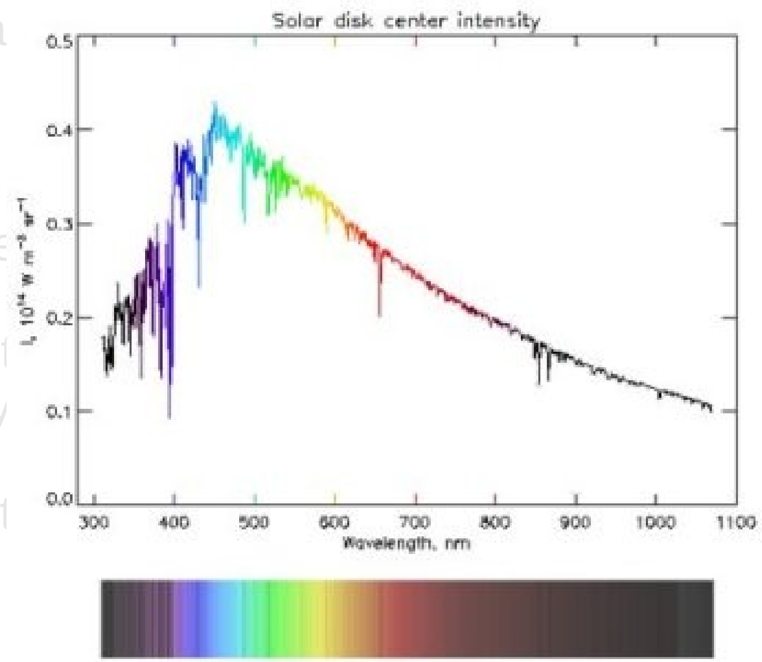

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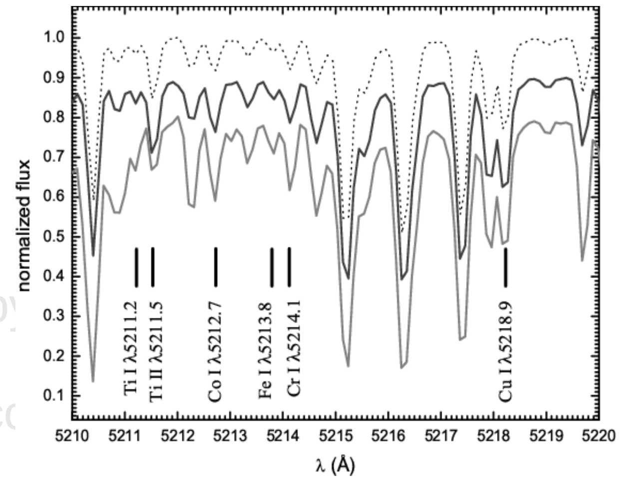

Kirchhoff's three laws of spectroscopy

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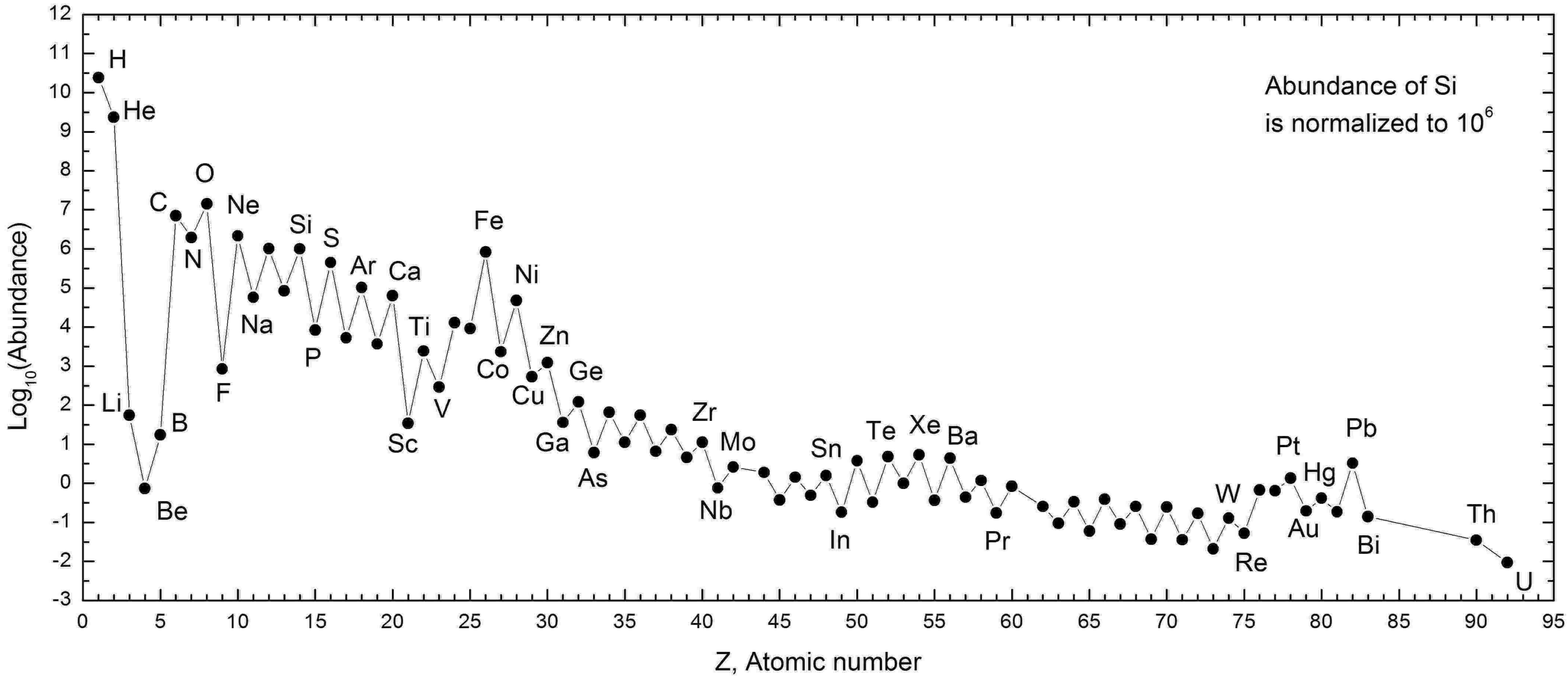
Spectral lines are chemical signatures, and a mine of information

Five photometric passbands UBVRI. Five magnitudes.



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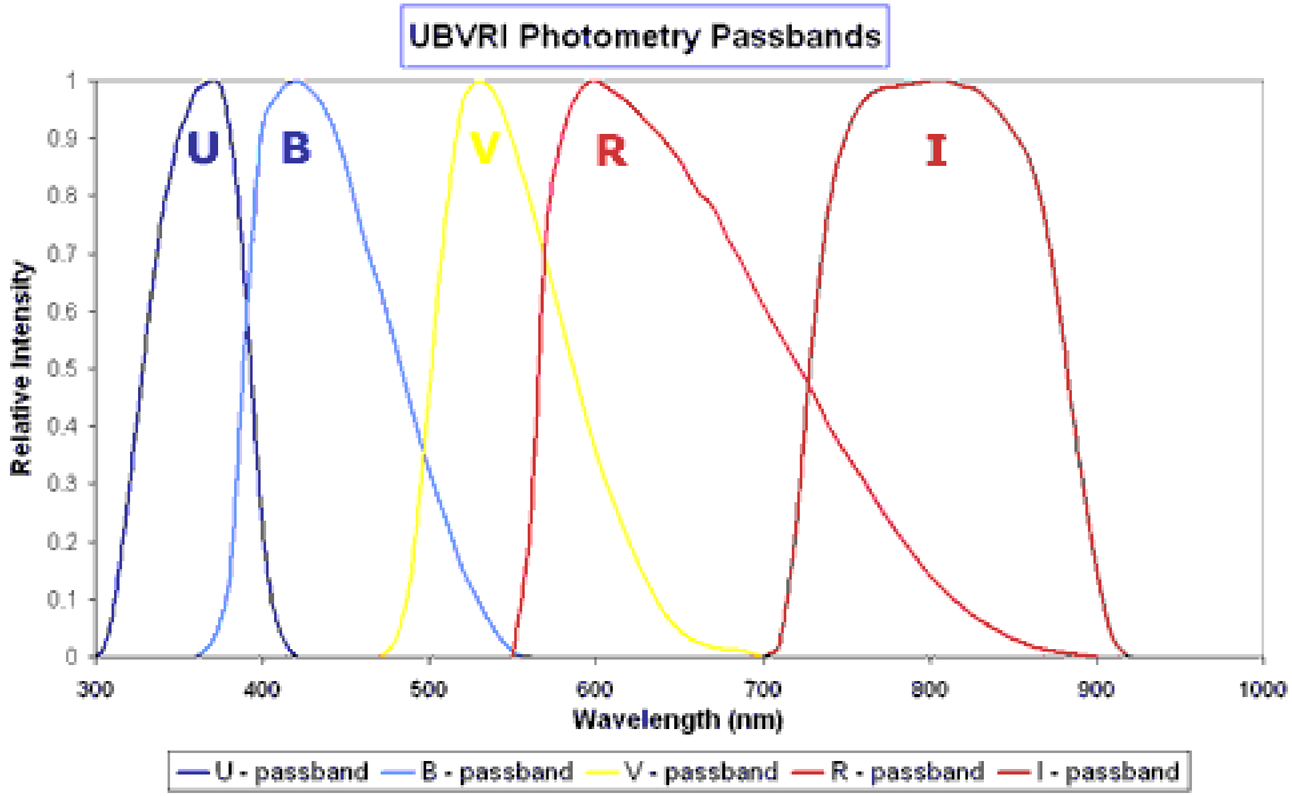

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Kirchhoff's three laws of spectroscopy

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Magnitude difference = color. A measurement of temperature.

large number statistics.
asured in a single frame.

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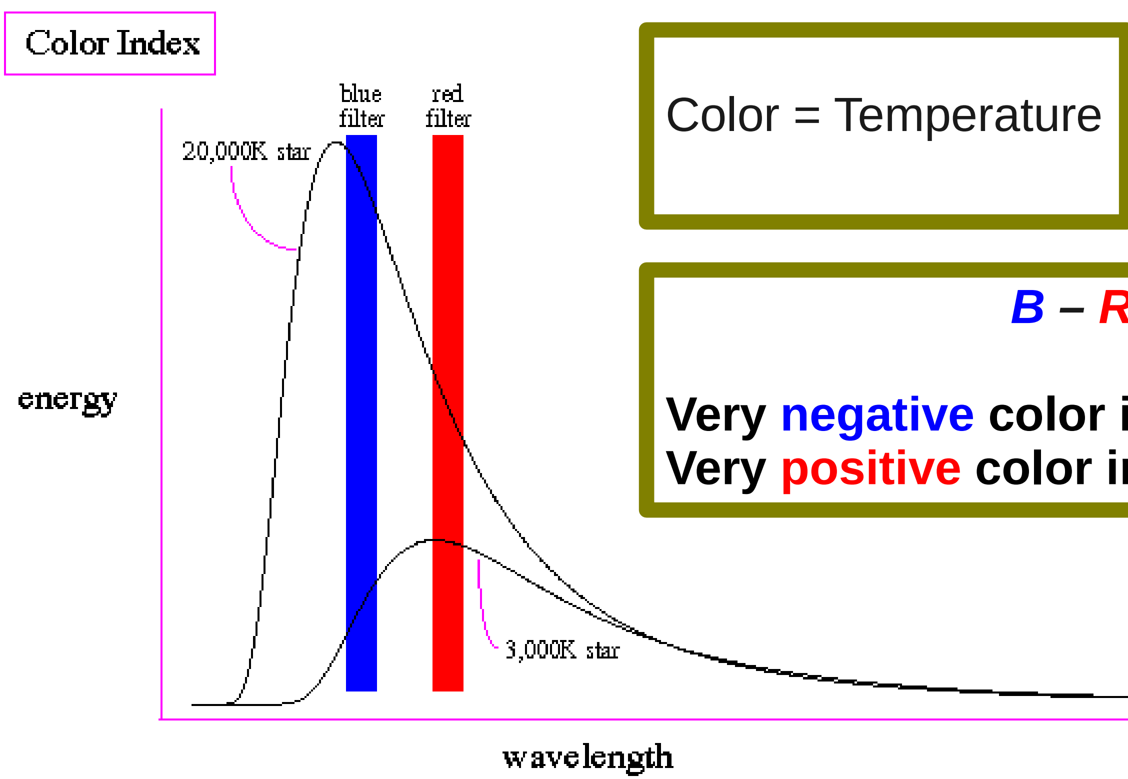

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Let's summarize

Proper motion: movement of stars in the sky. Typical 0.1"/yr. Barnard's star 10"/yr.

Distance is hard to measure. Parallaxes only work up to 1000 pc.

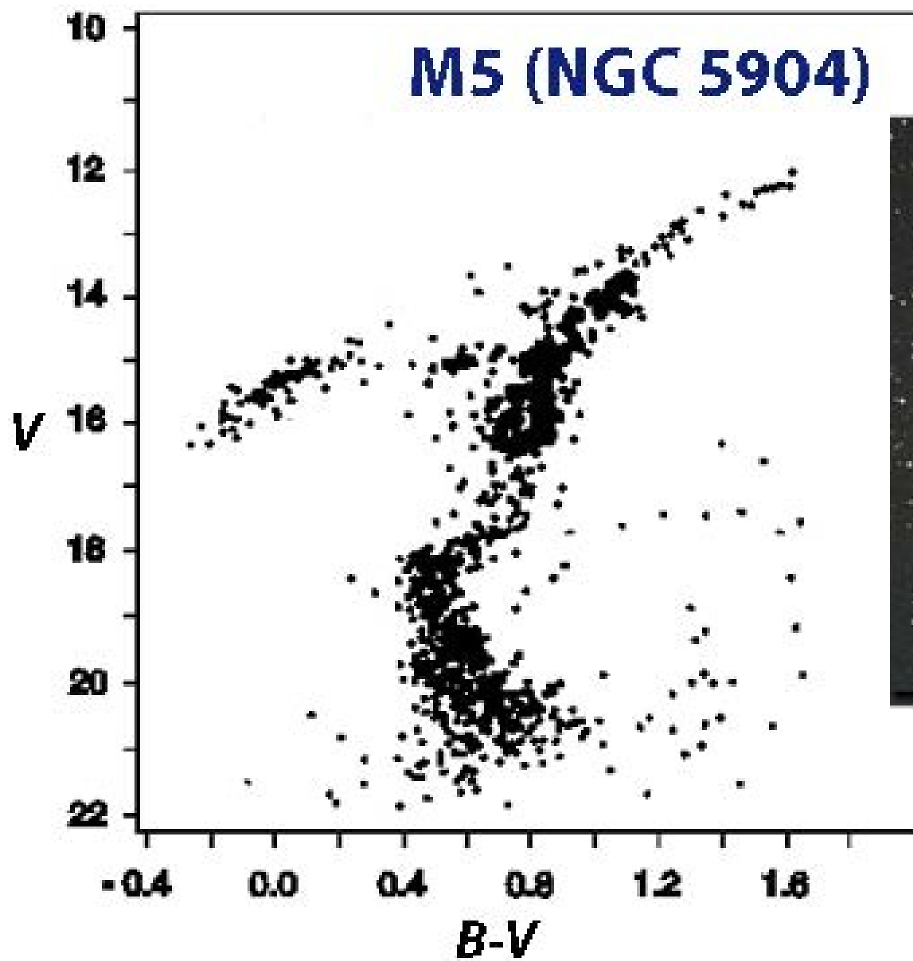
Beyond tha ... d candles.

E ... a

Type Ia Super ... gical distances

Stellar ... der gas

S ... n



Spectroscopy = individual accuracy. Photometry = large number statistics.
Tens of thousands of stars can be automatedly measured in a single frame.

CMD is the photometrically equivalent to the HR diagram.

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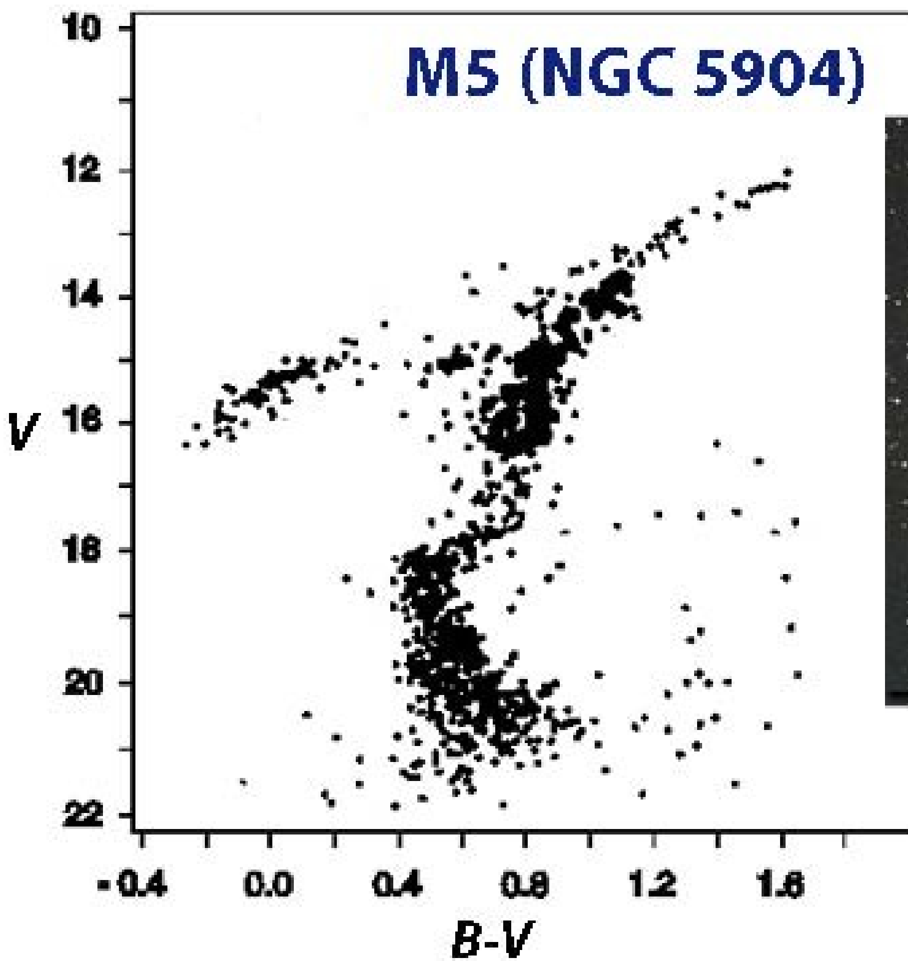

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