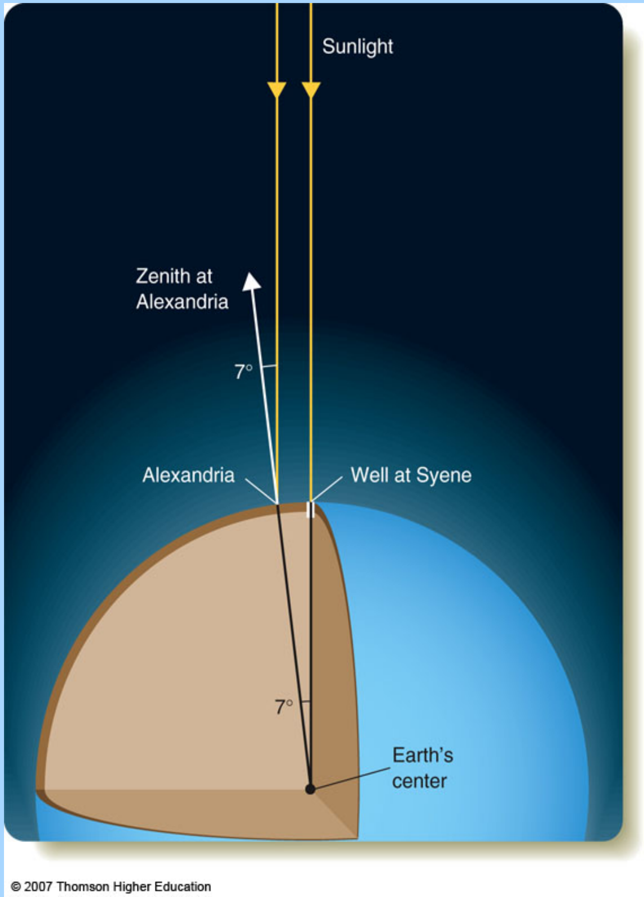
The Cosmological Distance Ladder

It's not perfect,
but it works!

First, we must know how big the Earth is.



Next, we must determine the scale of the solar system. Copernicus (1543) correctly determined the *relative* sizes of the orbits of the known planets. But we needed to know the Astronomical Unit in km.

One way to determine this is to observe a transit of Venus across the disk of the Sun from a variety of locations spread out over the Earth. (Using the Earth as a baseline, we determine the distance.)

These transits have occurred in 1761, 1769, 1874, 1882, and 2004. The last one occurred in 2012.

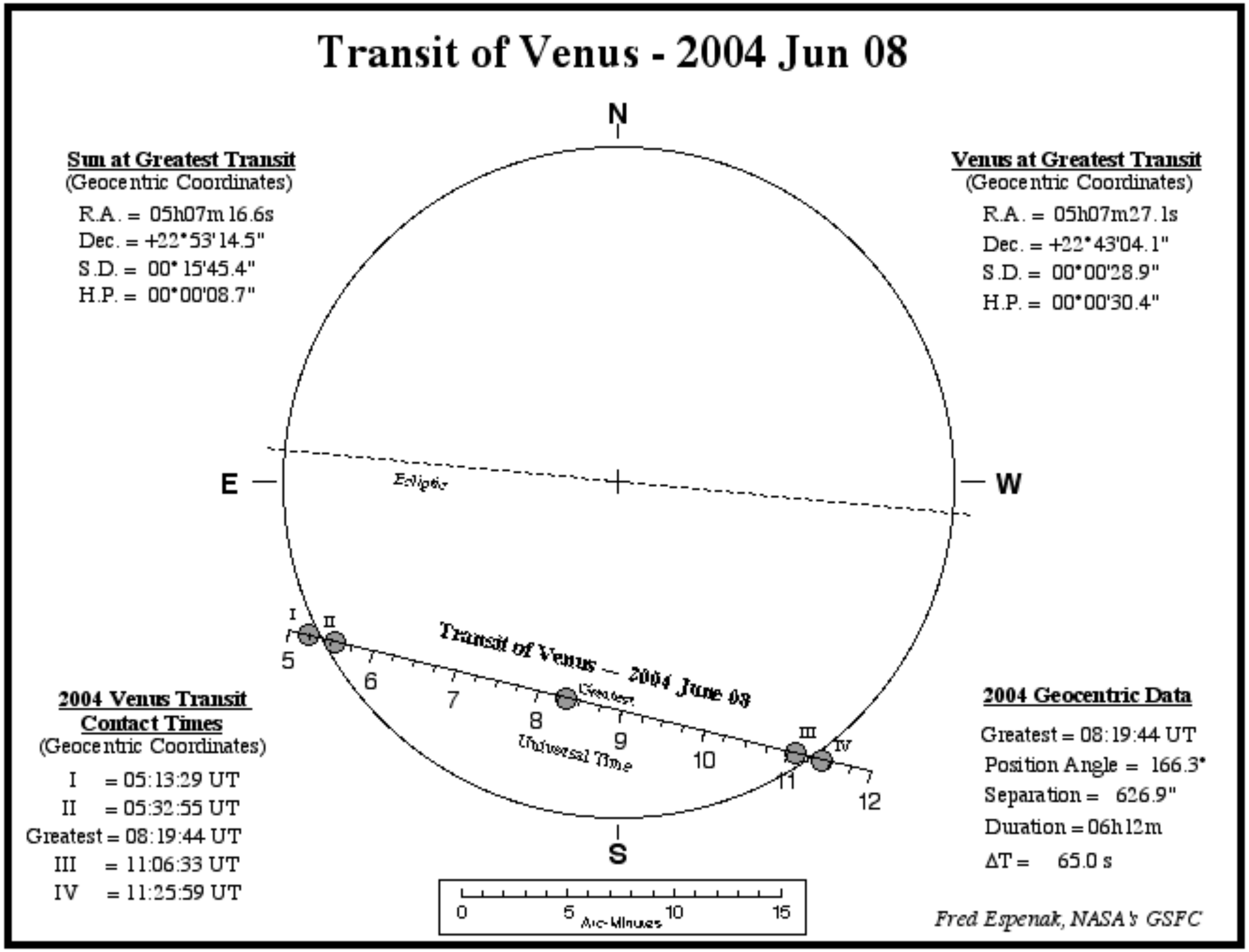
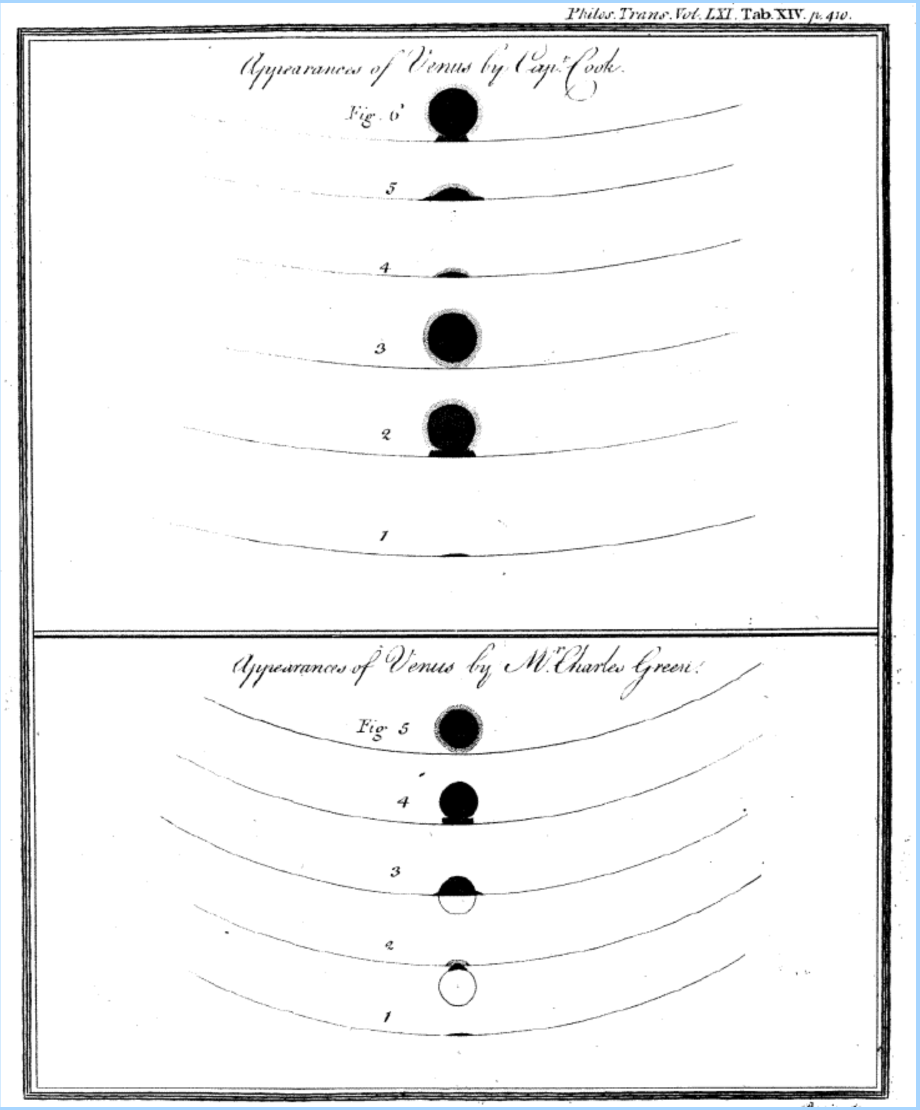
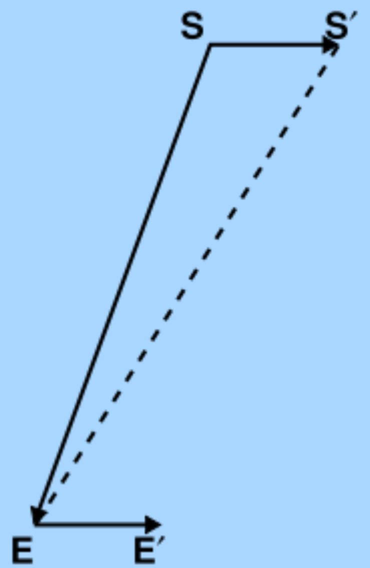


Figure 2 - Path of Venus across the Sun's disk on 2004 June 08.



The big problem
with these observations
is related to the thick
atmosphere of Venus.

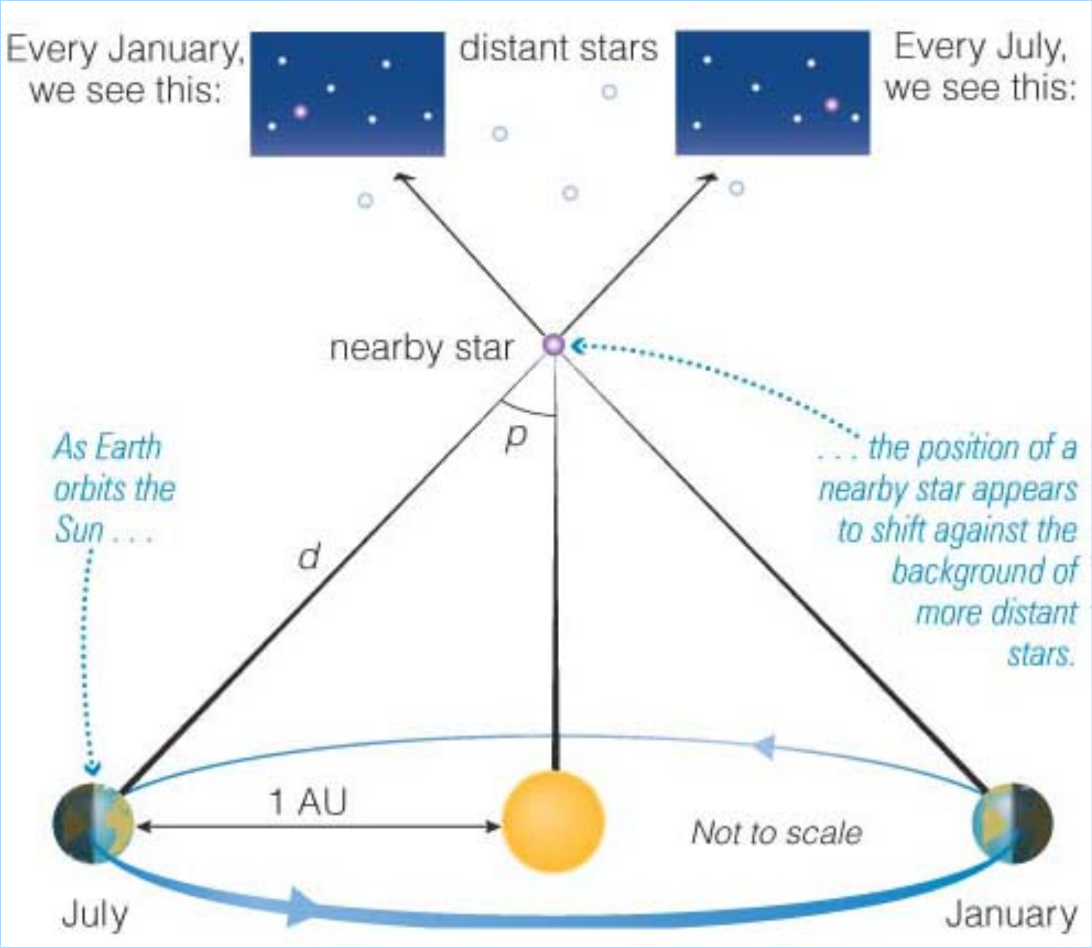
The most accurate value for the length of the AU until the 20th century was obtained using measurements of the constant of aberration. Discovered by James Bradley in 1725, aberration arises from the finite speed.



The Earth orbits the Sun at 30 km/sec, or 10^{-4} of the speed of light. Star positions are shifted 20.5 arcsec from the positions they would have if the Earth were stationary.

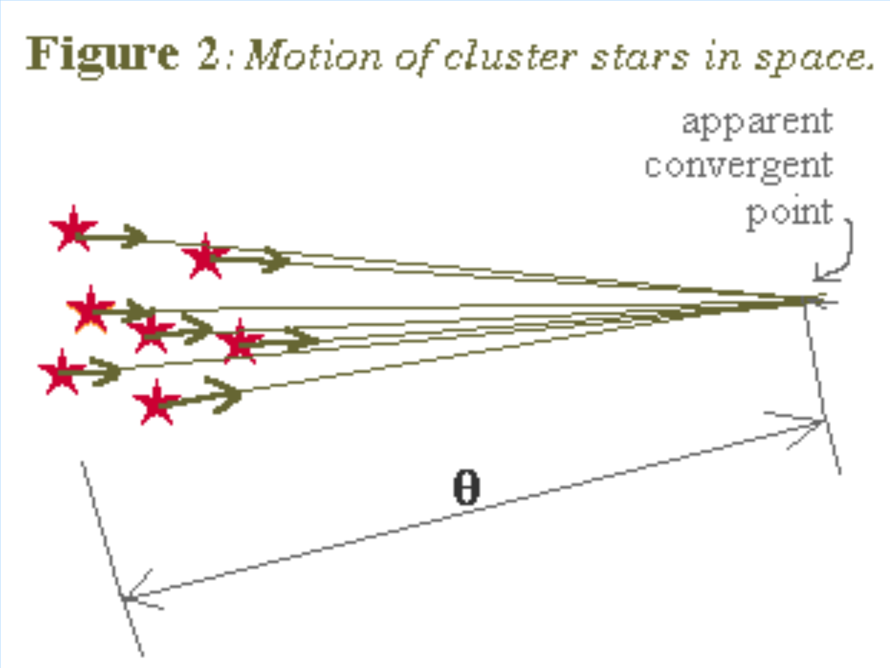
If we know the constant of aberration and the speed of light, we can derive what the mean speed is of the Earth's revolution about the Sun. Since we know how many second long the year is, we can then calculate how many km the circumference of the Earth's orbit amounts to. Then we can determine the mean distance to the Sun.

In the 20^{th} century it became possible to determine the distance to Venus directly, using **radar**. Mars and various asteroids could have their absolute distances measured too. Since their orbits were also determined, very accurate values of the AU could be obtained.



By measuring stellar parallaxes we can determine the distances to the nearby stars. The Hipparcos satellite measured many thousands of parallaxes.

Proxima Centauri (courtesy Adric Riedel, GSU)



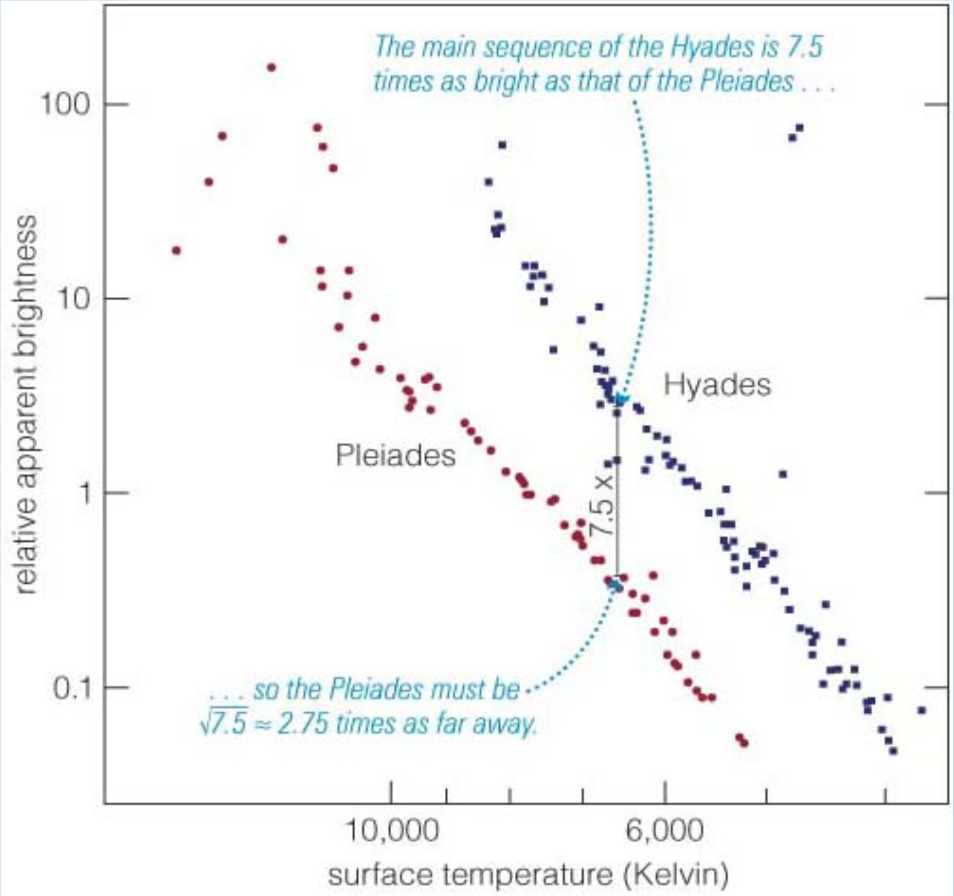
As the stars in the Hyades star cluster (in Taurus) move through space their proper motions appear to converge at a particular point on the sky. This is an effect of perspective. Think of a flock of birds all flying towards the horizon.

If the angular distance of the cluster from the apparent convergent point is λ, then there is simple relationship between the radial velocity of a star in the cluster and its transverse velocity:

$$v_T = v_R \tan(\lambda)$$

Since the transverse velocity $v_T = 4.74\, d_{pc}\, \mu$ (where μ is the proper motion in arcsec per year and d is the distance in parsecs), we can use the moving cluster method to get estimates of the distance to all the Hyades stars with measured proper motions and radial velocities. The average would be the distance to the cluster.

The method of main sequence fitting



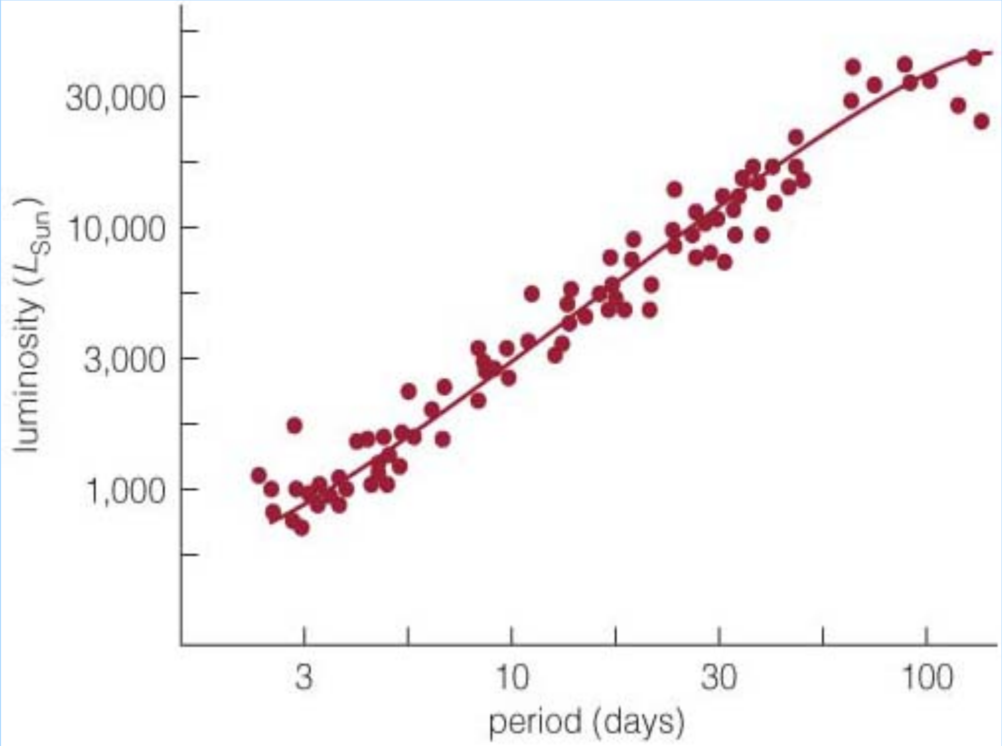
Since main sequence stars of a particular temperature all have the “same” intrinsic brightness, a cluster with a main sequence some number of magnitudes fainter than the Hyades gives us its distance in terms of the distance to the Hyades.

Pulsating stars of known intrinsic brightness

RR Lyrae stars have mean absolute magnitudes of about $M_V \sim +0.7$. If you know the apparent magnitude and absolute magnitude of a star, you can determine its distance using this formula

$$M_V = m_V + 5 - 5 \log d \ ,$$

where the apparent magnitudes have been corrected for interstellar extinction and d is the distance in parsecs.



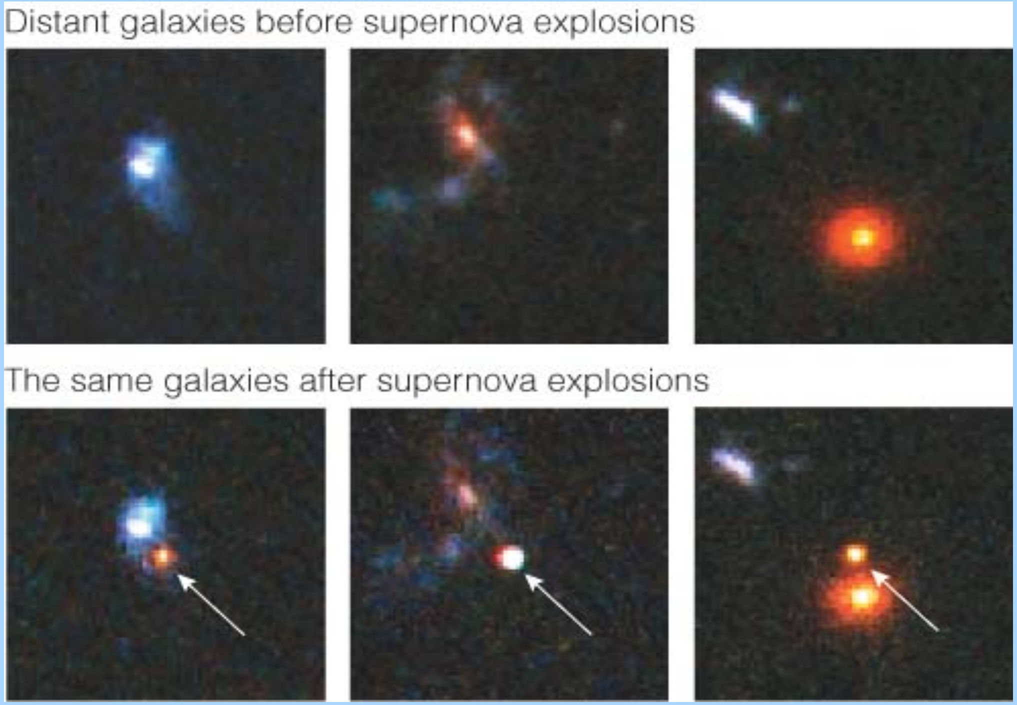
If you find a Cepheid variable star with a period of 30 days, it is telling you, "I am a star that is 10,000 times more luminous than the Sun!"

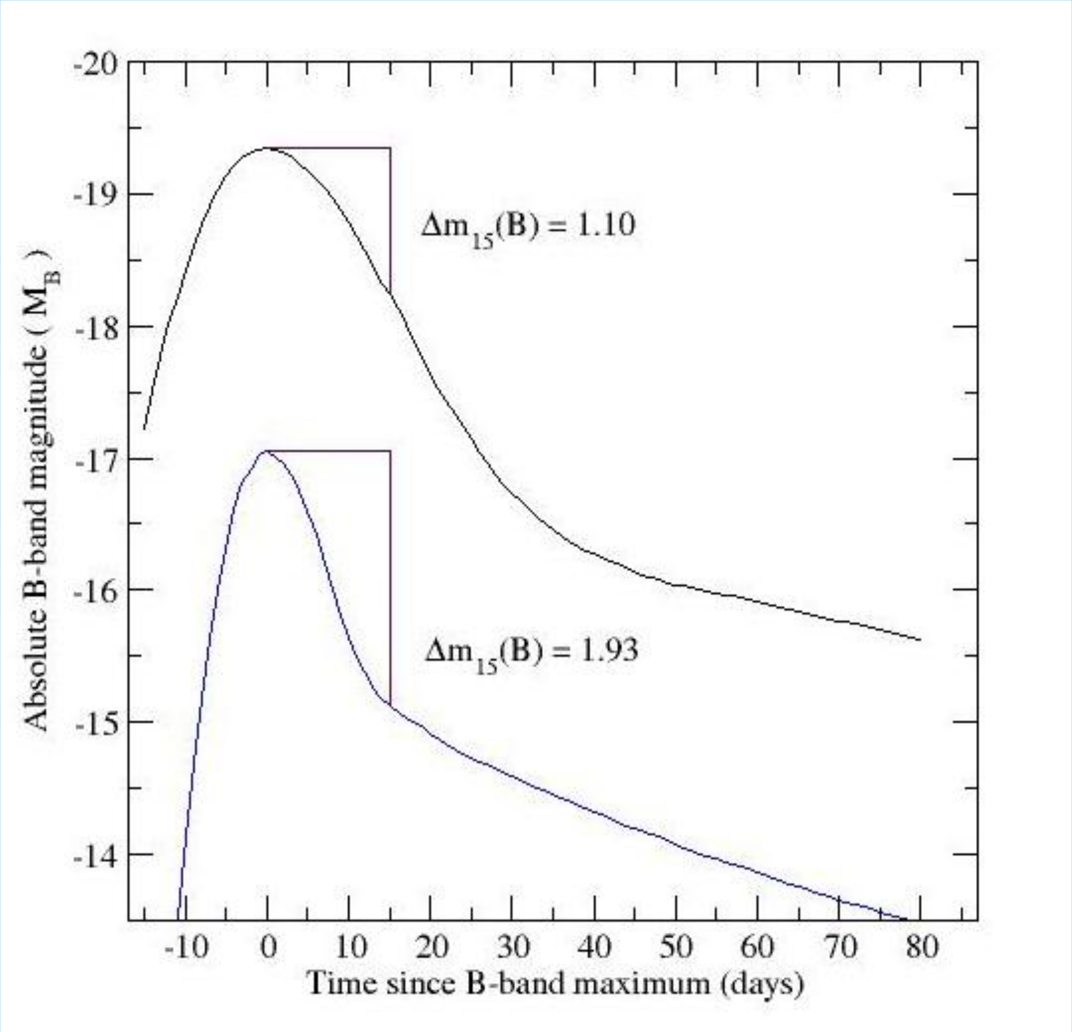
Cepheid variable stars were used by Shapley to determine the distances to globular clusters in our Galaxy. This allowed him to determine the distance to the center of the Galaxy.

In 1924 Edwin Hubble used Cepheids to show that the Andromeda Nebula is very much like our Milky Way Galaxy. Both are large ensembles of a couple hundred billion stars. And the Andromeda Galaxy is a couple million light years away.

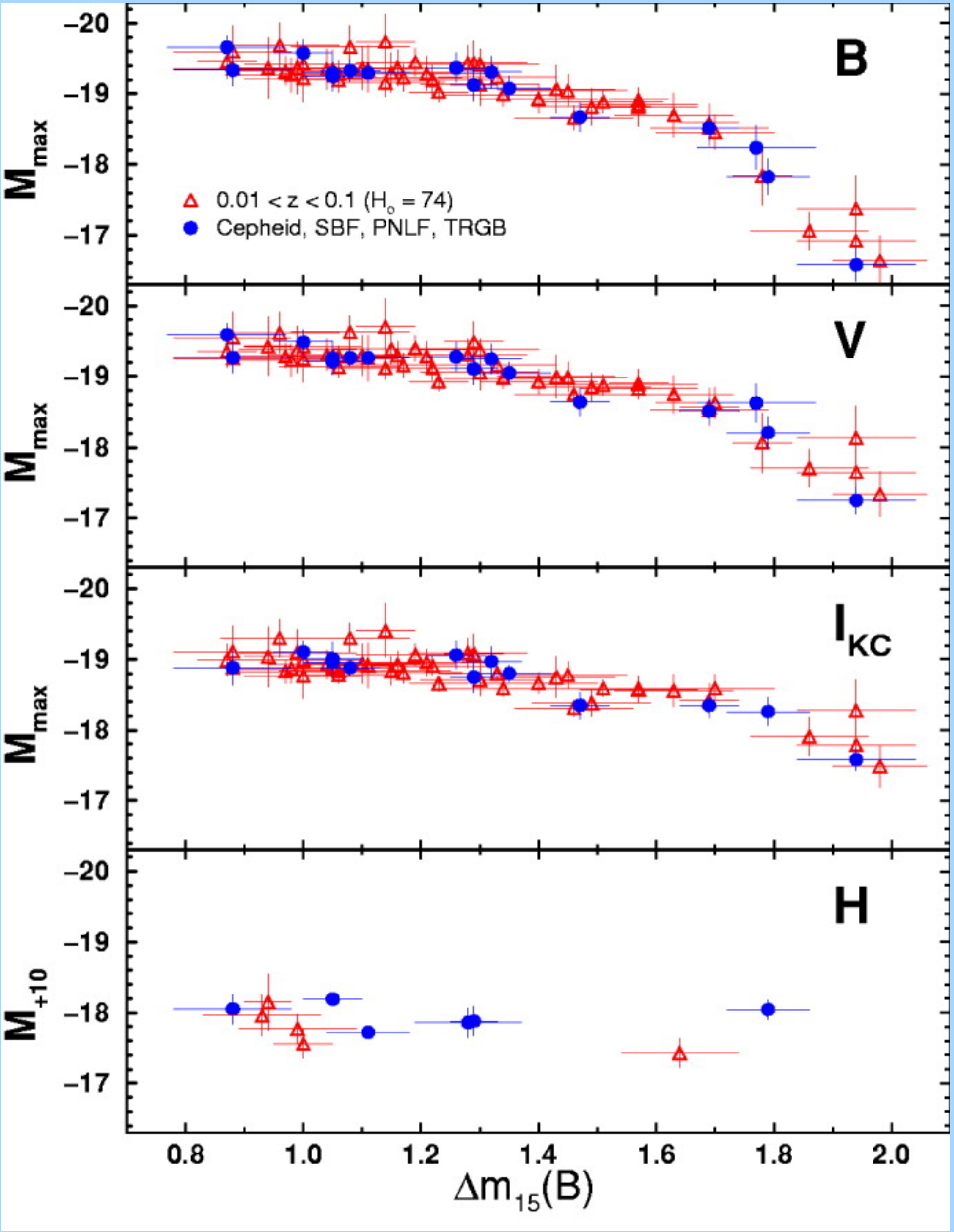
In the 1990's, using the Hubble Space Telescope, we used observations of Cepheids in somewhat more distant galaxies to determine their distances.

Perhaps the best standard candles to use for extragalactic astronomy are white dwarf (Type Ia) supernovae. There is a relationship between their absolute magnitudes and the shape of their light curves that allows us to determine their absolute magnitudes.



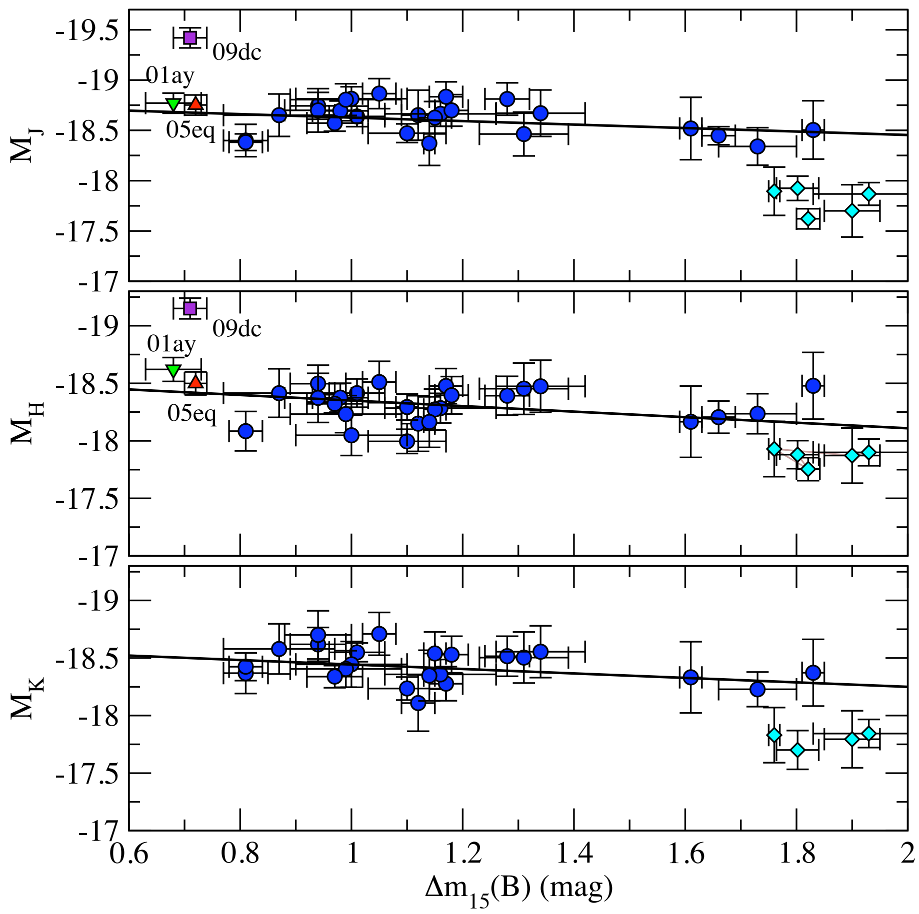


For Type Ia supernovae we define the "decline rate" as the number of magnitudes the object gets dimmer in the first 15 days after maximum light in the blue. Fast decliners are fainter objects.



On the x-axis is the number of magnitudes that a Type Ia super-nova gets fainter in the first 15 days after maximum light.

Krisciunas et al. (2003)



In the near-infrared, Type Ia supernovae are even better standard candles. Only the very fastest decliners are fainter than the rest.

Krisciunas (2012)

Which of the following is NOT an astronomical standard candle?

A. A0 main sequence star
B. Cepheid variable with a period of 20 days
C. Type Ia supernova with a normal decline rate
D. White dwarf star of mass 0.6 solar masses

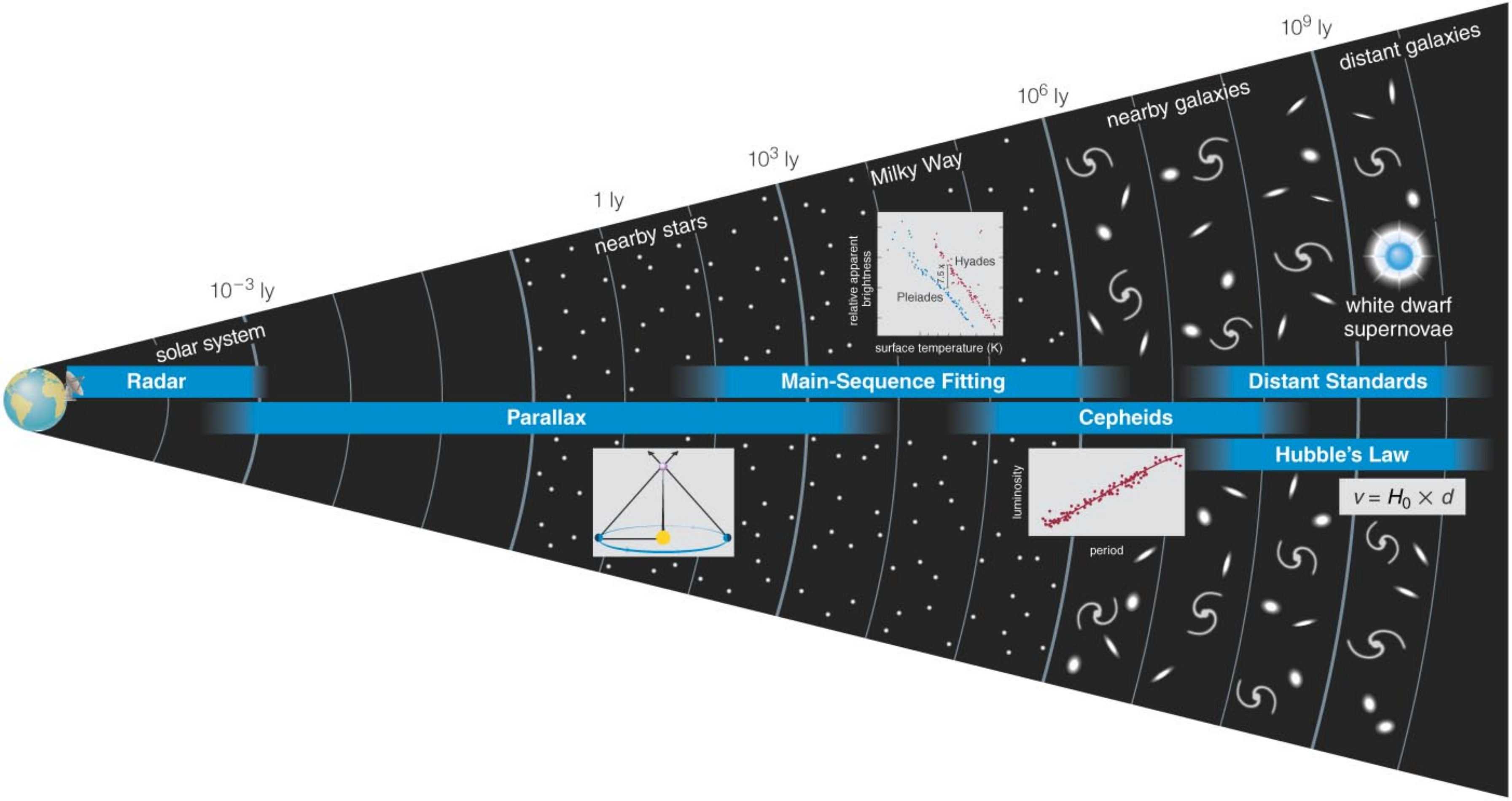
A typical Type Ia supernova at maximum light is 4 billion times brighter than the Sun. As a result, such an object can be detected halfway across the observable universe, further than 8 billion light-years away.

As with RR Lyr stars and Cepheids, if you know the absolute magnitude and the apparent magnitude of an object, you can calculate its distance, providing you properly account for any effects of interstellar dust.

Because galaxies exert gravitational attraction to each other, galaxies have “peculiar velocities” on the order of 300 km/sec. For galaxies at $d \sim 42$ Megaparsecs, their recessional velocities are roughly 3000 km/sec for a Hubble constant of 72 km/sec/Mpc. So one can get an estimate the galaxy's distance using Hubble's Law ($V = H_0\ d$) with a 10% uncertainty due to the peculiar velocity. At a redshift of 3 percent the speed of light (9000 km/sec), the effect of any perturbations on the galaxy's motion are correspondingly smaller (roughly 3 percent).

The bottom line is that from a redshift of $z = 0.01$ to 0.1 (recessional velocity 3000 to 30,000 km/sec) one can use the radial velocity of a galaxy to determine its distance.

Beyond $z = 0.1$ one needs to know the mean density of the universe and the value of the cosmological constant in order to get the most accurate distances. In fact, it was the discovery that distant galaxies (with redshifts of about $z = 0.5$) are "too faint" that implied that they were too far away. This was the first observational evidence for the Dark Energy that is causing the universe to accelerate in its expansion.



10^{-3} ly
1 ly
10^3 ly
10^6 ly
10^9 ly
solar system
nearby stars
Milky Way
nearby galaxies
distant galaxies
relative apparent brightness
Hyades
Pleiades
surface temperature (K)
white dwarf supernovae
Radar
Main-Sequence Fitting
Distant Standards
Parallax
Cepheids
Hubble's Law
$v = H_0 \times d$
luminosity
period

For more information on the extragalactic distance scale, see:

www.astr.ua.edu/keel/galaxies/distance.html