6. Star Colors and the Hertzsprung-Russell Diagram

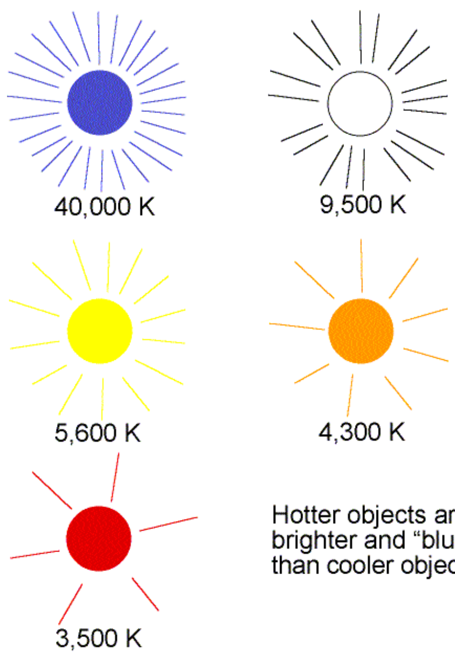
http://apod.nasa.gov/apod/

What we can learn about stars from their light: II Color

In addition to its brightness, light in general is characterized by its *color* (actually its wavelength)

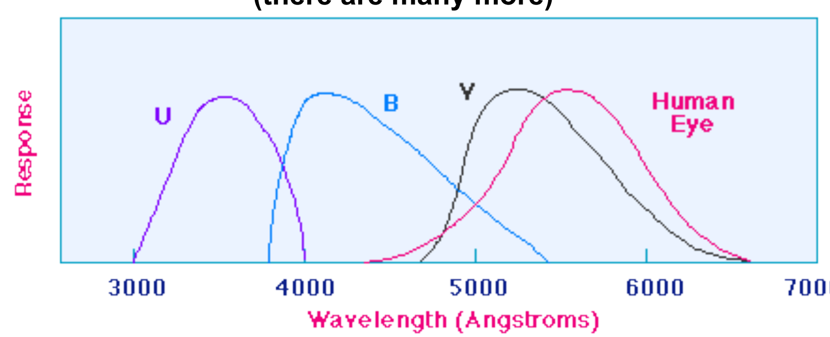
Depending on the *temperature* of the matter at the star's surface where the light last interacted (its "photosphere") starlight will have a characteristic color. The hotter the star, the bluer its color. In fact, starlight is comprised of a variety of colors or "wavelengths". Its perceived color is the band of wavelengths where most of the emission is concentrated weighted by the response of the detector.

From Nick Strobel's Astronomy Notes



Hotter objects are brighter and "bluer" than cooler objects.

FREQUENTLY USED FILTERS ON THE TELESCOPE (there are many more)



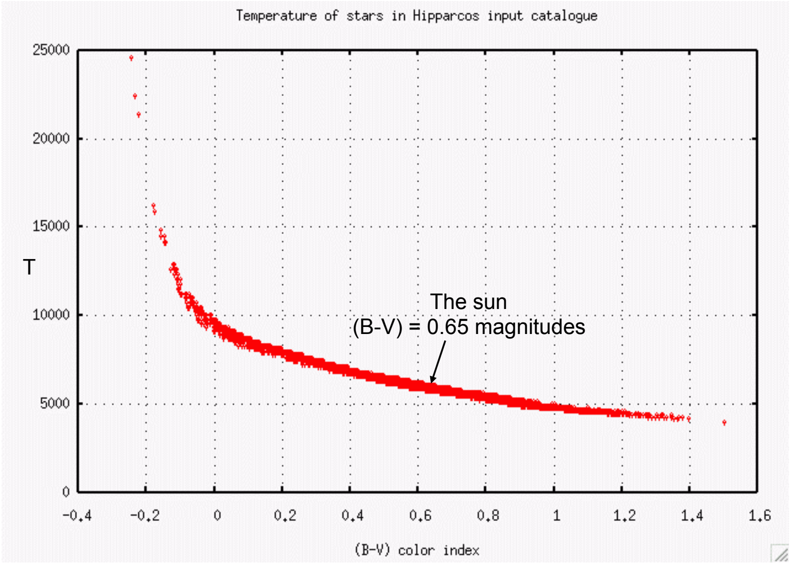
$1\ \mathring{A} = 1\ \text{Angstrom} = 10^{-8}\ \text{cm}$

Astronomers historically have measured the color of a star by the difference in its brightness (magnitude) in two images, one with a blue filter (B) and another with a visual filter (V). (i.e., $B = m_B$; $V = m_V$)

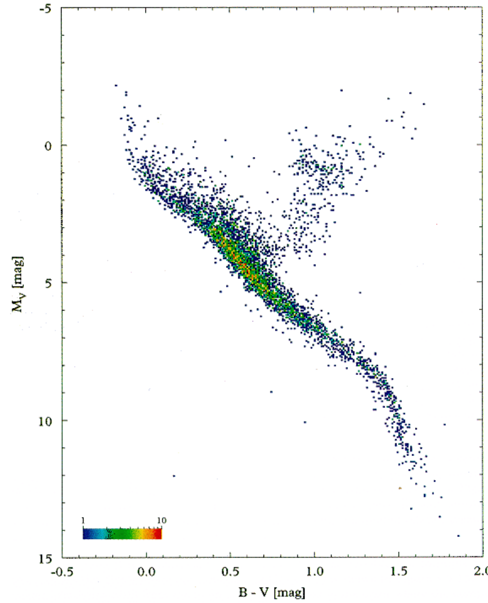
This difference, denoted (B-V), is a crude measure of the temperature.

> *Note that the "bluer" the object, the smaller B will be (small magnitudes mean greater fluxes), so small or more negative (B-V) means bluer and hence hotter temperature.*

A SMALLER COLOR INDEX MEANS A HOTTER STAR



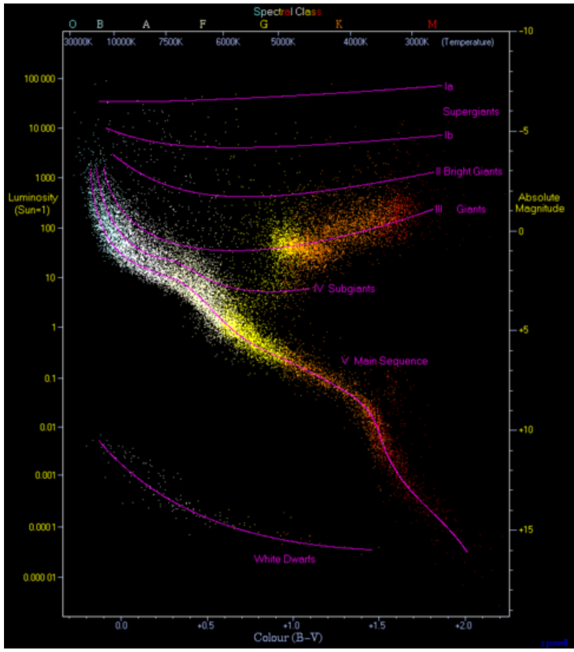
> *The **Hertzsprung-Russell Diagram** - or HR-diagram - of a group of stars is a plot of their colors (or temperatures) vs. their bolometric absolute magnitudes (or luminosities)*



HR diagram for nearby stars from Hipparcos - 4477 stars, distance good to 5%. Absolute visual magnitude vs. (B-V)

(color indicates star density on the plot. 1 red point = 10 stars)

Sun = 0.65, 4.83

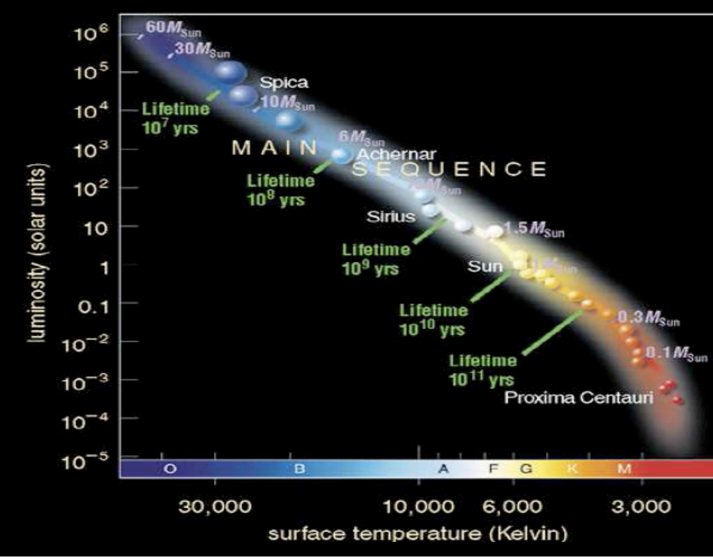


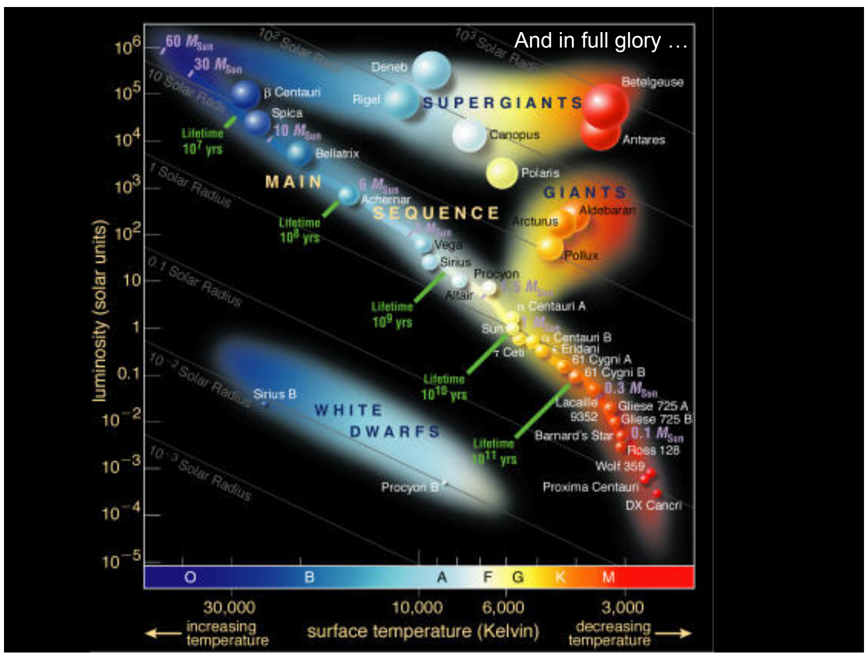
Hertzsprung–Russell diagram with 22,000 nearby stars from the Hipparcos catalog supplemented with 1000 stars from other catalogs.

Absolute bolometric magnitude has been converted into luminosity,

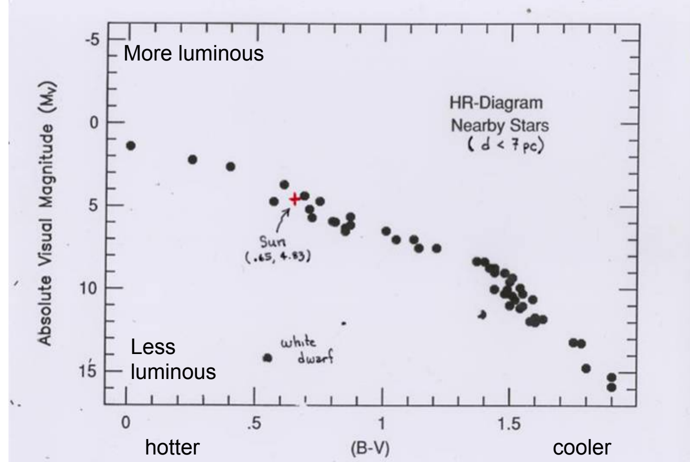
Note that the stars prefer to congregate in well defined strips

Looking ahead, color can be converted to temperature and absolute magnitude to luminosity to give the Hertzsprung-Russel diagram in more physical units





Hertzsprung-Russell Diagram
for Local Stars (a volume-limited sample)



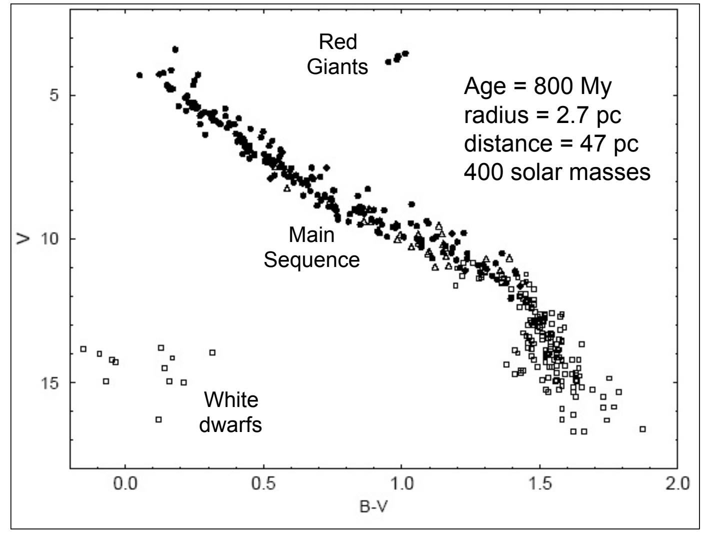
In many cases, the stars themselves can be used as standard candles, once the HR-diagram is calibrated. But need to know it is a *main sequence* star.

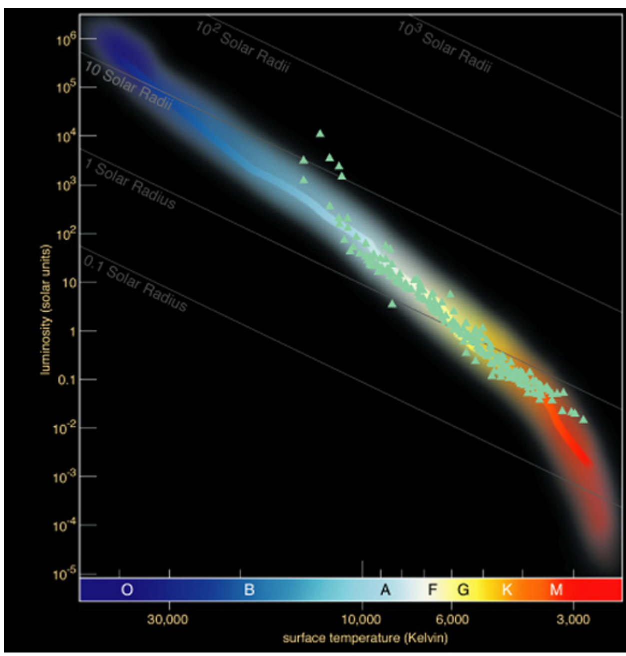
Hyades
- Open cluster
- Constellation Taurus
- Magnitude 0.5
- Angular size 330'

Pleiades:
- Open cluster
- Constellation Taurus
- Magnitude 1.6
- Angular size 110'

Stars in each cluster were born together and are approximately equidistant though the two clusters themselves were born at different times

Hyades Cluster

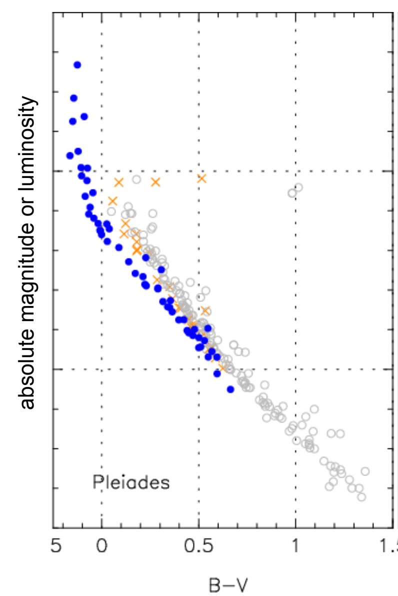




HR Diagram for the Pleiades – an open cluster of about 1000 stars.

No red giants or white dwarfs. Some of the more massive stars are starting to evolve away from the main sequence

Age = 65 My



Open circles are Hyades; blue points are Pleiades

One can also use the HR-diagram of a cluster (or even individual main sequence stars) to get distances.

Because of the spread in the main sequence width, the distances are not very precise (compared, e.g., with Cepheids) but there are a lot more ordinary stars than Cepheids and some of them are very luminous.

compare at B-V = 0.4

m = 6.5 and 9

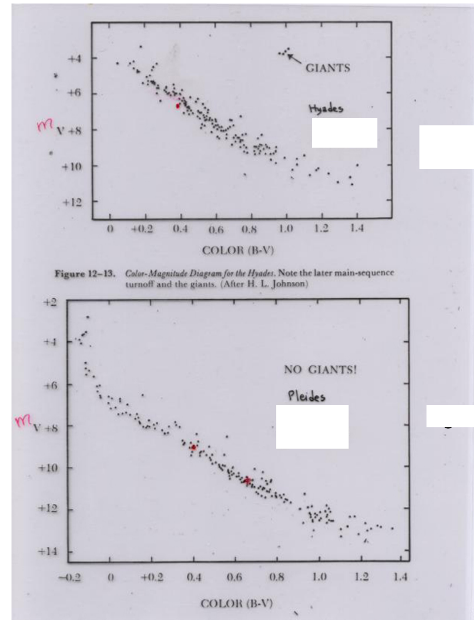


Figure 12-13. *Color-Magnitude Diagram for the Hyades.* Note the later main-sequence turnoff and the giants. (After H. L. Johnson)

Which is older?

Which is closer? By how much?

E.g., at B-V = 0.4 (assume MS stars with same B-V have same absolute M)

Hyades m = 6.5

Pleiades m = 9

$\Delta m = m_H - m_P = -2.5$

$m_2 - m_1 = 2.5 \log(\phi_1/\phi_2)$ let 2 = Hyades

$m_H - m_P = -2.5 = 2.5 \log(\phi_P/\phi_H)$

$\log(\phi_P/\phi_H) = -1.0$

So $\phi_P/\phi_H = 0.1$

But for main sequence stars of a given B –V, L is constant, and since

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

the distance to the Pleiades must be farther by a factor of $\sim\sqrt{10}$, or about 3 times farther away. (Hyades 47 pc; Pleiades 140 pc)

We could also just use the sun and Pleiades cluster to get a distance. For its color, the sun would have an apparent magnitude in the Pleides of 10.3 (see graph)

$$(B\text{-}V)_\odot = 0.65 \quad M_V = 4.83$$

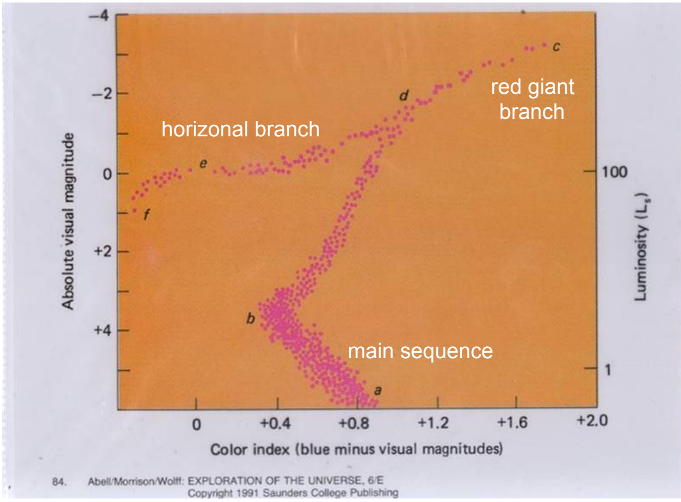
$$M - m = 5 - 5\log(d)$$

$$\frac{4.8 - 10.3 - 5}{-5} = 2.1 = \log(d)$$

$$d = 126 \text{ pc}$$

or use any other star whose absolute magnitude is known

An old cluster



If the cluster is highly evolved and most of the massive stars are gone, one can still use that portion of the main sequence that remains unburned.

Age of cluster = main sequence life time of the heaviest star still on the main sequence

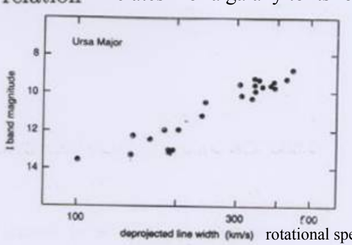
E.g., if that mass is 1.0 solar masses the cluster's age is the main sequence lifetime of a 1.0 solar mass star which is very nearly 10 billion years
if the turn off mass is instead 0.8 solar masses

$$\tau \approx 10^{10}\ \text{yr}\left(\frac{1\,M_\odot}{0.85\,M_\odot}\right)^2 = 13.8\ \text{billion years}$$

Turn off masses are our main tool for dating the ages of star clusters

Other distance indicators

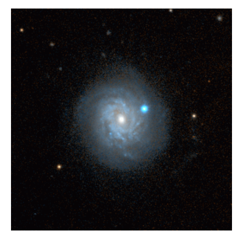
- Brightest half dozen or so galaxies in a cluster of galaxies (very uncertain)
- Tulley-Fisher relation - relates L of a galaxy to its rotation rate



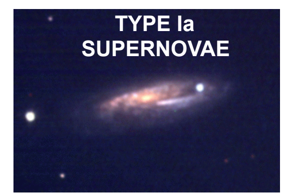
$$L \propto v_{rot}^4$$

The rotational velocity of spiral galaxies, as measured by spectral line broadening, is a measure of the mass of the galaxy, and the mass in turn correlates with the luminosity.

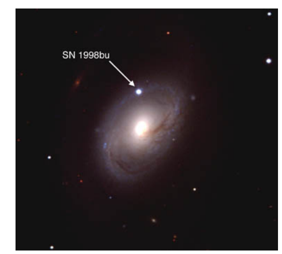
A similar relation called the Faber-Jackson relation holds for the stellar velocity distribution in elliptical galaxies



SN 1998aq



SN 1998dh



SN 1998bu

SN 1994D

For several weeks the luminosity of a Type Ia supernova rivals that of a large galaxy - 10^{43} erg s^{-1}, or several billion solar luminosities.

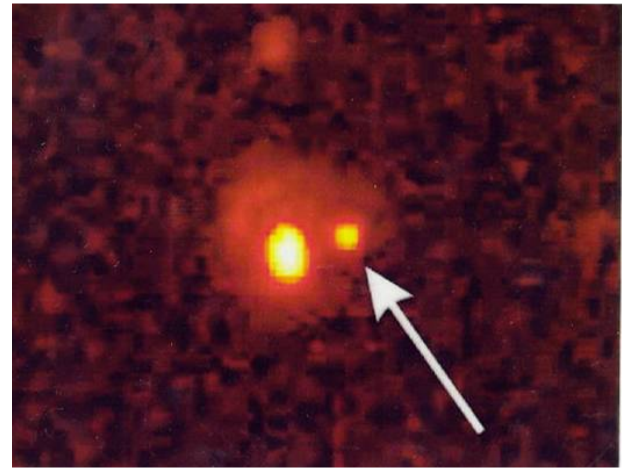
It is currently quite feasible to measure supernova light curves down to a magnitude $m = 22$. If the absolute magnitude of a typical Type Ia supernova is $M = -19.5$, how far away can we use them as standard candles for getting distance?

$$M - m = 5 - 5\log(d)$$
$$-19.5 - 22 = 5 - 5\log(d)$$
$$-41.5 - 5 = -5\log(d)$$
$$\log(d) = \frac{-46.5}{-5} = 9.3$$
$$10^{9.3} = 2\times10^{9}\ \text{pc}$$

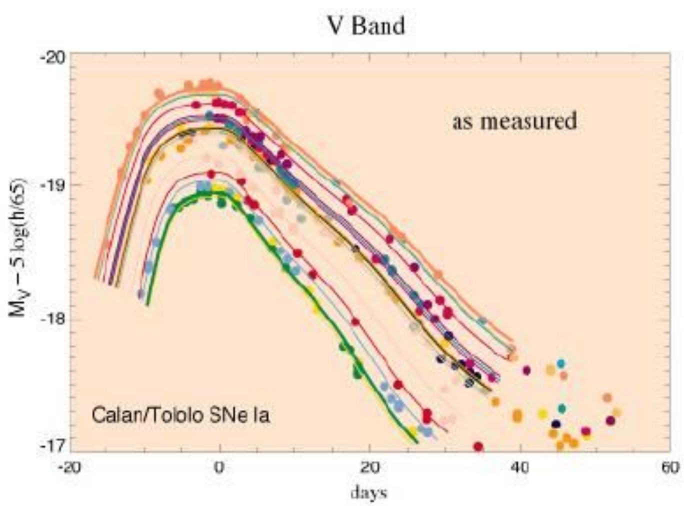
So, two billion parsecs or about 6 billion light years

*the magnitude of the moon at its brightest is – 12.7; the sun -26.75

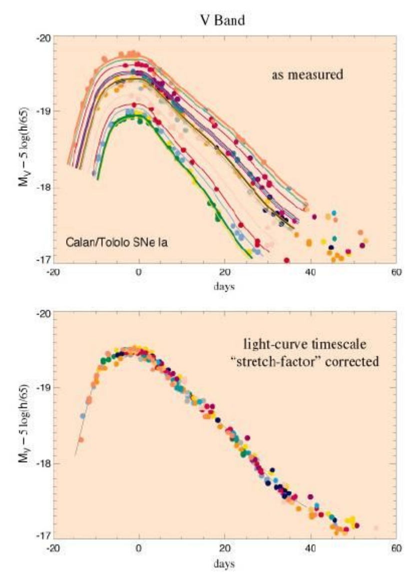
Type Ia supernova in a galaxy 7 billion light years away (z = 0.5) - Garnavitch et al (1998)



TYPE Ia SUPERNOVAE ARE ALMOST STANDARD CANDLES



AND IT CAN BE MADE EVEN BETTER ...



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.

Distance Determination Summary

- The AU by radar and Kepler's Third Law

- Ordinary trigonometric parallax. After Hipparchos, this is good to 1000 pc. Angles of 1 mas can be accurately measured. Distances determined for about 10,000 stars.

- Color magnitude diagram (HR-diagram) - reliable to 10% for distances up to 50 kpc

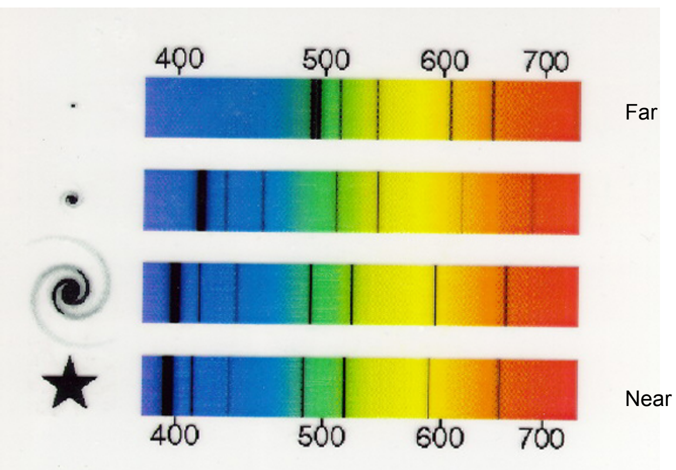
- Cepheid variables. Good to about 50 Mpc using Hubble Space Telescope. Gets us to the Virgo Cluster of galaxies (about 1000 galaxies). Historical problem with calibration because of 2 populations and lack of nearby Cepheids. Hipparchos improved the situation.

- Tulley-Fisher Relation. Relates absolute magnitude to rotational velocity for spiral galaxies. $L \propto v_{rot}^4$. Used with decreasing accuracy out to 1000 Mpc. Caution - galaxy based standard candles are subject to evolution. Measure v_{rot} in the radio or optical

  Faber-Jackson Relation is a similar technique for elliptical galaxies.

- Type Ia supernovae. Assume a calibrated standard candle. Average M_{bol} is -19.6, but can correct for dispersion about this using "templates". Bright SNae of Type Ia have broader light curve peaks. Good to 10% to several 1000 Mpc. Evolution?

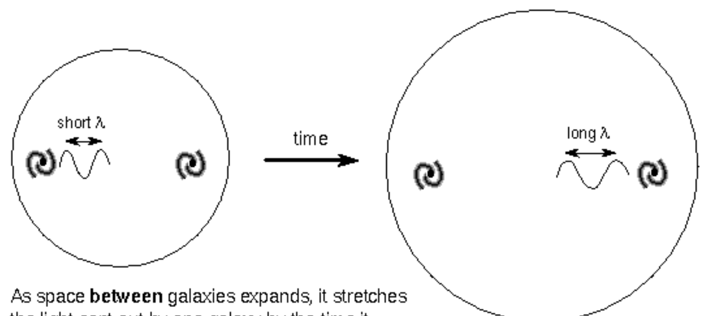
- Eventually the expansion of the universe becomes apparent. One measures a cosmological red shift that is correlated with the distance



wavelength is in units of 10^{-7} cm (nanometers)

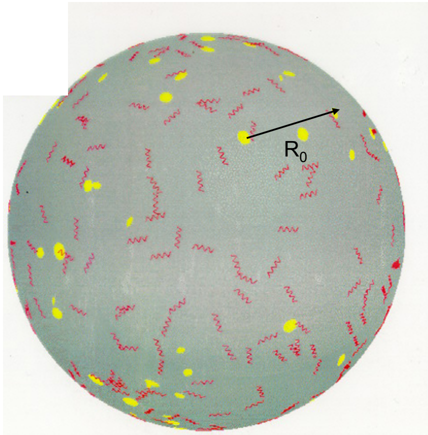
From Nick Strobel's *Astronomy Notes*

The cosmolgical expansion of the universe.

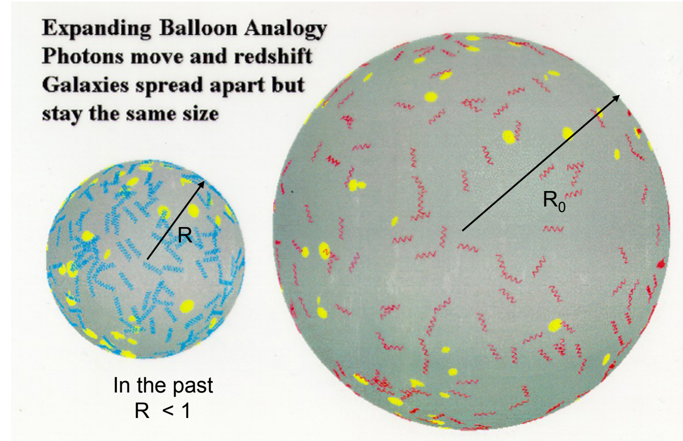


As space **between** galaxies expands, it stretches the light sent out by one galaxy by the time it reaches another far away galaxy. Looks like **redshift**.

nb. The distance to the sun is not increasing nor are you getting any larger.



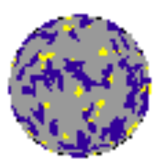
Let R be the distance between two very widely separated galaxies, at least 100 Mpc. Normalize R such that its present day value R_0 = 1. Use that as a yardstick and see how it varies with time.
In the past R < 1

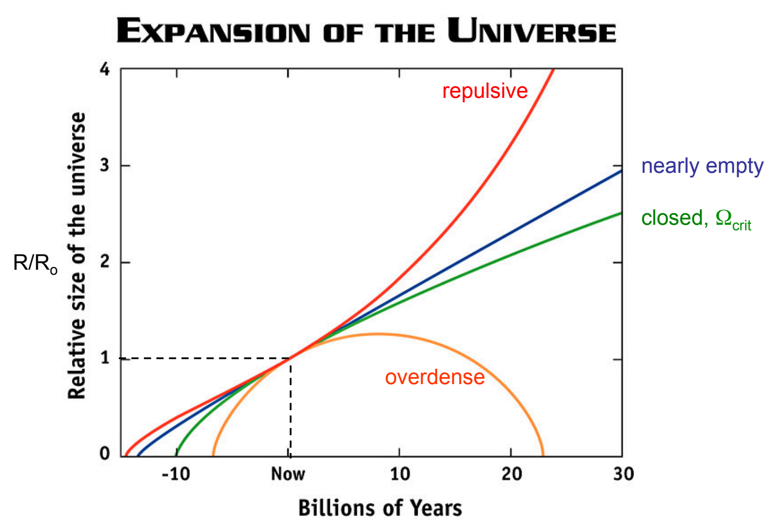


Now R_o = 1

$$1+z = \frac{R_0}{R} \qquad R \le R_0$$

http://www.astro.ucla.edu/%7Ewright/balloon0.html





The "expansion velocity" is the slope of these curves at a given time

If one could measure R at different times in the past epochs in the evolution of the universe, then one might discriminate not only the age of the universe but what kind of universe we live in. In fact, what we measure is the redshift, z,

$$1 + z = \frac{R_0}{R} \qquad R \leq R_0$$

and the brightness of some standard candle, like a SN Ia.

So z tells us what R is and the distance, inferred from the brightness of the standard candle, divided by the speed, tells us how long ago the light was emitted. Actually one needs a "cosmological model" to interpret all these quantities accurately, but the models exist and are not too complicated.

So we can infer R(t).

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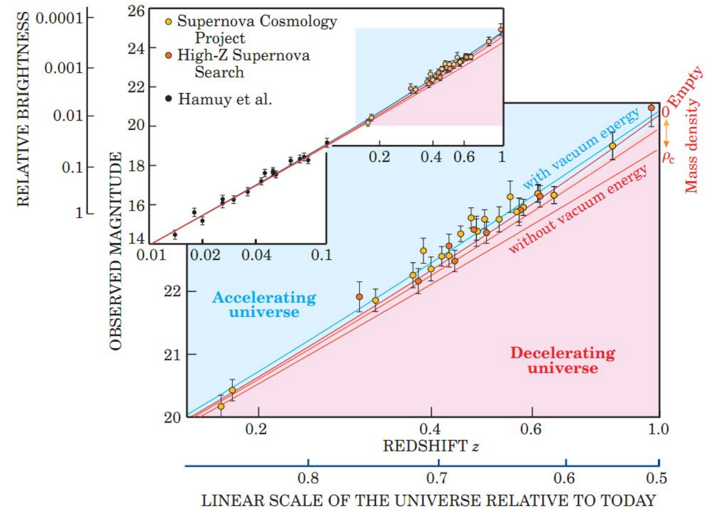
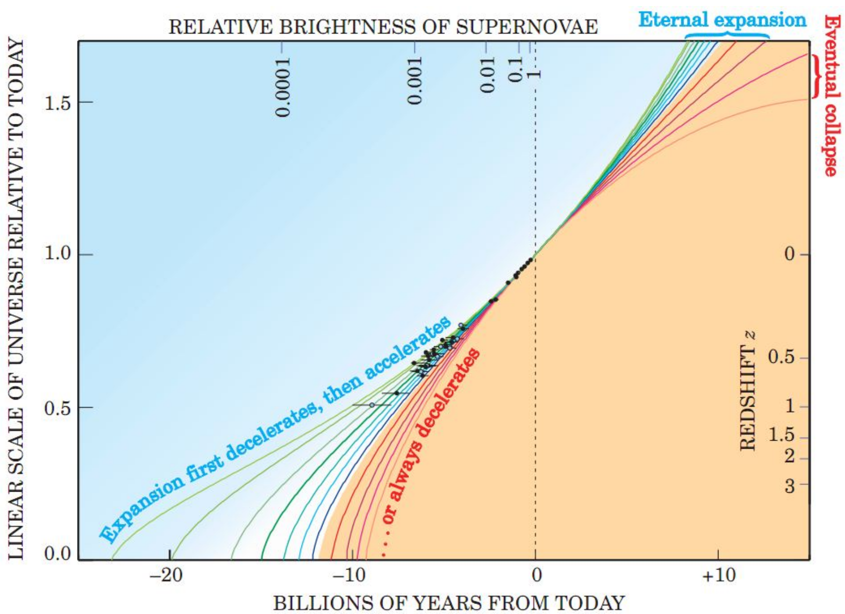
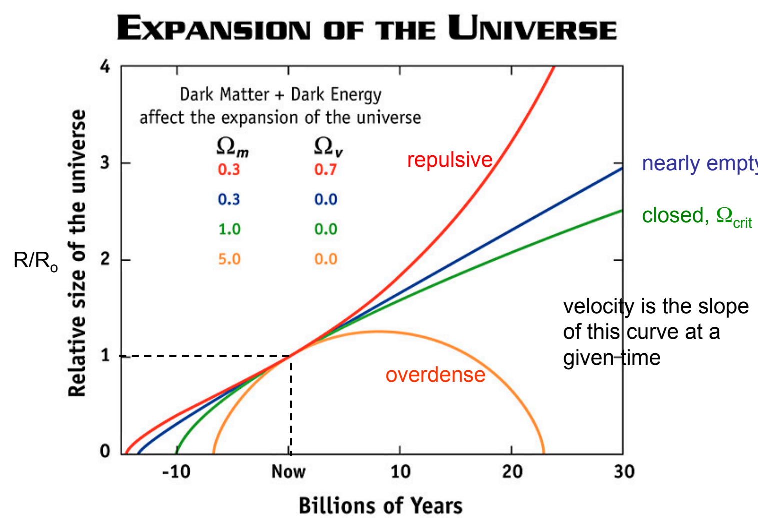


http://physicsforme.com/2011/10/04/supernovae-dark-energy-and-the-accelerating-universe/





The "expansion velocity" is the slope of these curves at a given time

Locally, the rate at which R is changing, $\frac{dR}{dt}$, is very nearly constant, so

$$R = R_o - \Delta t \frac{dR}{dt}$$

where Δt is just the time it took light to reach us from the object at distance, d

$$\Delta t = \frac{d}{c}$$

Then

$$1+z = \frac{R_o}{R} = \frac{R_o}{R_0 - \frac{d}{c}\left(\frac{dR}{dt}\right)} = \frac{1}{1-\frac{d}{R_o c}\left(\frac{dR}{dt}\right)}$$

$$= \left(1-\frac{d}{R_o c}\left(\frac{dR}{dt}\right)\right)^{-1} \approx 1+\frac{d}{R_o c}\left(\frac{dR}{dt}\right)$$

So $z \approx \frac{H_o d}{c}$ which we can define as $\frac{v_{recession}}{c}$

$$v_{recession} = H_o d$$

where $H_o = \frac{1}{R_o}\left(\frac{dR}{dt}\right)$ is Hubble's constant

http://hubblesite.org/newscenter/archive/releases/2009/08/full/

If $H_0 = 71 \text{km s}^{-1}\ \text{Mpc}^{-1}$ (from Cepheid Variables + Type Ia SN+WMAP)

$1 \text{Mpc} = 3.08 \times 10^{24}\ \text{cm} = 3.08 \times 10^{19}\ \text{km}$

$H_o = (71/3.08x10^{19})\text{s}^{-1}$

$1/H_o = (3.08x10^{19}/71)\ \text{s}$

$= 4.33\,x10^{17}\ \text{s} =$ 13.7 billion years

but this is for a universe that expanded with constant speed (i.e., contains no matter). For one that contains just enough matter to coast to infinity and stop -

The blue line on the previous plot

$$\left(\frac{2}{3}\right)(1/H_o) = 9.1 \text{ by}$$

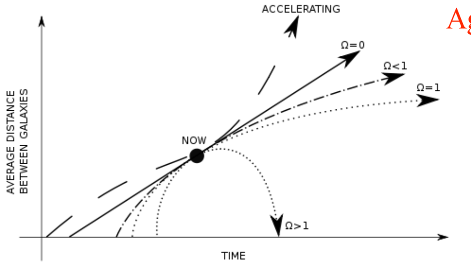
But other measures are consistent with 12 – 14 billion years.

- Globular cluster ages
- Radioactive dating of the elements

WMAP (2011)

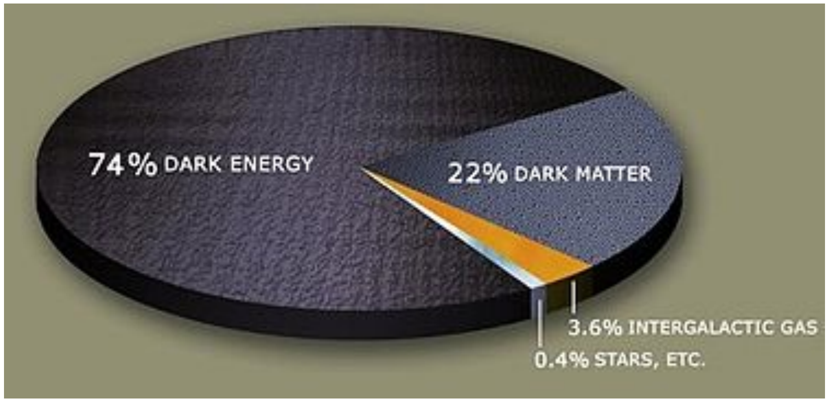
$$H_o = 71 \pm 2\ \text{km}/(\text{s Mpc})$$

$$\text{Age} = 13.75\ \pm 0.11\ \text{billion years}$$



http://map.gsfc.nasa.gov/universe/uni_age.html
http://en.wikipedia.org/wiki/Age_of_the_universe

If the expansion of the universe is now accelerating, it moved slower in the past and took longer to get to its present size than just $1/H_o$ would suggest.



http://en.wikipedia.org/wiki/Dark_energy

More recent Planck mission results suggest 26.8% dark matter, 68.3% dark energy and 4.9% ordinary matter

A major question: Is dark energy constant in space and time – a certain amount of energy per unit volume for the vacuum or does it change with time and place.

Is it a cosmological constant or some sort of scalar field (quintessence)?

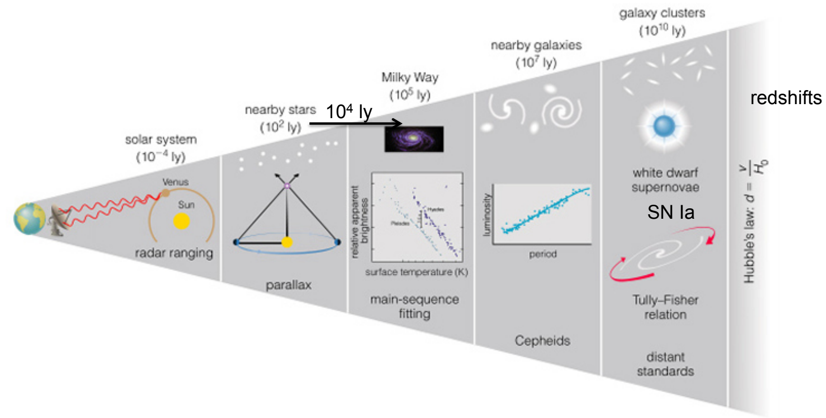
Or do we misunderstand gravity – or time - on very large scales? Does our basic cosmological principle still hold (uniform physics)?

Dark energy has no effect on scale of the solar system which is completely dominated by ordinary matter.

Dark energy and dark matter are, for now, totally different things.

The most profound mystery in modern physical science.

Cosmic Distance Ladder



http://www.daviddarling.info/encyclopedia/C/cosmic_distance_ladder.html