

# Chapter 2

## CELESTIAL COORDINATE SYSTEMS

### 2-A. Introduction

There are several different ways of representing the appearance of the sky or describing the locations of objects that we see in the sky. One way is to imagine that every object in the sky is located on a very large and distant sphere called the **celestial sphere**. This imaginary sphere has its center at the center of the Earth. Since the radius of the Earth is very small compared to the radius of the celestial sphere, we can imagine that this sphere is also centered on any person or observer standing on the Earth's surface. Every celestial object (e.g., a star or planet) has a definite location in the sky with respect to some arbitrary reference point. Once defined, such a reference point can be used as the origin of a celestial coordinate system. Now, there is an astronomically important point in the sky called the **vernal equinox**, which astronomers use as the origin of such a celestial coordinate system. The meaning and significance of the vernal equinox will be discussed later.

In an analogous way, we represent the surface of the Earth by a globe or sphere. Locations on the geographic sphere are specified by the coordinates called geographic **longitude** and **latitude**. The origin for this geographic coordinate system is the point where the Prime Meridian and the Geographic Equator intersect. This is a point located off the coast of west-central Africa. To specify a location on a sphere, the coordinates must be angles, since a sphere has a curved surface. Hence, longitude and latitude are angular distances from the origin described above. Longitude is measured west or east from the origin (or prime meridian), and latitude is measured north or south from the origin (or geographic equator). If a ship happens to be located exactly at the geographic origin, we would say it has a longitude of 0 degrees (also written  $0^\circ$ ) and latitude of  $0^\circ$ .

When one uses the celestial sphere to represent the sky, any measurements of position must also be angles. As on a geographic globe, two such angles are necessary to uniquely specify the location of any object on the celestial sphere. The two angles or coordinates that astronomers use to specify position with respect to the vernal equinox are called **right ascension** and **declination**.

A peculiar thing about right ascension is that, though it is an angle, it is usually expressed in time units, that is, hours, minutes and seconds of time. This is because there is a definite relationship between right ascension and something called **sidereal time** (sidereal time will be defined and studied later). An analogous relationship exists between longitude and time. A star located exactly at the vernal equinox would have a right ascension of 0 hours, 0 minutes (other ways of designating this are  $0^h 00^m$  or 0:00) and a declination of 0 degrees, 0 arcminutes ( $0^\circ 00'$  or 0:00).

**Note: Do not confuse minutes of time with arcminutes, they are not the same. See section 2-B.**

### 2-B. Angular or Arc Measurement.

Any circle can be divided into any number of equal parts. For example, imagine dividing a circle into 4 equal parts. Any of these parts is called an **arc** and would be a certain fraction of the circumference of the circle; in this case, one fourth of a circumference. The ancient Babylonians found it convenient to divide a circle into 360 equal parts, which we call **degrees**. Thus,

**One degree is 1/360th of a circle's circumference.**

The Babylonians had an apparent fixation on multiples of 60, so they further divided each degree into 60 equal parts called arcminutes, or minutes of arc. That is,

**1 arcminute (1') is 1/60th of a degree.**

To allow for greater precision, they decided to divide each arcminute into 60 equal parts called arcseconds, or seconds of arc. Hence,

**1 arcsecond is 1/60th of an arcminute or 1/3600th of a degree.**

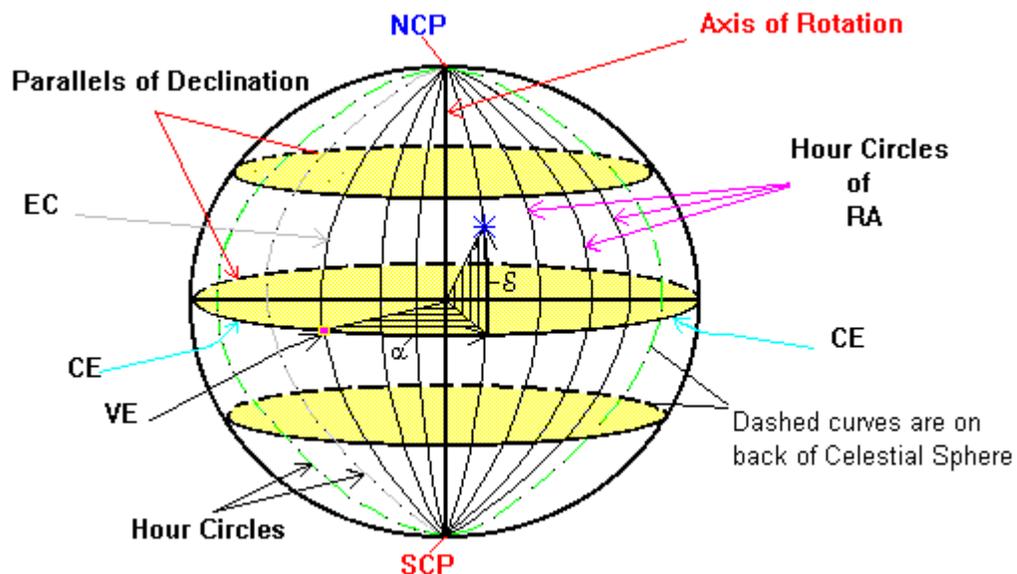
Such a system of measurement, based on the number 60, is called a **sexagesimal** system. We find a sexagesimal system far more difficult to use than a decimal system, but such a system did not daunt the Babylonians or the Egyptians and Greeks who also adopted this system. Unfortunately, it became so ingrained in early western civilization that it is still in common use for making angular measurements today. Thus we must learn to work with it. You should note that we also use a sexagesimal system for counting time. Often, we shall also want to express angular distance in decimal degrees. That is,  $5^{\circ} 15'$  in the sexagesimal system is equivalent to 5.25 degrees in the decimal system.

Remember that astronomers find it useful to express the celestial coordinate, right ascension, in time units. This is because the Earth rotates eastward on its axis, once every day. This makes the celestial sphere appear to turn at the same rate, but in the opposite direction, namely, westward. That is, if one faces south, stars would appear to move from the east towards the west, which would be from your left to your right and is referred to as the **apparent diurnal rotation of the celestial sphere**.

The rate of this motion is 15 degrees per hour. This number comes from the fact that Earth, or celestial sphere (you may assume one or the other rotates but not both), makes one complete turn through 360 degrees in 24 hours. This also means that the Earth rotates through an angle of 1 degree every four minutes of time. Since 1 degree contains 60', then the Earth turns 15' every 1m. This should point out the distinct difference between arcminutes and time minutes. One is an angle and the other is a time. **Never substitute one unit's abbreviation for the other, that is, never write 45' (forty-five arcminutes) when you mean 45m (forty-five minutes of time), or vice versa.**

## 2-C. The Equatorial Coordinate System

The diagram below is a schematic of the celestial sphere. The axis of rotation of the Earth or the Celestial sphere, depending on which you assume is rotating, is labeled. The two points where



the axis touches the celestial sphere are called the **north** and **south celestial poles**, **NCP** and **SCP**.

Midway between the poles is a great circle that divides the celestial sphere into two hemispheres. This circle is called the celestial equator (**CE**).

**Celestial Equator: The great circle on the celestial sphere, every point of which is exactly 90 degrees from the celestial poles.**

There is a family of great circles that run from one celestial pole to the other and cross the celestial equator at a right angle. These are called hour circles of right ascension and they are analogous to meridians of longitude on the Earth

Remember that a point called the vernal equinox (**VE**) is the origin of our celestial coordinate system. This point is located on the celestial equator. Right ascension starts at the vernal equinox and increases eastward from there, all the way around the celestial sphere back to the vernal equinox again. That is, RA increases eastward from 0 to 24 hours. On a globe or star chart, the number zero marks the hour circle passing through the vernal equinox. This hour circle is called the **equinoctial colure (EC)**.

There is another family of circles, each member of which runs around the celestial sphere parallel to the celestial equator, anywhere between the latter and the celestial poles. These are called **parallels of declination** and are analogous to parallels of latitude on the Earth. All of these circles are smaller than the celestial equator and the closer one is to the celestial poles, the smaller it is. The celestial equator is itself a parallel of declination. On a globe or star chart, there should be a number written somewhere on each of these circles to identify what declination that circle represents.

Declination is an angle measured north or south from the celestial equator. This angle can be imagined as an arc drawn on a globe starting at the celestial equator and extending along an hour circle to the parallel of declination passing through the object we are trying to locate. Note and memorize the following:

**Right ascension ( $\alpha$ )** is the angular distance measured eastward around the sky from the vernal equinox.

**Declination ( $\delta$ )** is the angular distance measured north (+) or south (-) from the celestial equator.

**All objects located on the same parallel of declination have the same declination but different right ascensions. Similarly, all objects located on the same hour circle have the same right ascension but different declinations.**

## **2-D. Locating Objects on a Celestial Globe or Star Chart by Interpolation**

The star chart below is an attempt to represent a portion of the celestial sphere in such a way so as to account for its curvature. This kind of map or chart is referred to as an orthographic projection. In the chart, there is an hour circle of right ascension drawn every hour for a limited portion of the sky centered on the equinoctial colure. The right ascension for each hour circle is labeled along the bottom of the chart and parallels of declination for every 10 degrees are labeled along the right edge of the chart.

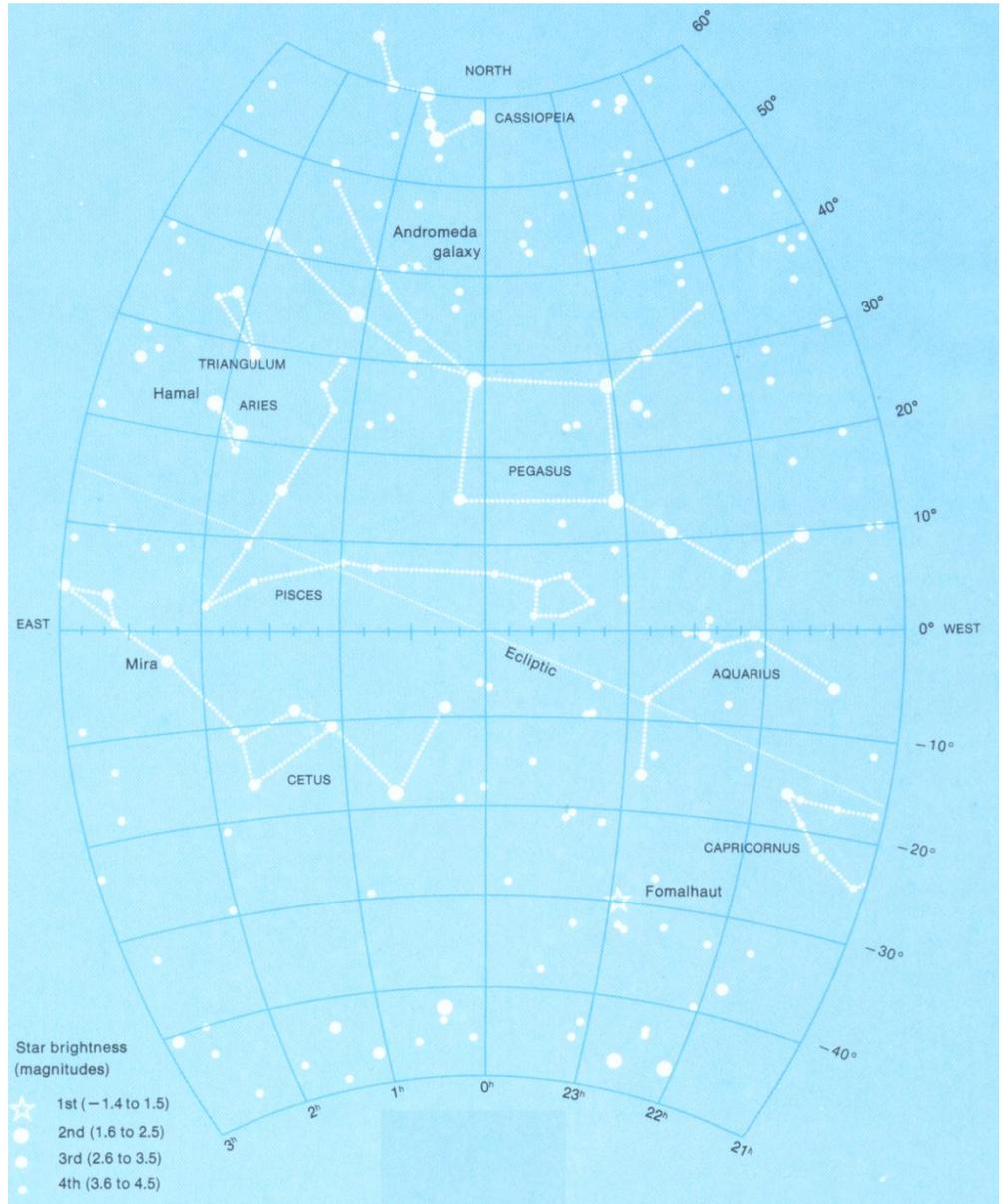
In order to locate an object on the celestial sphere, remember the following rule:

**Through any object on the celestial sphere, one can draw a definite hour circle of right ascension and a definite parallel of declination.**

That is, the hour circles and declination parallels that are already drawn on a globe or star chart are referred to as **fiducial** ones, but they are not the only ones that could be drawn. Hence, if the parallel of declination passing through an object is not exactly one of the fiducial values, you will need to employ a technique called **interpolation** to determine the value of that object's declination,  $\delta$ .

For example, if an object has a declination of  $17^\circ 30'$ , and the fiducial parallels of declination are drawn every  $10^\circ$  apart, you will need to know what fraction of the distance between the 10th and 20th parallels corresponds to this declination. The fractional distance from the 10th parallel towards the 20th parallel would be  $(17.50-10.00)/(20.0-10.0)$  or  $7.50/10.00=0.75$ , that is,  $3/4$ ths the distance. Notice that we have converted the sexagesimal value of  $17^\circ 30'$  to its decimal equivalent,  $17.50$  degrees, with 2 decimal place precision, for convenience in using a calculator.

Similarly, if a star has  $RA=2^h 20^m$ , its hour circle is on third of the distance from the 2nd hour circle to the 3rd hour circle. This is because  $20^m$  is  $1/3$ rd (or 0.33) of an hour.



## 2-E. The Celestial Horizon System

When we stand at most locations on the Earth, we have the distinct impression that the Earth is flat. This occurs because the curvature of the small area of the Earth usually visible is very slight. We call this "flat Earth" the **Plane of the Horizon** and divide it up into 4 quadrants, each containing  $90^\circ$ , by using the cardinal points of the compass. The latter are the North, South, East, and west points of the horizon. We describe things as being vertical or "straight up" if they line up with the direction of gravity at that location. It is easy for us to determine "straight up" because we have a built in mechanism for this in the inner ear (the semicircular canals). Because it seems so "natural", we build a coordinate system on these ideas called the Horizon System.



**The vertical circle that connects the north point of the horizon, the zenith, and the south point of the horizon is very special and is known as the Local Celestial Meridian (LCM).**

In the diagram, the LCM is the only vertical circle that lies in the plane of the paper. The Local Celestial Meridian is a reference circle that is used for measuring local time and will be referred to frequently in future exercises.

The half of the local celestial meridian (LCM) from the north celestial pole (NCP), through the zenith, to the south celestial pole (SCP) is called the upper meridian and the other half is the lower meridian. Notice that a part of the upper meridian can be below the horizon and part of the lower meridian can be above the horizon, depending on one's latitude.

Almucantars and vertical circles form a grid of intersecting circles on the celestial sphere for the celestial horizon system. This grid is analogous to that formed by the parallels of latitude and meridians of longitude on the surface of the Earth.

The first coordinate of the horizon system (analogous to latitude on the Earth) is called **ALTITUDE**. It is the **angular distance of a point from the horizon**. The altitude is  $0^{\circ} 00'$  for an object that is located on the horizon and increases upwards towards the zenith. The altitude at the zenith is exactly  $90^{\circ}$ . Negative values for altitude mean an object is below the horizon. All objects with the same altitude lie along a circle parallel to the horizon. Such a circle is often called a **parallel of altitude** or an almucantar and they are labeled such in the above diagram.

The other angle of the celestial horizon system is called **AZIMUTH**. This is an angle that is measured around the celestial sphere, starting at the vertical circle passing through the **north point**. The value of the angle increases from  $0^{\circ}$  anywhere along this vertical circle, eastward. At the east point the azimuth is  $90^{\circ}$ . The azimuth at the south point is  $180^{\circ}$  and it is  $270^{\circ}$  at the west point. Refer to the above diagram. The point where any vertical circle crosses the horizon has a definite azimuth, that is, it is located at a definite angular distance from the North Point of the horizon.

## **2-F. Orientation of the Equatorial System within the Horizon System**

Figure 2 below depicts the Earth with its axis of rotation shown vertical and its geographic equator shown lying in a horizontal plane that is perpendicular to the axis. If an observer is located at point **A**, their latitude is indicated by the angle  $\phi$  ( $\phi$ ). A line drawn from the center of the Earth, through the observer at A, and then continued upwards towards the celestial sphere, points to the observer's zenith, which is labeled  $Z_A$  in the figure. A similar line is drawn for an observer standing at point **B**, with latitude  $\beta$  ( $\beta$ ), pointing to their zenith which is labeled  $Z_B$  and for an observer at **C**, with latitude  $\gamma$  ( $\gamma$ ), whose zenith is labeled  $Z_C$ . It should be clear that the zenith is located at a different point on the celestial sphere for different observers. Additionally, the horizon for each of these observers intersects the celestial sphere in a different way so that what is above or below their horizon will be different.

A line through A, tangent to the Earth lies in the plane of the observer's horizon and indicates the directions to the north and south points (labeled NPH & SPH in the figure) of the horizon. Similar remarks are true for the hypothetical observers at B and C. Clearly, the half of the sky that is above an observer's celestial horizon is different for different observers.

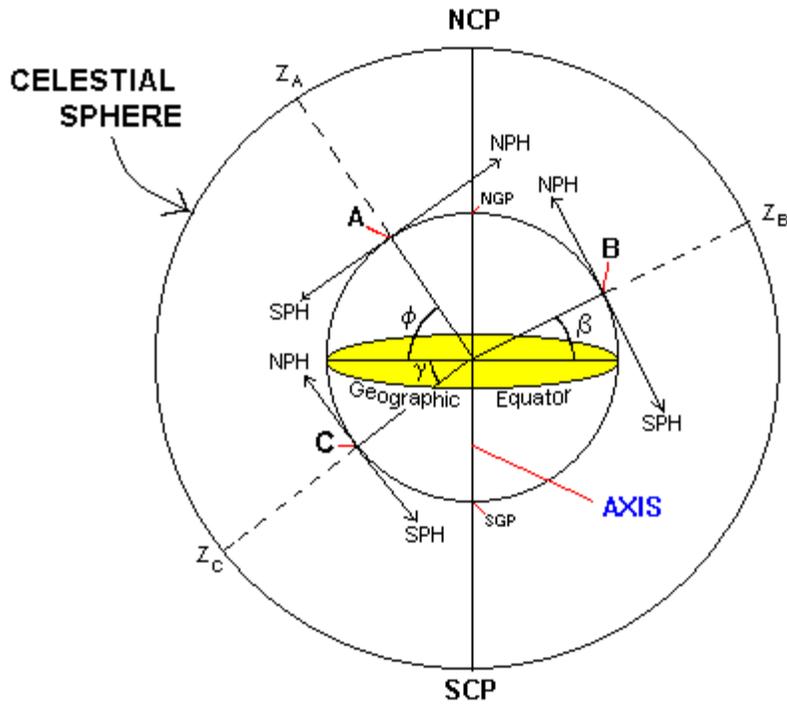


Fig. 2. A schematic diagram showing how the location of an observer's zenith and nader in their sky depends on latitude.

Figure 3 depicts the Earth with the shaded plane of the geographic equator drawn midway between the north geographic pole and the south geographic pole (labeled NGP & SGP). The line

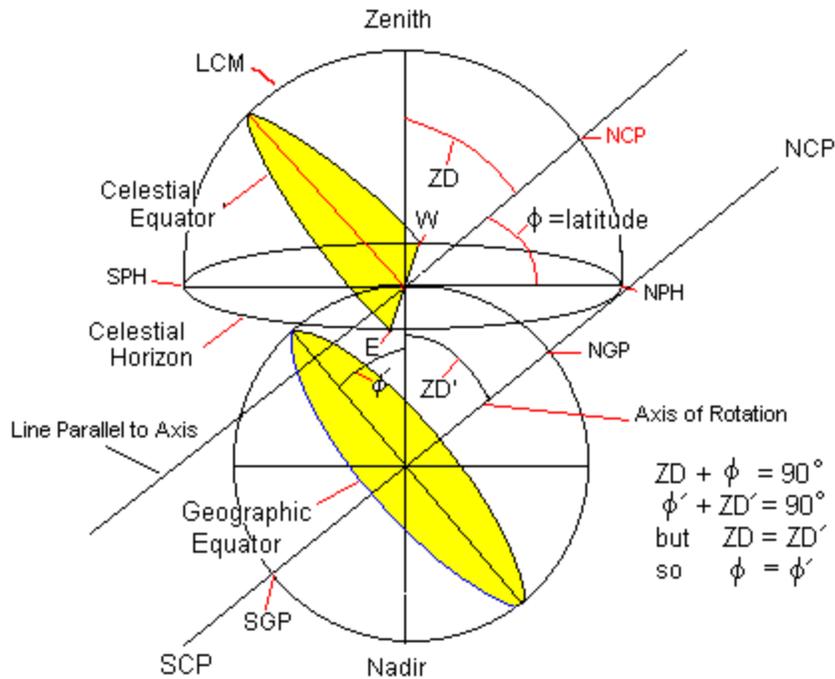


Figure 3. A schematic diagram showing why the altitude of the NCP for an observer is equal to the observer's latitude.

drawn connecting the geographical poles is the axis of rotation of the Earth. A celestial hemisphere, reduced in size to fit in the diagram, is drawn centered on an observer who is located somewhere

near mid-latitude in the Northern Hemisphere. A line is drawn through the observer parallel to the Earth's axis of rotation. Since parallel lines may be considered to indicate the same point on the celestial sphere, both of these lines indicate the direction of the north celestial pole (labeled NCP in the figure). Although the NCP is shown in the figure to be two separate points, they are actually the same place in the sky as seen by the observer. Similar geometric remarks may be applied to show that the plane of geographic equator and the plane of the celestial equator, as labeled in the diagram, lie in the same plane as seen by the observer.

By definition, the angle between the observer and the geographic equator is the observer's latitude, labeled as  $\phi$ . The point on the celestial sphere over the observer's head is the zenith (Z), and the point under foot on the other side of the celestial sphere is the nadir.

Using some plane geometry, it is easy to show that the observer would see the north celestial pole (NCP) located at an angle above the North Point of the horizon equal to the observer's latitude ( $\phi$ ). This geometric argument is shown in the lower right of Fig. 3.

Now imagine yourself in Figure 2, standing at the north geographic pole (latitude  $90^\circ$  N.). The north celestial pole (NCP) would have an altitude of  $90^\circ$  and, therefore, be at your zenith. The celestial equator and celestial horizon would coincide.

Now picture yourself on the Earth's equator, at  $0^\circ$  latitude. Here the celestial equator would pass through your zenith and the north celestial pole (NCP) would lie at the North Point of the horizon and have an altitude of  $0^\circ$ . Hence, the following general rule:

**THE ALTITUDE OF THE NORTH CELESTIAL POLE IN DEGREES IS ALWAYS NUMERICALLY EQUAL TO THE LATITUDE OF THE OBSERVER.**

Also, for any observer located in the northern hemisphere of the Earth, the north celestial pole (NCP) is always a point located on the local celestial meridian, between the zenith and the north point of the horizon. Since the LCM is also the vertical circle connecting the zenith and the north point of the horizon, and azimuth is measured from the latter point eastward, the azimuth of the north celestial pole (NCP) is always equal to  $0^\circ$ .

Furthermore, from Fig. 2 the following geometric relationship may be deduced:

**THE CELESTIAL EQUATOR INTERSECTS THE LOCAL CELESTIAL MERIDIAN AT ANGLE BELOW THE ZENITH NUMERICALLY EQUAL TO THE LATITUDE.**

This is a corollary to the previous general rule about the altitude of the north celestial pole.

## **2-G. Other Astronomical Coordinate Systems**

Two other commonly used coordinate systems used in astronomy are :

1. Ecliptic coordinates
2. Galactic coordinates.

The ecliptic is the circle in the sky that results from projecting the Earth's orbit onto the celestial sphere. The ecliptic is the fundamental circle of the ecliptic coordinate system. Latitude is the angular distance of an object north or south from the ecliptic and longitude is measured from the vernal equinox, eastward along the ecliptic. This system is used from computing the positions of the planets.

The fundamental circle of the galactic coordinate system is based on what is believed to be the central plane of the disk of the Milky Way Galaxy and is called the galactic equator. Galactic latitude

is the angular distance north or south of this circle and galactic longitude is measured along the galactic equator eastward from what is believed to be the center of the galaxy .