Astronomy Tutorial

For newcomers to astronomy there are many novel concepts to get acquainted with. This document attempts to introduce most of those in an intuitive order.

# The Basics

## Astronomical Objects

The following is not intended to be exhaustive, there are many types of astronomical objects which are not mentioned here.

Perhaps both the most obvious and the most overlooked (as an astronomical object) is the Earth. Astronomy is typically associated with looking up rather than down, as that is where the sky is. However, since an observer is overwhelmingly likely to be located on Earth, it is essential to know there the Earth is relative to all the other astronomical objects, as that determines where those objects will appear in the sky.

### The Sun

Of the objects we observe in the sky, the Sun is by far the most obvious. It is the centre of our solar system, and many interesting objects travel on orbits around the Sun. The Sun is by far the most massive object in the solar system, accounting for 99.86% of the total mass. It is also the only object within the solar system emitting light in the visible spectrum.

The Earth’s atmosphere scatters the light from the Sun, mainly due to nitrogen molecules which have a peak scattering cross-section in the blue part of the spectrum. This is why the sky appears blue during the day, and why sunrises and sunsets appear orange. The blue light is scattered in all directions while the orange light is not scattered much.

When light has bounced around scattering several times, it arrives at our eyes from all directions. Since the scattered light is primarily blue, the sky appears blue in all directions. When the sun is near the horizon, it’s light passes through a lot more atmosphere, and thus a larger part of the blue light is scattered away from the line of sight towards the Sun. The remaining (non-blue) light arrives without scattering, and thus the sunrise or sunset appears orange.

Earth orbits the Sun at approximately 150 million kilometres (1 astronomical unit, AU), taking 365.2422 days (which is 365 days, 5 hours, 48 minutes and 46 seconds) to complete one orbit. Due to conservation of angular momentum, the orbit is essentially a plane ellipse with the Sun at one focal point. Gravitational influences from the other solar system objects do cause small perturbations to this perfect ellipse, but in many cases an elliptical orbit offers a good approximation for Earth’s orbit.

### The Moon

The second most noticeable object in the sky is the Moon. Although it has about the same angular size as the Sun, it is much closer and much smaller than the Sun. The Moon is the closest astronomical object, and it is in orbit around the Earth. The Moon is approximately ¼ the diameter of the Earth, and orbits in about 1 month. The Moon is tidally locked to the Earth, which means it is always showing the same side to the Earth.

When the Moon is seen in the opposite direction to that of the Sun, the Moon appears fully illuminated as seen from Earth. Likewise, when it is seen in the same direction as the Sun, the side of the Moon facing away from Earth is fully illuminated, and the Moon is barely visible. Between the two extremes only a portion of the Moon appears illuminated. Varying degrees of illumination are called the phases of the Moon.

The apparent angle in the sky between the Moon (or any other astronomical object) and the Sun is called the elongation of the Moon. The elongation determines the illuminated fraction of the Moon, and thus the phase. During a full moon, at maximum elongation, the Moon will be highest in the sky around midnight. This makes it more difficult to observe faint astronomical objects.

### The Stars

While the Sun and the Moon appear to cover around ½ a degree in the sky, the remaining bright objects in the sky all appear point-like to the naked eye. Most of those bright points appear to move together across the sky, as if fixed to a sphere surrounding the observer. A few of the bright points seem to move relative to the rest of the points, so those are called planets, from the Greek word for wanderer. The remaining thousands of points are called stars.

While the stars appear to a naked-eye observer to maintain their relative positions during a human lifespan, they do in fact move relative to each other. But they are so far away that it requires either large magnification or a long time to measure this movement accurately. This movement is called proper motion.

Our Sun is the closest star, at a distance of approximately 150.000.000 kilometres, and is at the centre of our solar system. The next closest star is Proxima Centauri at 4.25 lightyears (approximately 40,208,000,000,000 kilometres). Stars differ in size and absolute brightness, so one star appearing brighter than another does not necessarily imply that the brighter star is closer to us.

# Celestial Coordinates

## Spherical Coordinates

While astronomers are now able to measure the distances to even very far objects, this is a recent ability. For most of the history of astronomy all people were able to measure with significant accuracy was the direction in which an astronomical object could be observed at a given time and location.

Thus, specifying directions in the sky rather than positions in space was the norm for many centuries. The most natural way to indicate a direction is by the direction along the horizon (the azimuth), and the elevation above the horizon (the altitude).

This works a bit like the longitude and latitude coordinates of Earth. Imagine being located at the centre of the Earth; every location on the surface is in a certain direction, indicated by the longitude along the equator, and the latitude above or below the equator.

Likewise, an imaginary sphere around the observer has a grid of azimuth and altitude laid upon it. Any direction corresponds to a unique (azimuth, altitude) coordinate, and every valid (azimuth, altitude) coordinate uniquely identifies a location on the sphere, i.e. a direction into the sky.

When intersecting a sphere with a plane, the boundary between the two surfaces is always a circle. In the special case where the plane passes through the centre of the sphere, this circle will have the same radius as that of the sphere, and the circle is called a great circle. This is the largest possible circle on the spherical surface. Circles formed by planes which do not contain the sphere centre are smaller than the great circles and are therefore called small circles.

[describe a reference plane and poles of a great circle]

[describe how one angle is measured within the reference plane and the other is measured from the reference plane towards the pole]

[add illustrations]

Angles in the reference plane, i.e. along the great circle, are measured to a full turn. Some coordinate systems will use a range from 0 to 1 full turn, i.e. 0 to 360 degrees, 0 to 2\*pi or 0 to 24 hours. Others will count from -1/2 turn to +1/2 turn, i.e. -180 to +180 degrees,-pi to pi radians or -12 to 12 hours. In astronomy we even see some coordinate systems where the angle measure is increasing in the counterclockwise direction (like in trigonometry), and some where the angle measure is increasing in the clockwise direction.

It is of course necessary to identify the direction of the zero coordinate within the reference plane. In coordinate systems on the surface of a rocky planet, this is typically identified by some surface feature. For example, on Earth that feature is the Greenwich observatory. On the imaginary sphere of the sky, things are a bit trickier.

In 3 dimensions, two non-parallel planes will intersect in a line. When intersecting two reference planes, the two great circles of those reference planes will intersect on this line at two diametrically opposite points. Those two points are called nodes, and the convention is to pick one of the nodes as the zero point.

When indicating the elevation above or below the reference plane, it is sufficient to cover the angle between the two poles. In astronomy this is typically counted positive above and negative below the reference plane. Which direction is above, and which is below is defined for each coordinate system, typically in terms of some naturally occurring rotation or orbit.

## Horizontal Coordinates

When pointing a telescope towards objects in the sky, it is convenient to have a coordinate system where the local observer horizon is the reference plane, and due north (or in the past, due south) is the zero point.

The point directly above the observer is called the Zenith and the point directly below is called the Nadir. Establishing the reference plane amounts to setting up a plumb line which will point directly to the Zenith, and then measuring down 90 degrees to find the astronomical horizon. Note that this does not coincide exactly with the visual horizon, which will be discussed further in an upcoming chapter.

Az/alt

LHA/alt

## Equatorial Coordinates

## Heliocentric Coordinates

Due to the efficiency of Kepler’s laws, centring a coordinate system on the Sun simplifies the calculations of planetary orbits when these are taken to be elliptical. The reference plane is taken as the orbital plane of the Earth, and the zero point is the northbound equinox.

[Celestial Coordinate topics] Spherical, uniform, easy to transform. Geocentric, heliocentric, barycentric, topocentric. Ecliptic, equatorial, horizontal.

# Lunar and Planetary Coordinates

When reducing the positions of celestial bodies to the coordinate system of the sky above an observer, it is necessary to consider the exact location of the observer. This will typically be on the surface of the Earth, where locations are naturally specified in geographical coordinates of latitude, longitude and height above sea level. But observers can also be considered on or above the surface of other celestial bodies, like the Moon or Mars.

The celestial coordinate systems detailed in the previous chapter are all considered perfectly spherical, without any loss of accuracy. But when specifying locations on an actual solar system body, the shape of the body must be accounted for. This chapter will consider the coordinate systems used on the Moon and the planets, which are all well approximated by ellipsoids of revolution, aka spheroids. The following will first cover coordinate systems on Earth, and then discuss the differences applicable to the Moon and the planets.

## Coordinates on Earth

As a first approximation, the Earth can be considered a sphere. However, due to the diurnal rotation Earth is slightly oblate (fat) around the equator and flattened at the poles. It turns out that an ellipsoid formed by rotating an ellipse around the minor axis is a much better approximation to the shape of the Earth. Both approximation methods (sphere and ellipsoid) are used depending on the situation. For example, in hand computed celestial navigation, Earth is modelled as a sphere to cut down on the necessary calculations, but with computer based navigational systems such as GPS, the ellipsoid model is used.

As in the previous chapter, spherical coordinates are simple to define. Earth rotates daily around an axis through the poles and the centre of the sphere. The plane perpendicular to this axis, and containing the centre, is the equatorial plane, and intersects the sphere in a great circle called the equator.

Latitudes are counted from zero at the equator towards the poles where they take the value 90. Northern latitudes are annotated by prepending an N, likewise southern latitudes use an S. Alternatively in calculations it is often convenient to consider northern latitudes positive and southern negative. Which hemisphere is considered positive is a matter of convention, mathematically either will work provided it is used in a consistent manner.

While the axis of diurnal rotation naturally gives rise to the equatorial plane, there is no natural zero point for longitudes. Somewhat arbitrarily the Greenwich observatory has been chosen as the zero point. From there, longitude is enumerated from 0 to 180 degrees in east and west directions, indicated by a prepended E or W respectively. These, along with the N and S indicators, of course vary with the language used. Again, in calculations it is often convenient to use + or – where east is taken to be positive. The values +180 and -180 refer to the same meridian, so for consistency that meridian is usually considered to be +180.

Longitudes on a sphere and on an ellipsoid are the same, as they can be considered to divide the equator, which is a great circle on both geometries. Latitudes are trickier to define on an ellipsoid than on a sphere. The reason for this is that several equivalent ways of considering latitude on a sphere lead to distinctly different latitudes on an ellipsoid.

On a sphere a north-south aligned angle at the centre of the sphere will span an equal distance at the surface of the sphere. In other words, one is free to define a degree of latitude by the distance it covers on the surface, or by the angle it subtends at the centre, both lead to the same result. On an ellipsoid this is not the case.

Likewise, the surface tangent of a point on the sphere is always perpendicular to the line from the centre to that point. In other words, the “up” direction at a location is equal to the direction of the radius to that location. It turns out that retaining this property of latitude on an ellipsoid is the most practical. This is because it is relatively easy to locally determine the angle between a plumb line and the celestial pole , calling it the co-latitude of the location. The latitude is then simply ninety minus the co-latitude.

Since “up” is perpendicular to the surface tangent, and the celestial pole corresponds to the geographic pole of the Earth, the assigned latitude is equal to the angle between the tangent plane and the Earth’s rotation axis. “Up” measured using a plumb line is not exactly the same as the surface normal of the ellipsoid at the location. The difference is called the deflection of the normal and is due to local variations in Earth’s density which slightly deflects the plumb line slightly.

The shape of the Earth as measured by plumb lines, i.e. local gravitational variations, is called a geoid, and is a complex shape which is not easily modelled for navigational purposes. Even this geoid is not the “true” shape of the Earth’s surface.