Astronomy 112
Physics of Stars

http://www.ucolick.org/~woosley/

- Stan Woosley

Why study stars?

- Most of luminous matter in universe
- Abodes of life and origin of the elements
- Applied physics laboratories
- Precursors to interesting high energy phenomena
- Particle physics laboratories
- Big explosions

A star is a gravitationally confined thermonuclear reactor. All “true stars” obtain their energy from nuclear fusion, though there are interesting variations that are not nuclear powered because they are not hot enough or have become “degenerate”.

Because stars radiate, they must evolve. Their energy is obtained at the expense of changing their composition. With time, these composition changes alter the stellar structure.

So long as a star is “non-degenerate”, the loss of energy from its surface requires that it gets *hotter* in its interior (Virial theorem). This continues until the star becomes degenerate, explodes, or becomes a black hole.

From these simple principles the scope of much of the course can already be discerned:

- Stellar structure resulting from an interaction of gravity, pressure (EOS), and nuclear fusion.

- Radiation transport and mass loss

- Nuclear and particle physics

- Solving the coupled differential equations to get the time history (usually done on a computer nowadays)

- Examining end points of stellar evolution

- Comparing with observations

Observations of Stars I:

- Age of the sun
- Stars – general properties
- Luminosity and brightness
  Stellar magnitudes
- Parallax and distances
- Standard candles

(Glatzmaier and Krumholz 1; Prialnik 1.1 1.2; Pols 1 and Ay 12)

The Sun

The star we can study in greatest detail is rather typical.

$M_\odot$ Mass = 1.989 x 10^{33} gm; about 300,000 Earth masses

$R_\odot$ Radius = 6.96 x 10^5 km; almost 100 Earth radii

Average density 1.41 gm/cm^3 $\frac{3M_\odot}{4\pi R_\odot^3}$

Age = 4.56 x 10^9 years

$L_\odot$ Luminosity = 3.83 x 10^{33} erg/s

Central temperature = 15.7 million K

Central density = 162 g cm^{-3}

Photospheric temperature 5772 K

Rotation period 24.47 days at the equator
slower near poles

Surface composition (by mass) 70.6% H
27.5% He, 1.9% C, N, O, Fe, Si, etc
(like the modern "universe")

A typical star, but a little on the heavy side.

Age of the earth and sun

While other techniques exist for showing that the age of the sun and earth is around 4 – 5 billion years (solar models, for example), the most reliable date come from radioactive dating.

Heavy elements often have several *isotopes*. Their nuclei have different numbers of neutrons, but the same number of protons. When the solar system was born, it was well mixed and isotopically very homogeneous. Samples from many places, on and off the earth, show that an isotopic variation of over 1/1000 is extremely unusual unless the isotopes have been affected by radioactive decay (or, for deuterium, evaporation).

Elemental abundances on the other hand are highly variable due to chemistry.

Age of the earth and sun

Consider uranium and lead. The solar system was born with some heterogeneous distribution of lead and uranium – chemically - but a homogeneous distribution of isotopes. Two uranium isotopes decay to lead, but all presently existing lead isotopes are stable.

In a primordial sample of lead with no uranium in it, the lead isotope ratios would then be just what the solar system was born with. In a sample that contains uranium (in variable proportions) though, both the lead and uranium isotopes will be different today than when the solar system was born.

It is assumed that the sun, earth, moon, and meteorites all have very similar ages. There are other techniques and models that show the interval between solar and earth formation was small.

Radioactive decay

The decay of a radioactive isotope with abundance n is described by by the well known equation

$$\frac{dn}{dt} = -n/\tau$$ where τ is the mean lifetime.

The solution is

$$n = n_0 e^{-t/\tau}$$ where n_0 is the initial abundance.

If this species is decaying to another that has initial abundance m_0 then the abundance of m_0 as a function of time is given by

$$m = m_0 + n_0 (1 - e^{-t/\tau})$$

Age of the earth and sun

$^{235}U \rightarrow {}^{207}Pb \qquad \tau_{235} = 1.015\ Gy \quad (\text{"mean" life} = \frac{\tau_{1/2}}{\ln 2})$

$^{238}U \rightarrow {}^{206}Pb \qquad \tau_{238} = 6.45\ Gy$

^{204}Pb not affected by radioactive decay

Observe ^{204}Pb, ^{206}Pb, ^{207}Pb in a large set of samples - oceanic sediment, meteorites, etc with a variable content of U/Pb chemical ratios

$$^{206}Pb_{now} = {}^{206}Pb_0 + {}^{238}U_0(1 - e^{-t/\tau_{238}})$$

$$^{207}Pb_{now} = {}^{207}Pb_0 + {}^{235}U_0(1 - e^{-t/\tau_{235}})$$

$$^{204}Pb_{now} = {}^{204}Pb_0$$

$$^{206}Pb_0 = f_1 Pb_0 \qquad {}^{207}Pb_0 = f_2 Pb_0 \qquad {}^{204}Pb_0 = f_3 Pb_0$$

$$^{235}U_0 = g_1 U_0 \qquad {}^{238}U_0 = g_2 U_0$$

Because isotopes are not subject to chemical fractionation, f_1, f_2, f_3, g_1, and g_2 are all constants through the solar system when it was born

$$^{206}Pb = {}^{206}Pb_0 + {}^{238}U_0\left(1 - e^{-t/\tau_{238}}\right)$$

$$^{207}Pb = {}^{207}Pb_0 + {}^{235}U_0\left(1 - e^{-t/\tau_{235}}\right)$$

$$^{206}Pb = f_1 Pb_0 + g_2 U_0\left(1 - e^{-t/\tau_{238}}\right)$$

$$^{207}Pb = f_2 Pb_0 + g_1 U_0\left(1 - e^{-t/\tau_{235}}\right)$$

$$^{204}Pb = f_3 Pb_0$$

$$y(t - now) = \frac{^{207}Pb}{^{204}Pb} = \frac{f_2\ Pb_0}{f_3\ Pb_0} + \frac{g_1\ U_0}{f_3\ Pb}\left(1 - e^{-t/\tau_{235}}\right)$$

$$x(t = now) = \frac{^{206}Pb}{^{204}Pb} = \frac{f_1\ Pb_0}{f_3\ Pb_0} + \frac{g_2\ U_0}{f_3\ Pb_0}\left(1 - e^{-t/\tau_{238}}\right)$$

$$x(t=now)=\frac{^{206}Pb}{^{204}Pb}=\frac{f_1\,Pb_0}{f_3\,Pb_0}+\frac{g_2\,U_0}{f_3\,Pb_0}\left(1-e^{-t/\tau_{238}}\right)$$

$$y(t=now)=\frac{^{207}Pb}{^{204}Pb}=\frac{f_2\,Pb_o}{f_3\,Pb_0}+\frac{g_1\,U_0}{f_3\,Pb_0}\left(1-e^{-t/\tau_{235}}\right)$$

Measure x and y at time t in a lot of samples with variable U_0/Pb_0 and plot. Use the x equation to get U_0/Pb_0

$$\frac{U_0}{Pb_0}=\frac{\left(x-\frac{f_1}{f_3}\right)}{\frac{g_2}{f_3}\left(1-e^{-t/\tau_{238}}\right)}$$

Substituting for $\frac{U_0}{Pb_0}$ in the equation for y

$$y=\frac{f_2}{f_3}+\frac{g_1}{f_3}\left(\frac{x-\frac{f_1}{f_3}}{\frac{g_2}{f_3}\left(1-e^{-t/\tau_{238}}\right)}\right)\left(1-e^{-t/\tau_{235}}\right)$$

Now take the derivative

$$\frac{dy}{dx} = \frac{g_1}{g_2} \frac{\left(1 - e^{-t/\tau_{235}}\right)}{\left(1 - e^{-t/\tau_{238}}\right)}$$

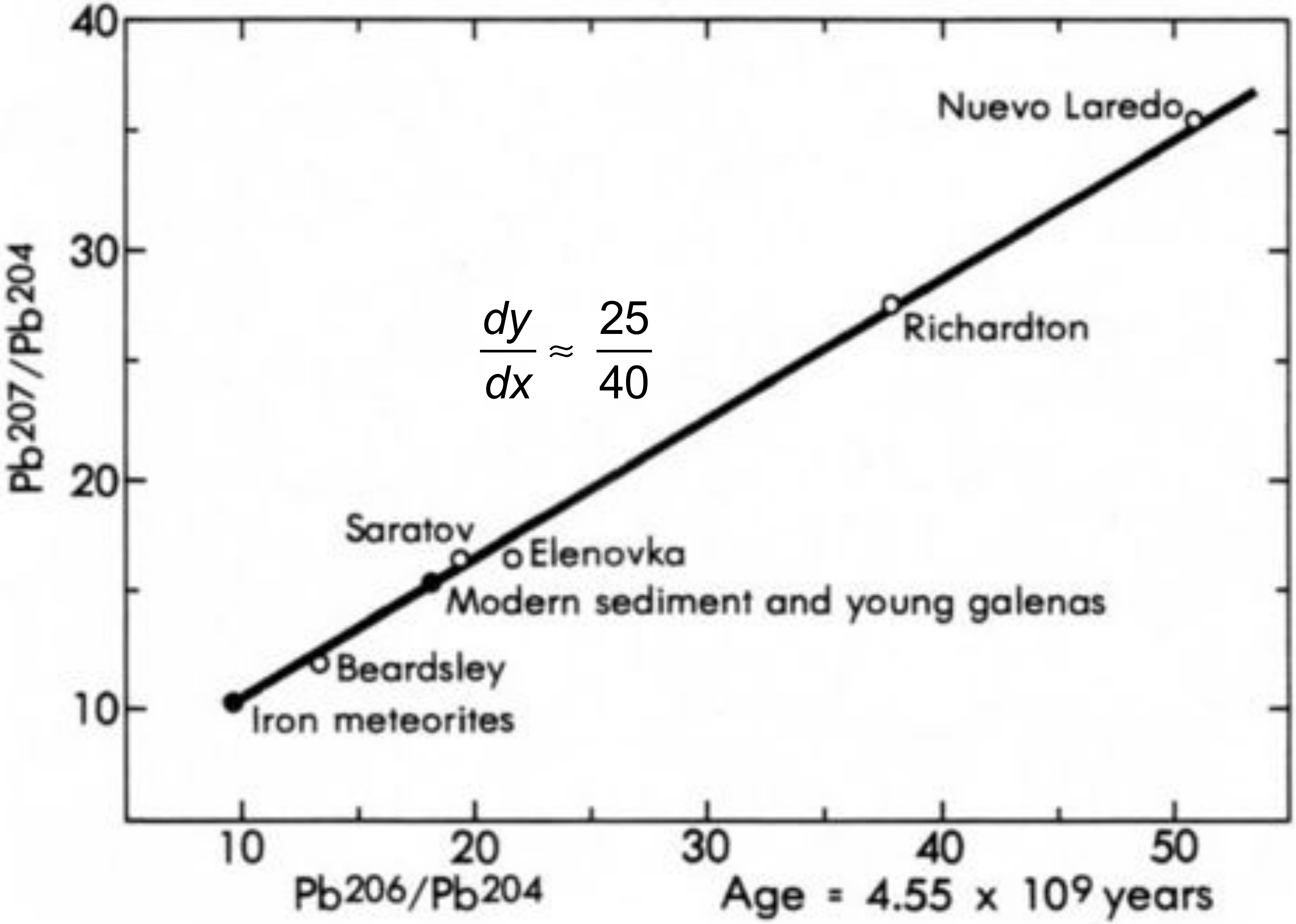
A prediction is that this derivative at a given time (now) should be constant for a wide variety of samples with different uranium contents and histories.

Also we can measure

$$\left.\frac{^{235}U}{^{238}U}\right)_{now} = \frac{1}{137.8} = \frac{g_1 e^{-t/\tau_{235}}}{g_2 e^{-t/\tau_{238}}}$$

can be used to get g_1 / g_2

Measure $\frac{dy}{dx}$ and compute



Dalrymple (1986)

http://www.talkorigins.org/faqs/dalrymple/scientific_age_earth.html

$$\frac{dy}{dx} = \frac{25}{40} = \frac{g_1}{g_2}\frac{\left(1 - e^{-t/\tau_{235}}\right)}{\left(1 - e^{-t/\tau_{238}}\right)} = \frac{1}{137.8}\quad\frac{e^{-t/\tau_{238}}}{e^{-t/\tau_{235}}}\frac{\left(1 - e^{-t/\tau_{235}}\right)}{\left(1 - e^{-t/\tau_{238}}\right)}$$

$$\frac{25}{40}(137.8) = 86 = \frac{\left(e^{t/\tau_{235}} - 1\right)}{\left(e^{t/\tau_{238}} - 1\right)}$$

t = 4.5 Gy

1. St. Severin (ordinary chondrite)

1. Pb-Pb isochron	4.543 ± 0.019 GY
2. Sm-Nd isochron	4.55 ± 0.33 GY
3. Rb-Sr isochron	4.51 ± 0.15 GY
4. Re-Os isochron	4.68 ± 0.15 GY

2. Juvinas (basaltic achondrite)

1. Pb-Pb isochron	4.556 ± 0.012 GY
2. Pb-Pb isochron	4.540 ± 0.001 GY
3. Sm-Nd isochron	4.56 ± 0.08 GY
4. Rb-Sr isochron	4.50 ± 0.07 GY

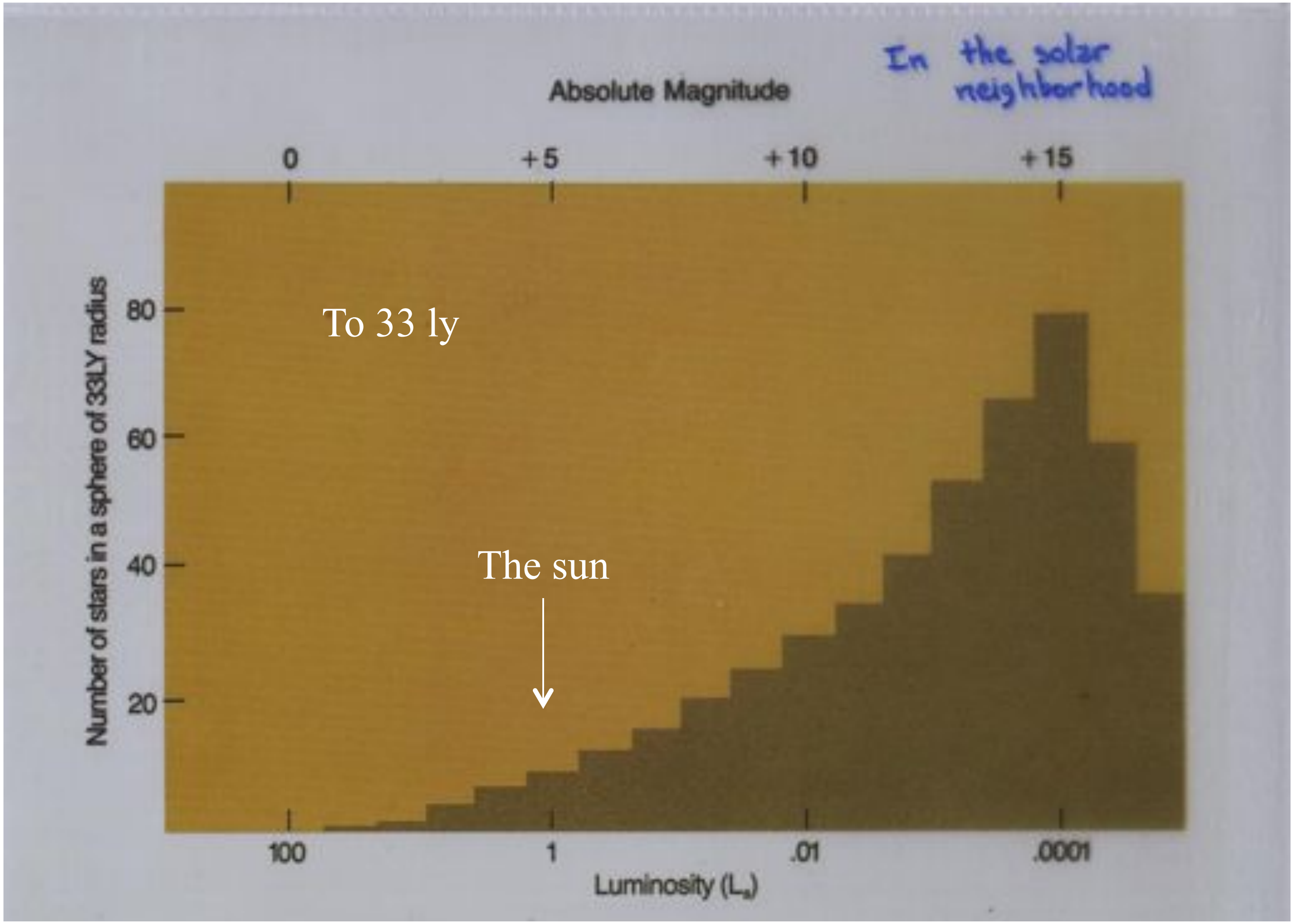
3. Allende (carbonaceous chondrite)

1. Pb-Pb isochron	4.553 ± 0.004 GY
2. Ar-Ar age spectrum	4.52 ± 0.02 GY
3. Ar-Ar age spectrum	4.55 ± 0.03 GY
4. Ar-Ar age spectrum	4.56 ± 0.05 GY

Best value
4.55 Gy

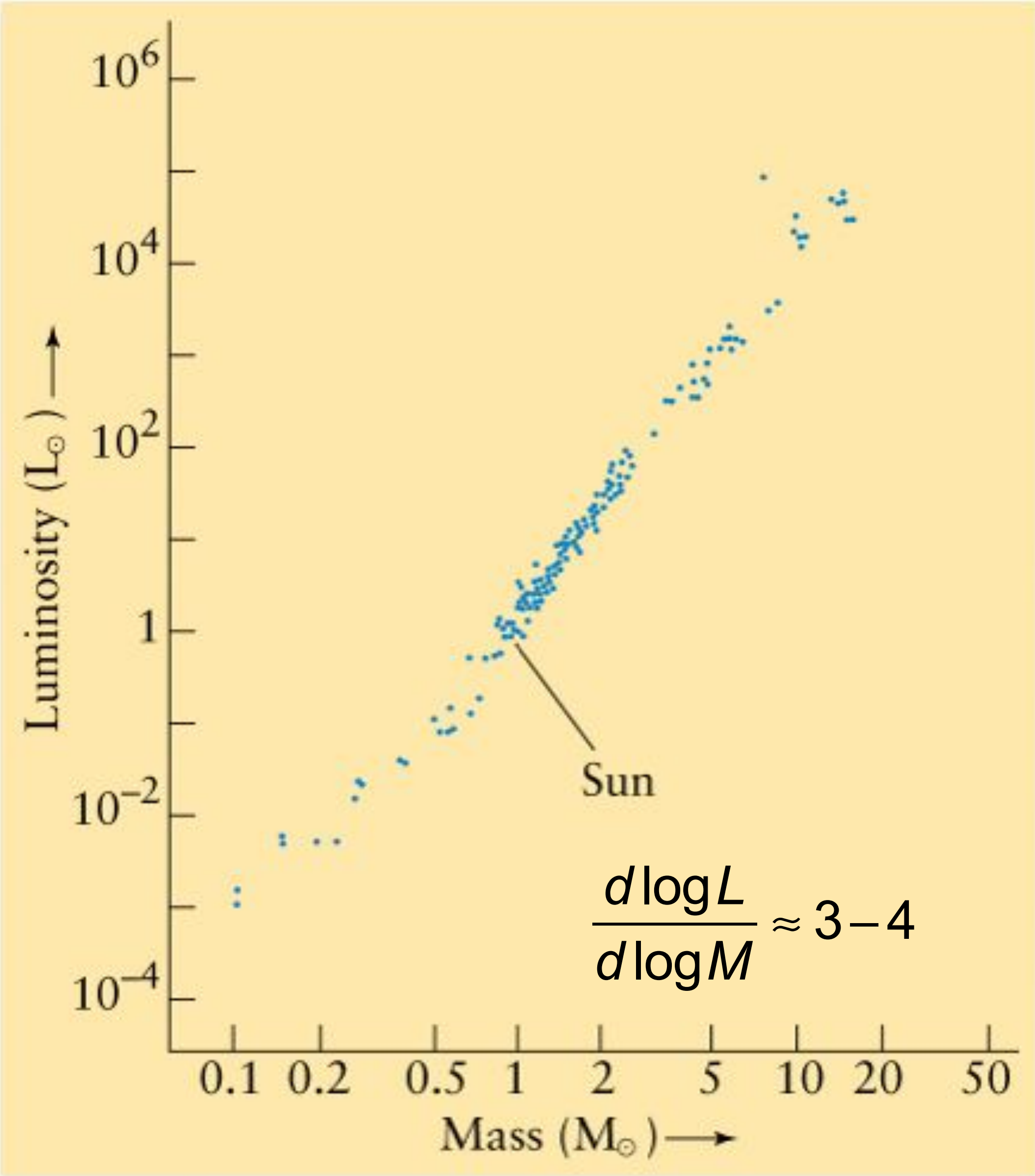
The sun as a star

In a volume limited sample – counting all stars – low luminosity stars are much more abundant



Only a few are more luminous than the sun

Mass-Luminosity Relationship



$$\frac{d \log L}{d \log M} \approx 3-4$$

Main sequence stars only

Very roughly

Since luminosity $\propto M^3$ (actually variable)

and fuel supply = f M (f ~ 0.1 - 0.2)

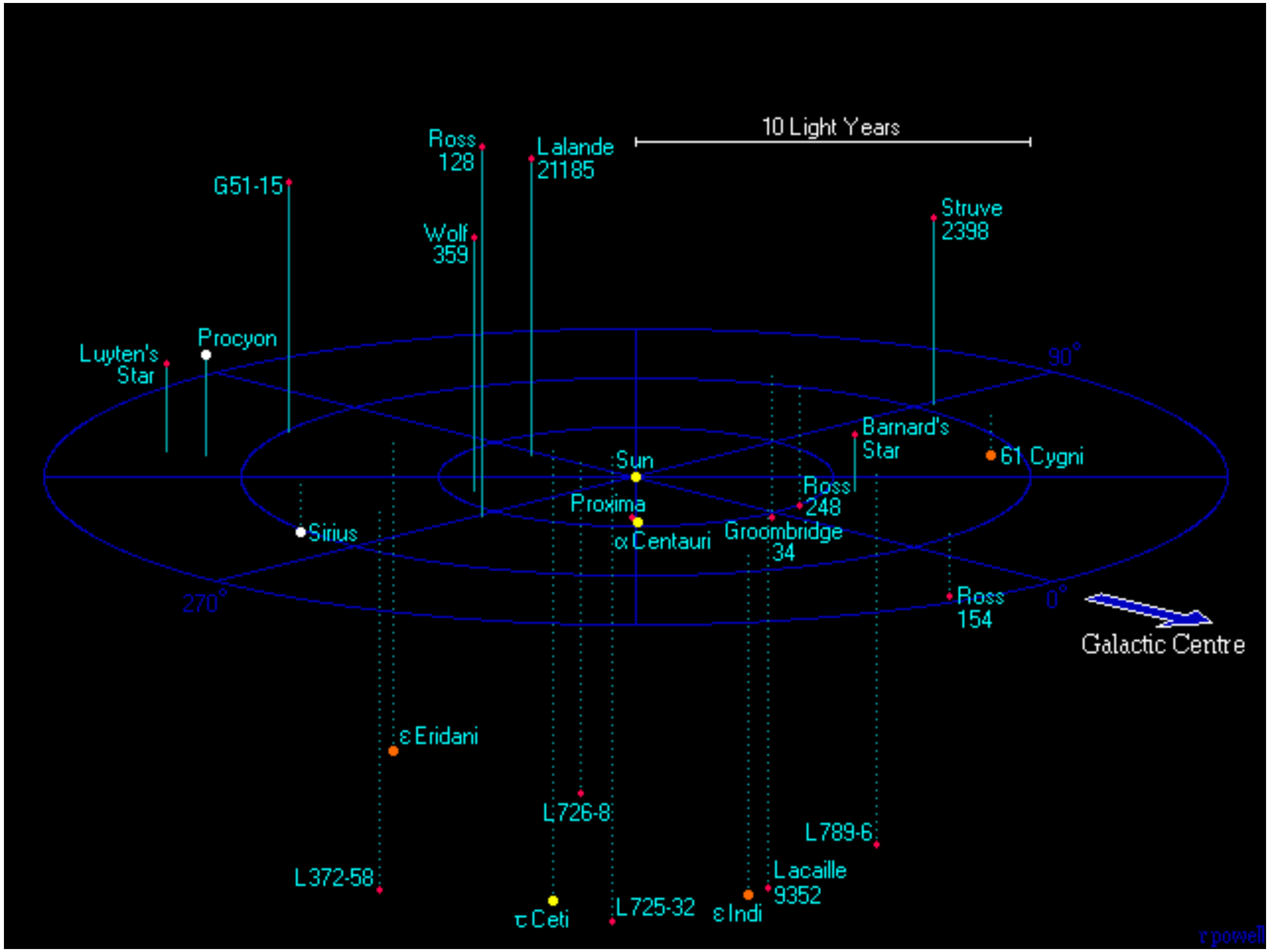
$$\text{Lifetime} \propto \frac{M}{M^3} \propto \frac{1}{M^2}$$

for stars that are spectroscopically main sequence stars

So more massive stars are more luminous but considerably shorter lived. For example, the sun lives in its present form 10 Gy but a star of 15 solar masses only lives 11 My.

12.5 ly

www.atlasoftheuniverse.com



circles indicate plane of Milky Way galaxy

The nearest (24) stars within 12.5 light years of the earth. The closest star system – Alpha Centauri– is about 7000 times the radius of Pluto's orbit. 270,000 times the radius of the Earth's orbit,

Some specific nearby stars:

- *The sun* – a typical yellow dwarf star. Type "G2" with 8 planets

- *Proxima Centauri* – closest of the triplet of stars loosely known as "alpha-Centauri" Proxima Centauri is a faint red star that orbits Alpha-Centauri A and B with a period of about one million years. Proxima Centauri is 4.22 light years from the Earth (now) and about 0.24 light years from Alpha-Centauri A and B.

- *Alpha-Centauri A and B* – a double star system with a period of about 80 years. Component A is a near twin of the sun (Type G2). Component B is a little fainter and orange. Alpha-Centauri A and B are 4.39 light years from the Earth.

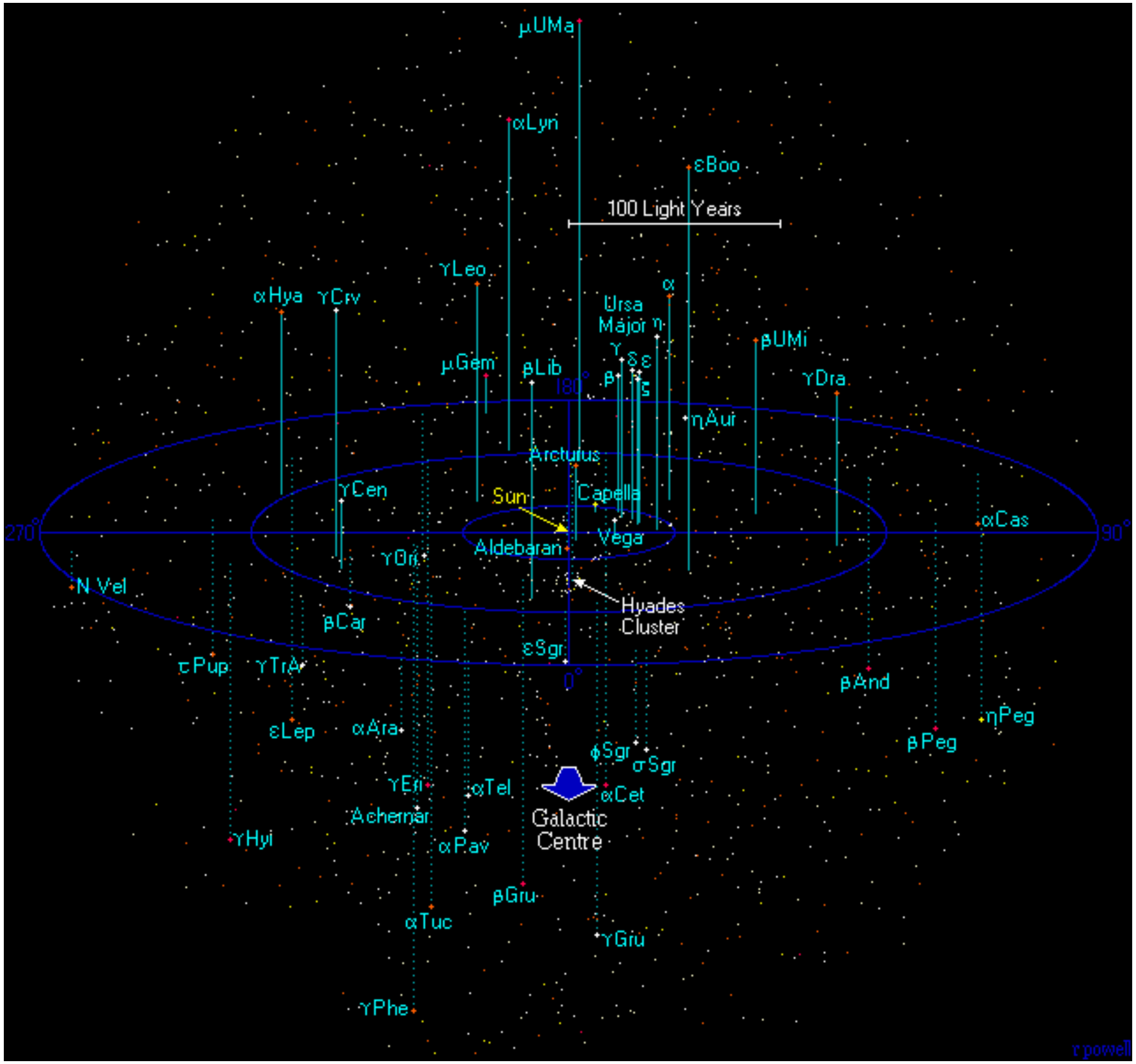
- *Barnards star* – highest proper motion of all stars. 5.9 light years away. It moves 0.29 degrees per century. In another 8000 years Barnard's star will be the closest star to us (3.8 ly in 11700 AD). M star, faint, red, about 11 Gyr old. No big planets.

- *Lalande 21185* – One of the brightest "red dwarfs" (low mass main sequence stars) in the sky but still requires binocular to see it. In 1996 a couple of Jupiter sized planets were discovered here

- *Epsilon Eridani* – 10.5 light years away. Searched for life by radio searches in the 1960's. May have a Jupiter sized planet orbiting at a distance of 3.2 AU. Young star (1Gyr?). K2

- *Sirius A,B* – At a distance of 8.60 light years Sirius A is the brightest star in the sky. Sirius B is a white dwarf

250 light years



Starting to see some preference for Galactic plane for distances beyond this.

Number for isotropic distribution and constant density

$$n \propto d^3$$

About 250,000 stars lie within 250 light years of the Earth. Beyond this distance it becomes difficult to see all the stars in the plane of the Milky Way Galaxy because of the presence of dust.

Only the 1500 most luminous of these stars are plotted. Most of these are visible to the unaided eye.

Note the presence of the Hyades cluster.

< 1500 stars are visible to the unaided eye. More often it's a few hundred.

The Hyades Open cluster of stars (151 light years)

The bright red star Aldebaran
is not in the Hyades

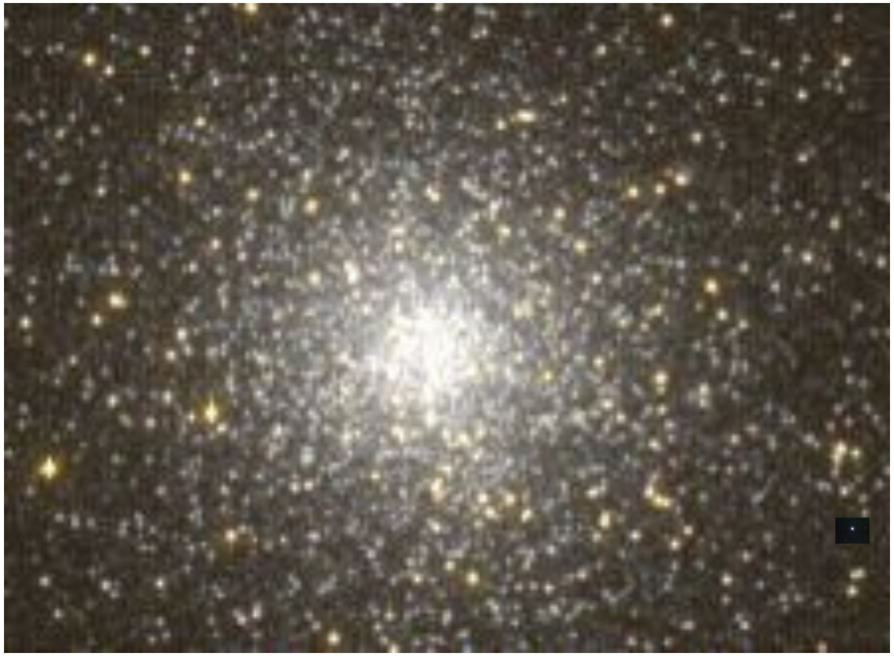
This cluster of stars is only about 625 million years old and is in the process of coming apart. Stars like this are born together from a giant cloud of molecular gas, most of which is blown away by the young stars. About 200 stars are catalogued at http://en.wikipedia.org/wiki/List_of_stars_in_Hyades

Star Clusters

Open Cluster

Globular Cluster

Globular Clusters



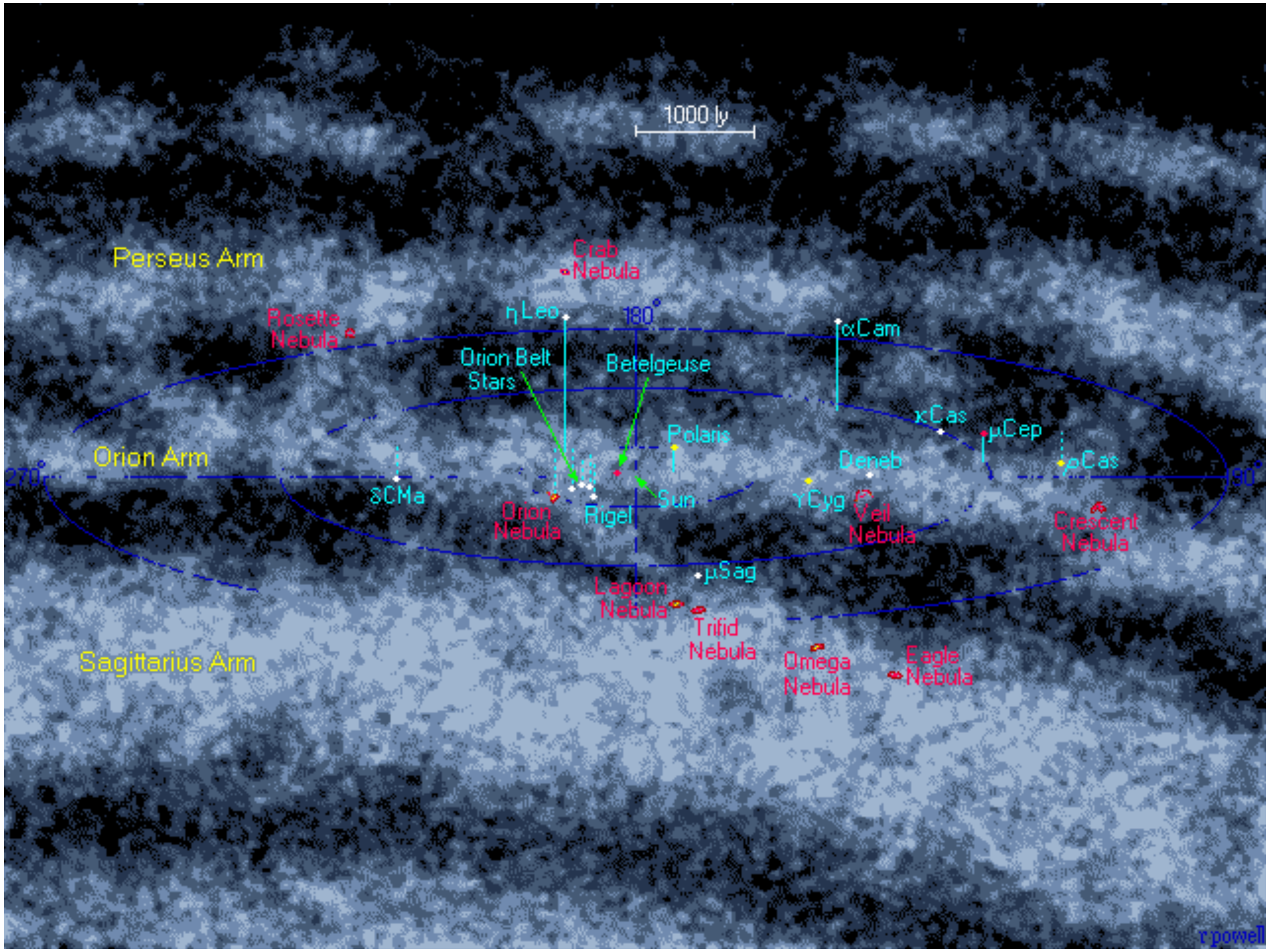
47 Tuc

M13

Second brightest globular cluster (behind Omega Cen). There are about 200 globular clusters altogether. This one is near the direction of the SMC in the sky and about 20,000 ly distant. Lots of red giants visible here.

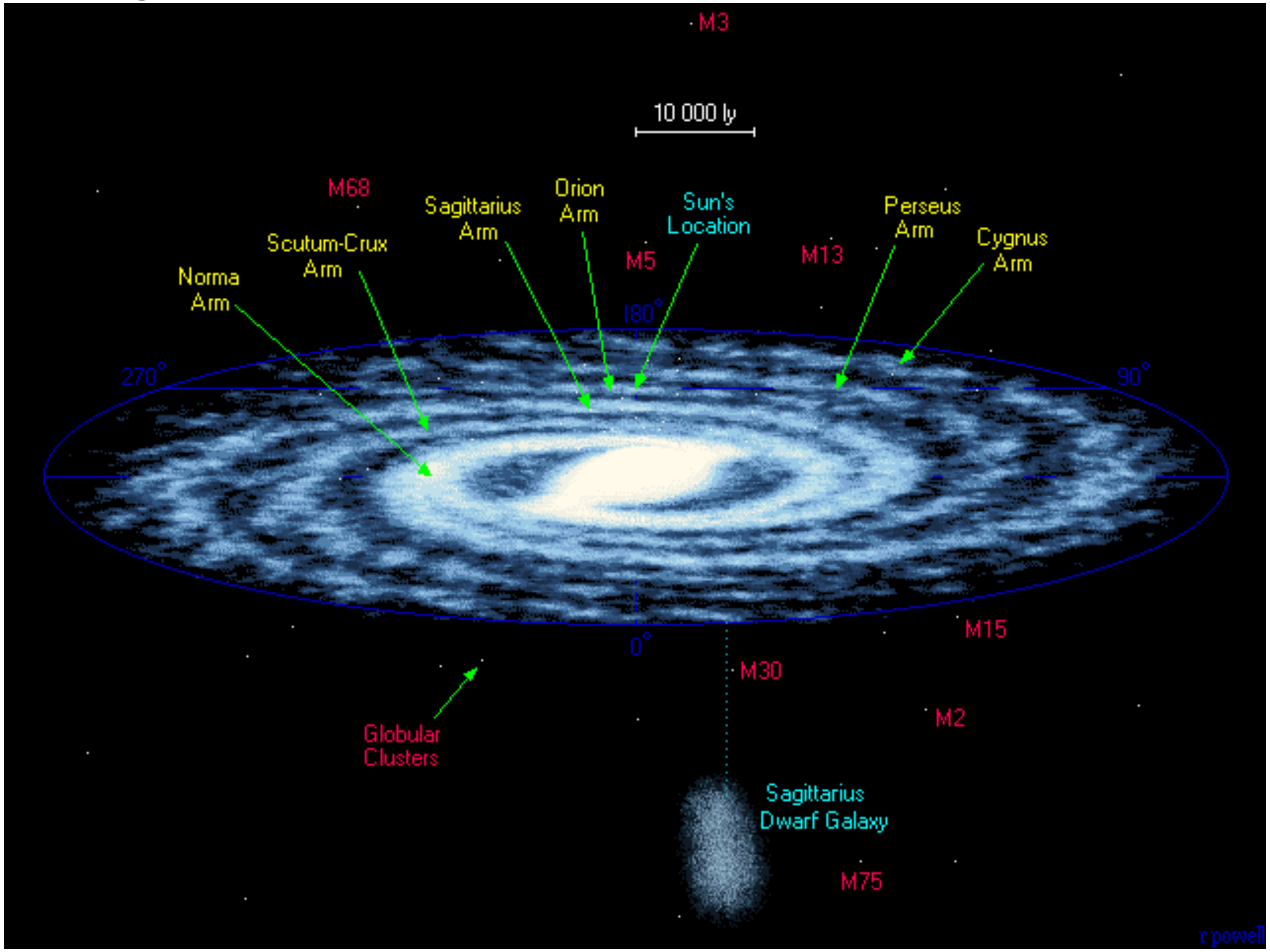
This globular cluster in Hercules is 22,000 ly distant and contains 10^5 – 10^6 stars.
Age ~ 12 to 14 billion years.
It is about 150 light years across.

5000 light year view – Galactic spiral arm structure is becoming apparent. The sun is on the “Orion Arm” a lesser arm of the Milky Way compared e.g., to the Sagitarius Arm. There is also a lot of gas and dust.



Betelgeuse 650 ly; Orion 1350 ly

The entire visible galaxy is about 80,000 light years across. Note orbiting galaxy and globular clusters



http://www.atlasoftheuniverse.com/galaxy.html


Andromeda (2.2 Mly away)
220,000 ly in diameter
(larger than Milky Way)

Mass of the Milky Way

Sun at 28,000 ly orbits the center of mass with a speed 256 km s^{-1}

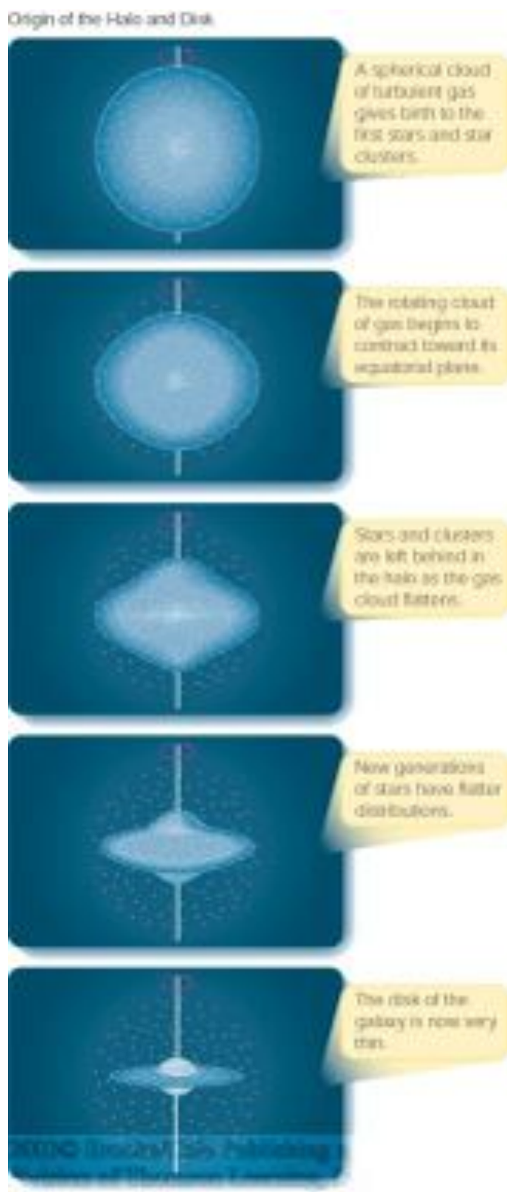
$$\frac{v^2}{r} \approx \frac{GM_{MW}}{r^2} \quad \text{(not exact for a disk)}$$

$$M \approx \frac{v^2 r}{G} = \frac{\left(2.56\times10^{7}\right)^2(2.8\times10^{4})(9.46\times10^{17})}{(6.67\times10^{-8})}$$

$$= 2.6\times10^{44}\ \text{gm} = 1.3\ \times10^{11}\ M_\odot$$

Much more outside the sun's orbit in the form of "dark matter"

History of the Milky Way



Traditional theory now somewhat out of date

Rotating cloud collapses into a disk-like structure

Quasispherical cloud collapses some part forms stars as the collapse continues (Population II)

Rest of matter forms centrifugally supported disk, Population I stars form

Population I	*Population II*
Low velocity perpendicular to disk	High velocity perpendicular to disk
Low and high mass	Low mass
Young and old stars	Old stars
Blue and red	Red
e.g the sun	e.g. globular clusters

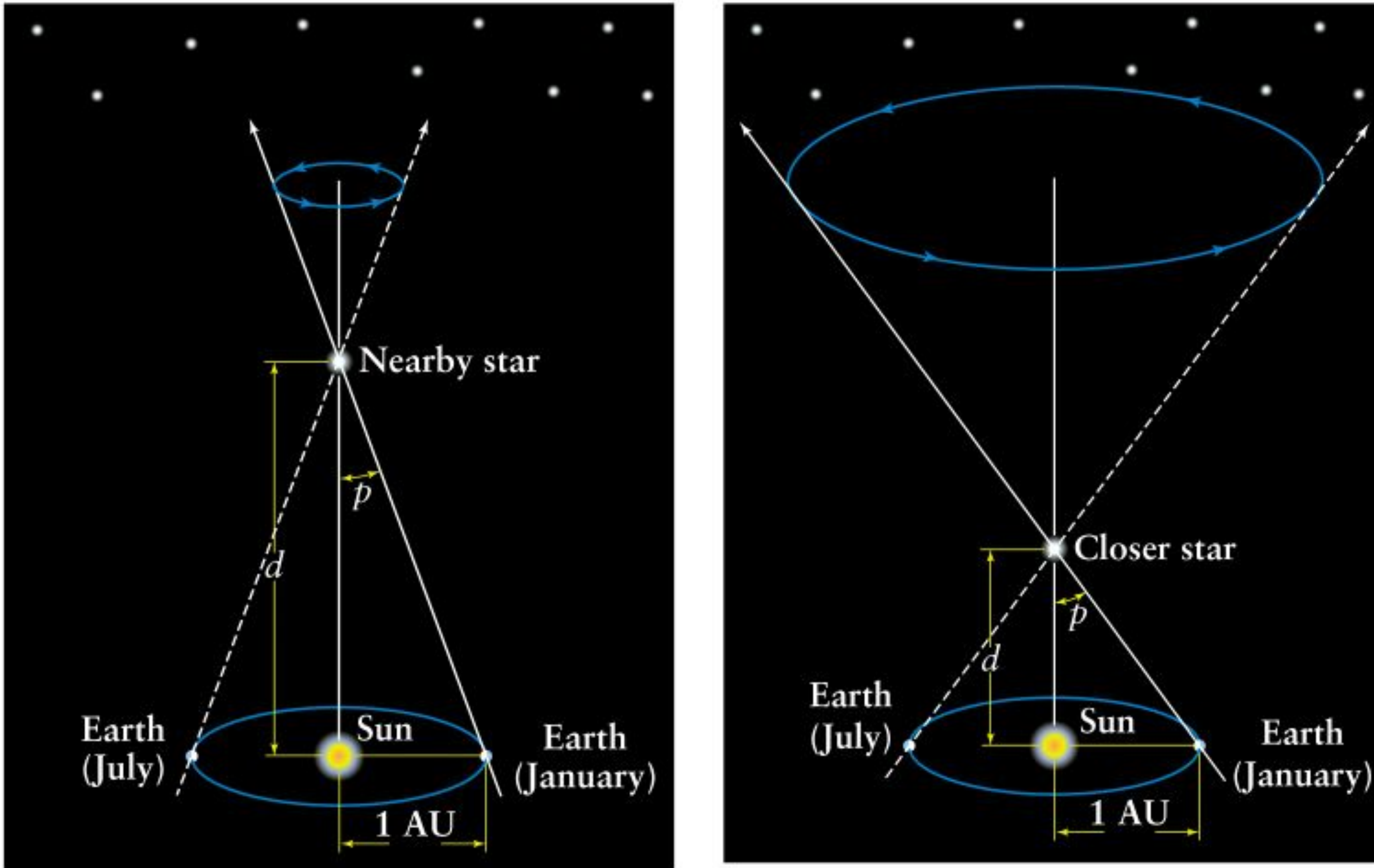
DETERMINING DISTANCES

For relatively nearby sources, one can measure distances by "surveying" - by measuring the very small angles that a star's position is displaced relative to very distant objects because of the motion of the Earth around the sun. Prior knowledge of the AU is essential here.

For more distant objects one uses either "standard candles" that are calibrated from nearby sources or a theoretical model.

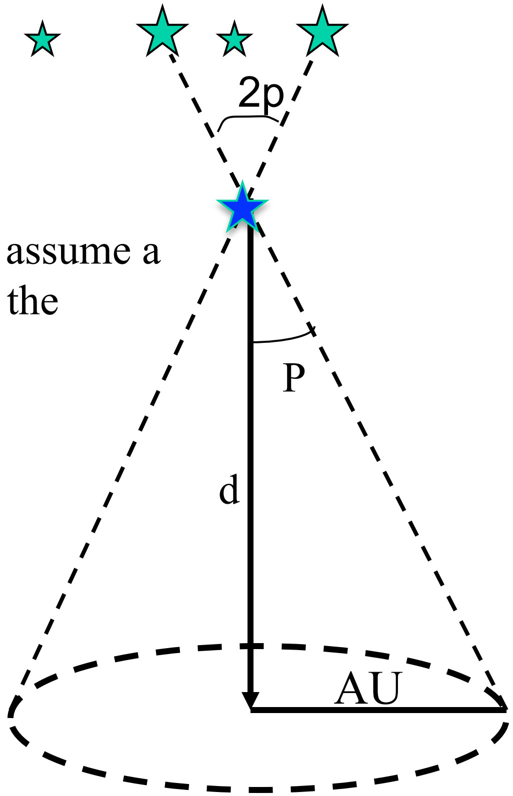
Stellar Parallax

-Wexler



a b

For simplicity assume a star 90° above the ecliptic



$$d = \left(\frac{AU}{p}\right)$$

if p measured in radians

1 radian = $360/2\pi$
= $57.296\ldots^{o}$

For small angles, $p \ll 1$, measured in radians

$$\text{Sin p} \approx \text{p} \qquad \text{Cos p} \approx 1$$

$$\frac{AU}{d} = \text{Tan p} = \frac{\text{Sin p}}{\text{Cos p}} \approx p$$

But astronomers actually report the angle p in seconds of arc.
1 radian is $360^{o}/2\pi = 57.296^{o}$ and each degree is
3600 arc seconds. So 1 radian = 206265 arc seconds.
Thus for p measured in seconds of arc (call it p''),

$$1 \text{ arc sec} = \frac{1}{206265} \text{ radians}$$

$$d = \frac{\text{AU}}{\text{p (in radians)}}$$

$$d = \frac{206265\, AU}{p''}$$

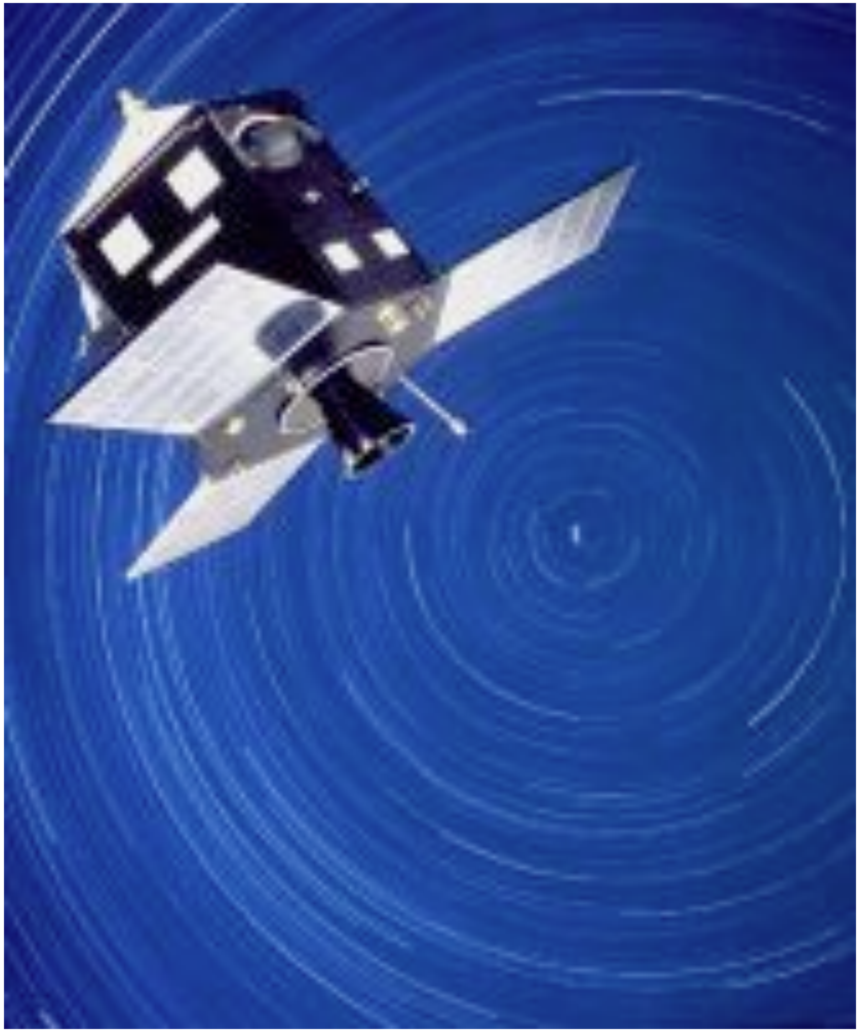
$$d = \frac{1\,\text{parsec}}{p''}$$

1 AU seen from one parsec away would subtend an angle of 1 arc second

p'' = parallax angle measured in seconds of arc

This defines the parsec, a common astronomical measure of length. It is equal to 206,265 AU's or 3.0856×10^{18} cm. It is also 3.26 light years.

A little thought will show that this also works for stars whose position is inclined at any angle to the ecliptic. What p measures then is the semi-major axis of the "parallactic ellipse".



Hipparcos Space Astrometry Mission (1989 – 1993)

Catalogue of accurate distances (1 milli arc s angular resolution)

118,218 stars

Total stars observed (Tycho 2 Catalogue; median astrometric accuracy 7 mas)

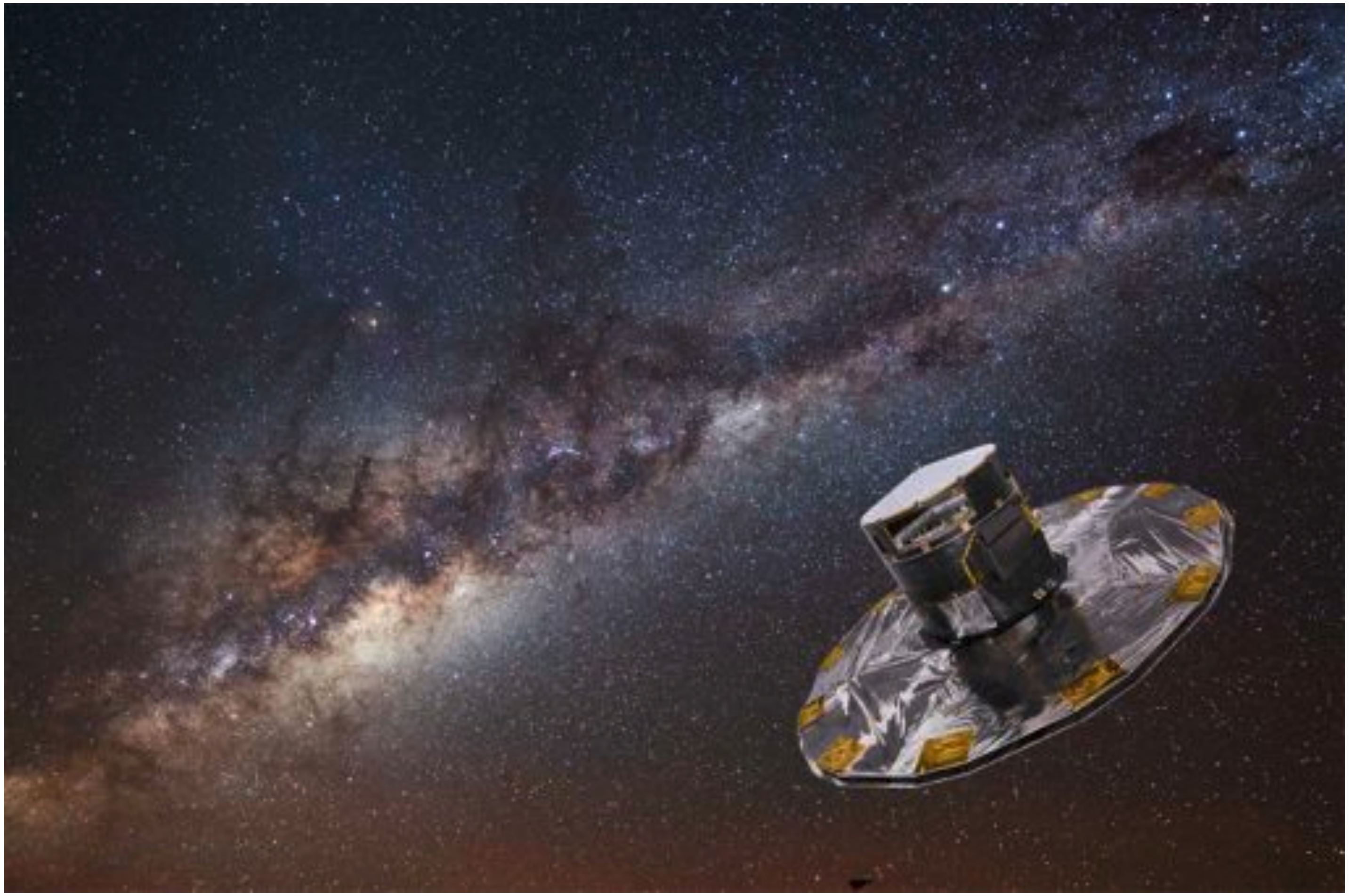
2,539,913 stars

Including 99% of all stars brighter than 11th magnitude

Aside: In AD 150 Ptolemy in his Almagest catalogued 1,022 of the brightest stars.

Gaia – the successor to Hipparcos – will "survey" *one billion stars*

launched Dec 2013 http://blogs.esa.int/gaia/2014/01/



5 year mission

parallax accuracy 20 micro arc seconds for 15 magnitude

200	“	“	“	“	20	“
7	“	“	“	“	10	“

7 μ arc sec is a human hair at 1000 km

Distance to 20 million stars determined to 1%

200 10%

Note implications for a lower bound to the age of the universe...

$$100\ \mu arc\,s = 10^{-4}\ arc\,s$$

$$d = \frac{1}{10^{-4}} = 10\text{ kpc}$$

or 31,000 ly

To go beyond distances that can be surveyed using) parallax, one needs "standard candles".

Even with Gaia, this will continue to be the case for most extragalactic objects

LUMINOSITY AND FLUX

- *Luminosity* is the total power emitted by a star. It is measured in ergs/sec. Usually we are speaking of the luminosity of light, or electromagnetic radiation of any wavelength. But one can also speak of neutrino luminosities. A synonym for luminosity is radiant *power*.

- *Flux* is a measure of how bright an object appears. Its value involves both the inherent luminosity of a source and its distance.

$$\varphi = \frac{L}{4\pi d^2}$$

If we had a "standard candle", a bright stellar source of known luminosity, L_{SC}, we could determine its distance from measuring its flux

$$\phi_{SC} = \frac{L_{SC}}{4\pi d^2}$$

$$d = \sqrt{\frac{L_{SC}}{4\pi\phi_{SC}}}$$

Measuring Flux: Magnitudes:

- The eye is a logarithmic flux detector

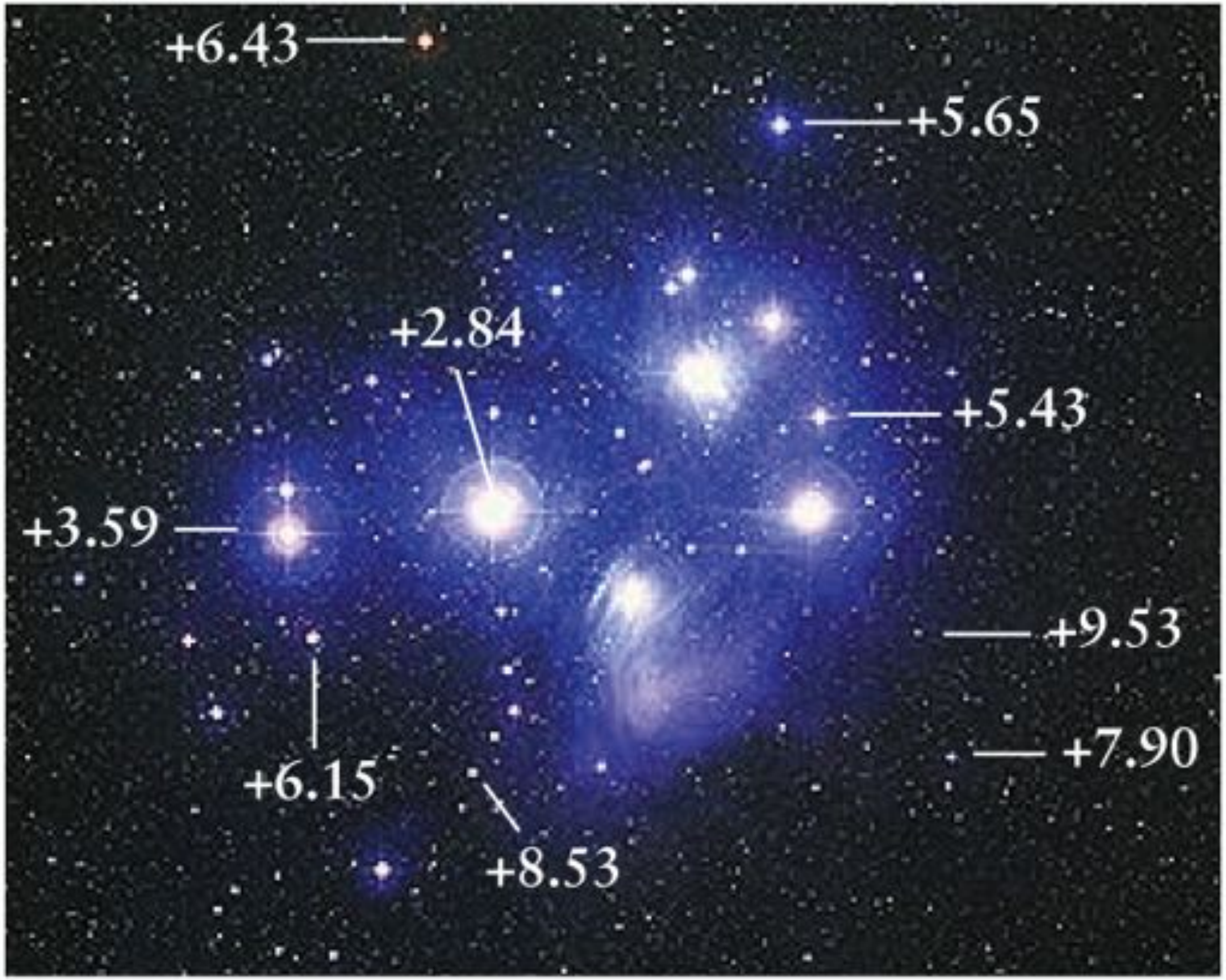
- In astronomy we measure fluxes using magnitudes. Historically, a magnitude was "about a factor of two".

- Calibrated more precisely by William Herschel in the late 18th century (see also Pogson (1856))

  5 magnitudes is defined to be precisely a factor of 100 in flux. One magnitude thus corresponds to a change in flux of $(100)^{1/5} = 2.512$, i.e. $(2.512)^5 = 100$

- A sixth magnitude star is thus 100 times less "bright" than a first magnitude star. Larger magnitude is fainter.

The Pleiades Cluster



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Magnitudes, apparent and absolute

According to Herschel's definition, for fluxes ϕ_1 and ϕ_2:

$$\phi = \frac{L}{4\pi d^2}$$

$$\frac{\phi_1}{\phi_2} = 100^{\frac{m_2 - m_1}{5}}$$

That is, a star 5 magnitudes brighter has a flux 100 times greater.

$$\frac{m_2 - m_1}{5}\log(100) = \log\frac{\phi_1}{\phi_2}$$

$$\frac{2}{5}(m_2 - m_1) = \log\frac{\phi_1}{\phi_2}$$

$$m_2 - m_1 = 2.5\log\frac{\phi_1}{\phi_2}$$

So, if $\phi_1 > \phi_2$, $m_2 > m_1$. Keep in mind that bigger m means "fainter".

Apparent magnitude, *m*, is a measure of *flux*.

Absolute Magnitude

Absolute magnitude, M, is the magnitude a star would have if located at a certain distance – 10 pc. Since the distance is the same for all cases, M is a measure of the star's *luminosity*.

From these definitions of m and M, we can derive a relation which is essentially the equivalent of $\phi = \frac{L}{4\pi d^2}$

$$\varphi \leftrightarrow m$$
$$L \leftrightarrow M$$

Consider a star with luminosity L at two distances, d_1 = its real distance = d, and d_2 =10 pc. At distance d the star's magnitude is m_1. At 10 pc the star's magnitude is $m_2 = M$. From the previous page:

$$m_2 - m_1 = 2.5 \log \frac{\phi_1}{\phi_2}$$

$$M - m = 2.5 \log \left(\frac{L / 4\pi d^2}{L / 4\pi (10)^2} \right)$$

$$M - m = 2.5\log\left(\frac{10^2}{d^2}\right)$$
$$= 2.5(2.0 - 2.0\log d)$$

M measures the luminosity, *m*, the brightness, and

d is the distance in pc.

$$M - m = 5.0 - 5.0\log d$$

For example, the apparent magnitude of the sun is -26.74. What is its absolute magnitude?

$$M = m + 5 - 5\log d(pc)$$

Here this (pc) just means that d is measured in parsecs

$$= -26.71 + 5 - 5\log\left(\frac{1}{206265}\right)$$
$$= -21.71 - 5(-5.31)$$
$$= 4.84$$

What would be the apparent magnitude of the sun at 10 pc? At 1.35 pc (distance to α-Centauri)?

$$4.84 - m = 5 - 5\log d$$
$$m = 4.84 - 5 + 5\log(1.35)$$
$$= -0.16 + 5\log(1.35) = -0.16 + 5(0.130)$$
$$= 0.49$$

The 10 **brightest** stars

Star		m	M
Sun	-	-26.74	4.8
Sirius	Alpha CMa	-1.46	1.4
Canopus	Alpha Car	-0.72	-5.6
Rigil Kentaurus	Alpha Cen (A+B)	-0.27	4.4
Arcturus	Alpha Boo	-0.04	-0.2
Vega	Alpha Lyr	0.03	0.6
Capella	Alpha Aur	0.08	-0.5
Rigel	Beta Ori	0.12	-7.0
Procyon	Alpha Cmi	0.34	2.6
Achernar	Alpha Eri	0.46	-2.7

m = 0 was historically defined by the star Vega, though modern readjustments have changed m(Vega) = 0.03.

Which stars are closer than 10 pc?

The 10 **brightest** stars

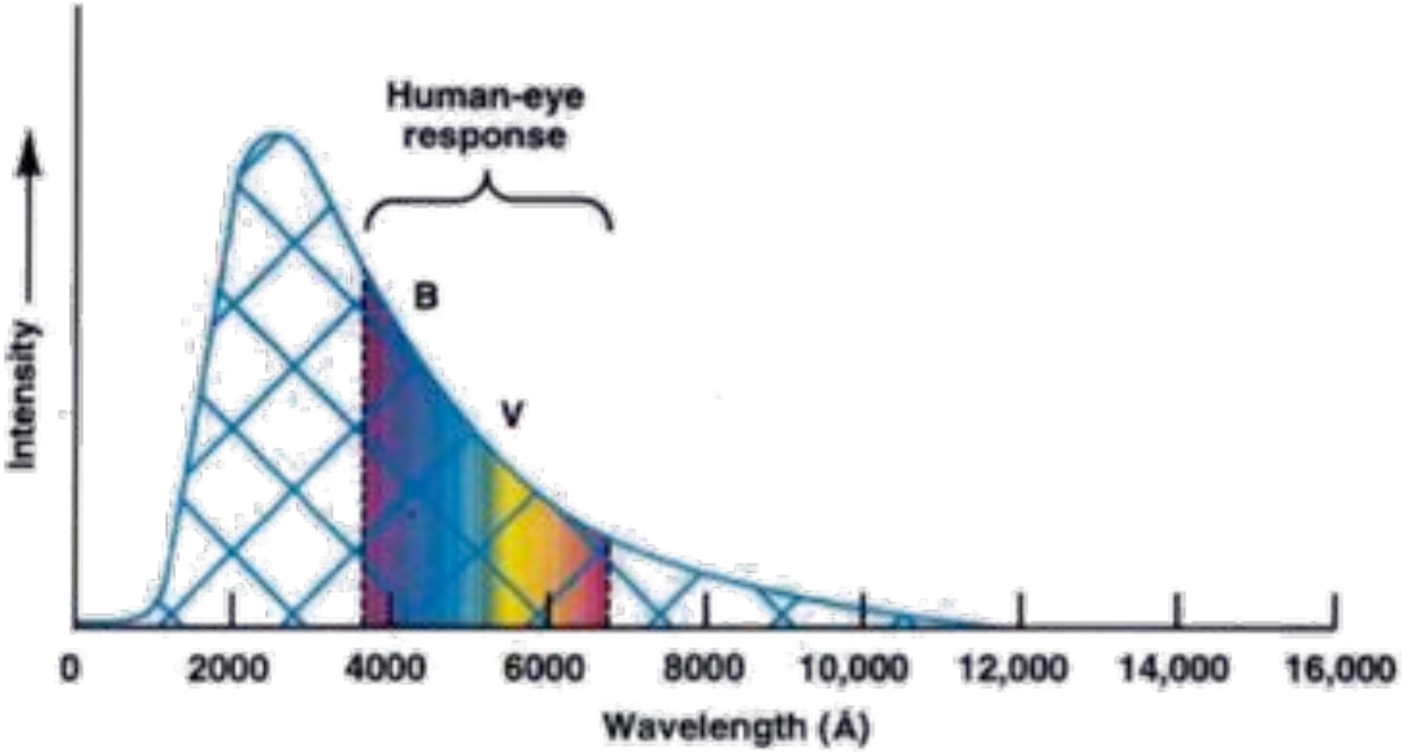
Star		dist(pc)	m	M
Sun	-		-26.74	4.8
Sirius	Alpha CMa	2.6	-1.46	1.4
Canopus	Alpha Car	95	-0.72	-5.6
Rigil Kentaurus	Alpha Cen (A+B)	1.3	-0.27	4.4
Arcturus	Alpha Boo	11	-0.04	-0.2
Vega	Alpha Lyr	7.7	0.03	0.6
Capella	Alpha Aur	13	0.08	-0.5
Rigel	Beta Ori	260	0.12	-7.0
Procyon	Alpha Cmi	3.5	0.34	2.6
Achernar	Alpha Eri	43	0.46	-2.7

m = 0 was historically defined by the star Vega, though modern readjustments have changed m(Vega) = 0.03.

Which stars are closer than 10 pc?

http://stars.astro.illinois.edu/sow/bright.html

A Complication: The Bolometric Correction



Unless otherwise indicated, m is usually the apparent *visual* magnitude.

BOLOMETRIC MAGNITUDE OF THE SUN

Our eyes have evolved to be most sensitive to the light emitted by the sun. Hence the bolometric correction for the missed emission in the infrared and ultraviolet is small for the sun.

The "visual" magnitude actually corresponds to the flux measured with a certain filter on the telescope. There are also blue magnitudes, red magnitudes, and others. We will discuss this later. For the sun.

$$M_{bol} = M_V - BC = 4.84 - 0.09 = 4.75$$

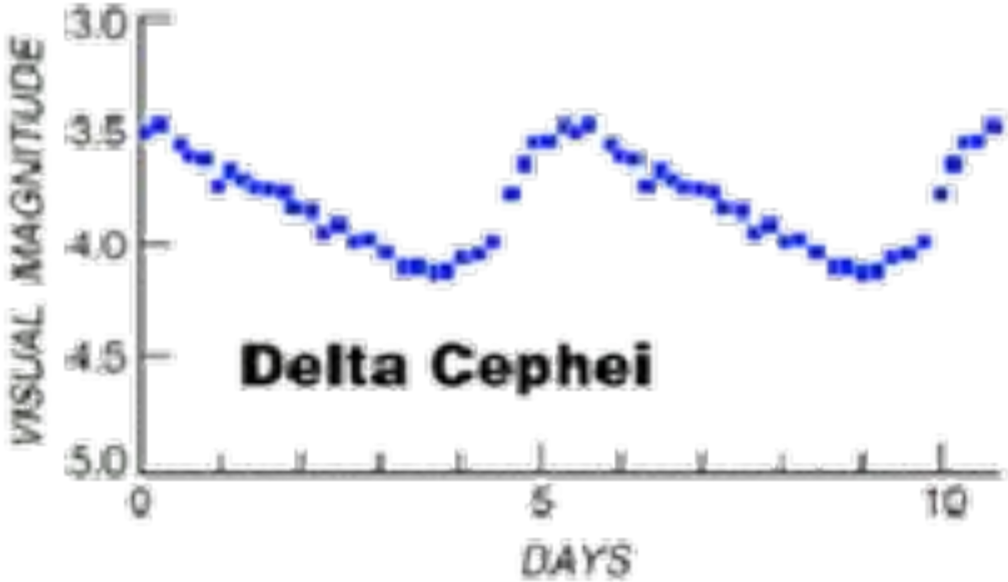
(actually 4.755 in 2012)

A similar equation would characterize apparent bolometric magnitudes, m_{bol}

https://sites.google.com/site/mamajeksstarnotes/bc-scale

Standard Candles

Cepheid variables are large luminous stars with regular variations in brightness. The variation ranges from a few per cent to a factor of 5



At 900 light years as judged by Hipparchos
Delta Cephi waxes and wanes with a period of 5 days.
200 Cepheids had their distances measured by Hipparcos.

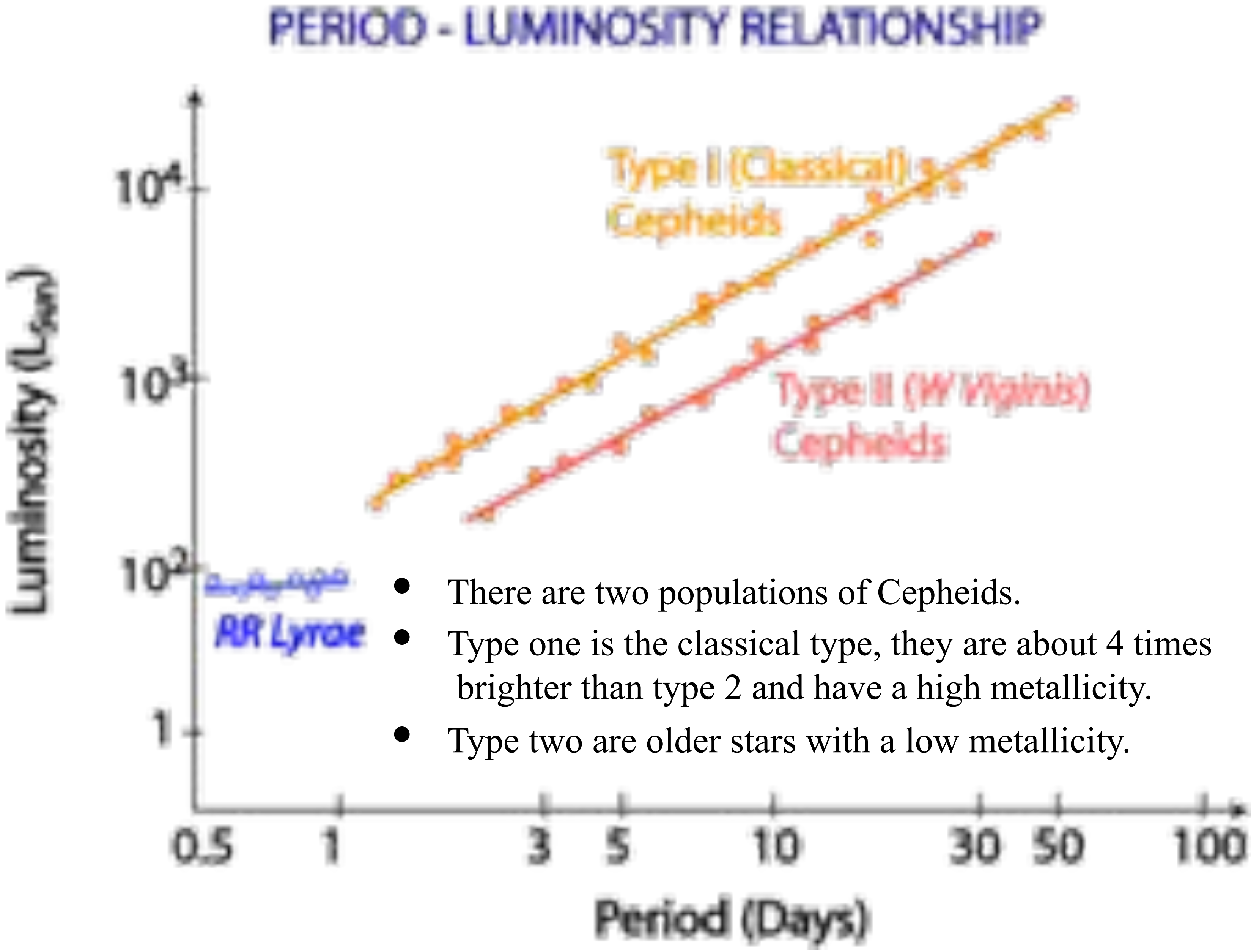
Polaris, the north star, is also a Cepheid. Its magnitude varies from 2.0 to 2.1 ever 4 days.

The great merit of Cepheid variables for distance determination is that there is a clear relation between the period of the brightness variation and the average luminosity of the star.

Cepheid variables are also very bright and can be seen from far away. (They are not main sequence stars).

A complication though is that there are two populations of Cepheids and they have different period luminosity relations

IN TERMS OF SOLAR LUMINOSITIES



- There are two populations of Cepheids.
- Type one is the classical type, they are about 4 times brighter than type 2 and have a high metallicity.
- Type two are older stars with a low metallicity.

Cepheids

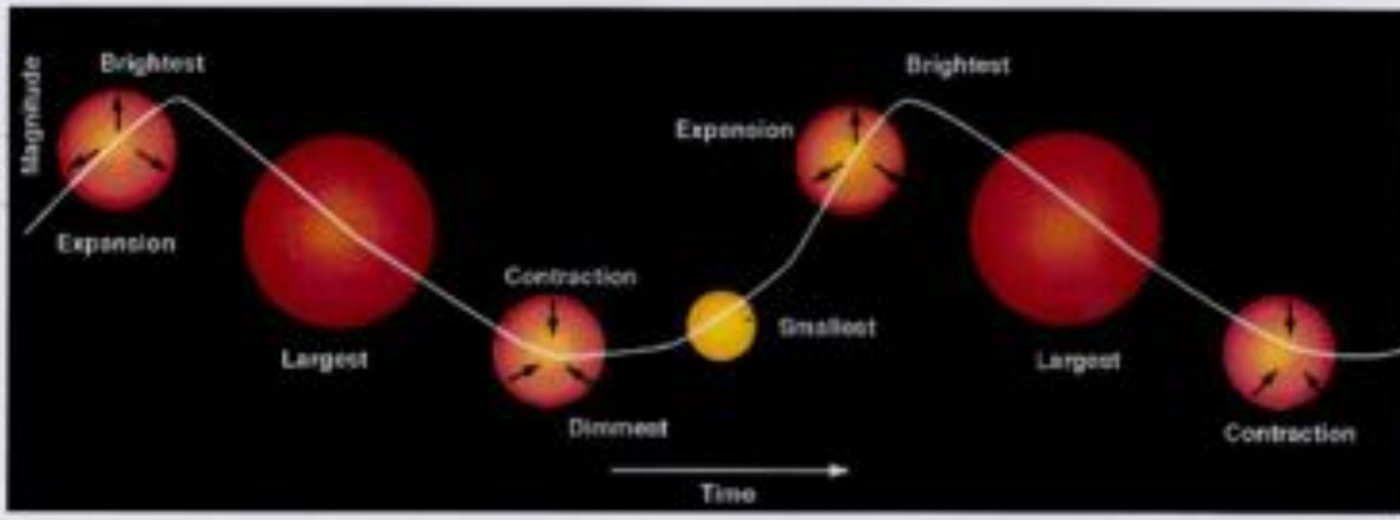
Periods of light variation are in the range 1 to 60 days and luminosities are up to 40,000 solar luminosities

The surface temperatures are similar to the sun but the star undergoes regular oscillations in size.

The radial velocity curve is almost a mirror image of the light curve, i..e., the maximum expansion velocity occurs at maximum light.

Light variation is in the range 0.5 to 2 magnitudes and radial velocities at maximum range from 30 to 60 km/s

A Cepheid variable is actually largest when its brightness is declining and smallest when it is rising.



Modern Cepheids

Variable	Example	where	Period	Mass	Luminosity (Lsun)
Type I Cepheids	δ-Cephei	disk	1 – 60 d	3 – 10	300 – 40,000
Type II Cepheids (W-Virginis stars)	W-Virginis	halo globular clusters	1 - 60 d	< 1	1.5 mag less than Type I
RR-Lyrae	RR-Lyrae	globular clusters	<1 d	< 1	~100

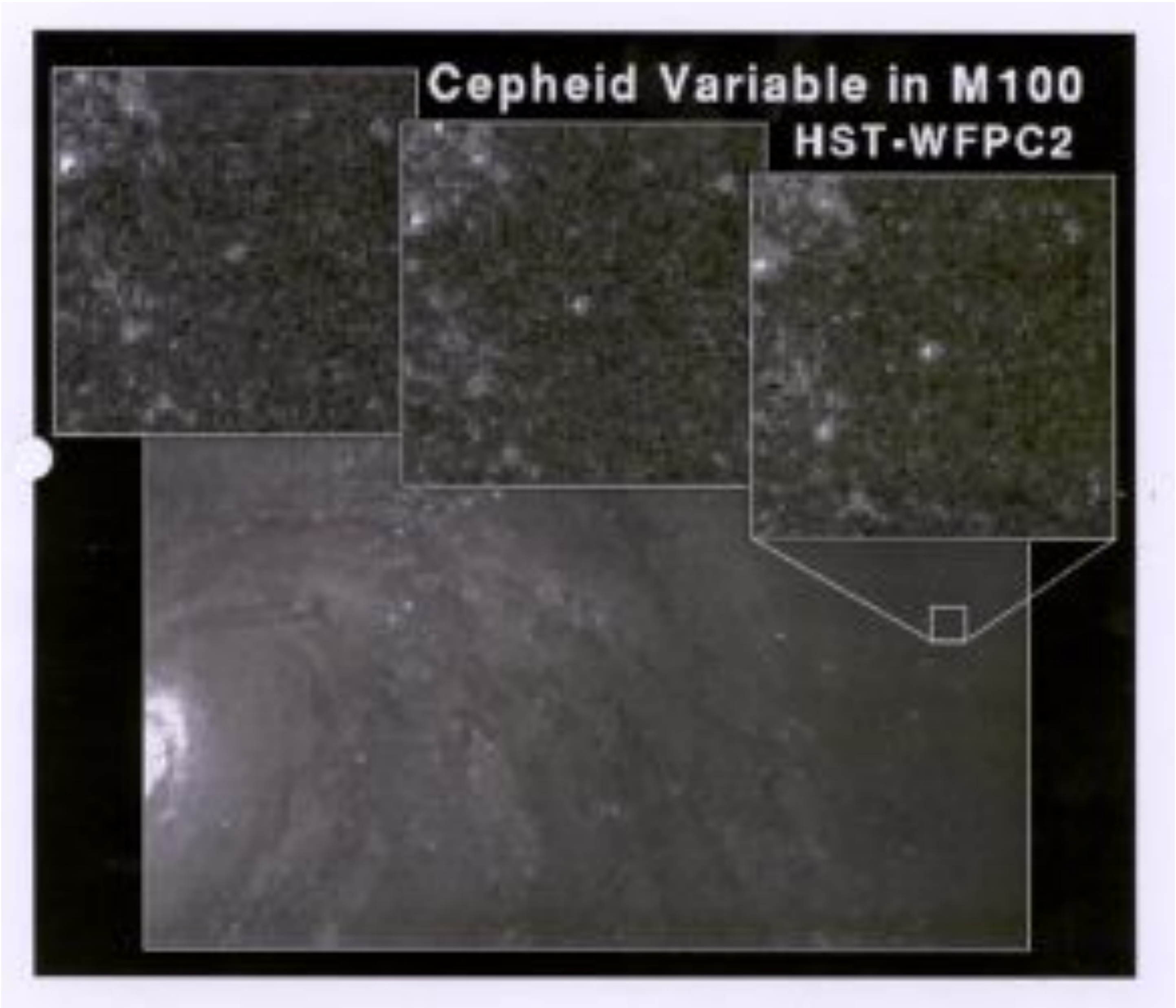
Most stars pass through a Cepheid stage at one time or another. However the phase is short lived and only about $1/10^6$ stars are Cepheids at any one time

Cepheid variables are not main sequence stars

Why do Cepheids Pulsate?

- He^{+} + light → He^{++}
- atmosphere becomes more opaque
- radiation pressure pushes the atmosphere out
- atmosphere cools, He^{++} → He^{+}
- pressure decreases, star contracts.

nb. This is an oversimplification. It's not just opacity - TBD



M100 is 17 Mpc (55 Mly) from the earth

- With available instrumentation, Cepheids can be used to measure distances as far as 20 Mpc to 10 - 20% accuracy.

- This gets us as far as the Virgo cluster of galaxies - a rich cluster with over 1000 galaxies.

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

Typical M_V for the brightest Cepheids is ~ -5

ST can easly measure fluxes to m = 28

$$-5 - 28 = 5 - 5 \log (d)$$

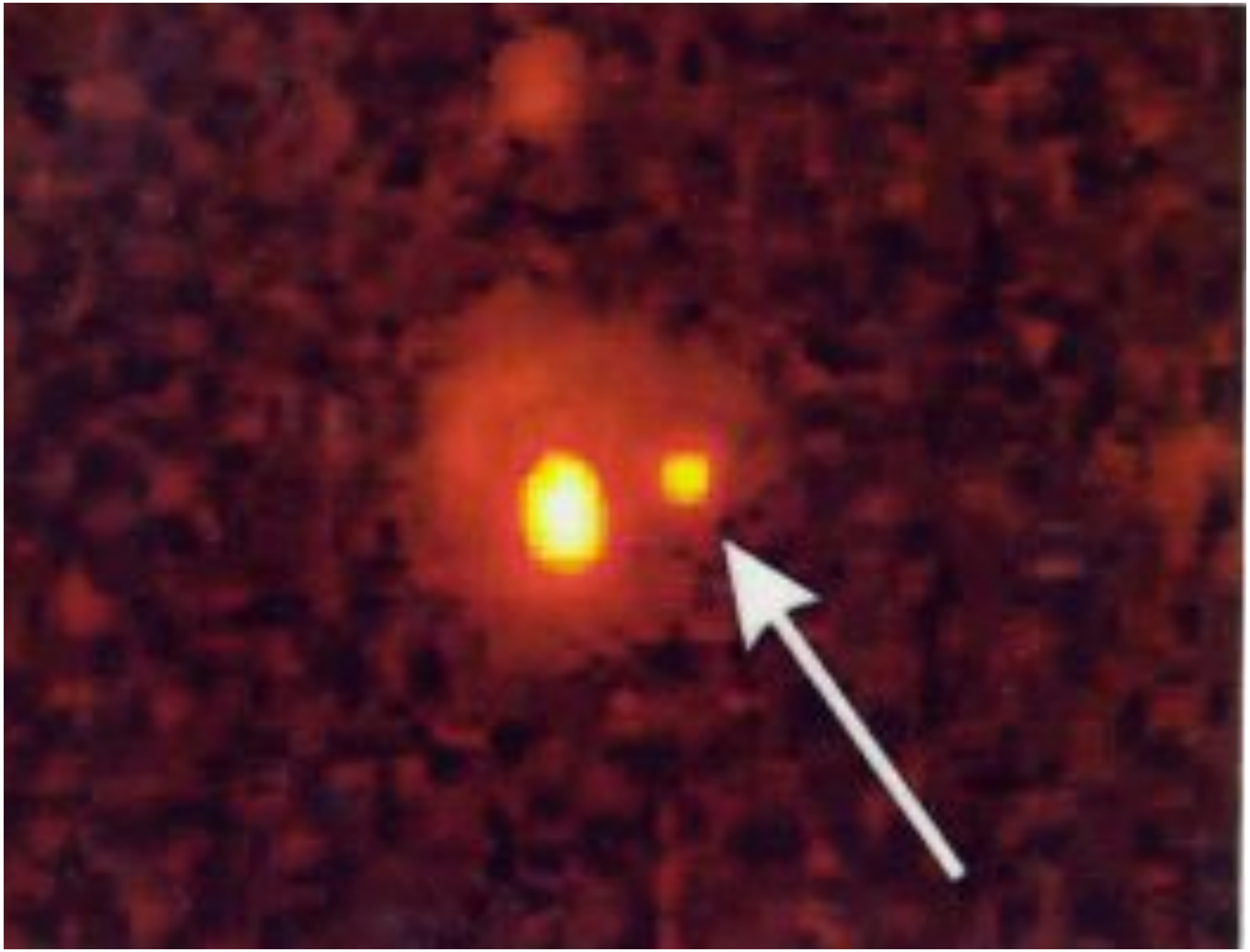
$$\log(d) = 38/5 = 7.6$$

$$10^{7.6} = 40 \text{ Mpc}$$

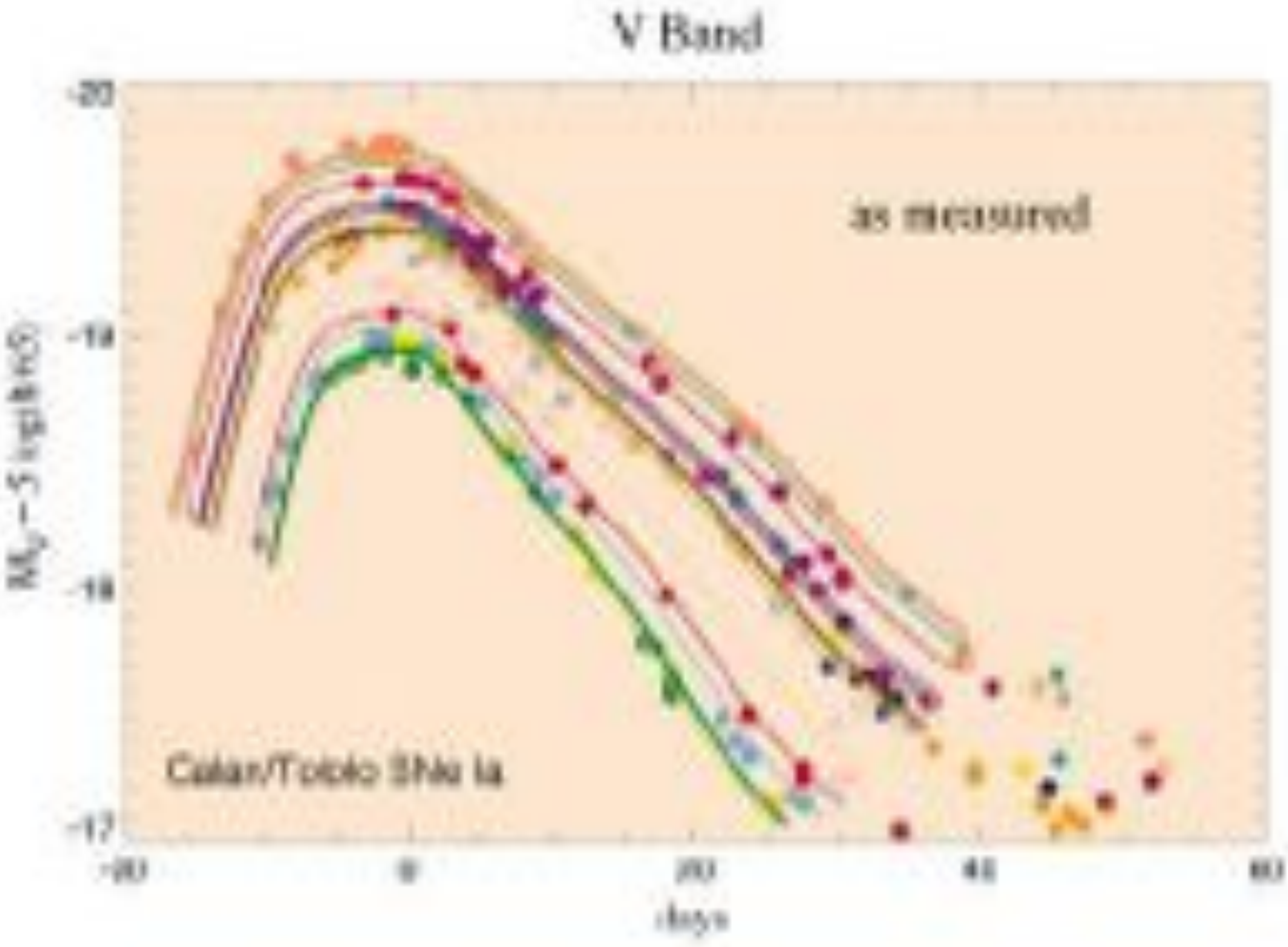
Cepheids play a critical role in bridging distance measurements in the Milky Way to other "nearby" galaxies

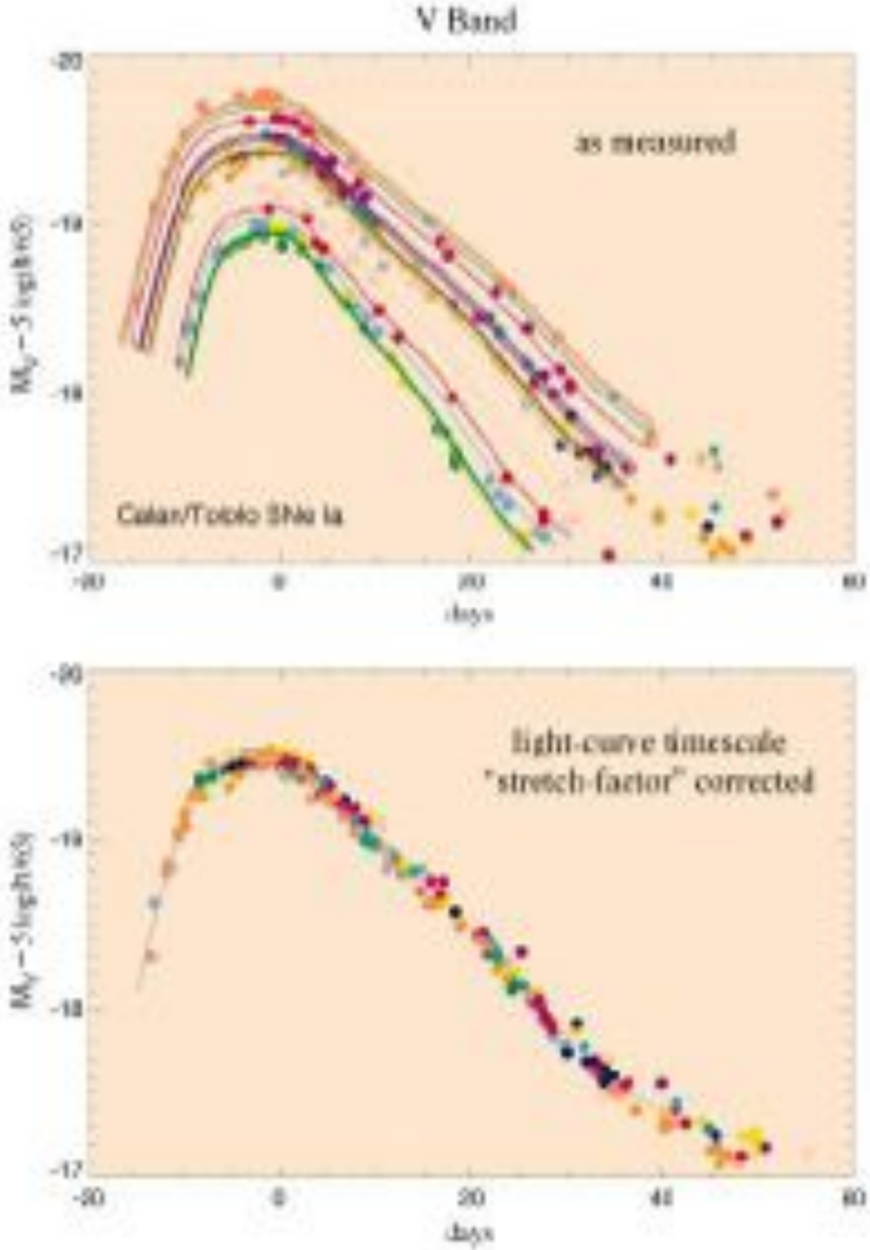
Type Ia Supernovae

Type Ia supernova in a galaxy 7 billion light years away (z = 0.5) - Garnavitch et al (1998)



TYPE Ia SUPERNOVAE ARE ALMOST STANDARD CANDLES





The width of the light curve is correlated with its peak luminosity. “Brighter = Broader”

This relation, known as the “Philipp’s relation” exists because both the brightness and width are correlated with the amount of radioactivity (^{56}Ni) each supernova makes (to be discussed).

Using this correlation, much of the spread in the observations can be narrowed.

It is currently quite feasible to measure supernova light curves down to a magnitude $m = 22$. If the absolute magnitude of a typical Type Ia supernova is $M = -19.5$, how far away can we use them as standard candles for getting distance?

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

$$-19.5 - 22 = 5 - 5\log(d)$$

$$-41.5 - 5 = -5\log(d)$$

$$\log(d) = \frac{-46.5}{-5} = 9.3$$

$$10^{9.3} = 2 \times 10^{9}\ \text{pc}$$

So, two billion parsecs or about 6 billion light years, but are the supernovae there (then) the same as the ones we observe locally (today)?