A LITTLE BOOK ABOUT
THE BIG BANG

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To my professors and colleagues,
who taught me more than they know

CONTENTS

ALSO BY TONY ROTHMAN

NONFICTION

Physics Mastery

Sacred Mathematics: Japanese Temple Geometry, with Hidetoshi Fukagawa

Everything's Relative, and Other Fables from Science and Technology

Doubt and Certainty, with George Sudarshan

Instant Physics

A Physicist on Madison Avenue

Science à la Mode

Frontiers of Modern Physics

FICTION

Firebird

The Course of Fortune

Censored Tales

The World is Round

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INTRODUCTION

WHY IS THERE SOMETHING RATHER THAN NOTHING?

This is a little book on the biggest subject conceivable—the big bang. It is not a book about a television show. It is a book about cosmology. Cosmology, as cosmologists think of it, is the study of the structure and evolution of the universe as a whole. Over the past century, it has increasingly come to mean the study of the early universe: investigation of the origin of galaxies, analysis of the lightest chemical elements, observation of the heat radiation pervading all space, and exploration of exotic phenomena we can't directly see—dark matter and dark energy. Generally, cosmologists concern themselves with our universe in the first eons, years, and even fractions of a second after its birth. Cosmology is precisely the theory of the universe's origin: the big bang.

Cosmology is occasionally called the place where physics and philosophy meet. That is to an extent true, and to an extent unavoidable. When we get down to it, all science is the asking of questions and the pursuit of answers to those questions. If we pursue the questions far enough, we inevitably run out of answers. Cosmology is uniquely prone to this difficulty. When a conversation arises about the big bang, the first question any non-cosmologist (which is most people) asks is "What came before the big bang?" This is a natural and legitimate question, but it presently has no answer and that state of affairs is likely to persist past the shelf life of this author.

Nevertheless, my plan is to pose the questions asked by laypersons, as well as others, and attempt to answer them in the simplest manner I can. Since this is a book meant primarily for people who are curious about science but lack scientific and mathematical backgrounds, my colleagues will find it equally lacking in rigor and completeness, but my aim is not to cover as much territory as possible; rather it is to uncover a little territory if possible.

To that end, I have tried to keep technical jargon to a minimum, and although there will be enough numbers to satisfy anyone, no equation in the text is more complicated than one for a straight line; anything else, I've relegated to the few footnotes. I also assume that readers can understand basic graphs and are willing to follow some fairly detailed arguments. On the other hand, I agree with one of the countless aphorisms Einstein never uttered, "You should make things as simple as possible, but not too simple." Over the years, I have become convinced that there really is a level below which certain things cannot be simplified; in cosmology this is largely because of its inherently mathematical nature. If I cannot explain the mathematics in terms of a comprehensible physical concept, I won't try.

Despite the lack of anything resembling real math in this book, one of its aims is to convince you that modern cosmology is an extraordinary edifice built on rock-solid foundations and that you should become a believer. To that end, each chapter generally builds on the previous. You should start the book at the beginning. If your only interest is the bottom line, you will grow impatient.

As I've said, cosmology does raise profound questions. In exploring the conceptual underpinnings of the modern big bang theory, my hope is not to shy away from such questions. As a mentor once advised, "If you ask a stupid question you may feel stupid. If you don't ask a stupid question, you remain stupid."

Inevitably, as the book progresses there will be more questions than answers. After all, in pondering the imponderable it is a short leap from "What came before the big bang?" to the ultimate conundrum: "Why is there something rather than nothing?" Given that people have been asking this question one way or another for millennia without consensus, it is not reasonable to expect to find the answer here. Indeed, if you put that question to any honest cosmologist, the only reply you will get is "I don't know." An easier question is, "Do those equations on the white board of the TV show mean anything?" The answer is yes. Personal experience suggests that cosmologists are underequipped to answer any questions regarding cosmetics.

Because this book is intended for general readers, I will make use of analogies rather than equations. A danger lurks here because sooner or later every analogy breaks down. Analogies, like theories, are models of reality, not reality itself. In the case of the big bang, cosmologists usually resort to balloons to explain certain properties of the expanding universe, but the real universe is not a balloon and the analogy is imperfect. When considering analogies, it is crucial to locate the differences between the analogy and the reality.

I have already used the word *theory* several times. Let me emphasize that when a scientist uses this term, it carries a different meaning than in daily life. The radio often informs listeners that a prosecutor has a certain theory about a crime, while the defense attorney has a theory that the prosecutor is crazy. Usually, these are conjectures made entirely without evidence and the situation changes too frequently to make any sense of it.

By contrast, a physical theory is a highly interconnected web of ideas and predictions underpinned by mathematics and firmly supported by experimental and observational evidence. When cosmologists speak of the big bang theory, they are referring to just such a web of predictions and observations. The elements of the big bang theory have by now been under scrutiny for an entire century, and so many precision observations support the overall picture that some cosmologists feel that their discipline already resembles engineering more than it does basic research. Believe in modern cosmology.

Yet a fundamental difference between cosmology and most other sciences remains: There exists a single observable universe. The essence of most sciences is experimentation and replication. A drug manufacturer tests a vaccine by running clinical trials on many subjects. If the results cannot be reproduced by scientists worldwide, the vaccine is not regarded as reliable. Cosmologists, at least at present, are denied the opportunity to run experiments on multiple universes and thus they cannot say with complete certainty how the universe would look had things started off differently than they did.

Nevertheless, although cosmologists can't say everything, they can say far more than nothing. Having a single universe at our disposal only makes it difficult when considering the universe as a whole, when addressing ultimate questions. Short of that, cosmologists draw on data and observations collected by their close cousins, the astronomers. Astronomers have traditionally investigated the behavior of planets, stars, and galaxies through earthbound telescopes or telescopes in near-earth orbit. Yes, astronomers are landlubbers, or might as well be; no spacecraft or telescope has yet traveled anywhere near the distance to the next star, yet alone another galaxy, which means it is impossible to perform experiments on astronomical objects. For good reason astronomy is termed an observational science.

The basic assumption underlying all astronomy, however, is that the fundamental laws of physics are the same throughout the universe. Astrophysicists, also close cousins to cosmologists and astronomers, have applied these laws to decode the behavior of stars and galaxies. Since it is impractical to send a space probe to the distant reaches of the universe, at least within the lifespan of a civilization, we have instead relied on light and other messengers to bring information from the far universe to us. It is, in fact, one of the great triumphs of modern science that we have been able to learn so much about the cosmos without going anywhere, by making this assumption that the laws of nature as we know them apply everywhere. To what extent the known laws of physics apply to the universe as a whole remains an open question.

Cosmologists attempt to reconstruct the evolution of the universe using the same approach as astronomers and astrophysicists: with pen and paper or computer, we apply established physics in a mathematically consistent way to model the system we are studying and check whether the results agree with observation. The system may be a cluster of galaxies or the whole universe. If the predictions of our model agree with the observations, we go out for a beer. If the predictions don't agree, we search for mathematical mistakes. If we find none, we search for conceptual errors. If, finally, no one's model agrees with the observations, we add new phenomena. If the new phenomena improve the results, we ask our observational colleagues to begin a search.

One thing any scientist should hesitate to do is add exotic phenomena to the current model before having exhausted more pedestrian explanations. In thinking about the earliest instants after the big bang, hmm. . . .

At this moment you may be wondering exactly where astronomy and astrophysics leave off and cosmology begins. There is no precise boundary, and typically a scientist working in one of these areas knows a fair bit about the others. The difference is mainly one of *scale*. As mentioned, astronomy and astrophysics are traditionally concerned with the behavior of stars, planets, and galaxies, more recently with entire clusters of galaxies and even the superclusters—clusters of clusters of galaxies. A cosmologist takes the biggest picture imaginable, which begins somewhere around the size of a supercluster and asks how all this came to resemble the universe we observe. Although the physics governing the behavior of galaxies is the same as for stars, this book will not be concerned with those, or with planets. It will barely touch on black holes, as fascinating as they are. From a cosmological perspective, these objects are so small as to be insignificant.

Cosmologists find it extremely helpful to keep in mind the various astronomical scales. Throughout the book I will use the standard astronomical practice of stating distances in terms of the time it takes light to travel those distances. You may know that it takes light about eight minutes to travel from the sun to the earth. Call it ten. We can thus say that earth lies at a distance of about ten light-minutes from the sun. Similarly, a light-year is simply the distance light travels in one year. Astronomers never convert light-years to miles or kilometers, and you shouldn't, either. Rather, you should just develop a feel for the different scales found in the universe:

Four light-years is the distance to the nearest star beyond the sun.
The diameter of our Milky Way galaxy is roughly 100,000 light-years.
The distance across a cluster of galaxies is millions of light-years.
The size of a supercluster of galaxies is hundreds of millions of light-years.
The size of the observable universe is about fourteen billion light-years.

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That is the scale of cosmology, the scale with which this book is concerned.

Can you give me advice on eyeshadow and mascara? **No.**

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GRAVITY, PUMPKINS, AND COSMOLOGY

COSMOLOGY IS the study of how gravity determines the evolution of the entire universe, so to understand cosmology requires understanding gravity.

Gravity is by far the weakest of the known natural forces. To a physicist, a force is nothing more than a push or a pull exerted on an object—no "dark side" enters the picture—and one of the main reasons that physicists call their field the most fundamental of all sciences is that, over the centuries, they have learned that only four fundamental forces exist in nature. One of these, termed the *strong nuclear force,* is easily the strongest natural force and holds the nuclei of atoms together. Any atomic nucleus consists of neutrons and protons, and the electrical repulsion among the positively charged protons would cause the nucleus to fly apart were it not for the strong force binding it together. The energy associated with the strong force is what is released in atomic explosions. The strong force, however, operates only within the atomic nucleus, which is extremely small, as cosmology goes.

The second fundamental force is the *weak nuclear force*. Billions of times weaker than the strong force, it governs certain forms of radioactive decay. Tritium, the extra-heavy version of hydrogen, is radioactive and decays into a form of helium; its rate of decay is determined by the weak force. But like the strong force, the weak force operates only within the atomic nucleus, which is insignificant on the scale of cosmology.

In daily life the most important forces are the electric and magnetic forces, which are actually two aspects of a single *electromagnetic force*. This force is responsible for all of chemistry and operates in any device requiring electrical currents, from toasters to smartphones to everything we take for granted today. The electromagnetic force is the basis of modern civilization. But to produce electric or magnetic forces requires electric charges. Because astronomical bodies, such as planets, are electrically uncharged they exert no electrical or magnetic forces on each other.

All objects do gravitationally attract one another. Gravity, though, is almost unimaginably weak—that the gravitational tug of the entire earth cannot budge a refrigerator magnet is a hint of how weak it is compared to the electromagnetic force. The way physicists tend to state it is that the gravitational attraction between two hydrogen nuclei, protons, is about thirty-six orders of magnitude smaller than the electrical repulsion between them. In designing consumer electronics, engineers pay no attention to gravity.

Yet, because nuclear forces operate only inside atomic nuclei and because astronomical bodies are electrically neutral, it is left to the weakest force in nature to determine the fate of the universe.

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Our modern theory of gravitation is Albert Einstein's general theory of relativity, which is often called the most beautiful scientific theory. This is true.

On a superficial level, we might regard general relativity as merely a refinement of Newton's theory of gravity, devised by Isaac Newton nearly four hundred years ago. It consists of a single immortal equation that shows how the gravitational force between two objects depends on their masses and the distance separating them. We don't even need to write the equation down to understand its message: knowing just the masses of the objects and their separation allows us to determine exactly the gravitational force they exert on one another.*

Above I said a force in physics is simply a push or a pull. More precisely, a force causes an object to change its velocity—in other words, to accelerate. If a piano is speeding up or slowing down, a force is acting on it. If the piano is moving at a constant velocity, no force is acting on it.

* For reference, Newton's law gives the gravitational force F between two masses, m_1 and m_2 as $F = Gm_1m_2/r^2$, where r is the distance between them and G is the *gravitational constant,* a number that must be measured in the laboratory and that determines the strength of the force.

According to Newton, if we know the forces on an object, we know its acceleration, and can then completely predict its future behavior. Thus, if we knew the masses and present separations of all the stars in the universe, we would know everything there is to know about the universe's future—and its past, as well. For this reason, the Newtonian universe is often compared to clockwork. For the most part, it is.

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Newton's theory of gravity works so well in ordinary circumstances that for two centuries astronomers believed it completely explained the motions of the solar system. In the mid-nineteenth century the first hints appeared that this might not be so. Like all the planets, Mercury travels around the sun in an elliptical orbit. If Mercury and the sun constituted the entire solar system, the point of Mercury's closest approach to the sun, called its *perihelion,* would always remain at a fixed point in space. Astronomers observed instead that the perihelion was gradually shifting its position over time. Calculations indicated that the gravitational tug from the other planets in the solar system could account for most of this shift, but a tiny amount was stubbornly left over. Many theories were proposed to explain the anomaly, but the ghost in the machine remained a mystery for over half a century.

When Einstein began work on general relativity in the early twentieth century, apart from Mercury's perihelion shift there was no observational evidence that Newtonian gravity might be inadequate. There was, however, James Clerk Maxwell's theory of the electromagnetic field.

You should first realize that Newton's theory is one of *particles* and *forces*. Two pumpkins sit in a pumpkin patch. We can think of them as two particles exerting a gravitational force on each other across the patch. Likewise, we can idealize the earth and moon as particles exerting a gravitational attraction on each other across space. In neither case does Newton's theory explain how the force travels from one particle to the other. For this reason, Newtonian gravitation is often called an *action at a distance* theory, *action* being the word for force in Newton's day.

Equally important is that the gravitational force between the two objects is evidently transmitted *instantaneously;* if the sun disappeared, nothing would be left for the planets to orbit and they would fly off into space with no delay whatsoever.

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Instead of a pumpkin patch, imagine that the pumpkins are floating in a pond. We immediately feel the picture has changed. The water in the pond is composed of an enormous number of molecules, but they are so tiny we forget about them and instead think of the water as having a certain density and pressure at each point. Density and pressure are "bulk" quantities, making no reference to individual particles. This is a signature characteristic of a *field*. The air in a room can be regarded as a field. So can the elastic surface of a trampoline. A swarm of bees in many respects resembles a field.

The field picture provides a natural mechanism for transmitting forces. If the pumpkins are bobbed up and down, they create small disturbances that propagate across the pond as water waves. These waves are local disturbances traveling through the water field at finite velocities. By contrast, in Newtonian gravity, one needs to imagine forces that are somehow transmitted across great voids, infinitely fast.

INDEX