

ASTROPHYSICS – THE BASICS

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Abstract

How do we measure the distance to stars and galaxies? How do we know that the stars and galaxies are in motion? How do we connect these data to make a model of our Universe?

The workshop will explore the cosmic distance scale from its origins with Henrietta Swan Leavitt via Edwin Hubble to the latest supernova data. It will contrast Hubble's original expansion data with the latest results from distant supernovae. It will touch on Dark Matter and Dark Energy.

Introduction

One hundred years ago we had no idea how big the Universe actually is. We thought that the galaxies were 'little island universes' in the Milky Way. We thought that the stars were dotted through space and that the whole system was 'just hanging there'!

In this workshop you will have a chance to review the key measurements that totally changed our view of the Universe! By the end of the workshop you should be able to:

- * State the definitions of magnitude, the parsec and the light-year.
- * Explain how annual parallax is used to calculate the distance of nearby stars.
- * Calculate the relative distances of stars using the 'inverse square law'.
- * Explain how Henrietta Swan Leavitt discovered that Cepheid variable stars can be used to measure the distances of stars and nearby galaxies.
- * Explain the importance of Type Ia Supernovae for measuring the distances of very distant galaxies.
- * Measure the velocity of a galaxy from its spectrum.
- * Understand that, for distant galaxies, Edwin Hubble discovered the link between velocity and distance.
- * Explain how better observational techniques have caused the value of the Hubble Constant to fall from 530 to $72 \text{ km s}^{-1} \text{ Mpc}$ and so have caused the Age of the Universe to rise from 2 to 13.7 billion years in just 80 years!
- * Explain how the value of the Hubble Constant at great distances could predict the fate of the Universe.
- * Appreciate the problems of Dark Matter and Dark Energy.

1) Distance Measurements

a) Definitions

* The light-year

This is the distance light travels in a year. Using $3.0 \times 10^8 \text{ m s}^{-1}$ for the velocity of light, this is a distance of $9.46 \times 10^{15} \text{ m}$ (9 460 000 000 000 000 m).

$$\text{Distance} = \text{velocity} \times \text{time} = 3.0 \times 10^8 \times \text{Number of seconds in one year.}$$

Use your calculator to check this here:

* The astronomical unit

This is the mean radius of the Earth's orbit around the Sun.

It is equal to $1.496 \times 10^8 \text{ km}$ (often taken as 150 000 000 km).

* The parsec

As the Earth travels round the Sun, the nearby stars appear to move relative to the distant 'fixed stars'. This motion is called the 'annual parallax'.

If a star appears to move by one second of arc ($1/3600$ of a degree)
when the Earth moves by one astronomical unit
the object is defined as being 1 parsec away.

If the star appears to move by 0.1 seconds of arc, the object is 10 parsecs away.

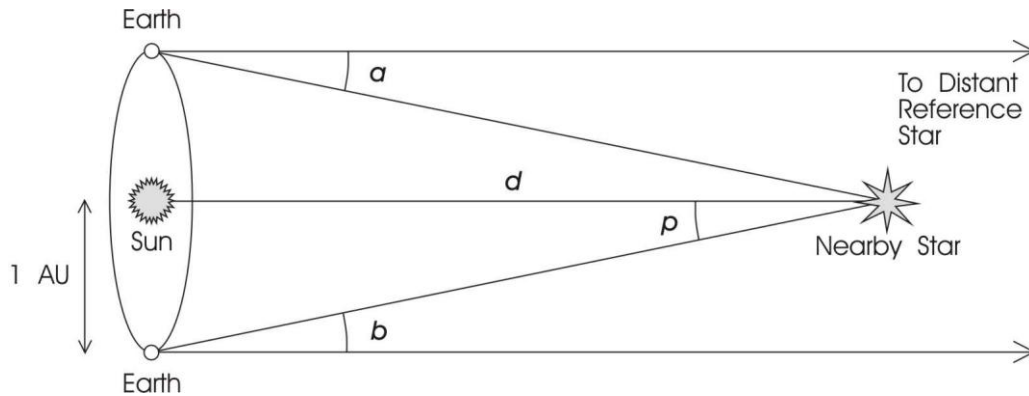
The name of this unit comes from the phrase 'second of parallax' being reversed to read 'parallax of second'.

One parsec is equal to 3.26 light-years.

b) Distance Measurement Methods

i) Trigonometric Parallax

This method is useful for nearby stars, those out to a distance of about 100 parsec (about 326 light-years). In the diagram the Earth is shown at two measurement positions, six months apart. This arrangement is used to obtain maximum accuracy.



Trigonometric Parallax

The nearby star would be many times more distant than the drawing implies. The angles a and b are measured and their average is angle p . The base of the triangle containing angle p is the Astronomical Unit (AU).

The great advantage of quoting distances in parsecs is that they are not affected by improvements in the accuracy of the AU. The AU was defined in 1963 to be 1.496×10^{11} m. However, more recent measurements give $1.49597892 \times 10^{11}$ m ($\pm$ about 3 km !!).

Using trigonometry in the figure we see that: $\tan p = 1 \text{ AU} / d$

This formula may then be used to calculate the distance of 1 pc:

$$\begin{aligned} d &= 1 \text{ AU} / \tan (1 \text{ second of arc}) \\ &= 1.496 \times 10^{11} / \tan (1/3600) \\ &= 3.09 \times 10^{16} \text{ m} = 3.26 \text{ light-years.} \end{aligned}$$

Note that the nearest star, Proxima Centauri, is 4.22 light-years away. This means that the parallaxes of even the nearest stars are very small indeed. Therefore we can only use this method for nearby stars.

* Calculation of the distance of the star Vega

The annual parallax of Vega is 0.12892 seconds of arc.

Distance of Vega in parsecs = $1/0.12892 =$ parsecs.

Using 1 parsec = 3.26 light-years.

Distance to Vega in light-years = light-years.

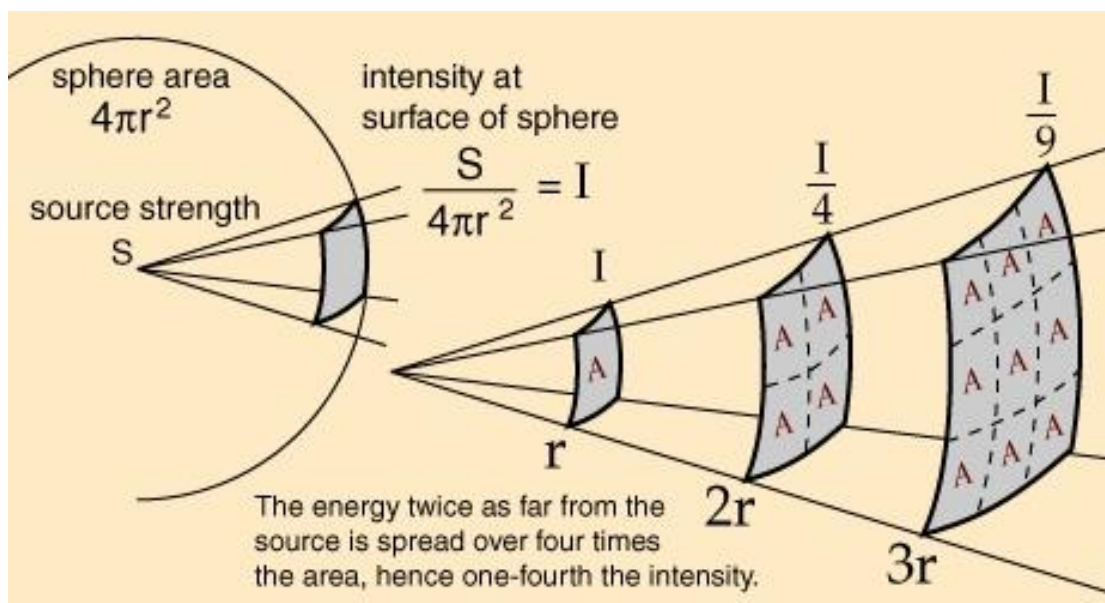
The ESA Hipparcos Satellite has measured parallaxes of stars as small as $1/1000$ second of arc. This gives the greatest measurable distance as 3250 light years. However, these stars are so close that they are 'in our back yard'!!

ii) Inverse Square Law

Now consider the effect of the Inverse Square Law. If one object is twice as far away as another, then its brightness will be one quarter ($1/2^2$) of the nearer object.

To help to check that you have understood this, complete the table:

2 times as far away	$1/4$ as bright
7 times as far away	$1/49$ as bright
100 times as far away	as bright
700 times as far away	as bright
2 000 times as far away	as bright



Inverse Square Law (Georgia State University Hyperphysics Project)

iii) Magnitudes

* Apparent Magnitude

Ever since the time of the ancient Greek astronomers, Hipparchus and Ptolemy, the visible stars have been divided into six magnitude groups as observed from the Earth. The brightest are called first magnitude and the ones that are just visible to the unaided eye are called sixth magnitude. The apparent magnitude depends on how brightly a star is shining and on how distant it is from the Earth; in other words, how bright it appears to the observer. In 1827 John Herschel deduced from his measurements that a five magnitude difference corresponded to a factor of 100 in the intensity (power per unit area) detected by the observer. In 1856 Norman Pogson proposed that all the magnitude steps should be the same ratio, one to another. This leads to the ratio being:

$$(100)^{1/5} : 1 = 2.51 : 1$$

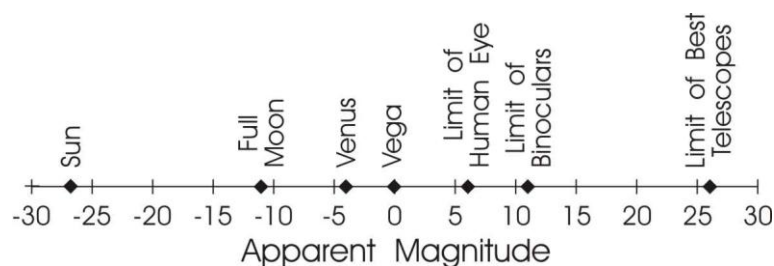
Check this yourself now by multiplying 2.512 by itself five times.

* Absolute Magnitude

To allow stars at different distances to be compared, it is convenient to adjust their Apparent Magnitudes to what they would have been if the stars were placed at the Standard Distance of 10 parsecs.

In the following, *upper case* letters refer to the star at 10 parsecs and *lower case* letters to the star at its true distance. The theory leads to the useful formula:

$$m - M = 5 \log (d/10) \quad \text{where} \quad \begin{array}{l} m \text{ is the apparent magnitude,} \\ M \text{ is the absolute magnitude and} \\ d \text{ is the distance in parsecs.} \end{array}$$



iv) Cepheid Variable Stars

* What is a Cepheid?

Consider a star a little larger than the Sun. As it grows old it will become a Red Giant star. During this process it passes through a phase where it 'breathes-in-and-out'. Heat is trying to escape from the core but it builds up inside the star. This pushes up the outer layers and the

star increases in radius by a few percent. Now it has a larger surface area and so it looks brighter. With a larger surface area, the build-up of heat can radiate away into space. This allows the surface to return to normal and so the star's brightness also returns to normal. However the heat starts to build up again and so the process repeats. Each cycle takes some days to repeat.

*** Why are Cepheids important?**

In 1912 Henrietta Swan Leavitt, working at Harvard, found that Cepheid variable stars could be used as 'standard candles'.



Henrietta Swan Leavitt

She worked on photographs of the Small Magellanic Cloud and found that:

The intrinsic brightness of a Cepheid Variable Star
is related to
The period of its light output variation.

The intrinsically brightest Cepheids vary with a period of perhaps 50 days. The intrinsically faintest Cepheids vary with a period of perhaps 2 days.

So if you find a Cepheid with a period of say 20 days, it will have the same intrinsic brightness as all other Cepheids that have a period of 20 days.

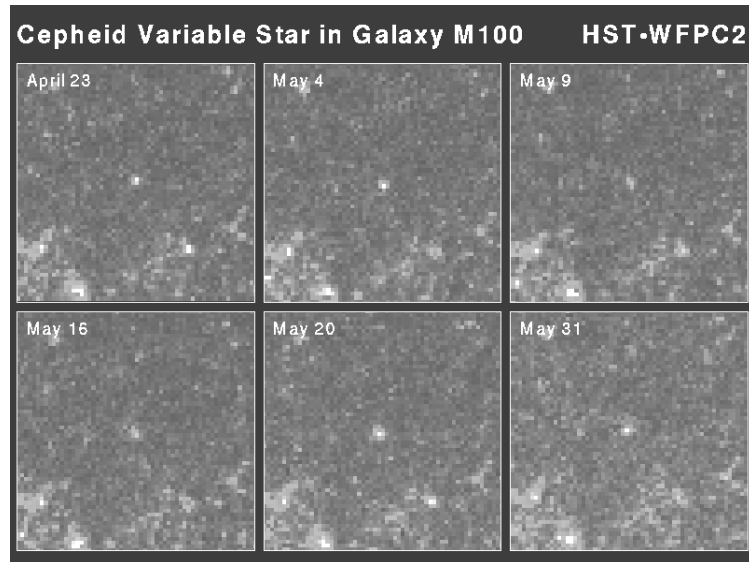
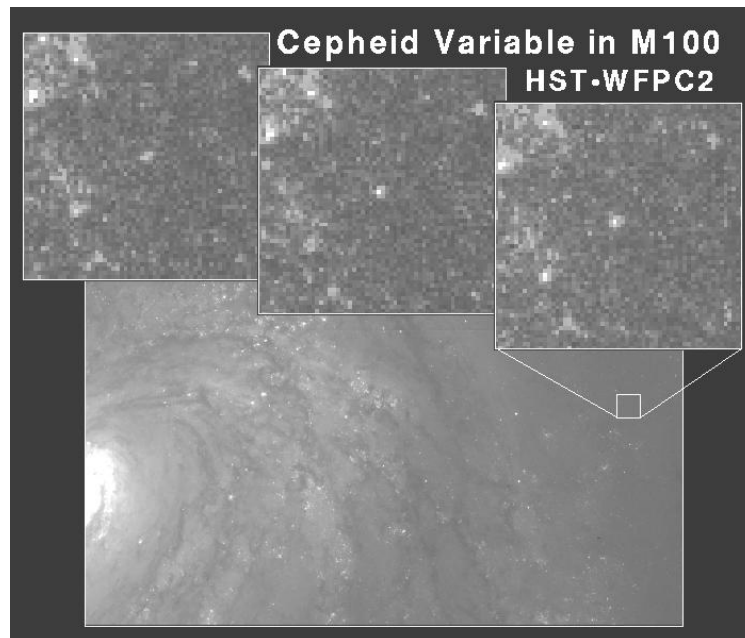
However, if one looks fainter than another, it is because it is more distant.

In summary:

- + We can use a direct method to measure the distance to a few nearby Cepheids.
- + We can then use the Inverse Square Law to calculate the distance to Cepheids in quite distant Galaxies.

* Recent Cepheid Results

To find the distance to galaxies is not easy because they are too far away to show any parallax. Most methods involve 'standard candles'. We measure the distance to a nearby star and also measure its magnitude. If we then observe a similar star in a distant galaxy we can compare the magnitudes of the two stars and so find the distance to the galaxy.

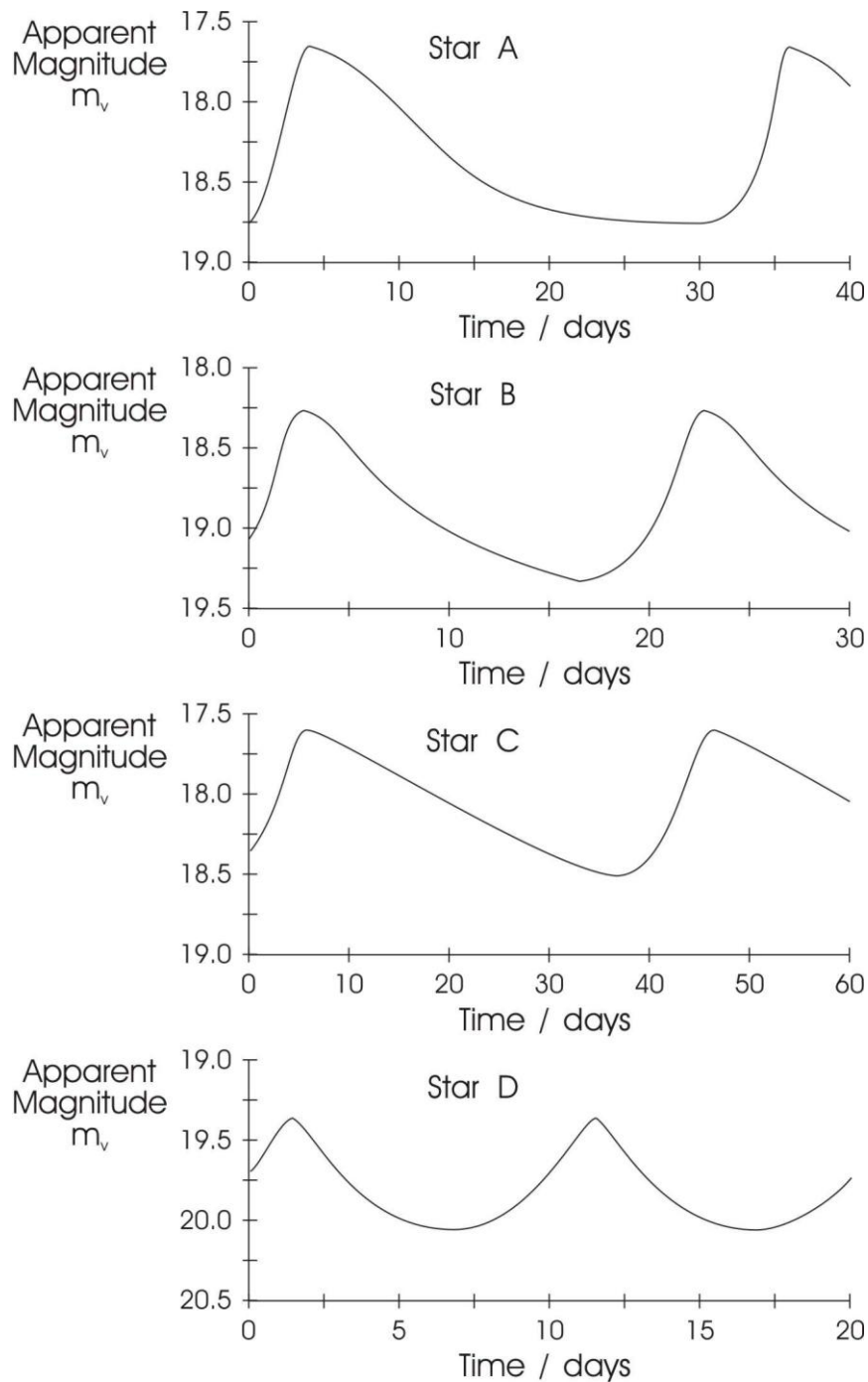


Distant Cepheids Variable Stars in the Galaxy M100 (HSTI, NASA)

These images show some of the most distant Cepheids observed. Dr Wendy Freedman of Carnegie Observatories headed a team that collected data from the Hubble Space Telescope. They observed 800 Cepheids, various Type Ia supernovae (see later) and two other distance indicators. They reported very good agreement between these methods for measuring distances to 18 distant galaxies. M100 is 56 million light years distant.

*** Exercise to Verify the Period-Luminosity Law**

These four light curves are for Cepheids in M31, the Andromeda galaxy.



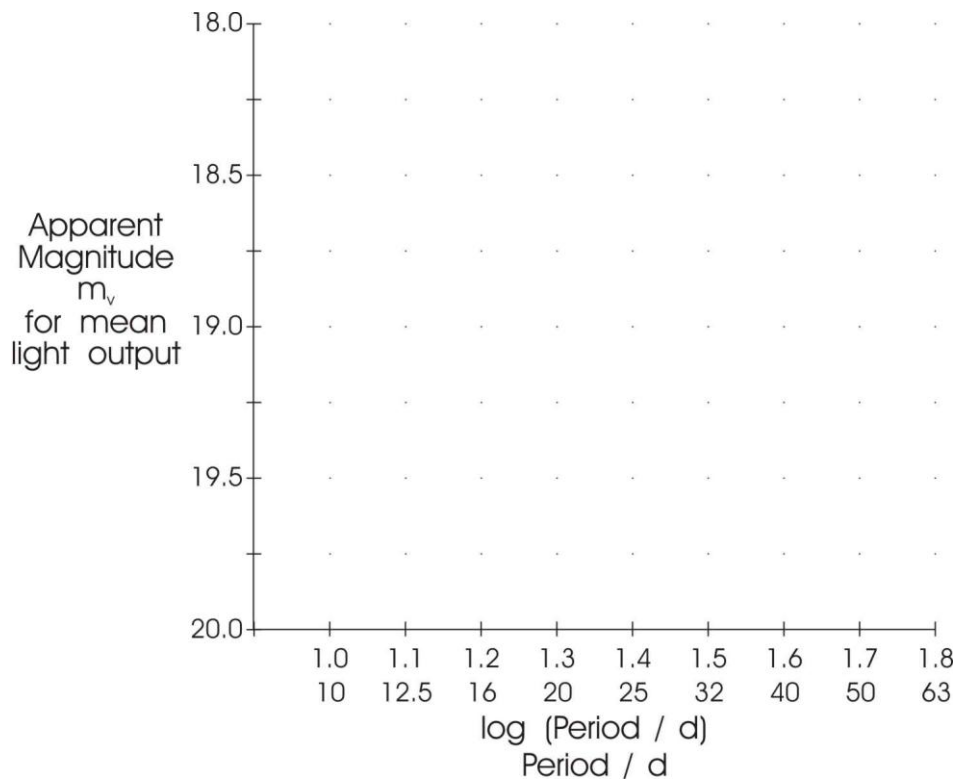
Cepheid Light Curves

From the curves, read off:

- * The average apparent magnitude of the star and
- * The period of the variability.

Complete the table and plot the results on the graph.

Star	Apparent Magnitude	Period / days
A		
B		
C		
D		



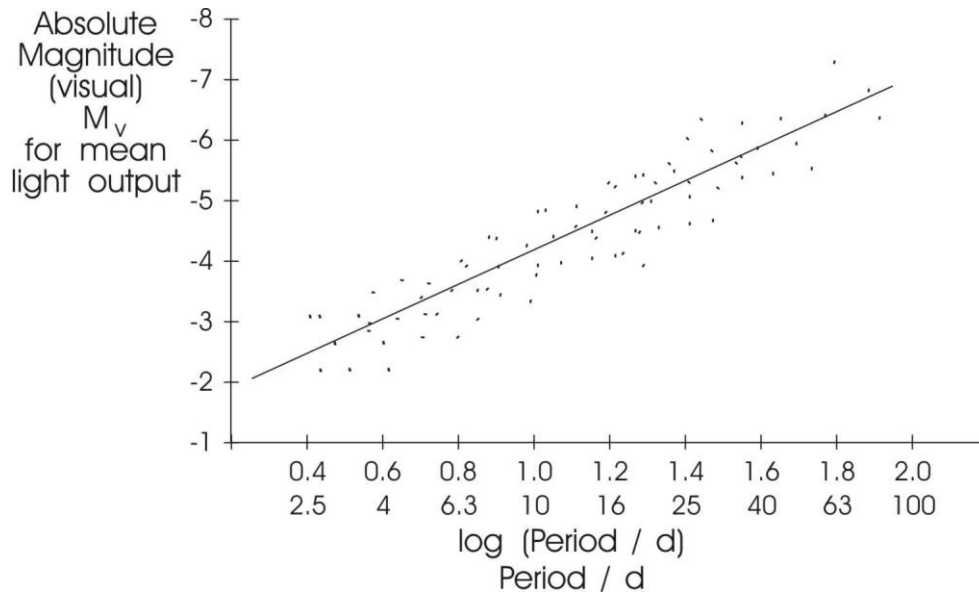
Cepheid Magnitude / Period Graph Axes

Henrietta Swan Leavitt plotted similar graphs and realised that the mean apparent magnitudes of the stars were proportional to the logarithms of their periods. This was a major step forward. A year later, in 1913, Harlow Shapley was able to measure directly the distance to a few nearby Cepheids and so was able to link their absolute magnitudes to their periods. The ‘standard candles’ had been found!

This led to the final proof that the galaxies (‘island universes’) were outside our own Milky Way and that the scale of the Universe was truly enormous.

* Distance to Andromeda

The graph shows modern results for Cepheid variable stars. We shall use this data to estimate the distance to the Andromeda galaxy. Using the period of Star C from the previous exercise, look up its absolute magnitude on the graph. Be careful with the signs of the magnitudes!



Cepheid Magnitude / Period Graph

M = Absolute magnitude of star C =

m = Apparent magnitude of star C =

Use the formula or the ‘Nomogram Calculator’:

$$m - M = 5 \log (d/10) \quad \text{where}$$

m is the apparent magnitude,

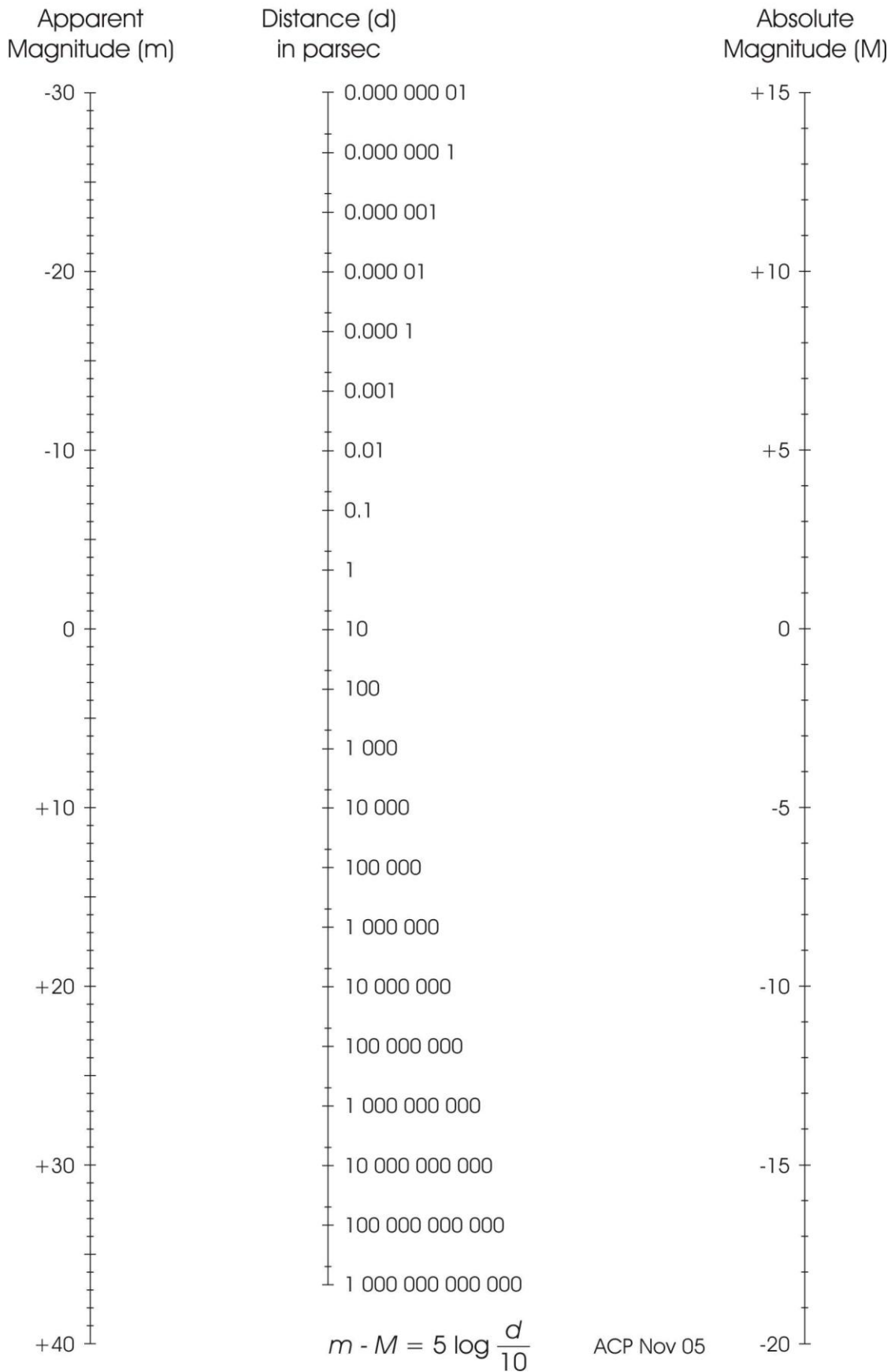
M is the absolute magnitude and

d is the distance in parsecs.

Hence d in parsec =

Using 3.26 light-years equals one parsec, d in light-years =

Nomogram for Magnitude - Distance Calculations



Although the Cepheids are super-giant stars, even the Hubble Space Telescope cannot observe them in the most distant galaxies. The next method solves this problem.

v) Type Ia Supernovae



Distant Supernova Explosion

* Type Ia – The explosive destruction of a White Dwarf star that has a companion Red Giant star.

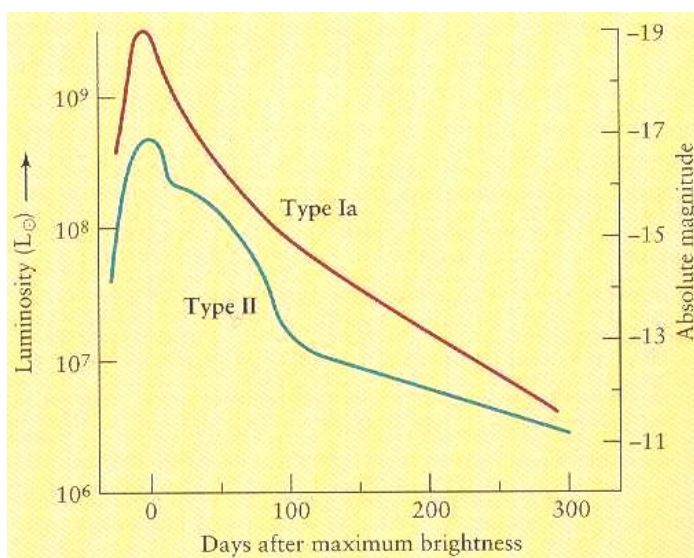
- + Stars are formed when clouds of gas and dust collapse under the attraction of gravity.
- + Very often, stars will be created in pairs, bound by gravity. Each will go through life with a companion! These are called binary star systems.
- + If the stars are about the mass of the Sun, they will evolve steadily over billions of years.
- + Eventually one partner of the system will go through the Red Giant phase and will leave behind its core as a White Dwarf star.
- + Some time later, the other partner will become a Red Giant and hydrogen gas from its outer layers will spill down onto the surface of the White Dwarf.
- + Some of this hydrogen fuses to carbon and oxygen, increasing the already significant quantities in the core.
- + Eventually the increase in pressure and temperature will start the fusion of the carbon.
- + When the mass of the White Dwarf passes the Chandrasekhar limit of 1.4 solar masses, the carbon core cannot resist the gravitational forces.
- + The material in the core is 'degenerate' – its electron shells have partially collapsed. This prevents it expanding to slow down the reaction. The reaction rate runs away uncontrollably and the White Dwarf explodes.

- + The explosion releases so much energy that the flash will be seen on the ‘other side of the Universe’!
- + In this type of explosion, most of the energy is released by the conversion of mass to energy ($E = mc^2$).
- + The explosion consumes about half a solar mass of carbon and oxygen. The product is nickel 56, which undergoes radioactive decay to cobalt 56 and finally to iron 56. This decay chain explains the exponential decay (60 day half-life) of the brightness of Type Ia supernovae. This half-life allows Type Ia supernovae to be identified unambiguously. (See next graph.)
- + In visible light there are no easily observable Type Ia remnants. However, the expanding shells of debris show up well in the radio and X-ray parts of the spectrum. Tycho Brahe’s 1572 AD supernova is now linked to such a shell of debris and very recently to its binary progenitor star system.

For contrast, here is the description of the other main supernova mechanism.

*** Type Ib, Ic and II – The collapse and explosion of the core of a massive star – a star with a mass of at least 8 times the mass of the Sun.**

- + As the core burns, hydrogen is fused into helium, carbon, neon, oxygen, silicon and finally iron. Beyond iron, energy is not released but is needed to fuse nuclei together.
- + When the star reaches this point, it is not producing enough heat energy to be stable. The core’s temperature is not high enough and hence not enough pressure is produced to balance the inward force of gravity. The star collapses very rapidly and rebounds. This rebound is the explosion we see.
- + Almost all the energy comes from the release of gravitational potential energy and not from the destruction of mass.
- + An example is the Crab Supernova, seen in 1054 AD. Its remnant is visible (Messier 1, 3C144).



Supernova Light Curves

The light curves of the two types are quite different allowing them to be easily distinguished.

(Universe, Kaufmann)

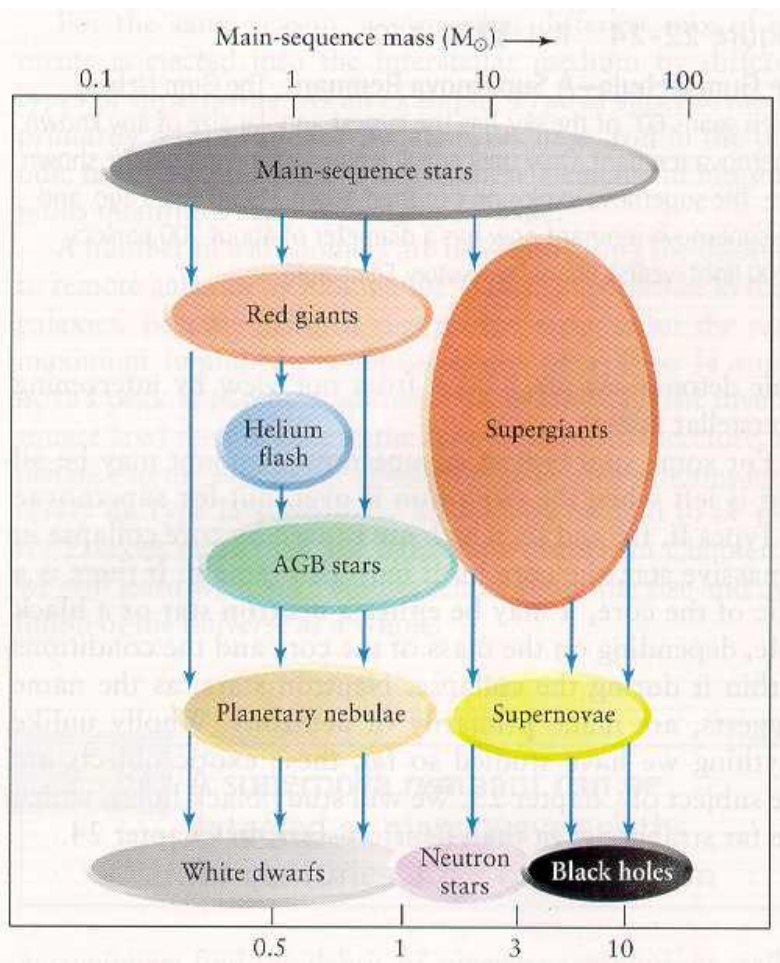
*** Calculation:**

The mass of the Sun is about 2.0×10^{30} kg. It is possible that in a White Dwarf explosion about half this mass is destroyed and converted into energy.

Substitute this mass into Einstein's Equation $E = mc^2 =$ J.

where the speed of light (c) = 3.0×10^8 m s⁻¹

The Sun has a normal output of 3.9×10^{26} W. Do a calculation to confirm that it would have to shine for 7.3×10^{12} years to radiate this much energy!



Evolution of Stars. (Universe, Kaufmann)



Albert Einstein and his sister Maja.

*** Why are Type Ia Supernovae important?**

We believe that all Type Ia Supernovae reach the same the peak intrinsic brightness. So we have another ‘standard candle’. These explosions are so bright that we can use them to measure the distances of very distant galaxies.

*** Calculation**

Observations show that a very distant supernova has a
Peak Apparent Magnitude (m) = 20.5

From studies of nearby supernovae we know that the
Peak Absolute Magnitude (M) = -19.5 (This is very very bright.)

Use the formula or the ‘Nomogram Calculator’:

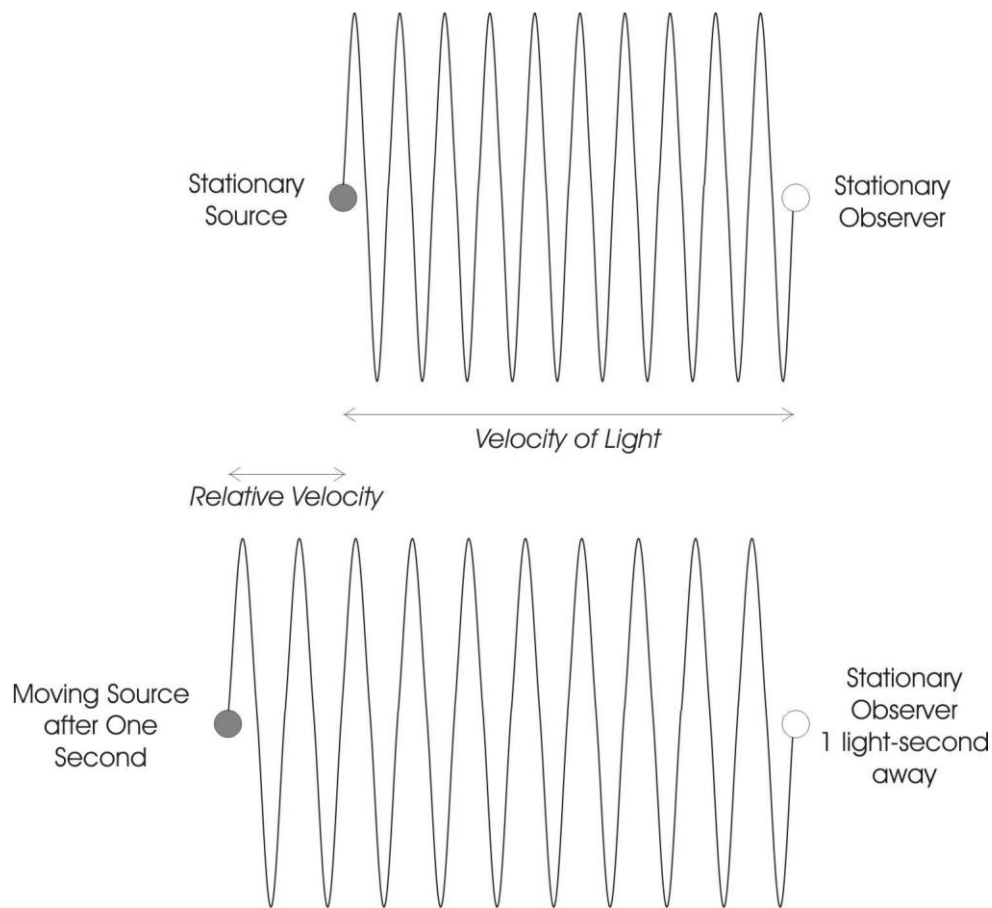
$$m - M = 5 \log (d / 10) \quad \text{where} \quad \begin{array}{l} m \text{ is the apparent magnitude,} \\ M \text{ is the absolute magnitude and} \\ d \text{ is the distance in parsecs.} \end{array}$$

Hence the distance (d) =

2) Velocity Measurements

a) What is the Doppler Effect?

Imagine a star that is moving away from us. Atoms in it are emitting light waves at particular (rest) wavelengths. As the waves are being emitted, the atoms are moving away from us. This 'stretches out' the waves. It makes their wavelengths longer. It makes the light more red than it would be at rest.



Doppler Effect Diagram

***** Whistle Demonstration.

* Doppler Effect Formula

$$\frac{\text{Change in wavelength}}{\text{Original wavelength}} = \frac{\text{Relative velocity}}{\text{Velocity of light}}$$

*** Doppler Calculation**

A police radar speed trap emits microwaves of wavelength 0.030 m. A car moves away from it at 30 m s^{-1} . What is the wavelength of the microwaves as detected in the car.

$$\text{Change in wavelength} / 0.030 = 30 / 3 \times 10^8$$

$$\begin{aligned} \text{Wavelength as detected in the car} \\ = \text{Change in wavelength} + \text{Original wavelength} = \end{aligned}$$

Radar can be used for measurements of Mercury, Venus, Mars, the Moon and asteroids. It can measure distances and rotation rates. However, it cannot reach the outer planets.

b) What is Redshift?

*** Be very careful with the definition of Redshift!**

The Redshift that we see in the distant galaxies seems like the Doppler Shift:

$$\text{Change in wavelength} / \text{Original wavelength}$$

More recently however, astrophysicists have made a clear distinction between Redshift and Doppler shift. Redshift is caused by the expansion of the fabric of space – the expansion of the ‘graph paper’ on which the Universe is drawn. Doppler Shift is caused by the relative motion of the source and the observer. Fortunately the simple mathematics are identical, but educators should be aware of this distinction.

*** Making Models of the Expansion of the Universe**

Incorrect: Galaxies drawn on a balloon.

Correct: Cotton wool on a balloon.
Clothes pegs on a length of elastic.
Paper clips on an elastic band.

3) Velocity and Distance

a) Hubble's Law Data Exercise

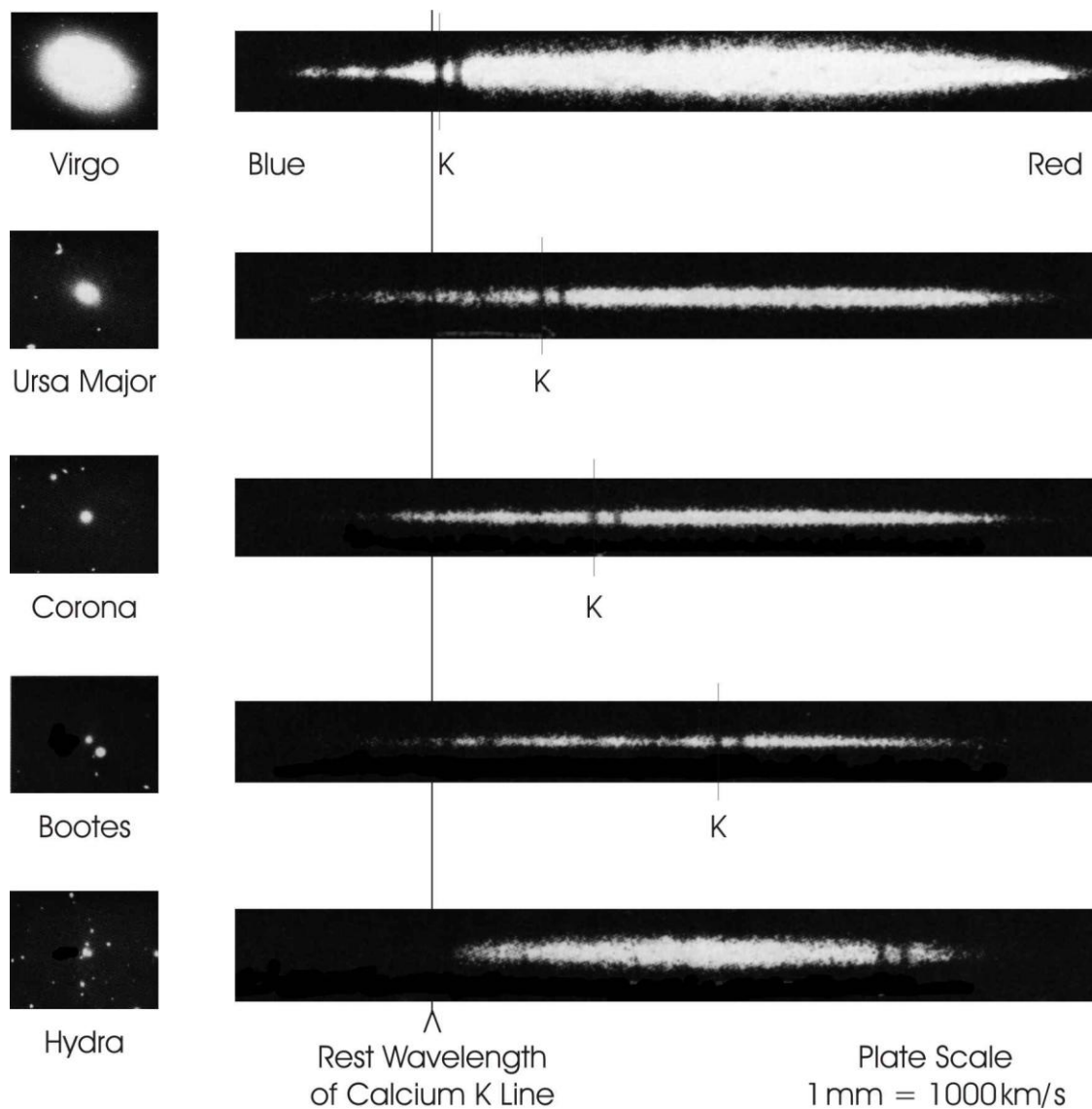
The light we receive from galaxies is very faint. With the naked eye we can only see one galaxy (Andromeda) in the Northern sky. To make a photograph of the spectrum of a galaxy requires a large telescope to collect the light. By the 1920s, spectra similar to the ones in this exercise had been collected. Work then progressed on finding the distance to the galaxies. Various methods were used and by 1929, Edwin Hubble had measured the distances to about twenty galaxies. With this information he was able to show a definite link between the distance to a galaxy and the velocity it is moving away from us.



Edwin Hubble

***** Spectral Lines demonstration.

You are provided with five spectra adapted from Hale Observatory originals. A spectral line of Calcium is marked. If the galaxy is stationary relative to us, the Calcium K-line is observed at its rest wavelength. If the galaxy is receding, the wavelength becomes longer – the Redshift.

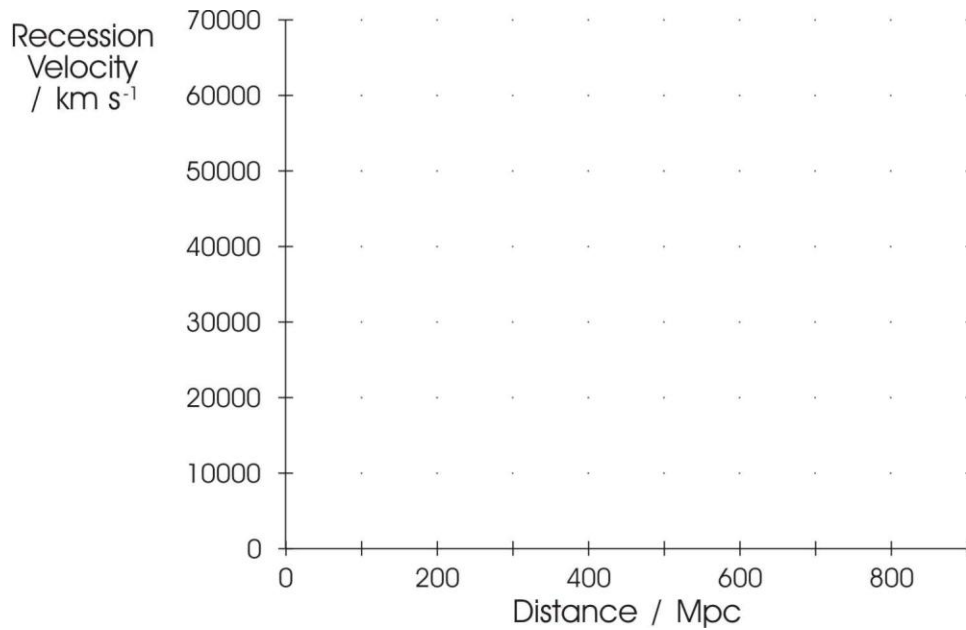


Spectra of Galaxies (Hale Observatory)

In the table below, four of the galaxies have their distances given. Use the 'plate scale' on the diagram to find the recession velocities of the galaxies. You will have to judge the position of the K-line in the Hydra spectrum for yourself.

- * Fill in the table and plot the graph of recession velocity against distance.
- * Use the graph to find the distance to the galaxy in Hydra.
- * Find the gradient of the graph. This is the value of the Hubble Constant.

Galaxy	Velocity / km s^{-1}	Distance / Mpc
Virgo		16
Ursa Major		200
Corona		293
Boötes		520
Hydra		



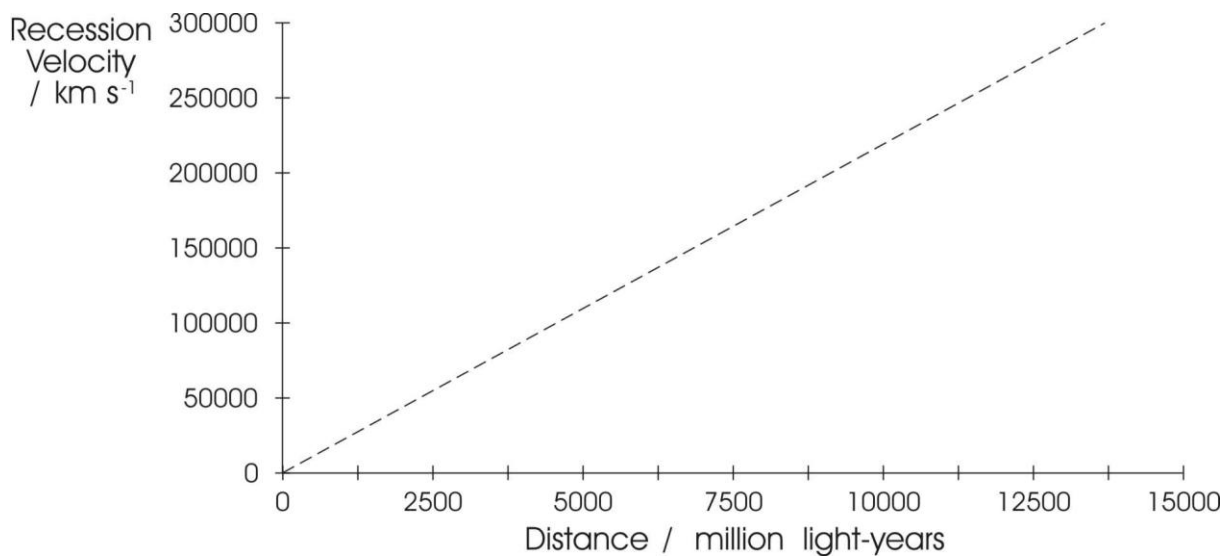
Hubble Velocity / Distance Graph Axes

The expected value of the gradient is $72 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Note that this exercise uses modern distance values. Hubble would have originally obtained a value about 7 times greater (see later). Also, modern spectra are very, very much clearer than the ones used in this exercise! It is instructive to consider the difficulties that early workers in this field overcame.

b) The Recession of the Galaxies and the Age of the Universe

The spectral lines of all distant galaxies show redshift. The fabric of space-time is expanding, creating this redshift. Here is an idealised graph, extrapolated out to the velocity of light.



Extended Hubble Velocity / Distance Graph

With a high degree of certainty, this graph can be plotted to about 10% of the distance to the edge of the observable Universe. Many galaxies have had their redshift and distance measured and so the lower part of the line is well defined.

Beyond that, there have only been about 100 very distant Type Ia supernovae observed. The line clearly extends approximately as shown but it will be several decades before its detailed shape is known.

The graph is extrapolated all the way up to the velocity of light ($3 \times 10^8 \text{ m s}^{-1}$).

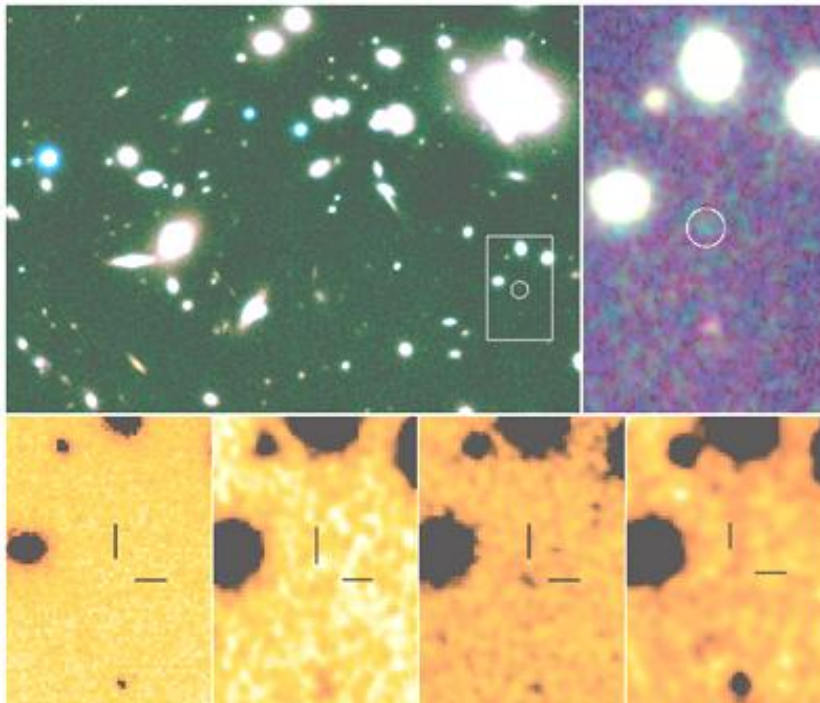
Note that the velocity of light defines the most distant objects that we could ever see.

From the graph, read off the 'distance to the edge of the Universe'.

This distance in light-years gives the time directly.

* The Greatest Distance Measured to Date

In March 2004, ESO announced that a newly discovered galaxy named Abell 1835 IR1916, has a redshift of 10. Using Hubble's Law, the galaxy is found to be 13 230 million light-years away. We see the galaxy as it was when the Universe was only 470 million years old. That is only 3 percent of its current age. These results were determined by spectral analysis of its light, not by observing a supernova in it.



Abell 1835 IR 1916.
The Most Distant
Galaxy So Far!

Abell 1835 IR1916 - the Farthest Galaxy - Seen in the Near-Infrared
(VLT ANTU + ISAAC)

ESO PR Photo 05a/04 (1 March 2004)

© European Southern Observatory



c) Why did the value of the Hubble Constant fall so much over the last 80 years?

In 1929 Hubble measured the constant to be $530 \text{ km s}^{-1} \text{ Mpc}$. At that time he only had the velocities and distances of about 30 galaxies.

His velocity data was good but his distance data was in error. It turns out that all the galaxies are much further away than he thought.

Some of his distances were based on identifying bright stars in the galaxies. It turns out that these 'stars' were compact ionized hydrogen gas clouds. Also, the brightest stars in galaxies are 25 times brighter than he originally thought.

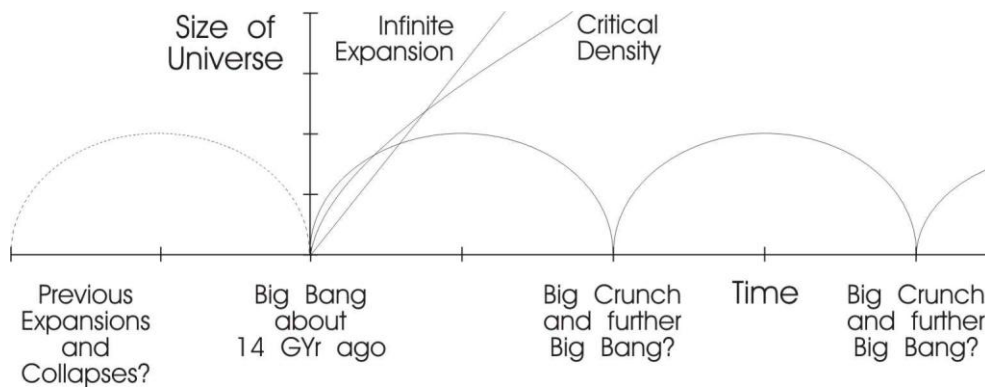
Some of the Cepheid variable stars that he measured were of a slightly different class (W Virginis stars) and were about 1.5 magnitudes fainter than the classical Cepheids.

Some of the Cepheid variable stars that he measured were of a significantly different class (RR Lyrae stars) and were about 2 magnitudes fainter than the classical Cepheids.

All Cepheids are actually 1.8 magnitudes brighter than originally thought.

All these improvements in our knowledge of the Universe have allowed us to make the current estimate of the Hubble Constant as $72 \text{ km s}^{-1} \text{ Mpc}$. This gives an age of the Universe of 13.7 billion years.

4) Dark Matter, Dark Energy and Fate of the Universe



The Fate of the Universe

When the Hubble graph is extended out to the most distant galaxies the data are so weak that it is not certain that the straight-line law holds. If the shape of the line/curve could be found with certainty, it would indicate the fate of the Universe. If the most distant galaxies are found to be moving away rapidly, then the universe will expand forever. If they are moving too slowly then gravity will pull them back to the Big Crunch. If the velocities are just right for the density of matter, then the Universe will come to rest at infinite size in the infinite future.

a) Evidence for Dark Matter

i) Rotation Curves of Galaxies

In a spiral galaxy, the stars, gas and dust rotate about the centre. The velocity of rotation is measured using the Doppler Effect. The visible light from stars is blue or red shifted. The radio emission from neutral hydrogen atoms (21 cm, 1420 MHz) is also Doppler shifted.

By way of contrast, consider our Solar System. Almost all of the mass is concentrated at the centre, in the Sun. The velocity of the Planets can be predicted using Newton's Law of Gravitation.

$$\text{Attractive force of gravity} = \text{Required centripetal force}$$

$$GMm/r^2 = mv^2/r$$

$$\text{Rearranging} \quad GM/r = v^2$$

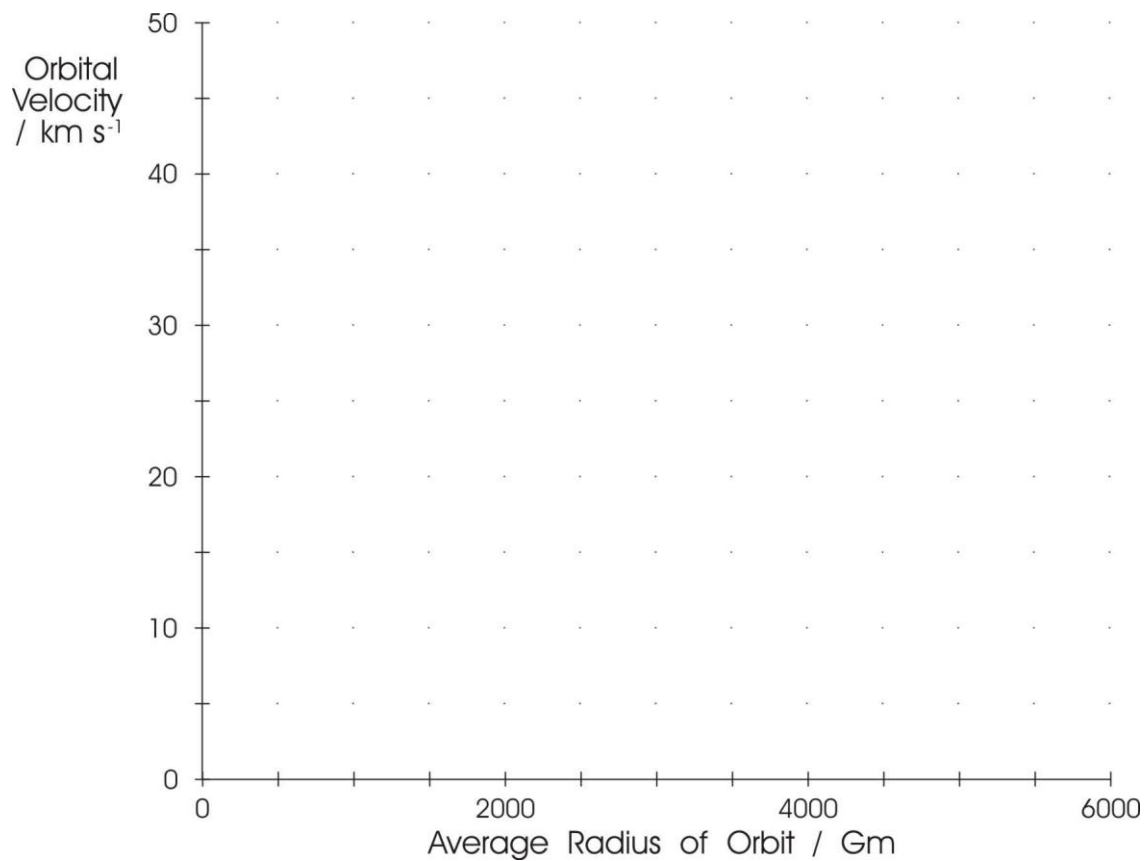
$$v = (GM/r)^{1/2}$$

This equation predicts that the orbital velocity will fall with increasing radius.

The next table shows the actual data for our Solar System.

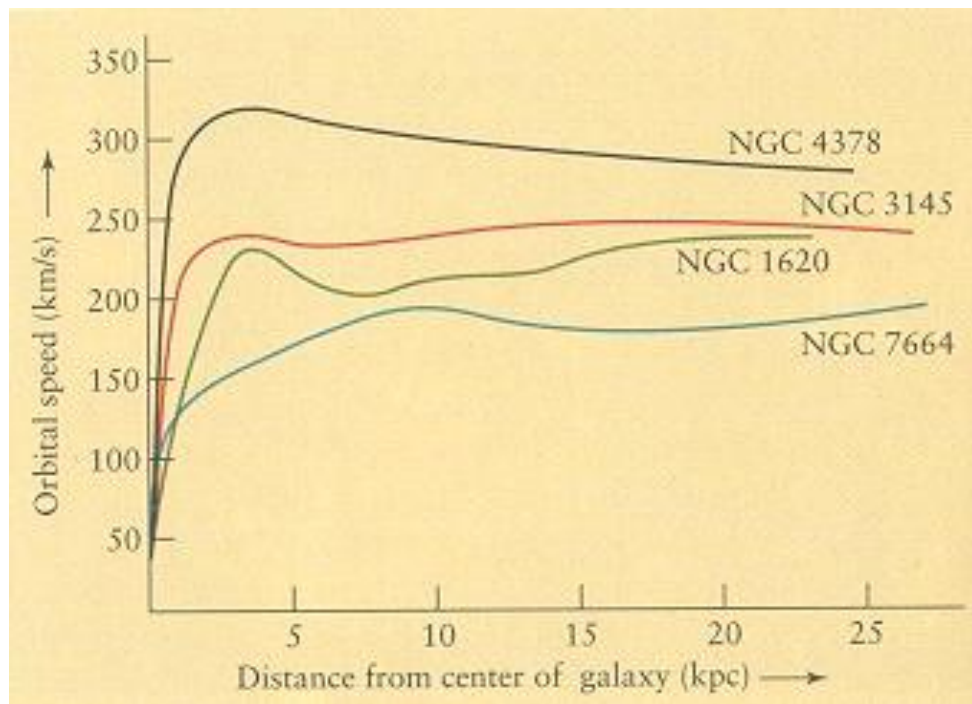
Planet	Average Orbital Velocity / km s^{-1}	Average Radius of Orbit / Gm
Mercury	48	58
Venus	35	108
Earth	30	150
Mars	24	228
Jupiter	13	778
Saturn	10	1430
Uranus	6.8	2870
Neptune	5.4	4500
Pluto	4.7	5910

Plot these data on the graph axes below.



Orbital Velocity / Radius of Orbit Graph Axes

Compare the shape of your curve with the rotation curves of the four Spiral Galaxies shown in the next graph. The velocity of the material in the outer regions of the galaxies does not decrease much with distance from the centre. Even the outermost detectable material rotates at this constant rate.



Rotation Curves of typical Spiral Galaxies.
(Universe, Kaufmann. Adapted from Rubin and Ford))

From this comparison we conclude that the mass distribution in a spiral galaxy is not like that in our Solar System:

Solar System – Mass is concentrated at the centre

Spiral Galaxy – Mass is distributed in the spiral arms and in a massive spherical halo stretching out beyond the visible spiral arms.

The ‘visible’ mass is in the form of:

Ordinary (baryonic) matter (1.5% of the mass of the Universe, mainly in stars)

Cold Normal Matter

White Dwarf Stars

Brown Dwarf Stars

Neutron Stars

Black Holes.

The rotation curves show that there is much more mass in the galaxies than is accounted for by the ‘visible’ stars, gas and dust clouds. This could be in the form of elementary particles:

Neutrinos – from fusion and beta decay

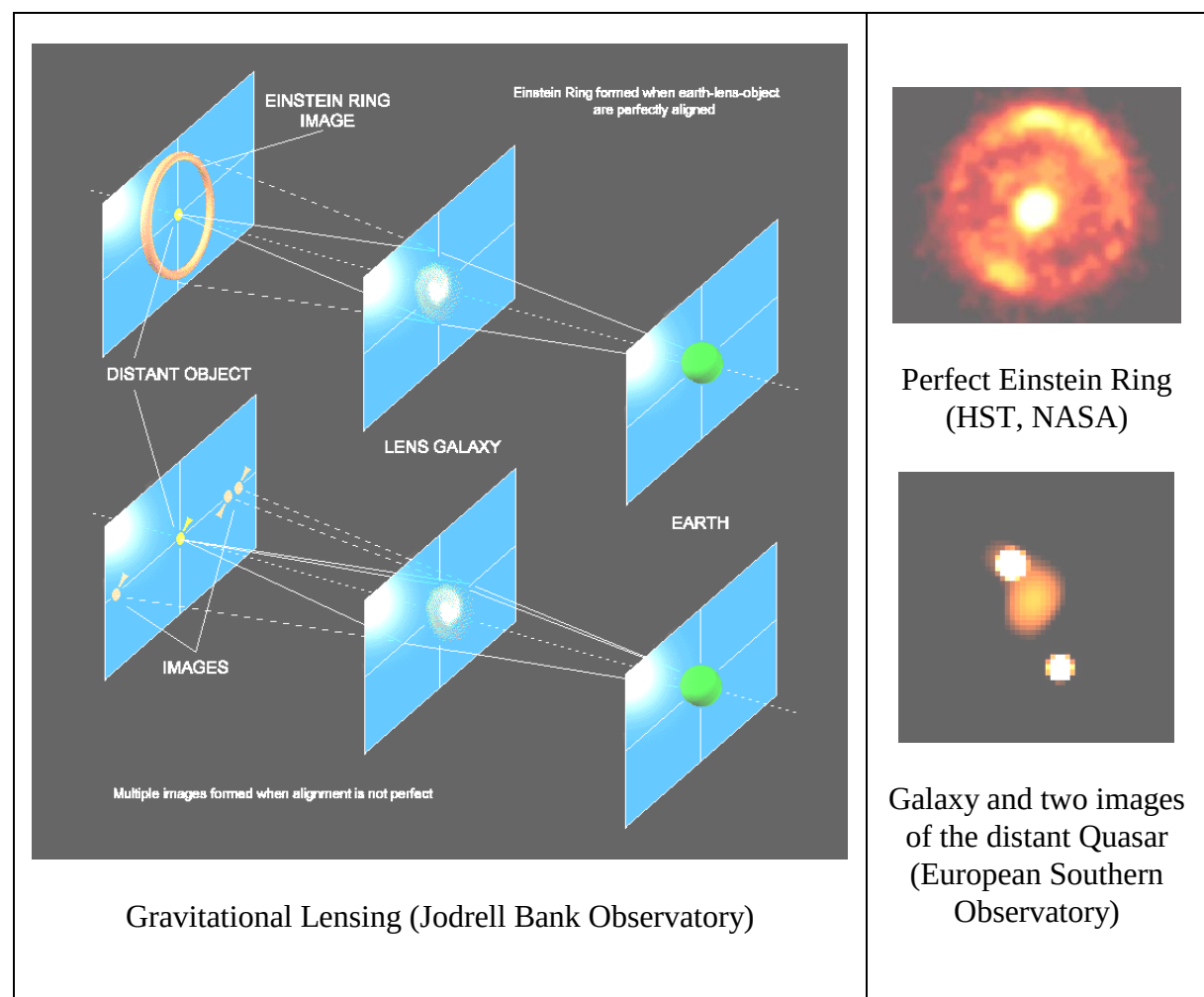
WIMPS (Weakly Interacting Massive Particles) – not yet observed.

ii) Gravitational Lensing

The most luminous objects in the Universe are Quasars. They are super-massive Black Holes at the centres of active galaxies. Matter from the galaxy falls into the Black Hole. Before it finally disappears, the matter is compressed and it reaches very high temperatures. This causes it to radiate very strongly. Powerful jets of particles are ejected above and below the galaxy. The particles in these jets collide with the low-density hydrogen gas that surrounds the galaxy and generate very strong radio emissions. If a jet happens to point towards the Earth, we detect a very strong radio signal. This is how Quasars were first discovered.

Sometimes, by chance, a very distant Quasar, a middle-distance galaxy and the Earth are in line. The gravitational field of the middle-distance galaxy acts as a lens to the light from the Quasar. If the alignment is perfect, an Einstein Ring is seen. If not, multiple images of the distant Quasar are seen.

This bending of the light is important because it is a result of the whole of the mass in the middle-distance galaxy – ‘visible’ and dark matter. The results from this work are still being interpreted.



b) Evidence for Dark Energy

Imagine a region of space with absolutely nothing in it. This would be the best vacuum possible. This vacuum is a physical state. There is no reason in principle for its energy to be zero. However, there is no way of measuring its energy on an absolute scale but we might be able to compare its energy to that of other systems.

In General Relativity, all energy has a gravitational effect. This vacuum energy is often called Dark Energy.

It appears that our Universe is one where Dark Energy is driving the galaxies apart and gravity is pulling them together. The two effects are in competition.

To test this model we need to study very distant galaxies. The brightness of a Type Ia supernova is used to determine distance. Its spectrum is used to determine the velocity of the galaxy of which it is a part.

The results are plotted and checked to see if the resulting line is above or below the projection from nearer galaxies. At present it looks as if the most distant galaxies are accelerating away.

Present evidence suggests the 70% of the density of the Universe is Dark Energy, 28.5% is Dark Matter and 1.5% is Visible Matter.

x-----Dark Energy-----x-----Dark Matter----^V_M

c) Fate of the Universe

As the data improves it will be possible to plot a more precise Hubble graph. From its shape it will be possible to link the expansion of the galaxies to the amount of matter in the Universe. At present the amount of mass estimated from 'visible' matter falls short by between 10 and 100 times that needed to close the Universe and so ensure a Big Crunch. Searches are continuing for black holes, brown dwarfs and molecular hydrogen clouds in particular, all of which are difficult to detect and are thought to hold a great deal of matter. The search for Dark Matter in the form of WIMPS (weakly interacting massive particles) continues and measurements to confirm the effect of Dark Energy will continue to tax the best astronomers.

Books:

Edwin Hubble the discoverer of the Big Bang Universe. Alexander S Sharov. Cambridge University Press 1993. 0-521-41617-5. The story of the discovery of the expanding universe and an excellent biography of Hubble. It ends with an excellent summary of the problems that face cosmologists.

Measuring the Universe. Stephen Webb. Springer-Praxis 1999. 1-85233-106-2. An excellent survey of the way in which the 'cosmological distance ladder' has been constructed.

Universe (6th Edition). William J Kaufmann & Roger A Freedman. Freeman. 0716746476.

Equipment:



Project Star Spectroscope (PS-14/Plastic)
\$24 + p&p.



Sunspotter – The Safer Solar Telescope
(LT-70) \$335 + p&p.

Available from Learning Technologies Inc., 40 Cameron Avenue, Somerville, MA, 02144, USA. Phone: 001-617-628-1459. Fax: 001-617-628-8606. Just fax your credit card details or use their internet shop at www.starlab.com

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I teach physics at Manchester Grammar School. The school was founded in 1515 and is an independent, fee-paying school for boys of ages 11 to 18 years. There are 1440 boys on roll, each of whom has passed our demanding academic entrance examination. Almost all boys go on to university and each year a little less than one quarter of the leavers (40 boys) win places at the universities of Oxford or Cambridge. The school prides itself in its sport, music and drama as well as its fund-raising for charity and its work in the community.

I have a BSc in Physics and an MSc in Radio Astronomy from The University of Manchester.

I am a founder member and currently Treasurer of the European Association for Astronomy Education and past Chair of the Education Committee of the Royal Astronomical Society.

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