CHAPTER I

UNDERSTANDING THE SKY

Outline:

⊙ *The Stars*
- *Constellations*
- *The name of the stars*

⊙ *The Sky and Its Motion*
- *Celestial sphere*
- *Coordinate systems (horizontal, equatorial, ecliptic and sidereal time)*
- *Daily phenomenon (twilight, rising and setting)*

⊙ *The Seasons*

⊙ *The Moving Planets*
- *Planet Configurations*
- *Retrograde motion*

I.1 The Stars

I.1.1 Constellations

At any one time, about 1000–1500 stars can be seen in the sky (above the horizon). Under ideal conditions, the number of stars visible to the naked eye can be as high as 3000 on a hemisphere, or 6000 altogether. Some stars seem to form figures vaguely resembling something; they have been ascribed to various mythological and other animals. This grouping of stars into constellations is a product of human imagination without any physical basis.

As an aid to remembering the stars in the night sky, the ancient astronomers grouped them into constellations; representing men and women such as Orion, the Hunter, and Cassiopeia, mother of Andromeda, animals and birds such as Taurus the Bull and Cygnus the Swan and inanimate objects such as Lyra, the Lyre. There is no real significance in these stellar groupings – stars are essentially seen in random locations in the sky – though some patterns of bright stars, such as the stars of the 'Plough' (or 'Big Dipper') in Ursa Major, the Great Bear, result from their birth together in a single cloud of dust and gas.

Different cultures have different constellations, depending on their mythology, history and environment. About half of the shapes and names of the constellations we are familiar with date back to Mediterranean antiquity. But the names and boundaries were far from unambiguous as late as the 19th century. Therefore the IAU *(International Astronomical Union)* confirmed fixed boundaries for 88 official constellations at its 1928 meeting.

The chart in **Figure 1.1** shows the brighter stars that make up the constellation of Ursa Major. The brightest stars in the constellation (linked by straight lines) form what in the Indonesia is called 'Pedati Usang (cow-drawn cart)', in UK 'The Plough' and in the USA 'The Big Dipper'. On star charts the brighter stars are delineated by using larger diameter circles which approximates to how stars appear on photographic images. The dotted lines define the borders of the constellations on the celestial sphere.

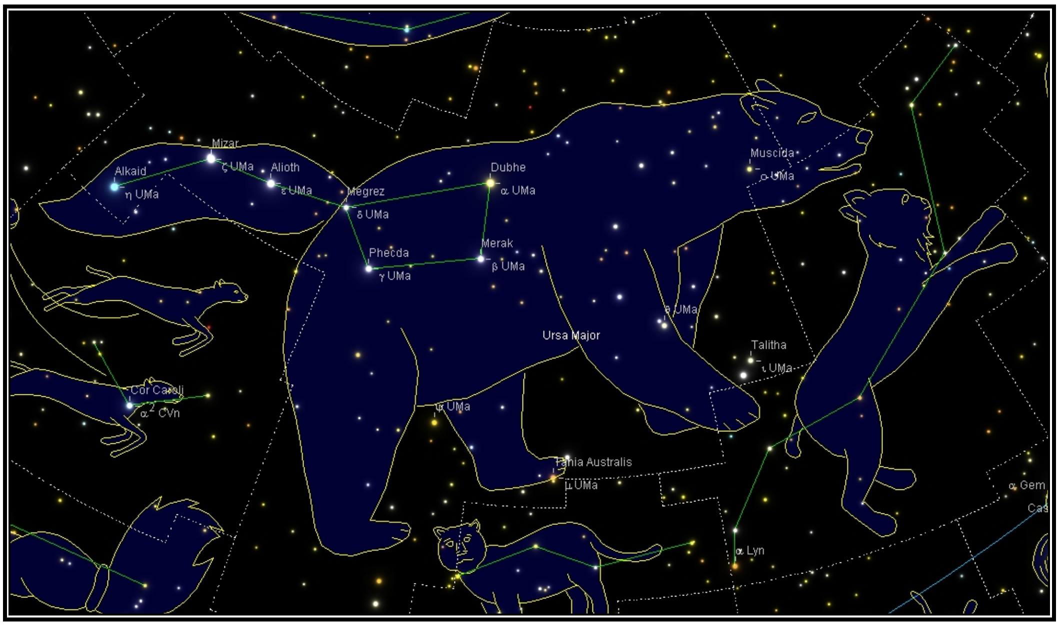


Figure 1.1 The constellation of Ursa Major (The Great Bear) in northern hemisphere.

The official boundaries of the constellations were established along lines of constant right ascension and declination for the epoch 1875. During the time elapsed since then, precession has noticeably turned the equatorial frame. However, the boundaries remain fixed with respect to the stars.

The stars of a constellation only appear to be close to one another. Usually, this is only a projection effect. The stars of a constellation may be located at very different distances from us (see **Figure 1.2**).

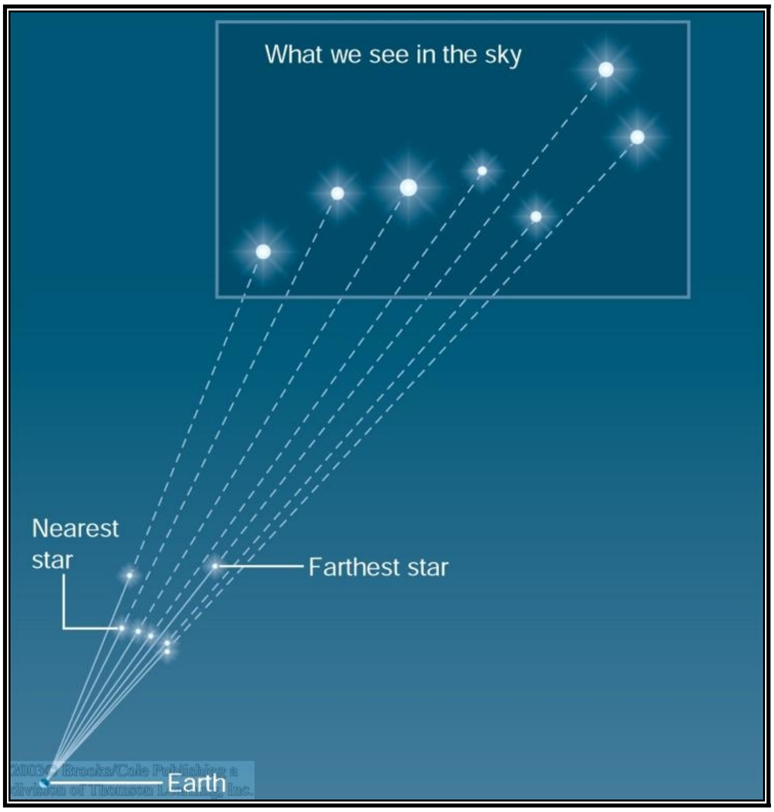


Figure 1.2 The projection effect makes stars at different distance appearing at the same distance as seen from the earth.

I.1.2 The name of the stars

In his star atlas *Uranometria* (1603) *Johannes Bayer* started the current practice to denote the brightest stars of each constellation by Greek letters. The brightest star is usually α (alpha), e.g. Deneb in the constellation Cygnus is α Cygni, which is abbreviated as α Cyg. The second brightest star is β (beta), the next one γ (gamma) and so on. There are, however, several exceptions to this rule; for example, the stars of the Big Dipper are named in the order they appear in the constellation. After the Greek alphabet has been exhausted, Latin letters can be employed.

Another method is to use numbers, which are assigned in the order of increasing right ascension; e.g. 30 Tau is a bright binary star in the constellation Taurus. Moreover, variable stars have their special identifiers. About two hundred bright stars have a proper name; e.g. the bright α Aur is called also Capella.

As telescopes evolved, more and more stars were seen and catalogued. It soon became impractical to continue this method of naming. Thus most of the stars are known only by their catalogue index numbers. One star may have many different numbers; e.g. the above mentioned Capella (α Aur) is number BD+45^0 1077 in the Bonner Durchmusterung and HD34029 in the Henry Draper catalogue.

I.2 The Sky and Its Motion

I.2.1 Celestial sphere

The ancient universe was confined within a finite spherical shell. The stars were fixed to this shell and thus were all equidistant from the Earth, which was at the centre of the spherical universe. This simple model is still in many ways as useful as it was in antiquity: it helps us to easily understand the diurnal and annual motions of stars, and, more important, to predict these motions in a relatively simple way. Therefore we will assume for the time being that all the stars are located on the surface of an enormous sphere and that we are at its centre. Because the radius of this celestial sphere is practically infinite, we can neglect the effects due to the changing position of the observer, caused by the rotation and orbital motion of the earth.

Since the distances of the stars are ignored, we need only two coordinates to specify their directions. Each coordinate frame has some fixed reference plane passing through the centre of the celestial sphere and dividing the sphere into two hemispheres along a great circle. One of the coordinates indicates the angular distance from this reference plane. There is exactly one great circle going through the object and intersecting this plane perpendicularly; the second coordinate gives the angle between that point of intersection and some fixed direction.

I.2.2 Coordinate systems

I.2.2.1 the horizontal system

The most natural coordinate frame from the observer's point of view is the *horizontal frame* (see **Figure 1.3**). Its reference plane is the tangent plane of the Earth passing through the observer; this horizontal plane intersects the celestial sphere along the *horizon*. The point just above the observer is called the *zenith* and the antipodal point below the observer is the *nadir* (these two points are the poles corresponding to the horizon.) Great circles through the zenith are called *verticals*. All verticals intersect the horizon perpendicularly.

Here, you measure how far above the horizon an object lies (its *altitude, h*) and how far east of due north it lies (its *azimuth, A*). The altitude lies in the range $[-90^0, +90^0]$; it is positive for objects above the horizon and negative for the objects below the horizon. The *zenith distance (z)*, or the angle between the object and the zenith, is obviously

$$\mathbf{z} = 90^0 - \mathbf{h} \text{..........(1.1)}$$

The values of azimuth are usually normalized between 0^0 and 360^0. More often than not, you'll read or hear directions given in this system. For example: *"Venus lies 15° high in the west an hour after sunset."*

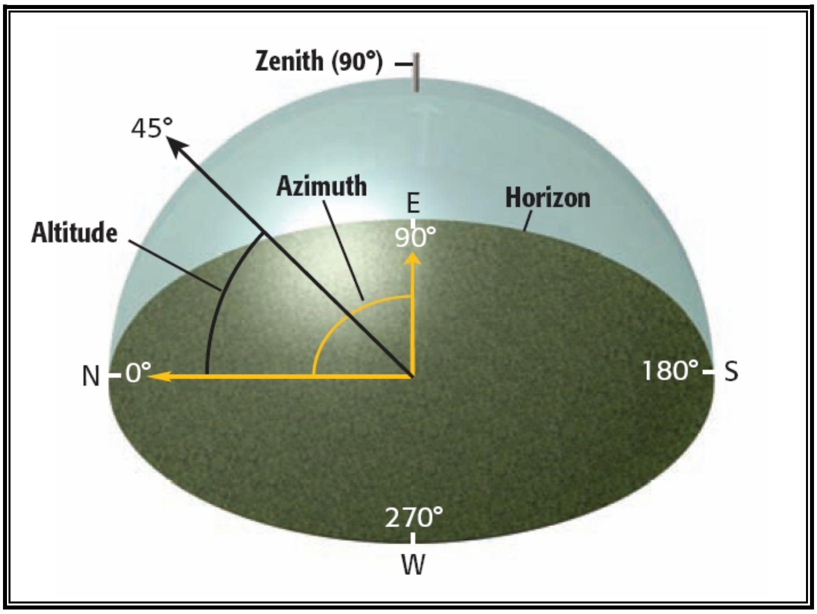


Figure 1.3 Determine the position of celestial object using the horizontal coordinate. Note that only a half of celestial sphere is drawn.

As the star moves along its daily track, both of its coordinates will change. Another difficulty with this coordinate frame is its local character. The coordinates of the same star at the same moment are different for different observers. Since the horizontal coordinates are time and position dependent, they cannot be used, for instance, in star catalogues.

1.2.2.2 the equatorial system

The direction of the rotation axis of the Earth remains almost constant and so does the equatorial plane perpendicular to this axis. Therefore the equatorial plane is a suitable reference plane for a coordinate frame that has to be independent of time and the position of the observer.

The equatorial coordinate closely matches the latitude and longitude we use on Earth. Imagine all celestial objects lying on the surface of an infinitely large celestial sphere centered on Earth. The celestial equator is an extension of Earth's equator into the sky, and the celestial poles mark where Earth's axis of rotation intersects the celestial sphere.

Astronomers measure how far north or south of the celestial equator an object lies (its *declination,* δ) and how far east of the vernal equinox an object lies (its *right ascension,* α). The advantage of the equatorial coordinate system is that it remains essentially fixed relative to the stars. So, if you know the right ascension and declination of the star Betelgeuse tonight, it will be in the same position next week, next year, and even next decade. In the horizon system, an object doesn't stay in the same place or coordinate from one hour to the next. Right ascension (α) measured eastwards from the vernal equinox, from 0 hour to 24 hours. Declination (δ) measured from 0 to $+90^0$ from the celestial equator to the north pole and from 0 to -90^0 from the celestial equator to the south pole along a secondary great circle to the celestial equator.

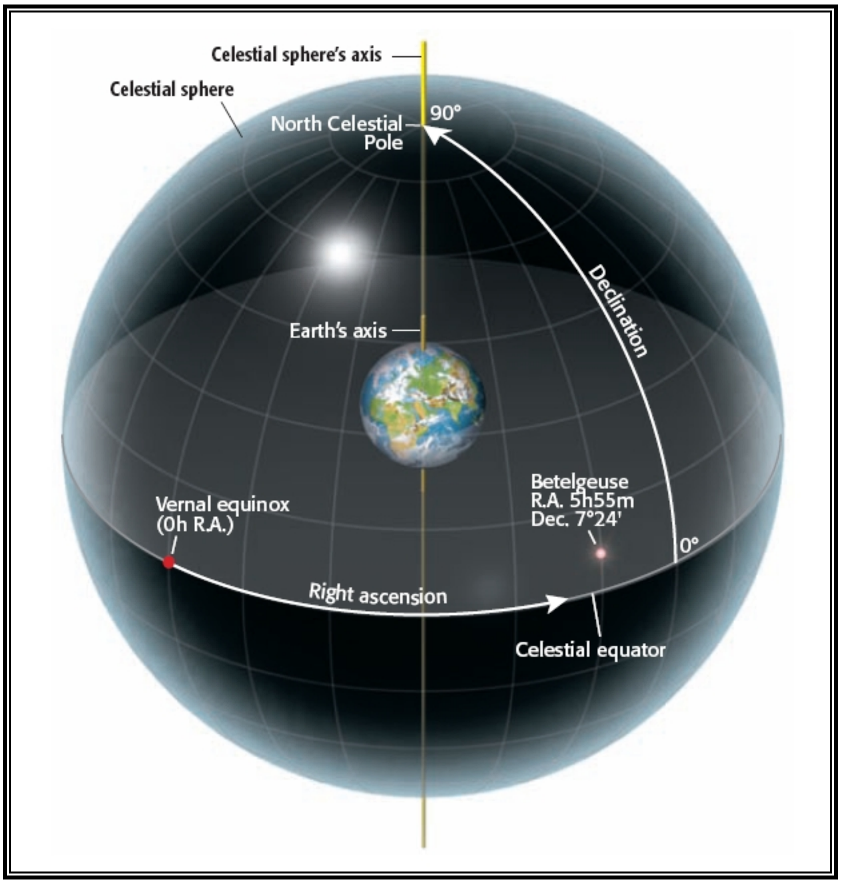


Figure 1.4 Determine the position of celestial object using the equatorial coordinate. In this system, all attributes on the surface of the earth (longitude, lalitude and poles) are attached to the inner surface of celestial sphere.

Note that the elevation of the pole –the angle between the polar axis and the horizon– is equal to the latitude (ϕ) of the observer (if you're at the south pole, the celestial pole is directly overhead; but if you are at the equator, your latitude is zero and the elevation of the celestial pole is zero, in other word it's on the horizon).

The origin or zero point of this system, the vernal equinox, also takes part in the diurnal and annual motion of the stars, so that the axes of the coordinate system are fixed by the celestial equator and poles and provided one knows where the origin is at any time, any star can be located from its (α,δ) position. We locate the vernal equinox using sidereal time.

1.2.2.3 the ecliptic system

The orbital plane of the earth, the *ecliptic*, is the reference plane of another important coordinate frame. The ecliptic can also be defined as the great circle on the celestial sphere described by the sun in the course of one year. This frame is used mainly for planets and other bodies of the solar system. The orientation of the earth's equatorial plane remains invariant, unaffected by annual motion. In spring, the sun appears to move from the southern hemisphere to the northern one (see **Figure 1.5**). The time of this remarkable event as well as the direction to the sun at that moment are called the *vernal equinox*. At the vernal equinox, the sun's right ascension and declination are zero. The equatorial and ecliptic planes intersect along a straight line directed towards the vernal equinox. Thus we can use this direction as the zero point for both the equatorial and ecliptic coordinate frames. The point opposite the vernal equinox is the *autumnal equinox*, it is the point at which the sun crosses the equator from north to south.

The *ecliptic latitude* β is the angular distance from the ecliptic; it is in the range $[-90^0, +90^0]$. The other coordinate is the *ecliptic longitude* λ, measured counterclockwise from the vernal equinox.

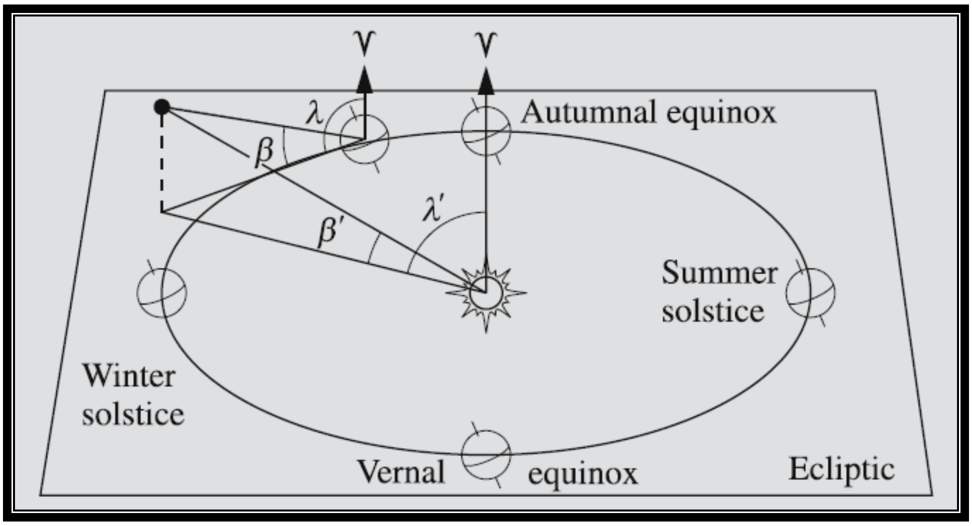


Figure 1.5 The ecliptic geocentric *(λ, β)* and heliocentric *(λ', β')* coordinates are equal only if the object is very far away. The geocentric coordinates depend also on the earth's position in its orbit.

1.2.2.4 sidereal time

The interval between two successive transits of a star across the meridian is one sidereal day. This is slightly shorter than the mean solar day because of the earth's motion around the sun. The sidereal day is divided into hours, minutes and seconds, in the same way as the mean solar day, but these of course are all a bit shorter than their mean solar counterparts. The sidereal day would be the measure of the true rotation period of the earth, except that it is not actually defined by the passage of stars across the meridian, but by the passage of the first point of Aries (γ), the vernal equinox.

From the point-of-view of determining star positions, 24 sidereal hours elapse between successive transits (or upper culmination) of a star across the meridian. Any given star thus completes 360^0 in 24h, so its hour angle increases at a rate of 15^0 per hour (15 arc-minutes per minute; 15 arc-seconds per second). The hour angle of a star is thus generally measured in elapsed units of sidereal time since the star crossed the meridian. In other words,

Local Hour Angle (LHA) = Local Sidereal Time (LST) - α of a star .....(1.2)

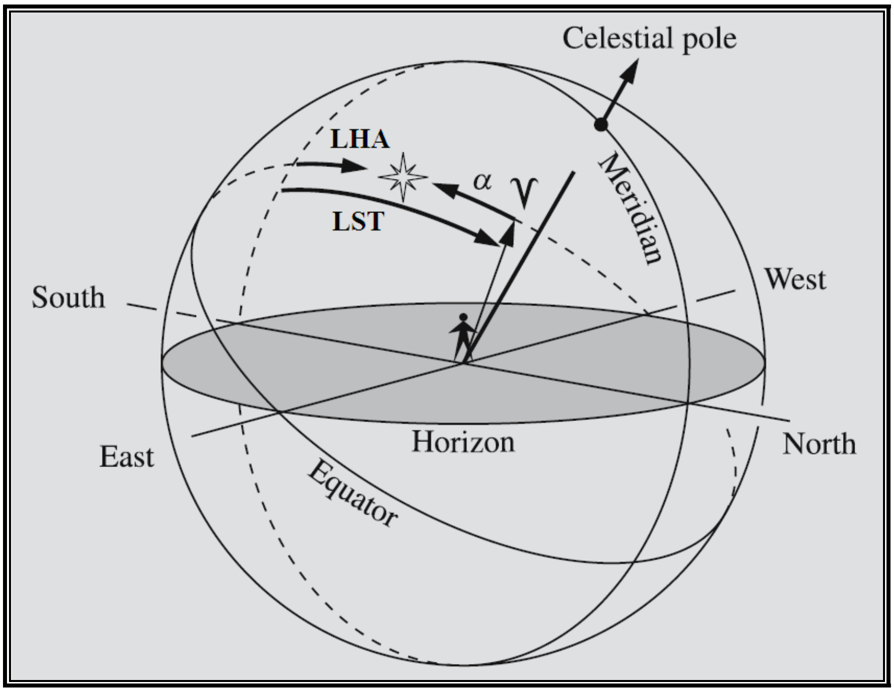


Figure 1.6 The sidereal time equals the hour angle plus right ascension of any objects.

Note that for a star on the meridian, the LHA of a star is zero. In particular, the start of the sidereal day is the instant that the vernal equinox crosses the meridian – and the sidereal time is the hour angle of that point. Since the meridian is specific to the observer, we refer to sidereal time as Local Sidereal Time. We have defined,

$$\textbf{LST = LHA of } \gamma \text{ ....(1.3)}$$

Example:

<u>Problem</u> *Where is the position of star Gamma Crucis (the most northern star in constellation Crux) which has right ascension 12h 31m on Sunday evening 08.00 local time according to observer in Bandung? It is known that the local sidereal time at the moment of observation is 13h.*

<u>Answer</u> *Using equation (1.2), we get*

LHA = 13h 00m – 12h 31m
LHA = 12h 60m – 12h 31m
LHA = 00h 29m.

The hour angle is positive. This means that star Gamma Crucis is in ***western part*** *of the sky rightnow. It has crossed the meridian 29 minutes* ***before*** *the observation time.*

1.2.3 Daily phenomenon

1.2.3.1 twilight

Since the atmosphere scatters sunlight, the sky does not become dark instantly at sunset; there is a period of twilight.

During **civil twilight,** it is still light enough to carry on ordinary activities out-of-doors; this continues until the Sun's centre altitude is -6^0. During **nautical twilight**, it is dark enough to see the brighter stars, but still light enough to see the horizon, enabling sailors to measure stellar altitudes for navigation; this continues until the Sun's centre altitude is -12^0. During **astronomical twilight,** the sky is still too light for making reliable astronomical observations; this continues until the Sun's centre altitude is -18^0. Once the Sun is more than 18^0 below the horizon, we have **astronomical darkness**. The same pattern of twilights repeats, in reverse, before sunrise.

1.2.3.2 rising and setting

The standard formula for the altitude of an object is,

$$\sin(\mathbf{h}) = \sin(\boldsymbol{\delta})\sin(\boldsymbol{\varphi}) + \cos(\boldsymbol{\delta})\cos(\boldsymbol{\varphi})\cos(\mathbf{HA}) \ldots\ldots\ldots (1.4)$$

In the equation above, each symbol represents altitude, declination, geographic latitude of the observer and hour angle of the object respectively. If the value of $h=0^0$ (the object is on horizon, either rising or setting), then this equation becomes**,**

$$\cos(\mathbf{HA}) = -\tan(\boldsymbol{\varphi})\tan(\boldsymbol{\delta}) \ldots\ldots\ldots (1.5)$$

which gives the **semi-diurnal arc** HA, that is the time between the object crossing the horizon and crossing the meridian.

Knowing the right ascension of the object, and its semi-diurnal arc, we can find the Local Sidereal Time of meridian transit, and hence calculate its rising and setting times. However, refraction means that this simplified formula is not accurate, since the altitude should be, not 0^0, but $-0^0 34'$. This is not too important for stars (point source of light), which are rarely observed close to the horizon. But it makes an important difference in calculating the times of rising and setting of the sun.

Furthermore, "sunrise" and "sunset" generally refer to the moment when the *top* of the sun's disc is just on the horizon. The formula would give us the time of rising or settingfor the *centre* of the sun's disc. So we must also allow for the *semi-diameter* of the sun's disc, which is 16 arc-minutes. So sunrise and sunset actually occur when the sun has altitude $-0^0 50'$ (34' for refraction, and another 16' for the semi-diameter of the disc).

Example:

Problem *The Sun is at declination −14⁰.* ***(i)*** *What will be its hour angle at sunrise (the moment the top edge of the Sun first appears over the horizon), at a latitude of* $+56^0 20'$*?* ***(ii)*** *If the Sun is on the local meridian at 12h 03m local time, what time is sunrise?* ***(iii)*** *What time is sunset?* ***(iv)*** *when will astronomical twilight start and finish?*

Answer *Using equation (1.4), we get*

$$\cos(HA) = \{ \sin(h) - \sin(\varphi)\sin(\delta) \} / \cos(\varphi)\cos(\delta)$$

$$\cos(HA) = \{ \sin(-0^0 50') - \sin(+56^0 20')\sin(-14^0) \} / \cos(+56^0 20')\cos(-14^0)$$

$$HA = 69{,}7^0 \ (= 4h\ 39m) \ \textbf{or} \ 290{,}3^0 \ (= 19h\ 21m)$$

To decide which, note that the Sun is to the ***east of the meridian*** *at sunrise, so HA = 19h 21m.*

The semi-diurnal arc is 4h 39m.
Sunrise *is at (12h 03m – 4h 39m) = 07h 24m local time.*
Sunset *is at (12h 03m + 4h 39m) = 16h 42m local time.*

For astronomical twilight, the Sun's centre altitude is -18^0*. Using the same equation, we get*

$$HA = 101.55^0 = 6h\ 46m.$$

So ***astronomical twilight starts*** *at (12h 03m – 6h 46m) = 05h 17m local time and* ***ends*** *at (12h 03m + 6h 46m) = 18h 49m local time.*

I.3 The Seasons

Earth revolves around the sun in a counterclockwise direction if viewed from space. Each year's complete revolution traces an elliptical orbit bringing earth closest to the sun in January and furthest away in July. The point at which a planet, comet, or asteroid most closely approaches its sun is termed *perihelion*, while the point furthest away is *aphelion*. At perihelion, about January 3rd, earth comes within 147,091,312 km of the sun. At aphelion, about July 4th, it is 152,109,813 km from the sun. But, it is not the elliptic orbit of the earth itself which causes the seasons.

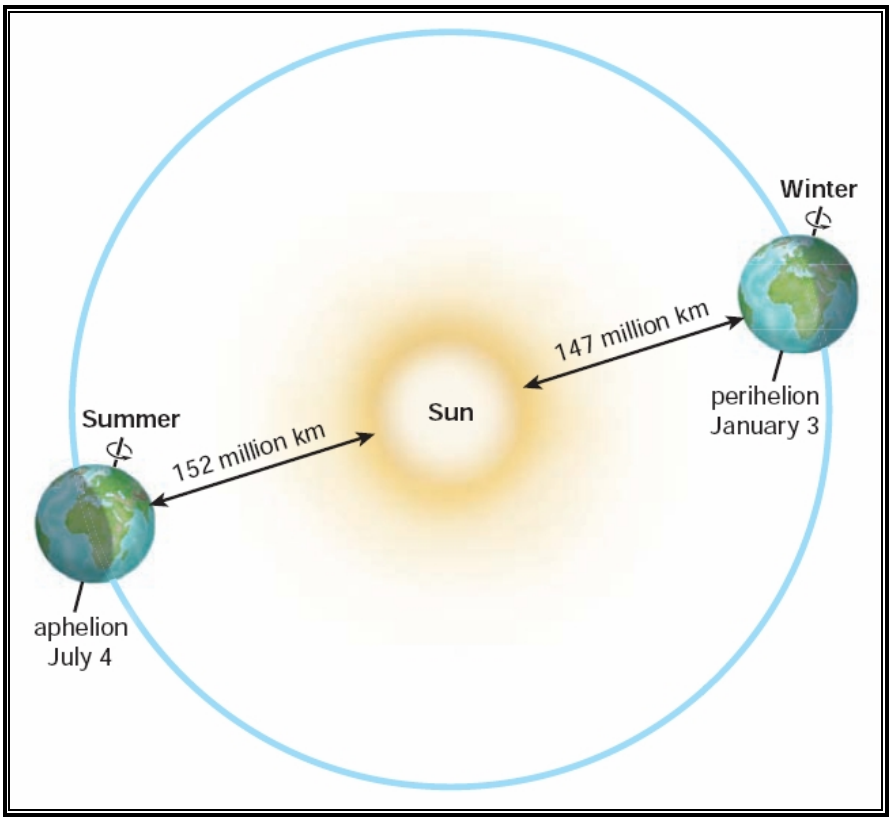


Figure 1.7 The path of earth's orbit around the sun. In the northern hemisphere, earth is farthest from the sun during early summer and closest during early winter.

Seasons are periods of the year with characteristic weather. Many tropical and subtropical regions have only wet and dry seasons. Temperate regions such as North America and Europe have four seasons: spring, summer, fall (autumn), and winter. Seasons result from the fact that earth's axis of rotation is not perpendicular to the plane of its orbit around the sun, but tilted by 23.5 degrees. This tilt means that northern and southern hemispheres receive more or less sunlight depending on whether they are tilted toward or away from the sun. Seasons depend on the intensity of solar radiation, so the northern summer coincides with the southern winter and vice versa. The figures below show seasons for the northern hemisphere.

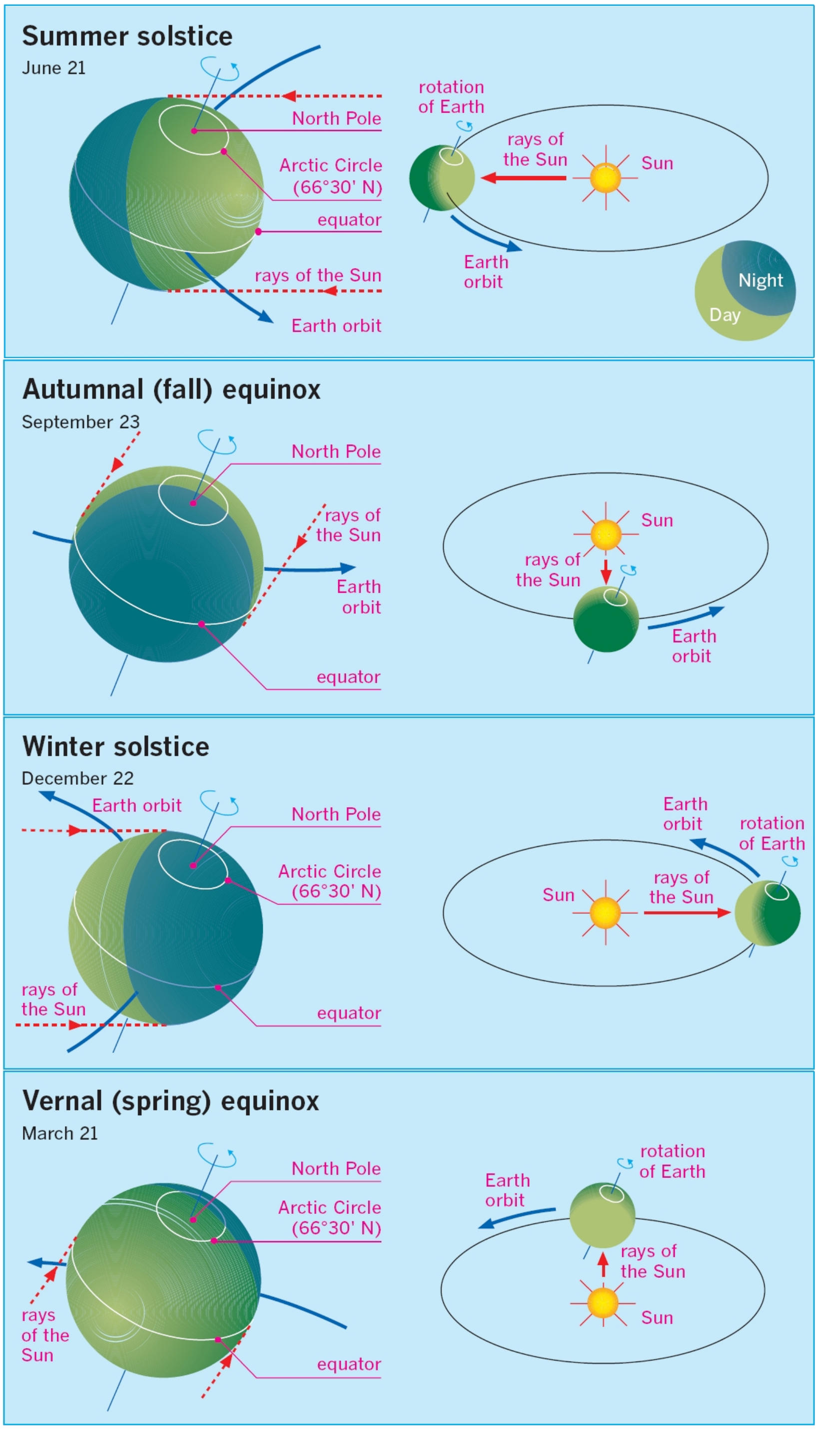


Figure 1.8 ***(Top)*** At the summer solstice the northern hemisphere is tilted toward the sun. Summer is the hottest time of year. ***(Middle top)*** At the autumnal equinox, the sun is directly overhead above the equator. In the fall daytime grows shorter, crops ripen, and deciduous trees shed leaves. ***(Middle bottom)*** At the winter solstice, the northern hemisphere is tilted away from the sun. Winter is the coldest time of year. Daytime hours are shortest. Plant growth slows or stops. ***(Bottom)*** At the vernal equinox, the sun is overhead at the equator. In spring days lengthen and plants grow.

What happens to the length of a day as we move from summer into fall and then winter? The number of hours of daylight changes over the course of a year and by latitude. The axial tilt places the sun directly overhead on the tropic of cancer during the noon of the summer solstice (June 21st), our longest day of the year in the northern hemisphere. The greater amount of solar radiation reaching the northern hemisphere at this time accounts for the warm temperatures of summer. Day and night are split equally on the first days of spring and fall (equinoxes) when the sun is directly overhead at the equator. The hours of daylight increase northward during summer in the northern hemisphere and decrease southward in the southern hemisphere (where it is winter). At the north pole, the sun rises above the horizon on the spring equinox and does not set until the fall equinox 6 months later. Imagine daylight 24 hours per day. This pattern is reversed during the winter when the south pole is illuminated for 24 hours and the north pole is dark 24 hours per day.

When summer solstice is occurring in the northern hemisphere, what is happening in the southern hemisphere? The rays are directly overhead in the northern hemisphere and the sun is farthest from the southern hemisphere than at any other time of year. Therefore, the suns rays strike the southern hemisphere at a low angle and transfer less energy resulting in lower temperatures. Thus, in the southern hemisphere, winter occurs in June and summer (with the sun overhead at the tropic of capricorn) occurs during our winter solstice, the shortest day of the year in the northern hemisphere.

I.4 The Moving Planets

I.4.1 Planet configurations

Extensive observations were carried out by *Tycho Brahe*, at Uraniborg, Denmark, late in the 16th century. Brahe moved to Prague in 1597, and died four years later. His results were taken over by an assistant, *Johannes Kepler*. Let's look briefly at how we survey the Solar System, measuring the periods and sizes of orbits. We take advantage of certain geometric arrangements. These are shown in **Figure 1.9**.

We first look at planets that are closer to the sun than the earth. When the planet is between the earth and the sun, we say that it is at *inferior conjunction*, and it appears too close to the sun in the sky to observe. As the planet moves in its orbit, the angle between it and the sun (as seen from earth) becomes larger. The planet appears farther and f arther from the sun. Eventually, since its orbit is smaller than the earth's, it reaches a maximum apparent separation from the sun. This is called the *greatest elongation*. At that point, the earth, the sun and the planet make a right triangle, with the planet at the right angle. After that the planet appears to get closer to the sun, and when it is on the far side it is at *superior conjunction*. The pattern then repeats on the other side of the line from the earth to the sun. When the planet is on one side of the sun it will appear east of the sun in the sky, and when it is on the other side it appears west of the sun. When it is west of the sun, it rises and sets before the sun, and it is therefore most easily visible in the morning. When it is east of the sun, it rises and sets after the sun, and is most easily visible in the evening.

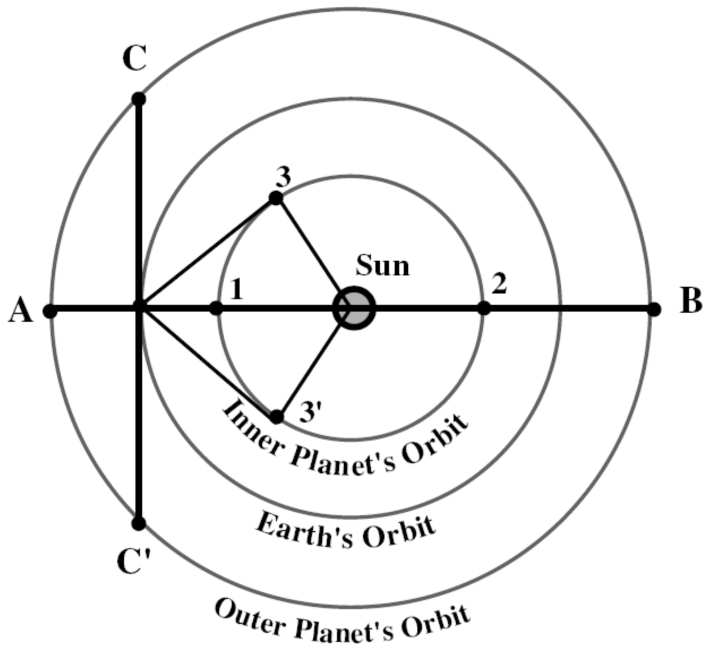


Figure 1.9 Configurations of the Earth and the inner and outer planets. Positions of the inner planets are indicated by numbers: (1) inferior conjunction, (2) superior conjunction, (3 and 3') greatest elongation. Positions of the outer planets are indicated by letters: (A) opposition, (B) conjunction, (C) quadrature.

We then look at planets that are farther from the sun than the earth. Let's start by looking at the planet when it is farthest from earth, on the far side of the sun. We say that the planet is simply at *conjunction.* At that point, it would be too close to the sun in the sky to see. As it moves farther from that position it appears farther from the sun on the sky. When it reaches a point where the earth, sun and planet make a right triangle, with the Earth at the right angle, we say that it is at *quadrature*. Notice that there is no limit on how far on the sky it can appear to get from the sun. Eventually, it reaches the point where it is on the opposite side of the sky from the sun. We call this point the *opposition*, and it is also the closest approach of the planet to earth. When the planet is at opposition, it is up at night (since it is opposite to the sun in the sky). Therefore, when a planet is favorably placed for observing, it is also closest to earth and can be studied in the greatest detail.

The maximum (eastern or western) *elongation*, i. e. the angular distance of the planet from the sun is 28^0 for Mercury and 47^0 for Venus. Elongations are called eastern or western, depending on which side of the sun the planet is seen. The planet is an "evening star" and sets after the sun when it is in eastern elongation; in western elongation the planet is seen in the morning sky as a "morning star".

When we talk about the orbital period of a planet, we mean the period with respect to a fixed reference frame, such as that provided by the stars. This period is called the *sidereal period* of the planet. However, we most easily measure the time it takes for the planet, earth and sun to come back to a particular configuration. This is called the *synodic period.* For example, the synodic period might be the time from one opposition to the next. How do we determine the sidereal period from the synodic period?

Suppose we have two planets, with planet 1 being closer to the Sun than planet 2 (for simplicity, we assume circular orbits). The angular speed ω_1 of planet 1 is therefore greater than that of planet 2, ω_2. The relative angular speed is given by,

$$\omega_{\mathbf{relative}} = \omega_1 - \omega_2 \ldots\ldots\ldots(1.6)$$

Since $\omega = 2\pi / P$, where P is the period of the planet, the period of the relative motion of the two planets, $P_{relative}$, is related to P_1 and P_2 by,

$$\frac{1}{\mathbf{P}_{\mathbf{relative}}} = \frac{1}{\mathbf{P}_1} - \frac{1}{\mathbf{P}_2} \quad \text{.........(1.7)}$$

Now we let one of the planets be the earth, and express the periods in years. First we look at the earth plus an inner planet. This means that P_1 is the period of the planet and P_2 is 1 year. Equation (1.7) then becomes,

$$\frac{1}{\mathbf{P}_{\mathbf{relative}}} = \frac{1}{\mathbf{P}_1} - 1 \quad \text{.........(1.8)}$$

Similarly for the earth and an outer planet, equation (1.7) becomes,

$$\frac{1}{\mathbf{P}_{\mathbf{relative}}} = 1 - \frac{1}{\mathbf{P}_2} \quad \text{........(1.9)}$$

In each case $P_{relative}$ is the synodic period and P_1 or P_2 is the sidereal period.

We now look at how the sizes of various planetary orbits are determined. The technique is different for planets closer to the sun than the earth and farther from the sun than the earth. **Figure 1.10** shows the situation for a planet closer to the sun. When the planet is at its greatest elongation, it appears farthest from the sun. The planet is then at the vertex of a right triangle, as shown in the figure. Since we can measure the angle E between the sun and the planet, we can use the right triangle to write,

$$\mathbf{\sin E} = \mathbf{r} / \mathbf{1AU} \quad \text{.........(1.10)}$$

where r is the distance from the planet to the sun. This equation can be solved for r to give us the distance to the planet, measured in astronomical units.

Methods like this gives us distances in terms of the astronomical unit. Even if we don't know how large the AU is, we can still have all of the distances on the same scale, so we can talk about the relative separations of the planets. The current best measurement of the AU comes from situations like **Figure 1.10**. We can now bounce radar signals off planets, such as Venus. By measuring the round-trip time for the radar signal (which travels at the speed of light), we know very precisely how far the planet is from the earth. The right triangle in **Figure 1.10** gives us,

$$\cos E = d / 1AU \quad \text{..........(1.11)}$$

Since E is measured and d is known from the radar measurements, the value of the astronomical unit can be found. This distance is approximately 150 million kilometers. The exact value is accurate to within a few centimeters.

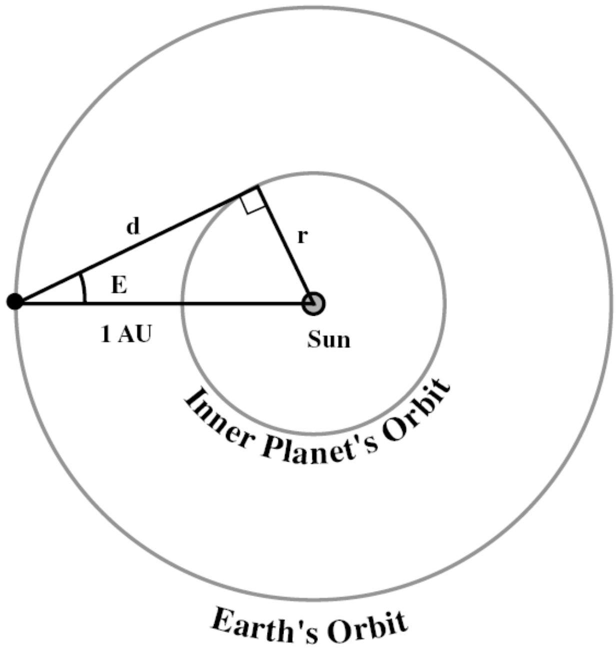


Figure 1.10 Diagram for finding the distance to an inner planet.

It is more complicated to find the distance to an outer planet. There are two different methods. The easier one was derived by Copernicus, but is not good for tracing out the full orbit. It just gives the distance of the planet from the Sun at one point in its orbit. Kepler's method of tracing the whole orbit is shown in **Figure 1.11**. We make two observations of the planet, one sidereal period of the outer planet apart. The earth is at E_1 and E_2, respectively, when these are made. The angles ψ_1 and ψ_2 are directly determined. The angles θ_1 and θ_2 are known, as well as the distance x (If the earth's orbit were circular, then $\theta_1 = \theta_2$). We then know $\psi_1 - \theta_1$ and $\psi_2 - \theta_2$, and can find d_1 and d_2, and, finally, r. The advantage of this method is that each point in the planet's orbit can be traced, with the observations overlapping in time.

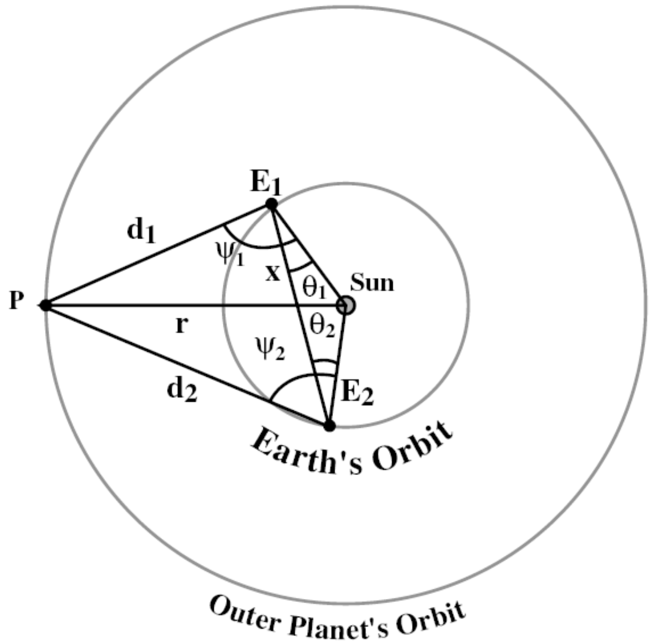


Figure 1.11 Diagram for finding the distance to an outer planet.

The angle sun–planet–earth is called the *phase angle*, often denoted by the Greek letter α. The phase angle is between 0^0 and 180^0 in the case of Mercury and Venus. This means that we can see "full Venus", "half Venus", and so on, exactly as in the phases of the moon. The phase angle range for the superior planets is more limited. For Mars the maximum phase is 41^0, for Jupiter 11^0, and for Neptune only 2^0.

I.4.2 Retrograde motion

When we look at the night sky, it is clear that most of the objects maintain their relative positions. These are the stars. However, apart from the sun and moon, a small number of objects move against the background of fixed stars. These are the planets. The study of the motions of the planets has occupied astronomers for centuries. These motions do not appear simple. The planets occasionally seem to double back along their paths, as shown in **Figure 1.12**. This doubling back is known as *retrograde motion*. Historically, any explanation of the motions of the planets had to include an explanation of this retrograde motion.

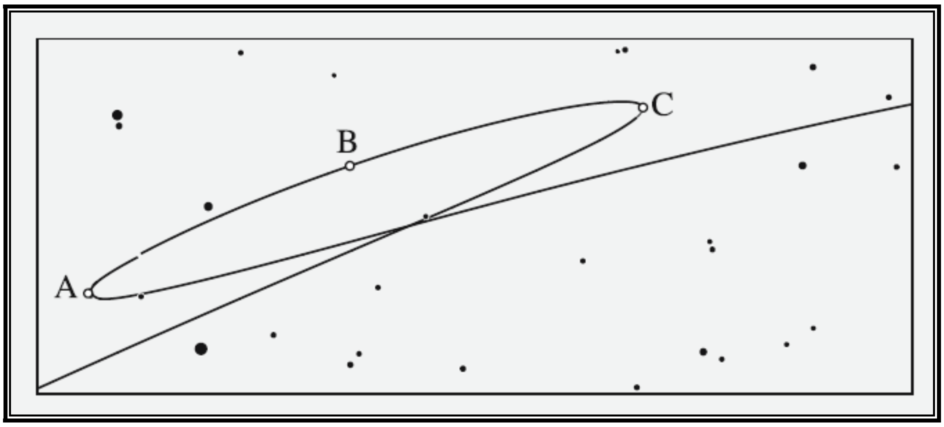


Figure 1.12 Apparent motion of Mars during the 1995 opposition.

The earliest models of our planetary system placed the earth at the center. This idea was supported by *Aristotle* in approximately 350 BC. His view was that the planets, the sun and the moon move in circular orbits about the earth. Even though there is now ample evidence against this picture, one can see how placing the earth at the center was a naturally simplifying assumption. The picture was modified by *Claudius Ptolemy*, in Alexandria, Egypt, around 140 AD. In order to explain retrograde motion, he added additional circles, called *epicycles*. As shown in **Figure 1.13**, each planet was supposed to move around its epicycle as the center of the epicycle orbits the earth. To obtain a closer fit to the observed motions, higher order epicycles were added.

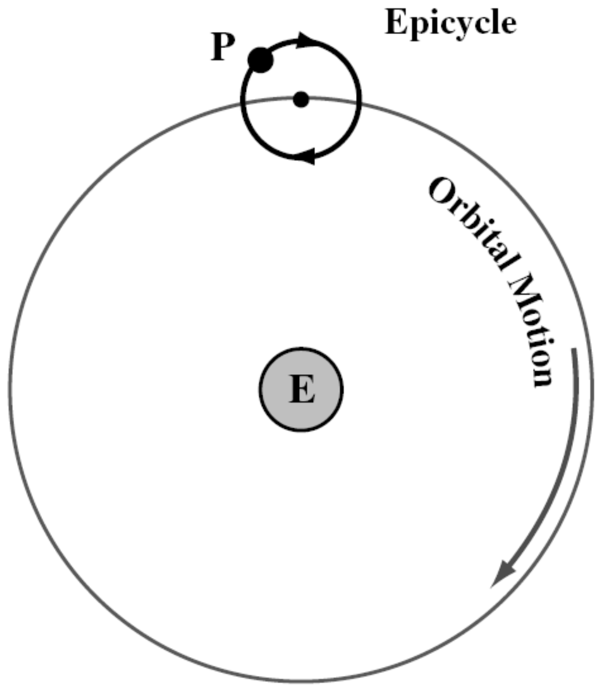


Figure 1.13 In this picture, the earth is at the center. The planet, P, doesn't simply orbit the earth. It goes around in a circle, which in turn orbits the earth. If the planet's motion along the epicycle is faster than the epicycle's motion around the earth, then the planet can appear to go backward for parts of each orbit. More layers of epicycles can be added to this picture.

An opposing picture was supported by the 16^{th} century Polish astronomer, *Nicholas Copernicus*. In the Copernican system, the sun is at the center of the planetary system. This picture is therefore called the *heliocentric* model. Copernicus showed that the retrograde motion is an artifact, caused by the motion of the earth. This is illustrated in **Figure 1.14**. The Copernican system had the planets in circular orbits, not ellipses. Therefore, detailed predictions of planetary positions had small errors. To correct those errors, epicycles had to be added to the Copernican model, taking away from the simplicity of the picture.

When *Galileo Galilei* turned his newly invented telescope to the planets, he found that Venus does not appear as a perfect disk. It goes through a series of phases, similar to those of the moon. The size of the disk also changes as the phase changes. These observations can be explained easily in the heliocentric model, because Venus would not always be at the same distance from earth. The phases result from the fact that we see differing amounts of the illuminated surface. There was no similar explanation in the earth-centered system. Though Galileo was persecuted for holding that the heliocentric picture is the true one, his work had great influence on future scientific thought. Work switched from trying to find what was at the center of the planetary system to trying to understand how the planets, the earth included, move around the Sun.

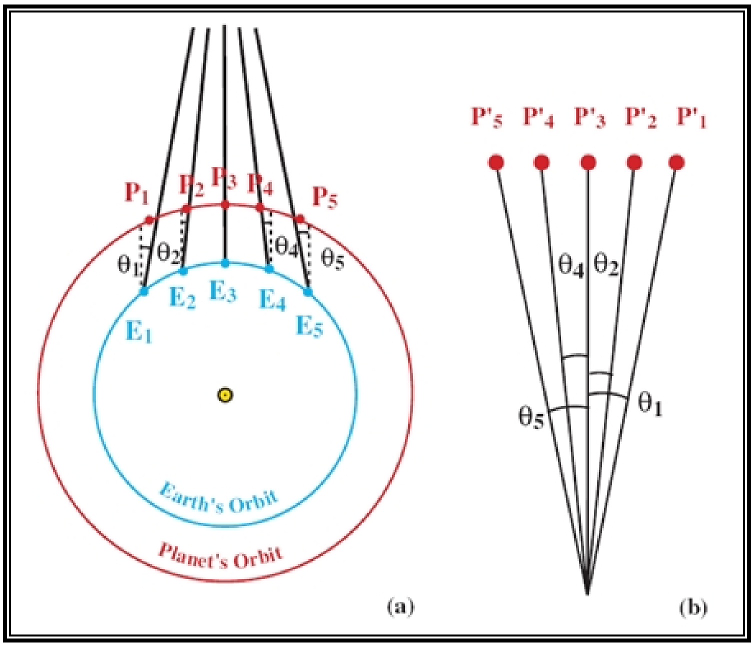


Figure 1.14 Retrograde motion in the heliocentric system. **(a)** The sun is at the center. We consider the earth at five positions E_1 through E_5 with the planet at P_1 through P_5 at the same times.We use the line of sight from the sun through E_3 and P_3 as a reference direction.The dashed lines are all parallel to that direction, and the angles θ_1 through θ_5 keep track of the differences between the line of sight from earth to the planet and the reference direction.We see that since the earth is moving faster than the planet, the line of sight goes from being ahead of the dashed line to being behind the dashed line. **(b)** The view from earth. The apparent position of the planet on the sky is indicated by P'_1 through P'_5. During this part of their orbits the planets appears to move backward on the sky.

Astronomy Laboratory

TIME AND THE SUN

Procedure:
Plotting an Analemma

1. The second column of **Solar Noon Data** table shows the latitude on Earth where the sun is directly overhead at solar noon on each date. Complete the third column by determining how far away you are from each location. For locations south of the equator add that latitude to your latitude. For locations north of the equator subtract that latitude from your latitude. For example, if you are at 40^0 N latitude on January 10, you are $40^0 + 22.1^0$, or 62.1^0, from the location where the sun is overhead on January 10.

2. Your angular distance from the latitude where the sun is overhead is the same as the difference of the local sun's altitude from 90^0 altitude. Using January 10 again, if you are at 40^0 N and are thus 62.1^0 from the overhead sun, the sun's altitude is $90° – 62.1^0$, or 27.9^0. Using your latitude, complete the fourth column of the **Solar Noon Data** table.

3. For each date, graph the clock time at solar noon versus the altitude of the sun at solar noon. Label the points that represent the 20th day of each month. Connect the points in chronological order with a smooth curve (1st graph).

4. Now, try to find declination of the Sun for each date using planetarium software such as *SkyGazer*. Graph the difference of clock time and solar time versus declination of the Sun (2nd graph).

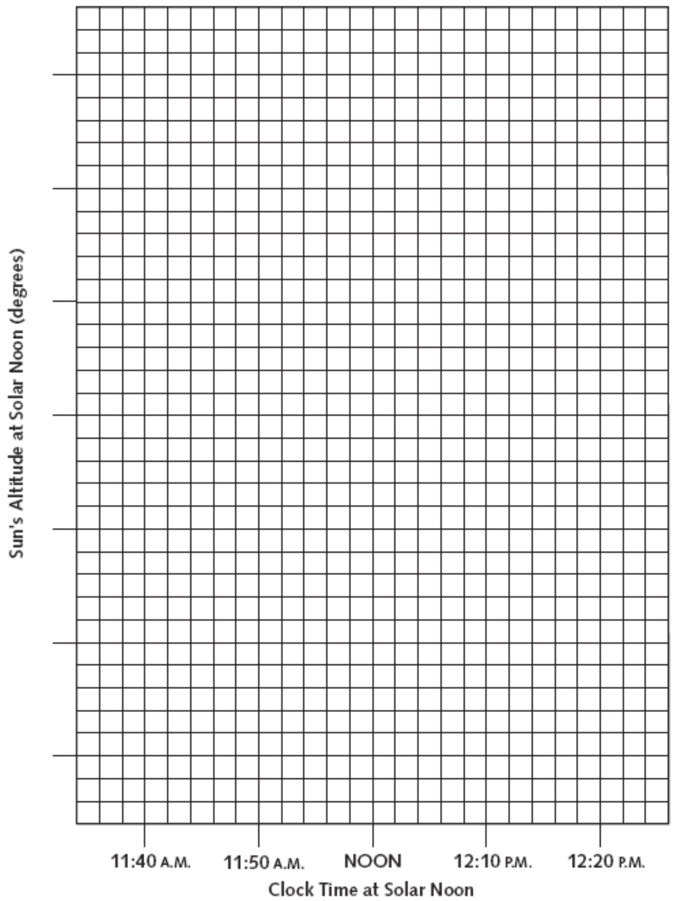
Lab Skills and Objectives

- **Graph an analemma**
- **Compare the altitude of the sun on different dates**
- **Identify the seasons during which solar time is ahead of and behind clock time**

Solar Noon Data Table				
Date	**Latitude where sun is overhead**	**Angular distance from overhead sun**	**Altitude of sun at solar noon**	**Clock time at solar noon**
Jan 10	22.1° S			12:07
Jan 20	20.3° S			12:11
Jan 30	17.9° S			12:13
Feb 10	14.6° S			12:14
Feb 20	11.2° S			12:14
Mar 5	6.4° S			12:12
Mar 10	4.4° S			12:11
Mar 20	0.5° S			12:08
Mar 30	3.4° N			12:05
Apr 10	7.6° N			12:02
Apr 20	11.2° N			11:59
Apr 30	14.5° N			11:57
May 10	17.4° N			11:56
May 20	19.8° N			11:56
May 30	21.6° N			11:57
Jun 10	22.9° N			11:59
Jun 20	23.4° N			12:01
Jun 30	23.2° N			12:04
Jul 10	22.3° N			12:05
Jul 20	20.8° N			12:06
Jul 30	18.7° N			12:06
Aug 10	15.8° N			12:05
Aug 20	12.7° N			12:04
Aug 30	9.3° N			12:01
Sep 10	5.3° N			11:57
Sep 20	1.4° N			11:54
Sep 30	2.5° S			11:50
Oct 10	6.3° S			11:47
Oct 20	10.0° S			11:45
Oct 30	13.5° S			11:44
Nov 10	16.9° S			11:44
Nov 20	19.5° S			11:46
Nov 30	21.5° S			11:49
Dec 10	22.8° S			11:53
Dec 20	23.4° S			11:57
Dec 30	23.2° S			12:02

Analysis and Conclusions

1. Based on your analemma, is the sun ever overhead at your latitude?
2. On your analemma, what is the maximum altitude of the sun? On what date does this maximum altitude occur?
3. On the date you gave in Question 2, at what latitude was the sun directly overhead at solar noon? What is the name of the imaginary circle around Earth very near this latitude? What season begins in the Northern Hemisphere on the this date?
4. On your analemma, what is the minimum altitude of the sun? On what date does the minimum altitude occur?
5. On the date you gave for Question 4, at what latitude was the sun directly overhead at solar noon? What is the name of the imaginary circle around Earth close to this latitude? What season begins in the Northern Hemisphere on this date?
6. Find the two dates when the sun is overhead closest to the equator at solar noon. Name the seasons that begin near each of these dates.
7. On your analemma, find the dates you listed for Question 6. How does apparent solar time relate to the clock time on these dates?
8. During which two seasons is apparent solar time ahead of clock time? During which two seasons is apparent solar time behind clock time?


Sun's Altitude at Solar Noon (degrees)
11:40 A.M.
11:50 A.M.
NOON
12:10 P.M.
12:20 P.M.
Clock Time at Solar Noon