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Cover Image: Map and angular power spectrum of the cosmic microwave background, produced from data of the WMAP satellite (http://map.gsfc.nasa.gov/).

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To my parents

Preface

Ever since its infancy, humankind has been seeking answers to some very basic and profound questions. Did the Universe begin? If it did, how old is it, and where did it come from? What is its shape? What is it made of? Fascinating myths and brilliant intuitions attempting to solve such enigmas can be found all through the history of human thought. Every culture has its own legends, its own world creation tales, its philosophical speculations, its religious beliefs. Modern science, however, cannot content itself with fanciful explanations, no matter how suggestive they are. Nowadays, our theories about the Universe, built upon rational deduction, have to survive the hard test of experiment and observation.

Cosmology, the science which studies the origin and evolution of the Universe, had to overcome enormous difficulties before it could achieve the same level of dignity as other physical disciplines. At first, it had no serious physical model and mathematical tools that could be used to address the complexity of the problems it had to face. Then, it suffered from a chronic lack of experimental data, which made it almost impossible to test the theoretical speculations. Given this situation, answering rigorously the many questions on the nature of the Universe seemed nothing more than a delusion.

Today, however, things have changed. We live in the golden age of cosmology: an exciting moment, when, for the first time, we are able to scientifically understand our Universe.

One of the greatest living cosmologists, James Peebles, once compared the situation of a cosmologist to that of Tantalus. According to the myth, Tantalus was punished by Zeus for having discovered the secret of ambrosia, the food which made the gods immortal. Sentenced to suffer from hunger and thirst, he was immersed in water, but he could not drink, because when he tried, the water receded; juicy fruits were suspended above his head, but when he raised his hands to grasp them, the branches rose away from him.

Similarly, cosmologists can look at celestial objects as long as they wish, but they cannot "touch" them. This is one of the facts that puts cosmology in a more difficult situation than other fields of physics. If we want to study the properties of a material, we can analyze a certain quantity of it in a laboratory, given some carefully controlled conditions. We can also repeat the experiment for as long as we like. Cosmologists cannot arrange anything like that. They just have one Universe to study, they cannot decide how to set up its conditions. Furthermore, the subject of investigation is, by its nature, very difficult to grasp. Delving into the furthest reaches of the Cosmos and observing the feeble light reaching us from unimaginable distances, requires sophisticated instruments which have not been available to us until very recently. Much more than for any other science, the history of cosmology is also a history of the tools we use to observe the world. Our idea of the Universe has been shaped by the extent of what we could observe of it. Starting from Galileo's telescope, the Cosmos became larger and stranger as we were able to look into it in more detail.

As a strange sort of compensation, however, the vastity of the Cosmos is also an unexpected tool that we can use to investigate its properties. The Universe is so large that it takes an enormous amount of time for light to travel through it (even at the maximum speed allowed by the laws of physics, about 300 thousand kilometers per second). When we look at the Sun, we see it as it was about 8 minutes ago; when we look at the closest star to the Sun, Alfa Centauri, we see it as it was about 4 years ago; the closest galaxy to our own, M31 in Andromeda, looks as it was about two and a half million years ago; and so on. Cosmologists measure such huge distances in terms of light-years—the distance traveled by light in one year. One light-year corresponds to a distance of about 9,460 billion kilometers.

This fact provides cosmologists with a sort of time machine. They can look at the Universe at different phases of its evolution and reconstruct its history, much as an archaeologist can look at fossils from different epochs. Using this extraordinary opportunity, and perfecting it over the years, cosmology slowly abandoned the status of immature science it had at the beginning of the 20th century, starting a tough path which, in the last few years, has led to its becoming one of the most advanced and successful fields of scientific research.

We now know, for example, that the Universe expands and evolves, and that it reached its current conditions starting from a much simpler state, when it was much smaller and denser than it is today. Pushing our physical description of the Universe to earlier and earlier times, we eventually reach a state of practically infinite temperature and density, taking place about 14 billion years ago, which is popularly known by the name of "Big Bang". The cosmological model based on Big Bang is extraordinarily effective in describing the evolution of the entire Universe—and, at the same time, surprisingly simple. It only takes a handful of parameters to characterize the physical state of the Cosmos from its very beginning to the present. The main features of the Big Bang cosmological model are described in Chapter 1 of this book.

At some point, during their incessant research about the origins of our Universe, cosmologists started asking how far in space—and then back in time—they could go with their observations. Was it perhaps possible to look directly at the moment when the Universe began? In its earliest phases, the entire Universe was extraordinarily hot and bright. At first, all this light could not travel a long way, because of the dense fog of matter which pervaded the Cosmos. But after a few hundred thousand years the Universe became transparent, so that light could finally stream unimpeded through space. Today, more than 13 billion years later, a dim trace of the immense primordial glow keeps coming to us from the farthest reaches of time and space. Although only cold cinders remain of that tremendous primordial incandescence, we can still measure its presence. It pervades the entire space, all around us. If we tune our radio on an empty channel, about one percent of the noise we hear is made up of this cosmic signal, the most distant and ancient in the Universe. This fossil relic of the Big Bang is called the *cosmic microwave background* (or CMB for short), and it is the real protagonist of this book. By observing it, cosmologists collected a number of important clues about the physical state of the Universe in its earliest phases. Chapter 2 deals with a detailed explanation of its origin, and tells the fascinating story of its discovery.

The primordial Cosmos was a realm of simplicity. A sort of uniform, thick fog pervaded the entire space, and every point in the Universe had almost identical density and temperature. But this extremely uniform situation was slightly altered by the presence of tiny clumps. Matter then started collapsing around these clumps, in a slow but inexorable process. The gigantic cosmic structure we observe in the present Cosmos—galaxies, clusters of galaxies, clusters of clusters and so on—was formed by a gradual process of aggregation around those ancient cosmic seeds. Our own existence, after all, is due to those slight imperfections existing in the primordial Universe. In Chapter 3, I will say more about the origin of cosmic seeds, and will explain how we finally measured their existence from the imprints they left in the cosmic background radiation.

Cosmic structure formation has been a tug of war between opposing forces. Dense regions tended to grow denser because of self-gravity, but internal pressure opposed this growth—just as a gas resists compression—forcing matter to re-expand. A strange kind of dance then took place, a series of alternating compressions and rarefactions of the cosmic fluid. Those periodic oscillations were identical to the ones passing through air when sounds propagate. In other words, acoustic waves traveled across space in the early Universe. By analysing the ripples these waves left imprinted in the cosmic background radiation, cosmologists can today reconstruct their complicated overlapping, which encodes crucial information on the physical state of the primordial Cosmos. Just as any musical instrument produces a characteristic spectrum of frequencies, so the physical parameters which define the nature of our Universe manifest themselves through the specific timbre of those primordial acoustic waves. The hunt for this "music" of the Big Bang kept cosmologists busy for decades. Chapters 4 and 5 tell the story of this fascinating endeavor, which was finally successful in recent years.

Throughout this book, then, we will see how the careful investigation of the cosmic background radiation gave us the answers to many fundamental questions about our Cosmos. We now know that the Universe has been expanding for almost 14 billion years and that, perhaps, it will keep expanding forever. We know that the majestic architecture of galaxies formed over the course of billions of years started from tiny primordial seeds. We also know that most of the matter in the Universe is of a completely different kind from the matter we are made of, and that we probably have to take into account an even stranger kind of energy. But even if we can take some pride in having made enormous progress in our understanding of the Universe, we cannot pretend to know all the answers. Every new finding generates further questions. Chapter 6 deals with some of the unanswered problems of modern cosmology.

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Contents

1. The Scenery

Naturally, we were all there,—old Qfwfq said,—where else could we have been? Nobody knew then that there could be space. Or time either: what use did we have for time, packed in there like sardines?
I say "packed like sardines," using a literary image: in reality there wasn't even space to pack us into. Every point of each of us coincided with every point of each of the others in a single point, which was where we all were.
—Italo Calvino, *All At One Point - The Cosmicomics*[a]

The investigation of the Cosmos by means of the scientific method only began in relatively recent times. The first scientifically sound ideas about the nature of the Universe date back to the 16th century, when Nicolaus Copernicus, Tycho Brahe and Johannes Kepler founded the Solar System model that we still use to interpret planetary motions. The idea of a motionless Earth, holding still at the center of the entire Universe, was replaced by a new conception—one where our planet is no different than any other orbiting around the Sun. During the 17th century, observations performed by Galileo Galilei strengthened the new world-view, and Isaac Newton's theory gave it a firmer conceptual basis. In the following centuries, Newton's notion of an absolute and unchanging space prevailed; later on, the prejudice of an eternal Universe was widespread among scholars. An eternal Universe eludes any question about its origin and its destiny: the Universe is because it always was—and it will always be. Only at beginning of the 20th century, a new change of perspective gave birth to modern cosmology.

Today, the scientifically accepted vision of the Universe relies on the *Big Bang model*. According to this model, the Universe began its evolution at a very precise moment in the past, and it went through radically different physical states over the course of

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[a] Harvest Books, Harcourt Brace & Co. (USA, 1976).

billions of years, until it became what it currently is. The term "Big Bang" was coined—as a derogatory epithet, as it happens—by Fred Hoyle, the great British astronomer, who was, over his entire career, one of the firmest opponents of the model. No matter how ironic were the intentions of its author, the "Big Bang" label became immediately popular. It is important to emphasize, however, that the name conveys a misleading picture: in fact, the birth of our Universe has not much in common with an explosion. As we will see in the following chapters, over the course of the past century the Big Bang model passed a number of observational tests, and cosmologists believe it provides the better available description of the structure and evolution of the Universe—at least, within the limits of its applicability. Let us then try to understand a bit more about the Big Bang model.

The Great Escape

When we observe the night sky—if we are lucky enough to be far away from city lights, perhaps on a mountain or at sea—our eyes can gaze at an astonishing view. Stars like dust, in every direction. Over the gleaming stripe that the ancients called *the Milky Way*, stars look so densely packed that we may not be able to single them out, unless we use a telescope. Near the end of the 18th century, astronomer William Herschel proved for the first time that all the stars in our sky, and our Sun of course, belong to a vast agglomerate, whose shape can roughly be compared to that of a thick disc or a pancake.

Astronomers call such a collection of stars a *galaxy*. When we observe the Milky Way, we see a larger number of stars only because we are looking along the denser regions of our Galaxy—along the disc.

We now know that our Galaxy—that we still call the Milky Way—is enormous: it has a diameter of about 100 thousand light-years, a thickness of roughly 10 thousand light-years, and it contains hundreds of billions of stars. We also know that the Cosmos is much, much larger than our Milky Way, and that it contains hundreds of billions of galaxies similar to our own. But still at the end of the 19th century only a few people thought that the

Universe could be any larger than our cosmic island. The Milky Way appeared to be all that existed.

Actually, ever since Herschel's time astronomers had observed many objects that could not be single stars. Dim puffs of light, some of them more elongated, some rounder. These objects were called *nebulae* (the Latin word for "clouds"). No one was able to establish their distance, not to mention their real nature. For the 18th century's astronomers, nebulae probably belonged to the Milky Way, being nothing more than clumps of interstellar matter. German philosopher Immanuel Kant, who thought that the Universe had necessarily to be eternal and infinite, was among the first to claim that nebulae might actually be vast aggregations of stars, lying well outside our Milky Way.

The question about the nature of the nebulae remained unanswered for a long time. Astronomers were divided into two factions: those who believed that nebulae were objects in our Galaxy, and those who considered them different galaxies, spread in a Universe much bigger than our Milky Way. The dispute was finally settled only in 1924, by American astronomer Edwin Hubble. He made good use of previous work by astronomer Henrietta Leavitt, who only a few years before had discovered a way to measure the distance of a particular kind of variable stars, the *Cepheids*. Using the most powerful astronomical tool available at the time, the 2.5 meters telescope of Mount Wilson, California, Hubble was able to determine the distance to one of the most brilliant nebulae: M31 in Andromeda, a nebula which is easily seen by the naked eye in optimal conditions. Hubble established that M31 was in fact about 900 thousand light-years from Earth—a much larger distance than the size of the Milky Way. (Today, we actually know that the distance to M31 is even larger than that initially estimated by Hubble, being more than 2 million light-years away.) Given such an enormous distance, M31 could only be visible if it contained a huge number of stars, comparable to those in the Milky Way. M31 was undoubtedly another galaxy. All of a sudden, Hubble's discovery made the Universe a vast place, surprisingly larger than one might have reasonably expected. An awful waste of space.

Such an extraordinary result, which solved a longtime controversy, brought Hubble immediate fame; but he did not relax. Helped by his assistant Milton Humason (who started as a janitor at Mount Wilson, but soon became one of the most scrupulous and skilled observers of his times), Hubble went on measuring the distance to many other nebulae, proving that they were separate galaxies[1]. In 1929, after they had observed and analyzed tens of such galaxies, Hubble and Humason announced a new discovery—possibly even more surprising than the first one. They had been able to determine not only the distance of many of those galaxies, but also their velocity. On average, one would expect to observe each galaxy moving with a random velocity, with no relation to the velocity of other galaxies. But Hubble noticed that all galaxies seemed to be moving away from the Milky Way. A similar observation had been made some years before by astronomer Vesto Slipher, but Hubble now had more and better data to confirm this finding.

Things got even stranger when Hubble decided to plot the velocities and distances for different galaxies on a graph (Figure 1.1). The two quantities, according to Hubble's data, followed a roughly linear relation. In other words, more distant galaxies seemed to move away from the Milky Way at higher speeds—a galaxy which was at a distance twice as great as another galaxy, was also moving two times faster. This fact, which actually was not that evident in Hubble's earlier data, was later confirmed by further and more accurate observations in 1931. Later, this apparent runaway motion of all galaxies has been confirmed countless times with every new observation, and is considered one of the pillars of modern cosmology. The law which relates the velocities of galaxies to their distances is now called the *Hubble law*, to honour its discoverer.

At first sight, the Hubble law seems to force us to assign a special—and unpleasant—position to our own Galaxy, since all other galaxies are apparently fleeing away from us. It would look like a suspicious anachronism, after the many centuries needed to progressively remove Earth from the center of Cosmos, to find out that we are indeed occupying a peculiar position in space, amidst a mysterious motion involving the entire content of the Universe.

Actually, it is possible to interpret the recession velocity of galaxies in an entirely different fashion. To understand this, let us begin with a simple mental experiment. Take a long rubber band,

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[1] As a matter of fact, there are objects which are nebulous in nature but do belong to our own Milky Way: they have nothing to do with other galaxies, being simply clouds of interstellar matter. We still call them nebulae.

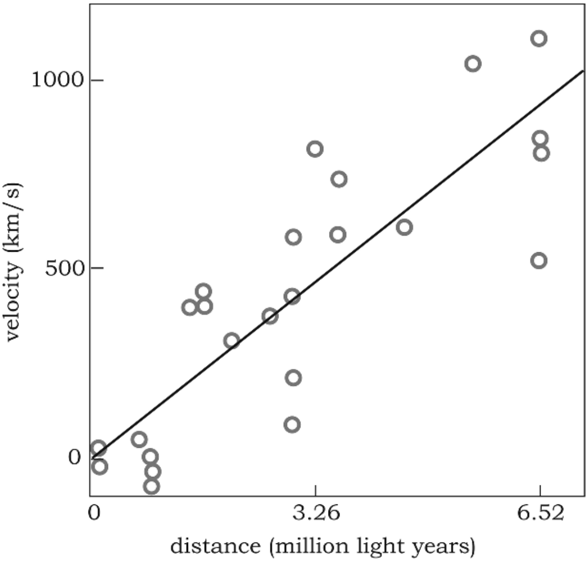

FIGURE 1.1 The original Hubble data suggested a linear relation between the velocity of galaxies and their distance from us. This law has been confirmed with greater precision by more recent observations. (Figure adapted from Hubble's 1929 paper.)

make a series of knots in it at regular distances, for example 1 cm. Then extend the rubber, until its length doubles. Now, every knot will be at a distance of 2 cm from the next one. Fine. Let us now look at the situation from the point of view of any one of the knots. Its nearest neighbours, which initially were at a distance of 1 cm, now are 2 cm away. The next closest neighbours, however, have changed their distance from 2 cm to 4 cm, and so on. In other words, if we constantly extend the rubber band and assume the point of view of any one knot, it will look as if all the other knots are moving away, the more distant with higher velocities. Every knot might then be considered at the center of a recession motion, which of course is only apparent.

In the Universe, galaxies are not aligned like knots along a rubber band. They are distributed in all three dimensions of space. However, with some imagination, we might imagine a situation which resembles that of galaxies in space. For example, we might consider the motion of raisins in a loaf of rising bread (Figure 1.2). As the dough expands, the raisins vary their distances in the same