Finding Our Place in the Solar System

The Scientific Story of the Copernican Revolution

Finding Our Place in the Solar System gives a detailed account of how the Earth was displaced from its traditional position at the center of the universe to be recognized as one of several planets orbiting the Sun under the influence of a universal gravitational force. The transition from the ancient geocentric worldview to a modern understanding of planetary motion, often called the Copernican Revolution, is one of the great intellectual achievements of humankind. This book provides a deep yet accessible explanation of the scientific disputes over our place in the solar system and the work of the great scientists who helped settle them. Readers will come away knowing not just that the Earth orbits the Sun, but why we believe that it does so. The Copernican Revolution also provides an excellent case study of what science is and how it works.

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For my mother, Susan Timberlake (1944–2018), who always encouraged me to pursue my dreams. I wish she could have seen this particular dream come to fruition.

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Preface

This book began as a college course. Astronomy 120: The Copernican Revolution was originally developed by my colleague Paul Wallace. The course was intended to fulfill a science requirement for students majoring in non-scientific fields at Berry College in Georgia (USA), where Paul and I taught. Paul's course was a great success, particularly when he taught it as a summer international course with stops in Poland, the Czech Republic, and Italy.

Then, rather suddenly, Paul decided to leave Berry. The decision was shocking if you didn't know Paul. It's not typical for a physicist to give up a tenured faculty position to go to seminary, but that's what Paul did and, for him, it made sense. His decision, though, left me in some difficulty. First and foremost my friend and mentor was leaving, but his departure caused some practical problems too. Paul had been the only person to teach astronomy at Berry for many years. Should we hire an astronomer to replace Paul? It made more sense for the department to hire a physicist, but we needed *someone* to teach astronomy.

I made what was, in hindsight, a rash decision, but one that I have never regretted. I decided that I would teach the astronomy courses at Berry. Although my doctoral degree is in physics, my undergraduate degree was in both physics and astronomy. I was confident that I could do it, but I only wanted to do it if I got to teach The Copernican Revolution. I had fallen in love with Paul's course. I loved it because it told a *story*, a story of science. Human beings love stories, but most students are never exposed to the story of science. They are taught science from a dry textbook that reads more like an encyclopedia than a novel. Teaching the history of science brings science to life. It shows students that science is a human activity, driven by the human passion to understand. It makes science interesting not just for the scientific knowledge, but for the *struggle* to gain that knowledge.

Moreover, I thought Paul's course was exactly what nonscience majors needed. Students who plan to be scientists need training in the most current

scientific knowledge, but students who don't plan on careers in science have different needs. They still need to know about science, but what they really need is an understanding of how science works. Students can gain that understanding by actually *doing* science, as the science majors would eventually do, but students majoring in other areas don't really have time to develop the expertise needed to conduct real scientific research. Paul's course led me to believe that the best way to teach those students about the nature of scientific inquiry was to teach them the historical development of some important piece of science; to pick some fundamental bit of scientific knowledge and teach them *how* we gained that knowledge.

It doesn't get much more fundamental than the idea that the Earth rotates on its axis and orbits the Sun. We learn these facts as young children and most of us never question them, but this is not knowledge that was easily obtained. It took thousands of years of inquiry into the workings of Nature before humans came to understand the basic functioning of our solar system. There were strong reasons to reject the idea of a moving Earth and it took a great deal of effort to overcome those objections. It is a fascinating and important story, but also an accessible one. Black holes and string theory are exciting, but a real understanding of those topics takes years of study and significant mathematical background. A deep understanding of the motions of the Sun or the planets can be gained much more quickly and with only a modest amount of mathematical knowledge. There is a great joy to be had in that kind of deep understanding, regardless of the topic. And let's face it: knowing how the Sun moves across the sky is likely to be of more practical value for most people than knowing the latest theory of quantum gravity.

I have taught The Copernican Revolution eight times since Paul left Berry and I have loved it every time. Although I developed my own curricular materials (more on that soon), I continued to use the textbook that Paul had assembled for his course. That book was a compilation of writings from various sources as well as a significant amount of Paul's own original writing. I added to it and modified it but it was never published. Paul had moved on to other things, and I was too busy teaching my courses to have time to revise and publish Paul's book.

Then I was awarded a sabbatical for the spring of 2017. Finally I had the opportunity to turn the book into something that could be published, but I decided I didn't want it to be a traditional textbook. I was convinced that the story of the Copernican Revolution should be told to the widest possible audience, so I decided, with Paul's blessing, to rewrite the book for a general audience of readers interested in astronomy and its history. I am incredibly grateful that Cambridge University Press was receptive to my idea, and the result is now in your hands.

The purpose of this book is, in the first place, to tell the scientific story of the Copernican Revolution with a sensitivity to the historical context in which that story took place. The focus of the book is on the evidence and ideas that led to our modern understanding of the solar system, but my aim is to present those ideas and that evidence with the necessary historical background so that readers can understand why some ideas that we now know are true were initially rejected, and why some ideas (and evidence) that we now know are false were initially accepted.

To really understand the story of the Copernican Revolution we must begin at the beginning, with naked eye observations of the skies. Chapter 2 gives a detailed account of what we can observe of the stars and the Sun, and how ancient astronomers devised a simple theory to account for all of these observations. Chapter 3 describes observations of the Moon and the mysterious wandering stars (what we would now call planets). Chapter 4 explains how ancient astronomers attempted to account for the strange behavior of these wanderers and how they tried to fit their theories into a bigger picture of how the universe as a whole functions. The efforts of these ancient astronomers and philosophers were incredibly successful and that success served as the background against which the Copernican Revolution played out. Without understanding the astronomy of the ancient Greeks, it is impossible to understand the Copernican Revolution.

In Chapter 5 we finally get to Copernicus himself. That chapter provides a detailed account of his revolutionary theory of the Earth's motions and how his ideas provided an entirely new perspective on what we see in the heavens. Chapter 6 examines the work of Tycho Brahe who, like so many others of his time, rejected the Copernican theory but whose meticulous observations of the heavens laid the groundwork for the eventual success of Copernicus' main ideas. It was Tycho's one-time assistant, Johannes Kepler, who would transform the insightful but flawed theories of Copernicus into a recognizably modern theory of the solar system. Kepler's work is detailed in Chapter 7.

Kepler's theory of *how* the planets move holds up well today, but his ideas about *why* the planets move that way have been discarded. A full understanding of the movements of the solar system required the development of a new physics. Galileo Galilei, whose work is discussed in Chapter 8, would provide the first steps toward that new physics as well as a host of telescopic discoveries that won many converts to the Copernican cause. It was the fully developed universal physics of Isaac Newton, detailed in Chapter 9, that would conclude the Copernican Revolution by providing an explanation of why the Earth *must* orbit the Sun. With Newton's physics the Copernican theory (as modified by Kepler) emerged triumphant, even though there was still no direct evidence for

the motions of the Earth. Chapter 10 gives an account of the additional evidence, gathered after the Revolution was already complete, that confirmed the ideas of Copernicus and Newton.

Although my main aim was to tell a particular scientific story, I also wrote this book to help readers understand the nature of science in general. To that end, Chapter 1 serves not only as an introduction to the book, but also as a commentary on what scientific theories are supposed to do and how they are judged. In addition, each of the remaining chapters ends with a section titled "Reflections on science." These sections highlight important lessons about the nature of science that can be drawn from the story in each chapter. I hope this material will help readers come away from the book with a better understanding of why science is so difficult, but also so *interesting*.

I have tried to make this book as accessible as possible, while still providing an accurate and detailed account of the scientific story I want to tell. Unlike the great *De revolutionibus* of Copernicus, this book was not written only for experts in astronomy. Although astronomy is a mathematical subject, and readers who wish to understand the development of astronomy must be prepared to tackle some mathematical arguments, I have tried to present these mathematical arguments in a form that is easy for nonexperts to understand. There are no equations in the main text. Instead, equations and detailed mathematical calculations are relegated to the Appendices. (I do, however, encourage everyone to read these Appendices!) Likewise, this book is not intended only for historians of astronomy. Although I provide citations to my sources, those citations are given in the Notes at the back of the book where they will not distract the more casual reader. Explanatory footnotes, on the other hand, are given at the bottom of the appropriate page of the main text.

As mentioned above, this book arose from a course that Paul and I taught at Berry College. I fully intend to use this book as the textbook for that course when I teach it again in the future. Anyone who wishes to use this book as a textbook for a course is invited to use my course materials, including the many open-source computer simulations and classroom activities that I have created to help students work through the story of the Copernican Revolution. I have also designed a series of class projects that allow students to make observations of a fictitious solar system and develop their own (Ptolemaic and Copernican) models for that system. All of these curricular materials are available on my website.[i] Many of the activities make use of the open-source planetarium program *Stellarium*.[ii] The use of *Stellarium* to make simulated observations of the skies,

[i] http://sites.berry.edu/ttimberlake/teaching/copernican-revolution/
[ii] http://stellarium.org/

or of my simulations for visualization of astronomical theories, will benefit any reader whether they are using this book as a textbook for a course or just reading it for their own interests.

Readers who want to learn more about the story of the Copernican Revolution should consult the References section, but let me take this opportunity to make a few specific recommendations. Thomas Kuhn gave a classic account of the transition from Ptolemaic to Copernican astronomy in his *The Copernican Revolution*. I. B. Cohen provided an excellent overview of the transition to the new physics of Galileo and Newton in his *The Birth of a New Physics*. To some extent this book is intended to combine those two classic works and update them using recent scholarship in the history of science. Millevolte's *The Copernican Revolution* complements this book by telling much the same story, but with greater emphasis on cultural aspects and less on the technical science. Koestler's *The Sleepwalkers* provides an entertaining account of that same story, although I disagree with many aspects of Koestler's presentation. Two other useful overviews of this material are Toulmin and Goodfield's *The Fabric of the Heavens* and Crowe's *Theories of the World from Antiquity to the Copernican Revolution*. Owen Gingerich's *Eye of Heaven* is a wonderful compilation of some of his brilliant essays on these topics. Hirshfeld's *Parallax* provides an engaging account of some of the material in Chapter 10.

I also highly recommend reading the words of the great scientists who played pivotal roles in the Copernican Revolution. English translations of many important works are available and some of these are accessible to a nonexpert reader (and perhaps after reading this book you will have enough expertise to tackle even the more difficult works!). Book I of Ptolemy's *Almagest* (translated by Toomer) is highly readable, as is Book I of Copernicus' *De revolutionibus* (translated by Rosen). Fuller, but still brief, accounts of Copernicus' theories are given in his *Commentariolus* and in the *Narratio Prima* of Rheticus, English translations of which can be found in Rosen's *Three Copernican Treatises*. I particularly recommend the works of Galileo, including his *Sidereus Nuncius* and *Il Saggiatore* (English translations available in Drake's *Discoveries and Opinions of Galileo*), but especially Galileo's *Dialogo* (Drake's translation). A fairly accessible account of Newton's work in his own words is given in his *A Treatise of the System of the World*.

For those seeking a more detailed account of the lives of these scientists, several accessible biographies are available. I recommend Sobel on Copernicus, Ferguson and Love on Tycho and Kepler, Wootton on Galileo, and Gleick on Newton. Those seeking more scholarly biographies should seek out the classic accounts by Armitage on Copernicus, Thoren on Tycho, Caspar on Kepler (English translation by Hellman), Drake on Galileo, and Westfall on Newton.

I have many people to thank for making this book possible, with the usual caveat that none of them should be held responsible for the errors I have, inevitably, made. I certainly never would have written this book without my co-author Paul Wallace. Although I take primary responsibility for the book you now hold, what I wrote was based on Paul's course and his original textbook (including his excellent figures and diagrams) and he has certainly earned his place as a co-author. His work laid the foundations for this book, and his guidance, advice, mentorship, and friendship have helped to sustain my interest in this project over many years. I wish Paul had never left Berry, but I am trying to view this book as a silver lining to that cloud.

I would also like to thank the many historians of science who have helped to uncover and illuminate all the bits and pieces that I have tried to assemble into this story of the Copernican Revolution. I am not a historian myself and I could not have hoped to write this book without relying on their work. My indebtedness to them will be apparent from my citations and the References. I would also like to acknowledge those with whom I have interacted directly, mostly though my participation in the Biennial History of Astronomy Workshops at the University of Notre Dame or through the H-ASTRO listserv. Owen Gingerich, Chris Graney, and Mike Crowe have been particularly helpful, not just with their knowledge of the history of astronomy but with their encouragement of my own efforts. I owe special thanks to Matt Dowd for organizing the Notre Dame workshops and welcoming an outsider into the fold. I thank Owen Gingerich and Johan Kärnfelt for feedback on an early draft of the book.

I also wish to thank all of my Astronomy 120 students over the past several years who have helped me to refine my explanations of the material in this book, and in some cases to improve my own understanding of those topics. Particular thanks go to my former student Tricia Steele for helping me to better understand Aristotle. Likewise, I am grateful to my former professors at Vanderbilt University, especially David Weintraub and Richard Haglund, who helped build my love for astronomy and for the history and philosophy of science. My thanks go to Berry College for awarding me the sabbatical semester during which I wrote the first full draft of this book and to the editorial staff at Cambridge University Press (especially Vince Higgs, Lucy Edwards, Margaret Patterson, and Esther Miguéliz Obanos) who expertly guided me through the process of turning a manuscript into a published book. I thank Mike Bailey, Sandy Meek, and Kalen Maloney for permission to use their photographs. I owe tremendous thanks to JoAnn Palmeri and the History of Science Collections at the University of Oklahoma Libraries for their generous permission to use many images from their fantastic collections.

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the ship of our family while her husband was busy playing with armillary spheres and reading 17th century astronomical treatises. I thank my sons, Max and Pete, whose interest in all things science gave me extra motivation when my energy began to flag. Finally, I thank my parents, Jack and Susan, who gave me the opportunity to pursue my dream of being a scientist. I only wish that my mom was still around to hold a copy of this book in her hands.

T. T.