# CHAPTER 15

# NAVIGATIONAL ASTRONOMY

## PRELIMINARY CONSIDERATIONS

### 1500. Definitions

The science of Astronomy studies the positions and motions of celestial bodies and seeks to understand and explain their physical properties. Navigational astronomy deals with their coordinates, time, and motions. The symbols commonly recognized in navigational astronomy are given in Table 1500.

**Celestial Bodies**

| | | | |
|---|---|---|---|
| ☉ | Sun | ⊙̲ ☾̲ | Lower limb |
| ☾ | Moon | ⊖ ☾̶ | Center |
| ☿ | Mercury | ⊙̄ ☾̄ | Upper limb |
| ♀ | Venus | ● | New moon |
| ⊕ | Earth | ◐ | Crescent moon |
| ♂ | Mars | ◐ | First quarter |
| ♃ | Jupiter | ◐ | Gibbous moon |
| ♄ | Saturn | ○ | Full moon |
| ♅ | Uranus | ◑ | Gibbous moon |
| ♆ | Neptune | ◑ | Last quarter |
| ♇ | Pluto | ◑ | Crescent moon |
| ☆ | Star | | |
| ☆-P | Star-planet altitude correction (altitude) | | |

**Miscellaneous Symbols**

| | | | |
|---|---|---|---|
| y | Years | ✳ | Interpolation impractical |
| m | Months | ° | Degrees |
| d | Days | ′ | Minutes of arc |
| h | Hours | ″ | Seconds of arc |
| m | Minutes of time | ☌ | Conjunction |
| s | Seconds of time | ☍ | Opposition |
| ▬ | Remains below horizon | □ | Quadrature |
| ▭ | Remains above horizon | ☊ | Ascending node |
| //// | Twilight all night | ☋ | Descending node |

**Signs of the Zodiac**

| | | | |
|---|---|---|---|
| ♈ | Aries (vernal equinox) | ♎ | Libra (autumnal equinox) |
| ♉ | Taurus | ♏ | Scorpius |
| ♊ | Gemini | ♐ | Sagittarius |
| ♋ | Cancer (summer solstice) | ♑ | Capricornus (winter solstice) |
| ♌ | Leo | ♒ | Aquarius |
| ♍ | Virgo | ♓ | Pisces |

*Table 1500. Astronomical symbols.*

**1501. The Celestial Sphere**

Looking at the sky on a dark night, imagine that celestial bodies are located on the inner surface of a vast, Earth-centered sphere (Figure 1501). This model is useful since we are only interested in the relative positions and motions of celestial bodies on this imaginary surface. Understanding the concept of the celestial sphere is most important when discussing sight reduction in Chapter 20.

**1502. Relative and Apparent Motion**

Celestial bodies are in constant motion. There is no fixed position in space from which one can observe absolute motion. Since all motion is relative, the position of the observer must be noted when discussing planetary motion. From the Earth we see apparent motions of celestial bodies on the celestial sphere. In considering how planets follow their orbits around the Sun, we assume a hypothetical observer at some distant point in space. When discussing the rising or setting of a body on a local horizon, we must locate the observer at a particular point on the Earth because the setting Sun for one observer may be the rising Sun for another.

Motion on the celestial sphere results from the motions in space of both the celestial body and the Earth. Without special instruments, motions toward and away from the Earth cannot be discerned.

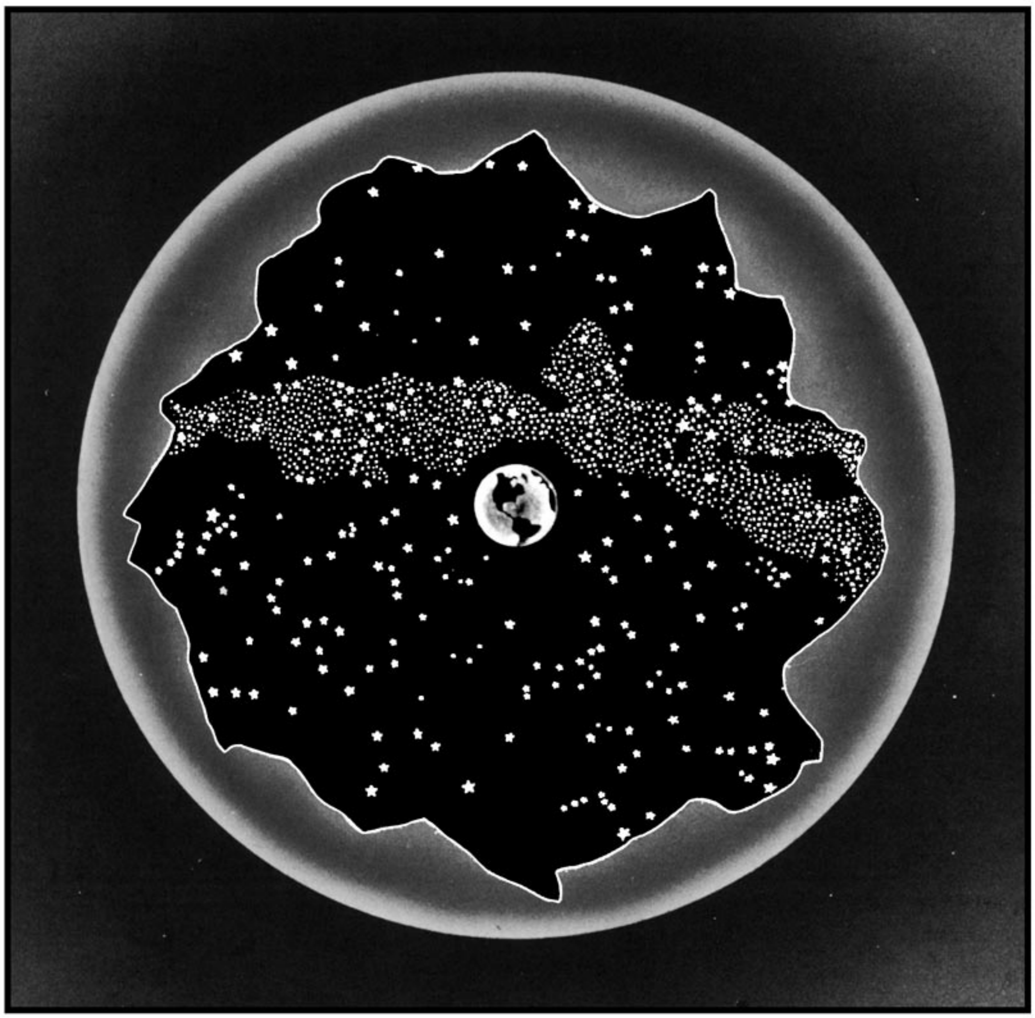


*Figure 1501. The celestial sphere.*

### 1503. Astronomical Distances

We can consider the celestial sphere as having an infinite radius because distances between celestial bodies are so vast. For an example in scale, if the Earth were represented by a ball one inch in diameter, the Moon would be a ball one-fourth inch in diameter at a distance of 30 inches, the Sun would be a ball nine feet in diameter at a distance of nearly a fifth of a mile, and Pluto would be a ball half an inch in diameter at a distance of about seven miles. The nearest star would be one-fifth of the actual distance to the Moon.

Because of the size of celestial distances, it is inconvenient to measure them in common units such as the mile or kilometer. The mean distance to our nearest neighbor, the Moon, is 238,855 miles. For convenience this distance is sometimes expressed in units of the equatorial radius of the Earth: 60.27 Earth radii.

Distances between the planets are usually expressed in terms of the **astronomical unit (AU)**, the mean distance between the Earth and the Sun. This is approximately 92,960,000 miles. Thus the mean distance of the Earth from the Sun is 1 AU. The mean distance of Pluto, the outermost known planet in our solar system, is 39.5 A.U. Expressed in astronomical units, the mean distance from the Earth to the Moon is 0.00257 A.U.

Distances to the stars require another leap in units. A commonly-used unit is the **light-year**, the distance light travels in one year. Since the speed of light is about $1.86 \times 10^5$ miles per second and there are about $3.16 \times 10^7$ seconds per year, the length of one light-year is about $5.88 \times 10^{12}$ miles. The nearest stars, Alpha Centauri and its neighbor Proxima, are 4.3 light-years away. Relatively few stars are less than 100 light-years away. The nearest galaxies, the Clouds of Magellan, are 150,000 to 200,000 light years away. The most distant galaxies observed by astronomers are several billion light years away.

### 1504. Magnitude

The relative brightness of celestial bodies is indicated by a scale of stellar **magnitudes**. Initially, astronomers divided the stars into 6 groups according to brightness. The 20 brightest were classified as of the first magnitude, and the dimmest were of the sixth magnitude. In modern times, when it became desirable to define more precisely the limits of magnitude, a first magnitude star was considered 100 times brighter than one of the sixth magnitude. Since the fifth root of 100 is 2.512, this number is considered the **magnitude ratio**. A first magnitude star is 2.512 times as bright as a second magnitude star, which is 2.512 times as bright as a third magnitude star,. A second magnitude is $2.512 \times 2.512 = 6.310$ times as bright as a fourth magnitude star. A first magnitude star is $2.512^{20}$ times as bright as a star of the 21st magnitude, the dimmest that can be seen through a 200-inch telescope.

Brightness is normally tabulated to the nearest 0.1 magnitude, about the smallest change that can be detected by the unaided eye of a trained observer. All stars of magnitude 1.50 or brighter are popularly called “first magnitude” stars. Those between 1.51 and 2.50 are called “second magnitude” stars, those between 2.51 and 3.50 are called “third magnitude” stars, etc. Sirius, the brightest star, has a magnitude of –1.6. The only other star with a negative magnitude is Canopus, –0.9. At greatest brilliance Venus has a magnitude of about –4.4. Mars, Jupiter, and Saturn are sometimes of negative magnitude. The full Moon has a magnitude of about –12.6, but varies somewhat. The magnitude of the Sun is about –26.7.

## THE UNIVERSE

### 1505. The Solar System

The **Sun**, the most conspicuous celestial object in the sky, is the central body of the solar system. Associated with it are at least nine principal **planets** and thousands of asteroids, comets, and meteors. Some planets have moons.

### 1506. Motions of Bodies of the Solar System

Astronomers distinguish between two principal motions of celestial bodies. Rotation is a spinning motion about an axis within the body, whereas revolution is the motion of a body in its orbit around another body. The body around which a celestial object revolves is known as that body’s primary. For the satellites, the primary is a planet. For the planets and other bodies of the solar system, the primary is the Sun. The entire solar system is held together by the gravitational force of the Sun. The whole system revolves around the center of the Milky Way galaxy (Article 1515), and the Milky Way is in motion relative to its neighboring galaxies.

The hierarchies of motions in the universe are caused by the force of gravity. As a result of gravity, bodies attract each other in proportion to their masses and to the inverse square of the distances between them. This force causes the planets to go around the sun in nearly circular, elliptical orbits.

In each planet’s orbit, the point nearest the Sun is called the **perihelion**. The point farthest from the Sun is called the **aphelion**. The line joining perihelion and aphelion is called the **line of apsides**. In the orbit of the Moon, the point nearest the Earth is called the **perigee**, and that point farthest from the Earth is called the **apogee**. Figure 1506 shows the orbit of the Earth (with exaggerated eccentricity), and the orbit of the Moon around the Earth.

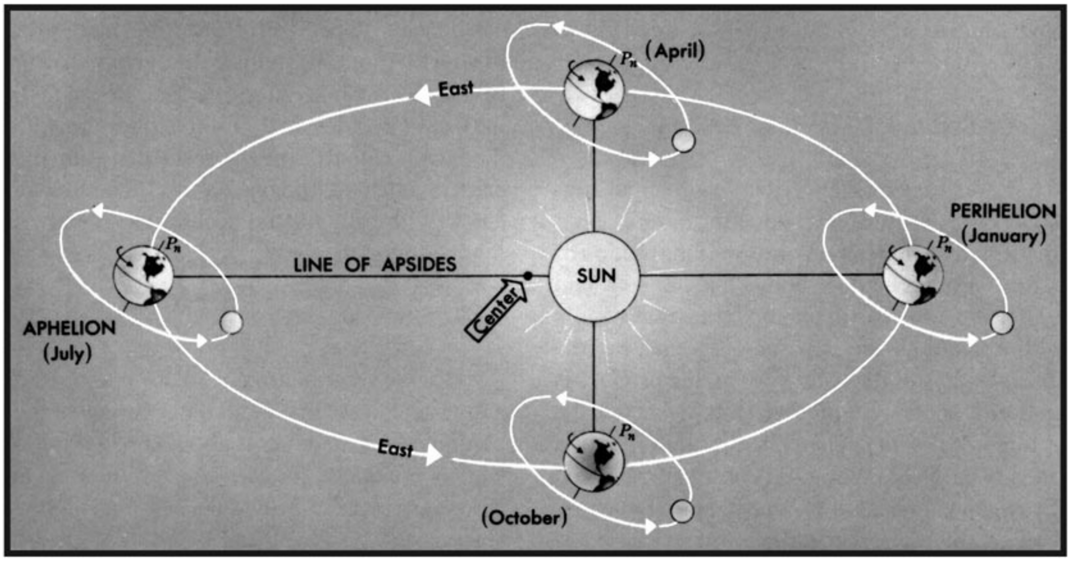



*Figure 1506. Orbits of the Earth and Moon.*

### 1507. The Sun

The Sun dominates our solar system. Its mass is nearly a thousand times that of all other bodies of the solar system combined. Its diameter is about 865,000 miles. Since it is a star, it generates its own energy through a thermonuclear reaction, thereby providing heat and light for the entire solar system.

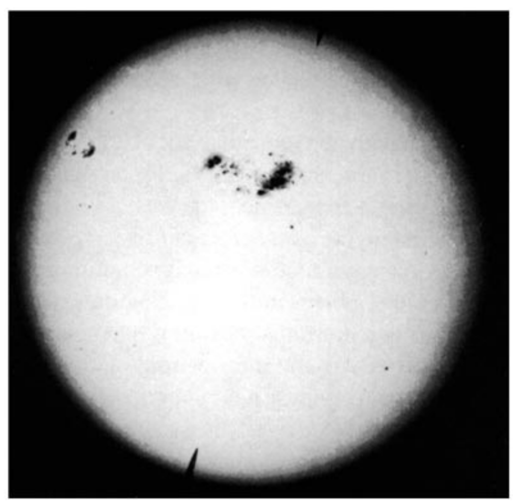
The distance from the Earth to the Sun varies from 91,300,000 at perihelion to 94,500,000 miles at aphelion. When the Earth is at perihelion, which always occurs early in January, the Sun appears largest, 32.6' of arc in diameter. Six months later at aphelion, the Sun's apparent diameter is a minimum of 31.5'.

Observations of the Sun's surface (called the **photosphere**) reveal small dark areas called **sunspots**. These are areas of intense magnetic fields in which relatively cool gas (at 7000°F.) appears dark in contrast to the surrounding hotter gas (10,000°F.). Sunspots vary in size from perhaps 50,000 miles in diameter to the smallest spots that can be detected (a few hundred miles in diameter). They generally appear in groups. See Figure 1507. Large sunspots can be seen without a telescope if the eyes are protected.

Surrounding the photosphere is an outer **corona** of very hot but tenuous gas. This can only be seen during an eclipse of the Sun, when the Moon blocks the light of the photosphere.

The Sun is continuously emitting charged particles, which form the **solar wind**. As the solar wind sweeps past the Earth, these particles interact with the Earth's magnetic field. If the solar wind is particularly strong, the interaction can produce magnetic storms which adversely affect radio signals on the Earth. At such times the auroras are particularly brilliant and widespread.

The Sun is moving approximately in the direction of Vega at about 12 miles per second, or about two-thirds as fast as the Earth moves in its orbit around the Sun.



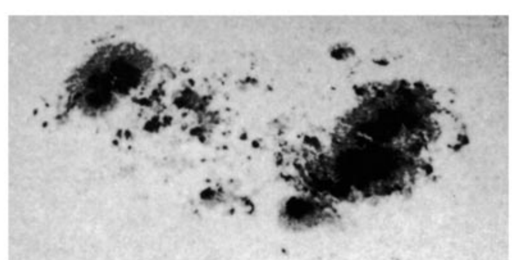


*Figure 1507. Whole solar disk and an enlargement of the great spot group of April 7, 1947. Courtesy of Mt. Wilson and Palomar Observatories.*

### 1508. The Planets

The principal bodies orbiting the Sun are called **planets**. Nine principal planets are known: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto. Of these, only four are commonly used for celestial navigation: Venus, Mars, Jupiter, and Saturn.

Except for Pluto, the orbits of the planets lie in nearly the same plane as the Earth's orbit. Therefore, as seen from the Earth, the planets are confined to a strip of the celestial sphere near the **ecliptic**, which is the intersection of the mean plane of the Earth's orbit around the Sun with the celestial sphere.

The two planets with orbits smaller than that of the Earth are called **inferior planets**, and those with orbits larger than that of the Earth are called **superior planets**. The four planets nearest the Sun are sometimes called the inner planets, and the others the outer planets. Jupiter, Saturn, Uranus, and Neptune are so much larger than the others that they are sometimes classed as major planets. Uranus is barely visible to the unaided eye; Neptune and Pluto are not visible without a telescope.

Planets can be identified in the sky because, unlike the stars, they do not twinkle. The stars are so distant that they are point sources of light. Therefore the stream of light from a star is easily scattered in the atmosphere, causing the twinkling effect. The naked-eye planets, however, are close enough to present perceptible disks. The broader stream of light from a planet is not easily disrupted.

The orbits of many thousands of tiny minor planets or asteroids lie chiefly between the orbits of Mars and Jupiter. These are all too faint to be seen with the naked eye.

### 1509. The Earth

In common with other planets, the Earth **rotates** on its axis and **revolves** in its orbit around the Sun. These motions are the principal source of the daily apparent motions of other celestial bodies. The Earth's rotation also causes a deflection of water and air currents to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Because of the Earth's rotation, high tides on the open sea lag behind the meridian transit of the Moon.

For most navigational purposes, the Earth can be considered a sphere. However, like the other planets, the Earth is approximately an **oblate spheroid**, or **ellipsoid of revolution**, flattened at the poles and bulged at the equator. See Figure 1509. Therefore, the polar diameter is less than the equatorial diameter, and the meridians are slightly elliptical, rather than circular. The dimensions of the Earth are recomputed from time to time, as additional and more precise measurements become available. Since the Earth is not exactly an ellipsoid, results differ slightly when equally precise and extensive measurements are made on different parts of the surface.

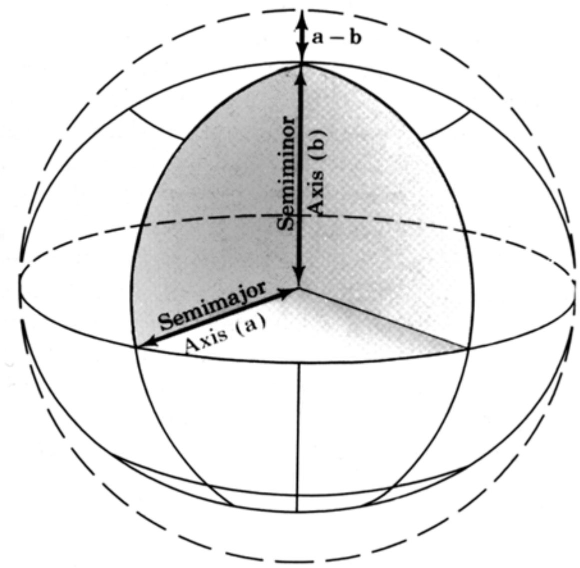



*Figure 1509. Oblate spheroid or ellipsoid of revolution.*

### 1510. Inferior Planets

Since Mercury and Venus are inside the Earth's orbit, they always appear in the neighborhood of the Sun. Over a period of weeks or months, they appear to oscillate back and forth from one side of the Sun to the other. They are seen either in the eastern sky before sunrise or in the western sky after sunset. For brief periods they disappear into the Sun's glare. At this time they are between the Earth and Sun (known as **inferior conjunction**) or on the opposite side of the Sun from the Earth (**superior conjunction**). On rare occasions at inferior conjunction, the planet will cross the face of the Sun as seen from the Earth. This is known as a **transit of the Sun**.

When Mercury or Venus appears most distant from the Sun in the evening sky, it is at greatest eastern elongation. (Although the planet is in the western sky, it is at its easternmost point from the Sun.) From night to night the planet will approach the Sun until it disappears into the glare of twilight. At this time it is moving between the Earth and Sun to inferior conjunction. A few days later, the planet will appear in the morning sky at dawn. It will gradually move away from the Sun to western elongation, then move back toward the Sun. After disappearing in the morning twilight, it will move behind the Sun to superior conjunction. After this it will reappear in the evening sky, heading toward eastern elongation.

Mercury is never seen more than about 28° from the Sun. For this reason it is not commonly used for navigation. Near greatest elongation it appears near the western horizon after sunset, or the eastern horizon before sunrise. At these times it resembles a first magnitude star and is sometimes reported as a new or strange object in the sky. The interval during which it appears as a morning or evening star can

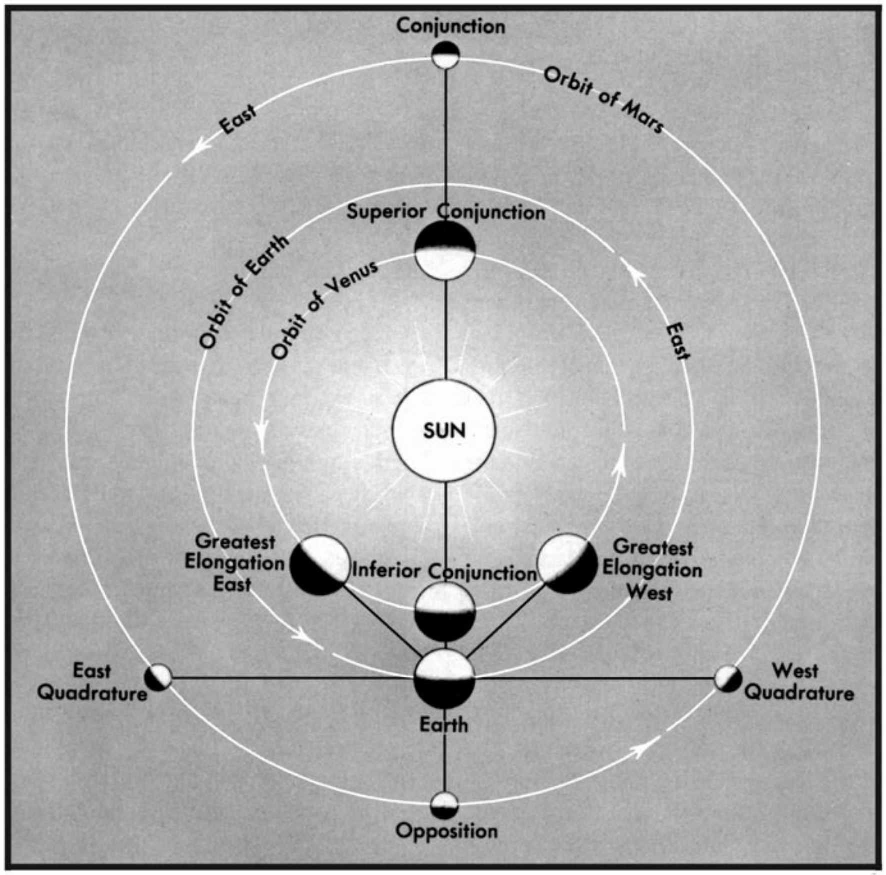



*Figure 1510. Planetary configurations.*

vary from about 30 to 50 days. Around inferior conjunction, Mercury disappears for about 5 days; near superior conjunction, it disappears for about 35 days. Observed with a telescope, Mercury is seen to go through phases similar to those of the Moon.

Venus can reach a distance of 47° from the Sun, allowing it to dominate the morning or evening sky. At maximum brilliance, about five weeks before and after inferior conjunction, it has a magnitude of about –4.4 and is brighter than any other object in the sky except the Sun and Moon. At these times it can be seen during the day and is sometimes observed for a celestial line of position. It appears as a morning or evening star for approximately 263 days in succession. Near inferior conjunction Venus disappears for 8 days; around superior conjunction it disappears for 50 days. When it transits the Sun, Venus can be seen by the naked eye as a small dot about the size of a group of Sunspots. Through strong binoculars or a telescope, Venus can be seen to go through a full set of phases.

### 1511. Superior Planets

As planets outside the Earth's orbit, the superior planets are not confined to the proximity of the Sun as seen from the Earth. They can pass behind the Sun (conjunction), but they cannot pass between the Sun and the Earth. Instead we see them move away from the Sun until they are opposite the Sun in the sky (**opposition**). When a superior planet is near conjunction, it rises and sets approximately with the Sun and is thus lost in the Sun's glare. Gradually it becomes visible in the early morning sky before sunrise. From day to day, it rises and sets earlier, becoming increasingly visible through the late night hours until dawn. Approaching opposition, the planet will rise in the late evening, until at opposition, it will rise when the Sun sets, be visible throughout the night, and set when the Sun rises.

Observed against the background stars, the planets normally move eastward in what is called **direct motion**. Approaching opposition, however, a planet will slow down, pause (at a stationary point), and begin moving westward (**retrograde motion**), until it reaches the next stationary point and resumes its direct motion. This is not because the planet is moving strangely in space. This relative, observed motion results because the faster moving Earth is catching up with and passing by the slower moving superior planet.

The superior planets are brightest and closest to the Earth at opposition. The interval between oppositions is known as the **synodic period**. This period is longest for the closest planet, Mars, and becomes increasingly shorter for the outer planets.

Unlike Mercury and Venus, the superior planets do not go through a full cycle of phases. They are always full or highly gibbous.

**Mars** can usually be identified by its orange color. It can become as bright as magnitude –2.8 but is more often between –1.0 and –2.0 at opposition. Oppositions occur at intervals of about 780 days. The planet is visible for about 330 days on either side of opposition. Near conjunction it is lost from view for about 120 days. Its two satellites can only be seen in a large telescope.

**Jupiter**, largest of the known planets, normally outshines Mars, regularly reaching magnitude –2.0 or brighter at opposition. Oppositions occur at intervals of about 400 days, with the planet being visible for about 180 days before and after opposition. The planet disappears for about 32 days at conjunction. Four satellites (of a total 16 currently known) are bright enough to be seen with binoculars. Their motions around Jupiter can be observed over the course of several hours.

**Saturn**, the outermost of the navigational planets, comes to opposition at intervals of about 380 days. It is visible for about 175 days before and after opposition, and disappears for about 25 days near conjunction. At opposition it becomes as bright as magnitude +0.8 to –0.2. Through good, high powered binoculars, Saturn appears as elongated because of its system of rings. A telescope is needed to examine the rings in any detail. Saturn is now known to have at least 18 satellites, none of which are visible to the unaided eye.

**Uranus**, **Neptune** and **Pluto** are too faint to be used for navigation; Uranus, at about magnitude 5.5, is faintly visible to the unaided eye.

### 1512. The Moon

The **Moon** is the only satellite of direct navigational interest. It revolves around the Earth once in about 27.3 days, as measured with respect to the stars. This is called the **sidereal month**. Because the Moon rotates on its axis with the same period with which it revolves around the Earth, the same side of the Moon is always turned toward the Earth. The cycle of phases depends on the Moon's revolution with respect to the Sun. This synodic month is approximately 29.53 days, but can vary from this average by up to a quarter of a day during any given month.

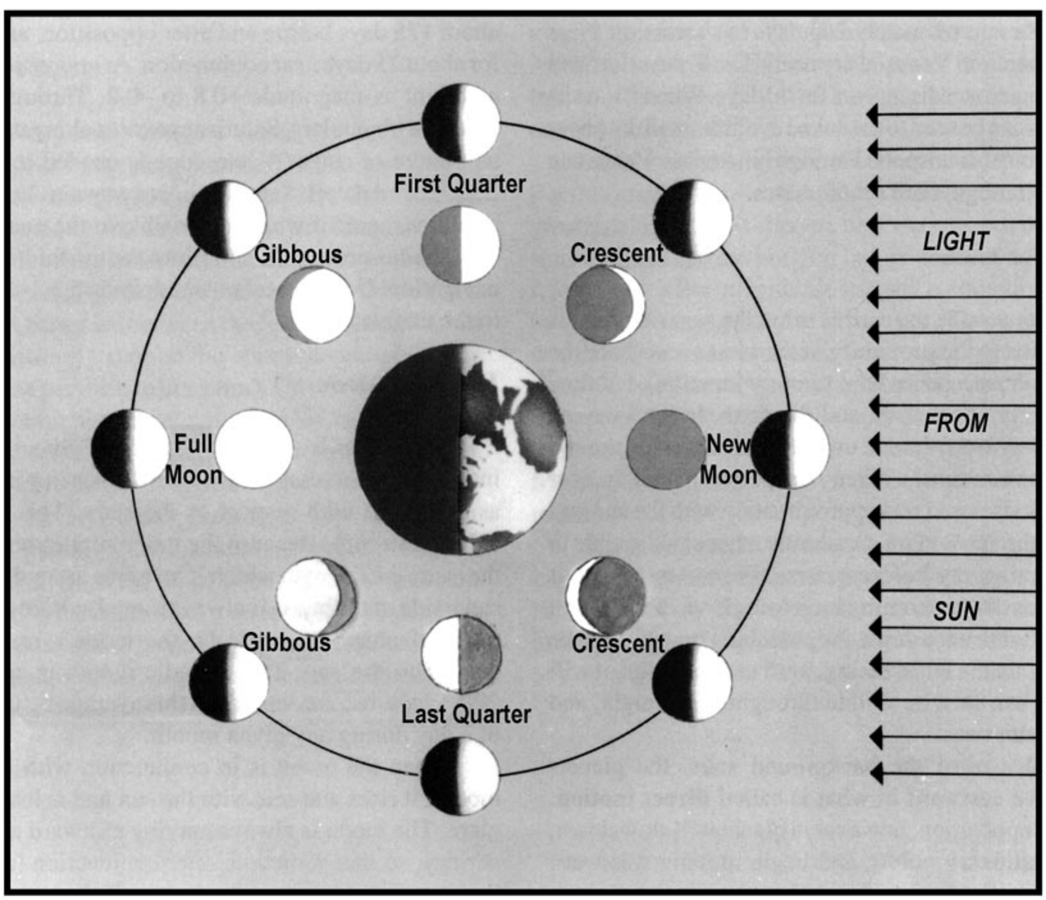



*Figure 1512. Phases of the Moon. The inner figures of the Moon represent its appearance from the Earth.*

When the Moon is in conjunction with the Sun (new Moon), it rises and sets with the Sun and is lost in the Sun's glare. The Moon is always moving eastward at about 12.2° per day, so that sometime after conjunction (as little as 16 hours, or as long as two days), the thin lunar crescent can be observed after sunset, low in the west. For the next couple of weeks, the Moon will **wax**, becoming more fully illuminated. From day to day, the Moon will rise (and set) later, becoming increasingly visible in the evening sky, until (about 7 days after new Moon) it reaches first quarter, when the Moon rises about noon and sets about midnight. Over the next week the Moon will rise later and later in the afternoon until full Moon, when it rises about sunset and dominates the sky throughout the night. During the next couple of weeks the Moon will **wane**, rising later and later at night. By last quarter (a week after full Moon), the Moon rises about midnight and sets at noon. As it approaches new Moon, the Moon becomes an increasingly thin crescent, and is seen only in the early morning sky. Sometime before conjunction (16 hours to 2 days before conjunction) the thin crescent will disappear in the glare of morning twilight.

At full Moon, the Sun and Moon are on opposite sides of the ecliptic. Therefore, in the winter the full Moon rises early, crosses the celestial meridian high in the sky, and sets late; as the Sun does in the summer. In the summer the full Moon rises in the southeastern part of the sky (Northern Hemisphere), remains relatively low in the sky, and sets along the southwestern horizon after a short time above the horizon.

At the time of the autumnal equinox, the part of the ecliptic opposite the Sun is most nearly parallel to the horizon. Since the eastward motion of the Moon is approximately along the ecliptic, the delay in the time of rising of the full Moon from night to night is less than at other times of the year. The full Moon nearest the autumnal equinox is called the **Harvest Moon**; the full Moon a month later is called the **Hunter's Moon**. See Figure 1512.

### 1513. Comets and Meteors

Although **comets** are noted as great spectacles of nature, very few are visible without a telescope. Those that become widely visible do so because they develop long, glowing tails. Comets are swarms of relatively small solid bodies held together by gravity. Around the nucleus, a gaseous head or coma and tail may form as the comet approaches the Sun. The tail is directed away from the Sun, so that it follows the head while the comet is approaching the Sun, and precedes the head while the comet is receding. The total mass of a comet is very small, and the tail is so thin that stars can easily be seen through it. In 1910, the Earth passed through the tail of Halley's comet without noticeable effect.

Compared to the well-ordered orbits of the planets, comets are erratic and inconsistent. Some travel east to west and some west to east, in highly eccentric orbits inclined at any angle to the ecliptic. Periods of revolution range from about 3 years to thousands of years. Some comets may speed away from the solar system after gaining velocity as they pass by Jupiter or Saturn.

The short-period comets long ago lost the gasses needed to form a tail. Long period comets, such as Halley's comet, are more likely to develop tails. The visibility of a comet depends very much on how close it approaches the Earth. In 1910, Halley's comet spread across the sky (Figure 1513). Yet when it returned in 1986, the Earth was not well situated to get a good view, and it was barely visible to the unaided eye.

**Meteors**, popularly called **shooting stars**, are tiny, solid bodies too small to be seen until heated to incandescence by air friction while passing through the Earth's atmosphere. A particularly bright meteor is called a **fireball**. One that explodes is called a **bolide**. A meteor that survives its trip through the atmosphere and lands as a solid particle is called a **meteorite**.

Vast numbers of meteors exist. An estimated average of some 1,000,000 meteors large enough to be seen enter the Earth's atmosphere each hour, and many times this number undoubtedly enter, but are too small to attract attention. The cosmic dust they create falls to earth in a constant shower.

**Meteor showers** occur at certain times of the year when the Earth passes through **meteor swarms**, the scattered remains of comets that have broken up. At these times the number of meteors observed is many times the usual number.

A faint glow sometimes observed extending upward approximately along the ecliptic before sunrise and after sunset has been attributed to the reflection of Sunlight from quantities of this material. This glow is called **zodiacal light**. A faint glow at that point of the ecliptic 180° from the Sun is called the **gegenschein** or **counterglow**.

### 1514. Stars

**Stars** are distant Suns, in many ways resembling our own. Like the Sun, stars are massive balls of gas that create their own energy through thermonuclear reactions.

Although stars differ in size and temperature, these differences are apparent only through analysis by astronomers. Some differences in color are noticeable to the unaided eye. While most stars appear white, some (those of lower temperature) have a reddish hue. In Orion, blue Rigel and red Betelgeuse, located on opposite sides of the belt, constitute a noticeable contrast.

The stars are not distributed uniformly around the sky. Striking configurations, known as **constellations**, were noted by ancient peoples, who supplied them with names and myths. Today astronomers use constellations—88 in all—to identify areas of the sky.

Under ideal viewing conditions, the dimmest star that can be seen with the unaided eye is of the sixth magnitude. In the entire sky there are about 6,000 stars of this

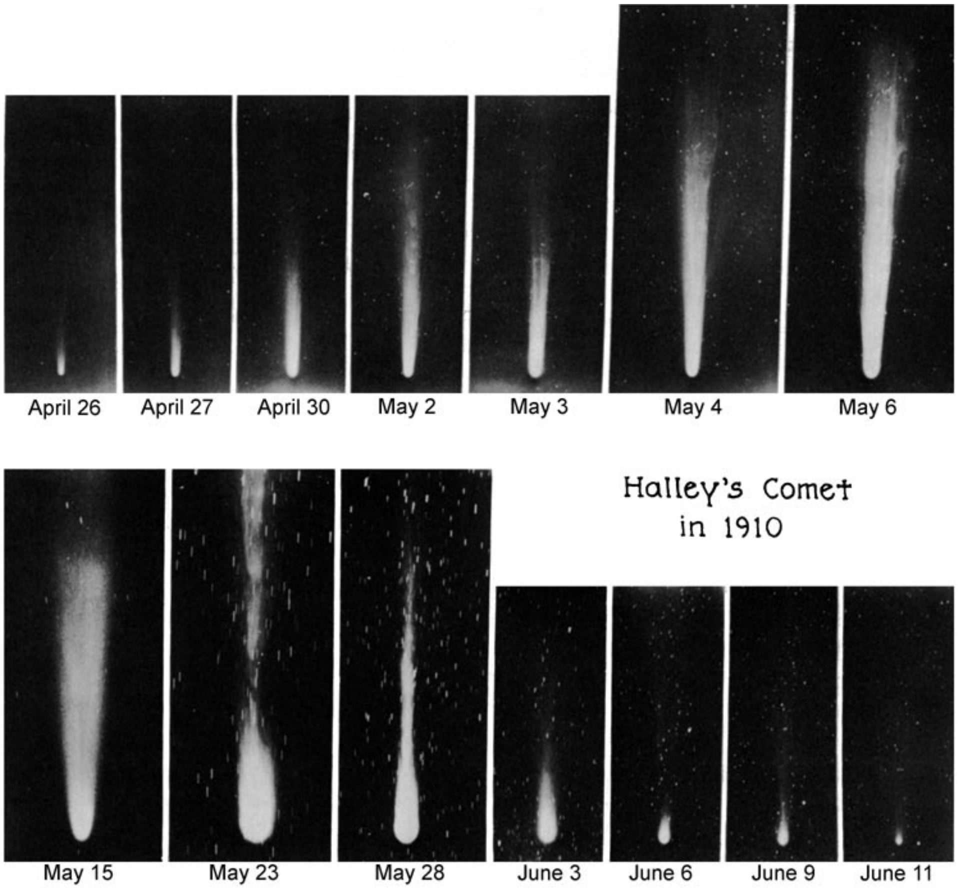



*Figure 1513. Halley's Comet; fourteen views, made between April 26 and June 11, 1910.*
*Courtesy of Mt. Wilson and Palomar Observatories.*

magnitude or brighter. Half of these are below the horizon at any time. Because of the greater absorption of light near the horizon, where the path of a ray travels for a greater distance through the atmosphere, not more than perhaps 2,500 stars are visible to the unaided eye at any time. However, the average navigator seldom uses more than perhaps 20 or 30 of the brighter stars.

Stars which exhibit a noticeable change of magnitude are called **variable stars**. A star which suddenly becomes several magnitudes brighter and then gradually fades is called a **nova**. A particularly bright nova is called a **supernova**.

Two stars which appear to be very close together are called a **double star**. If more than two stars are included in the group, it is called a **multiple star**. A group of a few dozen to several hundred stars moving through space together is called an **open cluster**. The Pleiades is an example of an open cluster. There are also spherically symmetric clusters of hundreds of thousands of stars known as **globular clusters**. The globular clusters are all too distant to be seen with the naked eye.

A cloudy patch of matter in the heavens is called a **nebula**. If it is within the galaxy of which the Sun is a part, it is called a **galactic nebula**; if outside, it is called an **extragalactic nebula**.

Motion of a star through space can be classified by its vector components. That component in the line of sight is called **radial motion**, while that component across the line of sight, causing a star to change its apparent position relative to the background of more distant stars, is called **proper motion**.

## 1515. Galaxies

A **galaxy** is a vast collection of clusters of stars and clouds of gas. In a galaxy the stars tend to congregate in groups called **star clouds** arranged in long spiral arms. The spiral nature is believed due to revolution of the stars about the center of the galaxy, the inner stars revolving more rapidly than the outer ones (Figure 1515).

The Earth is located in the Milky Way galaxy, a slowly spinning disk more than 100,000 light years in diameter. All the bright stars in the sky are in the Milky Way. However, the most dense portions of the galaxy are seen as the great, broad band that glows in the summer nighttime sky. When we look toward the constellation Sagittarius, we are looking toward the

*Figure 1515. Spiral nebula Messier 51, In Canes Venetici. Satellite nebula is NGC 5195.*
*Courtesy of Mt. Wilson and Palomar Observatories.*

center of the Milky Way, 30,000 light years away.

Despite their size and luminance, almost all other galaxies are too far away to be seen with the unaided eye. An exception in the northern hemisphere is the Great Galaxy (sometimes called the Great Nebula) in Andromeda, which appears as a faint glow. In the southern hemisphere, the Large and Small Magellanic Clouds (named after Ferdinand Magellan) are the nearest known neighbors of the Milky Way. They are approximately 1,700,000 light years distant. The Magellanic Clouds can be seen as sizable glowing patches in the southern sky.

## APPARENT MOTION

### 1516. Apparent Motion due to Rotation of the Earth

**Apparent motion** caused by the Earth's rotation is much greater than any other observed motion of celestial bodies. It is this motion that causes celestial bodies to appear to rise along the eastern half of the horizon, climb to maximum altitude as they cross the meridian, and set along the western horizon, at about the same point relative to due west as the rising point was to due east. This apparent motion along the daily path, or **diurnal circle**, of the body is approximately parallel to the plane of the equator. It would be exactly so if rotation of the Earth were the only motion and the axis of rotation of the Earth were stationary in space.

The apparent effect due to rotation of the Earth varies with the latitude of the observer. At the equator, where the equatorial plane is vertical (since the axis of rotation of the Earth is parallel to the plane of the horizon), bodies appear to rise and set vertically. Every celestial body is above the horizon approximately half the time. The celestial sphere as seen by an observer at the equator is called the right sphere, shown in Figure 1516a.

For an observer at one of the poles, bodies having constant declination neither rise nor set (neglecting precession of the equinoxes and changes in refraction), but circle the sky, always at the same altitude, making one complete trip around the horizon each day. At the North Pole the motion is clockwise, and at the South Pole it is counterclockwise. Approximately half the stars are always above the horizon and the other half never are. The parallel sphere at the poles is illustrated in Figure 1516b.

Between these two extremes, the apparent motion is a combination of the two. On this oblique sphere, illustrated in Figure 1516c, circumpolar celestial bodies remain above the horizon during the entire 24 hours, circling the elevated celestial pole each day. The stars of Ursa Major (the Big Dipper) and Cassiopeia are circumpolar for many observers in the United States.

An approximately equal part of the celestial sphere remains below the horizon during the entire day. For example, Crux is not visible to most observers in the United States. Other bodies rise obliquely along the eastern horizon, climb to maximum altitude at the celestial meridian, and set along the western horizon. The length of time above the horizon and the altitude at meridian transit vary with both the latitude of the observer and the declination of the body. At the polar circles of the Earth even the Sun becomes circumpolar. This is the land of the midnight Sun, where the Sun does not set during part of the summer and does not rise during part of the winter.

The increased obliquity at higher latitudes explains why days and nights are always about the same length in the tropics, and the change of length of the day becomes greater as latitude increases, and why twilight lasts longer in higher latitudes. Evening twilight starts at sunset, and morning twilight ends at sunrise. The darker limit of twilight occurs when the center of the Sun is a stated number of degrees below the celestial horizon. Three kinds of twilight are

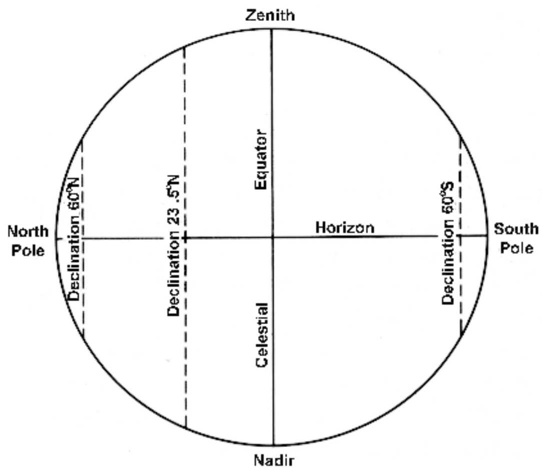



*Figure 1516a. The right sphere.*

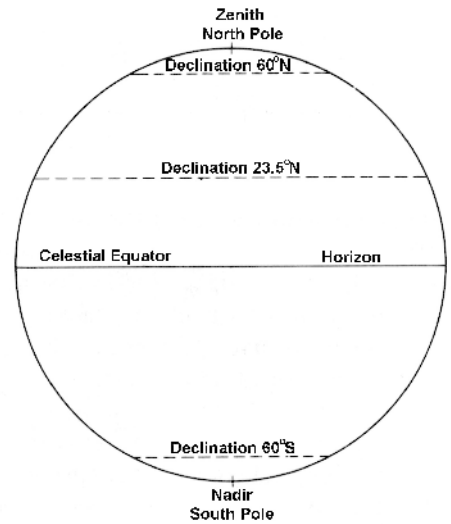



*Figure 1516b. The parallel sphere.*

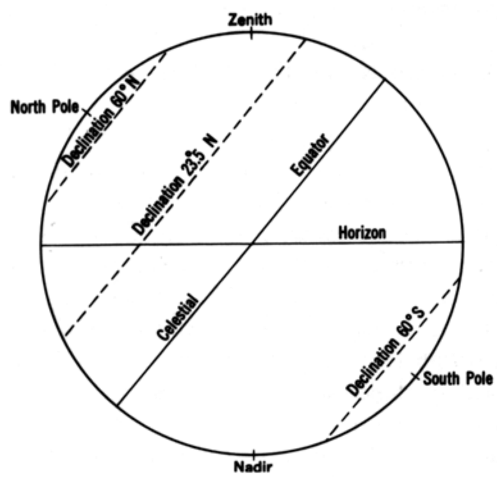



*Figure 1516c. The oblique sphere at latitude 40°N.*

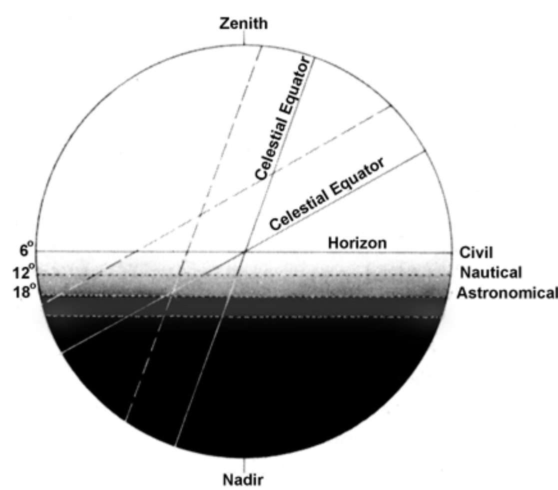



*Figure 1516d. The various twilight at latitude 20°N and latitude 60°N.*

| *Twilight* | *Lighter limit* | *Darker limit* | *At darker limit* |
|---|---|---|---|
| civil | –0°50' | –6° | Horizon clear; bright stars visible |
| nautical | –0°50' | –12° | Horizon not visible |
| astronomical | –0°50' | –18° | Full night |

*Table 1516. Limits of the three twilights.*

defined: civil, nautical and astronomical. See Table 1516.

The conditions at the darker limit are relative and vary considerably under different atmospheric conditions.

In Figure 1516d, the twilight band is shown, with the darker limits of the various kinds indicated. The nearly vertical celestial equator line is for an observer at latitude 20°N. The nearly horizontal celestial equator line is for an observer at latitude 60°N. The broken line in each case is the diurnal circle of the Sun when its declination is 15°N. The relative duration of any kind of twilight at the two latitudes is indicated by the portion of the diurnal circle between the horizon and the darker limit, although it is not directly proportional to the relative length of line shown since the projection is orthographic. The duration of twilight at the higher latitude is longer, proportionally, than shown. Note that complete darkness does not occur at latitude 60°N when the declination of the Sun is 15°N.

### 1517. Apparent Motion due to Revolution of the Earth

If it were possible to stop the rotation of the Earth so that the celestial sphere would appear stationary, the effects of the revolution of the Earth would become more noticeable. In one year the Sun would appear to make one complete trip around the Earth, from west to east. Hence, it would seem to move eastward a little less than 1° per day. This motion can be observed by watching the changing position of the Sun among the stars. But since both Sun and stars generally are not visible at the same time, a better way is to observe the constellations at the same time each night. On any night a star rises nearly four minutes earlier than on the previous night. Thus, the celestial sphere appears to shift westward nearly 1° each night, so that different constellations are associated with different seasons of the year.

Apparent motions of planets and the Moon are due to a combination of their motions and those of the Earth. If the rotation of the Earth were stopped, the combined apparent motion due to the revolutions of the Earth and other bodies would be similar to that occurring if both rotation and revolution of the Earth were stopped. Stars would appear nearly stationary in the sky but would undergo a small annual cycle of change due to aberration. The motion of the Earth in its orbit is sufficiently fast to cause the light from stars to appear to shift slightly in the direction of the Earth's motion. This is similar to the effect one experiences when walking in vertically-falling rain that appears to come from ahead due to the observer's own forward motion. The apparent direction of the light ray from the star is the vector difference of the motion of light and the motion of the Earth, similar to that of apparent wind on a moving vessel. This effect is most apparent for a body perpendicular to the line of travel of the Earth in its orbit, for which it reaches a maximum value of 20.5". The effect of aberration can be noted by comparing the coordinates (declination and sidereal hour angle) of various stars throughout the year. A change is observed in some bodies as the year progresses, but at the end of the year the values have returned almost to what they were at the beginning. The reason they do not return exactly is due to proper motion and precession of the equinoxes. It is also due to nutation, an irregularity in the motion of the Earth due to the disturbing effect of other celestial bodies, principally the Moon. Polar motion is a slight wobbling of the Earth about its axis of rotation and sometimes wandering of the poles. This motion, which does not exceed 40 feet from the mean position, produces slight variation of latitude and longitude of places on the Earth.

### 1518. Apparent Motion due to Movement of other Celestial Bodies

Even if it were possible to stop both the rotation and revolution of the Earth, celestial bodies would not appear stationary on the celestial sphere. The Moon would make one revolution about the Earth each sidereal month, rising in the west and setting in the east. The inferior planets would appear to move eastward and westward relative to the Sun, staying within the zodiac. Superior planets would appear to make one revolution around the Earth, from west to east, each sidereal period.

Since the Sun (and the Earth with it) and all other stars are in motion relative to each other, slow apparent motions would result in slight changes in the positions of the stars relative to each other. This space motion is, in fact, observed by telescope. The component of such motion across the line of sight, called proper motion, produces a change in the apparent position of the star. The maximum which has been observed is that of Barnard's Star, which is moving at the rate of 10.3 seconds per year. This is a tenth-magnitude star, not visible to the unaided eye. Of the 57 stars listed on the daily pages of the almanacs, Rigil Kentaurus has the greatest proper motion, about 3.7 seconds per year. Arcturus, with 2.3 seconds per year, has the greatest proper motion of the navigational stars in the Northern Hemisphere. In a few thousand years proper motion will be sufficient to materially alter some familiar configurations of stars, notably Ursa Major.

### 1519. The Ecliptic

The **ecliptic** is the path the Sun appears to take among the stars due to the annual revolution of the Earth in its orbit. It is considered a great circle of the celestial sphere, inclined at an angle of about 23°26' to the celestial equator, but undergoing a continuous slight change. This angle is called the **obliquity of the ecliptic**. This inclination is due to the fact that the axis of rotation of the Earth is not perpendicular to its orbit. It is this inclination which causes the Sun to appear to move north and south during the year, giving the Earth its seasons and changing lengths of periods of daylight.

Refer to Figure 1519a. The Earth is at perihelion early

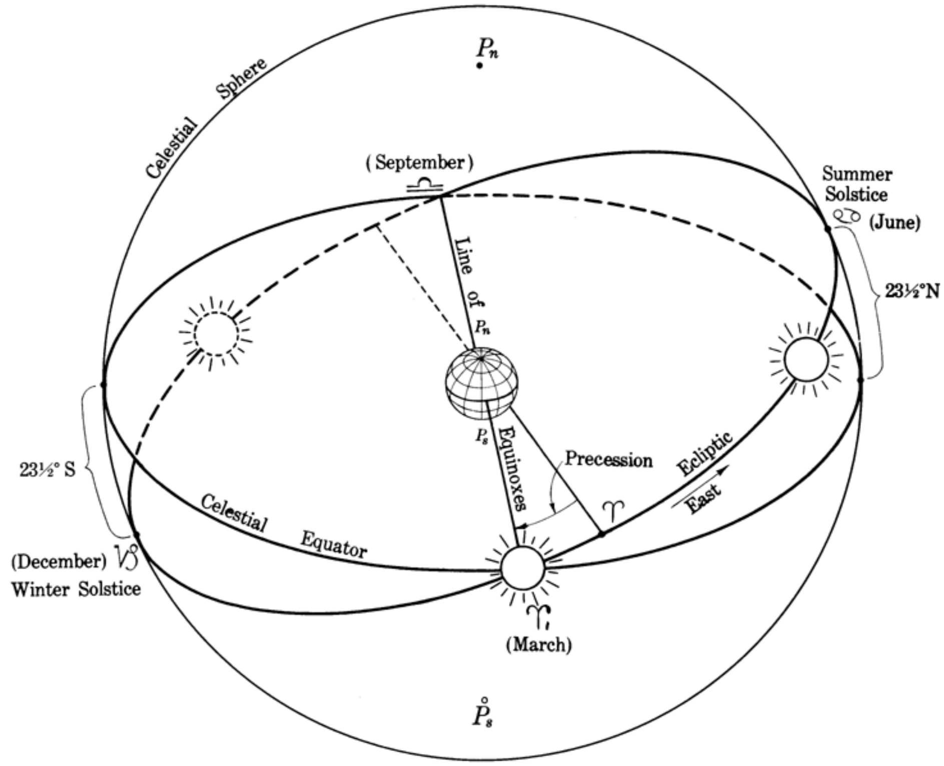



*Figure 1519a. Apparent motion of the Sun in the ecliptic.*

in January and at aphelion 6 months later. On or about June 21, about 10 or 11 days before reaching aphelion, the northern part of the Earth's axis is tilted toward the Sun. The north polar regions are having continuous Sunlight; the Northern Hemisphere is having its summer with long, warm days and short nights; the Southern Hemisphere is having winter with short days and long, cold nights; and the south polar region is in continuous darkness. This is the **summer solstice**. Three months later, about September 23, the Earth has moved a quarter of the way around the Sun, but its axis of rotation still points in about the same direction in space. The Sun shines equally on both hemispheres, and days and nights are the same length over the entire world. The Sun is setting at the North Pole and rising at the South Pole. The Northern Hemisphere is having its autumn, and the Southern Hemisphere its spring. This is the **autumnal equinox**. In another three months, on or about December 22, the Southern Hemisphere is tilted toward the Sun and conditions are the reverse of those six months earlier; the Northern Hemisphere is having its winter, and the Southern Hemisphere its summer. This is the **winter solstice**. Three months later, when both hemispheres again receive equal amounts of Sunshine, the Northern Hemisphere is having spring and the Southern Hemisphere autumn, the reverse of conditions six months before. This is the **vernal equinox**.

The word "equinox," meaning "equal nights," is applied because it occurs at the time when days and nights are of approximately equal length all over the Earth. The word "solstice," meaning "Sun stands still," is applied because the Sun stops its apparent northward or southward motion and momentarily "stands still" before it starts in the opposite direction. This action, somewhat analogous to the "stand" of the tide, refers to the motion in a north-south direction only, and not to the daily apparent revolution around the Earth. Note that it does not occur when the Earth is at perihelion or aphelion. Refer to Figure 1519a. At the time of the vernal equinox, the Sun is directly over the equator, crossing from the Southern Hemisphere to the Northern Hemisphere. It rises due east and sets due west, remaining above the horizon for approximately 12 hours. It is not exactly 12 hours because of refraction, semidiameter, and the height of the eye of the observer. These cause it to be above the horizon a little longer than below the horizon. Following the vernal equinox, the northerly declination increases, and the Sun climbs higher in the sky each day (at the latitudes of the United States), until the summer solstice, when a declination of about 23°26' north of the celestial equator is reached. The Sun then gradually retreats southward until it is again over the equator at the autumnal equinox, at about 23°26' south of the celestial equator at the winter solstice, and back over the celestial equator again at the next vernal equinox.

The Earth is nearest the Sun during the northern hemisphere winter. It is not the distance between the Earth and Sun that is responsible for the difference in temperature during the different seasons, but the altitude of the Sun in the sky and the length of time it remains above the horizon.

During the summer the rays are more nearly vertical, and hence more concentrated, as shown in Figure 1519b. Since the Sun is above the horizon more than half the time, heat is being added by absorption during a longer period than it is being lost by radiation. This explains the lag of the seasons. Following the longest day, the Earth continues to receive more heat than it dissipates, but at a decreasing proportion. Gradually the proportion decreases until a balance is reached, after which the Earth cools, losing more heat than it gains. This is analogous to the day, when the highest temperatures normally occur several hours after the Sun reaches maximum altitude at meridian transit. A similar lag occurs at other seasons of the year. Astronomically, the seasons begin at the equinoxes and solstices. Meteorologically, they differ from place to place.

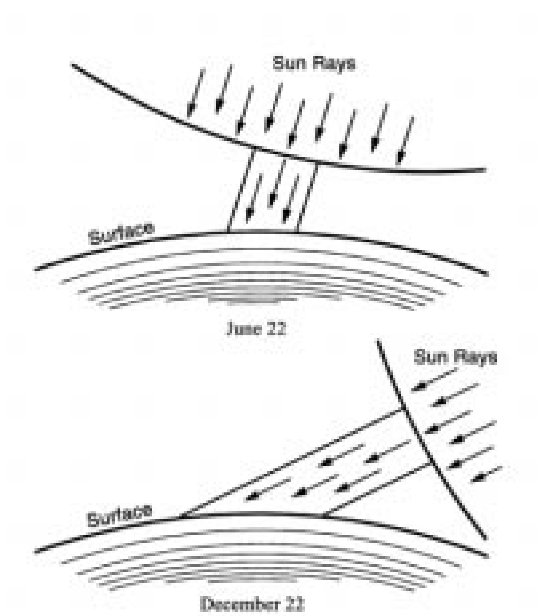



*Figure 1519b. Sunlight in summer and winter. Winter sunlight is distributed over a larger area and shines fewer hours each day, causing less heat energy to reach the Earth.*

Since the Earth travels faster when nearest the Sun, the northern hemisphere (astronomical) winter is shorter than its summer by about seven days.

Everywhere between the parallels of about 23°26'N and about 23°26'S the Sun is directly overhead at some time during the year. Except at the extremes, this occurs twice: once as the Sun appears to move northward, and the second time as it moves southward. This is the **torrid zone**. The northern limit is the **Tropic of Cancer**, and the southern limit is the **Tropic of Capricorn**. These names come from the constellations which the Sun entered at the solstices when the names were first applied more than 2,000 years ago. Today, the Sun is in the next constellation toward the west because of precession of the equinoxes. The parallels about 23°26' from the poles, marking the approximate limits of the circumpolar Sun, are called **polar circles**, the one in the Northern Hemisphere being the **Arctic Circle** and the one in the Southern Hemisphere the **Antarctic Circle**. The areas inside the polar circles are the north and south **frigid zones**. The regions between the frigid zones and the torrid zones are the north and south **temperate zones**.

The expression "vernal equinox" and associated expressions are applied both to the times and points of occurrence of the various phenomena. Navigationally, the vernal equinox is sometimes called the **first point of Aries** (symbol ♈) because, when the name was given, the Sun entered the constellation Aries, the ram, at this time. This point is of interest to navigators because it is the origin for measuring **sidereal hour angle**. The expressions March equinox, June solstice, September equinox, and December solstice are occasionally applied as appropriate, because the more common names are associated with the seasons in the Northern Hemisphere and are six months out of step for the Southern Hemisphere.

The axis of the Earth is undergoing a precessional motion similar to that of a top spinning with its axis tilted. In about 25,800 years the axis completes a cycle and returns to the position from which it started. Since the celestial equator is 90° from the celestial poles, it too is moving. The result is a slow westward movement of the equinoxes and solstices, which has already carried them about 30°, or one constellation, along the ecliptic from the positions they occupied when named more than 2,000 years ago. Since sidereal hour angle is measured from the vernal equinox, and declination from the celestial equator, the coordinates of celestial bodies would be changing even if the bodies themselves were stationary. This westward motion of the equinoxes along the ecliptic is called **precession of the equinoxes**. The total amount, called **general precession**, is about 50 seconds of arc per year. It may be considered divided into two components: precession in right ascension (about 46.10 seconds per year) measured along the celestial equator, and precession in declination (about 20.04" per year) measured perpendicular to the celestial equator. The annual change in the coordinates of any given star, due to precession alone, depends upon its position on the celestial sphere, since these coordinates are measured relative to the polar axis while the precessional motion is relative to the ecliptic axis.

Due to precession of the equinoxes, the celestial poles are slowly describing circles in the sky. The north celestial pole is moving closer to Polaris, which it will pass at a distance of approximately 28 minutes about the year 2102. Following this, the polar distance will increase, and eventually other stars, in their turn, will become the Pole Star.

The precession of the Earth's axis is the result of gravitational forces exerted principally by the Sun and Moon on the Earth's equatorial bulge. The spinning Earth responds to these forces in the manner of a gyroscope. Regression of the nodes introduces certain irregularities known as **nutation** in the precessional motion. See Figure 1519c.

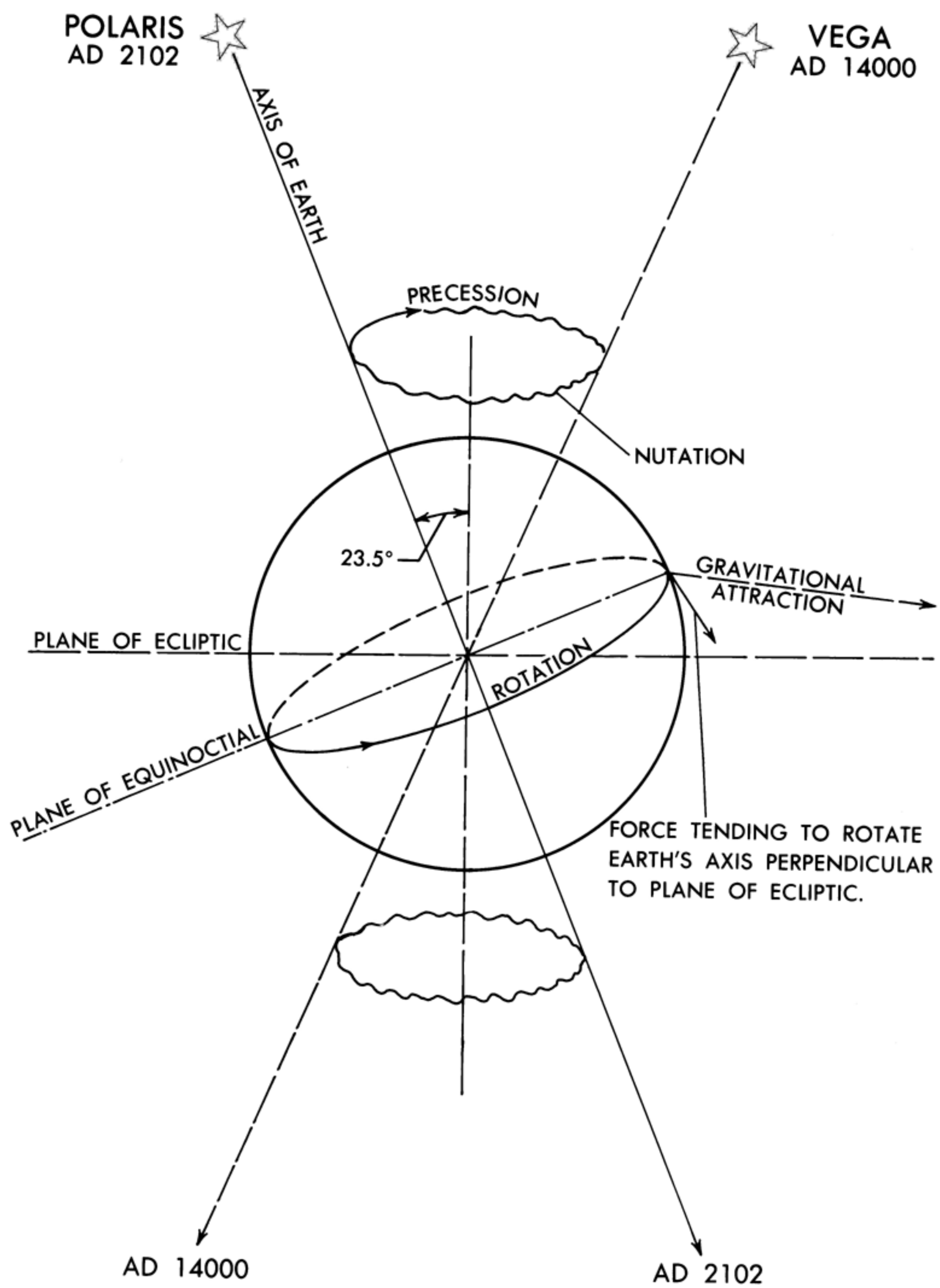



*Figure 1519c. Precession and nutation.*

**1520. The Zodiac**

The **zodiac** is a circular band of the sky extending 8° on each side of the ecliptic. The navigational planets and the Moon are within these limits. The zodiac is divided into 12 sections of 30° each, each section being given the name and symbol (“sign”) of a constellation. These are shown in Figure 1520. The names were assigned more than 2,000 years ago, when the Sun entered Aries at the vernal equinox, Cancer at the summer solstice, Libra at the autumnal equinox, and Capricornus at the winter solstice. Because of precession, the zodiacal signs have shifted with respect to the constellations. Thus at the time of the vernal equinox, the Sun is said to be at the “first point of Aries,” though it is in the constellation Pisces.

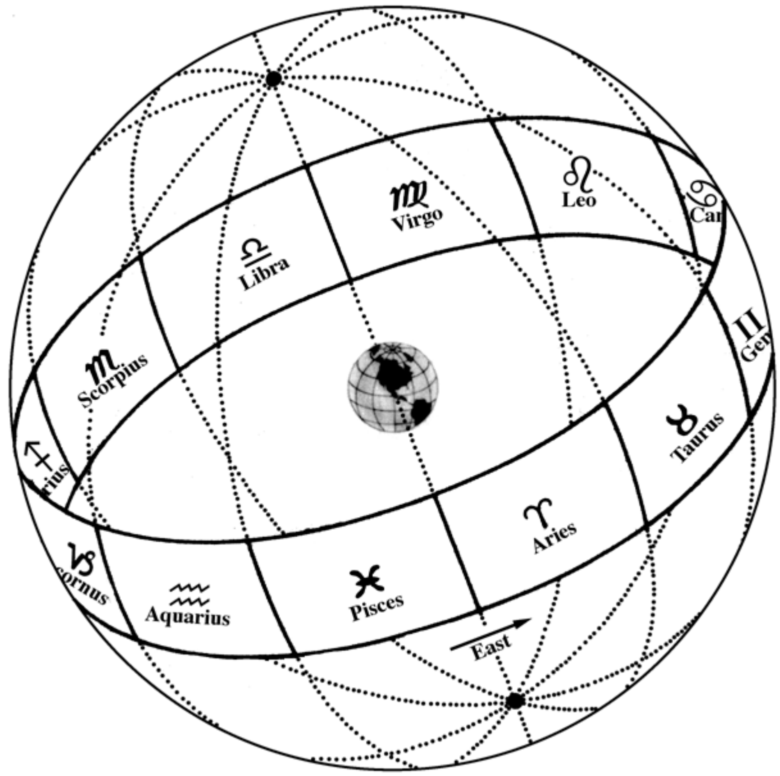



*Figure 1520. The zodiac.*

**1521. Time and the Calendar**

Traditionally, astronomy has furnished the basis for measurement of time, a subject of primary importance to the navigator. The **year** is associated with the revolution of the Earth in its orbit. The **day** is one rotation of the Earth about its axis.

The duration of one rotation of the Earth depends upon the external reference point used. One rotation relative to the Sun is called a **solar day**. However, rotation relative to the apparent Sun (the actual Sun that appears in the sky) does not provide time of uniform rate because of variations in the rate of revolution and rotation of the Earth. The error due to lack of uniform rate of revolution is removed by using a fictitious **mean Sun**. Thus, mean solar time is nearly equal to the average apparent solar time. Because the accumulated difference between these times, called the **equation of time**, is continually changing, the period of daylight is shifting slightly, in addition to its increase or decrease in length due to changing declination. Apparent and mean Suns seldom cross the celestial meridian at the same time. The earliest sunset (in latitudes of the United States) occurs about two weeks before the winter solstice, and the latest sunrise occurs about two weeks after winter solstice. A similar but smaller apparent discrepancy occurs at the summer solstice.

**Universal Time** is a particular case of the measure known in general as mean solar time. Universal Time is the mean solar time on the Greenwich meridian, reckoned in days of 24 mean solar hours beginning with 0 hours at midnight. Universal Time and sidereal time are rigorously related by a formula so that if one is known the other can be found. Universal Time is the standard in the application of astronomy to navigation.

If the vernal equinox is used as the reference, a **sidereal day** is obtained, and from it, **sidereal time**. This indicates the approximate positions of the stars, and for this reason it is the basis of star charts and star finders. Because of the revolution of the Earth around the Sun, a sidereal day is about 3 minutes 56 seconds shorter than a solar day, and there is one more sidereal than solar days in a year. One mean solar day equals 1.00273791 mean sidereal days. Because of precession of the equinoxes, one rotation of the Earth with respect to the stars is not quite the same as one rotation with respect to the vernal equinox. One mean solar day averages 1.0027378118868 rotations of the Earth with respect to the stars.

In tide analysis, the Moon is sometimes used as the reference, producing a **lunar day** averaging 24 hours 50 minutes (mean solar units) in length, and lunar time.

Since each kind of day is divided arbitrarily into 24 hours, each hour having 60 minutes of 60 seconds, the length of each of these units differs somewhat in the various kinds of time.

Time is also classified according to the terrestrial meridian used as a reference. **Local time** results if one’s own meridian is used, **zone time** if a nearby reference meridian is used over a spread of longitudes, and **Greenwich** or **Universal Time** if the Greenwich meridian is used.

The period from one vernal equinox to the next (the cycle of the seasons) is known as the **tropical year**. It is approximately 365 days, 5 hours, 48 minutes, 45 seconds, though the length has been slowly changing for many centuries. Our calendar, the Gregorian calendar, approximates the tropical year with a combination of common years of 365 days and leap years of 366 days. A leap year is any year divisible by four, unless it is a century year, which must be divisible by 400 to be a leap year. Thus, 1700, 1800, and 1900 were not leap years, but 2000 was. A critical mistake was made by John Hamilton Moore in calling 1800 a leap year, causing an error in the tables in his book, *The Practical Navigator*. This error caused the loss of at least one ship and was later discovered by Nathaniel Bowditch while writing the first edition of *The New American Practical Navigator*.

See Chapter 18 for an in-depth discussion of time.

### 1522. Eclipses

If the orbit of the Moon coincided with the plane of the ecliptic, the Moon would pass in front of the Sun at every new Moon, causing a solar eclipse. At full Moon, the Moon would pass through the Earth's shadow, causing a lunar eclipse. Because of the Moon's orbit is inclined 5° with respect to the ecliptic, the Moon usually passes above or below the Sun at new Moon and above or below the Earth's shadow at full Moon. However, there are two points at which the plane of the Moon's orbit intersects the ecliptic. These are the **nodes** of the Moon's orbit. If the Moon passes one of these points at the same time as the Sun, a **solar eclipse** takes place. This is shown in Figure 1522.

The Sun and Moon are of nearly the same apparent size to an observer on the Earth. If the Moon is at perigee, the Moon's apparent diameter is larger than that of the Sun, and its shadow reaches the Earth as a nearly round dot only a few miles in diameter. The dot moves rapidly across the Earth, from west to east, as the Moon continues in its orbit. Within the dot, the Sun is completely hidden from view, and a total eclipse of the Sun occurs. For a considerable distance around the shadow, part of the surface of the Sun is obscured, and a **partial eclipse** occurs. In the line of travel of the shadow a partial eclipse occurs as the round disk of the Moon appears to move slowly across the surface of the Sun, hiding an ever-increasing part of it, until the total eclipse occurs. Because of the uneven edge of the mountainous Moon, the light is not cut off evenly. But several last illuminated portions appear through the valleys or passes between the mountain peaks. These are called **Baily's Beads**.

A total eclipse is a spectacular phenomenon. As the last light from the Sun is cut off, the solar **corona**, or envelope of thin, illuminated gas around the Sun becomes visible. Wisps of more dense gas may appear as **solar prominences**. The only light reaching the observer is that diffused by the atmosphere surrounding the shadow. As the Moon appears to continue on across the face of the Sun, the Sun finally emerges from the other side, first as Baily's Beads, and then as an ever widening crescent until no part of its surface is obscured by the Moon.

The duration of a total eclipse depends upon how nearly the Moon crosses the center of the Sun, the location of the shadow on the Earth, the relative orbital speeds of the Moon and Earth, and (principally) the relative apparent diameters of the Sun and Moon. The maximum length that can occur is a little more than seven minutes.

If the Moon is near apogee, its apparent diameter is less than that of the Sun, and its shadow does not quite reach the Earth. Over a small area of the Earth directly in line with the Moon and Sun, the Moon appears as a black disk almost covering the surface of the Sun, but with a thin ring of the Sun around its edge. This **annular eclipse** occurs a little more often than a total eclipse.

If the shadow of the Moon passes close to the Earth, but not directly in line with it, a partial eclipse may occur without a total or annular eclipse.

An eclipse of the Moon (or **lunar eclipse**) occurs when the Moon passes through the shadow of the Earth, as shown in Figure 1522. Since the diameter of the Earth is about $3^1/_2$ times that of the Moon, the Earth's shadow at the distance of the Moon is much larger than that of the Moon. A total eclipse of the Moon can last nearly $1^3/_4$ hours, and some part of the Moon may be in the Earth's shadow for almost 4 hours.

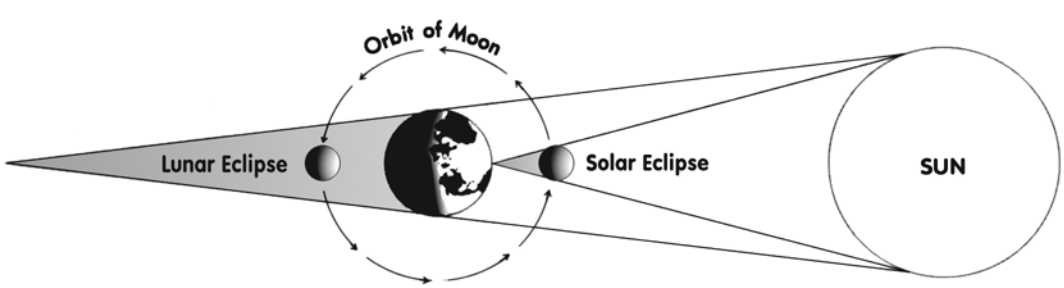



*Figure 1522. Eclipses of the Sun and Moon.*

During a total solar eclipse no part of the Sun is visible because the Moon is in the line of sight. But during a lunar eclipse some light does reach the Moon, diffracted by the atmosphere of the Earth, and hence the eclipsed full Moon is visible as a faint reddish disk. A lunar eclipse is visible over the entire hemisphere of the Earth facing the Moon. Anyone who can see the Moon can see the eclipse.

During any one year there may be as many as five eclipses of the Sun, and always there are at least two. There may be as many as three eclipses of the Moon, or none. The total number of eclipses during a single year does not exceed seven, and can be as few as two. There are more solar than lunar eclipses, but the latter can be seen more often because of the restricted areas over which solar eclipses are visible.

The Sun, Earth, and Moon are nearly aligned on the line of nodes twice each eclipse year of 346.6 days. This is less than a calendar year because of **regression of the nodes**. In a little more than 18 years the line of nodes returns to approximately the same position with respect to the Sun, Earth, and Moon. During an almost equal period, called the **saros**, a cycle of eclipses occurs. During the following saros the cycle is repeated with only minor differences.

## COORDINATES

### 1523. Latitude And Longitude

**Latitude** and **longitude** are coordinates used to locate positions on the Earth. This article discusses three different definitions of these coordinates.

**Astronomic latitude** is the angle (ABQ, Figure 1523) between a line in the direction of gravity (AB) at a station and the plane of the equator (QQ'). **Astronomic longitude** is the angle between the plane of the celestial meridian at a station and the plane of the celestial meridian at Greenwich. These coordinates are customarily found by means of celestial observations. If the Earth were perfectly homogeneous and round, these positions would be consistent and satisfactory. However, because of deflection of the vertical due to uneven distribution of the mass of the Earth, lines of equal astronomic latitude and longitude are not circles, although the irregularities are small. In the United States the prime vertical component (affecting longitude) may be a little more than 18", and the meridional component (affecting latitude) as much as 25".

**Geodetic latitude** is the angle (ACQ, Figure 1523) between a normal to the spheroid (AC) at a station and the plane of the geodetic equator (QQ'). **Geodetic longitude** is the angle between the plane defined by the normal to the spheroid and the axis of the Earth and the plane of the geodetic meridian at Greenwich. These values are obtained when astronomical latitude and longitude are corrected for deflection of the vertical. These coordinates are used for charting and are frequently referred to as **geographic latitude** and **geographic longitude**, although these expressions are sometimes used to refer to astronomical latitude.

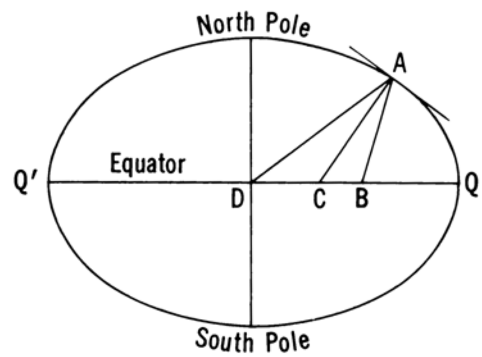



*Figure 1523. Three kinds of latitude at point A.*

**Geocentric latitude** is the angle (ADQ, Figure 1523) at the center of the ellipsoid between the plane of its equator (QQ') and a straight line (AD) to a point on the surface of the Earth. This differs from geodetic latitude because the Earth is a spheroid rather than a sphere, and the meridians are ellipses. Since the parallels of latitude are considered to be circles, geodetic longitude is geocentric, and a separate expression is not used. The difference between geocentric and geodetic latitudes is a maximum of about 11.6' at latitude 45°.

Because of the oblate shape of the ellipsoid, the length of a degree of geodetic latitude is not everywhere the same, increasing from about 59.7 nautical miles at the equator to about 60.3 nautical miles at the poles. The value of 60 nautical miles customarily used by the navigator is correct at about latitude 45°.

## MEASUREMENTS ON THE CELESTIAL SPHERE

### 1524. Elements of the Celestial Sphere

The **celestial sphere** (Article 1501) is an imaginary sphere of infinite radius with the Earth at its center (Figure 1524a). The north and south celestial poles of this sphere are located by extension of the Earth's axis. The **celestial equator** (sometimes called **equinoctial**) is formed by projecting the plane of the Earth's equator to the celestial sphere. A **celestial meridian** is formed by the intersection of the plane of a terrestrial meridian and the celestial sphere. It is the arc of a great circle through the poles of the celestial sphere.

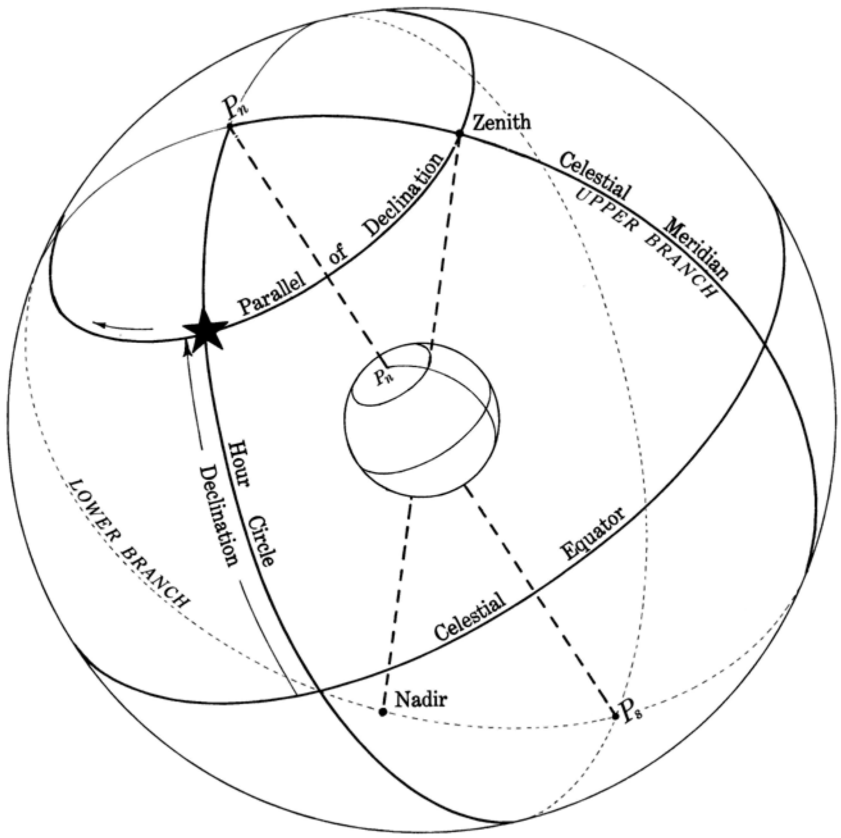



*Figure 1524a. Elements of the celestial sphere. The celestial equator is the primary great circle.*

The point on the celestial sphere vertically overhead of an observer is the **zenith**, and the point on the opposite side of the sphere vertically below him is the **nadir**. The zenith and nadir are the extremities of a diameter of the celestial sphere through the observer and the common center of the Earth and the celestial sphere. The arc of a celestial meridian between the poles is called the **upper branch** if it contains the zenith and the **lower branch** if it contains the nadir. The upper branch is frequently used in navigation, and references to a celestial meridian are understood to mean only its upper branch unless otherwise stated. Celestial meridians take the names of their terrestrial counterparts, such as 65° west.

An **hour circle** is a great circle through the celestial poles and a point or body on the celestial sphere. It is similar to a celestial meridian, but moves with the celestial sphere as it rotates about the Earth, while a celestial meridian remains fixed with respect to the Earth.

The location of a body on its hour circle is defined by the body's angular distance from the celestial equator. This distance, called **declination**, is measured north or south of the celestial equator in degrees, from 0° through 90°, similar to latitude on the Earth.

A circle parallel to the celestial equator is called a **parallel of declination**, since it connects all points of equal declination. It is similar to a parallel of latitude on the Earth. The path of a celestial body during its daily apparent revolution around the Earth is called its **diurnal circle**. It is not actually a circle if a body changes its declination. Since the declination of all navigational bodies is continually changing, the bodies are describing flat, spherical spirals as they circle the Earth. However, since the change is relatively slow, a diurnal circle and a parallel of declination are usually considered identical.

A point on the celestial sphere may be identified at the intersection of its parallel of declination and its hour circle. The parallel of declination is identified by the declination.

Two basic methods of locating the hour circle are in use. First, the angular distance west of a reference hour circle through a point on the celestial sphere, called the vernal equinox or first point of Aries, is called **sidereal hour angle (SHA)** (Figure 1524b). This angle, measured eastward from the vernal equinox, is called **right ascension** and is usually expressed in time units.

The second method of locating the hour circle is to indicate its angular distance west of a celestial meridian (Figure 1524c). If the Greenwich celestial meridian is used as the reference, the angular distance is called **Greenwich hour angle (GHA)**, and if the meridian of the observer, it is called **local hour angle (LHA)**. It is

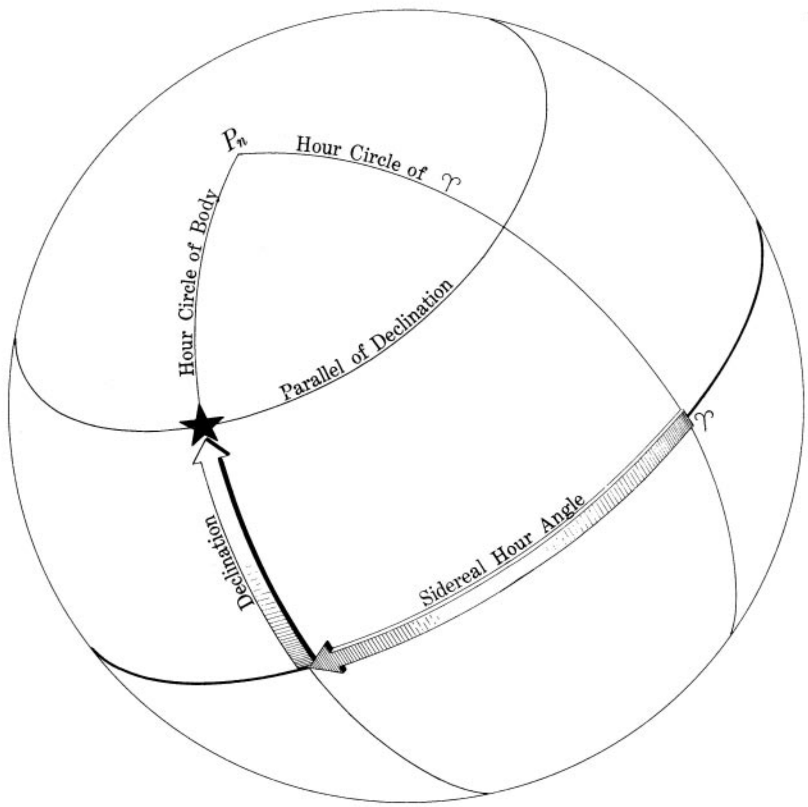



*Figure 1524b. A point on the celestial sphere can be located by its declination and sidereal hour angle.*

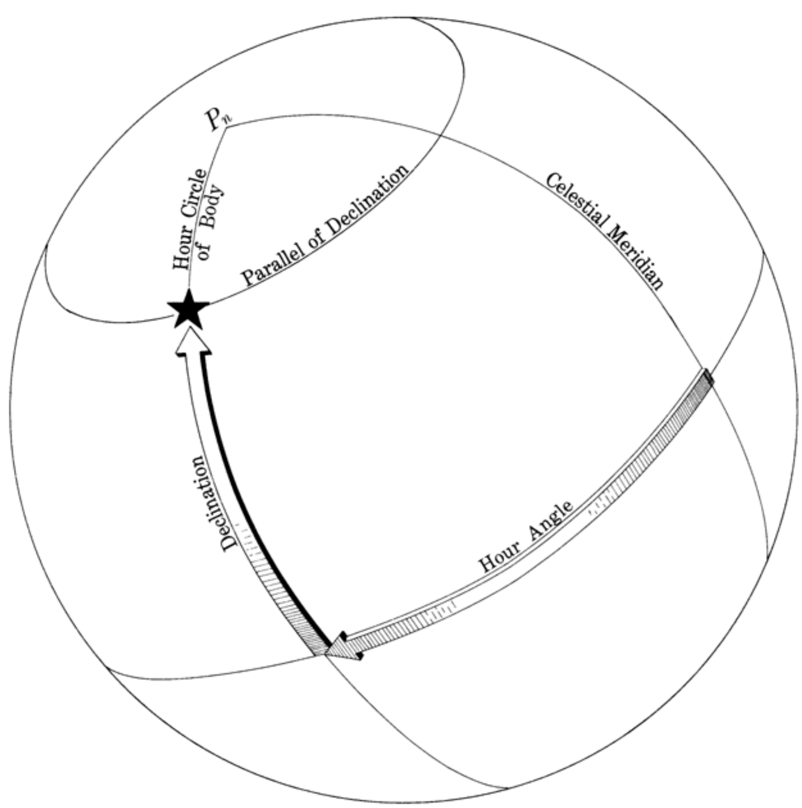



*Figure 1524c. A point on the celestial sphere can be located by its declination and hour angle.*

sometimes more convenient to measure hour angle either eastward or westward, as longitude is measured on the Earth, in which case it is called **meridian angle** (designated "t").

A point on the celestial sphere may also be located using altitude and azimuth coordinates based upon the horizon as the primary great circle instead of the celestial equator.

## COORDINATE SYSTEMS

### 1525. The Celestial Equator System of Coordinates

The familiar graticule of latitude and longitude lines, expanded until it reaches the celestial sphere, forms the basis of the celestial equator system of coordinates. On the celestial sphere latitude becomes declination, while longitude becomes sidereal hour angle, measured from the vernal equinox.

Declination is angular distance north or south of the celestial equator (d in Figure 1525a). It is measured along an hour circle, from 0° at the celestial equator through 90° at the celestial poles. It is labeled N or S to indicate the direction of measurement. All points having the same declination lie along a parallel of declination.

**Polar distance (p)** is angular distance from a celestial pole, or the arc of an hour circle between the celestial pole and a point on the celestial sphere. It is measured along an hour circle and may vary from 0° to 180°, since either pole may be used as the origin of measurement. It is usually considered the complement of declination, though it may be either 90° – d or 90° + d, depending upon the pole used.

**Local hour angle (LHA)** is angular distance west of the local celestial meridian, or the arc of the celestial equator between the upper branch of the local celestial meridian and the hour circle through a point on the celestial sphere, measured westward from the local celestial meridian, through 360°. It is also the similar arc of the parallel of declination and the angle at the celestial pole, similarly measured. If the Greenwich (0°) meridian is used as the reference, instead of the local meridian, the expression **Greenwich hour angle (GHA)** is applied. It is sometimes convenient to measure the arc or angle in either an easterly or westerly direction from the local meridian, through 180°, when it is called **meridian angle (t)** and labeled E or W to indicate the direction of measurement. All bodies or other points having the same hour angle lie along the same hour circle.

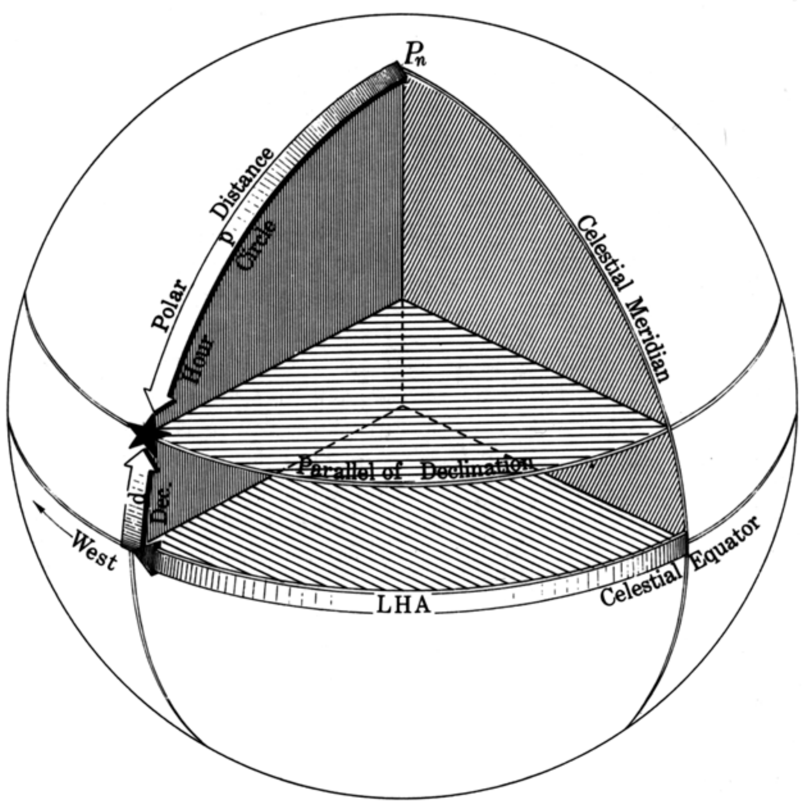



*Figure 1525a. The celestial equator system of coordinates, showing measurements of declination, polar distance, and local hour angle.*

Because of the apparent daily rotation of the celestial sphere, hour angle continually increases, but meridian angle increases from 0° at the celestial meridian to 180°W, which is also 180°E, and then decreases to 0° again. The rate of change for the mean Sun is 15° per hour. The rate of all other bodies except the Moon is within 3' of this value. The average rate of the Moon is about 15.5°.

As the celestial sphere rotates, each body crosses each branch of the celestial meridian approximately once a day. This crossing is called **meridian transit** (sometimes called culmination). It may be called **upper transit** to indicate crossing of the upper branch of the celestial meridian, and **lower transit** to indicate crossing of the lower branch.

The **time diagram** shown in Figure 1525b illustrates the relationship between the various hour angles and meridian angle. The circle is the celestial equator as seen from above the South Pole, with the upper branch of the observer's meridian ($P_sM$) at the top. The radius $P_sG$ is the Greenwich meridian; $P_s$ ♈ is the hour circle of the vernal equinox. The Sun's hour circle is to the east of the observer's meridian; the Moon's hour circle is to the west of the observer's meridian Note that when LHA is less than 180°, t is numerically the same and is labeled W, but that when LHA is greater than 180°, t = 360° – LHA and is labeled E. In Figure 1525b arc GM is the longitude, which in this case is west. The relationships shown apply equally to other arrangements of radii, except for relative magnitudes of the quantities involved.

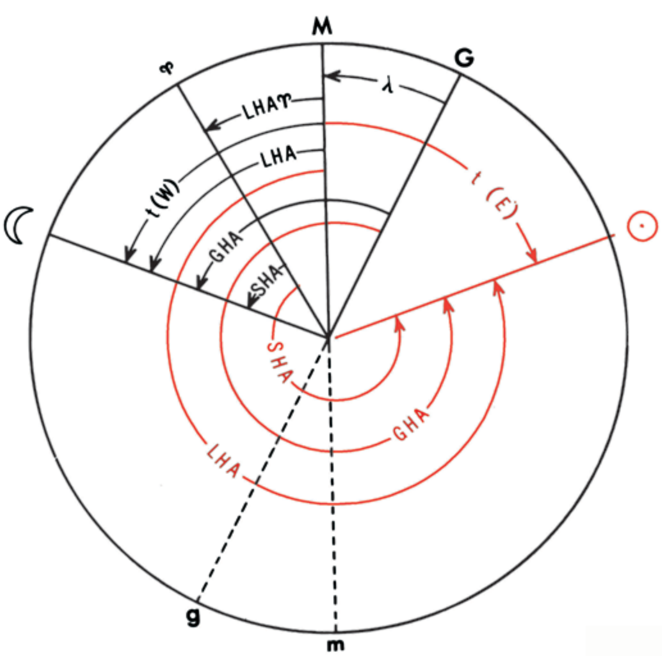



*Figure 1525b. Time diagram.*

**1526. The Horizons**

The second set of celestial coordinates with which the navigator is directly concerned is based upon the horizon as the primary great circle. However, since several different horizons are defined, these should be thoroughly understood before proceeding with a consideration of the horizon system of coordinates.

The line where Earth and sky appear to meet is called the **visible** or **apparent horizon**. On land this is usually an irregular line unless the terrain is level. At sea the visible horizon appears very regular and is often very sharp. However, its position relative to the celestial sphere depends primarily upon (1) the refractive index of the air and (2) the height of the observer's eye above the surface.

Figure 1526 shows a cross section of the Earth and celestial sphere through the position of an observer at A. A straight line through A and the center of the Earth O is the vertical of the observer and contains his zenith (Z) and nadir (Na). A plane perpendicular to the true vertical is a horizontal plane, and its intersection with the celestial sphere is a horizon. It is the **celestial horizon** if the plane passes through the center of the Earth, the **geoidal horizon** if it is tangent to the Earth, and the **sensible horizon** if it passes through the eye of the observer at A. Since the radius of the Earth is considered negligible with respect to that of the celestial sphere, these horizons become superimposed, and most measurements are referred only to the celestial horizon. This is sometimes called the **rational horizon**.

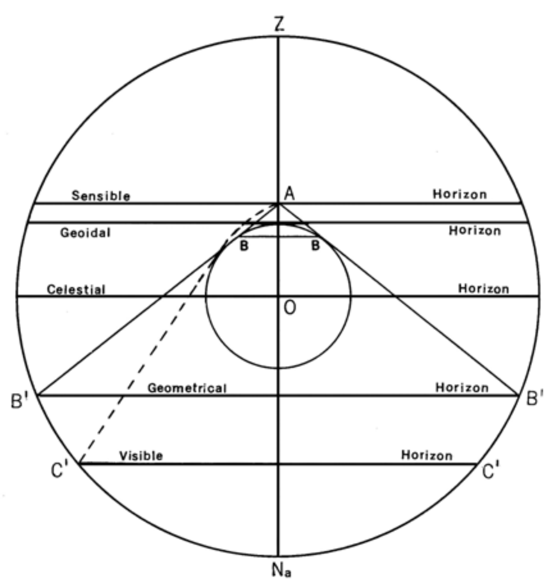



*Figure 1526. The horizons used in navigation.*

If the eye of the observer is at the surface of the Earth, his visible horizon coincides with the plane of the geoidal horizon; but when elevated above the surface, as at A, his eye becomes the vertex of a cone which is tangent to the

Earth at the small circle BB, and which intersects the celestial sphere in B'B', the **geometrical horizon**. This expression is sometimes applied to the celestial horizon.

Because of refraction, the visible horizon C'C' appears above but is actually slightly below the geometrical horizon as shown in Figure 1526. In Figure 1525b the Local hour angle, Greenwich hour angle, and sidereal hour angle are measured westward through 360°. Meridian angle (t) is measured eastward or westward through 180° and labeled E or W to indicate the direction of measurement.

For any elevation above the surface, the celestial horizon is usually above the geometrical and visible horizons, the difference increasing as elevation increases. It is thus possible to observe a body which is above the visible horizon but below the celestial horizon. That is, the body's altitude is negative and its zenith distance is greater than 90°.

### 1527. The Horizon System of Coordinates

This system is based upon the celestial horizon as the primary great circle and a series of secondary vertical circles which are great circles through the zenith and nadir of the observer and hence perpendicular to his horizon (Figure 1527a). Thus, the celestial horizon is similar to the equator, and the vertical circles are similar to meridians, but with one important difference. The celestial horizon and vertical circles are dependent upon the position of the observer and hence move with him as he changes position, while the primary and secondary great circles of both the geographical and celestial equator systems are independent of the observer. The horizon and celestial equator systems coincide for an observer at the geographical pole of the Earth and are mutually perpendicular for an observer on the equator. At all other places the two are oblique.

The vertical circle through the north and south points of the horizon passes through the poles of the celestial equator system of coordinates. One of these poles (having the same name as the latitude) is above the horizon and is called the **elevated pole**. The other, called the **depressed pole**, is below the horizon. Since this vertical circle is a great circle through the celestial poles, and includes the zenith of the observer, it is also a celestial meridian. In the horizon system it is called the **principal vertical circle**. The vertical circle through the east and west points of the horizon, and hence perpendicular to the principal vertical circle, is called the **prime vertical circle**, or simply the **prime vertical**.

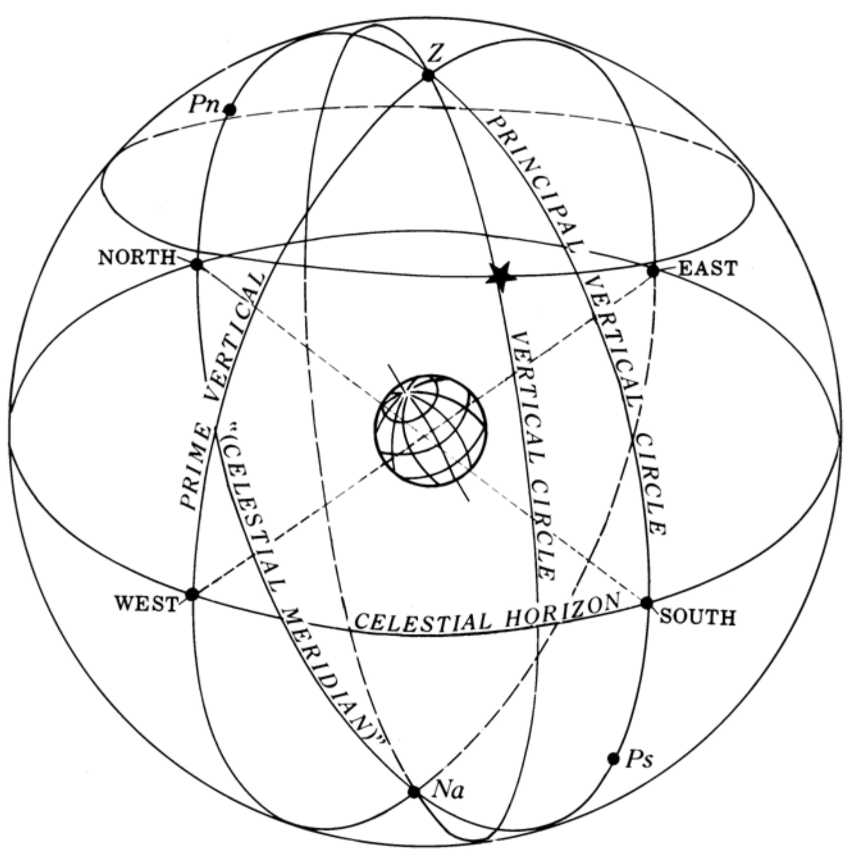



*Figure 1527a. Elements of the celestial sphere. The celestial horizon is the primary great circle.*

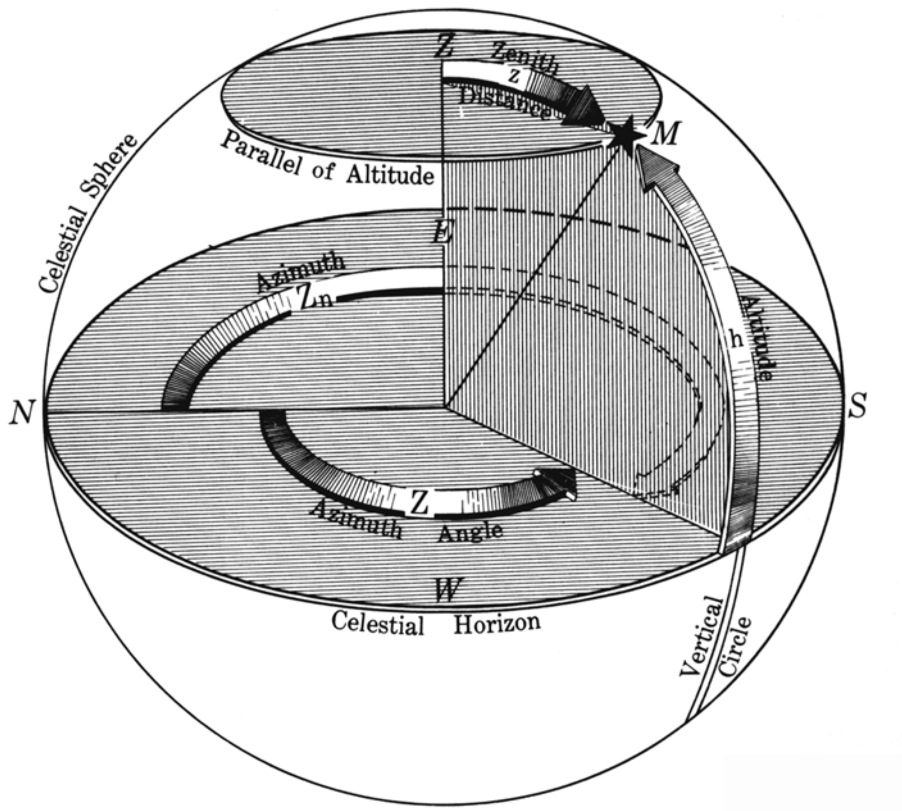



*Figure 1527b. The horizon system of coordinates, showing measurement of altitude, zenith distance, azimuth, and azimuth angle.*

| *Earth* | *Celestial Equator* | *Horizon* | *Ecliptic* |
|---|---|---|---|
| equator | celestial equator | horizon | ecliptic |
| poles | celestial poles | zenith; nadir | ecliptic poles |
| meridians | hours circle; celestial meridians | vertical circles | circles of latitude |
| prime meridian | hour circle of Aries | principal or prime vertical circle | circle of latitude through Aries |
| parallels | parallels of declination | parallels of altitude | parallels of latitude |
| latitude | declination | altitude | celestial altitude |
| colatitude | polar distance | zenith distance | celestial colatitude |
| longitude | SHA; RA; GHA; LHA; t | azimuth; azimuth angle; amplitude | celestial longitude |

*Table 1527. The four systems of celestial coordinates and their analogous terms.*

As shown in Figure 1527b, altitude is angular distance above the horizon. It is measured along a vertical circle, from 0° at the horizon through 90° at the zenith. Altitude measured from the visible horizon may exceed 90° because of the dip of the horizon, as shown in Figure 1526. Angular distance below the horizon, called negative altitude, is provided for by including certain negative altitudes in some tables for use in celestial navigation. All points having the same altitude lie along a parallel of altitude.

**Zenith distance** (z) is angular distance from the zenith, or the arc of a vertical circle between the zenith and a point on the celestial sphere. It is measured along a vertical circle from 0° through 180°. It is usually considered the complement of altitude. For a body above the celestial horizon it is equal to 90° – h and for a body below the celestial horizon it is equal to 90° – (– h) or 90° + h.

The horizontal direction of a point on the celestial sphere, or the bearing of the geographical position, is called **azimuth** or **azimuth angle** depending upon the method of measurement. In both methods it is an arc of the horizon (or parallel of altitude), or an angle at the zenith. It is **azimuth** (Zn) if measured clockwise through 360°, starting at the north point on the horizon, and **azimuth angle** (Z) if measured either clockwise or counterclockwise through 180°, starting at the north point of the horizon in north latitude and the south point of the horizon in south latitude.

The ecliptic system is based upon the ecliptic as the primary great circle, analogous to the equator. The points 90° from the ecliptic are the north and south ecliptic poles. The series of great circles through these poles, analogous to meridians, are circles of latitude. The circles parallel to the plane of the ecliptic, analogous to parallels on the Earth, are parallels of latitude or circles of longitude. Angular distance north or south of the ecliptic, analogous to latitude, is celestial latitude. Celestial longitude is measured eastward along the ecliptic through 360°, starting at the vernal equinox. This system of coordinates is of interest chiefly to astronomers.

The four systems of celestial coordinates are analogous to each other and to the terrestrial system, although each has distinctions such as differences in directions, units, and limits of measurement. Table 1527 indicates the analogous term or terms under each system.

### 1528. Diagram on the Plane of the Celestial Meridian

From an imaginary point outside the celestial sphere and over the celestial equator, at such a distance that the view would be orthographic, the great circle appearing as the outer limit would be a celestial meridian. Other celestial meridians would appear as ellipses. The celestial equator would appear as a diameter 90° from the poles, and parallels of declination as straight lines parallel to the equator. The view would be similar to an orthographic map of the Earth.

A number of useful relationships can be demonstrated by drawing a diagram on the plane of the celestial meridian showing this orthographic view. Arcs of circles can be substituted for the ellipses without destroying the basic relationships. Refer to Figure 1528a. In the lower diagram the circle represents the celestial meridian, QQ' the celestial equator, Pn and Ps the north and south celestial poles, respectively. If a star has a declination of 30° N, an angle of 30° can be measured from the celestial equator, as shown. It could be measured either to the right or left, and would have been toward the south pole if the declination had been south. The parallel of declination is a line through this point and parallel to the celestial equator. The star is somewhere on this line (actually a circle viewed on edge).

To locate the hour circle, draw the upper diagram so that Pn is directly above Pn of the lower figure (in line with the polar axis Pn-Ps), and the circle is of the same diameter as that of the lower figure. This is the plan view, looking down on the celestial sphere from the top. The circle is the celestial equator. Since the view is from above the north celestial pole, west is clockwise. The diameter QQ' is the celestial meridian shown as a circle in the lower diagram. If the right half is considered the upper branch, local hour angle is measured clockwise from this line to the hour circle, as shown. In this case the LHA is 80°. The intersection of the hour circle and celestial equator, point A, can be projected down to the lower diagram (point A') by a straight line parallel to the polar axis. The elliptical hour circle can be represented approximately by an arc of a circle through A', Pn, Ps. The center of this circle is somewhere along the celestial equator line QQ', extended if necessary. It is usually found by trial and error. The intersection of the hour circle and parallel of declination locates the star.

Since the upper diagram serves only to locate point A' in the lower diagram, the two can be combined. That is, the LHA arc can be drawn in the lower diagram, as shown, and point A projected upward to A'. In practice, the upper diagram is not drawn, being shown here for illustrative purposes.

In this example the star is on that half of the sphere toward the observer, or the western part. If LHA had been greater than 180°, the body would have been on the eastern or “back” side.

From the east or west point over the celestial horizon, the orthographic view of the horizon system of coordinates would be similar to that of the celestial equator system from a point over the celestial equator, since the celestial meridian is also the principal vertical circle. The horizon would appear as a diameter, parallels of altitude as straight lines parallel to the horizon, the zenith and nadir as poles 90° from the horizon, and vertical circles as ellipses through the zenith and nadir, except for the principal vertical circle, which would appear as a circle, and the prime vertical, which would appear as a diameter perpendicular to the horizon.

A celestial body can be located by altitude and azimuth in a manner similar to that used with the celestial equator system. If the altitude is 25°, this angle is measured from the horizon toward the zenith and the parallel of altitude is drawn as a straight line parallel to the horizon, as shown at hh' in the lower diagram of Figure 1528b. The plan view from above the zenith is shown in the upper diagram. If north is taken at the left, as shown, azimuths are measured clockwise from this point. In the figure the azimuth is 290° and the azimuth angle is N70°W. The vertical circle is located by measuring either arc. Point A thus located can be projected vertically downward to A' on the horizon of the lower diagram, and the vertical circle represented approximately by the arc of a circle through A' and the zenith and nadir. The center of this circle is on NS, extended if necessary. The body is at the intersection of the parallel of altitude and the vertical circle. Since the upper diagram serves only to locate A' on the lower diagram, the two can

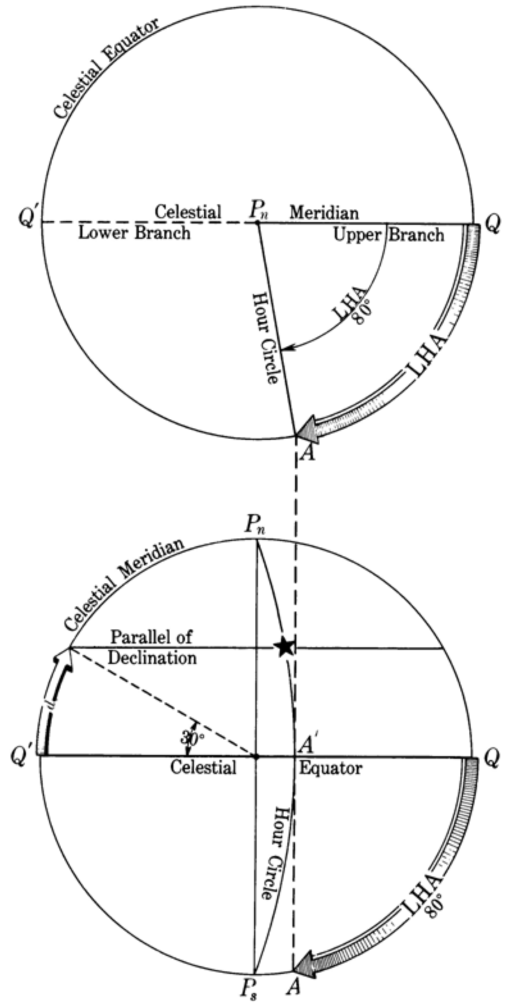



*Figure 1528a. Measurement of celestial equator system of coordinates.*

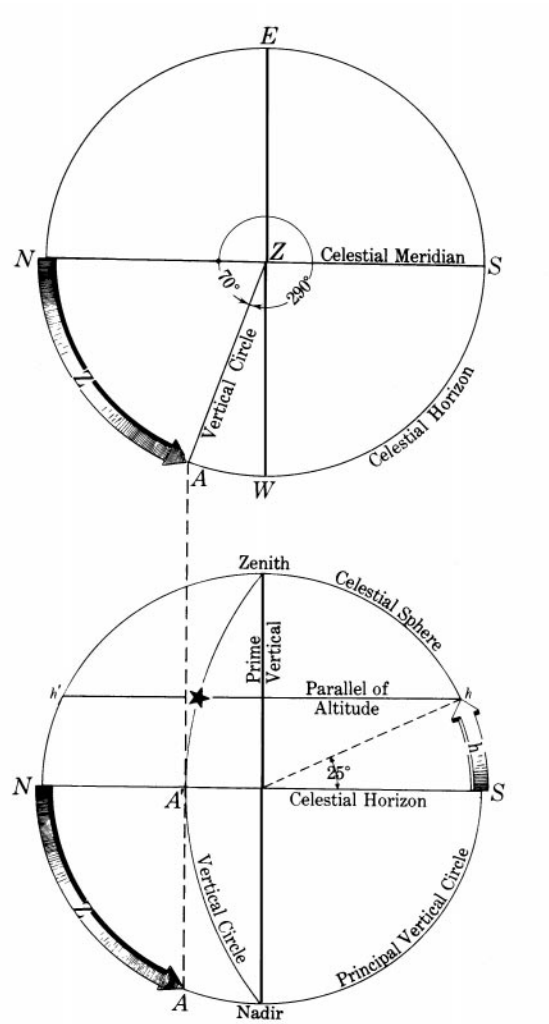



*Figure 1528b. Measurement of horizon system of coordinates.*

be combined, point A located on the lower diagram and projected upward to A', as shown. Since the body of the example has an azimuth greater than 180°, it is on the western or “front” side of the diagram.

Since the celestial meridian appears the same in both the celestial equator and horizon systems, the two diagrams can be combined and, if properly oriented, a body can be located by one set of coordinates, and the coordinates of the other system can be determined by measurement.

Refer to Figure 1528c, in which the black lines represent the celestial equator system, and the red lines the horizon system. By convention, the zenith is shown at the top and the north point of the horizon at the left. The west point on the horizon is at the center, and the east point directly behind it. In the figure the latitude is 37°N. Therefore, the zenith is 37° north of the celestial equator. Since the zenith is established at the top of the diagram, the equator can be found by measuring an arc of 37° toward the south, along the celestial meridian. If the declination is 30°N and the LHA is 80°, the body can be located as shown by the black lines, and described above.

The altitude and azimuth can be determined by the reverse process to that described above. Draw a line hh' through the body and parallel to the horizon, NS. The altitude, 25°, is found by measurement, as shown. Draw the arc of a circle through the body and the zenith and nadir. From A', the intersection of this arc with the horizon, draw a vertical line intersecting the circle at A. The azimuth, N70°W, is found by measurement, as shown. The prefix N is applied to agree with the latitude. The body is left (north) of ZNa, the prime vertical circle. The suffix W applies because the LHA, 80°, shows that the body is west of the meridian.

If altitude and azimuth are given, the body is located by means of the red lines. The parallel of declination is then drawn parallel to QQ', the celestial equator, and the declination determined by measurement. Point L' is located by drawing the arc of a circle through Pn, the star, and Ps. From L' a line is drawn perpendicular to QQ', locating L. The meridian angle is then found by measurement. The declination is known to be north because the body is between

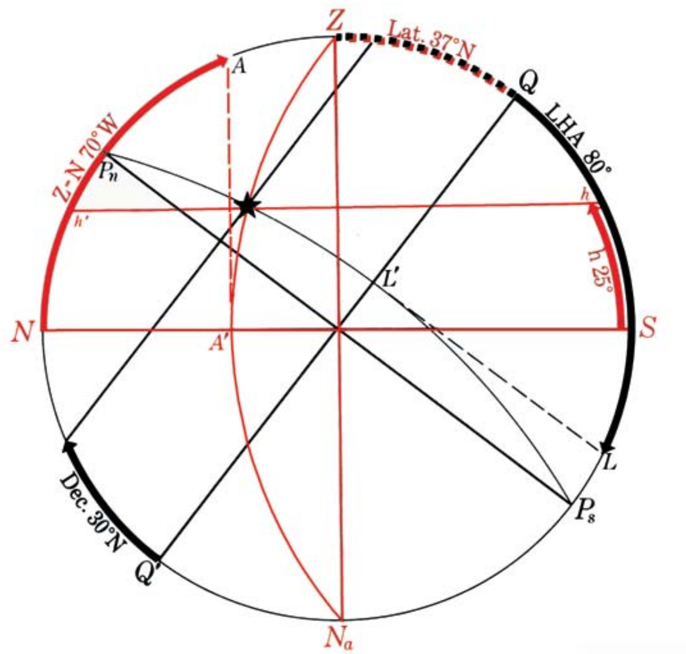



*Figure 1528c. Diagram on the plane of the celestial meridian.*

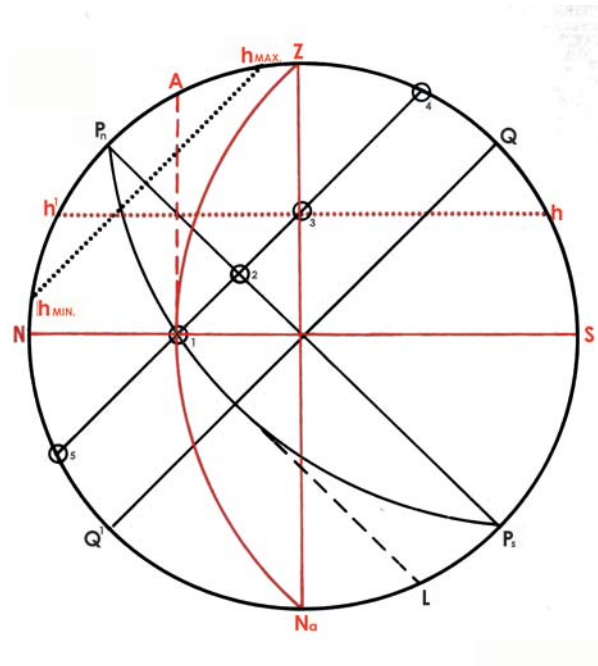



*Figure 1528d. A diagram on the plane of the celestial meridian for lat. 45°N.*

the celestial equator and the north celestial pole. The meridian angle is west, to agree with the azimuth, and hence LHA is numerically the same.

Since QQ' and PnPs are perpendicular, and ZNa and NS are also perpendicular, arc NPn is equal to arc ZQ. That is, the altitude of the elevated pole is equal to the declination of the zenith, which is equal to the latitude. This relationship is the basis of the method of determining latitude by an observation of Polaris.

The diagram on the plane of the celestial meridian is useful in approximating a number of relationships. Consider Figure 1528d. The latitude of the observer (NPn or ZQ) is 45°N. The declination of the Sun (Q4) is 20°N. Neglecting the change in declination for one day, note the following: At sunrise, position 1, the Sun is on the horizon (NS), at the “back” of the diagram. Its altitude, h, is 0°. Its azimuth angle, Z, is the arc NA, N63°E. This is prefixed N to agree with the latitude and suffixed E to agree with the meridian angle of the Sun at sunrise. Hence, Zn = 063°. The amplitude, A, is the arc ZA, E27°N. The meridian angle, t, is the arc QL, 110°E. The suffix E is applied because the Sun is east of the meridian at rising. The LHA is 360° – 110° = 250°.

As the Sun moves upward along its parallel of declination, its altitude increases. It reaches position 2 at about 0600, when t = 90°E. At position 3 it is on the prime vertical, ZNa. Its azimuth angle, Z, is N90°E, and Zn = 090°. The altitude is Nh' or Sh, 27°.

Moving on up its parallel of declination, it arrives at position 4 on the celestial meridian about noon-when t and LHA are both 0°, by definition. On the celestial meridian a body’s azimuth is 000° or 180°. In this case it is 180° because the body is south of the zenith. The maximum altitude occurs at meridian transit. In this case the arc S4 represents the maximum altitude, 65°. The zenith distance, z, is the arc Z4, 25°. A body is not in the zenith at meridian transit unless its declination’s magnitude and name are the same as the latitude.

Continuing on, the Sun moves downward along the “front” or western side of the diagram. At position 3 it is again on the prime vertical. The altitude is the same as when previously on the prime vertical, and the azimuth angle is numerically the same, but now measured toward the west. The azimuth is 270°. The Sun reaches position 2 six hours after meridian transit and sets at position 1. At this point, the azimuth angle is numerically the same as at sunrise, but westerly, and Zn = 360° – 63° = 297°. The amplitude is W27°N.

After sunset the Sun continues on downward, along its parallel of declination, until it reaches position 5, on the lower branch of the celestial meridian, about midnight. Its negative altitude, arc N5, is now greatest, 25°, and its azimuth is 000°. At this point it starts back up along the “back” of the diagram, arriving at position 1 at the next sunrise, to start another cycle.

Half the cycle is from the crossing of the 90° hour circle (the PnPs line, position 2) to the upper branch of the celestial meridian (position 4) and back to the PnPs line (position 2). When the declination and latitude have the same name (both north or both south), more than half the parallel of declination (position 1 to 4 to 1) is above the horizon, and the body is above the horizon more than half the time, crossing the 90° hour circle above the horizon. It rises and sets on the same side of the prime vertical as the elevated pole. If the declination is of the same name but numerically smaller than the latitude, the body crosses the prime vertical above the horizon. If the declination and latitude have the same name and are numerically equal, the body is in the zenith at upper transit. If the declination is of the same name but numerically greater than the latitude, the body crosses the upper branch of the celestial meridian between the zenith and elevated pole and does not cross the prime vertical. If the declination is of the same name as the latitude and complementary to it (d + L = 90°), the body is on the horizon at lower transit and does not set. If the declination is of the same name as the latitude and numerically greater than the colatitude, the body is above the horizon during its entire daily cycle and has maximum and minimum altitudes. This is shown by the black dotted line in Figure 1528d.

If the declination is 0° at any latitude, the body is above the horizon half the time, following the celestial equator QQ', and rises and sets on the prime vertical. If the declination is of contrary name (one north and the other south), the body is above the horizon less than half the time and crosses the 90° hour circle below the horizon. It rises and sets on the opposite side of the prime vertical from the elevated pole. If the declination is of contrary name and numerically smaller than the latitude, the body crosses the prime vertical below the horizon. If the declination is of contrary name and numerically equal to the latitude, the body is in the nadir at lower transit. If the declination is of contrary name and complementary to the latitude, the body is on the horizon at upper transit. If the declination is of contrary name and numerically greater than the colatitude, the body does not rise.

All of these relationships, and those that follow, can be derived by means of a diagram on the plane of the celestial meridian. They are modified slightly by atmospheric refraction, height of eye, semidiameter, parallax, changes in declination, and apparent speed of the body along its diurnal circle.

It is customary to keep the same orientation in south latitude, as shown in Figure 1528e. In this illustration the latitude is 45°S, and the declination of the body is 15°N. Since Ps is the elevated pole, it is shown above the southern horizon, with both SPs and ZQ equal to the latitude, 45°. The body rises at position 1, on the opposite side of the prime vertical from the elevated pole. It moves upward along its parallel of declination to position 2, on the upper branch of the celestial meridian, bearing north; and then it moves downward along the "front" of the diagram to position 1, where it sets. It remains above the horizon for less than half the time because declination and latitude are of contrary name. The azimuth at rising is arc NA, the amplitude ZA, and the azimuth angle SA. The altitude circle at meridian transit is shown at hh'.

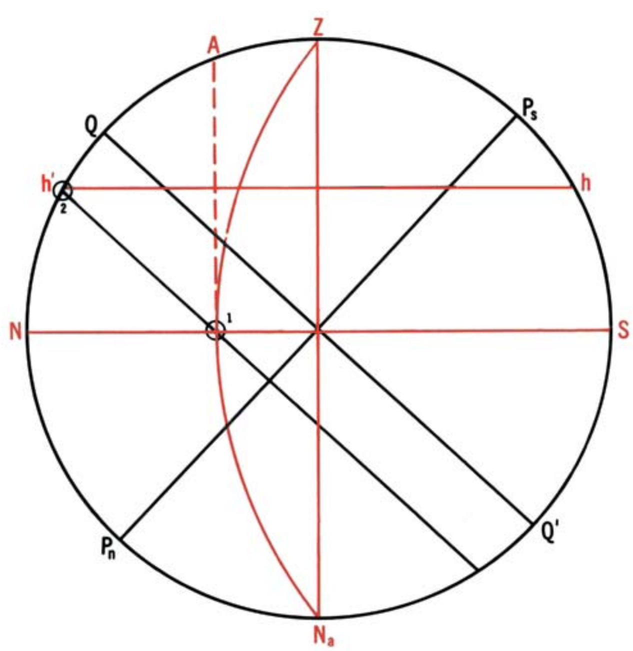



*Figure 1528e. A diagram on the plane of the celestial meridian for lat. 45°S.*

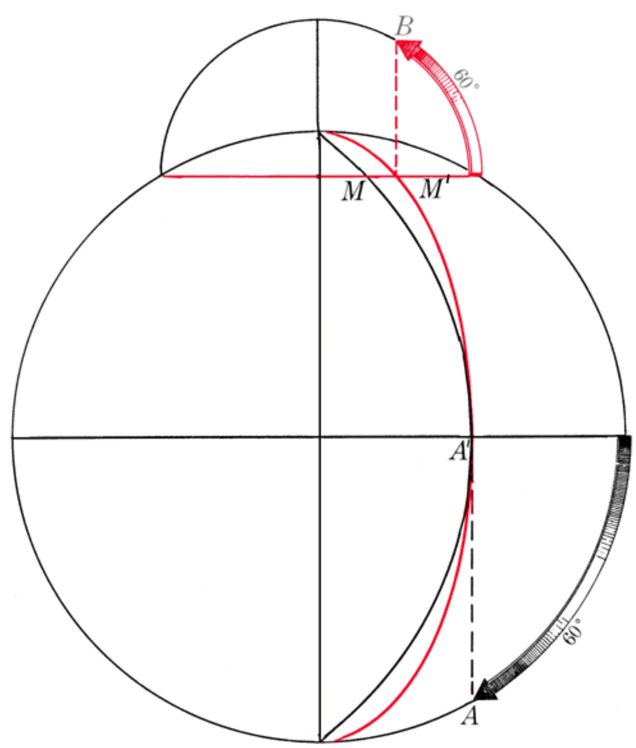



*Figure 1528f. Locating a point on an ellipse of a diagram on the plane of the celestial meridian.*

A diagram on the plane of the celestial meridian can be used to demonstrate the effect of a change in latitude. As the latitude increases, the celestial equator becomes more nearly parallel to the horizon. The colatitude becomes smaller increasing the number of circumpolar bodies and those which neither rise nor set. It also increases the difference in the length of the days between summer and winter. At the poles celestial bodies circle the sky, parallel to the horizon. At the equator the 90° hour circle coincides with the horizon. Bodies rise and set vertically; and are above the horizon half the time. At rising and setting the amplitude is equal to the declination. At meridian transit the altitude is equal to the codeclination. As the latitude changes name, the same-contrary name relationship with declination reverses. This accounts for the fact that one hemisphere has winter while the other is having summer.

## NAVIGATIONAL COORDINATES

| Coordinate | Symbol | Measured from | Measured along | Direction | Measured to | Units | Precision | Maximum value | Labels |
|---|---|---|---|---|---|---|---|---|---|
| latitude | L, lat. | equator | meridian | N, S | parallel | °, ′ | 0′.1 | 90° | N, S |
| colatitude | colat. | poles | meridian | S, N | parallel | °, ′ | 0′.1 | 90° | — |
| longitude | λ, long. | prime meridian | parallel | E, W | local meridian | °, ′ | 0′.1 | 180° | E, W |
| declination | d, dec. | celestial equator | hour circle | N, S | parallel of declination | °, ′ | 0′.1 | 90° | N, S |
| polar distance | p | elevated pole | hour circle | S, N | parallel of declination | °, ′ | 0′.1 | 180° | — |
| altitude | h | horizon | vertical circle | up | parallel of altitude | °, ′ | 0′.1 | 90°* | — |
| zenith distance | z | zenith | vertical circle | down | parallel of altitude | °, ′ | 0′.1 | 180° | — |
| azimuth | Zn | north | horizon | E | vertical circle | ° | 0°.1 | 360° | — |
| azimuth angle | Z | north, south | horizon | E, W | vertical circle | ° | 0°.1 | 180° or 90° | N, S...E, W |
| amplitude | A | east, west | horizon | N, S | body | ° | 0°.1 | 90° | E, W...N, S |
| Greenwich hour angle | GHA | Greenwich celestial meridian | parallel of declination | W | hour circle | °, ′ | 0′.1 | 360° | — |
| local hour angle | LHA | local celestial meridian | parallel of declination | W | hour circle | °, ′ | 0′.1 | 360° | — |
| meridian angle | t | local celestial meridian | parallel of declination | E, W | hour circle | °, ′ | 0′.1 | 180° | E, W |
| sidereal hour angle | SHA | hour circle of vernal equinox | parallel of declination | W | hour circle | °, ′ | 0′.1 | 360° | — |
| right ascension | RA | hour circle of vernal equinox | parallel of declination | E | hour circle | h, m, s | $1^s$ | $24^h$ | — |
| Greenwich mean time | GMT | lower branch Greenwich celestial meridian | parallel of declination | W | hour circle mean Sun | h, m, s | $1^s$ | $24^h$ | — |
| local mean time | LMT | lower branch local celestial meridian | parallel of declination | W | hour circle mean Sun | h, m, s | $1^s$ | $24^h$ | — |
| zone time | ZT | lower branch zone celestial meridian | parallel of declination | W | hour circle mean Sun | h, m, s | $1^s$ | $24^h$ | — |
| Greenwich apparent time | GAT | lower branch Greenwich celestial meridian | parallel of declination | W | hour circle apparent Sun | h, m, s | $1^s$ | $24^h$ | — |
| local apparent time | LAT | lower branch local celestial meridian | parallel of declination | W | hour circle apparent Sun | h, m, s | $1^s$ | $24^h$ | — |
| Greenwich sidereal time | GST | Greenwich celestial meridian | parallel of declination | W | hour circle vernal equinox | h, m, s | $1^s$ | $24^h$ | — |
| local sidereal time | LST | local celestial meridian | parallel of declination | W | hour circle vernal equinox | h, m, s | $1^s$ | $24^h$ | — |

*When measured from celestial horizon.

*Figure 1528g. Navigational Coordinates.*

The error arising from showing the hour circles and vertical circles as arcs of circles instead of ellipses increases with increased declination or altitude. More accurate results can be obtained by measurement of azimuth on the parallel of altitude instead of the horizon, and of hour angle on the parallel of declination instead of the celestial equator. Refer to Figure 1528f. The vertical circle shown is for a body having an azimuth angle of S60°W. The arc of a circle is shown in black, and the ellipse in red. The black arc is obtained by measurement around the horizon, locating A' by means of A, as previously described. The intersection of this arc with the altitude circle at 60° places the body at M. If a semicircle is drawn with the altitude circle as a diameter, and the azimuth angle measured around this, to B, a perpendicular to the hour circle locates the body at M', on the ellipse. By this method the altitude circle, rather than the horizon, is, in effect, rotated through 90° for the measurement. This refinement is seldom used because actual values are usually found mathematically, the diagram on the plane of the meridian being used primarily to indicate relationships.

With experience, one can visualize the diagram on the plane of the celestial meridian without making an actual drawing. Devices with two sets of spherical coordinates, on either the orthographic or stereographic projection, pivoted at the center, have been produced commercially to provide a mechanical diagram on the plane of the celestial meridian. However, since the diagram's principal use is to illustrate certain relationships, such a device is not a necessary part of the navigator's equipment.

Figure 1528g summarizes navigation coordinate systems.

### 1529. The Navigational Triangle

A triangle formed by arcs of great circles of a sphere is called a **spherical triangle**. A spherical triangle on the celestial sphere is called a **celestial triangle**. The spherical triangle of particular significance to navigators is called the **navigational triangle**, formed by arcs of a *celestial meridian*, an *hour circle*, and a *vertical circle*. Its vertices are the *elevated pole*, the *zenith*, and a *point on the celestial sphere* (usually a celestial body). The terrestrial counterpart is also called a navigational triangle, being formed by arcs of two meridians and the great circle connecting two places on the Earth, one on each meridian. The vertices are the two places and a pole. In great-circle sailing these places are the point of departure and the destination. In celestial navigation they are the **assumed position (AP)** of the observer and the **geographical position (GP)** of the body (the point having the body in its zenith). The GP of the Sun is sometimes called the **subsolar point**, that of the Moon the **sublunar point**, that of a satellite (either natural or artificial) the **subsatellite point**, and that of a star its **substellar** or **subastral point**. When used to solve a celestial observation, either the celestial or terrestrial triangle may be called the **astronomical triangle**.

The navigational triangle is shown in Figure 1529a on a diagram on the plane of the celestial meridian. The Earth is at the center, O. The star is at M, dd' is its parallel of declination, and hh' is its altitude circle.

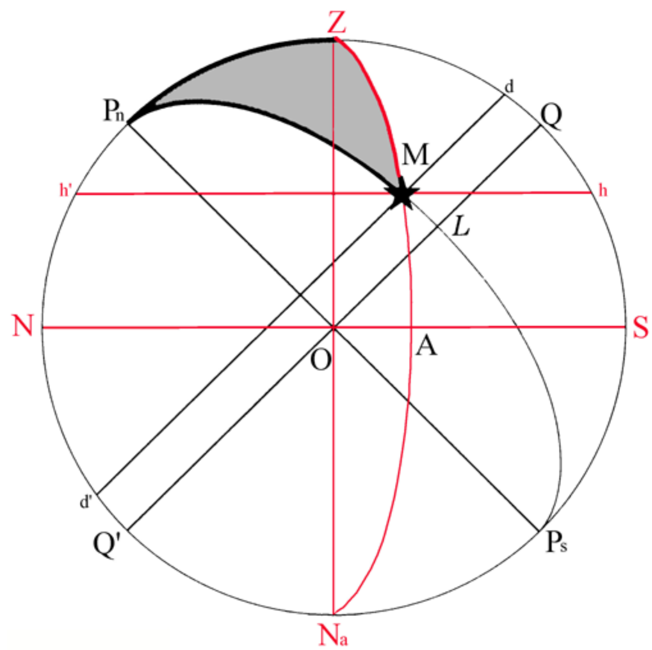



*Figure 1529a. The navigational triangle.*

In the figure, arc QZ of the celestial meridian is the latitude of the observer, and PnZ, one side of the triangle, is the colatitude. Arc AM of the vertical circle is the altitude of the body, and side ZM of the triangle is the zenith distance, or coaltitude. Arc LM of the hour circle is the declination of the body, and side PnM of the triangle is the polar distance, or codeclination.

The angle at the elevated pole, ZPnM, having the hour circle and the celestial meridian as sides, is the meridian angle, t. The angle at the zenith, PnZM, having the vertical circle and that arc of the celestial meridian, which includes the elevated pole, as sides, is the azimuth angle. The angle at the celestial body, ZMPn, having the hour circle and the vertical circle as sides, is the parallactic angle (X) (sometimes called the position angle), which is not generally used by the navigator.

A number of problems involving the navigational triangle are encountered by the navigator, either directly or indirectly. Of these, the most common are:

1. Given latitude, declination, and meridian angle, to find altitude and azimuth angle. This is used in the reduction of a celestial observation to establish a line of position.
2. Given latitude, altitude, and azimuth angle, to find declination and meridian angle. This is used to identify an unknown celestial body.

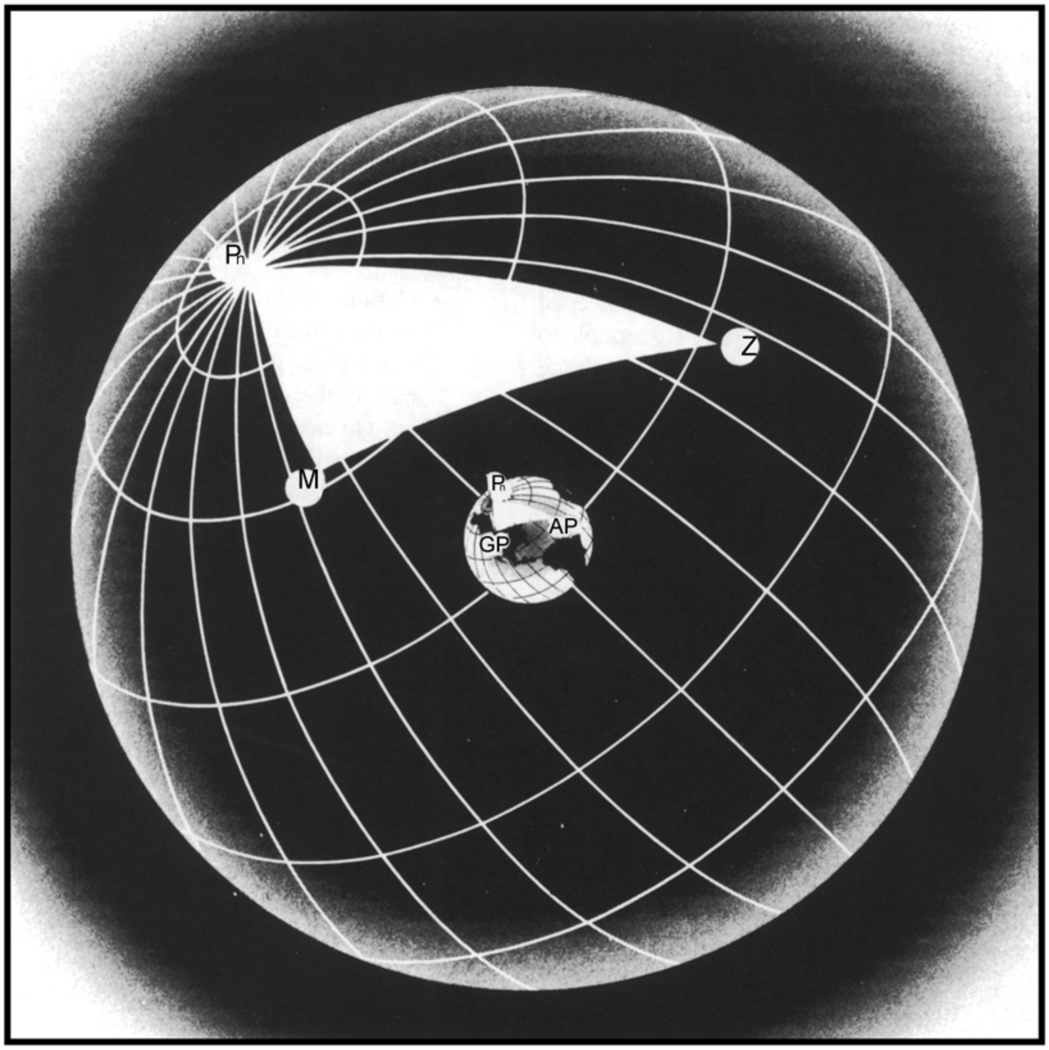



*Figure 1529b. The navigational triangle in perspective.*

3. Given meridian angle, declination, and altitude, to find azimuth angle. This may be used to find azimuth when the altitude is known.
4. Given the latitude of two places on the Earth and the difference of longitude between them, to find the initial great-circle course and the great-circle distance. This involves the same parts of the triangle as in 1, above, but in the terrestrial triangle, and hence is defined differently.

Both celestial and terrestrial navigational triangles are shown in perspective in Figure 1529b.

## IDENTIFICATION OF STARS AND PLANETS

**1530. Introduction**

A basic requirement of celestial navigation is the ability to identify the bodies observed. This is not difficult because relatively few stars and planets are commonly used for navigation, and various aids are available to assist in their identification. See Figure 1530a and Figure 1532a.

Navigational calculators or computer programs can identify virtually any celestial body observed, given inputs of DR position, azimuth, and altitude. In fact, a complete round of sights can be taken and solved without knowing the names of a single observed body. Once the data is entered, the computer identifies the bodies, solves the sights,

## NAVIGATIONAL STARS AND THE PLANETS

| Name | Pronunciation | Bayer name | Origin of name | Meaning of name | Distance* |
|---|---|---|---|---|---|
| Acamar | ā′kȧ·mąr | θ Eridani | Arabic | another form of Achernar | 120 |
| Achernar | ā′kĕr·nąr | α Eridani | Arabic | end of the river (Eridanus) | 72 |
| Acrux | ā′krŭks | α Crucis | Modern | coined from Bayer name | 220 |
| Adhara | ȧ·dā′rȧ | ε Canis Majoris | Arabic | the virgin(s) | 350 |
| Aldebaran | ăl dĕb′ȧ·rȧn | α Tauri | Arabic | follower (of the Pleiades) | 64 |
| Alioth | ăl′ĭ·ŏth | ε Ursa Majoris | Arabic | another form of Capella | 49 |
| Alkaid | ăl·kād′ | η Ursa Majoris | Arabic | leader of the daughters of the bier | 190 |
| Al Na′ir | ăl·nār′ | α Gruis | Arabic | bright one (of the fish's tail) | 90 |
| Alnilam | ăl′nĭ·lăm | ε Orionis | Arabic | string of pearls | 410 |
| Alphard | ăl′fąrd | α Hydrae | Arabic | solitary star of the serpent | 200 |
| Alphecca | ăl·fĕk′ȧ | α Corona Borealis | Arabic | feeble one (in the crown) | 76 |
| Alpheratz | ăl·fē′răts | α Andromeda | Arabic | the horse's navel | 120 |
| Altair | ăl·tār′ | α Aquilae | Arabic | flying eagle or vulture | 16 |
| Ankaa | ąn′ką | α Phoenicis | Arabic | coined name | 93 |
| Antares | ăn·tā′rēz | α Scorpii | Greek | rival of Mars (in color) | 250 |
| Arcturus | ąrk·tū′rŭs | α Bootis | Greek | the bear's guard | 37 |
| Atria | ăt′rĭ·ȧ | α Trianguli Australis | Modern | coined from Bayer name | 130 |
| Avior | ā′vĭ·ôr | ε Carinae | Modern | coined name | 350 |
| Bellatrix | bĕ·lā′trĭks. | γ Orionis | Latin | female warrior | 250 |
| Betelgeuse | bĕt′ĕl·jûz | α Orionis | Arabic | the arm pit (of Orion) | 300 |
| Canopus | kȧ·nō′pŭs | α Carinae | Greek | city of ancient Egypt | 230 |
| Capella | kȧ·pĕl′ȧ | α Aurigae | Latin | little she-goat | 46 |
| Deneb | dĕn′ĕb | α Cygni | Arabic | tail of the hen | 600 |
| Denebola | dĕ·nĕb′ŏ·lȧ | β Leonis | Arabic | tail of the lion | 42 |
| Diphda | dĭf′dȧ | β Ceti | Arabic | the second frog (Fomalhaut was once the first) | 57 |
| Dubhe | dŭb′ē | α Ursa Majoris | Arabic | the bear's back | 100 |
| Elnath | ĕl′năth | β Tauri | Arabic | one butting with horns | 130 |
| Eltanin | ĕl·tā′nĭn | γ Draconis | Arabic | head of the dragon | 150 |
| Enif | ĕn′ĭf | ε Pegasi | Arabic | nose of the horse | 250 |
| Fomalhaut | fō′mȧl·ôt | α Piscis Austrini | Arabic | mouth of the southern fish | 23 |
| Gacrux | gā′krŭks | γ Crucis | Modern | coined from Bayer name | 72 |
| Gienah | jē′nȧ | γ Corvi | Arabic | right wing of the raven | 136 |
| Hadar | hā′dąr | β Centauri | Modern | leg of the centaur | 200 |
| Hamal | hăm′ȧl | α Arietis | Arabic | full-grown lamb | 76 |
| Kaus Australis | kôs ôs·trā′lĭs | ε Sagittarii | Ar., L. | southern part of the bow | 163 |
| Kochab | kō′kăb | β Ursa Minoris | Arabic | shortened form of "north star" (named when it was that, c. 1500 BC–AD 300) | 100 |
| Markab | mąr′kăb | α Pegasi | Arabic | saddle (of Pegasus) | 100 |
| Menkar | mĕn′kąr | α Ceti | Arabic | nose (of the whale) | 1,100 |
| Menkent | mĕn′kĕnt | θ Centauri | Modern | shoulder of the centaur | 55 |
| Miaplacidus | mī′ȧ·plăs′ĭ·dŭs | β Carinae | Ar., L. | quiet or still waters | 86 |
| Mirfak | mĭr′făk | α Persei | Arabic | elbow of the Pleiades | 130 |
| Nunki | nŭn′kē | σ Sagittarii | Bab. | constellation of the holy city (Eridu) | 150 |
| Peacock | pē′kŏk | α Pavonis | Modern | coined from English name of constellation | 250 |
| Polaris | pō·lā′rĭs | α Ursa Minoris | Latin | the pole (star) | 450 |
| Pollux | pŏl′ŭks | β Geminorum | Latin | Zeus' other twin son (Castor, α Geminorum, is first twin) | 33 |
| Procyon | prō′sĭ·ŏn | α Canis Minoris | Greek | before the dog (rising before the dog star, Sirius) | 11 |
| Rasalhague | rás′ąl·hā′gwē | α Ophiuchi | Arabic | head of the serpent charmer | 67 |
| Regulus | rĕg′ū·lŭs | α Leonis | Latin | the prince | 67 |
| Rigel | rī′jĕl | β Orionis | Arabic | foot (left foot of Orion) | 500 |
| Rigil Kentaurus | rī′jĭl kĕn·tô′rŭs | α Centauri | Arabic | foot of the centaur | 4.3 |
| Sabik | sā′bĭk | η Ophiuchi | Arabic | second winner or conqueror | 69 |
| Schedar | shĕd′ȧr | α Cassiopeiae | Arabic | the breast (of Cassiopeia) | 360 |
| Shaula | shō′lȧ | λ Scorpii | Arabic | cocked-up part of the scorpion's tail | 200 |
| Sirius | sĭr′ĭ·ŭs | α Canis Majoris | Greek | the scorching one (popularly, the dog star) | 8.6 |
| Spica | spī′kȧ | α Virginis | Latin | the ear of corn | 155 |
| Suhail | sŏŏ·hāl′ | λ Velorum | Arabic | shortened form of Al Suhail, one Arabic name for Canopus | 200 |
| Vega | vē′gȧ | α Lyrae | Arabic | the falling eagle or vulture | 27 |
| Zubenelgenubi | zŏŏ·bĕn′ĕl·jĕ·nū′bē | α Librae | Arabic | southern claw (of the scorpion) | 66 |

### PLANETS

| Name | Pronunciation | Origin of name | Meaning of name |
|---|---|---|---|
| Mercury | mûr′kū·rĭ | Latin | god of commerce and gain |
| Venus | vē′nŭs | Latin | goddess of love |
| Earth | ûrth | Mid. Eng. | — |
| Mars | märz | Latin | god of war |
| Jupiter | jōō′pĭ·tĕr | Latin | god of the heavens, identified with the Greek Zeus, chief of the Olympian gods |
| Saturn | săt′ĕrn | Latin | god of seed-sowing |
| Uranus | ū′rȧ·nŭs | Greek | the personification of heaven |
| Neptune | nĕp′tūn | Latin | god of the sea |
| Pluto | plōō′tō | Greek | god of the lower world (Hades) |

*Guide to pronunciations:*
fāte, ădd, finȧl, lȧst, ȧbound, ärm; bē, ĕnd, camĕl, readẽr; īce, bĭt, anĭmal; ōver, pȯetic, hŏt, lôrd, mōōn; tūbe, ūnite, tŭb, circŭs, ûrn

*Distances in light-years. One light-year equals approximately 63,300 AU, or 5,880,000,000,000 miles. Authorities differ on distances of the stars; the values given are representative.

*Figure 1530a. Navigational stars and the planets.*

and plots the results. In this way, the navigator can learn the stars by observation instead of by rote memorization.

No problem is encountered in the identification of the Sun and Moon. However, the planets can be mistaken for stars. A person working continually with the night sky recognizes a planet by its changing position among the relatively fixed stars. The planets are identified by noting their positions relative to each other, the Sun, the Moon, and the stars. They remain within the narrow limits of the zodiac, but are in almost constant motion relative to the stars. The magnitude and color may be helpful. The information needed is found in the *Nautical Almanac*. The "Planet Notes" near the front of that volume are particularly useful. Planets can also be identified by planet diagram, star finder, sky diagram, or by computation.

### 1531. Stars

The *Nautical Almanac* lists full navigational information on 19 first magnitude stars and 38 second magnitude stars, plus Polaris. Abbreviated information is listed for 115 more. Additional stars are listed in the *Astronomical Almanac* and in various star catalogs. About 6,000 stars of the sixth magnitude or brighter (on the entire celestial sphere) are visible to the unaided eye on a clear, dark night.

Stars are designated by one or more of the following naming systems:

- **Common Name:** Most names of stars, as now used, were given by the ancient Arabs and some by the Greeks or Romans. One of the stars of the *Nautical Almanac*, Nunki, was named by the Babylonians. Only a relatively few stars have names. Several of the stars on the daily pages of the almanacs had no name prior to 1953.

- **Bayer's Name:** Most bright stars, including those with names, have been given a designation consisting of a Greek letter followed by the possessive form of the name of the constellation, such as $\alpha$ Cygni (Deneb, the brightest star in the constellation Cygnus, the swan). Roman letters are used when there are not enough Greek letters. Usually, the letters are assigned in order of brightness within the constellation; however, this is not always the case. For example, the letter designations of the stars in Ursa Major or the Big Dipper are assigned in order from the outer rim of the bowl to the end of the handle. This system of star designation was suggested by John Bayer of Augsburg, Germany, in 1603. All of the 173 stars included in the list near the back of the *Nautical Almanac* are listed by Bayer's name, and, when applicable, their common name.

- **Flamsteed's Number:** This system assigns numbers to stars in each constellation, from west to east in the order in which they cross the celestial meridian. An example is 95 Leonis, the 95th star in the constellation Leo. This system was suggested by John Flamsteed (1646-1719).

- **Catalog Number:** Stars are sometimes designated by the name of a star catalog and the number of the star as given in the catalog, such as A. G. Washington 632. In these catalogs, stars are listed in order from west to east, without regard to constellation, starting with the hour circle of the vernal equinox. This system is used primarily for fainter stars having no other designation. Navigators seldom have occasion to use this system.

### 1532. Star Charts

It is useful to be able to identify stars by relative position. A **star chart** (Figure 1532a and Figure 1532b) is helpful in locating these relationships and others which may be useful. This method is limited to periods of relatively clear, dark skies with little or no overcast. Stars can also be identified by the *Air Almanac* **sky diagrams**, a **star finder**, *Pub. No. 249*, or by computation by hand or calculator.

Star charts are based upon the celestial equator system of coordinates, using declination and sidereal hour angle (or right ascension). The zenith of the observer is at the intersection of the parallel of declination equal to his latitude, and the hour circle coinciding with his celestial meridian. This hour circle has an SHA equal to 360° – LHA ♈ (or RA = LHA ♈). The horizon is everywhere 90° from the zenith. A **star globe** is similar to a terrestrial sphere, but with stars (and often constellations) shown instead of geographical positions. The *Nautical Almanac* includes instructions for using this device. On a star globe the celestial sphere is shown as it would appear to an observer outside the sphere. Constellations appear reversed. Star charts may show a similar view, but more often they are based upon the view from inside the sphere, as seen from the Earth. On these charts, north is at the top, as with maps, but east is to the left and west to the right. The directions seem correct when the chart is held overhead, with the top toward the north, so the relationship is similar to the sky.

The *Nautical Almanac* has four star charts. The two principal ones are on the polar azimuthal equidistant projection, one centered on each celestial pole. Each chart extends from its pole to declination 10° (same name as pole). Below each polar chart is an auxiliary chart on the Mercator projection, from 30°N to 30°S. On any of these charts, the zenith can be located as indicated, to determine which stars are overhead. The horizon is 90° from the zenith. The charts can also be used to determine the location of a star relative to surrounding stars.

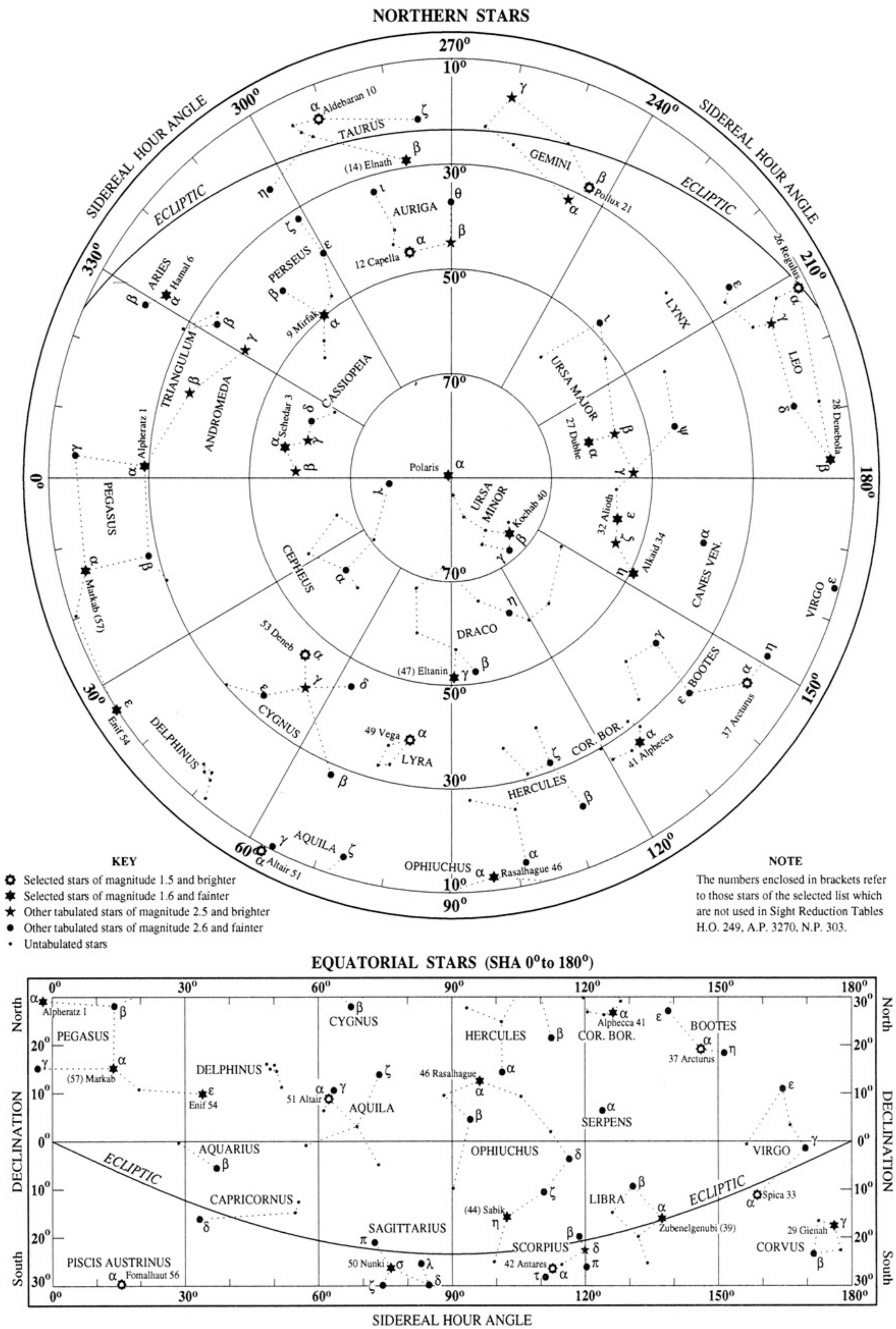



*Figure 1532a. Star chart from Nautical Almanac.*

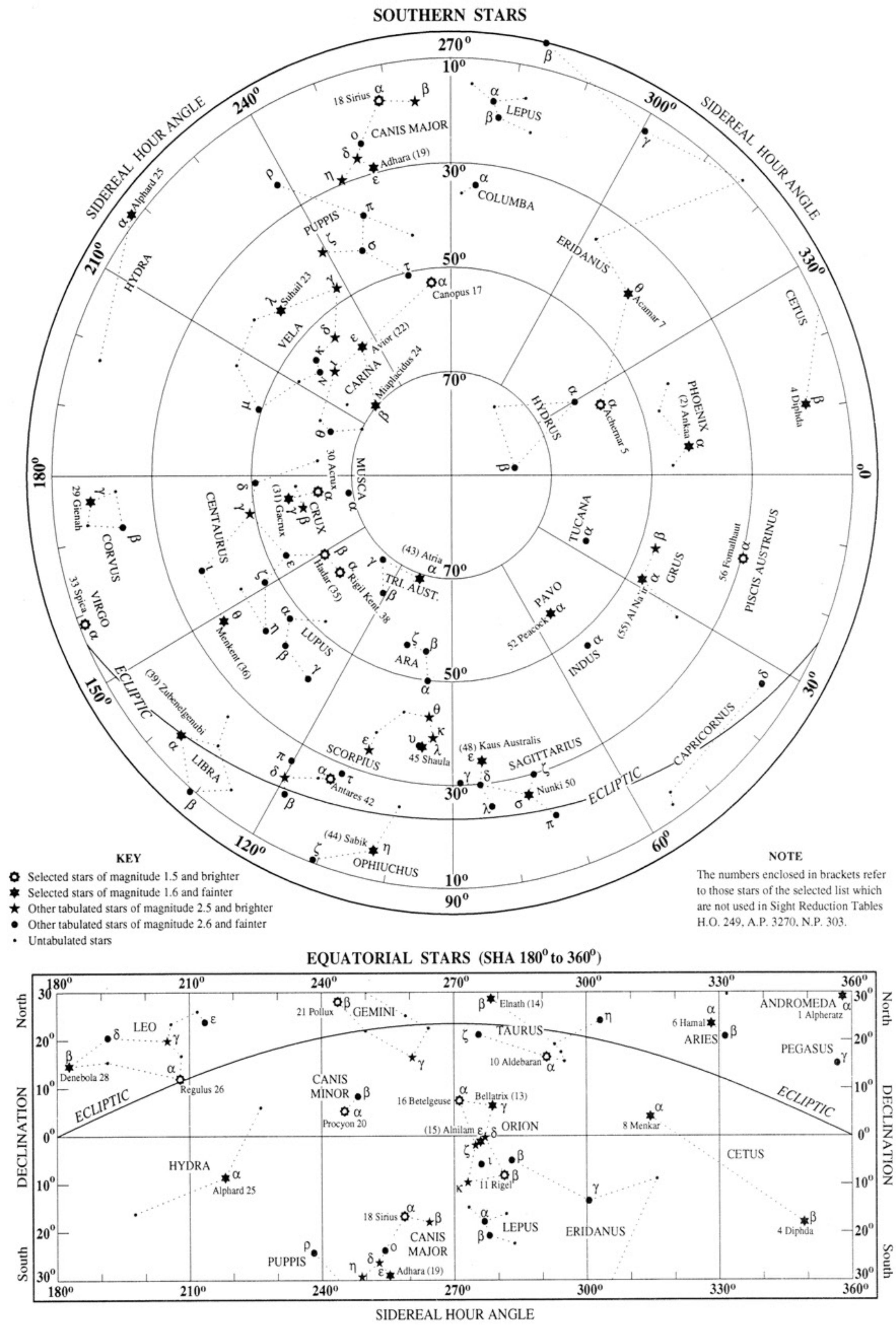



*Figure 1532b. Star chart from Nautical Almanac.*

| | Fig. 1534 | Fig.1535 | Fig. 1536 | Fig. 1537 |
|---|---|---|---|---|
| Local sidereal time | 0000 | 0600 | 1200 | 1800 |
| LMT 1800 | Dec. 21 | Mar. 22 | June 22 | Sept. 21 |
| LMT 2000 | Nov. 21 | Feb. 20 | May 22 | Aug. 21 |
| LMT 2200 | Oct. 21 | Jan. 20 | Apr. 22 | July 22 |
| LMT 0000 | Sept. 22 | Dec. 22 | Mar. 23 | June 22 |
| LMT 0200 | Aug. 22 | Nov. 22 | Feb. 21 | May 23 |
| LMT 0400 | July 23 | Oct. 22 | Jan 21 | Apr. 22 |
| LMT 0600 | June 22 | Sept. 21 | Dec. 22 | Mar. 23 |

*Table 1532. Locating the zenith on the star diagrams.*

The star charts shown in Figure 1533 through Figure 1536, on the transverse Mercator projection, are designed to assist in learning Polaris and the stars listed on the daily pages of the *Nautical Almanac*. Each chart extends about 20° beyond each celestial pole, and about 60° (four hours) each side of the central hour circle (at the celestial equator). Therefore, they do not coincide exactly with that half of the celestial sphere above the horizon at any one time or place. The zenith, and hence the horizon, varies with the position of the observer on the Earth. It also varies with the rotation of the Earth (apparent rotation of the celestial sphere). The charts show all stars of fifth magnitude and brighter as they appear in the sky, but with some distortion toward the right and left edges.

The overprinted lines add certain information of use in locating the stars. Only Polaris and the 57 stars listed on the daily pages of the *Nautical Almanac* are named on the charts. The almanac star charts can be used to locate the additional stars given near the back of the *Nautical Almanac* and the *Air Almanac*. Dashed lines connect stars of some of the more prominent constellations. Solid lines indicate the celestial equator and useful relationships among stars in different constellations. The celestial poles are marked by crosses, and labeled. By means of the celestial equator and the poles, one can locate his zenith approximately along the mid hour circle, when this coincides with his celestial meridian, as shown in Table 1532. At any time earlier than those shown in Table 1532 the zenith is to the right of center, and at a later time it is to the left, approximately one-quarter of the distance from the center to the outer edge (at the celestial equator) for each hour that the time differs from that shown. The stars in the vicinity of the North Pole can be seen in proper perspective by inverting the chart, so that the zenith of an observer in the Northern Hemisphere is up from the pole.

**1533. Stars in the Vicinity of Pegasus**

In autumn the evening sky has few first magnitude stars. Most are near the southern horizon of an observer in the latitudes of the United States. A relatively large number of second and third magnitude stars seem conspicuous, perhaps because of the small number of brighter stars. High in the southern sky three third magnitude stars and one second magnitude star form a square with sides nearly 15° of arc in length. This is Pegasus, the winged horse.

Only Markab at the southwestern corner and Alpheratz at the northeastern corner are listed on the daily pages of the *Nautical Almanac*. Alpheratz is part of the constellation Andromeda, the princess, extending in an arc toward the northeast and terminating at Mirfak in Perseus, legendary rescuer of Andromeda.

A line extending northward through the eastern side of the square of Pegasus passes through the leading (western) star of M-shaped (or W-shaped) Cassiopeia, the legendary mother of the princess Andromeda. The only star of this constellation listed on the daily pages of the *Nautical Almanac* is Schedar, the second star from the leading one as the configuration circles the pole in a counterclockwise direction. If the line through the eastern side of the square of Pegasus is continued on toward the north, it leads to second magnitude Polaris, the North Star (less than 1° from the north celestial pole) and brightest star of Ursa Minor, the Little Dipper. Kochab, a second magnitude star at the other end of Ursa Minor, is also listed in the almanacs. At this season Ursa Major is low in the northern sky, below the celestial pole. A line extending from Kochab through Polaris leads to Mirfak, assisting in its identification when Pegasus and Andromeda are near or below the horizon.

Deneb, in Cygnus, the swan, and Vega are bright, first magnitude stars in the northwestern sky. The line through the eastern side of the square of Pegasus approximates the hour circle of the vernal equinox, shown at Aries on the celestial equator to the south. The Sun is at Aries on or about March 21, when it crosses the celestial equator from south to north. If the line through the eastern side of Pegasus is extended southward and curved slightly toward the east, it leads to second magnitude Diphda. A longer and straighter line southward through the western side of Pegasus leads to first magnitude Fomalhaut. A line extending northeasterly from Fomalhaut through Diphda leads to Menkar, a third magnitude star, but the brightest in its vicinity. Ankaa, Diphda, and Fomalhaut form an isosceles triangle, with the apex at Diphda. Ankaa is near or below the southern horizon of observers in latitudes of the United States. Four stars farther south than Ankaa may be visible when on the celes-

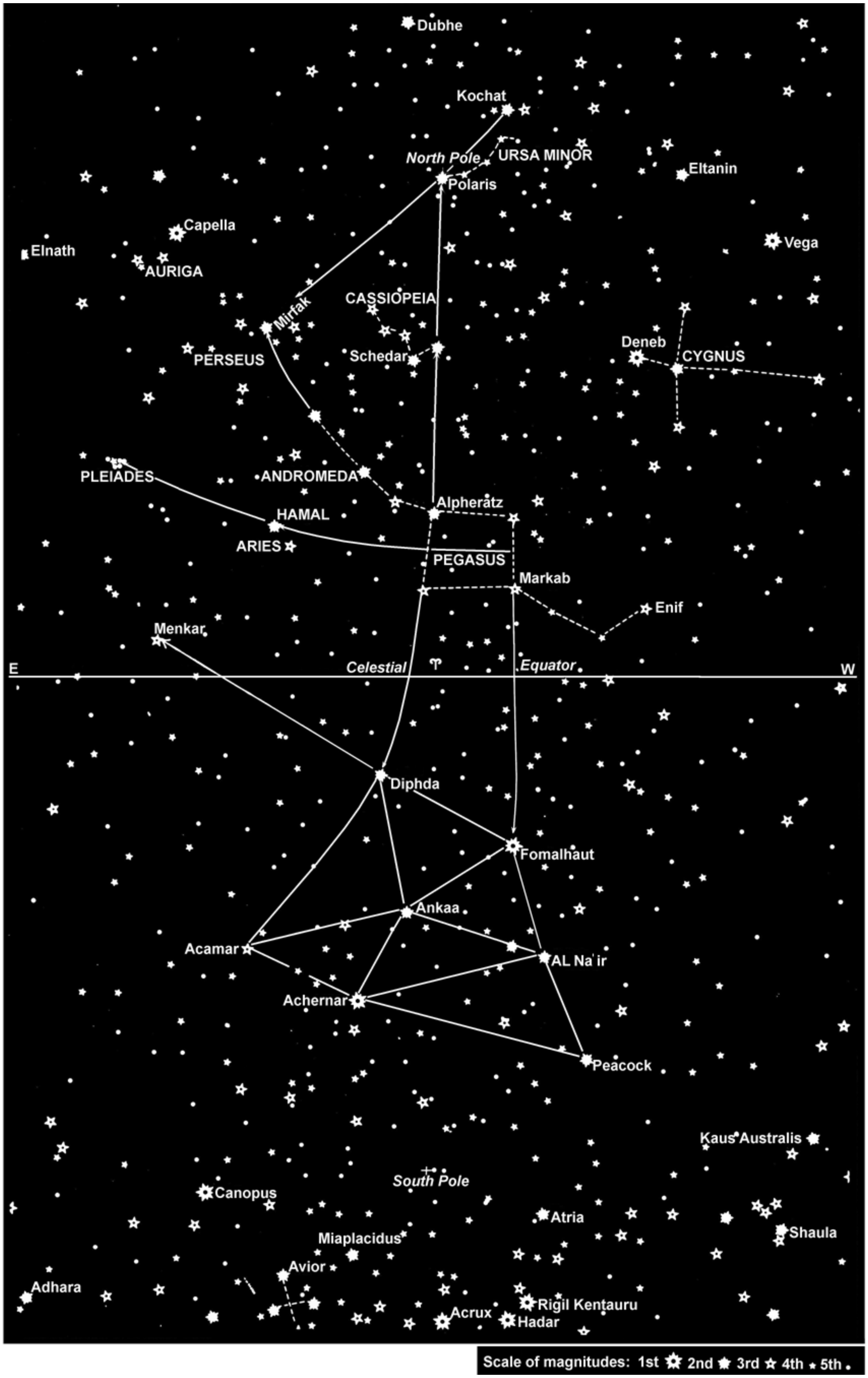



*Figure 1533. Stars in the vicinity of Pegasus.*

tial meridian, just above the horizon of observers in latitudes of the extreme southern part of the United States. These are Acamar, Achernar, Al Na'ir, and Peacock. These stars, with each other and with Ankaa, Fomalhaut, and Diphda, form a series of triangles as shown in Figure 1533. Almanac stars near the bottom of Figure 1533 are discussed in succeeding articles.

Two other almanac stars can be located by their positions relative to Pegasus. These are Hamal in the constellation Aries, the ram, east of Pegasus, and Enif, west of the southern part of the square, identified in Figure 1533. The line leading to Hamal, if continued, leads to the Pleiades (the Seven Sisters), not used by navigators for celestial observations, but a prominent figure in the sky, heralding the approach of the many conspicuous stars of the winter evening sky.

### 1534. Stars in the Vicinity of Orion

As Pegasus leaves the meridian and moves into the western sky, Orion, the hunter, rises in the east. With the possible exception of Ursa Major, no other configuration of stars in the entire sky is as well known as Orion and its immediate surroundings. In no other region are there so many first magnitude stars.

The belt of Orion, nearly on the celestial equator, is visible in virtually any latitude, rising and setting almost on the prime vertical, and dividing its time equally above and below the horizon. Of the three second magnitude stars forming the belt, only Alnilam, the middle one, is listed on the daily pages of the *Nautical Almanac*.

Four conspicuous stars form a box around the belt. Rigel, a hot, blue star, is to the south. Betelgeuse, a cool, red star lies to the north. Bellatrix, bright for a second magnitude star but overshadowed by its first magnitude neighbors, is a few degrees west of Betelgeuse. Neither the second magnitude star forming the southeastern corner of the box, nor any star of the dagger, is listed on the daily pages of the *Nautical Almanac*.

A line extending eastward from the belt of Orion, and curving toward the south, leads to Sirius, the brightest star in the entire heavens, having a magnitude of –1.6. Only Mars and Jupiter at or near their greatest brilliance, the Sun, Moon, and Venus are brighter than Sirius. Sirius is part of the constellation Canis Major, the large hunting dog of Orion. Starting at Sirius a curved line extends northward through first magnitude Procyon, in Canis Minor, the small hunting dog; first magnitude Pollux and second magnitude Castor (not listed on the daily pages of the *Nautical Almanac*), the twins of Gemini; brilliant Capella in Auriga, the charioteer; and back down to first magnitude Aldebaran, the follower, which trails the Pleiades, the seven sisters. Aldebaran, brightest star in the head of Taurus, the bull, may also be found by a curved line extending northwestward from the belt of Orion. The V-shaped figure forming the outline of the head and horns of Taurus points toward third magnitude Menkar. At the summer solstice the Sun is between Pollux and Aldebaran.

If the curved line from Orion's belt southeastward to Sirius is continued, it leads to a conspicuous, small, nearly equilateral triangle of three bright second magnitude stars of nearly equal brilliancy. This is part of Canis Major. Only Adhara, the westernmost of the three stars, is listed on the daily pages of the *Nautical Almanac*. Continuing on with somewhat less curvature, the line leads to Canopus, second brightest star in the heavens and one of the two stars having a negative magnitude (–0.9). With Suhail and Miaplacidus, Canopus forms a large, equilateral triangle which partly encloses the group of stars often mistaken for Crux. The brightest star within this triangle is Avior, near its center. Canopus is also at one apex of a triangle formed with Adhara to the north and Suhail to the east, another triangle with Acamar to the west and Achernar to the southwest, and another with Achernar and Miaplacidus. Acamar, Achernar, and Ankaa form still another triangle toward the west. Because of chart distortion, these triangles do not appear in the sky in exactly the relationship shown on the star chart. Other daily-page almanac stars near the bottom of Figure 1534 are discussed in succeeding articles.

In the winter evening sky, Ursa Major is east of Polaris, Ursa Minor is nearly below it, and Cassiopeia is west of it. Mirfak is northwest of Capella, nearly midway between it and Cassiopeia. Hamal is in the western sky. Regulus and Alphard are low in the eastern sky, heralding the approach of the configurations associated with the evening skies of spring.

### 1535. Stars in the Vicinity of Ursa Major

As if to enhance the splendor of the sky in the vicinity of Orion, the region toward the east, like that toward the west, has few bright stars, except in the vicinity of the south celestial pole. However, as Orion sets in the west, leaving Capella and Pollux in the northwestern sky, a number of good navigational stars move into favorable positions for observation.

Ursa Major, the great bear, appears prominently above the north celestial pole, directly opposite Cassiopeia, which appears as a "W" just above the northern horizon of most observers in latitudes of the United States. Of the seven stars forming Ursa Major, only Dubhe, Alioth, and Alkaid are listed on the daily pages of the *Nautical Almanac*. See Figure 1535.

The two second magnitude stars forming the outer part of the bowl of Ursa Major are often called the pointers because a line extending northward (down in spring evenings) through them points to Polaris. Ursa Minor, the Little Bear, contains Polaris at one end and Kochab at the other. Relative to its bowl, the handle of Ursa Minor curves in the opposite direction to that of Ursa Major.

A line extending southward through the pointers, and curving somewhat toward the west, leads to first magnitude Regulus, brightest star in Leo, the lion. The head,

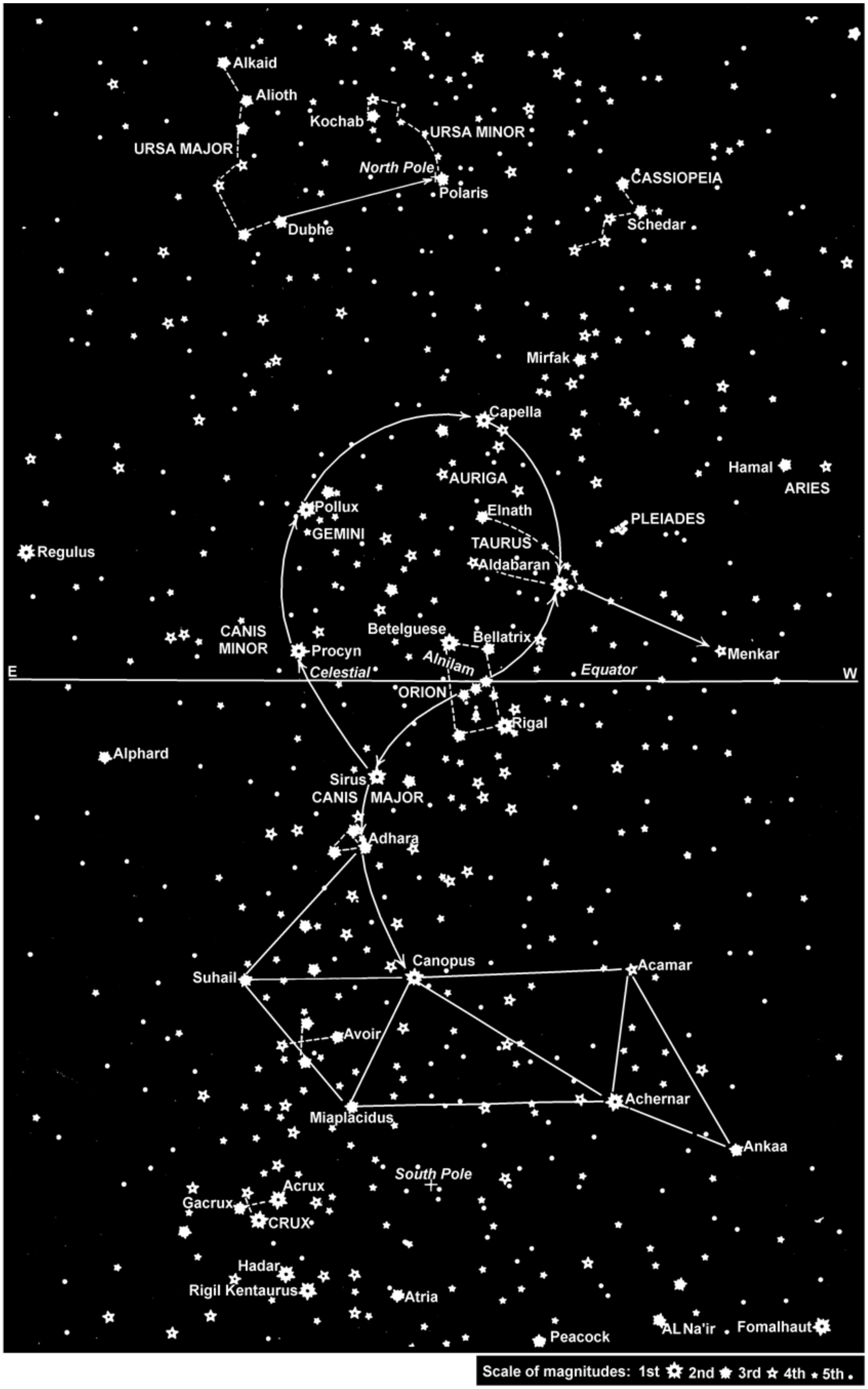



*Figure 1534. Stars in the vicinity of Orion.*

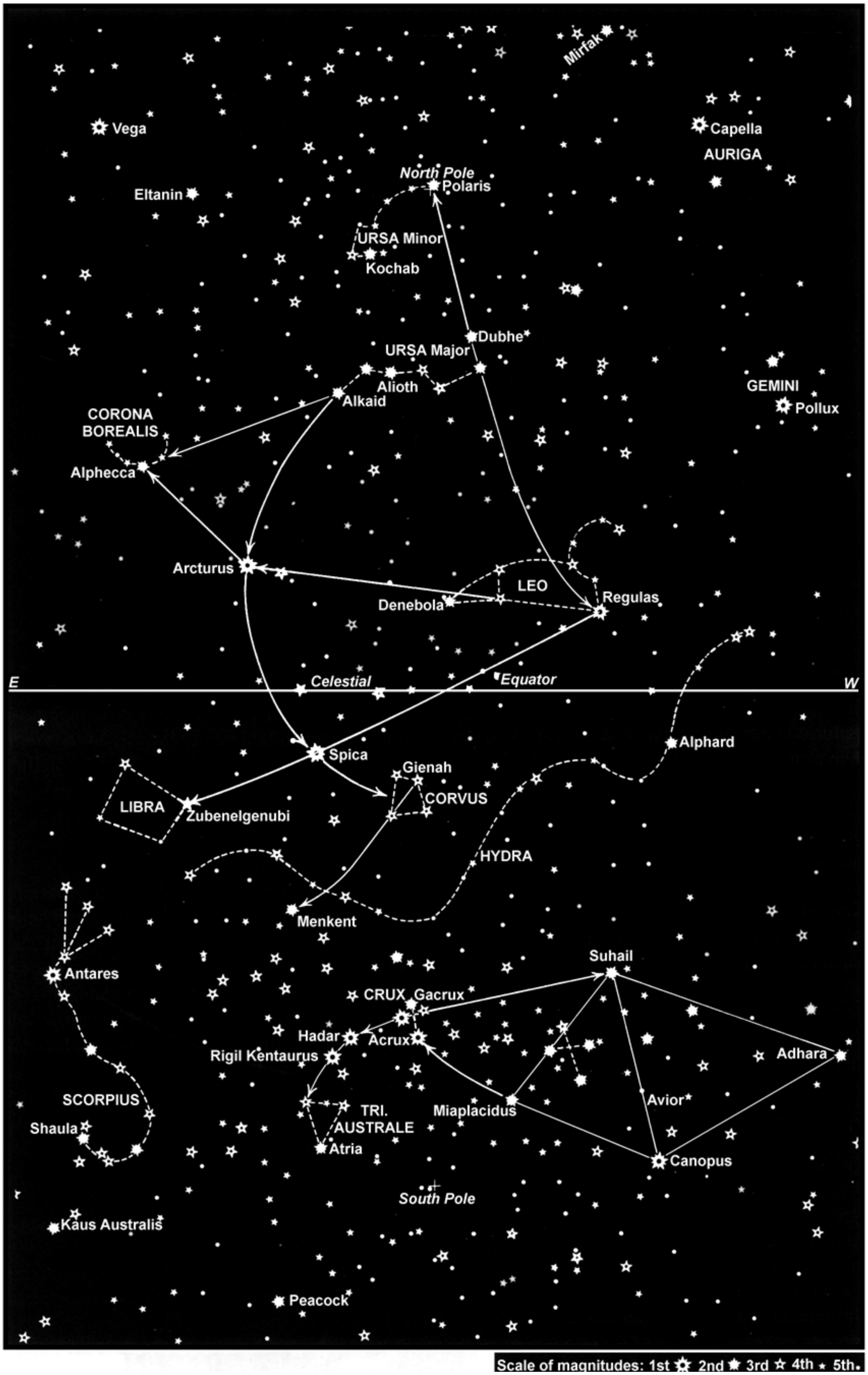



*Figure 1535. Stars in the vicinity of Ursa Major.*

shoulders, and front legs of this constellation form a sickle, with Regulus at the end of the handle. Toward the east is second magnitude Denebola, the tail of the lion. On toward the southwest from Regulus is second magnitude Alphard, brightest star in Hydra, the sea serpent. A dark sky and considerable imagination are needed to trace the long, winding body of this figure.

A curved line extending the arc of the handle of Ursa Major leads to first magnitude Arcturus. With Alkaid and Alphecca, brightest star in Corona Borealis, the Northern Crown, Arcturus forms a large, inconspicuous triangle. If the arc through Arcturus is continued, it leads next to first magnitude Spica and then to Corvus, the crow. The brightest star in this constellation is Gienah, but three others are nearly as bright. At autumnal equinox, the Sun is on the celestial equator, about midway between Regulus and Spica.

A long, slightly curved line from Regulus, east-southeasterly through Spica, leads to Zubenelgenubi at the southwestern corner of an inconspicuous box-like figure called Libra, the scales.

Returning to Corvus, a line from Gienah, extending diagonally across the figure and then curving somewhat toward the east, leads to Menkent, just beyond Hydra.

Far to the south, below the horizon of most northern hemisphere observers, a group of bright stars is a prominent feature of the spring sky of the Southern Hemisphere. This is Crux, the Southern Cross. Crux is about 40° south of Corvus. The “false cross” to the west is often mistaken for Crux. Acrux at the southern end of Crux and Gacrux at the northern end are listed on the daily pages of the *Nautical Almanac*.

The triangles formed by Suhail, Miaplacidus, and Canopus, and by Suhail, Adhara, and Canopus, are west of Crux. Suhail is in line with the horizontal arm of Crux. A line from Canopus, through Miaplacidus, curved slightly toward the north, leads to Acrux. A line through the east-west arm of Crux, eastward and then curving toward the south, leads first to Hadar and then to Rigil Kentaurus, both very bright stars. Continuing on, the curved line leads to small Triangulum Australe, the Southern Triangle, the easternmost star of which is Atria.

**1536. Stars in the Vicinity of Cygnus**

As the celestial sphere continues in its apparent westward rotation, the stars familiar to a spring evening observer sink low in the western sky. By midsummer, Ursa Major has moved to a position to the left of the north celestial pole, and the line from the pointers to Polaris is nearly horizontal. Ursa Minor, is standing on its handle, with Kochab above and to the left of the celestial pole. Cassiopeia is at the right of Polaris, opposite the handle of Ursa Major. See Figure 1536.

The only first magnitude star in the western sky is Arcturus, which forms a large, inconspicuous triangle with Alkaid, the end of the handle of Ursa Major, and Alphecca, the brightest star in Corona Borealis, the Northern Crown.

The eastern sky is dominated by three very bright stars. The westernmost of these is Vega, the brightest star north of the celestial equator, and third brightest star in the heavens, with a magnitude of 0.1. With a declination of a little less than 39°N, Vega passes through the zenith along a path across the central part of the United States, from Washington in the east to San Francisco on the Pacific coast. Vega forms a large but conspicuous triangle with its two bright neighbors, Deneb to the northeast and Altair to the southeast. The angle at Vega is nearly a right angle. Deneb is at the end of the tail of Cygnus, the swan. This configuration is sometimes called the Northern Cross, with Deneb at the head. To modern youth it more nearly resembles a dive bomber, while it is still well toward the east, with Deneb at the nose of the fuselage. Altair has two fainter stars close by, on opposite sides. The line formed by Altair and its two fainter companions, if extended in a northwesterly direction, passes through Vega, and on to second magnitude Eltanin. The angular distance from Vega to Eltanin is about half that from Altair to Vega. Vega and Altair, with second magnitude Rasalhague to the west, form a large equilateral triangle. This is less conspicuous than the Vega-Deneb-Altair triangle because the brilliance of Rasalhague is much less than that of the three first magnitude stars, and the triangle is overshadowed by the brighter one.

Far to the south of Rasalhague, and a little toward the west, is a striking configuration called Scorpius, the scorpion. The brightest star, forming the head, is red Antares. At the tail is Shaula.

Antares is at the southwestern corner of an approximate parallelogram formed by Antares, Sabik, Nunki, and Kaus Australis. With the exception of Antares, these stars are only slightly brighter than a number of others nearby, and so this parallelogram is not a striking figure. At winter solstice the Sun is a short distance northwest of Nunki.

Northwest of Scorpius is the box-like Libra, the scales, of which Zubenelgenubi marks the southwest corner.

With Menkent and Rigil Kentaurus to the southwest, Antares forms a large but unimpressive triangle. For most observers in the latitudes of the United States, Antares is low in the southern sky, and the other two stars of the triangle are below the horizon. To an observer in the Southern Hemisphere Crux is to the right of the south celestial pole, which is not marked by a conspicuous star. A long, curved line, starting with the now-vertical arm of Crux and extending northward and then eastward, passes successively through Hadar, Rigil Kentaurus, Peacock, and Al Na’ir.

Fomalhaut is low in the southeastern sky of the southern hemisphere observer, and Enif is low in the eastern sky at nearly any latitude. With the appearance of these stars it is not long before Pegasus will appear over the eastern horizon during the evening, and as the winged horse climbs evening by

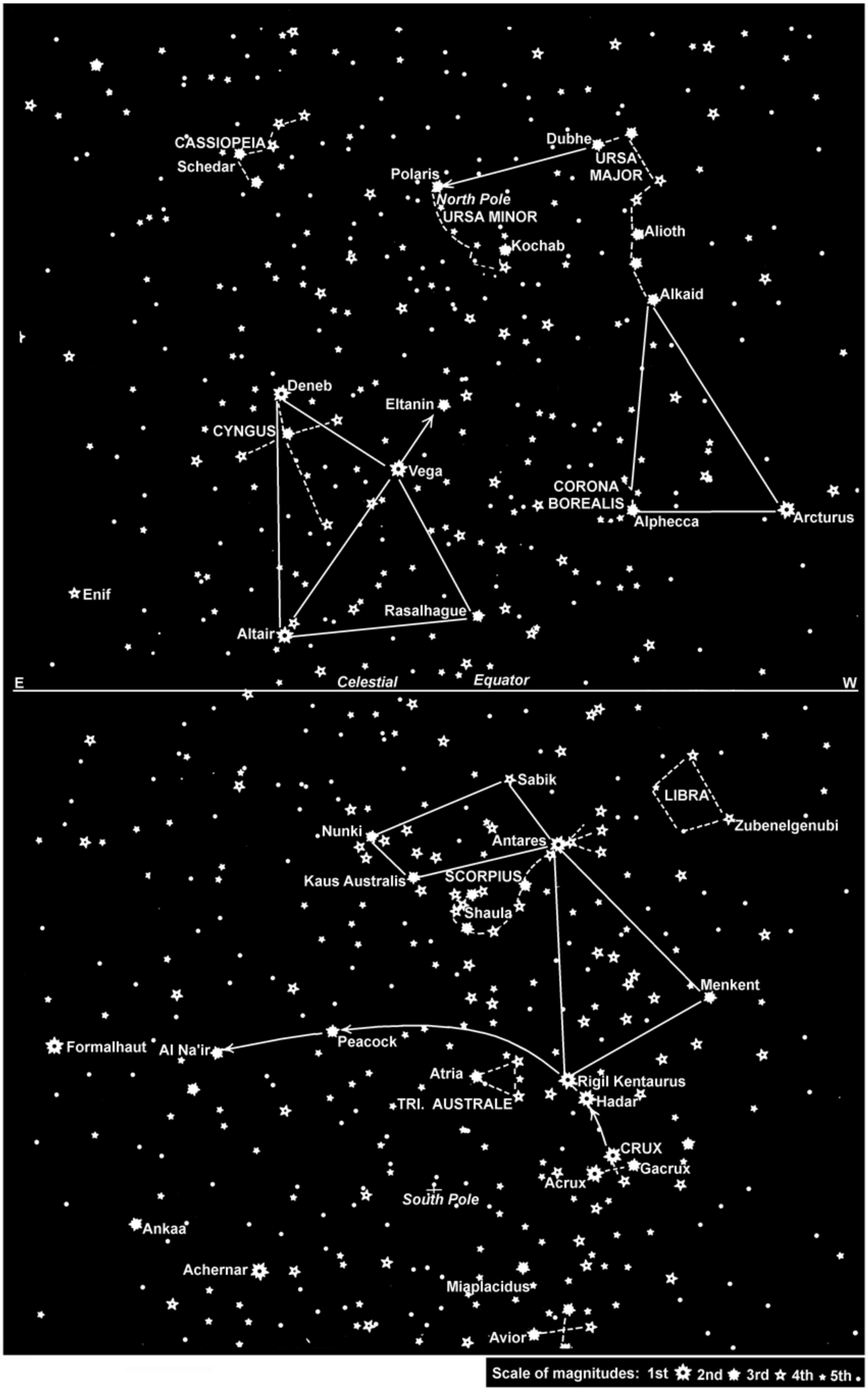



*Figure 1536. Stars in the vicinity of Cygnus.*

evening to a position higher in the sky, a new annual cycle approaches.

### 1537. Planet Diagram

The planet diagram in the *Nautical Almanac* shows, for any date, the LMT of meridian passage of the Sun, for the five planets Mercury, Venus, Mars, Jupiter, and Saturn, and of each 30° of SHA. The diagram provides a general picture of the availability of planets and stars for observation, and thus shows:

1. Whether a planet or star is too close to the Sun for observation.
2. Whether a planet is a morning or evening star.
3. Some indication of the planet's position during twilight.
4. The proximity of other planets.
5. Whether a planet is visible from evening to morning twilight.

A band 45 minutes wide is shaded on each side of the curve marking the LMT of meridian passage of the Sun. Any planet and most stars lying within the shaded area are too close to the Sun for observation.

When the meridian passage occurs at midnight, the body is in opposition to the Sun and is visible all night; planets may be observable in both morning and evening twilights. As the time of meridian passage decreases, the body ceases to be observable in the morning, but its altitude above the eastern horizon during evening twilight gradually increases; this continues until the body is on the meridian at twilight. From then onwards the body is observable above the western horizon and its altitude at evening twilight gradually decreases; eventually the body comes too close to the Sun for observation. When the body again becomes visible, it is seen as a morning star low in the east. Its altitude at twilight increases until meridian passage occurs at the time of morning twilight. Then, as the time of meridian passage decreases to $0^h$, the body is observable in the west in the morning twilight with a gradually decreasing altitude, until it once again reaches opposition.

Only about one-half the region of the sky along the ecliptic, as shown on the diagram, is above the horizon at one time. At sunrise (LMT about $6^h$) the Sun and, hence, the region near the middle of the diagram, are rising in the east; the region at the bottom of the diagram is setting in the west. The region half way between is on the meridian. At sunset (LMT about $18^h$) the Sun is setting in the west; the region at the top of the diagram is rising in the east. Marking the planet diagram of the *Nautical Almanac* so that east is at the top of the diagram and west is at the bottom can be useful to interpretation.

If the curve for a planet intersects the vertical line connecting the date graduations below the shaded area, the planet is a morning star; if the intersection is above the shaded area, the planet is an evening star.

A similar planet location diagram in the *Air Almanac* represents the region of the sky along the ecliptic within which the Sun, Moon, and planets always move; it shows, for each date, the Sun in the center and the relative positions of the Moon, the five planets Mercury, Venus, Mars, Jupiter, Saturn and the four first magnitude stars Aldebaran, Antares, Spica, and Regulus, and also the position on the ecliptic which is north of Sirius (i.e. Sirius is 40° south of this point). The first point of Aries is also shown for reference. The magnitudes of the planets are given at suitable intervals along the curves. The Moon symbol shows the correct phase. A straight line joining the date on the left-hand side with the same date of the right-hand side represents a complete circle around the sky, the two ends of the line representing the point 180° from the Sun; the intersections with the curves show the spacing of the bodies along the ecliptic on the date. The time scale indicates roughly the local mean time at which an object will be on the observer's meridian.

At any time only about half the region on the diagram is above the horizon. At sunrise the Sun (and hence the region near the middle of the diagram), is rising in the east and the region at the end marked "West" is setting in the west; the region half-way between these extremes is on the meridian, as will be indicated by the local time (about $6^h$). At the time of sunset (local time about $18^h$) the Sun is setting in the west, and the region at the end marked "East" is rising in the east. The diagram should be used in conjunction with the Sky Diagrams.

### 1538. Finding Stars for a Fix

Various devices have been invented to help an observer find individual stars. The most widely used is the **Star Finder and Identifier**, formerly published by the U.S. Navy Hydrographic Office as *No. 2102D*. It is no longer issued, having been replaced officially by the STELLA computer program, but it is still available commercially. A navigational calculator or computer program is much quicker, more accurate, and less tedious.

In fact, the process of identifying stars is no longer necessary because the computer or calculator does it automatically. The navigator need only take sights and enter the required data. The program identifies the bodies, solves for the LOP's for each, combines them into the best fix, and displays the lat./long. position. Most computer programs also print out a plotted fix, just as the navigator might have drawn by hand.

The data required by the calculator or program consists of the DR position, the sextant altitude of the body, the time, and the azimuth of the body. The name of the body is not necessary because there will be only one possible body meeting those conditions, which the computer will identify.

Computer sight reduction programs can also automatically predict twilight on a moving vessel and create a plot of the sky at the vessel's twilight location (or any location, at any time). This plot will be free of the distortion inherent in the mechanical star finders and will show all bodies, even planets, Sun, and Moon, in their correct relative orientation centered on the observer's zenith. It will also indicate which stars provide the best geometry for a fix.

Computer sight reduction programs or celestial navigation calculators are especially useful when the sky is only briefly visible thorough broken cloud cover. The navigator can quickly shoot any visible body without having to identify it by name, and let the computer do the rest.

**1539. Identification by Computation**

If the altitude and azimuth of the celestial body, and the approximate latitude of the observer, are known, the navigational triangle can be solved for meridian angle and declination. The meridian angle can be converted to LHA, and this to GHA. With this and GHA ♈ at the time of observation, the SHA of the body can be determined. With SHA and declination, one can identify the body by reference to an almanac. Any method of solving a spherical triangle, with two sides and the included angle being given, is suitable for this purpose. A large-scale, carefully-drawn diagram on the plane of the celestial meridian, using the refinement shown in Figure 1528f, should yield satisfactory results.

Although no formal star identification tables are included in *Pub. No. 229*, a simple approach to star identification is to scan the pages of the appropriate latitudes, and observe the combination of arguments which give the altitude and azimuth angle of the observation. Thus the declination and LHA ★ are determined directly. The star's SHA is found from SHA ★ = LHA ★ – LHA ♈. From these quantities the star can be identified from the *Nautical Almanac*.

Another solution is available through an interchange of arguments using the nearest integral values. The procedure consists of entering *Pub. No. 229* with the observer's latitude (same name as declination), with the observed azimuth angle (converted from observed true azimuth as required) as LHA and the observed altitude as declination, and extracting from the tables the altitude and azimuth angle respondents. The extracted altitude becomes the body's declination; the extracted azimuth angle (or its supplement) is the meridian angle of the body. Note that the tables are always entered with latitude of same name as declination. In north latitudes the tables can be entered with true azimuth as LHA.

If the respondents are extracted from above the C-S Line on a right-hand page, the name of the latitude is actually contrary to the declination. Otherwise, the declination of the body has the same name as the latitude. If the azimuth angle respondent is extracted from above the C-S Line, the supplement of the tabular value is the meridian angle, t, of the body. If the body is east of the observer's meridian, LHA = 360° – t; if the body is west of the meridian, LHA = t.