

M. Mitchell Waldrop

# COSMIC ORIGINS

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Science's Long Quest to Understand  
How Our Universe Began

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FOUNDATIONAL QUESTIONS INSTITUTE

 Springer


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*To A.E.F*

# Acknowledgements

The book you're now reading is a much-expanded version of a report originally commissioned by the [John Templeton Foundation](#) (JTF), and published online by the [Foundational Questions Institute](#) (FQXi). I highly encourage you to take a look at the original, which can be found both at <https://tinyurl.com/8uent6u5>, and on the JTF site: <https://tinyurl.com/2p86wf9k>. It was written as part of a larger JTF program to produce deep-dive reviews on four aspects of fundamental physics: cosmological origins (this one), time, [emergence](#), and [fine tuning](#). Each of these reviews was supposed to be as scientifically accurate as possible, complete with citations to the original research, yet so clear, engaging, and easy to read that even non-scientists could use it as a reference.

This was a tricky balance to pull off, to put it mildly. And to the extent that I succeeded, I had lots of help. Alexander Vilenkin and Andrei Linde took the time to help me understand some of the subtleties of cosmic inflation theory, and João Magueijo explained how certain “constants” of physics may actually have varied over time; please accept my deep appreciation. My thanks also go to Anthony Aguirre and David Sloan at FQXi, and to Thomas Burnett from the John Templeton Foundation, who not only conceived of this project and coordinated the JTF/FQXi reviews, but provided generous support while I was writing it.

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course, it was Zeeya who forwarded the JFT/FQXi version to Angela Lahee, editor extraordinaire at Springer, and asked if they would be interested in expanding it into a full-fledged book. To my delight, they said yes—with the result that you now hold. So to Angela and her team, a heart-felt thank you.

Finally, none of this would have been possible at all without the love, devotion, support—and yes, patience—of my wife Amy. Thank you, thank you, and thank you.

January 2022

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## About the Author

**M. Mitchell Waldrop** is a freelance writer and editor. He earned a Ph.D. in elementary particle physics at the University of Wisconsin-Madison in 1975, and a Master's in journalism at Wisconsin in 1977. From 1977 to 1980 he was a writer and West Coast bureau chief for Chemical and Engineering News. From 1980 to 1991 he was a senior writer at Science magazine, where he covered physics, space, astronomy, computer science, artificial intelligence, molecular biology, psychology, and neuroscience. He was a freelance writer from 1991 to 2003 and from 2007 to 2008; in between he worked in media affairs for the National Science Foundation from 2003 to 2006. He was the editorial page editor at Nature magazine from 2008 to 2010, and a features editor at Nature until 2016. He is the author of *Man-Made Minds* (Walker, 1987), a book about artificial intelligence; *Complexity* (Simon & Schuster, 1992), a book about the Santa Fe Institute and the new sciences of complexity; and *The Dream Machine* (Viking, 2001), a book about the history of computing. He lives in Washington, D.C. with his wife, Amy E. Friedlander.



# 1

## Introduction

They're some of the oldest questions that human beings have ever asked—renewed again and again by every child who looks up in wonder at the sun, the moon, the stars, and planets: What *are* they? Why do they move and change the way they do? Where do they all come from? And where do *we* come from?

These questions are so fundamental that every culture and every religion provides answers—often in the form of origin stories that illuminate equally fundamental questions about the group's identity, worldview, values, and purpose. Who are we? How should we live our lives? What is our role in the cosmos [1]?

Those origin stories are a fascinating study in themselves, ranging from the Acoma Indians' tale of humankind's birth from the womb of the Earth, to the Hebrews' story of God's creating the cosmos from nothing, to the Zulu tale of a hero who created mountains, cattle, people and everything else from the reeds [2]. But science doesn't try to answer the cultural questions these stories pose—or rather, it doesn't try to answer them directly. Instead, science focuses on the kind of factual questions raised in our first paragraph: mysteries that can be addressed by methods rooted in reason, experiment, and meticulous observation.

Yet, as this book will explore, that focus has guided scientists to a cosmic story that is far stranger than our ancestors could have imagined.

## 1.1 Four Radical Shifts in Perspective

Our long journey toward this 21st-century story has spanned millennia. But more than that, it has required (at least) four radical shifts in perspective.

### **The Planets are Other Worlds, and the Stars are Other Suns**

To readers who have grown up on science fiction tales depicting other worlds in other galaxies, this answer to the “What are they?” question might seem obvious. In fact, it required a massive upheaval in Western thought, which began in 1543 when the Polish astronomer Nicolaus Copernicus published a sun-centered model of the universe that he had been working on for the past three decades [3]. Prior to that, just about everyone had believed the evidence of their senses—that the Earth was solid and immovable—and assumed that the universe revolved around us.

Copernicus’ primary motivation for challenging this assumption was mathematical beauty: He realized that the complex, looping movements of the celestial lights known as *planets* (from the Greek word for “wanderer”) would make far more sense if they were actually just simple circular motions around the Sun—but circular motions as seen from a moving vantage point (the Earth) that was whirling around the Sun in its own orbit.

Yet this mathematical exercise was also a demotion of humankind’s home from the cosmic center, a move that upended entrenched ideas about physics, morality, and even the God-man relationship—not to mention our own sense of self-importance [3]. This may have been why Copernicus published his theory only when he was near death, and only after much persuasion. It was definitely why the Catholic Church would ban Copernicus’ book outright in 1616 [4].

Still, the evidence for this Copernican picture continued to accumulate, most famously when the Italian physicist Galileo Galilei built one of the first telescopes and pointed it at the heavens. He published his observations in 1610 as a short pamphlet whose Latin title is generally translated as *The Starry Messenger* [5]. What he saw in the sky—including mountains on our moon, and four previously unknown moons orbiting Jupiter—proved that these celestial points of light were far more like our world than ever imagined.

### **The Heavens and the Earth are One, and Operate According to Natural Law**

Again, this seems axiomatic in the age of interplanetary spacecraft. Yet for most of human history it seemed just as obvious that the celestial realm is

profoundly different from the base matter here on the ground, and that every event—storms, childbirth, the coming of spring, victory in battle, everything—depends on the whim of the gods. It wasn't until the time of Aristotle that the ancient Greek philosophers began to think in terms of natural law: fixed rules that apply everywhere, to everything, at all times. And it wasn't until the 1600s that this notion was made mathematically rigorous by the English polymath Isaac Newton; his laws of motion and gravity gave his fellow natural philosophers a set of equations that governed both the orbit of the moon and the fall of an apple, and that could predict the motions of planets, satellites, comets, projectiles, and anything else in the cosmos.

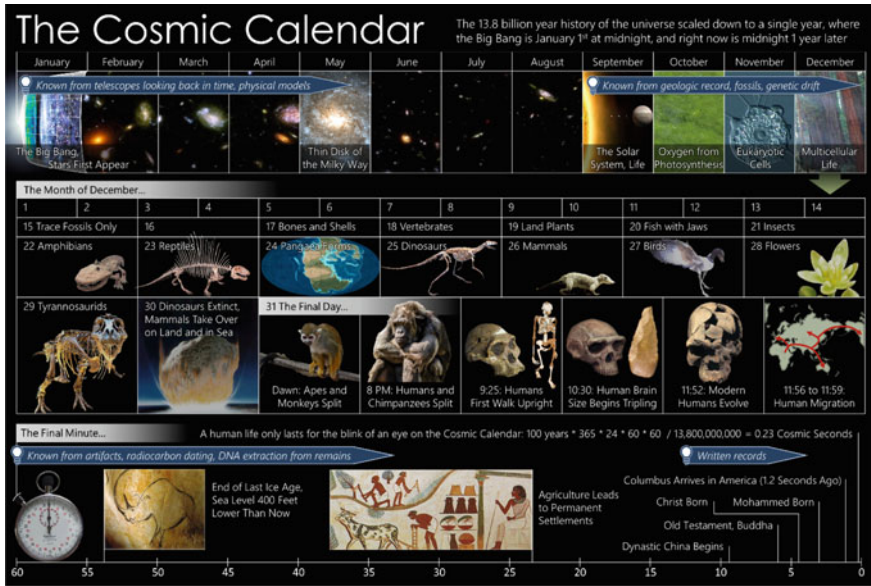
### **The Universe is Very Large and Very Old**

On an everyday human scale, a thousand kilometers is a long, long way and a thousand years is forever. But from the cosmic perspective, both are miniscule. The immense size of the universe was already implied by Copernicus' theory in the 1500s. If you were willing to believe that a tiny, reddish dot of light like Mars was in fact a world like our own, then you also had to believe that it was ridiculously far away. (The modern figure is 55 million to 400 million kilometers, depending on where Earth and Mars are in their orbits.) The fixed stars had to be much further still.

Even then, however, most natural philosophers continued to accept that the universe was a few thousand years old (roughly 6000, according to *Genesis*). Their thinking began to change only in the late 1700s, when pioneering geologists began to realize that the ancient rocks they saw in cliffs, quarries, and road cuts had been formed by erosion, sedimentation, volcanic activity, and the like—the same processes that are slowly and steadily reshaping the landscape today. But the critical word was “slowly”: When those early scientists calculated how long it would take geologic processes operating at today's rates to create the existing landforms, they came up with estimates in the millions of years. So the Earth—and by extension, the heavens—must be at least that old. (The modern figure is 4.6 billion years for the Earth and everything else in the solar system, and 13.8 billion years for the entire universe.) Scientists henceforth had to deal with the dizzying reality of what one 19th-century natural philosopher called “the abyss of time” [6].

### **The Universe Started Small and Grew**

According to the origin stories found in *Genesis* and many other traditional accounts, the world around us was formed pretty much as we see it now—plants, animals, mountains, oceans, all brought forth in a single act of



**Fig. 1.1** The 13.8-billion-year lifetime of the universe mapped onto a single year. This one-year scale was popularized by the late astronomer Carl Sagan. (Credit: Efbrazil/Wikimedia Commons, CC BY-SA 3.0)

creation [7]. But according to the story that’s been uncovered by science over the past two centuries or so, cosmic history is a long process of *becoming*: everything that we see today took shape according to natural law from much simpler beginnings.

The quest to understand how that happened—and what those cosmic beginnings might be—has defined much of 20th- and 21st-century astronomy and physics, and is the subject of this book (Fig. 1.1).

## 1.2 The Modern Shift

The cosmic story we’ve arrived at today is familiar enough. Our universe began with the “Big Bang,” an event some 13.8 billion years ago in which space, time, matter, energy, light, and everything else came into being as an infinitesimal point of infinite temperature and density. And the universe has been expanding ever since, allowing the superhot energy of that initial point to cool and condense into electrons, protons, atoms, galaxies, stars, planets and eventually, us.

As we’ll see, however, getting to this answer has required that scientists shift their perspective in ways that were at least as profound as any that came

before—and just as difficult. Again and again, what are now considered to be foundational discoveries were met with indifference, incomprehension, or even hostility—and achieved widespread acceptance only after accumulating evidence made the new ideas impossible to ignore.

## Chapter 2: The Expanding Universe

In Chap. 2 we review how this dynamic played out in the discovery of the first key piece of evidence for the Big Bang: the realization that just about all the galaxies in the universe are flying apart from one another, like sparks from some titanic explosion. This was a story that unfolded along two parallel tracks, as theorists and observers found themselves coming to the same conclusion only after working in near-total ignorance of one another.

The theoretical track began with Albert Einstein and his two theories of relativity. The 1905 version, now known as the *special* theory of relativity, showed that space and time are different aspects of a single, underlying unity: space–time. The 1915 version, known as the *general* theory of relativity, showed that space–time can bend, ripple, and curve—and that its curvature is the origin of the force we call gravity. In 1917, Einstein also laid the foundations for modern cosmology by pointing out that the equations of general relativity determine the shape and dynamics of the universe as a whole.

On the observational track, meanwhile, astronomers’ understanding of the universe’s true scale was undergoing a dramatic expansion of its own. They already knew that the visible stars are an astonishing distance away—so far that their light takes years to reach us. But in the 1910s, observers training ever more powerful telescopes on the sky discovered that these nearest-neighbor stars comprised only a tiny fraction of our Milky Way galaxy, which in turn proved to be an immense flattened disk many tens of thousands of light years across. Then in the 1920s, astronomers found that even this huge structure is just a dust mote on the cosmic scale. When they looked more closely at the mysterious pinwheels known as “spiral nebulae”, the structures turned out to be star-filled galaxies just like ours, but located at distances measured in millions of light-years. And finally, at the dawn of the 1930s, astronomers realized that this vast cosmos isn’t just big, but getting bigger. The universe—in keeping with Einstein’s equations—is expanding quite literally.

## Chapter 3: The Discovery of the Big Bang

In Chap. 3 we trace how astronomers and physicists confirmed that the universe did indeed begin in a cosmic fireball. Again, this conclusion did not come quickly or easily. The implications of cosmic expansion may seem

obvious in retrospect. If the galaxies are flying apart now, after all, then they surely must have exploded outward from some much denser initial state somewhere in the distant past, billions of years ago. But few astronomers in the 1930s were comfortable with the idea of a cosmic beginning. And even fewer had time for speculations about an event that (they thought) could never be observed.

That attitude began to change only in the 1940s, when a handful of scientists realized that the new field of nuclear physics allowed them to observe the fireball indirectly, by calculating how thermonuclear reactions would have unfolded during the first few minutes of the universe. They found that the suite of chemical elements produced in those reactions would form a kind of fossil record of the event. And indeed, the abundances they calculated for the various isotopes of hydrogen and helium—the lightest, and by far the most abundant elements in the cosmos—turned out to match the observed values very closely.

This account of the observed abundances is now considered a second key piece of evidence for the Big Bang, after cosmic expansion. Yet even then, many scientists continued to be reluctant to consider origins—an attitude that was popularized for a while as the “steady-state” model, in which the universe had no beginning or end. But then in 1964, radio astronomers uncovered a third key piece of evidence: a faint whisper of low-energy radio waves now known as the Cosmic Microwave Background (CMB). These waves are essentially the Big Bang’s afterglow, made up of photons that were emitted some 380,000 years after that initial cataclysm, when the superhot plasma it produced had cooled the point where electrons and protons could condense to form neutral hydrogen atoms and the universe became transparent.

The CMB not only made the Big Bang idea<sup>1</sup> almost inescapable, but it has proved to be our richest source of information about the very early universe—a subject we will return to again and again.

## Chapter 4: Behind the Veil

This chapter recounts how our understanding of the Big Bang was enriched in the 1960s and 1970s by one of the most spectacularly successful achievements in modern physics: The development of a *standard model* that provided a

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<sup>1</sup> It’s worth noting that many scientists use the phrase “Big Bang” in different ways. Some apply it only to the initial singularity that’s conjectured to occur at the very first instant of the universe, when the cosmos is compacted to a point of infinite temperature and density. But many others use the phrase as a shorthand for some or all of the expansion and condensation processes that led up to the formation of the CMB. In this book we will generally follow the second convention, but will always try to make the meaning clear in context.