Chapter Thirteen

The Ptolemaic System

The transition from the Aristotelian worldview to the Newtonian worldview involved, in important ways, competing theories as to the structure of the universe. In the next few chapters, we look at the central astronomical theories involved in this transition, some Earth-centered and some sun-centered. We will begin with a look at the Ptolemaic system.

The main goal of this chapter is to provide an overview of this system, as it was presented in Ptolemy's *Almagest*, published around AD 150. As noted earlier, the *Almagest* is a substantial and technical work, composed of 13 books spanning about 700 pages. We will begin with some background material on Ptolemy's system, and then look at some of the details of the system.

Background Information

As with any theory, Ptolemy's system needed to respect the relevant facts. In this case, the relevant facts consist largely of the empirical facts discussed in Chapter 11, as well as the philosophical/conceptual facts of circular, uniform motion discussed in the previous chapter.

Generally speaking, Ptolemy's system succeeds at respecting these facts. His system clearly respects the perfect circle fact, in that his entire approach is based on using only perfect circles for the motions of the heavenly bodies. As we will see below, he has some difficulties with the uniform motion fact, but he manages at least in some sense to respect this fact.

With respect to the empirical facts, his system does an especially nice job. That is, when it comes to explaining and predicting the facts discussed in Chapter 11, although his system is not perfect (few theories are), the margin of error is low.

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For example, if we use Ptolemy's system to predict, say, where Mars will appear in the night sky on this date a year from now, or if we use the system to predict when and for how long Mars will next exhibit retrograde motion, the prediction will be very close to what we observe. It is very much worth emphasizing that no other theory of the universe before Ptolemy, or for 1,400 years after Ptolemy, was anywhere close to his with respect to prediction and explanation. It is fitting that the name by which we know this work, *Almagest*, was given it by Arabic translators and derives from a phrase meaning simply "the greatest." Although the theory may appear somewhat archaic to our eyes, the Ptolemaic system was a spectacularly impressive accomplishment.

We should take a moment to clarify what Ptolemy did and did not do. Ptolemy's approach is a mathematically based one, and he makes intricate use of various mathematical devices. Most of the mathematical devices he employs, however, were not original to him, but had been discovered in earlier centuries.

Nor, of course, was Ptolemy the first to develop an Earth-centered view of the universe. As we saw earlier, the view that the Earth was spherical, stationary, and at the center of the universe goes back to before Aristotle, 500 years before Ptolemy.

So Ptolemy did not originate the general Earth-centered approach that he takes, nor did he originally develop the mathematical devices that he employs. But what he did was take these rough notions and develop them into a precise theory, and a theory capable, for the first time in history, of providing accurate predictions concerning astronomical events. Or to put the point another way, before Ptolemy there were at best rough sketches, rather than anything that could properly be used in making predictions about astronomical events. With Ptolemy came a precisely crafted theory, capable of impressively accurate predictions and explanations.

As a final note in this section, you will sometimes hear that Ptolemy's system is not really a system, in the proper sense of the word. In a sense, this is correct, in that Ptolemy treats each of the heavenly bodies in an isolated, rather than unified, way. For example, one book of the *Almagest* deals exclusively with Mars, another exclusively with Venus, another with the sun, and so on, without ever providing a unified system of the entire universe. In that sense, one might say that Ptolemy's approach is not, strictly speaking, a system of the universe, but rather a collection of independent treatments of the various components of the universe. I will, however, continue to use the word "system" to describe Ptolemy's theory, since all these independent treatments add up to an approach that can be used to make predictions for all of the components of the universe.

With these background observations in mind, we will move on to consider an overview of the Ptolemaic system. For ease of discussion, we will focus on just one planet, in this case, Ptolemy's treatment of Mars. Let's begin with a description of the components involved in Ptolemy's treatment of Mars, and then discuss the rationale behind those components.

A Brief Description of the Components of Ptolemy's Treatment of Mars

Figure 13.1 illustrates the key components of Ptolemy's treatment of Mars. Here, Mars moves around a point, labeled point A in the diagram. The circle this movement traces out, that is, the small circle that has A as its center, is called an *epicycle*.

The center of the epicycle, that is, point A, itself moves around on a larger circle that has point B as its center. A larger circle such as this is called either a *deferent* or an *eccentric*, depending on whether B is located at the center of the system (in this case, the center of the Earth), or is instead displaced from the center of the system. In this particular case, this is an eccentric, since as you can see, the center of the movement of the epicycle, point B, is not centered on the center of the Earth.

To clarify the distinction between deferents and eccentrics, note the Earth is at the center of Ptolemy's system. That is, the outermost boundary of the system is the sphere of the fixed stars (this is the periphery of the universe), and since the Earth is at the center of that sphere, the Earth is at the center of the system. If point B coincided with the center of the Earth (that is, the center of the system), then the large circle centered on B would be termed a deferent. On the other hand, if, as in the picture above, point B is not at the center of the system, then the larger circle is termed an eccentric.

In short, deferents and eccentrics are basically the same, in that both are the larger circles on which epicycles revolve. Think of an eccentric as an off-centered deferent.

The equant point is a point involved in the speed at which Mars' epicycle moves. The equant point is the most difficult component to explain, and so I will hold off on the details until we consider the rationale for these components.

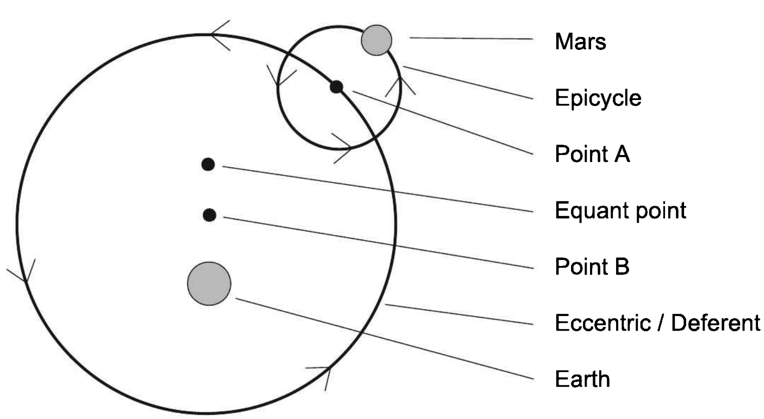

Figure 13.1 Treatment of Mars on the Ptolemaic system

Finally, this sort of a structure – that is, an epicycle moving on a larger circle – is termed an *epicycle–deferent system*. For convenience, we will call such an arrangement an epicycle–deferent system even if, strictly speaking, the system employs eccentrics rather than deferents.

The Rationale behind These Components

The Ptolemaic treatment of Mars is clearly somewhat complicated, with circles moving on circles, some circles off-centered, and with the still mysterious equant point involved. What were the reasons for these components?

First, some comments on epicycle–deferent systems in general. Epicycle–deferent systems are enormously flexible, in the sense that an extremely broad range of motions can be produced simply by varying the size, speed, and direction of motion of the components. That is, in any epicycle–deferent system, one has a broad range of options in how large or small one makes the epicycle and the deferent, one likewise has a broad range of options in how fast one has the planet moving on the epicycle, also how fast one has the epicycle moving on the deferent (or on the eccentric, as the case may be), and one also has the option of having the movement on the epicycle and deferent be either clockwise or counterclockwise.

This flexibility allows one to produce a wide range of motions, simply by adjusting these options. For example, all of the motions shown in Figure 13.2 were produced by an epicycle moving on a deferent. The dotted lines represent the path traced out by Mars as it moves on its epicycle, as the epicycle itself is moving around the Earth. All of these motions (and a wide variety of other motions as well) can be produced simply by varying factors such as the size of the epicycle, the size of the deferent (or eccentric), the speed at which Mars moves on its epicycle, the speed at which the epicycle moves, and so on.

So epicycle–deferent systems are useful for the amount of flexibility they provide. But in addition, any Earth-centered approach needs epicycles (or some method at least as complex as epicycles) in order to account for the retrograde motion of the planets. Recall from Chapter 11 that retrograde motion is when a planet appears to move "backward" from its usual motion. For example, Mars usually drifts slightly eastward each night relative to the fixed stars, but about every two years Mars will drift westward for a few weeks, before resuming its usual eastward motion for another two years.

To see how epicycles are used to account for retrograde motion, suppose we focus on the Earth, Mars, and the fixed stars. If we draw a line of sight from the Earth, through Mars, to the stars, that line will show where Mars will appear, as viewed from the Earth, in the night sky against the backdrop of the stars (see Figure 13.3).

Now suppose we imagine Mars moving on its epicycle, with the epicycle moving around the Earth. If we draw continual lines of sight from the Earth

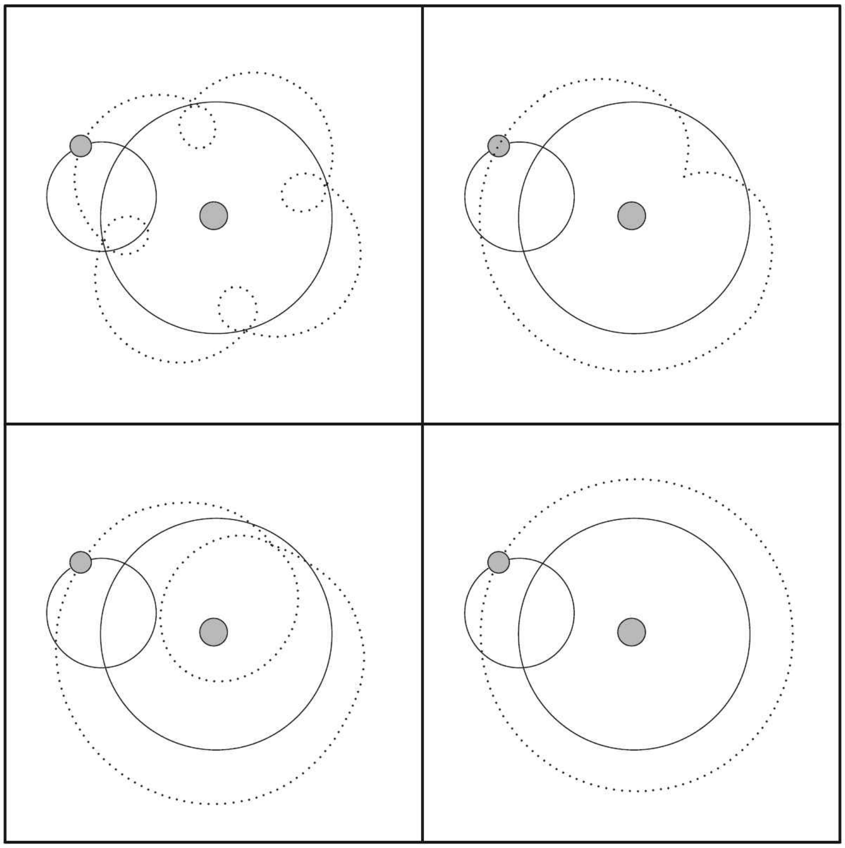

Figure 13.2 The flexibility of epicycle–deferent systems

through Mars, this will indicate where Mars will appear in the night sky, over the course of time, against the backdrop of the stars (see Figure 13.4). The numbers in Figure 13.4 represent the consecutive positions of Mars. As you see, Mars usually appears to move in one direction against the backdrop of the stars. That is, numbers 1 to 7 represent a steady motion eastward relative to the fixed stars. Then at 8, Mars has just begun to drift westward. Mars continues drifting westward at 9 and 10, and then from 11 to 15 resumes its usual eastward drifting. And in general, this is how an epicycle–deferent system accounts for retrograde motion. In fact, if one is committed to an Earth-centered system, with uniform circular motion, then epicycles turn out to be the best way to account for retrograde motion.

Incidentally, it should be noted that the sizes and speeds of the epicycle and deferent in these diagrams are not the correct sizes and speeds for Mars. These sizes and speeds were chosen to make for a simpler illustration. But by adjusting the sizes and speeds (and using eccentrics, as described below), one can get the "backward" appearance of Mars' motion to work out so that the model accurately predicts and explains when Mars is actually exhibiting retrograde motion.

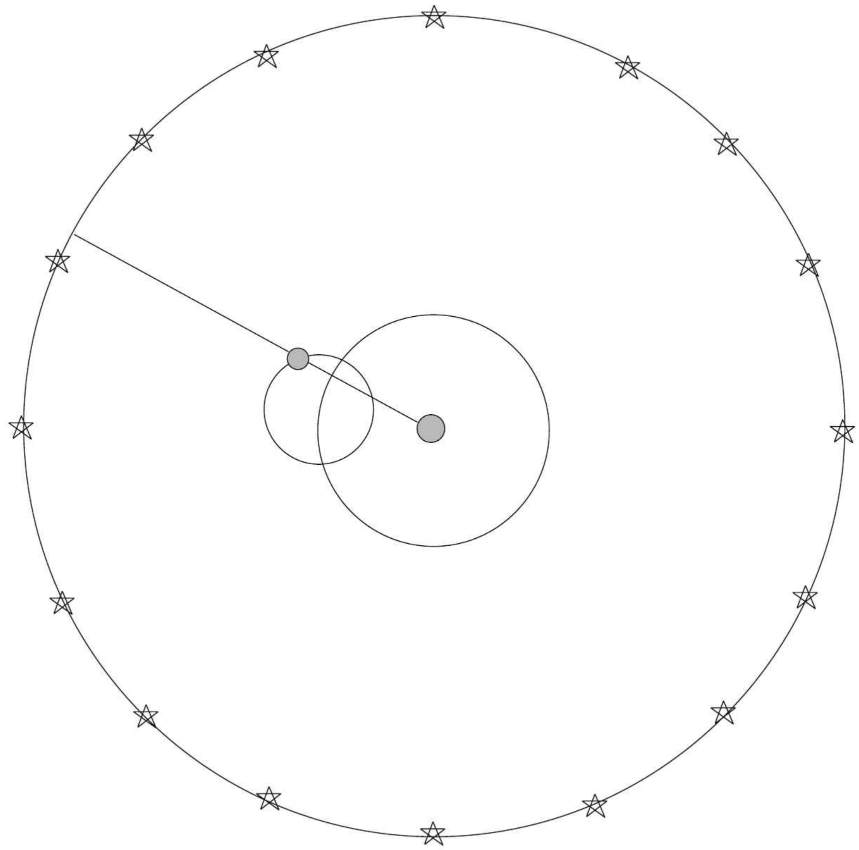

Figure 13.3 Position of Mars against the backdrop of the fixed stars

Let's now turn to the question of why Ptolemy used an off-center deferent, that is, an eccentric. The reason is simply that, if one uses a simple epicycle and deferent (again, the deferent would be a circle centered on the Earth), then one cannot get the model to make accurate predictions and explanations. That is, the model simply will not do what you need it to do, namely, make accurate predictions and explanations. But either of two modifications to the simple combination of epicycle and deferent will produce a model that quite accurately predicts and explains the motion of Mars.

The first option is to introduce an additional, small epicycle on the epicycle shown in Figure 13.1 above. The result would be as pictured in Figure 13.5. This additional epicycle adds even more flexibility to the model. With this additional flexibility, one can now adjust the model such that the predictions and explanations concerning Mars will be extremely accurate.

Such additional epicycles are sometimes called *minor epicycles*, to distinguish them from the *major epicycles*, such as the single epicycle pictured in Figure 13.1 and the larger epicycle pictured in Figure 13.5. The difference between major and minor epicycles is that major epicycles are the ones needed to handle retrograde

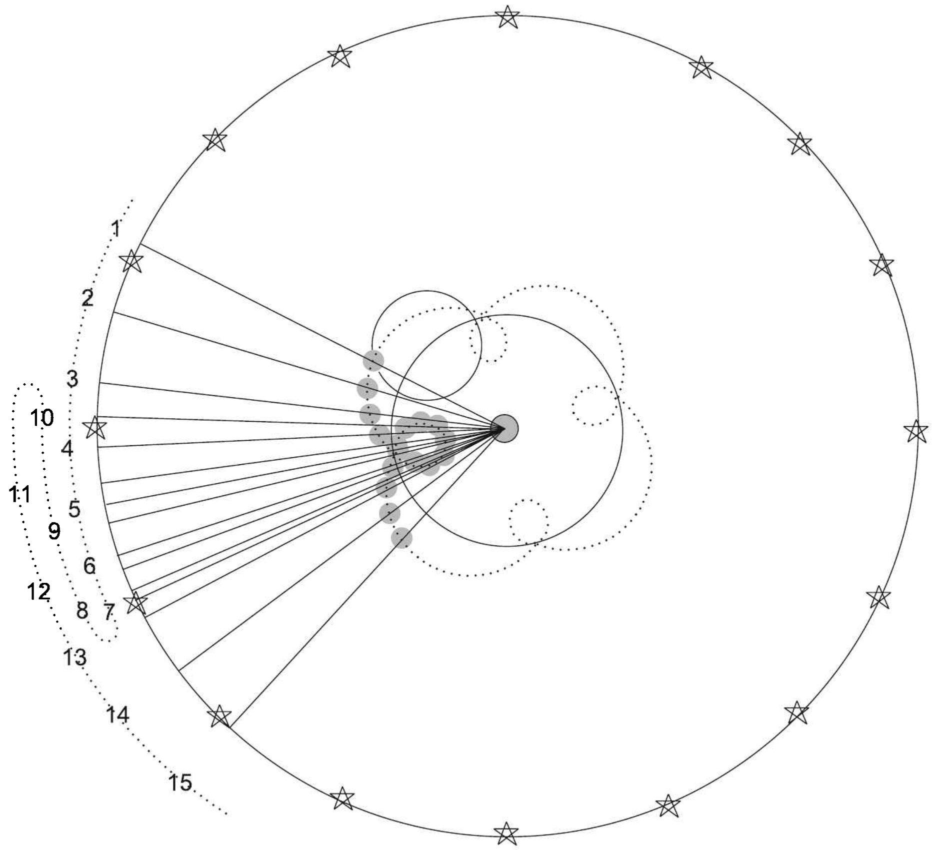

Figure 13.4 Explanation of retrograde motion on the Ptolemaic system

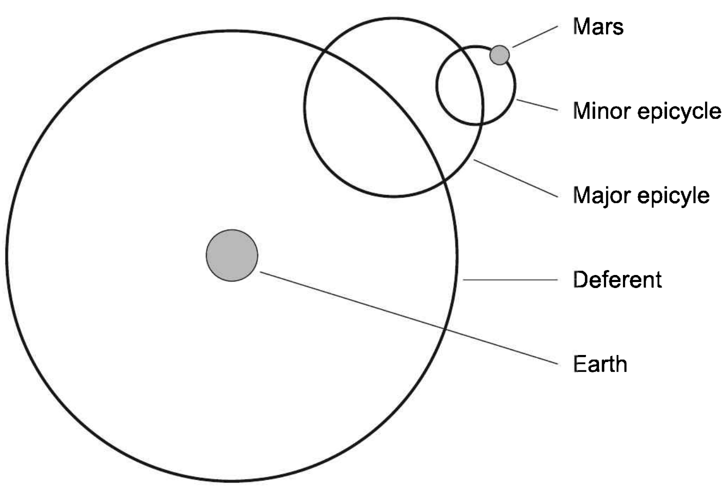

Figure 13.5 Minor and major epicycles

motion. Major epicycles also provide flexibility, but their primary function is to account for retrograde motion. In contrast, minor epicycles are not needed to handle retrograde motion, but rather are used to give the model additional flexibility.

As mentioned, adding minor epicycles is one way to get the predictions and explanations for Mars to come out right. The other option is to move the deferent off-center, that is, to use an eccentric. This option is what is pictured in Figure 13.1.

Either option – adding a minor epicycle or using an eccentric – will work to get the predictions and explanations back in line with the observed data. In fact, the two options are mathematically equivalent, so either will work equally well. Ptolemy chose to use eccentrics, and thus the construction for Mars looks as it does in Figure 13.1.

The final component to explain is the equant point. This also involves a problem with getting the model to correctly predict and explain the observed data. In particular, this problem is tied to the philosophical/conceptual fact of uniform motion. Recall that the two key philosophical/conceptual facts the Ptolemaic system needed to respect were the perfect circle fact (that all motions of heavenly bodies are perfectly circular) and the uniform motion fact (that the motion of heavenly bodies is uniform, that is, neither speeding up nor slowing down).

If you look at the figures in this chapter, you can note that the Ptolemaic system clearly respects the perfect circle fact. That is, all motions are in terms of perfect circles. We have actually looked only at the treatment of Mars, but in all of Ptolemy's constructions, all minor and major epicycles, deferents, and eccentrics are perfect circles. So clearly, there is no problem respecting the perfect circle fact.

The uniform motion fact is a different matter, and provides a problem for Ptolemy's system. This problem is sometimes difficult to see, so let's approach it slowly.

First, note that the speed and direction something appears to be moving will depend on the point of view from which one considers the motion. For example, suppose you are on a train with a bag at your feet. From your point of view, that bag is not moving – it remains in the same position relative to you and your feet. But from the point of view of someone not on the train, your bag (and you, and everyone else on the train) is moving. Again, this is simply the point that whether something is moving, and if so at what speed and in what direction, is relative to the point of view chosen.

So when we consider the uniform motion fact, which again requires that the movements involved be uniform, a legitimate question is "uniform relative to what point of view?" And the natural answer to this would be "uniform relative to whatever is the center of the movement."

If we look at just the movement of Mars on its epicycle, there is no problem. That movement is indeed uniform, that is, as Mars moves around the center of the epicycle, it moves with uniform speed relative to that center.

But now consider the motion of the center of the epicycle. If we ask "What should this motion be uniform relative to?" there are two natural answers. The first would be that the center of the epicycle moves with uniform speed relative to the center of the entire system, that is, relative to the center of the Earth. The second would be that the center of the epicycle moves with uniform speed relative to the center of the eccentric on which it moves.

The problem is, if you take either of these options – that is, if you make the motion of Mars' epicycle uniform relative either to the center of the Earth or to the center of Mars' eccentric – the system won't work. When I say it won't work, I mean simply that your predictions and explanations will not be accurate. In other words, if Ptolemy tries to respect the uniform motion fact in the most straightforward way, his system will not handle the data in an acceptable way. That is, the predictions and explanations are no longer accurate.

One option for addressing this problem would be to abandon the uniform motion fact. But again, this was a well-established fact, and had been for centuries before Ptolemy, and even before the time of Aristotle. Moreover, as discussed in the previous chapter, the uniform motion fact is closely tied to the understanding of how the heavenly bodies move, so abandoning this fact would likewise mean abandoning the long-held understanding of what accounts for the motion of the heavenly bodies. In short, giving up the uniform motion fact was not really a viable option.

The other option for Ptolemy was to make the motion of Mars' epicycle uniform relative to some point other than the center of the Earth or the center of the eccentric, and this was the option Ptolemy adopted. As it turns out, one can calculate a point, within the eccentric on which Mars' epicycle moves, such that if Mars' epicycle moves with uniform speed relative to this point, then the model will come back in line with the data. And this point is what is called the *equant point*.

In summary, the equant point for Mars is the point with respect to which Mars' epicycle moves with uniform speed. But that point is a somewhat contrived point, calculated so as to make the predictions come out accurate, rather than being either of the places from which you would expect the movement to the uniform.

This, then, completes the overview of the main components needed to handle the motion of Mars. Clearly, this is a complex apparatus. But, to a remarkable degree of accuracy – it works.

Concluding Remarks

Above, we described only the parts of the Ptolemaic system that concern Mars. This treatment of Mars should be sufficient to provide a flavor for the Ptolemaic system. As noted, Ptolemy treats each of the five planets, the moon, the sun, and stars separately. The treatment of the other planets, and to some extent the moon and sun, bear similarities to the treatment of Mars. That is, generally speaking, the constructions needed to account for the motions of the other planets are similar (though not identical) to those for Mars, with the planets requiring their own epicycles, eccentrics, and equant points. The apparatus needed to account for the motions of Mercury and the moon are somewhat more complex than those described above for Mars, while handling the motions of the sun is somewhat less complex. In general, it should be clear that the Ptolemaic system is a quite complex collection of constructions for handling the sun, moon, stars, and planets.

But – and this is a crucial point – in spite of its complexity, the Ptolemaic system did a marvelous job of handling the data, providing for the first time in history the ability to accurately predict and explain an extraordinarily wide range of astronomical data.