II. How do we know?

In the previous chapter we started with the diameter of the Earth. We then considered the circumference of the Earth, the distance to and diameter of the Moon, the distance to and diameter of the Sun, the distances to inner and outer planets and the Oort Cloud. From the neighborhood of the Solar System we then moved to nearby starts, to the center of the Galaxy and the diameter of the Galaxy, the size of the Local Group of galaxies, of superclusters of galaxies, the Walls and Voids they form and, finally, how far to the most distant objects we detect. But how do we *know* these distances? In the latter cases, how can we possibly *know* them?!

The process started a long time ago and involves a lot of assumptions and imagination and slowly, and sometimes frustratingly, grows in a self correcting way. Strictly speaking we don't *know* these distances, especially the larger ones. **Instead, we have reasons and evidence, of variable degrees of reliability, for thinking the distances have various values, and as our reasons and evidence improve with time, we correct those values.** Let's examine some of the reasons and evidence.

1. The Greeks on the Earth, Sun and Moon: It was the ancient Greeks who first concocted arguments for determining the sizes of the Earth, Moon and Sun and the distances to the Moon and Sun! Their estimates for the Earth and Moon were pretty good but their estimates for the Sun were much too small. *Their reasoning in every case was impeccable* in the sense that we still accept their assumptions and we can't fault their logic. Their problem with the Sun was that to implement their arguments for the Sun required them to make some measurements that, with very simple instruments, they simply could not make with adequate precision.

First for the Earth, the seafaring Greeks assumed the spherical shape of the Earth from witnessing the increased distance to the horizon from elevated observation points and the bottom up gradual disappearance of sailing vessels over the horizon and the different maximum elevation angles for given stars viewed from different locations on the same night. Around 200 BCE, **Eratosthenes**, of the library at Alexandria, assessed the diameter and circumference of the Earth by measuring the shadow cast at high noon by a vertical rod at Alexandria on a day when library documents noted the Sun to be directly overhead at noon at Syene, roughly 500 miles to the South. The shadows length compared to the rods height indicated the Sun's rays were making an angle of 7 and ½ degrees with the vertical, whereas in Syene the Sun's rays would be very nearly vertical. This resulted in the calculation of

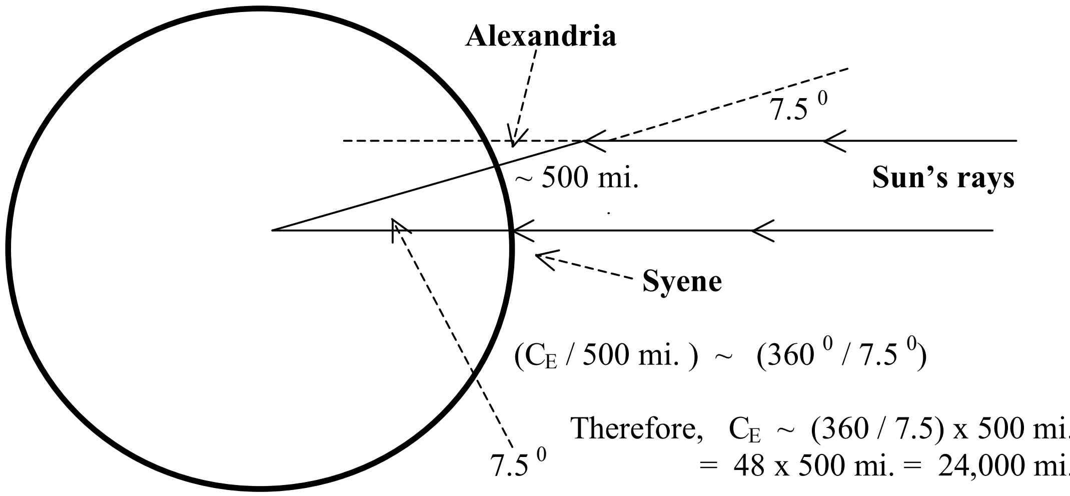


Fig. II.1: Eratosthenes determination of the circumference of the Earth

the Earth's circumference, C_E, to be about 24,000 mi. (**Fig. II.1**), pretty close to our present estimate of 25,000 mi.

To determine the size of and distance to the Moon, the mathematician and astronomer, **Aristarchus** of Samos (~250 BCE), used observations taken from lunar and solar eclipses. First remember our comment from the previous chapter that the Moon exactly blots out the Sun at totality of a solar eclipse. We mentioned then that this meant that the ratio of diameter to distance, D/d, is the same for the Moon and the Sun, i.e., $D_S/d_S = D_M/d_M$. It also means that the conical shadow of the Moon cast by the Sun has its vertex very near the Earth's surface. If the vertex was noticeably above the Earth's surface the Moon would look smaller than the Sun and if the vertex was noticeably below the Earth's surface the Moon would look larger than the Sun (**Fig. II.2**). We will soon make use of this fact.

The value of the ratio, D_M/d_M , (which is measured by the visual angle subtended by the Moon, ~ ½ ^{0}, and can be estimated by visual comparison with the ratio of the width of your thumb knuckle to the distance from your eye of your upright thumb at the end of your outstretched arm ~ 1/27) is given by,

$$D_M / d_M \simeq 1 / 110,$$

i.e., the distance to the Moon is about 110 times the Moon's diameter.

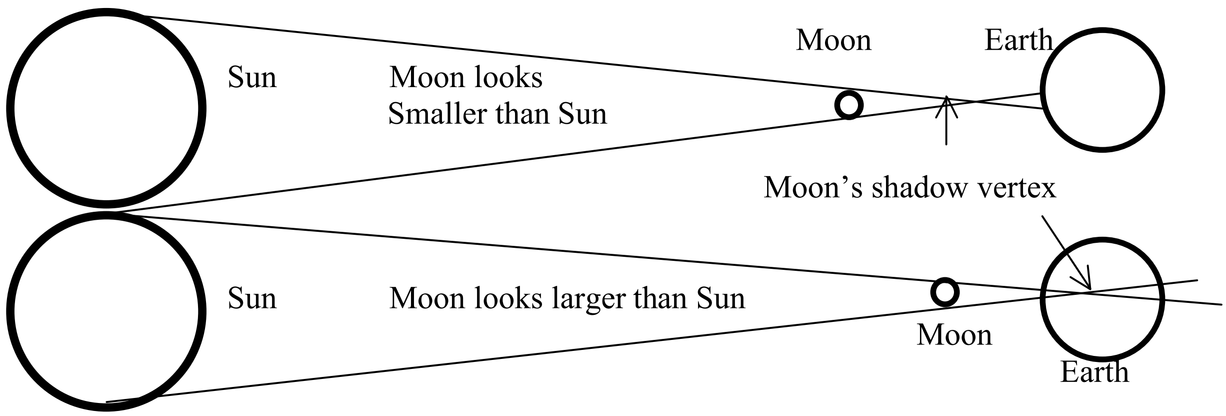


Fig. II.2: Apparent size of Moon vs. Sun and location of Moon's shadow vertex for different Moon distances (not to scale).

Aristarchus then considered a lunar eclipse and timed, as best he could, the various stages of the event (**Fig. II.3**). From the moment the Moon begins to enter the Earth's shadow in a lunar eclipse it takes about 2 and ½ times as long to begin reemerging from the shadow as it does to become completely engulfed in the shadow. Assuming the Moon's orbital motion is constant,

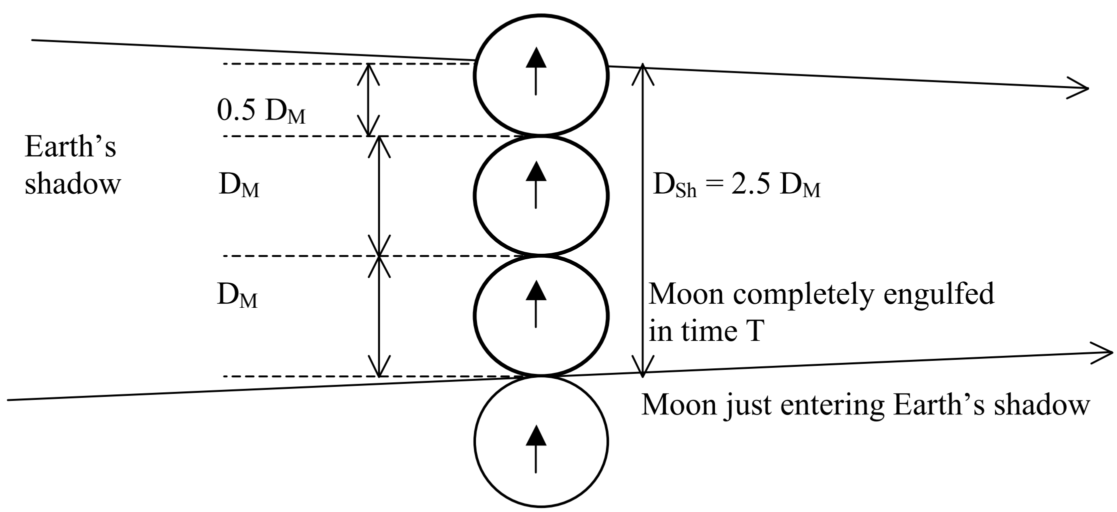


Fig. II.3: Moon passing through Earth's shadow during lunar eclipse.

this means that the diameter of the Earth's shadow, D_{Sh}, at the Moon is 2 and ½ times the Moon's diameter.

Now what else can we know about the size of D_{Sh}? **If** the Sun is much larger than the Earth, the Earth's shadow will be conical as the Moon's shadow is. **If** the Sun is also *much* farther away than the Moon, then the Earth's conical shadow will have the same *shape* as the Moon's shadow. Under these *assumptions* the Earth's shadow will shrink in diameter by one Moon diameter at the Moon's distance just as the Moon's shadow shrinks by one Moon diameter in the Moon's distance (remember $D_M/d_M = D_S/d_S$) (**Fig. II.4**). Consequently,

$$D_{Sh} = D_E - D_M \; .$$

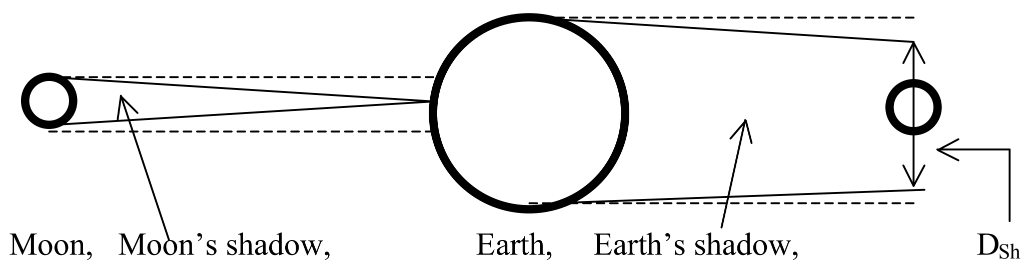


Fig. II.4: Earth and Moon conical shadows both shrink by one Moon Diameter in the distance between Earth and Moon (not to scale).

From $D_{Sh} = 2.5\ D_M = D_E - D_M$ we have $3.5\ D_M = D_E$ or

$$D_M \sim 8{,}000 \text{ mi.} / 3.5 \sim 2{,}300 \text{ mi.}$$

Then from $D_M/d_M \sim 1/110$ we get,

$$d_M \sim 110\ D_M \sim 110 \times 2{,}300 \text{ mi.} = 253{,}000 \text{ mi.}$$

We know now that both these values are a bit high and the major part of the error comes from underestimating the time the Moon is totally engulfed in the Earth's shadow during the lunar eclipse. If the factor of 2.5 is increased to 2.6 then we obtain the more accurate values $D_M \sim 2{,}200$ mi. and $d_M \sim 240{,}000$ mi. Of course, today we can simply measure the time required to send a radar pulse, traveling at the vacuum speed of light, to the Moon and back to get a very precise distance to the Moon.

Next, Aristarchus turns to the Sun. We already know that $D_S/d_S \sim 1/110$, just as for the Moon. To this Aristarchus adds the observation of the angular separation between the Sun and the Moon on those days when an exact half-Moon phase can be seen in the sky along with the Sun (**Fig. II.5**). The half-Moon phase means that the light rays from the Sun to the Moon and a line from the Earth to the Moon are perpendicular. The angle, θ, between the lines from the Earth to the Sun and to the Moon is then measured to also be very close to 90^0, i.e., these lines are nearly perpendicular. This means that the angle, $90^0 - \theta$, between the rays from the Sun to the Earth and to the Moon is very small and the approximate relationship,

$$d_M / d_S \simeq 2\pi(90^0 - \theta) / 360^0 \sim (90^0 - \theta) / 57^0$$

is very accurate.

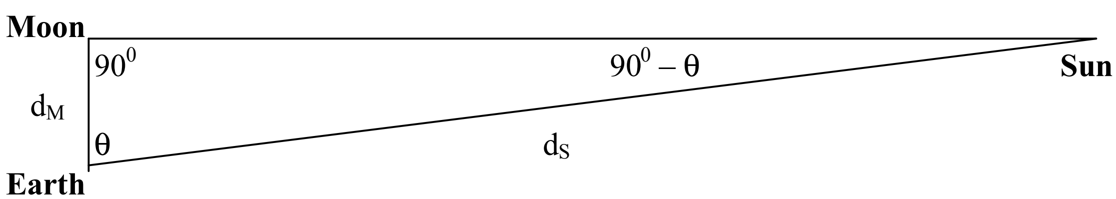


Fig. II.5: Aristarchus' Earth-Moon-Sun triangle when the half-moon and Sun are simultaneously visible.

Unfortunately, it's very difficult to measure θ accurately without precise instruments. The main reason is not that the Sun is in the measurers eyes but that θ is *very* close to 90^0 and the tiny difference from 90^0 is all important. Aristarchus greatly overestimated that tiny difference and, consequently, greatly overestimated the ratio d_M / d_S, i.e., he estimated the Sun to be much closer and much smaller than it actually is. An accurate measurement yields $\theta \simeq 89^0\ 51'$ and $d_M / d_S \sim 1 / 390$. So

$$d_S \sim 390 \times d_M \sim 390 \times 240{,}000 \text{ mi.} \sim 93{,}000{,}000 \text{ mi.} ,$$

and, consequently, $D_S \sim d_S / 110 \sim 93,000,000$ mi. / 110 ~ 850,000 mi.

2. The Planets: Prior to **Copernicus' heliocentric system** for interpreting the planetary motions one could not measure distances to the planets. But upon accepting that the planets and the Earth orbit the Sun in nearly circular orbits with the Sun near the center of the circles, such measurements could be made. The big difference between the planets or stars and the Sun or Moon, which we've just discussed, is that the latter display sizeable disks to our naked eye vision while the former are just 'points' of light of variable brightness. Less than a century after Copernicus, when **telescopes** are trained on the sky, the planets display visible discs and the possibilities of measurement for them greatly improves. But even before the telescope, the Copernican system allowed the determination of the orbital radii of the five then known planets.

From the Earth-bound perspective the inner planets, Mercury and Venus, followed the Sun's motion through the sky, oscillating back and forth from one side of the Sun to the other but never straying too far away (just enough to be seen as evening or morning 'stars'). The fact that they were never seen to deviate from the Sun by more than a fixed maximum angle determined the ratio of their distance from the Sun to our distance from the Sun (**Fig. II.6**).

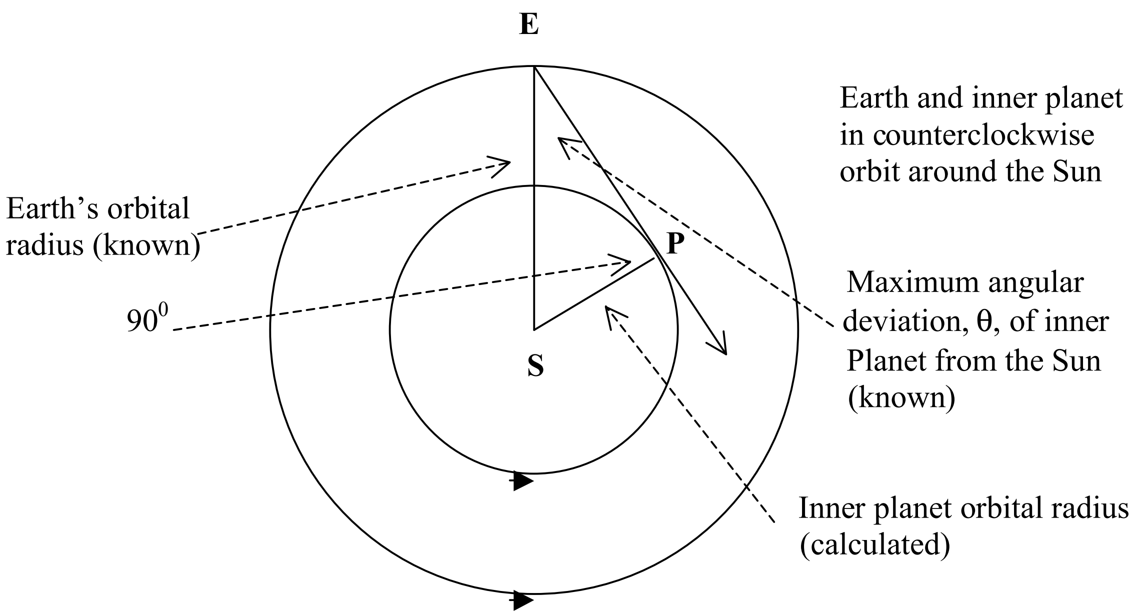
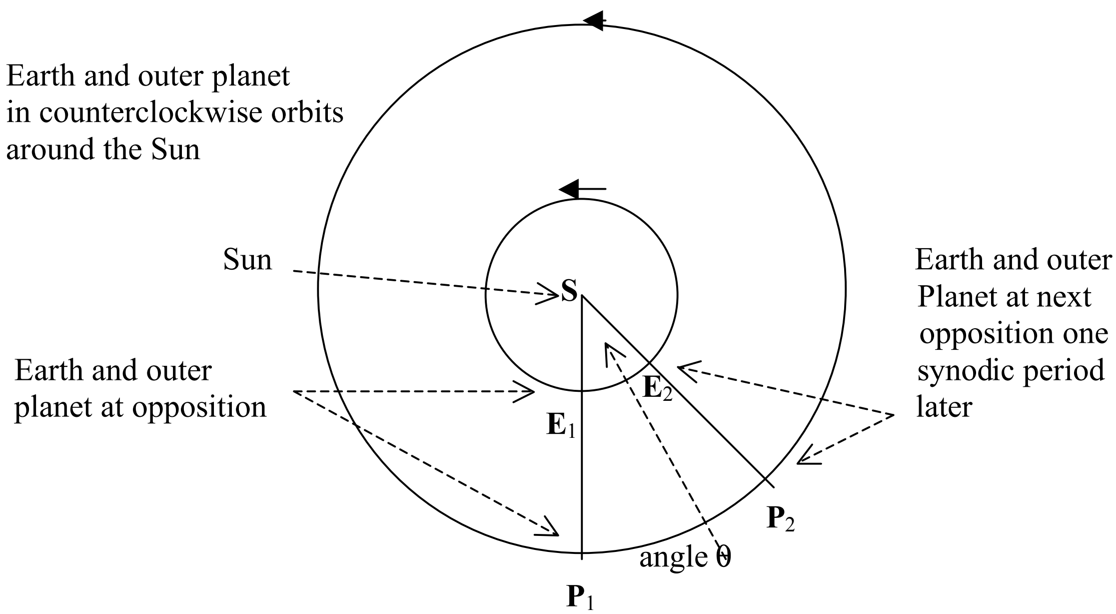


Fig. II.6: Determining the orbital radius of an inner planet in the Copernican model

By measuring the maximum deviation angle one determined a **right triangle** with the Earth's orbital radius as **hypotenuse** and the planet's orbital radius as the **leg opposite the angle**. The angle determined the shape of the triangle and the shape determined the ratio of the opposite leg to the hypotenuse.

The determination of orbital radii for the planets farther from the Sun than Earth was somewhat more complicated. In fact, it was just the greater complexity of their apparent motion as seen from the Earth that determined which planets were the ones farther from the Sun than Earth. The other known planets, Mars, Jupiter and Saturn, had no limitation on their angular separation from the direction to the Sun and could be observed in the opposite direction from the Sun at regular time intervals, T_{syn}, called the **synodic period** of the planet. When this observed period was plugged into the Copernican model one could calculate the orbital or **sidereal period**,



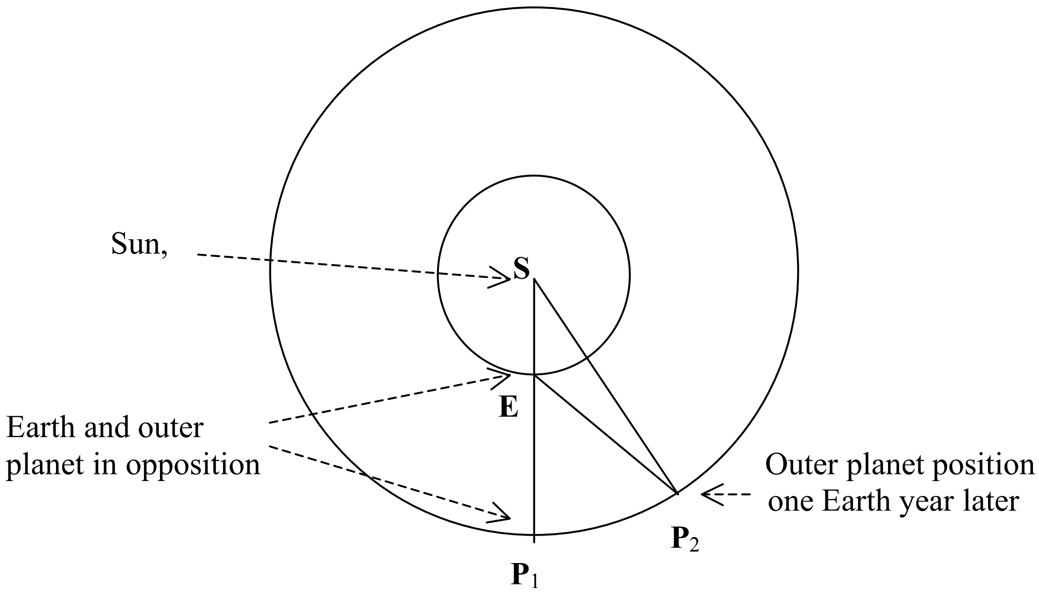
$$\text{Considering the Earth's motion;} \quad (360^0 + \theta) / 360^0 = T_{syn} / 1 \text{ yr.}$$

$$\text{Considering the outer planet's motion;} \quad \theta / 360^0 = T_{syn} / T_{sid}\,.$$

Consequently, $1 + (T_{syn} / T_{sid}) = T_{syn} / 1$ yr., or $(1 / T_{syn}) + (1 / T_{sid}) = 1 / 1$ yr.

Fig. II.7: Determining the sidereal period of an outer planet in the Copernican Model.

T_{sid}, that the planet took to orbit the Sun. Then, with the help of a little geometry, the planets orbital radius could be determined (**Figs. II.7, 8**).



Let α denote the angle at S between the lines P_1S and SP_2.
Let β denote the angle at E between the lines P_1E and EP_2.
Let θ denote the angle at E between the lines SE and EP_2.

Then $\alpha / 360^0 = 1$ yr. / T_{sid} and $\theta = 180^0 - \beta$ where β is observed. Since $\underline{SE} = 1$ AU, we know two angles, α and θ, and one side length of the triangle ESP_2. From this the side length $\underline{SP_2}$, the orbital radius of the outer planet, can be calculated.

Fig. II.8: Determining the orbital radius of an outer planet in the Copernican Model.

After **Johannes Kepler** discovered his **three laws of planetary motion** (see **Appendix A**), which were significant improvements on the Copernican model (which I have simplified somewhat here), **Galileo** brought the telescope to bear on the heavens and **Isaac Newton** discovered the force law and dynamical principles which governs planetary motion (see **Appendix B**), determination of planetary orbits became more precise. But the results of these important improvements in understanding were, quantitatively, just small corrections of the results obtained from the methods we have considered. More important than the small corrections for the planets known to the ancients was the use of the ideas and methods of Kepler, Galileo and Newton to firmly secure the Copernican heliocentric idea and to lead to the identification of the three (four ?) remaining planets of the solar system.

Uranus was discovered in 1781 by **William Herschel** who originally thought it was a comet oddly devoid of a cometary tail. Only by treating it as a planet could one make sense of its motion. **Neptune** was predicted, by **Adams** in England and **Leverrier** in France in 1845, as a planet needed to explain regular small perturbations in the orbit of Uranus. It was discovered where predicted to be in 1846. [**Pluto**]* was discovered in 1930 by **Clyde Tombaugh**.

3. The Oort Cloud: The Oort Cloud has never been seen, but if one calculates the orbits of observed long period comets, using Newtonian gravitation theory, their farthest distance from the Sun tends to concentrate around 50,000 AU. Since they appear to enter the solar system from all directions pretty uniformly, the Oort Cloud has been conjectured as their origin.

4. Stars: At last, the stars! They're farther away than the Oort Cloud and although they can easily be seen they don't send anything into the solar system to orbit the Sun. At first glance they just seem to sit there, endlessly, not moving among themselves and appearing to move across the sky because of the Earth's daily rotation. So how can we possibly determine how far away they are?

Most ancient Greek astronomers believed all the stars to be the same distance away; being tiny apertures in the outermost crystalline sphere through which the primordial fire of heaven glowed. Some early European astronomers tried to estimate variable distances for different stars on the basis of the assumption that they were all the same size and brightness as the Sun and appeared smaller and dimmer only because of their distances. The first such effort was by **Christian Huygens**, a contemporary of both Galileo and Newton. Assuming the brightest star, **Sirius**, was just like the Sun, Huyghens concluded it must be 200,000 AU distant. His grounds were that the intensity of light from a star must decrease with the square of the distance and the light we receive from the Sun, he estimated (?), is about 40 billion times as intense as that from Sirius! We now place Sirius 20 times as far away as Huygens did because we have reasons (to be discussed later) for believing Sirius is actually 400 times brighter than the Sun.

Near the end of the eighteenth century, William Herschel, the astronomer who earlier had discovered Uranus, found clear evidence that stars did not all have the same intrinsic brightness. Searching for pairs of bright and dim stars that were very close to one another in the telescope, so as to facilitate the comparison of their apparent brightness and the estimate of their distances, Herschel discovered pairs that were clearly **double star systems** orbiting each other. This discovery was important for strongly suggesting that Newtonian gravity was, indeed, universal and existed between distant stars as well as in the solar system. But since gravitationally bound and orbiting pairs of stars were guaranteed to be the same distance from Earth, the fact of their difference in apparent brightness meant that they were also of different intrinsic brightness. Unfortunately, even Herschel refused to give up the assumption of at least rough equivalence in intrinsic brightness of all stars and the notion lingered on for a long time.

Every procedure for assessing distances and other properties of the objects of astronomy starts with assumptions that can not, themselves, be tested directly. Only the repeated examination of the internal consistency of the accumulated results of employing the assumptions can lead to tests, corrections and improvements of the assumptions on which our measurements depend. The more procedures for making measurements we have, the better. For then it is not only internal consistency within a single procedure but consistency of results between procedures that we can demand and use for improving assumptions for all procedures. Strickly speaking, this account applies to all kinds of measurements of anything throughout science. But in stellar astronomy the objects of measurement are so remote that the assumptions employed are all risky gambles that need constant monitoring.

5. Stellar Parallax: It had been recognized from the time of Galileo that one of the least questionable methods for assessing stellar distances could be based on a procedure with which we judge the distance of terrestrial objects when we move passed them. For a given change in our position, the change in direction that we have to look in order to observe an object usually increases with the distance we have moved and decreases with increasing distance of the object from us. Measuring the angular change in the direction we have to look can determine the distance to the object. But the angular measurement requires a fixed reference direction, which ideally would be provided by an object *infinitely* far away.

To apply this idea to stars we note that we maximize our change of position by observing at six month intervals when we are at opposite ends of Earth's orbit around the Sun. While we don't have access to any infinitely far away objects for reference, the use of more distant stars as reference for the measurement of nearer stars can put a limit on the distances of the nearer stars (**Fig. II.9**). The shift in the angular separation between stars when viewed from opposite sides of Earth's orbit is called **stellar parallax**. Unfortunately, throughout the 17^{th} and 18^{th} century no one could detect any parallax, notwithstanding the use of the best telescopes of the day,. This meant that either the stars were all the same distance away or that they were so very far away the stellar parallax was too small to detect.

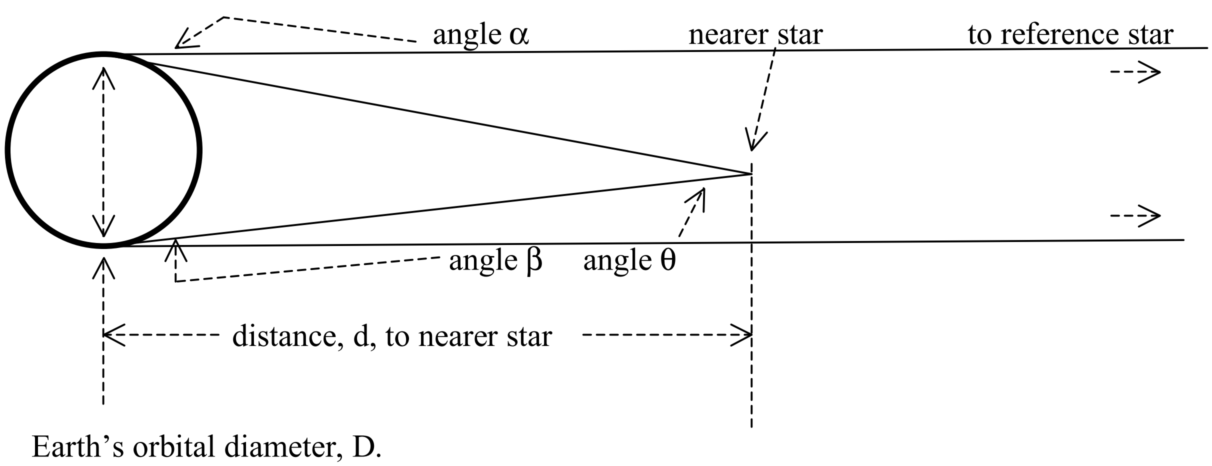


Fig. II.9: Parallax measurement of near star distance. The angles, α and β, are directly measured. The angle, θ, is given by, $\theta = \alpha + \beta$. If θ is small then $(D/2\pi d) \simeq (\theta/360^0)$, or, $d \simeq (360^0/\theta)(D/2\pi)$. If the reference star is a finite distance away, then $\theta \geq \alpha + \beta$. Therefore $d \leq (360^0/(\alpha + \beta))(D/2\pi)$. One half of θ is called the **parallax angle**. If the parallax angle is $1" = (1/3600)^0$ then the distance d is called 1 parsec ~ 3.26 lgt.yr.

The first successful detection and measurement of stellar parallax was made in 1838 by **Friedrich Bessel** who determined the **parallax angle**, $\theta/2$, for the star, **61 Cygni**, to be 0.31 seconds of arc. That's 31/100 x 1/3600 of a degree! The resulting distance to 61 Cygni is 3.4 parsecs, where a parsec is

3.26 lgt.yrs. and is defined as the distance corresponding to a parallax angle of 1 second of arc. Stellar parallax angles are never as large as 1 second of arc and the technique for measuring the angles is sufficiently delicate that by 1900 only 100 stars had had their distances measured this way. For objects farther away than about 100 parsecs the method becomes unreliable with ground based telescopes because of atmospheric fluctuations. With orbiting space telescopes, however, parallax measurements have been made on stars 1000 parsecs, or one kiloparsec, away.

6. Classifying Stars: From about 1880 to 1925 a group of women were organized by **Edward Pickering** of Harvard observatory to examine the optical spectra from stars and develop a classification scheme for stars of different types, a tedious task regarded by Pickering as suitable for a woman's temperament! The most important contributions to the work were made by **Williamina Fleming**, **Antonia Maury**, **Annie Jump Cannon** and **Henrietta Leavitt**.

Fleming was Pickering's housekeeper and he hired her to replace an incompetent male manager of the astronomical work, but wouldn't pay her more than was "suitable for a woman". Maury was a brilliant analyst who discovered subtleties in star spectra that Pickering regarded as trivial and the significance of which was understood only much later. She also distressed Pickering by her lack of attention to grooming and, after much important work, she left the group. Cannon and Pickering got along much better and Cannon became extremely expert at identifying star spectral types quickly. Their work eventually led to the publication, in 1918, of the **Draper catalogue** (named for a funding source) of 225,300 stars of the Northern hemisphere which was subsequently augmented by 130,000 additional stars. All of these stars had been classified by Cannon, personally, in about half a dozen years and the catalogue became the standard reference and backbone of astronomy for many years. Cannon was recognized around the world for her work but was not granted a faculty position by Harvard until 1938 at the age of 75.

Between 1908 and 1912, Henrietta Leavitt, discovered a relationship between the luminosity and period of a class of variable stars called **Cepheid variables**. The name springs from the first such star having been discovered in the **constellation of Cepheus**. We now know these stars to be giants which swell and cool and dim and then contract and heat up and brighten (Why? See **Appendix C**). They go through these cycles with rather precise, clockwork, periods that vary from a few days to longer than a month (**Fig. II.10**). Leavitt noticed that the longer the period, the brighter the star, and established a precise **period-luminosity relationship**. Since all of the stars she examined were in the **Small Magellenic Cloud**, she assumed them to be equidistant (in the same way we would say the people in Boston are all equidistant from the people in London) and so the variations in apparent luminosity (AL) could be regarded as indicating variations in intrinsic luminosity (IL). This was important because if one could pin down the distance to any one of these kinds of stars then the intrinsic luminosities could be determined for all of them and then Leavitt's relationship could be used to infer the distance of any such star – and these stars were very bright, so they could be seen at very great distances.

Unfortunately all the Cepheid variables were beyond parallax range and some other means had to be found for determining the distances to some of them. But Pickering, true to form, did not appreciate the significance of Leavitt's work and re-assigned her to more prosaic data gathering.

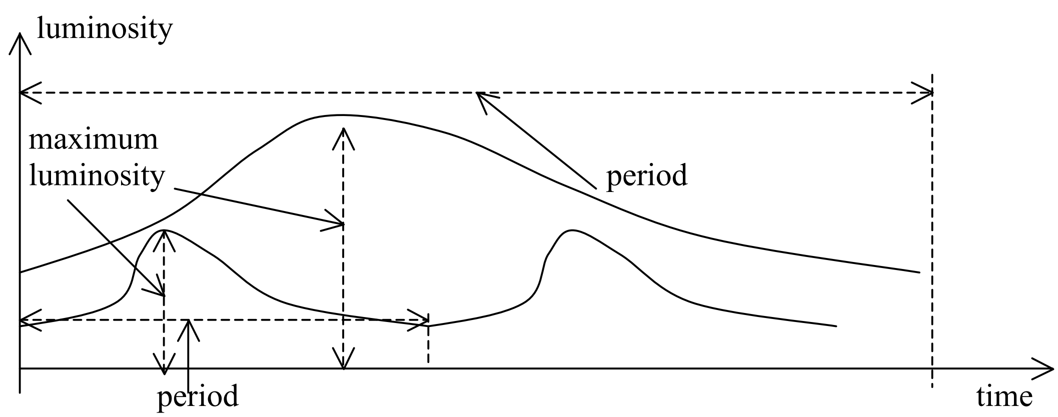


Fig. II.10: Schematic illustration of dependence of luminosity on period for Cepheid variable stars.

The final determination of the intrinsic luminosity of the Cepheid variables was a complicated, multi-stage, error and correction filled procedure which we don't have time to make clear. Instead I will present a greatly simplified argument that captures the essential ideas. One focuses on a large collection of stars of great variety that *seem* to belong together and that contains some Cepheid variables. The *assumption* is made that all such large collections will contain the same variety of stars. In particular, the brightest stars in each collection are *assumed* to be of the same intrinsic luminosity. They are also *assumed* to be of the same luminosity as the brightest stars among those whose distance is known. The distance to the collection is then estimated via the inverse square rule applied to these brightest stars, i.e.,

$$(AL_{max} \text{ known stars} / AL_{max} \text{ in collection})$$

$$= (\text{distance to collection} / \text{distance to known star})^2$$

With the distance estimate the intrinsic luminosity (IL) of the Cepheid variables in the collection can be estimated via,

$$(IL / AL) = (\text{distance to collection} / 1 \text{ AU})^2,$$

(the distance, 1 AU, appears because AL is judged by comparison with the Sun which is 1 AU distant).

Internal consistency of the procedure requires that the same IL estimate, for variables of a given period, is obtained over all the different collections used. This is roughly achieved. Once the ILs for all periods are well established any newly observed Cepheid can quickly have its distance assessed. In this way Cepheids have been measured at distances in excess of 16 million lgt.yrs. or 5 megaparsecs (5 Mpc).

In fact, two distinct classes of Cepheid variable stars have been found as well as a different kind of variable star called Lyra variables. Using the properties, assessed with difficulty, of all these types of variable stars, the dimensions of our Galaxy and of The Local Group and somewhat beyond can be roughly established.

7. Spectral Shift: The final distance indicator we will consider is the **red shift** of the electromagnetic spectra from very distant galaxies. This indicator was discovered by the astronomer, **Edwin Hubble**, in the 1920's and is our primary evidence that the Universe as a whole is expanding.

To begin we consider the **Doppler effect**. The siren of an approaching ambulance or fire truck has a certain pitch and, usually, an (ear straining) increasing volume. As the ambulance or fire truck passes by the pitch drops suddenly while the volume decreases gradually with increasing distance. Why the change in pitch?

Sound propagates through the air as oscillating pressure waves. The intensity of the sound is determined by the amplitude of the waves (half the difference between the maximum pressure and the minimum). The pitch is determined by the number of oscillations that pass our ears per second. This is called the **frequency**, f, of the wave. Since the pressure waves move through the air at a fixed speed, v, the frequency is determined by the distance separating consecutive maximum (or minimum) pressure regions. This is called the **wavelength**, λ, of the wave. The relation between f, v and λ is given by,

$$v = f\lambda .$$

This relationship is not peculiar to sound waves. It is universal and holds for all kinds of waves; water waves, seismic waves, light waves, - - -, just because of the nature of the concepts; propagation speed, frequency and wavelength.

Suppose the frequency of the siren is f_0 if the ambulance isn't moving. This means that the time interval between consecutive maximum pressure regions produced by the siren is $(1/f_0)$. This will also be the time interval between consecutive maximum pressure regions sweeping past your ears. So you will hear the frequency f_0. Now suppose the ambulance is moving away with speed, u (**Fig. II.11**). The siren still produces pressure maxima separated in time by $(1/f_0)$. But now while a produced maxima moves towards you with speed, v, the siren moves away with speed, u, before it produces the next maxima. So when the next maxima is produced the distance between it and the previous maxima is $(1/f_0)(v + u)$. This is the distance that separates the consecutive maxima that sweep over your ears. In other words, this is the wavelength, λ, you receive. But the propagation speed is still v. So the frequency you hear is

$$f = v/\lambda = v/[(1/f_0)(v + u)] = f_0\,[v/(v + u)] < f_0 .$$

This is the Doppler shift to a lower frequency, or pitch, from a receding sound source. If one knows both the resting frequency, f_0, and the received frequency, f, then the recession speed, u, is given by,

$$u = v\,[(f_0/f) - 1] .$$

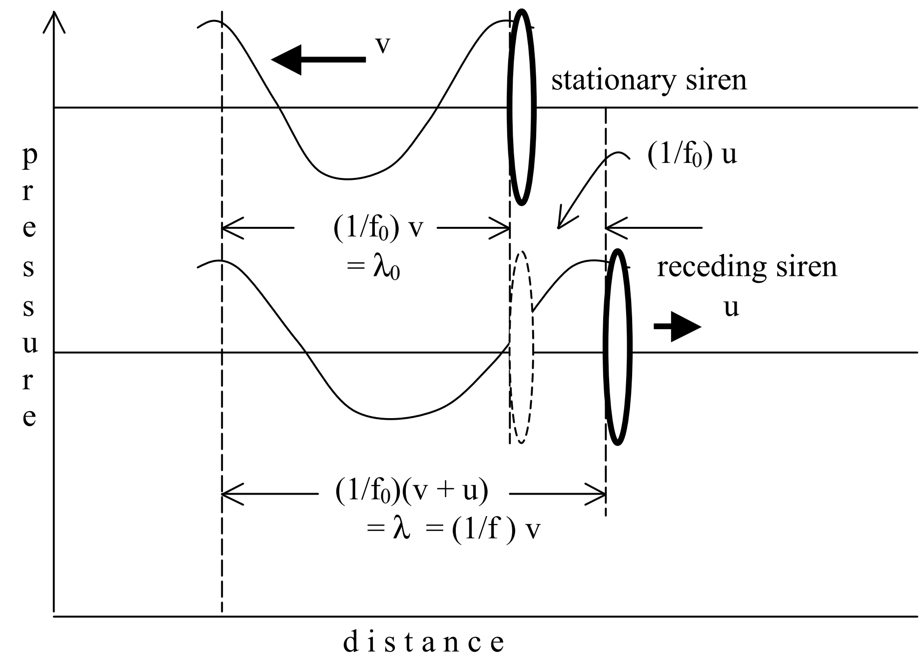


Fig. II.11: Doppler shift of sound wave from receding siren.

A similar analysis shows that an approaching sound source yields a Doppler shift to a higher frequency

Now in fact an analysis similar to this holds for all kinds of wave propagation from moving sources. Some details may be different but the general gist is the same. In particular it holds for the light waves emitted by stars and galaxies. So if we can tell whether the light from individual stars and galaxies has been Doppler shifted to lower or higher frequencies from the emitted frequency we can tell whether the star or galaxy is moving away from or towards us and at what speed. Fortunately, the light from stars and galaxies carries markers, called **spectral lines**, which we will discuss next time, and it's very easy to tell if the light has been Doppler shifted by locating these lines.

Combining this technique with various distance measurements, including using Cepheid variables, Hubble found that stars and collections of stars that were not too far away were sometimes moving towards us and sometimes moving away, as he expected. By identifying Cepheid variables in various

Nebulae he discovered that many were, in fact, not part of our Milky Way galaxy, but outside it. In this way he estimated the great nebula in Andromeda to be 0.9 Mlgt yr away and moving towards the Miky Way (currently 2.5 Mlgt yr). Such measurements helped establish, for the first time, the existence of other galaxies, then called island universes!

But as the distances got greater and greater a preponderance of moving away started to grow. Furthermore, for galactic distances so great that only the brightest stars in the galaxies (or their novae) were distinguishable with then existing telescopes, the speeds of recession, u, were found to be roughly directly proportional to the distance, d, or

$$u = H_0 \, d \, .$$

This relationship is called **Hubble's Law** and the constant, H_0 , is called the **Hubble constant** and presently is judged to have a value lying between (60 km/sec)/Mpc and (80 km/sec)/Mpc. We will adopt the present best estimate of,

$$H_0 \sim \text{(71 km/sec)/Mps.}$$

Today, using the spectral **red shift** to determine recession speeds and then Hubble's Law to infer distance is the basis for most of our assessments of the greatest observable distances of the Universe. Distances of the order of billions of lgt.yrs. or Giga parsecs have been inferred (at these extreme distances relativistic corrections to the relationship between Doppler shift and velocity must be employed and will be discussed later). The conclusion the astronomical community reached from the applicability of this law at intergalactic distances and beyond (but which Hubble, himself, resisted accepting) and which the scientific community now, pretty uniformly, accepts, is that **the Universe as a whole is expanding!**

8. Supernovae: We would be more out on a limb than usual if spectral red shift and the presumed Hubble Law was the *only* way to estimate the distances to *very* distant galaxies. Fortunately, there is at least one useful check on the Hubble Law at such distances. There is a particular kind of stellar explosion, called a **Type 1A Supernova**, that emits a readily recognized pattern of electromagnetic radiation with a very high and uniform peak intensity level wherever and whenever it occurs (**Fig. II.12**). By calibrating the intensity for such supernovae at independently known distances we can use the inverse square rule to measure the distances to such supernovae when they're *very* far away. Even though such explosions involve individual stars, they are so bright they can be detected *billions* of light years away. Thus they corroborate the use of the Hubble Law for such distances.

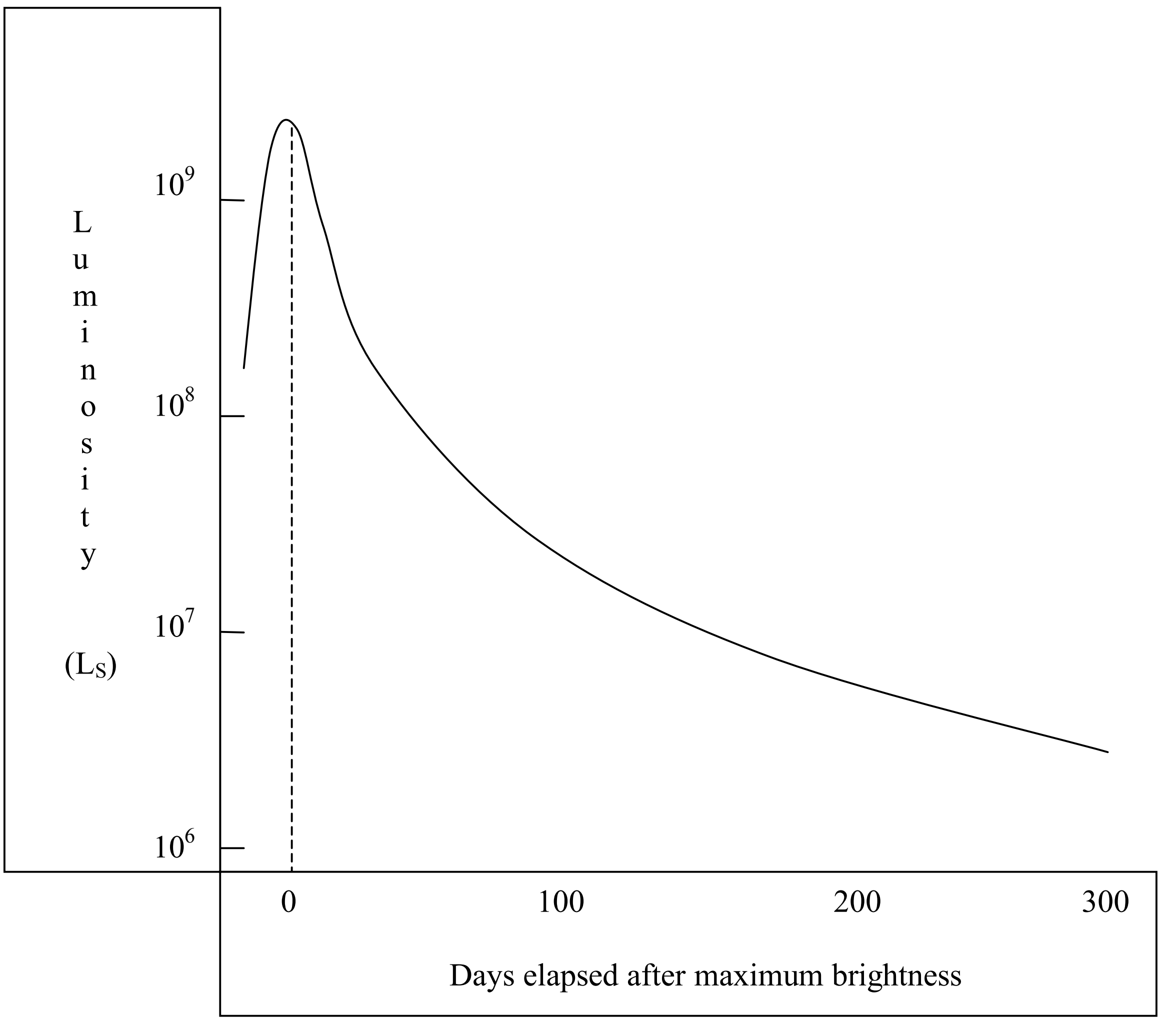
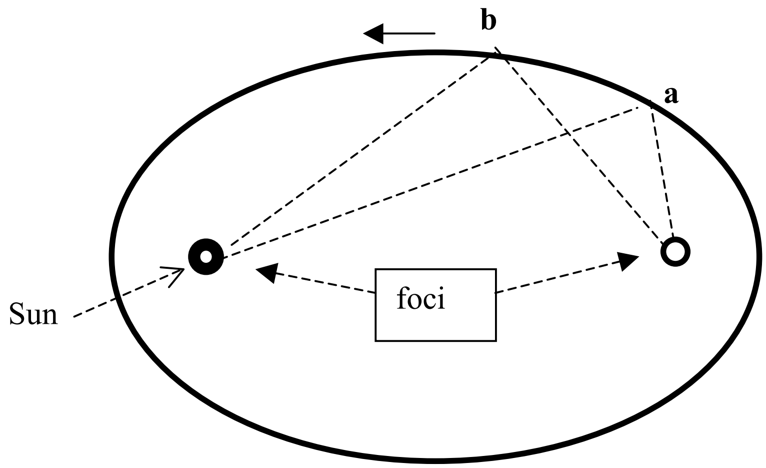


Fig. II.12: Intrinsic luminosity curve for a Type 1A Supernova

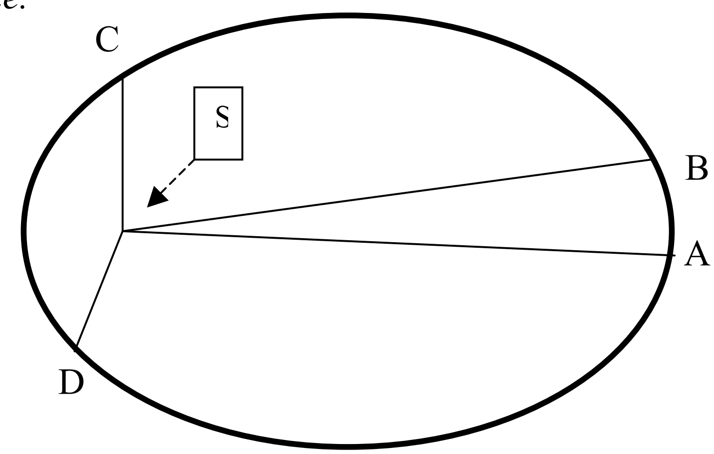
Appendix A: Kepler's Laws of Planetary Motion

(1.) Every planet orbits the Sun in an elliptical orbit with the Sun at one of the foci of the ellipse.



An ellipse is defined as a planar closed curve such that the sum of the distances of every point of the curve from two fixed points (the foci) is the same.

(2.) For each planet the line from the Sun to the planet sweeps out area at a constant rate.



$$\frac{\text{Area (SAB)}}{T_{AB}} = \frac{\text{Area (SCD)}}{T_{CD}}$$

(3.) For all the planets the ratio of the cube of the average distance from the Sun to the square of the orbital period is the same, i.e.,
$d_{av}^3/T^2 = (1AU)^3/(1yr)^2$ *,for each planet.*

The average distance is defined as half the sum of the minimum and maximum distance (the semi-major axis of the ellipse).

Appendix B: Newton's Theory of Gravitation

(1.) Every particle of matter ***attracts*** *every other particle of matter with a force proportional to the product of the particle's masses and inversely proportional to the square of the distance between them, i.e.,*

$$F_{AB} = G\, m_A m_B / d_{AB}^2.$$

(2.) The total force acting on a particle, as regards both its magnitude and direction, is equal to the product of the particle's mass and its acceleration, i.e.,

$$\mathbf{F}_A = m_A\, \mathbf{a}_A\ .$$

(3.) If any particle, A*, exerts a force*, $\mathbf{F}_{BA}$, *on any other particle,* B*, then particle,* B*, exerts an equal and opposite force,* $\mathbf{F}_{AB} = -\,\mathbf{F}_{BA}$, *on particle* A.

Appendix C: Why Cepheid variable Stars pulsate

In 1917 Arthur Stanley Eddington proposed that Cepheid Variable stars were surrounded by a cloud of gas. When the gas cloud was close to the surface of the star it was ionized by the high ambient temperature. This made the gas, now a plasma, opaque to the stars radiation and to distant observers, the star was dim. But radiation pressure built up underneath the ionized gas and this pushed the gas cloud further away from the stars surface where the gas cooled and its molecules regained their neutralizing electrons. No longer ionized, the gas became transparent to the stars radiation and the star brightened. But without the radiation pressure to hold the gas cloud away, the stars gravity pulled the gas cloud back towards the surface and high temperatures where ionization reoccurred and the cycle began again.

Until 1953 astronomers were uncertain as to the composition of the gas. Then the Russian astronomer S. A. Zhevakin identified Helium as the most likely gas and that identification has been widely accepted ever since.