CHAPTER THREE

The Motion of the Moon

The moon is the earth's large natural satellite and its closest neighbor in space. As such it has been used as a source for the cause of love (moonstruck) and madness (lunacy). The moon has been used in plays and poems to express man's awareness of his place in the universe of space and time. In the middle of the 20th century, the moon became the target of man's first adventure into outer space. In spite of this interest in the moon, the majority of people today know little about its motion through the sky.

The motion of the moon, as seen projected against the background stars of the celestial sphere, is eastward along a great circle that is inclined 5° 08′ with respect to the ecliptic. The motion of the moon will therefore closely parallel the motion of the sun through the zodiac constellations. The angular rate at which the moon moves along its projected orbit is much faster than the angular rate that the sun moves along the ecliptic. The sidereal period of the moon is $27.^{d}3217$ ($27^{d}7^{h}43^{m}11.5^{s}$). This is the time it takes the moon to complete one revolution (360°) with respect to the background stars. This means that the moon moves eastward along its path at an average rate of 13°.2 per day with respect to the background stars. Since the sun appears to move an average of 1° per day in the same eastward direction, the moon will appear to move eastward through the background stars at an average rate of 12°.2 per day with respect to the sun. It will take the moon $29^{d}.5306$ ($29^{d}12^{h}44^{m}2^{s}.8$) to move 360° and gain one lap on the sun. This is the synodic (coming together) period of the moon. The moon's nightly motion is easily discernible to an observer since it appears to move through an arc equal to its mean angular diameter of 31′5″ in roughly one hour.

The true orbit of the moon is an ellipse with the earth at the major foci point. The Keplerian motion of the moon about the earth will cause it to change its angular rate of motion and apparent angular diameter during the month. When the moon is near perigee, its closest approach to the earth, it will appear to move through the background stars at its fastest angular rate and exhibit its largest apparent diameter. When the moon is near apogee, its farthest distance from the earth, it will appear to move at its slowest angular rate and exhibit its smallest angular diameter. Changes or deviations in the orbital motion of the moon are caused by the gravitational effects of the other masses in the solar system. The greatest deviations, or perturbations, are caused by the sun. These perturbations require the statistics of the moon's orbit to be stated in qualified terms, thus the usually given distances of the moon at perigee (221,463 miles) and apogee (252,710 miles) will vary from month to month depending upon the relative positions of the earth and moon with respect to the sun. Perturbations due to the sun will also cause the inclination of the orbit with respect to the celestial equator to vary between 4°57′ and 5°20′.

The lunar orbit will cross the ecliptic at two diametrically opposite points. The position on the ecliptic where the moon appears to cross in going from south of the ecliptic to north is referred to as the ascending (☊) node. The position on the ecliptic where the moon appears to cross in going from north to south of the ecliptic is referred to as the descending (☋) node. The two nodal points are connected by an imaginary line that passes through the earth and is called the line of nodes. The ascending and descending nodes of the lunar orbit are analogous to the March and September equinox points on the ecliptic. A perturbation of the moon's orbit by the sun causes the two nodal points to slowly move westward along the ecliptic. The line of nodes will complete one 360° westward movement around the ecliptic in 18.6 years. This motion of the nodal points is referred to as the "regression of nodes." This means that the lunar ascending and descending nodes are moving westward at a rate of approximately 1°.5 per draconic or nodical period. Since the nodes are moving westward, the moon will complete one 360° revolution with respect to one of its nodes before it completes one 360° revolution with respect to the background stars. The draconic period of 27.2122 days will therefore be shorter than the lunar sidereal period. Since the westward regression of the lunar nodes causes the moon to move such that it crosses the ecliptic 1°.5 westward of its previous crossing, the moon does not move in a closed orbit with respect to the earth.

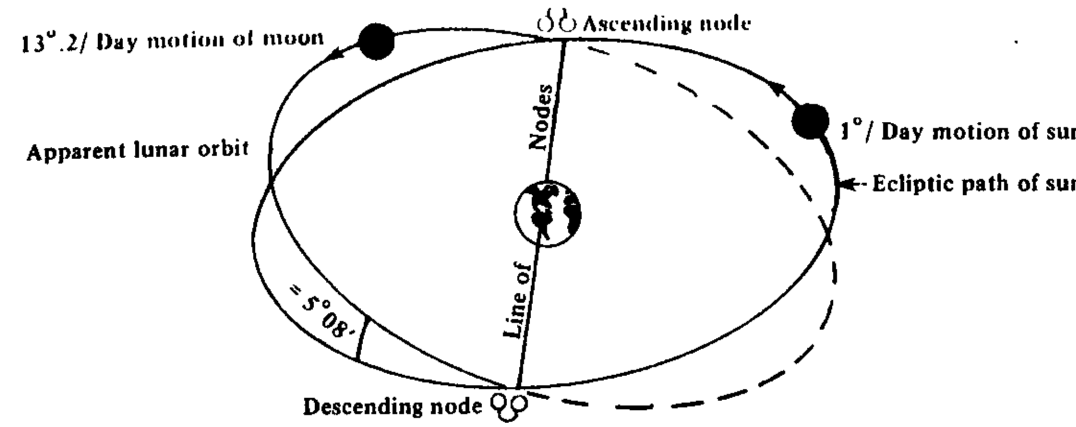

Figure 35. The inclination of the lunar orbit.

The gravitational effect of the sun on the moon will also cause the moon to change its velocity in different parts of its orbit. The result is to cause the major axis of the moon's orbit (line of apsides) to move 360° eastward in the lunar orbital plane in a period of 8.85 years. This means that the position in the sky where the moon reaches perigee will move eastward at an angular rate of approximately 3° per anomalistic or perigee period. Since the line of apsides is moving eastward, the moon will complete one 360° revolution with respect to the background stars before it completes one 360° revolution with respect to its perigee position. The anomalistic period of 27.5546 days will therefore be longer than the lunar sidereal period.

The above considerations of the lunar orbit should help to convince the reader that the mathematical application of the laws of gravity to the theory of the motion of the moon is a very complex problem.

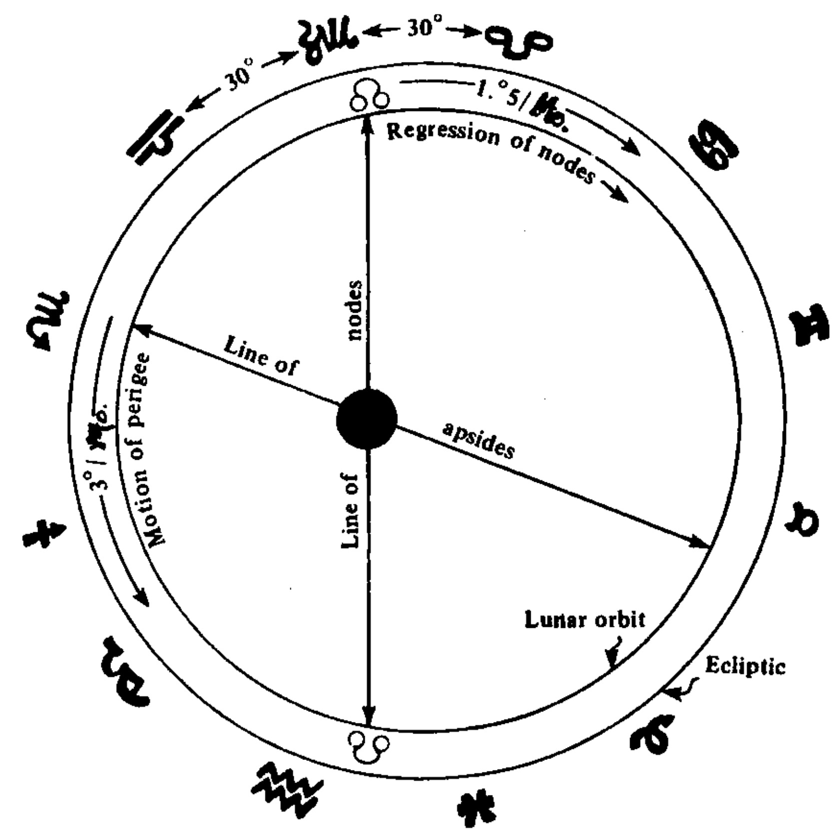

Figure 36. The projected lunar orbit.

The most conspicuous observation of the moon is that its appearance changes from night to night. The changes in the shape of the lighted part of the moon as seen from the earth are called the phases of the moon. The visibility of the moon, as seen from the earth, is due to the reflection of incident light from the sun. The moon would be a much brighter object in the sky if it were a better reflector. The ratio of the intensity of the light reflected from the moon to the intensity of the light incident upon the moon is called the albedo of the moon. The value of the albedo of the moon is 0.07 which means that the lunar surface reflects 7% of the sunlight it receives and absorbs 93% of the sunlight it receives.

The reason that the moon exhibits the phenomena of phasing was well understood by the earliest astronomers. Figure 37 shows the moon at various positions during its synodic period as it is seen from north of the solar system. The diagram also shows the view of the moon that is seen by an earth observer for each of the moon positions.

When the moon is in conjunction with the sun, that is when the moon is between the earth and the sun, the dark side of the moon is facing the earth and we have the invisible new phase. As the moon moves 12°.2 per day eastward from the position of the sun it will appear as a waxing (growing) crescent. The crescent will be growing from west to east across the moon. Since the moon is to the east of the sun, it will appear, in the early evening hours, above the western horizon. Soon after the new phase the moon will appear as a thin crescent engulfing a faint lunar disk. This is referred to as the "old moon in the new moon's arms". The light coming from the night side of the moon is reflected "earthshine" or light that has been reflected from the earth to the moon and back to the earth. The moon will continue to move east of the sun and the crescent will continue to grow until the moon reaches eastern quadrature. At this position in its orbit, the

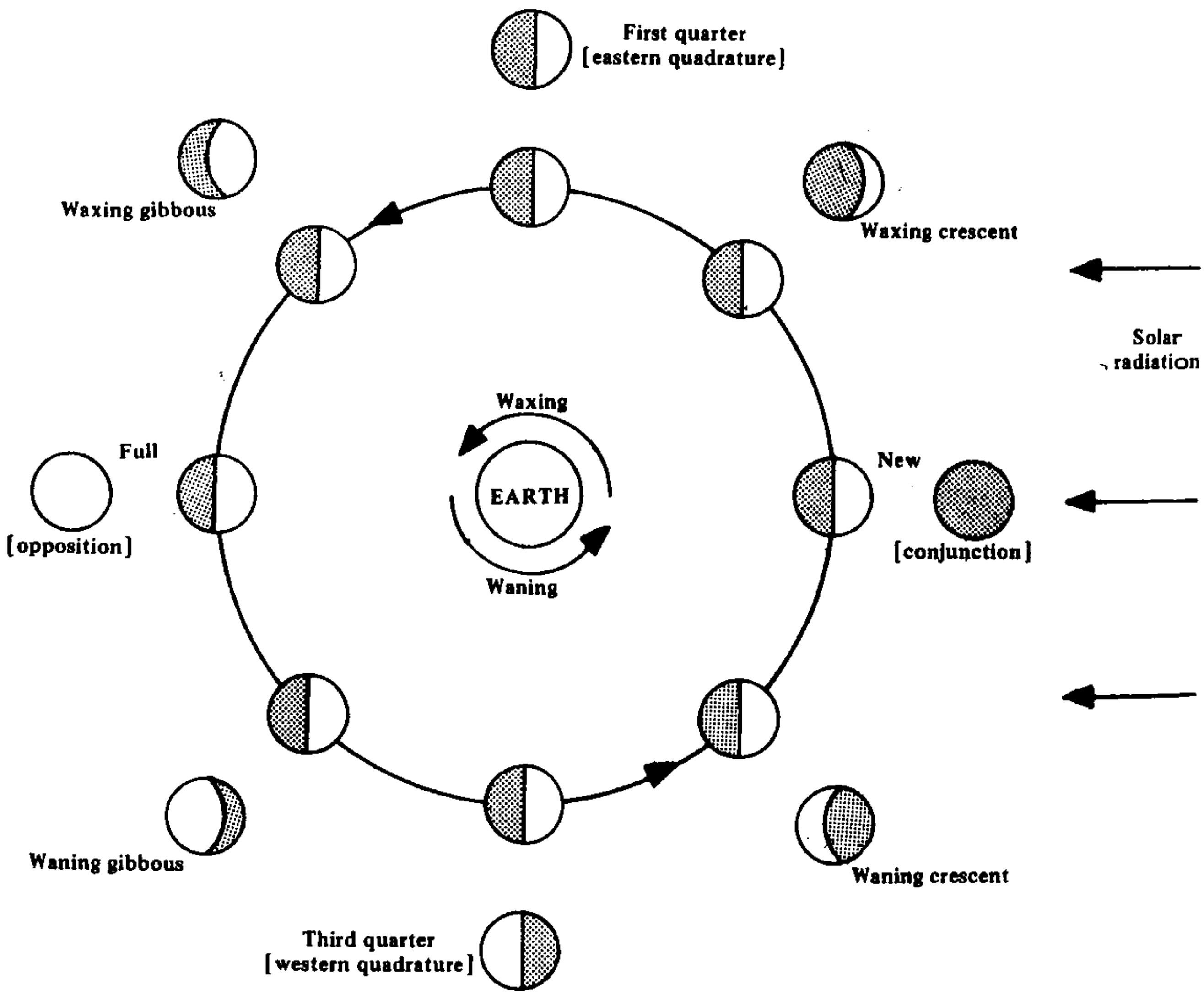

Figure 37. The phases of the moon.

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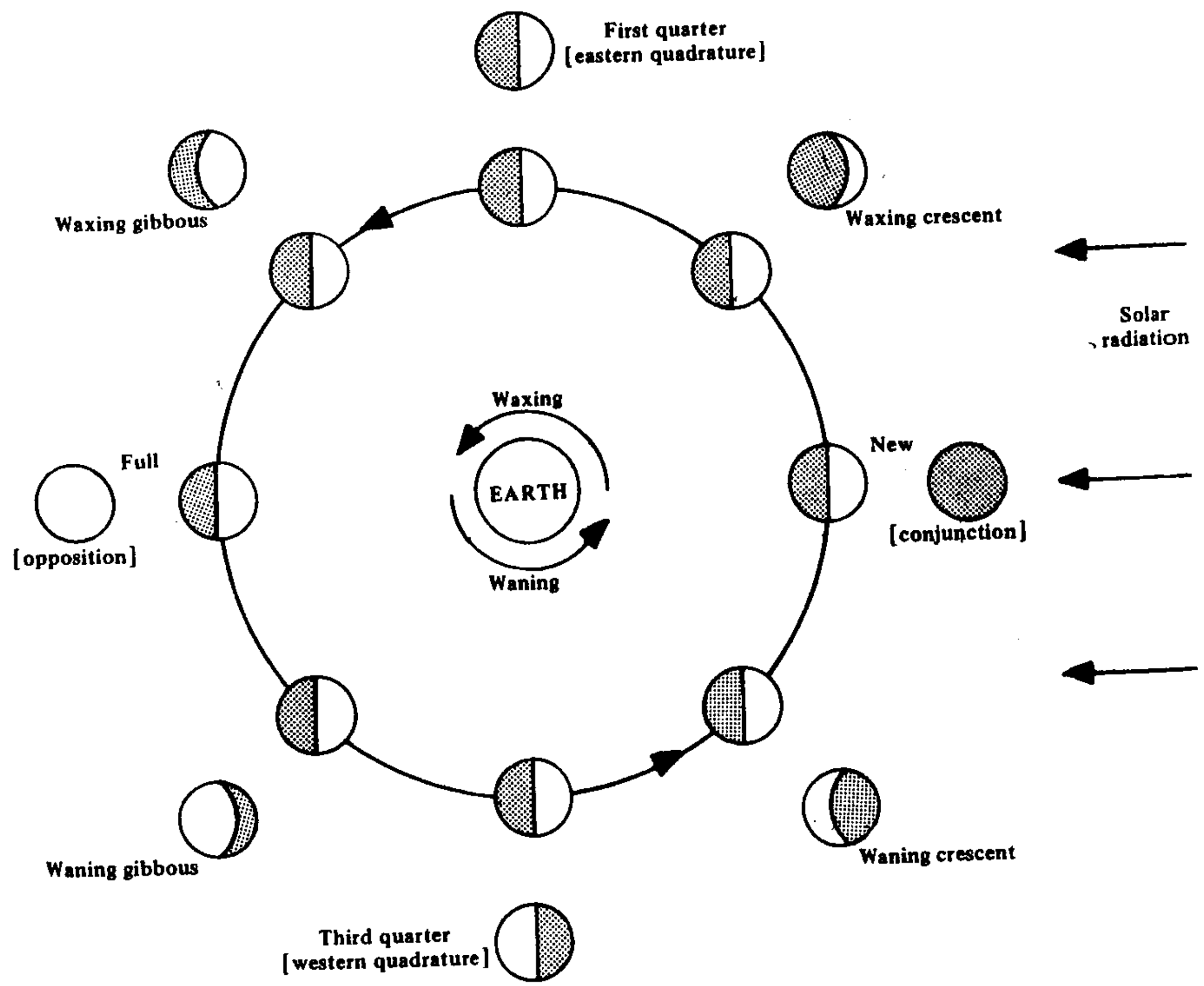


Figure 37. The phases of the moon.

moon will be 90° to the east of the sun. It will be seen from the earth as a half illuminated hemisphere. The western half of the moon will be illuminated. The moon is at first quarter because one-fourth of a synodic period has elapsed since the time of new moon.

The first quarter moon will cross the observer's meridian around the time of sunset. At successive sunsets, the position of the moon will be closer to the eastern horizon and the moon will appear as a waxing gibbous moon. A gibbous moon is one in which the dividing line between the day and night side of the moon, called the terminator, allows more than fifty per cent, but not one hundred per cent, of the moon to be visible to an earth observer. The moon will continue to move to the east and the lighted portion will continue to grow until the moon is in opposition, 180° from the sun. The moon will now be "full". It will be seen as a fully lighted disk in the evening sky.

The full moon will rise in the east as the sun sets in the west. The full moon will also set in the west as the sun rises in the east. After the full moon the phases will be repeated in a reverse order. The moon will continue to move eastward but now it will appear as a waning (paling) gibbous moon until it reaches western quadrature. At this position in its orbit, the moon will be 90° to the west of the sun. It will be seen from the earth as a half illuminated hemisphere. Since the terminator and the night part of the moon will move from west to east across the lunar disk, the eastern half of the moon will now be illuminated. The moon is at third quarter because three quarters of a synodic period have elapsed since the time of new moon.

The third quarter moon will cross the observer's meridian around the time of sunrise since it is now 90° to the west of the sun. At successive sunrises, the position of the moon will be closer to the eastern horizon and the moon will appear as a waning crescent. The early morning crescent will get thinner and thinner until the moon is in conjunction with the sun once again. The entire cycle from new moon to new moon takes $29^d.5$ or one synodic period. The synodic period of the moon is the time between occurrences of a particular configuration, such as new moon to new moon, or the time it takes the moon to gain one 360° lap on the sun.

The moon rises in the east and sets in the west at some time each day. This is due to the rotation of the earth. If the moon did not have its own motion with respect to the background stars, it would rise, set and cross the observer's meridian four minutes earlier each night. This would also be due to the rotation of the earth. The eastward motion of the moon with respect to the sun and stars causes it to appear in a different part of the sky at a given time. It also causes the time of moonrise and moonset to be retarded or delayed each day by an average of 50 minutes. In one synodic period ($29^d.5$) the moon loses one 360° lap on the sun with respect to meridian crossings. The lap is equivalent to the loss of a 24 hour mean solar day. The average apparent lunar day is therefore

$$\frac{29.5 \text{ solar days}}{(29.5 - 1) \text{ lunar days}}$$

of a day longer than the 24 hour mean solar day.

$$\frac{24 \text{ hours}}{\text{solar day}} \times \frac{29.5 \text{ solar days}}{(29.5 - 1) \text{ lunar days}} = \frac{24.84 \text{ hours}}{\text{lunar day}} = 24^h50^m$$

The average length of an apparent lunar day is therefore 24^h50^m. This causes the time of moonrise and moonset to be delayed an average of 50 minutes each day.

There are several factors that cause the time of delay of moonrise, moonset and the meridian crossing of the moon to vary throughout the year. The elliptical orbit of the moon causes its eastward angular rate to vary according to the position of the moon in its orbit. When the moon is near apogee, its contribution to the delay will be less than when it is near perigee. Since the lunar orbit is inclined to the celestial equator, its projected eastward motion on the celestial equator will vary. When the moon is in that part of its orbit which is near the solar equinox points, its projected motion will be less than when it is near the solstice points and the inclination's contribution to the total delay will be less. The latitude of the observer will also affect the time of delay of moonrise and moonset. At latitudes other than the equator, the moon will rise and set at angles that are oblique to the horizon.

The eastward motion of the moon will require varying amounts of apparent westward rotation of the celestial sphere in order to bring the moon back to its horizon position. This can be demonstrated for the intermediate north latitudes by the "harvest moon" of autumn and the Easter moon of spring.

Figure 38 (a) illustrates the conditions for the harvest moon effect. In the autumn, the full moon will be near the March equinox point on the celestial sphere. The moon's orbit, like the ecliptic, will be at a relatively low angle with respect to the horizon. The 13°.2 motion of the moon will make a small change in the position of the moon, below the horizon, from the time of moonrise on one night to that same time the following night. The delay in moonrise from one night to the next will therefore be a minimum. The full moon that occurs near the time of the September equinox, will have a minimum delay in the time of moonrise from night to night. This will cause the near full moon to slowly rise above the horizon in the early evening sky for several evenings, in late September or early October. Since the extra light

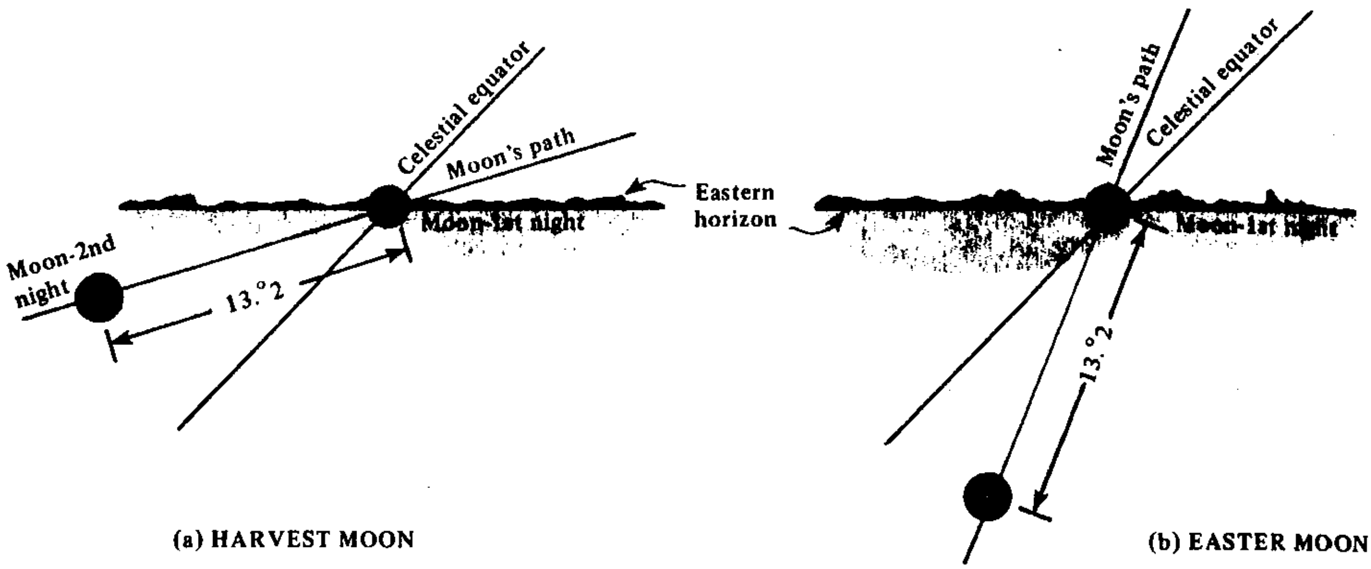


Figure 38. The autumn and spring full moon.

was to the great advantage of the harvester, the full moon nearest the autumnal equinox came to be known as the harvest moon. The next full moon is sometimes referred to as the "Hunter's Moon."

Figure 38 (b) illustrates the conditions for the Easter moon effect. In the spring, the full moon will be near the September equinox point on the celestial sphere. The moon's orbit will be at a relatively high angle with respect to the horizon. In this situation, the 13°.2 motion of the moon will cause a maximum change in the position of the moon, below the horizon, from the time of moonrise on one night to that same time the following night. The full moon that occurs near the time of the March equinox will have a maximum delay in the time of moonrise from night to night. This will cause the near full moon to be seen for only a few nights in the evening sky. Table 8 shows the change in moonrise delay as a function of latitude for a harvest moon and an Easter moon.

TABLE 8
Moonrise Delay as a Function of Latitude

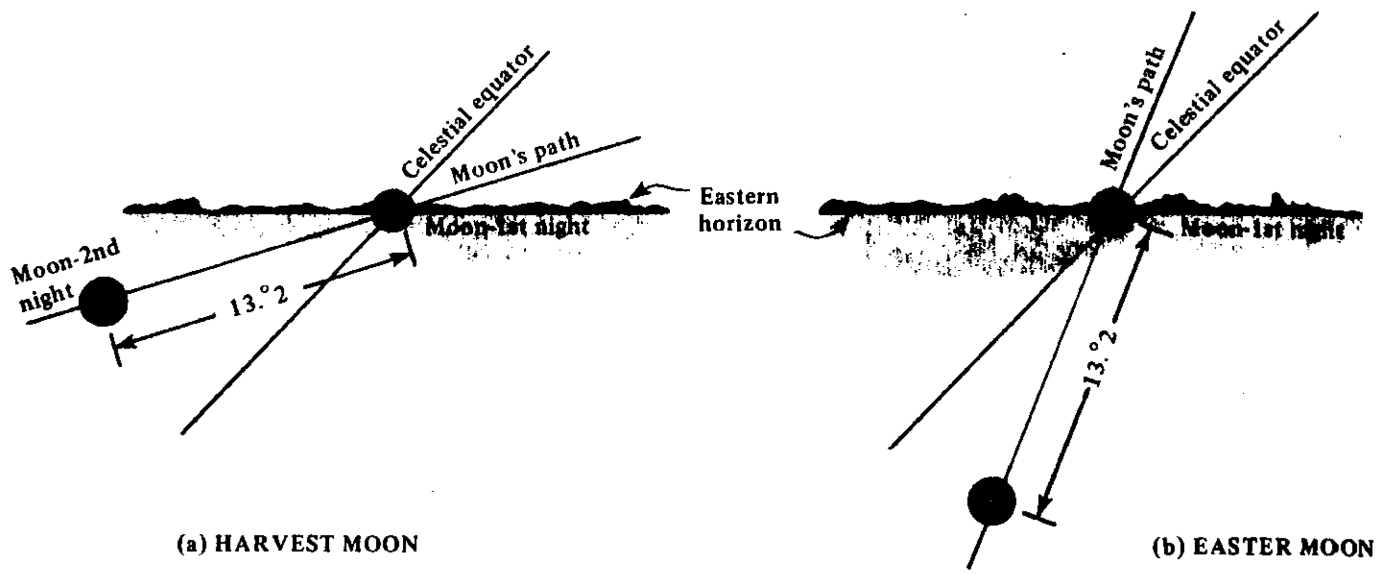
Latitude	Minimum Delay[1]	Maximum Delay[2]
	Min	Min
30°	35	59
35°	32	61
40°	28	64
45°	24	68
50°	19	73
55°	13	82
60°	5	88

1. Full moon 1 day after September equinox
2. Full moon 2 days before March equinox

The time of day and the place in the sky where the moon is visible will change with the phase of the moon. Figure 39 illustrates the sky position of different moon ages at the time of sunset or sunrise.

At the time of sunset, the waxing crescent moon will be visible in the western sky. Each night the moon will be higher in the sky than the night before and each night the moon will set at a later time than the night before. The first quarter moon will be on the meridian at the time of sunset. The moon will now set approximately six hours after the sun.

The waxing gibbous moon will be seen in the eastern sky during the late afternoon and at the time of sunset. It will



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The time of day and the place in the sky where the moon is visible will change with the phase of the moon. Figure 39 illustrates the sky position of different moon ages at the time of sunset or sunrise.

At the time of sunset, the waxing crescent moon will be visible in the western sky. Each night the moon will be higher in the sky than the night before and each night the moon will set at a later time than the night before. The first quarter moon will be on the meridian at the time of sunset. The moon will now set approximately six hours after the sun.

The waxing gibbous moon will be seen in the eastern sky during the late afternoon and at the time of sunset. It will remain visible for most of the night since it sets each morning closer to the time of sunrise. The full moon will rise at the time of sunset and remain above the horizon until the time of sunrise.

The waning gibbous moon will rise later and later each night and set later and later after sunrise the next day. The waning gibbous moon can often be seen in the morning western sky. The third quarter moon will rise approximately six hours after sunset and will be seen on the meridian at the time of sunrise.

The waning crescent moon will be seen in the eastern sky at the time of sunrise. Each morning the crescent will be thinner and closer to the eastern horizon. After the new moon, a waxing crescent moon will again appear in the early evening western sky and the cycle will be repeated. The crescent moon can be observed within 24 hours of the time of new moon. In favorable situations it can be seen much closer to the time of conjunction. The best conditions for first seeing a young crescent occur after a conjunction that has taken place between noon and sunset and near the date of the March equinox.

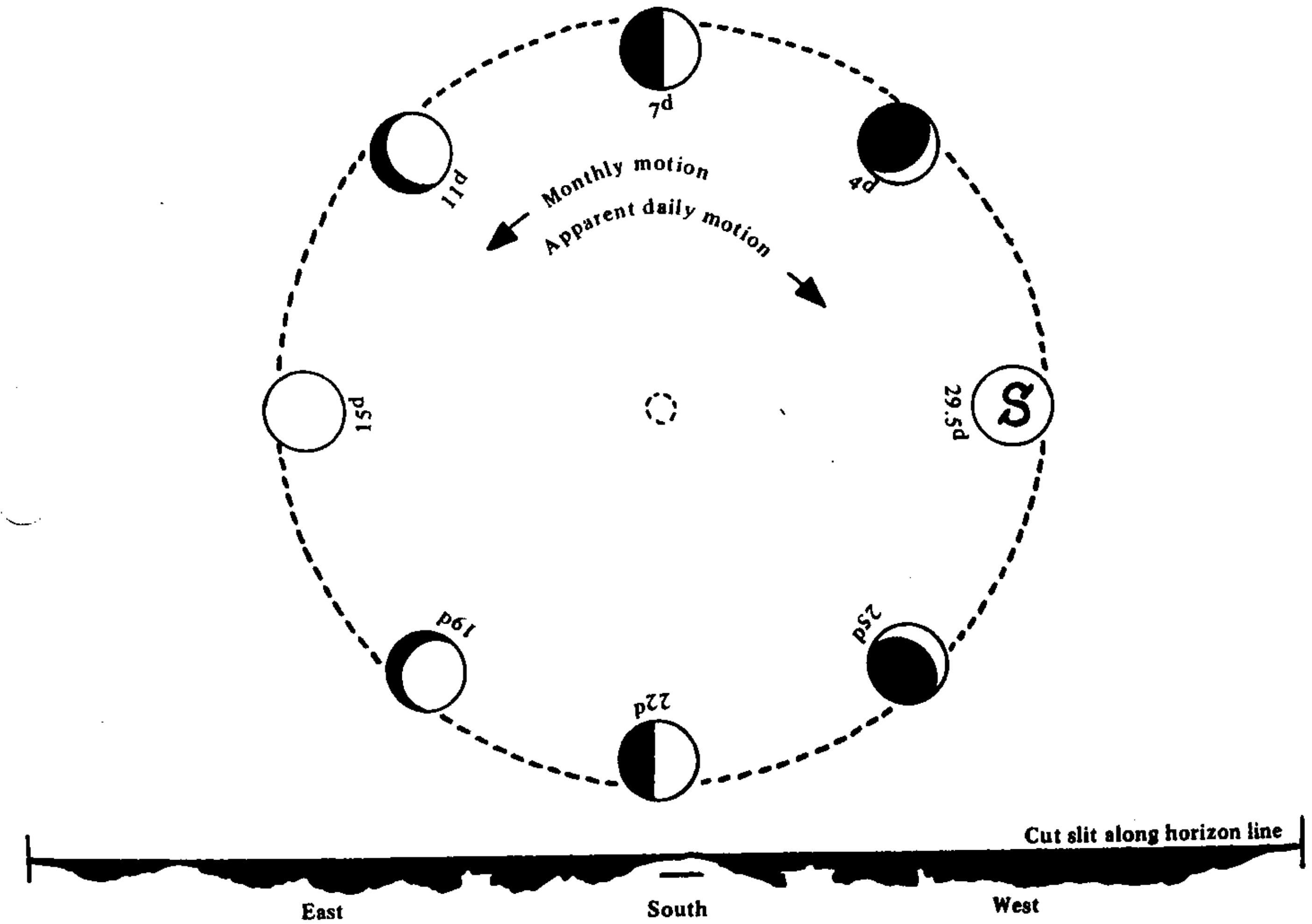
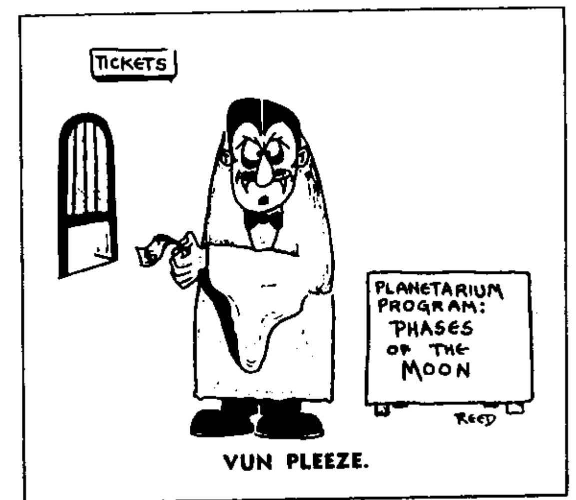


Figure 39. The daily motion of the moon.

Instructions:
1. Completely cut out the above "phases of the moon" circle. Cut out the center circle.
2. Cut along the above horizon slit.
3. Slip the "phases of the moon": circle behind the horizon slit. Place a brass fastener through the slit above "south" and the center of the circle.
4. The positions of the waxing moon at sunset are illustrated when the sun is placed at the western horizon.
5. The positions of the waning moon at sunrise are illustrated when the sun is placed at the eastern horizon.
6. Movement of the circle in the direction of the apparent daily motion will illustrate the daily changing position of the moon for each phase.

The altitude of the moon as it crosses the meridian will change with the phase of the moon and the season of the year. The new moon will cross the meridian within five degrees of the altitude of the sun. The new moon would therefore be low in the sky near the time of the December solstice and high in the sky near the time of the June solstice. The full moon, since it will be on the ecliptic 180° away from the sun, will be high in the sky near the time of the December solstice and low in the sky near the time of the June solstice. The new and full moon will cross the meridian within five degrees of the altitude of the sun near the time of the March and September equinoxes.

If the moon is observed, through even a part of its synodic period, it will soon become apparent that it orbits the earth, so that the same side is always facing the earth. During the course of the month we always see some part of the "man in the moon". This is because the lunar rotation period is equal to the lunar period of revolution. Figure 40 illustrates the rotation and revolution of the moon during one sidereal period. The moon probably rotated much faster than it revolved at some time in the distant past. The gravitational effect of the earth caused solid tides on the moon that are analogous to the ocean tides that we experience on the earth. Over millions of years the moon tides caused the lunar period of rotation to slow down. Today the tidal bulges are pointing toward and away from the earth and the lunar rotational period has become equal to the lunar period of revolution by what is called tidal coupling.



Courtesy of *Griffith Observer.*

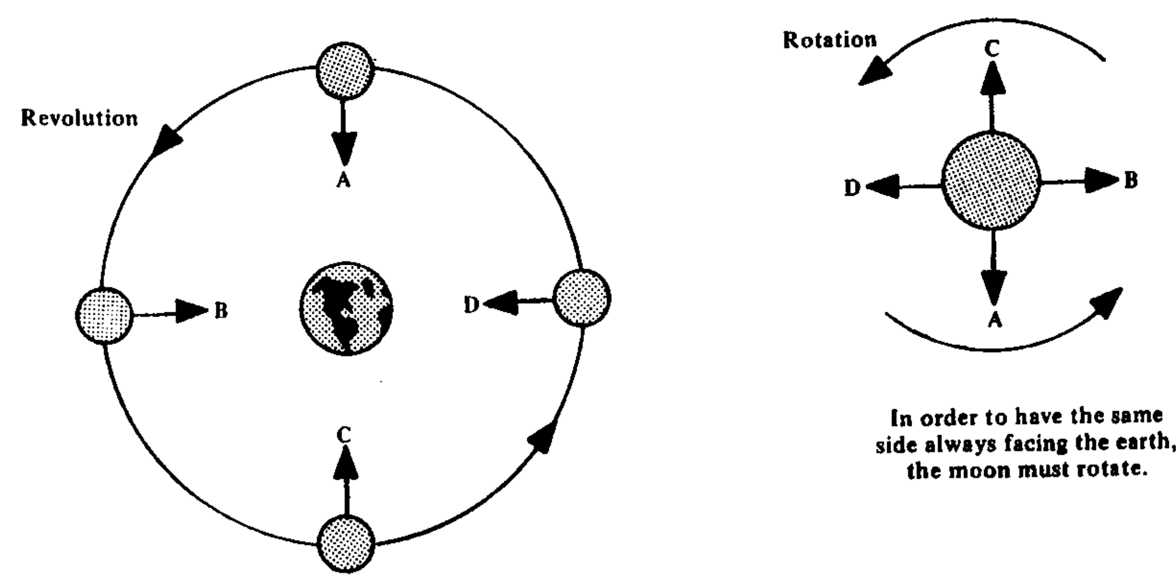
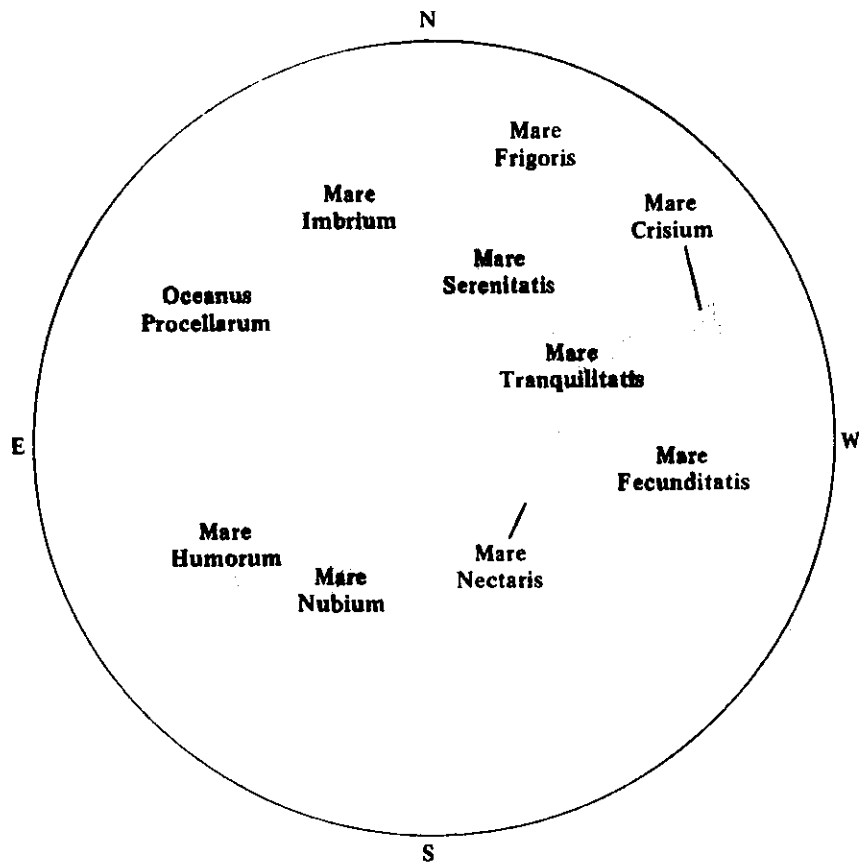


Figure 40. The rotation and revolution of the moon.

Figure 41 is a lunar map that identifies the features that make the "man in the moon" that is seen with the unaided eye. This is the side of the moon that always faces the earth. The dark areas that are seen on the lunar sphere were mistakenly termed maria or "seas" (singular-mare) by Galileo in the early seventeenth century. These mare areas, which cover approximately 40% of the lunar surface visible from earth, are broad, relatively smooth, circular plains that are several hundred kilometers in radius. The different mare were named according to the superstition that the first quarter moon promoted good weather while the last quarter moon promoted bad weather. The western hemisphere of the moon, which is visible at the first quarter, contains the seas of Serenity, Tranquillity and Fertility. The eastern hemisphere of the moon, which is visible at third quarter, contains the Seas of Showers and Clouds and the Ocean of Storms.

Archeological discoveries indicate that as long as 20,000 years ago, man was observing the phases of the moon in what was probably an attempt to develop a calendar that would accurately mark the seasons. The "month" was probably the first unit of time developed after the day.

Explanations to account for the dark lunar markings have provided a rich mythological heritage. The "man in the moon" has been at some time and place a lady with long, flowing hair as well as other creatures. The Chinese, for instance, have a tradition which depicts the lunar markings as a rabbit standing on its hind legs as it pounds rice in a bowl.



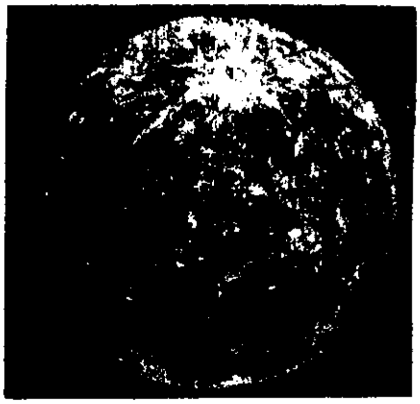


Figure 41. Moon map for unaided observation.

Naked Eye Features

A. Mare Crisium—Sea of Crisis
B. Mare Fecunditatis—Sea of Fertility
C. Mare Frigoris—Sea of Cold
D. Mare Humorum—Sea of Humors
E. Mare Imbrium—Sea of Showers
F. Mare Nectaris—Sea of Nectar
G. Mare Nubium—Sea of Clouds
H. Mare Serenitatis—Sea of Serenity
I. Mare Tranquilitatis—Sea of Tranquillity
J. Oceanus Procellarum—Ocean of Storms