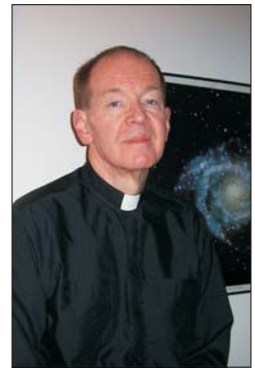
Article

Does the Earth Move?

George L. Murphy



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Einstein's theory of relativity means, among other things, that a modified version of Tycho Brahe's earth-centered model of the planetary system is, in principle, as good as Copernicus' sun-centered model. The question of whether the earth or the sun "really" moves is meaningless in this theory. After dealing with challenges to this claim, implications of relativity for understanding biblical texts that were involved in historical debates about the planetary system, as well as some further theological issues, are considered. An appendix provides some mathematical details.

Why This Topic Again?

I have gotten strange looks or emails when I have suggested that the answer to the title question is not simply "Yes," but "It depends." It is not hard to guess why. Copernicus' theory that the earth and other planets orbit the sun was a major factor in the development of science, and opposition to it in some parts of the church helped to create the "warfare model" of the science-religion relationship. Many scientifically literate people today "know" that the earth goes around the sun, not the sun around the earth, and any qualification of that claim by appeal to Einstein's relativity theory may seem reactionary. That concern is not entirely baseless, for at least one theologian thought, hopefully, that Einstein's theory might "give the death blow to Copernicanism."[1]

Nevertheless, general relativity really is general. One of its basic principles is that the laws of physics have the same form in all space-time reference frames—i.e., systems of spatial and temporal coordinates. A reference frame fixed with respect to the sun's center is no better in principle than one fixed with respect to the earth or, for that matter, with respect to Halley's Comet.

One might think that since relativity theory has been studied well and widely enough, these results would be generally known, at least among physicists, so that further discussion would be unnecessary. This would be too optimistic, for there has been disagreement on the question, even among experts.[2] Einstein and Infeld said that if physics is fully relativistic, the struggle "between the views of Ptolemy and Copernicus would then be quite meaningless," and Born agreed that "from Einstein's point of view Ptolemy and Copernicus are equally right," though the latter view is "certainly more convenient." However, Whittaker called the idea that "the Copernican conception of the universe" is "not preferable to the Aristotelian conception" a misunderstanding, while Fock argued against "the inadmissible view that the heliocentric Copernican system and the geocentric Ptolemaic system are equivalent." Physicist and philosopher Mario Bunge summoned up the shades of "the enemies of Galileo" to support his argument against the possible equivalence of geocentric and heliocentric

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coordinate systems. As surprising as their disagreement is the fact that all these writers mentioned only the Ptolemaic (or Aristotelian) system as an alternative to the Copernican one, with no reference to the system of Tycho Brahe.

There is even less general agreement on this matter among those without training in physics, as informal conversations will show. Among physics students and others interested in the field, there is also misunderstanding. We may note, for example, recent statements on two websites. On "Physics Forums," where we can probably assume that participants are either students of physics or at least interested in the field, "a copernicus/relativity question" was posted in 2009.[3] Some of the responses to this question are satisfactory, but numbers 9, 10, and 20 employ different incorrect arguments against the equivalence of earth-centered and sun-centered frames.

Then, in a discussion of geocentrism by "Answers in Genesis," it is said that "common misconceptions include the beliefs that general relativity does not allow for a preferred standard of rest and that general relativity leads to moral relativism."[4] Linkage of Einstein's theory with moral relativism is indeed a misconception, but the claim that it allows a preferred reference frame is (in spite of an appeal to Mach's principle) wrong.

The historical controversy about the Copernican system strongly influenced religion-science relations in the past and continues to do so today. Thus it seems wise for people interested in those relations, and not just those trained in physics, to understand how matters stand in the light of modern science. Of course, it would be anachronistic to judge Galileo and his contemporaries in terms of a theory that lay three centuries in their future, and in any case, this article will not detail the history of the sixteenth- and seventeenth-century debates. But discussions about the truth of astronomical statements in the Bible continue in the Christian community, and it would also be anachronistic to talk about relationships between biblical texts and science with only the physics of 1600. Our study will not rehabilitate "enemies of Galileo," but it will suggest that our conclusions be more nuanced than many popular accounts suggest.

Ptolemy, Copernicus—and Tycho

The historical debate is often pictured as one between the earth-centered system of Ptolemy and the sun-centered view of Copernicus, but there was a third contender. The greatest observational astronomer of the time, Tycho Brahe, proposed that the earth was at rest, the sun orbited the earth, and the other planets orbited the sun.[5]

Ptolemy's system conflicts with observations. Venus is never seen from Earth to be more than 40° from the sun, and with the Ptolemaic arrangement of orbits, could never appear fully illuminated to us. In the Copernican system, however, Venus should go through a full range of phases as the moon does. Galileo could see with his telescopes that Venus does imitate the moon in this regard.[6] Tycho's theory, however, predicts the same apparent planetary motions as that of Copernicus. Galileo's observations of the phases of Venus show the theories of Tycho and Copernicus to be superior to Ptolemy's to the same extent but do not decide between those two theories.

The Tychonic theory has often been ignored or treated as a historical footnote because of an important idea that originated with Kepler and was given definitive form by Newton, that the force responsible for the planetary orbits comes from the sun.[7] This suggests that the sun is really at rest and the planets, including Earth, are in motion. Acceptance of Newton's ideas about absolute space reinforced that idea. While velocity is a purely relative concept in mechanics, Newton thought his experiment with a rotating bucket of water showed that *acceleration* has absolute significance: The acceleration in his second law of motion is with respect to absolute space.[8] If that is so, and if the planets rather than the sun are accelerated, then it is the planets that really move.

Accelerated reference frames can be used in Newtonian mechanics at the cost of introducing "fictitious forces." These are simply the negative of "mass times acceleration" terms in Newton's second law moved to the other side of the equation and called forces. Centrifugal and Coriolis forces are examples. Planetary orbits can then be calculated in a fixed-earth frame, but within the Newtonian worldview, the earth is still thought of as "really" moving.

Some Things Really Are Relative

The popular notion that relativity theory says that everything is relative is badly mistaken. In Einstein's theory, there are absolutes, things that will be observed to be the same in all reference frames: The local speed of light in a vacuum, space-time intervals, and the electric charge of an isolated system are a few examples. However, many things *are* relative. The velocity of an object differs for observers moving in different ways, and therefore only relative velocities are important. Einstein enshrined this idea in his special theory of relativity, stating that all the laws of physics (and not just mechanics, as in classical physics) are the same for observers in uniform motion with respect to one another. There is no way to tell which are "really" moving or at rest.[9]

Einstein then extended this idea to accelerated reference frames and provided an explanation of gravitation in his general theory. In special relativity, there is no preferred reference frame for determination of velocities. In general relativity, there are no preferred frames at all and no absolute space. Any system of space-time coordinates is, in principle, as good as another, though for a given problem some systems will be more convenient than others. Thus we can use a reference frame in which the sun is stationary (Copernicus) or one in which the earth is fixed (Tycho). Einstein's equations for the curvature of space-time due to the sun's mass and the geodesic equations for the worldlines of planets have the same form in both frames and could, in principle, be solved in either one.

Actually, there is not just one reference frame with the sun stationary, but an infinite number of them. We can, for example, rotate the spatial coordinate system about the sun by various angles. The coordinates that are most convenient for calculating orbits around a star can be transformed in many ways, such as to coordinates that are helpful in the study of black holes. There is similar freedom in choosing a fixed-earth frame.

It is also worth noting that use of a particular reference frame does not require an observer to adopt it as her or his rest frame. As Schrödinger put it in making this point,

> It is the very gist of relativity that anybody may use any frame. We study, for example, particle collisions alternately in the laboratory frame and in the centre-of-mass frame without having to board a supersonic aeroplane in the latter case.[10]

We do not have to be on the sun in order to use the Copernican model, and an observer on Mars could use a frame in which the earth is at rest.

Tycho wanted to have not only an earth whose center was fixed but also a nonrotating one. The "sphere of the fixed stars" was to turn around the earth every twenty-four hours, just as in Ptolemy's model. This would require use of a co-rotating frame, one that turns with the earth, so that in it, the earth's rotation has been eliminated. We usually do adopt such a frame for everyday terrestrial phenomena, tacitly ignoring the earth's rotation.[11] But the linear velocity across our line of sight of an object in such a frame would increase in proportion to its distance from the earth, and an object farther than about 4×10^9 km (somewhat beyond the orbit of Neptune) would be moving faster than light.

Thus a frame with a nonrotating earth cannot be used for phenomena beyond a certain distance. However, what historians of science have called a "semi-Tychonic" system, in which the earth rotates but its center is at rest, is possible.[12] Tycho's contemporary Nicolaus Bär (who may have stolen the idea of Tycho's system from him), in fact, proposed such a modification long ago.[13]

This type of limitation is not unique to rotating frames. It is often the case that a single coordinate system cannot cover an entire manifold. For example, the coordinate system of latitude and longitude on the surface of a sphere breaks down at the poles, where longitude is undefined.

Stellar parallax, the possible shift in position of stars over the course of a year, also has to be considered. In Ptolemy's model, with the stars fixed on a celestial sphere centered on the earth, there is no annual parallax, whereas in Copernicus' model, with a celestial sphere centered on the sun, the earth's annual motion should result in shifts in stellar positions. Stellar parallaxes are so small that astronomers in 1600 were unable to detect them, but when this became possible in the 1830s, it was seen as another triumph of the Copernican theory over the Ptolemaic.

How do things look with Tycho's theory? That depends on where the sphere of the fixed stars is centered. But just stating the matter in that way should make us realize that our understanding of the universe has now developed to a point where some concepts common to all three original theories are obsolete. There is no sphere of the fixed stars and, in fact, there are no fixed stars. Stars move with respect to the sun, and the motion of many across our line of sight (their proper motion) is larger than their annual parallax. If we adopt coordinates moving with the earth, as a semi-Tychonic model requires, there will be annual shifts in position after proper motions and stellar aberration are subtracted, just as in Copernicus' theory. For Copernicus these shifts are due to our change in position as the earth orbits the sun; for Tycho they are due to an annual back and forth motion of the stars themselves in the coordinates we have adopted.

What was at issue in the historical debate is often described as the question of whether a heliocentric or a geocentric model was correct, but to put things that way today really misses the point. Neither the earth, the sun, nor the whole solar system is at the center of the universe, a concept that does not even have any meaning in modern cosmology. The real issue is not "centricity" but whether we can adopt a fixed-earth or a fixed-sun reference frame. The answer relativity gives is that we can use either one. Either type of reference frame, or in fact, a frame moving in any way at all, is legitimate. And even when we want to think of the sun at the "center" of the solar system, we must recognize that it is accelerated because of the gravitational influence of the planets. It is actually the center of mass of the whole system that is "at rest"—or, more precisely, that moves under the influence of the rest of the galaxy and ultimately the universe.

Earth and Sun in Biblical Texts

For readers of this journal, the implications of the previous discussion for the interpretation of Scripture and the relationship between science and theology will be important. Opponents of Copernicus and Galileo could quote biblical passages in support of their claim that the sun, not the earth, moved. Does relativity's validation of a semi-Tychonic model mean that they were right?

It is important, first of all, to understand that relativity does not say that one of these models, the Copernican or semi-Tychonic, is right and the other wrong. The whole thrust of the relativistic argument is that *both* are valid. We can say that the earth is stationary as long as we do not then say that the sun cannot be considered stationary, or vice versa. But we cannot say that both are stationary in the same reference frame. In Einstein's theory, there are absolutes (i.e., things that are the same for all observers) but there are no reference frames that are, in principle, better than others. Relativity does not deal a "death blow to Copernicanism."

Most of the biblical material that has any relevance to these issues has to do with diurnal rather than annual motions. What would be in question would be whether the earth turns on its axis every twenty-four hours, not whether it goes around the sun once a year. Biblical references to the sun rising or setting (e.g., Eccles. 1:5) cannot be considered "wrong." Modern astronomers still use the same language. We should remember that reference to a diurnal motion of the sun implies use of a frame in which the earth's rotation has been eliminated, and that, as we noted, such usage encounters problems for objects far from the earth. But the fact that use of such a frame would imply a speed for the sun of about 4% that of light does not mean that there is any fundamental problem with it.

More to the present point is the fact that modern astronomers can, if they need to, justify their use of such language on the basis of Einstein's theory. But the fact that biblical writers spoke of the sun rising and setting does not mean that they knew anything about that theory, and they could have argued in the same way. There is no hidden reference to modern science in such texts.[14] The biblical writers were simply using a common way of speaking about the appearance of the phenomena from the earth.

The language about the sun and moon standing still at the Battle of Gibeon in Josh. 10:12–14 "for about a whole day" (v. 13, NRSV) also involves diurnal rather than annual motions. Again the language implies that the sun and moon normally move (and that presumably the earth does not) but temporarily stopped. One question we have to ask today about this text is not whether it was those celestial bodies or the earth that stopped moving, but whether there was any actual stoppage of the *relative* motions of these bodies. Are we to read this text as if it were an account of an astronomer's observations?

The text as we have it in Joshua is a combination of poetry (vv. 12b–13) from "the Book of Jasher" and later prose interpretation. The very nature of poetry suggests that we may not be required to understand the language literally. If we were, then we would have to insist that the stars really did fight from heaven against Sisera, as the Song of Deborah says in Judges 5:20. Since there are a number of ways of understanding these lines, we are hardly compelled to read them as an accurate scientific account of astronomical events.[15] Nevertheless, ancient Israelites may indeed have thought that the sun and moon temporarily stopped their motions across the sky.

Then we should consider Ps. 93:1b and Ps. 104:5, which speak of the earth as being immoveable. This is a tautology in a fixed-earth frame, but again it would be a mistake to see here an indication of a knowledge of relativity. If these texts were anachronistically thought to be claims about a preferred physical reference frame, then we would have to regard them, like the dome over the earth or the cosmic ocean above it in Genesis 1, as accommodation to an ancient cultural understanding of the world.[16] But there is no reason to think that the writer of the psalm was thinking in those terms. The point of these texts is the praise of God, and the emphasis is really on the durability of God's reign.[17]

Further Implications of Relativity

It has sometimes been suggested that the microwave background provides a preferred reference frame (or more precisely, a set of such frames). A frame in which this radiation is uniform over the sky (averaging over small temperature fluctuations) is the most convenient one for discussion of cosmological phenomena and is tacitly used when we say that the elapsed time since the big bang is about 13.7 billion years. In answer to our title question, the earth and sun are both moving with respect to this preferred frame.

Polkinghorne has made use of this reference frame to deal with a question raised by his theological approach.[18] Having said that "God knows now all that can be known now, but God does not yet know all that will eventually become knowable," he confronts the question of which "now" defines the boundary of divine knowledge. A basic result of relativity is that observers in relative motion keep time differently and generally do not agree on whether two events are simultaneous, so that the sets of events they judge to be "now" differ. Polkinghorne suggests that "it would not be surprising" if the Creator chose to use the reference frame defined by the microwave background.

Polkinghorne's suggestion should not be misunderstood. He knows that the microwave background does not define a preferred reference frame in contradiction to the ideas of relativity theory. While such a frame is very useful, it is not privileged in the sense that the form of basic laws of physics is valid only in it (as was the case with the aether before Einstein). Polkinghorne says explicitly that God has *chosen* a limitation on divine knowledge and thus of a particular reference frame in which that limit is specified. What is at issue here is the concept of kenosis, divine self-limitation, which has to be considered on its theological merits, not a matter of some external necessity imposed upon God.[19] The point here, however, is simply to be clear about the physics.

Finally, we should note that the way in which the structure of relativity theory enables us to relate the appearance of the physical world in different reference frames might provide some guidance for dealing with the variety of Christian theologies that arise from different historical traditions and various social, economic, racial, and gender contexts. An earlier article dealt with this possibility.[20]

Conclusions

Controversies about the Copernican system played an important role in the development of attitudes about science and religion, and the results of those historical debates continue to influence such attitudes today. While nothing really new has been said here, an accurate statement of the implications of relativity theory for celestial mechanics should contribute to a better understanding. As we have seen, these implications have not been appreciated by all physicists, let alone by non-experts. And while there is no need to think that biblical writers were aware of concepts of modern science, it is helpful to see what the differences really are between their picture of the world and current scientific views.

Appendix: Details of a Semi-Tychonic Model

The idea of a fixed-earth reference frame in general relativity is not new but the mathematical details supporting it are not easily available, so it may be helpful to sketch them here. In principle, the equations of the theory could be solved in such a frame to begin with, but that would be difficult. It suffices here to show that we can transform from a fixed-sun frame to a fixed-earth one in the Newtonian limit of general relativity.

We put $M = Gm/c^2$, with m the sun's mass, G the gravitational constant and c the speed of light, and omit terms beyond those needed to calculate Newtonian orbits. The approximate Schwarzschild metric of general relativity in a coordinate system with the sun at rest at the origin ($x = y = z = 0$) can then be written

$$ds^2 = -(1 - 2M/r)c^2dt^2 + (dx^2 + dy^2 + dz^2),$$

where $r = (x^2 + y^2 + z^2)^{1/2}$.[21] The earth's orbit in the x-y plane can be approximated by a circle with radius a, angular velocity Ω, and equations $x = a\cos\Omega t$, $y = a\sin\Omega t$. (Elliptical orbits can be defined with more general parametric equations.[22]) In space-time, this describes a helical worldline about the straight worldline of the stationary sun.

We transform to a frame whose origin moves with the earth by writing

$$X = x - a\cos\Omega t\ ,\ Y = y - a\sin\Omega t\ ,\ Z = z,\ T = t.$$

(This is *not* a rotating frame, which would give superluminal speeds to distant objects.[23]) The line element is then

$$ds^2 = -[1 - 2M/D - (a\Omega/c)^2]c^2dT^2 + (dX^2 + dY^2 + dZ^2) + 2(a\Omega/c)(\cos\Omega T dY - \sin\Omega T dX)c dT,$$

where $D = [X^2 + Y^2 + Z^2 + a^2 + 2a(X\cos\Omega T + Y\sin\Omega T)]^{1/2}$. This has no coordinate singularity at large distances, as for a rotating frame, but ds^2 does not have the Minowski form at spatial infinity.

The geodesic equations for motion in the X-Y plane give approximately

$$d^2X/dT^2 = -GmX/D^3 + a\cos\Omega T(\Omega^2 - Gm/D^3) \text{ and}$$

$$d^2Y/dT^2 = -GmY/D^3 + a\sin\Omega T(\Omega^2 - Gm/D^3).$$

The curve $X = Y = Z = 0$ (so that $D = a$) satisfies these equations with $d^2X/dT^2 = d^2Y/dT^2 = 0$ if $\Omega^2 = Gm/a^3$, which is Kepler's third law.

Another planet with an orbit given by $x = a'\cos\Omega' t$, $y = a'\sin\Omega' t$ in the fixed-sun frame (so that the planet, the earth, and the sun are aligned at $t = 0$) will have a path in the X-Y plane defined by $X = a'\cos\Omega' T - a\cos\Omega T$, $Y = a'\sin\Omega' T - a\sin\Omega T$. These satisfy the geodesic equations if $\Omega'^2 = Gm/a'^3$—i.e., if Kepler's law holds for this planet also.

Notes

1 Francis Pieper, *Christian Dogmatics* 1 (St. Louis, MO: Concordia, 1950), 474. This is a translation of the German edition of 1924.

2 For this and the following quotations, see respectively: Albert Einstein and Leopold Infeld, *The Evolution of Physics* (New York: Simon and Schuster, 1938), 212; Max Born, *Einstein's Theory of Relativity*, rev. ed. (New York: Dover, 1962), 345; Edmund Whittaker, *From Euclid to Eddington* (Cambridge: Cambridge University, 1949), 120; V. Fock, *The Theory of Space, Time, and Gravitation* (New York: Macmillan, 1964), 375; Mario Bunge, *Foundations of Physics* (New York: Springer-Verlag, 1967), 216.

3 www.physicsforums.com/showthread.php?t=311143 (last accessed November 17, 2010).

4 www.answersingenesis.org/tj/v15/i2/geocentrism.asp (last accessed November 17, 2010).

5 For the history, focused on the work of Tycho and Kepler, see Kitty Ferguson, *Tycho and Kepler: The Unlikely Partnership That Forever Changed Our Understanding of the Heavens* (New York: Walker and Co., 2002). Diagrams of the three systems are on p. 142. Speaking of "other planets" in Tycho's system is not strictly correct because the word "planet" referred originally to "wandering stars." The distinctive claim of the Copernican system is that the earth *is* a planet in this sense. But I forego pedantic circumlocutions.

6 Galileo Galilei, "History and Demonstrations Concerning Sunspots and Their Phenomena" in Stillman Drake, *Discoveries and Opinions of Galileo* (Garden City, NY: Doubleday Anchor, 1957), 93–4 and 133.

7 For Kepler, see Ferguson, *Tycho and Kepler*, 308–11.

8 Sir Isaac Newton, *Principia* 1 (Berkeley, CA: University of California, 1934), 10–1.

9 There are many popular and many technical treatments of relativity available. Albert Einstein, *Relativity: The Special and General Theory* (www.bartleby.com/173/ [last accessed March 15, 2011] and other editions) is still a good introduction, though out-of-date in its treatment of cosmology.

10 Erwin Schrödinger, *Expanding Universes* (Cambridge: Cambridge University, 1957), 20.

11 For some phenomena such as meteorology, precise measurements of the acceleration of gravity, or long-range artillery, Coriolis and centrifugal forces are significant.

[12]*Dictionary of the History of Science* (Princeton, NJ: Princeton University, 1981), *s.v.* "Tychonic systems," by Michael A. Hoskin.

[13]Ferguson (*Tycho and Kepler*, 147–8) is sure that Bär did indeed plagiarize Tycho's basic idea, although Arthur Berry, *A Short History of Astronomy* (1898; reprint of the John Murray edition, New York: Dover, 1961), 138, thought it quite possible that he came up with it independently.

[14]George L. Murphy, "Possible Influences of Biblical Beliefs upon Physics," *Perspectives on Science and Christian Faith* 48, no. 2 (1996): 82.

[15]Richard D. Nelson, *Joshua, A Commentary* (Louisville, KY: Westminster John Knox, 1997), 141–5 is a helpful discussion of this text.

[16]Denis O. Lamoureux, *Evolutionary Creation: A Christian Approach to Evolution* (Eugene, OR: Wipf and Stock, 2008), 120–5. George L. Murphy, "Couldn't God Get It Right?" *Covalence* (March 2006), www.elca.org/faithandscience/covalence/story/default.asp?Copyright=06-03-15&Author=murphy&Pages=1.

[17]Arthur Weiser, *The Psalms* (Philadelphia, PA: Westminister, 1962), on Psalm 93, p. 619.

[18]J. C. Polkinghorne, *Science and the Trinity: The Christian Encounter with Reality* (New Haven, CT: Yale, 2004), 108–10.

[19]Cf. George L. Murphy, "Science as Goad and Guide for Theology," *dialog* 46, no. 3 (2007): 225.

[20]George L. Murphy, "What Can We Learn from Einstein about Religious Language?" *Currents in Theology and Mission* 15 (1988): 342.

[21]E.g., Steven Weinberg, *Gravitation and Cosmology* (New York: John Wiley and Sons, 1972), chap. 9.

[22]E.g., L.D. Landau and E.M. Lifshitz, *Mechanics* (Reading, MA: Addison-Wesley, 1960), 38.

[23]A transformation to a rotating frame would be given by equations of the form

$$\xi = x\cos\omega t + y\sin\omega t,\ \eta = -x\sin\omega t + y\cos\omega t,\ \zeta = z,\ T = t.$$

C A L L   F O R   P A P E R S

Perspectives on Science and Christian Faith

special issue on

Responsible Technology and Issues of Faith

Perspectives on Science and Christian Faith announces a forthcoming special issue on "Responsible Technology and Issues of Faith" to be co-edited by Arie Leegwater and Jack C. Swearengen. We favor having a balance of theoretical-reflective articles, weighing normative principles which should guide sustainable technological development, with a number of case studies in which responsible technology is practiced.

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