# AST 120 Activity 9
# Eudoxus' Spheres, Apollonius' Epicycles

| Name | Full | Partial | None |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

1. Eudoxus of Cnidus was an ancient Greek astronomer who lived in the $4^{th}$ century BC. He took the basic picture of Aristotle's cosmology (the series of concentric spheres) and tried to make workable models that would reproduce the motion of the planets. To get an idea of how his models worked, download and run the `SpheresOfEudoxus` program. The top window shows four concentric spheres. The outermost sphere represents the Celestial Sphere, while the other three are spheres associated with a single planet. The innermost sphere is red, the middle sphere is blue, and the outer sphere is green. The planet is represented by a magenta dot on the red (innermost) sphere. In this model we assume the Earth to be stationary at the center of all four spheres, so to see the planet we are looking out from the center. The bottom window shows the view from Earth. We see a background of stars and the magenta planet. We also see a green line which is the ecliptic (which matches up with the equator of the green sphere in the top window).

   The way Eudoxus' model is constructed is that each sphere spins about its own axis, but the axis of each sphere is attached to the surface of the next sphere out. So the axis of the red sphere is connected to the blue sphere and the axis of the blue sphere is connected to the green sphere. You can tilt the red sphere's axis relative to that of the blue sphere. You can also change the angular velocities of the blue and green spheres (the angular velocity of the red sphere is automatically set to +1.0, in arbitrary units). Let's play with this a little. In Options, deselect Link Speeds of Red and Blue Spheres. Then set all the sliders to zero (you should only need to change $\omega$ (Blue)) and then hit Play. Notice that the blue and green spheres don't spin at all and the axis of the red sphere lines up with the axis of the blue sphere. In the bottom window the planet moves ______________.

   (a) parallel to the ecliptic and to the west.
   (b) parallel to the ecliptic and to the east.
   (c) perpendicular to the ecliptic
   (d) at an angle to the ecliptic, but not at a right angle

2. Does this fit very well with the actual motion of the planets? Explain.

3. For the rest of this activity you probably want to Trace the Path of the planet (in the Options menu). Tilt the axis of the red sphere by about 30 degrees. Clear the Traces and Run the simulation again. Describe the motion of the planet relative to the stars (or relative to the ecliptic) below. Is this the correct motion?

4. Leave the red sphere tilted at 30 degrees and now let's adjust the angular velocity of the blue sphere. Try several different values and watch the resulting simulation (Clear the Traces with the eraser button between each run). Try both positive and negative values. After you have played around for a while, set the blue sphere's angular velocity to -1. The easiest way to do this is to just select Link Speeds ... from the Options menu. Play the simulation again and then describe (or sketch, if you prefer) the motion of the planet relative to the stars in the space below.

5. Now let's get that third sphere moving. Adjust the angular velocity of the green sphere to somewhere in the range 0.2-0.3. Clear the Traces and play the simulation again. Describe the motion of the planet relative to the stars in the space below.

6. Does this fit (at least qualitatively) the actual motion of the planets? Explain.

7. Now increase the angular velocity of the green sphere to 0.8 or so, Clear the Traces, and play the simulation. What happens now?

8. Eudoxus' model was a brilliant way to extract the correct type of motion from Aristotle's idea of concentric spheres. But could it explain all the observable features of the planets? Whether the planets reflect sunlight or emit their own light (both theories were considered in Ancient Greece) we would expect the planets to appear brighter when they are closer and dimmer when they are farther away. Can Eudoxus' model account for the observed changes in the brightness of the planets? Why or why not?

9. In addition, Eudoxus' model could not be made to fit with detailed observations of the positions of the planets among the stars. So this model, brilliant as it was, was abandoned once something better came along. The next serious attempt to model the motion of the planets was made by Apollonius of Perga in the 3rd century BC. He discarded the spheres and instead used circles. His model consisted of a giant circle called a *deferent* which was centered on Earth and which rotated uniformly about its axis. Attached to a point on the deferent was the center of a smaller circle known as an *epicycle*. The epicycle was carried around by the motion of the deferent, but at the same time it spun on its own axis. In Apollonius' model, which was later perfected by Claudius Ptolemy, the planet was placed at a point on the epicycle. To see how this works run the `SuperiorPtolemaic` program. Make sure the box to Use Simplified Orbits is checked. The simulation shows two views of a deferent-epicycle model for the motion of Mars. One view is from above the plane of the ecliptic, looking down on the North pole of the Earth (you can see the constellations of the zodiac marked along the white circle that represents the Celestial Sphere). The other view is what an observer on the Earth would see looking out at the sky (also with zodiacal constellations marked). Play the simulation and watch it for a while. Does this model produce retrograde motion?

10. Does this model reproduce the proper changes in the brightness of Mars (so that it is brightest when it is in retrograde motion)?

11. We know that the Mars undergoes retrograde motion when it is in opposition to the Sun. To see how this works in the deferent-epicycle model use the Select Planet menu to return to the (simplified) orbit for Mars. Note that the simulation shows the motion of the Sun (in both views) as well as that of the planet (Mars in this case). Watch it carefully. Does this model reproduce the proper correlation between retrograde motion, brightness, and the position of the Sun?

12. Ptolemy ensures that Mars will retrograde in opposition by carefully synchronizing two motions in his model. Let's try to identify which motions he is synchronizing. First, carefully watch the simulation and look for two lines that remain parallel at all times. Which pair of lines are always parallel as Mars moves around in its orbit?

    (a) the orange (Earth-Sun) line and the green (Earth-epicycle center) line
    (b) the orange (Earth-Sun) line and the red (Earth-Mars) line
    (c) the orange (Earth-Sun) line and the magenta (epicycle center-Mars) line
    (d) the red (Earth-Mars) line and the magenta (epicycle center-Mars) line

13. The fact that these two lines remain parallel indicates that one of the motions in Ptolemy's theory for Mars is synchronized to Ptolemy's motion for the Sun. Which of the following motions of Mars is synchronized with that of the Sun? (Note: if you are having a hard time seeing this, just ask for help.)
    (a) the motion of the epicycle center around the deferent
    (b) the motion of Mars around the epicycle
    (c) the motion of Mars around the Earth
    (d) none of the above
14. What happens if we disrupt that synchronization? In the Select Planet menu, choose User Defined. Uncheck the Link Planet to Sun box. Change the value of Epicycle $\omega$ to 0.9, or 1.1, or something similar. Play the simulation and watch it for a while. Does the simulation now display the proper relationship between retrograde motion, brightness, and opposition?
15. You may want to quickly explore the orbits of Jupiter and Saturn, which work much the same way as the orbit for Mars. Things work a little differently for Mercury and Venus. These planets never stray far from the Sun and they undergo retrograde motion when they are in conjunction. To see how the deferent-epicycle model works for Venus, quit `SuperiorPtolemaic` and run `InferiorPtolemaic`. This shows the model for the motion of Venus. Watch it carefully. Does this model reproduce the proper correlation between retrograde motion and the position of the Sun?
16. Does this model keep Venus close to the Sun at all times?
17. What motion in this model is synchronized with that of the Sun?
    (a) the motion of the epicycle center around the deferent
    (b) the motion of Venus around the epicycle
    (c) the motion of Venus around the Earth
    (d) none of the above
18. See what happens if you break this synchronization. Use the Select Planet menu, choose User Defined, uncheck Link Planet to Sun, and alter the value of Deferent $\omega$. What do you now notice about the motion of Venus relative to the sun that doesn't fit with what we observe in the night sky?