Alien Skies

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Have you ever wanted to send your students to another planet? What would they see while looking up at the skies from their new home? Would they be able to interpret what they see? Could they even build a model of their new solar system on the basis of their observations? Our own skies give us a good idea of what it would be like to view the night sky from another world, and Ptolemy and Copernicus provide us with two different approaches to modeling an alien solar system.

One thing our stranded students are sure to notice is that their "Sun" moves across the sky. Using our Earth convention we will say that this alien Sun moves from east to west across the sky each day, but it also moves up and down in the sky. The *altitude* of the Sun, or how many degrees it is above the horizon, can be determined by measuring the shadow cast by a stick (or gnomon). The longer the shadow, the lower the altitude and vice versa. Our student astronomers can use careful observations of how shadows change over the course of a day (see Figure 1) to determine the time of *local noon*, when the Sun is highest in the sky (see Figure 2). Local noon occurs when the Sun *transits*, or passes across the north-south meridian line, so at local noon the shadow of a gnomon will point either due north or due south. The time between successive local noons defines a *solar day* (Figure 3).

Observant students will also notice that the stars move east to west across the night sky, very much as though the stars are all fixed to the inside of a giant "celestial sphere" that spins around the home world. Careful observations can determine when a particular star transits and the time between successive transits is a *sidereal day*. This sidereal day is the same for all stars, but it is different from the solar day. Our exiled students will likely find that their solar day is slightly longer than their sidereal day. For example, they may find that their sidereal day is 24 hours, 37.4 minutes while their solar day is 24 hours, 39.6 minutes. In this case, our students should realize that the Sun must drift eastward relative to the stars.

Inspired by this discovery, our budding exo-astronomers may decide to trace out the motion of the Sun against the starry background. One way to do this is to observe the shadow cast by an object at local noon each day. The length of the noon shadow will slowly vary from day to day, getting longer and then shorter and then longer again (Figure 4). The noon shadow may even disappear or change directions, or there may be days when the Sun never rises, but for now let us assume the Sun always rises and sets and its noon shadow always points north. (As we shall see, this indicates that our students are in the temperate zone of the northern hemisphere of their new home world.) In keeping with Earth conventions we might call the day of the longest shadow, when the sun's noon altitude is lowest, the *winter solstice*, while the day of the shortest shadow, or highest noon altitude, is the *summer solstice.* The days when the Sun's noon altitude is at its median value would be the *equinoxes*. This pattern of variation repeats itself after a certain number of days, 669 in our hypothetical example. This period of time is known as the *tropical year*.

If our stranded students are good at spherical geometry, they may realize that the variations in altitude are what one might expect if the Sun were to move along a circular path on the celestial sphere, but a path that is tilted somewhat with respect to the equator of the celestial sphere. The angle of this tilt, known as the *obliquity*, is exactly half of the variation in the sun's altitude over the course of a year. If the students make these measurements at many locations on their new home world they may discover that the median (equinox) noon altitude of the Sun varies as they move north and south. This variation may help them to realize that their home world is spherical and from there they may discover that the median noon altitude of the Sun at a given location tells them how many degrees they are from the north pole of their home world (or 90° minus their latitude). Perhaps a clever exo-Eratosthenes might devise a way to measure the distance between two points that are north/south of each other, use the Sun's equinox noon altitude to determine the difference in latitude of the two spots, and thus find the diameter of their home world.

These discoveries will give our students insight into how sunlight varies from location to location on their new home world. Say they find the obliquity to be 25° (as in Figure 3). They can infer the existence of a *tropical zone* on their home world, in a range of latitude from 25° south of the equator to 25° north of the equator. Within this tropical zone the direction of the noon shadow will be northward on the winter solstice, but southward on the summer solstice. In the tropics, there will be two days on which the Sun passes directly overhead at noon. Likewise there is a range of latitudes from 65° to 90° in both hemispheres for which there are days when the Sun never sets, and others when it never rises. Perhaps our stranded students will find these *arctic zones* the most hospitable part of their home world! They will also realize that in the *temperate zone* of the southern hemisphere (latitudes 25° to 65° south) the pattern of shadows will be reversed, with longest shadows (lowest altitudes) occurring on the date of the (northern) summer solstice and shortest shadows (highest altitudes) on the (northern) winter solstice.

Once they have their Sun figured out, our castaway students might turn a closer eye to the stars in their night sky. They would likely discover that some of their stars are not well behaved. A small number of stars appear to wander around relative to the others (see Figure 5). They would probably find that these wandering stars generally move eastward along much the same path as the Sun, but not exactly along that path. But these wandering stars, or *planets*, occasionally do something very odd: they halt their eastward motion relative to the stars and move westward for a while in what is called *retrograde* motion, then return to their eastward motion.

Careful observation of these planets over many years will reveal that they come in two main flavors. One group of planets never gets very far from the Sun on the sky.

These planets seem to be tethered to the Sun, so we will call them *tethered planets*. Tethered planets are visible shortly after sunset, or shortly before sunrise, but never in the middle of the night. The middle of their retrograde motion always occurs when they are very close to the Sun on the sky (in *conjunction*). The angle between a planet and the Sun on the sky is known as the planet's *elongation*. Each tethered planet will have a different maximum elongation. For example, say our young exo-astronomers find three tethered planets wandering their night sky. They may see that one of these planets has a maximum elongation of 15°, while another has an elongation that can reach 29°, and the third has a maximum elongation of 41°. Watching these planets over a long period of time, our exo-astronomers notice that they each have their own distinct period between successive retrograde motions (say 99, 326, and 756 solar days, respectively). This time is known as the *synodic period* of the planet. But our stranded students will also notice that all of these planets have the same *celestial period*, which is the observed time it takes the planet to complete its motion around the celestial sphere, averaged over many cycles. In fact, all of these planets will have celestial periods of one year (669 solar days).

The second group of planets can be at any angle from the Sun on the sky, so we will call them *untethered planets*. For untethered planets the middle of their retrograde motion always occurs at an elongation of 180° from the Sun (in *opposition*). They all take longer than a year to go around the celestial sphere, perhaps much longer. For example, maybe our students see two untethered planets with celestial periods of 6.3 and 15.7 years, respectively. Their synodic periods are also different, but those with longer celestial periods will have synodic periods closer to one year. In our example, the synodic periods would be 1.19 and 1.07 years, respectively.

As they move around among the stars, the planets also vary in brightness. The variations in brightness among the tethered planets are not great. However, the variations among the untethered planets can be quite large. The untethered planets will be brightest when they are in opposition to the Sun and undergoing retrograde motion. In some cases an untethered planet that is clearly visible in opposition may fade to invisibility as its elongation from the Sun decreases. In our example, however, both untethered planets are visible at all times.

Once they have made all of these observations, how might our spacefaring students make sense of it all? We have already seen that a model with the stars fixed to the inside of a giant celestial sphere rotating about the home world serves well to explain the motion of the stars. The motion of the Sun can be explained by assuming that the Sun slides along the celestial sphere, following a circular path that is tilted relative to the celestial equator. But what shall our young exo-astronomers make of the odd motion of the planets?

Perhaps one of the most brilliant of our exiled students, let's call her exo-Ptolemy, would conclude that the motion of the planets consists of two circular motions. The planet itself moves along a smaller circle, or epicycle. Meanwhile, the epicycle moves around in a larger circle, or deferent, which is centered on the home world.

Figures 6 and 7 illustrate this theory for tethered and untethered planets. The deferent motion accounts for the planet's general drift relative to the stars, while the epicycle motion accounts for the occasional retrograde motion. Therefore, the motion of the epicycle along the deferent must have a period equal to the planet's celestial period, while the motion of the planet along the epicycle must have a period (measured relative to the deferent, not to the stars) equal to the planet's synodic period. This model explains the motions of the planets, as well as their variations in brightness (at least for the untethered planets). But some mysteries remain. This model cannot tell our castaway students which planets are closer to their home world and which are farther away. Moreover, there seems to be a mysterious connection between the motion of the Sun and the motion of each planet: the deferent motion of each tethered planet, and the epicycle motion of each untethered planet, is synchronized to the motion of the Sun.

Of course, there is another way of understanding these observations and perhaps an exo-Copernicus would figure it out even before our stranded students developed telescope technology. The motions of the planets can be explained by assuming that the home world is itself a planet, and that all planets orbit the Sun in (roughly) circular orbits in the same direction. This model explains the mysterious connection between the motion of the planets and the motion of the Sun. This connection occurs because these synchronized motions (of the Sun, the deferent of a tethered planet, and the epicycle of an untethered planet) are really only apparent motions that are caused by the same real motion: the orbit of the home planet about the Sun. This model even tells us the specific ordering of the planets. The tethered planets must be closer to the Sun than the home planet, and the smaller the maximum elongation of the planet the closer it is to the Sun (Figure 8). Untethered planets must be farther from the Sun than the home planet, and the closer the synodic period is to one year the farther the planet is from the Sun (Figure 9). As a bonus, this ordering reveals a wonderful new pattern: the closer a planet is to the Sun, the shorter its orbital period.

You may have guessed by now that the example we have been considering describes the view from one of the planets in our own solar system. By now, you should be able to figure out which one (Figure 10). Note that the numbers given above assume a highly simplified solar system in which all planets orbit in circles with the Sun at the center. Moons have been completely ignored. What we have been calling a tethered planet is what has traditionally been called an *inferior planet*, while untethered planets are traditionally known as *superior planets*.

Some Astro 101 students may think that astronomy is useless. Exiling those students to an alien world, and forcing them to figure out their new solar system using only what they can observe is an excellent way to teach them the usefulness of astronomy! Would *your* Astro 101 students be able to model their solar system if you exiled them to an alien planet? They might be able to if you gave them the opportunity in your class to model Earth's solar system based on the observational data we can gather from Earth. The online resources listed below contain materials that can help your students learn about the patterns of motion that can be seen with the naked eye from Earth. Once your students understand these motions and know how to interpret them (in either a Ptolemaic or Copernican sense), they can apply what they know to observe and interpret the motions that are visible from another planet. You can even give them a computer simulation that lets them observe and measure the motion of shadows or planets as seen from a planet in a fictitious solar system, and they can construct Ptolemaic and Copernican models of this fictitious system using only their own observations!

You can go even farther by getting students to think about how to interpret unusual variations on these patterns of motion. For example, what would it mean if the solar day were shorter than the sidereal day? How would you explain a planet whose motion relative to the stars was in the opposite direction from the Sun's motion? What would happen if the obliquity of a planet were greater than 45° so that its tropical zones merge into its arctic zones? Note that the answers to these questions may depend on which system (Ptolemaic or Copernican) you use to interpret your observations. There are many ways to get students to engage deeply with these ideas – the (alien) sky is the limit!

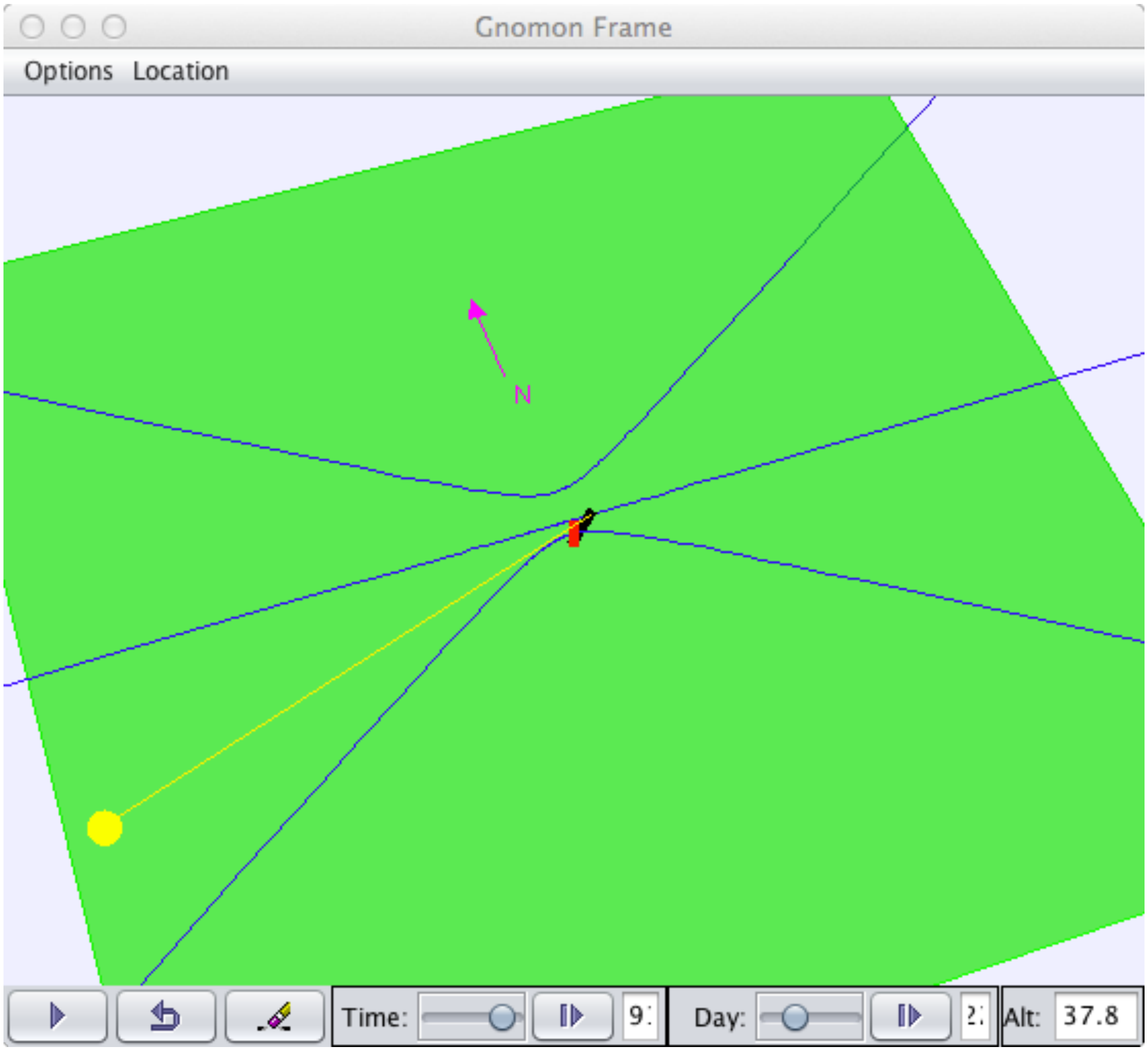
Online Resources

The Open Source Physics Collection: http://www.compadre.org/osp/
This collection of open-source computer programs includes several astronomy simulations, including some that model shadows on Earth, the Ptolemaic planetary system, and the Copernican planetary system. The images in Figures 1-9 are drawn from these simulations.

Modeling the History of Astronomy:
http://www.compadre.org/OSP/filingcabinet/share.cfm?UID=12250&FID=33000&code=A816D1F75A
This shared folder on the Open Source Physics site contains materials for teaching students how to observe and model the motion of planets using Ptolemaic and Copernican principles. An article describing these materials was published in *Astronomy Education Review*. This article is available online: http://scitation.aip.org/content/aas/journal/aer/12/1/10.3847/AER2013001.

The Copernican Revolution: http://facultyweb.berry.edu/ttimberlake/copernican/
This page contains activities and computer simulations for teaching a course on the Copernican Revolution. Many of the activities focus on observing and modeling the motions of the Sun, stars and planets. Activities and simulations for observing shadows and modeling the motion of the Sun can be found here.

Figures



Alt: 37.8

Figure 1: Movement of shadows over a day and throughout the year. The short red line is a gnomon and the thick black line shows the gnomon's shadow. The "Sun" is shown as a yellow disk. The blue lines trace the tip of the shadow on three different days: the winter solstice, the vernal equinox, and the summer solstice.

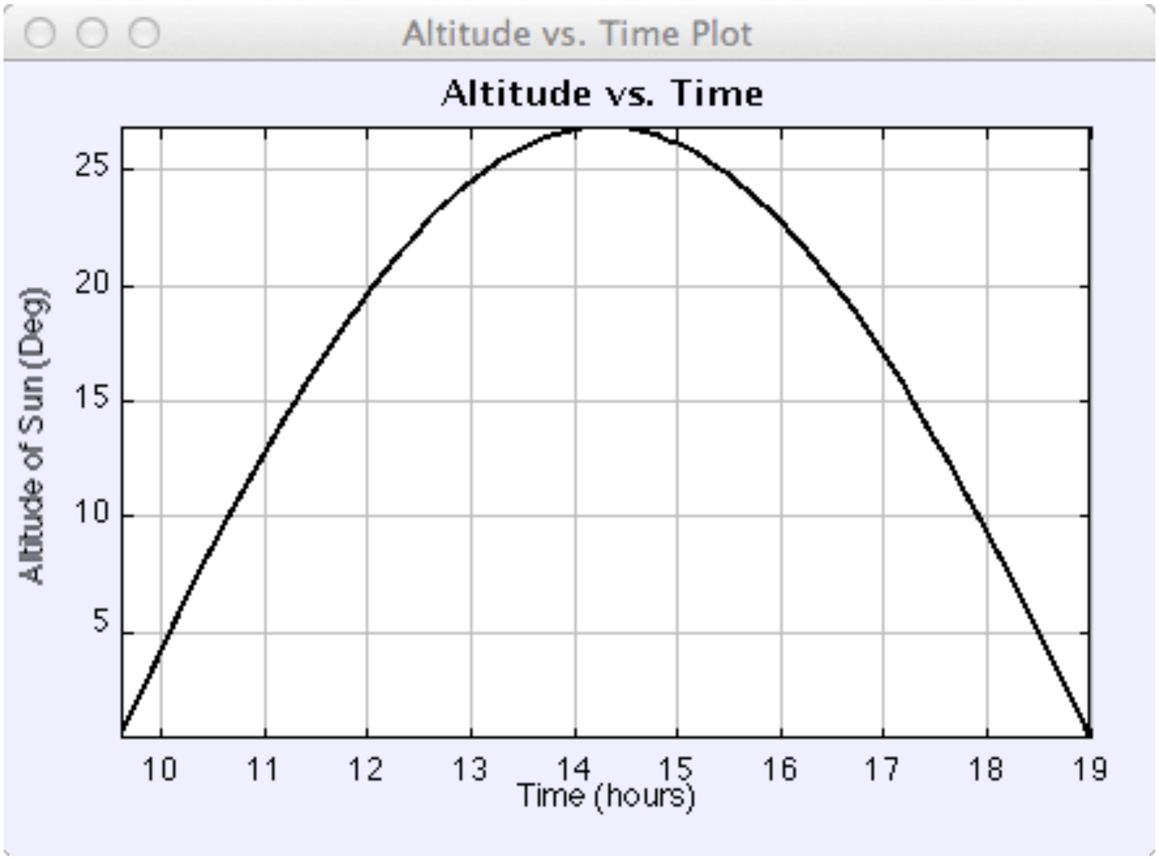


Figure 2: Plot of the Sun's altitude versus time over a single day. The altitude peaks around 14.2 hours, which is the time of local noon.

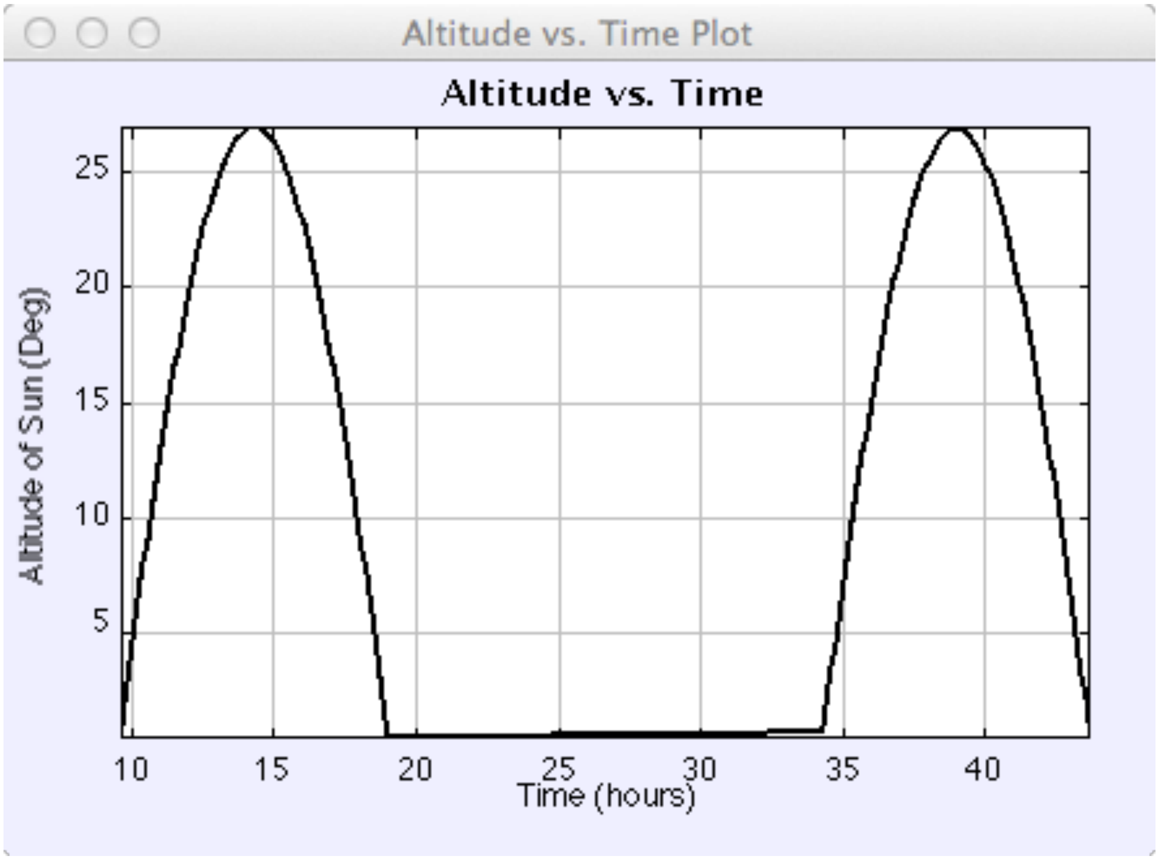


Figure 3: Plot of the Sun's altitude versus time over two days. The time between the two peaks, or two consecutive local noons, is the solar day. In this case the solar day is about 24.66 hours.

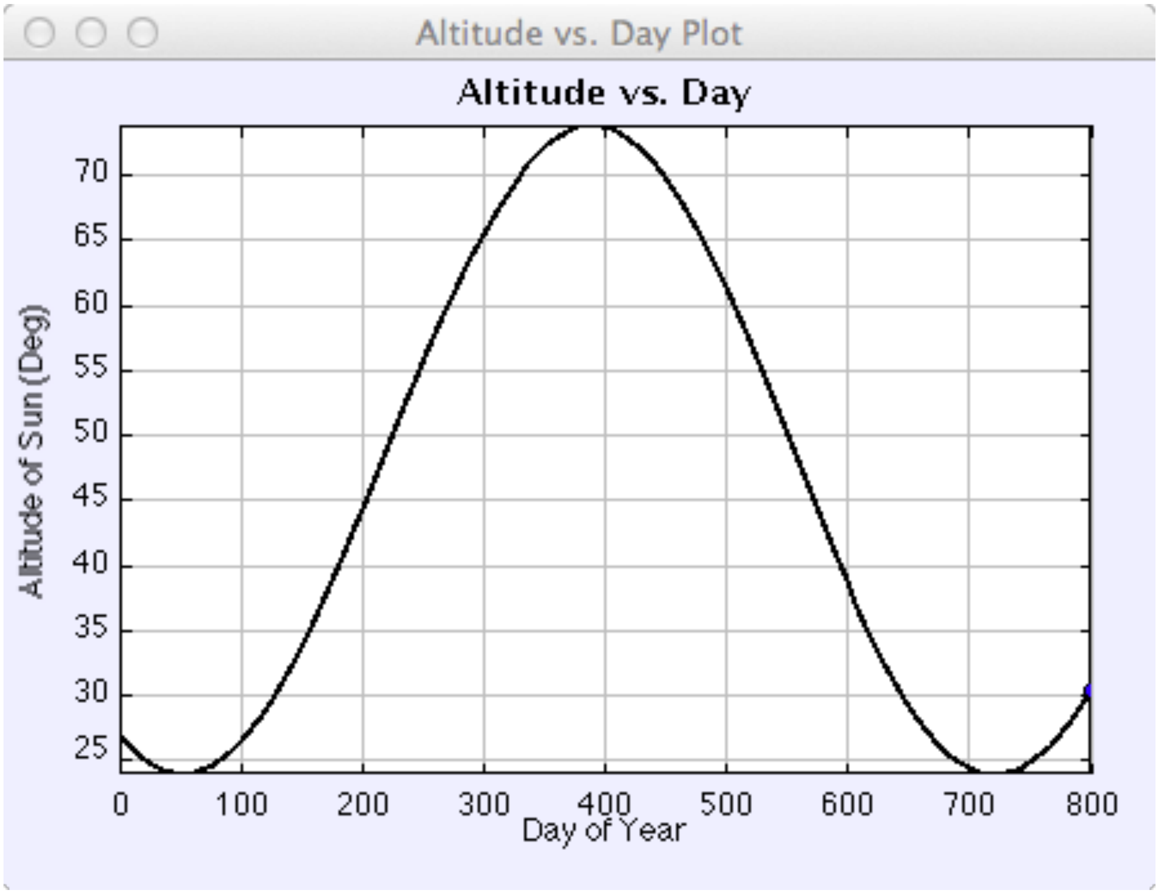
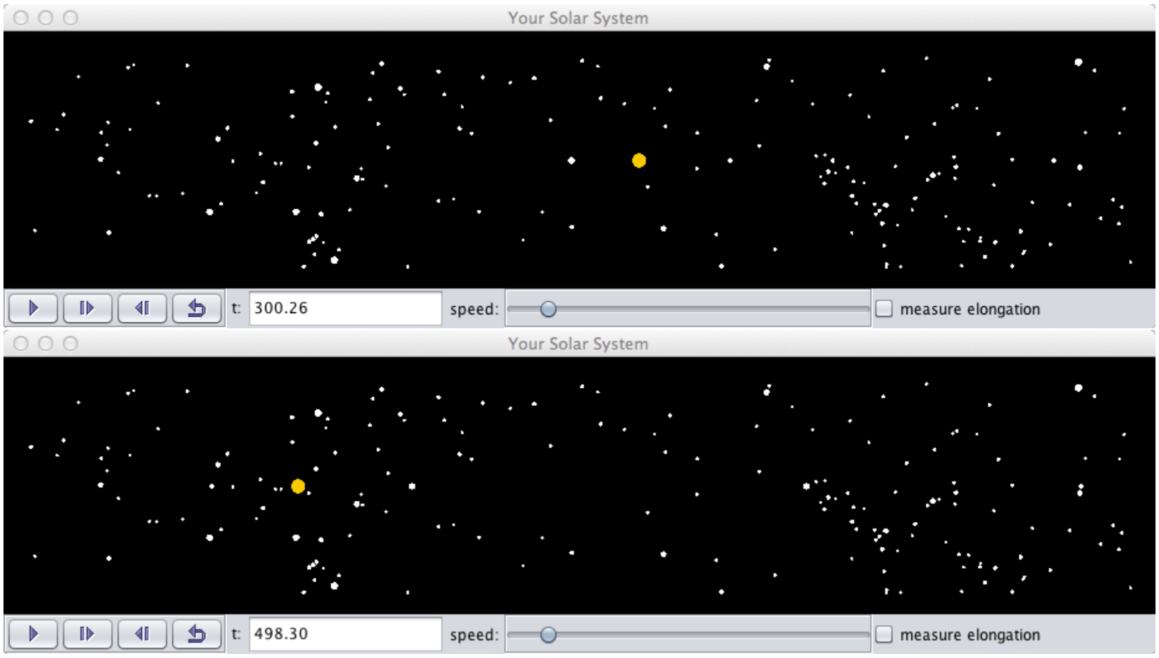


Figure 4: Variation of the Sun's local noon altitude over the course of a year. The pattern repeats itself after one tropical year, which in this case is 669 days. Can you determine the obliquity and the observer's latitude from this plot?



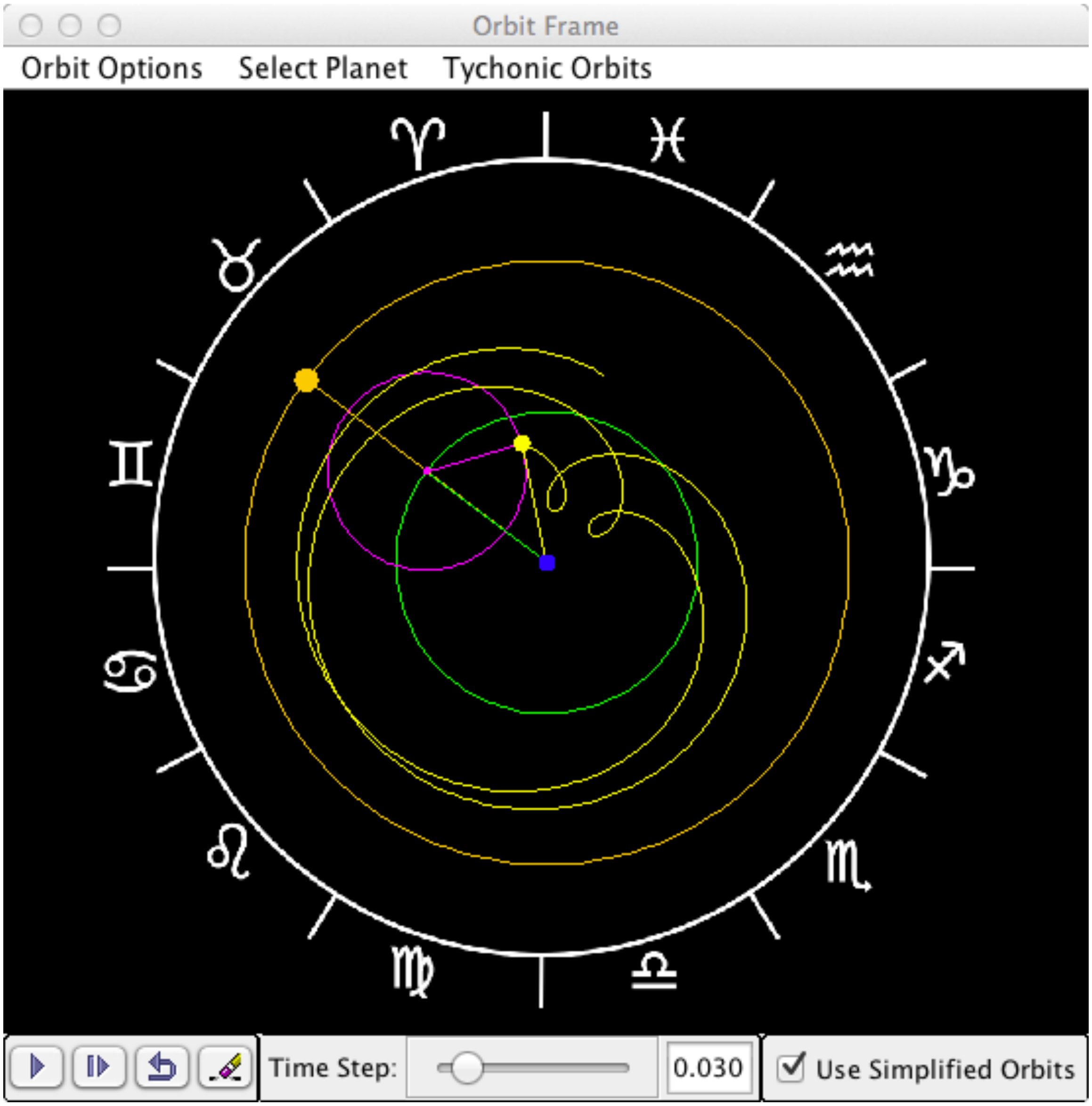
t: 300.26

☐ measure elongation

t: 498.30

☐ measure elongation

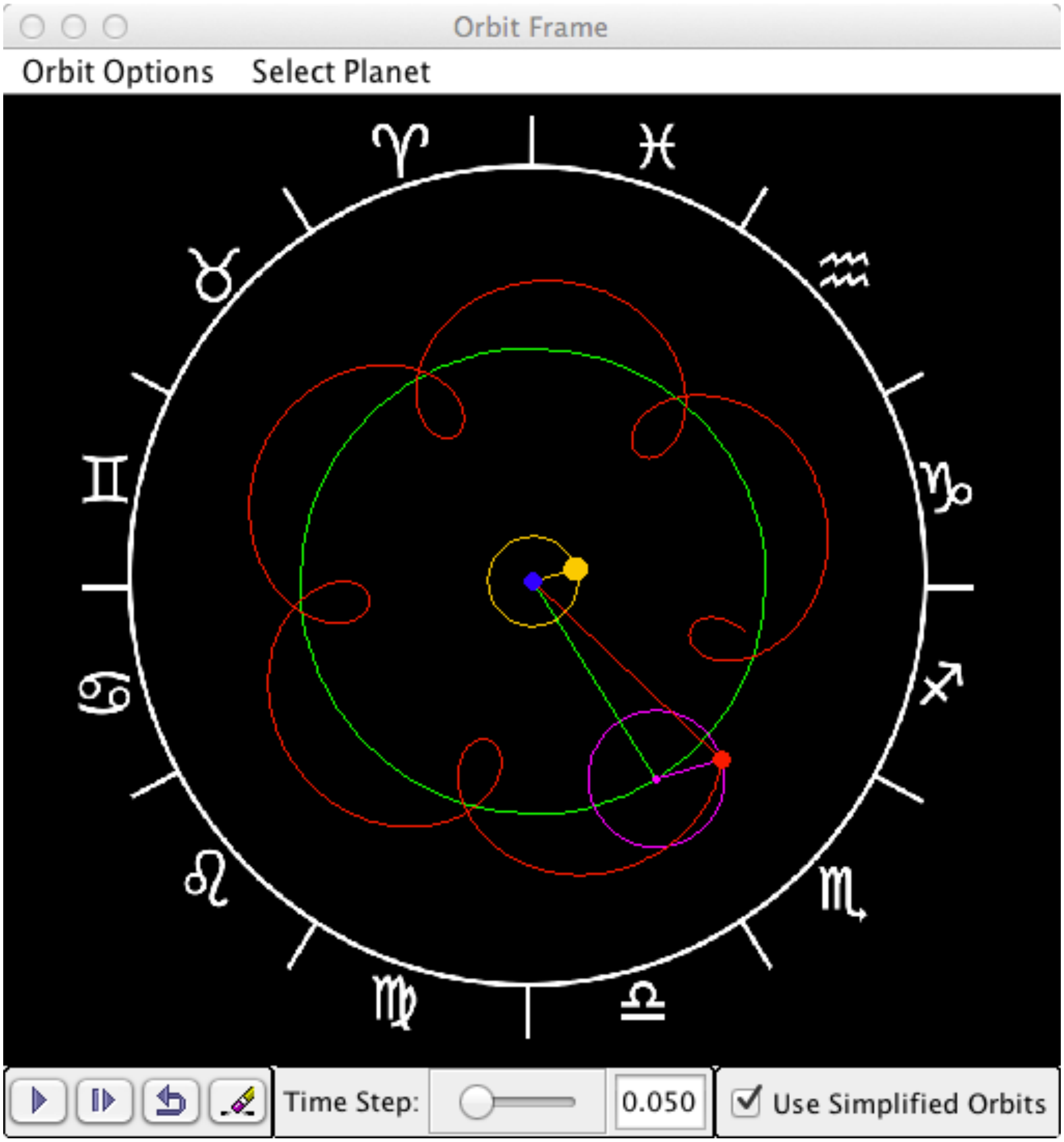
Figure 5: A portion of the sky along the ecliptic shown on two different days (about 198 days apart). The orange disk is the "Sun". Can you spot the four planets? (Note: the fifth planet of the system is hidden by the Sun in both images.)



Time Step: 0.030

☑ Use Simplified Orbits

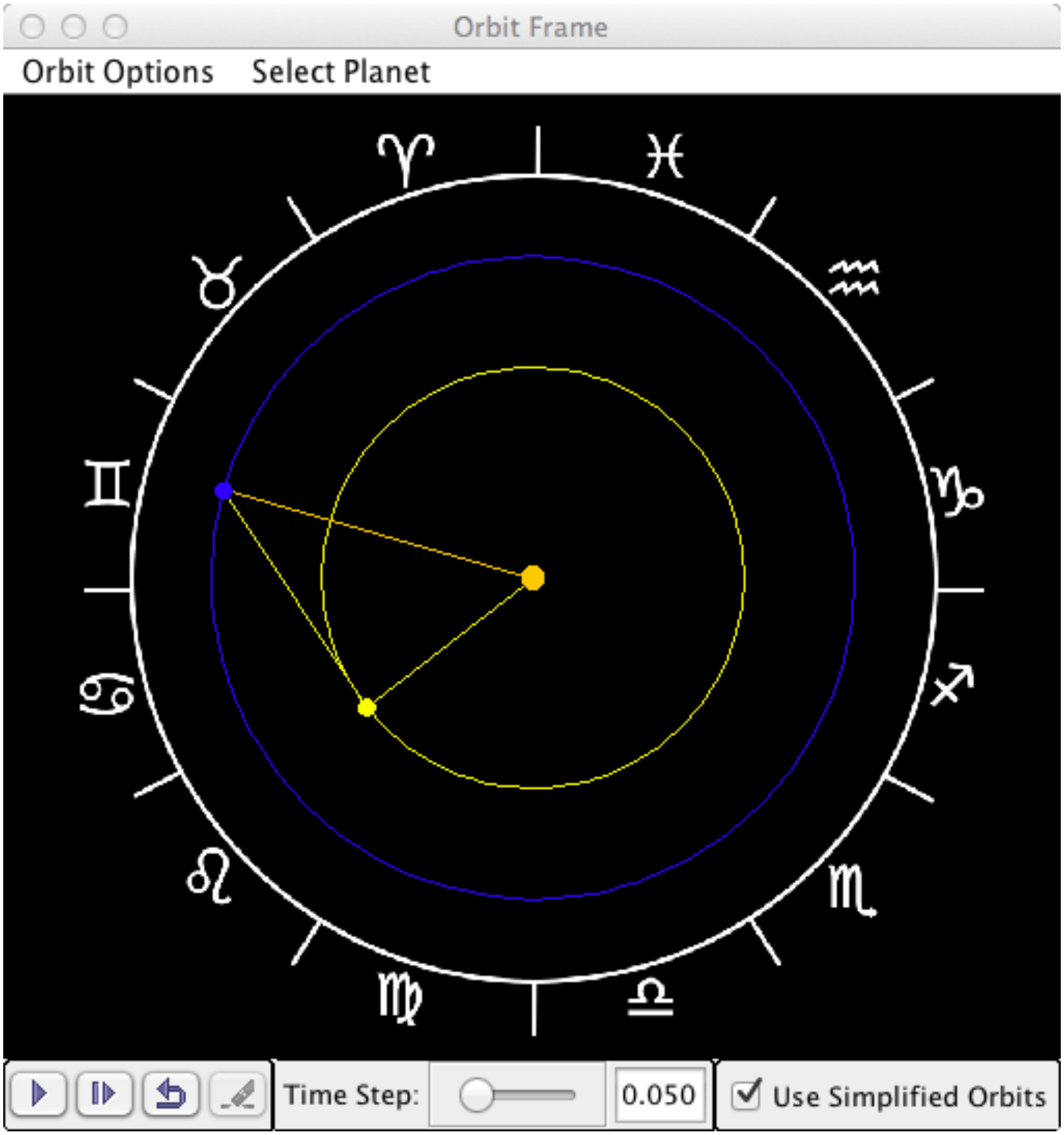
Figure 6: The motion of a “tethered” planet as described in the Ptolemaic system. The home world is the blue disk at the center. The yellow disk is the tethered planet, whose motion is described with a combination of two circles: the green deferent and the magenta epicycle. The Sun and its orbit are shown in orange. Note that the center of the epicycle lies along the line from the home world to the Sun. The symbols on the outside represent constellations of the Zodiac. The planet is shown at its maximum elongation of about 41°.



Time Step: 0.050

☑ Use Simplified Orbits

Figure 7: The Ptolemaic motion of an "untethered" planet. This diagram is like that in Figure 4, except that the planet is shown in red. Note that the line from the epicycle center to the planet is parallel to the line from the home world to the Sun. The planet shown is the one with a celestial period of 6.3 years and a synodic period of 1.19 years.



Time Step: 0.050

☑ Use Simplified Orbits

Figure 8: The Copernican orbit of a tethered planet. The tethered planet and its orbit are shown in yellow, while the home planet and its orbit are shown in blue. The Sun is the orange disk at the center. The planet is shown at its maximum elongation of 41°.

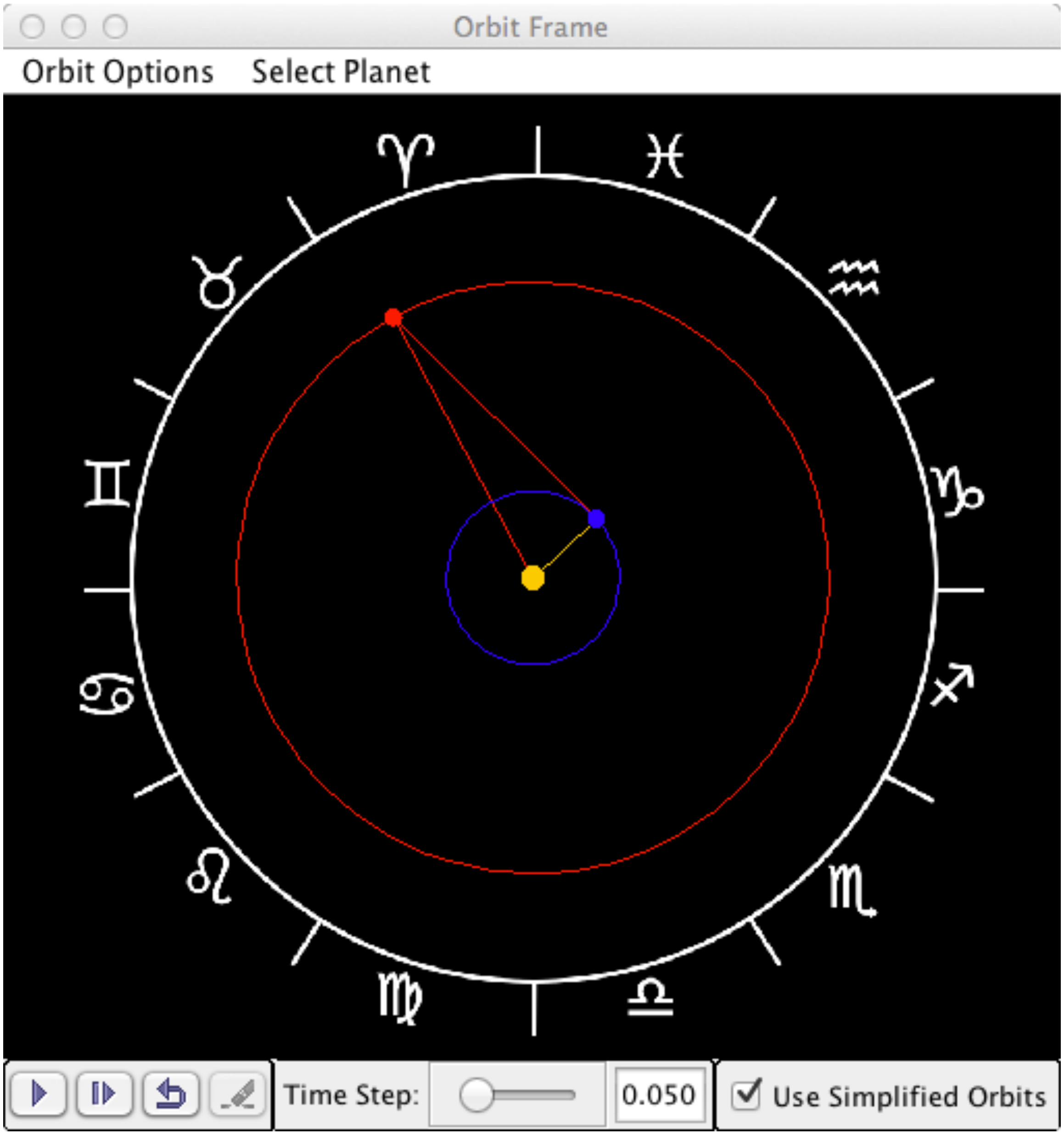


Figure 9: The Copernican orbit of an untethered planet. The untethered planet and its orbit are shown in red, while the home planet and its orbit are shown in blue. The orange disk at the center is the Sun. The planet shown is the same as in Figure 5.

Figure 10: The night sky of Mars as photographed by the Curiosity rover. The Earth is the brightest point in the sky, a little to the left of center in the image. Image Credit: NASA/JPL-Caltech/MSSS/TAMU. The brightness and contrast of the image have been adjusted to make the Earth more easily visible.