After the First Three Minutes

The Story of Our Universe

T Padmanabhan

最初的三分钟后

——宇宙的故事

剑桥英语科普注释读物系列

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章伟良 徐霆 注释

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出版说明

随着我国改革开放的深入和对外科技交流的发展，广大科技工作者迫切需要通过英语媒介获取专业科技知识，了解相关学科领域的最新发展动态；而有一定英语基础的普通读者则亟需通过阅读大量英语版的科普文章来扩大知识面，获取信息，同时提高英语水平。因此，引进一批国外原版优秀科普读物，满足广大读者的需要，是改革开放进一步深化的需要，是当务之急。

我社从英国剑桥大学出版社引进的《最初的三分钟后——宇宙的故事》(*After the First Three Minutes: The Story of Our Universe*)就是这样一部优秀的科普作品。作者以通俗易懂的语言、引人入胜的故事情节向读者讲述了我们生活的宇宙是如何演变的、恒星和星系等天体结构是怎样形成的以及科学家们对宇宙科学的最新认识。为使普通读者能轻松、愉快地阅读，作者尽量少用专业术语；不可避免时，则不仅对这些术语的概念作出解释，还提供了相关的背景知识。因此，本书不仅有助于广大读者了解天文学方面的知识，对英语水平的提升也大有帮助。

本书可作为天文学等相关专业学生的专业英语教材和课外读物，也可供广大英语爱好者扩大知识面、提高英语水平用。

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... to my daughter Hamsa, who thinks I should be playing with her instead of writing such books...

Preface

One thing I have learnt in a long life: that all our science, measured against reality, is primitive and childlike — and yet it is the most precious thing we have. A. EINSTEIN

The subject of cosmology — and our understanding of how structures like galaxies, etc., have formed — have developed considerably in the last two decades or so. Along with this development came an increase in awareness about astronomy and cosmology among the general public, no doubt partly due to the popular press. Given this background, it is certainly desirable to have a book which presents current thinking in the subject of cosmology in a manner understandable to the common reader. This book is intended to provide such a non-mathematical description of this subject to the general reader, at the level of articles in *New Scientist* or *Scientific American*. An average reader of these magazines should have no difficulty with this book.

The book is structured as follows: chapter 1 is a gentle introduction to the panorama in our universe, various structures and length scales. Chapter 2 is a rapid overview of the basic physical concepts needed to understand the rest of the book. I have tried to design this chapter in such a manner as to provide the reader with a solid foundation in various concepts, which (s)he will find useful even while reading any other popular article in physical sciences. Chapter 3, I must confess, is a bit of a digression. It provides the useful survey of astronomical observations which a reader will enjoy, but it is closely connected with chapter 4. Because of the interdependence of chapters 3 and 4, I strongly recommend that the reader return to chapter 3 after reading chapter 4. The fourth chapter describes a gamut of astrophysical structures and processes: stars, stellar evolution, galaxies, clusters of galaxies, etc. find their place here. Chapter 5 is devoted to the big bang model of the universe and a description of the early universe. This lays the foundation for *the* key chapter of the book, viz. chapter 6, which deals with the formation of various structures in the universe. The current thinking in this subject is presented in detail, and I have also provided a critical appraisal of models. Chapter 7 deals with the farthest objects in the universe which astronomers are currently studying, viz. quasars, radio galaxies, etc. The final chapter summarizes the entire book and emphasizes the broad picture available today.

The choice of topics necessarily reflects the bias of the author, but I have consciously tried to increase the 'shelf-life' of the book, in spite of the fact that it deals with a rapidly evolving area. For example, chapters 2, 4, 5 and most of 3 will remain useful for a fair amount of time. Some of the details in chapters 6 and 7 will doubtless change, but I think the broad ideas and concepts will remain useful for a longer time.

The discussion is non-mathematical, but I have not avoided mentioning actual numbers, units, etc. when it is required. This is essential in the discussion of several topics; any attempt to present these results in 'pure English' would have oversimplified matters. In fact, I have tried to avoid oversimplification as much as possible, though I might have cut corners as regards details in a few places. This book is intended for the serious reader who *really* wants to know, and I do expect such a reader to put in some effort to understand the ideas which are presented. I have also avoided telling the reader stories; you will not find any of '... as Prof. Great was driving with his wife to the concert, it suddenly occured to him .... ' kind of stuff in this book. Ideas and discoveries are more important than individuals, and I have kept the discussion mostly impersonal and non-historical. (You will find some exceptions, which are — of course — intentional.) The publishers and I debated whether to go for a glossy book with lots of colour pictures or to go for a no-nonsense version, and decided on the latter. It was a difficult choice, and I hope the clarity of the contents compensates for the lack of colour.

You will find a fairly detailed glossary at the end of the book, containing the technical terminology introduced in various chapters. Since concepts developed in chapter 2 or 4 (say) may be needed in chapter 7, the glossary will serve the useful purpose of reminding the reader of unfamiliar jargon. I have also included a brief list of books for further reading; this choice is definitely biased and should be merely taken as an indicative sample. Some of these books contain more extensive bibliographies.

This book originated from a comment made by John Gribbin. While reviewing my book *Structure formation in the universe* (CUP, 1993), he said that: 'It would be good to see the author attempting a popular book on the same theme'. Rufus Neal of CUP responded positively to this suggestion, and I hope I haven't disappointed them.

Several others have contributed significantly to the making of this book: This is the second time I have worked with Adam Black of CUP, and it was delightful. The entire TEXing, formatting of figures and proof-reading was done by Vasanthi Padmanabhan, and I am grateful to her for the hours of effort she has put in. Most of the figures were done by Prem Kumar (NCRA) and I thank him for his help. I am grateful to my friends Jasjeet Bagla, Mangala Narlikar, Lakshmi Vivekanand, Ramprakash, Srianand, Srinivasan, Sriramkumar and Vivekanand, who have read earlier drafts of the book and have made useful comments and suggestions. I thank IUCAA for the use of computer facilities.

T. PADMANABHAN

Contents

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Introducing the universe

1.1 Cosmic inventory

Think of a large ship sailing through the ocean carrying a sack of potatoes in its cargo hold. There is a potato bug, inside one of the potatoes, which is trying to understand the nature of the ocean through which the ship is moving. Sir Arthur Eddington, famous British astronomer, once compared man's search for the mysteries of the universe to the activities of the potato bug in the above example. He might have been right as far as the comparison of dimensions went①; but he was completely wrong in spirit. The 'potato bugs' — called more respectably astronomers and cosmologists — have definitely learnt a lot about the contents and nature of the Cosmos.

If you glance at the sky on a clear night, you will see a vast collection of glittering stars and — possibly — the Moon and a few planets. Maybe you could also identify some familiar constellations② like the Big Bear. This might give you the impression that the universe is made of a collection of stars, spiced with③ the planets and the Moon. No, far from it; there is a lot more to the universe than meets the naked eye!

Each of the stars you see in the sky is like our Sun, and the collection of all these stars is called the 'Milky Way' galaxy④. Telescopes reveal that the universe contains millions of such galaxies⑤— each made of a vast number of stars — separated by enormous distances. Other galaxies are so far away that

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① as far as the comparison of dimensions went: when he was making this/such comparison of dimensions

② constellations: named groups of stars (e.g. the Great Bear) 星座(经命名的星群,如大熊星座)

③ spiced with: added 加入

④ the 'Milky Way' galaxy: 银河系

⑤ galaxies: 星系

we cannot see them with the naked eye. So what you see at night is only a tiny drop in the vast sea of the cosmos. To understand and appreciate our universe, it is necessary to first come to grips with① the large numbers involved in the cosmological description.

To do this systematically, let us start with our own home planet, Earth. The radius of the Earth is about 6 400 kilometers (km, for short), and by modern standards of transport this is a small number. A commercial jetliner can fly around the Earth in about 40 hours. The nearest cosmic object to the Earth is the Moon, which is about 400 000 km away. This distance is about 60 times the radius of the Earth, and Apollo 11 — which landed men on the Moon for the first time — took about four days to cover this distance. As you know, the Moon is a satellite of Earth and orbits around us once in about 30 days. The Earth itself, of course, is moving around the Sun, which is about 150 million km away. Apollo 11 would have taken nearly five years to travel this distance. There are several other planets like the Earth which are orbiting the Sun at varying distances from it. The closest one to the Sun is Mercury②, the next one is Venus③(which may be familiar to you as the 'Evening Star'④ in the sky) and the third one is the Earth. After Earth comes Mars (the red planet), Jupiter, Saturn (the one with rings), Uranus, Neptune and Pluto⑤ in order of increasing distance. The farthest known planet in the solar system, Pluto, is at a distance which is nearlv 40 times as large as the distance between the Earth and the Sun. Thus our planetary system has a radius of about 6 000 million km.

The distances are already beginning to be quite large, and it will be convenient if we use bigger units to express these astronomical distances. After all, you measure the length of a pencil in centimeters but give the distance between two cities in kilometers, which is a much larger unit. In the same spirit, a terrestrial⑥ unit like the kilometer is inadequate to express cosmic dimensions⑦ and it would be nice to have bigger units. One such unit, which is

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① come to grips with: begin to deal with (a problem, challenge, etc.); begin to look at... first 开始应付(难题,挑战等)

② Mercury: 水星

③ Venus: 金星

④ the 'Evening Star': 昏星; 长庚星

⑤ Mars (the red planet), Jupiter, Saturn (the one with rings), Uranus, Neptune and Pluto: 火星、木星、土星、天王星、海王星、冥王星

⑥ terrestrial: of the planet Earth 地球的

⑦ cosmic dimensions: the size of the whole/entire universe 宇宙的范围、大小

used extensively, is called the 'light year'. In spite of the word 'year', this is a unit of *distance* and *not* of time. One light year is the distance travelled by light in one year. Light can travel nearly 300 000 km in one second, and so a light year is about 10 million million km. Written in full, this would be 10 000 000 000 000 km. For convenience of writing, we use the symbol 10^{13} km to denote① this quantity. This symbol stands for the number obtained by multiplying 10 thirteen times or —equivalently — the number with 1 followed by 13 zeros. So we may say that one light year is about 10^{13} km.

This unit, the light year, becomes really useful when we consider still larger scales. As we said before, our Sun is only one among 100 000 million stars which exist together in a galaxy named the 'Milky Way'. Using our shorthand notation, we can say that our galaxy has about 10^{11} stars. The star nearest to our Sun is called 'Proxima Centauri'②(which is in the constellation Centaurus③) and is about four light years away from us. In other words, a light ray — which can go through our planetary system in about eleven hours — will take about four years to reach the *nearest* star! (Apollo 11 would have taken nearly one million years!) All the stars you see in the sky belong to the Milky Way galaxy and are at different distances from us. Each one of them could be as big and bright as our Sun, and could possibly have a planetary system around it. Sirius④, the brightest star in the sky, is about eight light years away; the reddish star, Betelgeuse⑤, in the familiar constellation of Orion⑥, is at a distance of 600 light years, and the Pole star is about 700 light years from us. The light which we receive today from the Pole star was emitted during the fourteenth century!

The entire Milky Way galaxy is about 45 000 light years in extent. To describe the galaxy, we find that even the light year is an inadequately small unit. So astronomers use a still bigger unit called a 'kiloparsec'⑦(kpc, for short). One kiloparsec is about 3 000 light years. The radius of a typical galaxy (like ours) is about 15 kpc. Kiloparsec is the most often used unit in map-

① denote: be the name, sign or symbol of; refer to; signify; mean 代表
② 'Proxima Centauri':(半人马座)比邻星,亦作 Proxima
③ Centaurus: 半人马座
④ Sirius: 天狼星
⑤ Betelgeuse: 参宿四,猎户星座中的一等星
⑥ Orion: 猎户座
⑦ 'kiloparsec': 千秒差距

ping the universe.

Just as the Sun is only an average star in the Milky Way, our galaxy itself is only one among a large number of galaxies in the universe. Powerful telescopes reveal that our universe contains more than 100 million galaxies similar to ours. The nearest big galaxy to the Milky Way is called 'Andromeda'①. This galaxy is at a distance of about 700 kpc, and is just barely visible to the naked eye as a hazy② patch in the constellation Andromeda. The Andromeda galaxy, like the Milky Way, is made of about 10^{11} stars(just to remind you, 10^{11} stands for the number 100 000 000 000 — which is 1 followed by 11 zeros; we shall use this notation repeatedly in this book). But since it is so far away we cannot see the individual stars of Andromeda with our naked eye.

Around the Milky Way and Andromeda there exist about 30 other galaxies. Some of these, called 'Dwarf galaxies'③, are considerably smaller in size, and each of them contains only about a million stars or so, while a few others are bigger. The Milky Way, Andromeda and these galaxies together form the next unit in the cosmic scale④, usually called the 'Local Group⑤ of galaxies'. The size of the Local Group is about 1 000 kpc, which is called 1 Megaparsec⑥(Mpc, for short).

The assembling of galaxies in the form of groups or clusters⑦ is also a general feature of our universe. Astronomers have detected a large number of clusters of galaxies, many of which are much bigger than our Local Group (which contains only about 30 galaxies). Some of the large clusters of galaxies — like the one called the 'Coma cluster' — contain nearly 1 000 individual galaxies.

Are there structures still bigger than the cluster of galaxies? Observations suggest that clusters themselves could be forming bigger aggregates⑧ called 'superclusters'⑨, with sizes of about 30 to 60 Mpc. For example, our Local

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① 'Andromeda': 仙女座
② hazy: not clear; vague 模糊的,朦胧的
③ 'Drawf galaxies': 白矮星系
④ form the next unit in the cosmic scale: become another/a second unit of the universe
⑤ Local Group: 本星系群
⑥ Megaparsec: 百万秒差距
⑦ clusters: 星团
⑧ aggregates: a mass or body of units or parts somewhat loosely associated with one another 聚合体
⑨ 'superclusters': 超星系团(多个疏散星团的集团)

Group is considered to be a peripheral① member of a supercluster called the 'Virgo supercluster'②. However, the evidence for superclusters is not as firm as that for clusters.

How big is the universe itself? With powerful telescopes we can now probe③ distances of about 3 000 – 6 000 Mpc. In other words, we can say that the size of the observable region of the universe is nearly 1 000 times bigger than the size of a galaxy cluster.

You must have noticed that, in going from the Earth to a supercluster, we have come across a hierarchy④ of structures (see figure 1.1). The smallest is the planetary system around a star. Such a system has a size of about 10 light hours. The collection of stars, in turn, make up a galaxy (with about 10^{11} stars per galaxy) having a size of about 20 kpc; the galaxies themselves combine to form groups and clusters with a typical size of a few Mpc. The clusters are part of superclusters with sizes of 50 Mpc or so. And the entire observed region of the universe has a size of about 6 000 Mpc.

If you assume⑤ that a penny, with a size of about 1 cm, represents the planetary system, the nearest star to us will be about 60 meters away and the size of our galaxy will be 700 kilometers! This should tell you how tiny our entire planetary system is compared to the galaxy we live in. The size of a cluster of galaxies will be 1 000 times bigger than this and the entire observed universe is another 1 000 times larger!

At the bottom of the ladder, we have the planets which are orbiting the Sun. What about larger structures in the hierarchy? It turns out that none of the structures described above are static⑥. (See table 1.1.) The Sun — or, for that matter, any other star in a galaxy — moves in the galaxy with a typical speed of about 200 km per second (km s^{-1} for short⑦). Even our galaxy is not at rest. It is moving towards the Andromeda galaxy with a speed of about

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① peripheral: subordinate 从属的
② 'Virgo supercluster': 处女座超星系团
③ probe: explore or èxamine 探查,探测
④ hierarchy: things arranged in a graded series 等级,层级
⑤ assume: accept as true before it is proved; suppose; consider as true 假设,假定
⑥ static: not moving or changing; stationary 静止的,稳定的
⑦ for short: as an abbreviation 简称

100 km s^{-1}. Further, the entire Local Group is moving coherently① (somewhere towards the Virgo supercluster) with a speed of about 600 km s^{-1}. It is a delicate balance② between motion and the gravitational force which keeps our universe going③.

Table 1.1 ***Structures in the universe***

Structure	Size	Speed
Planetary system	6×10^9 km	30 km s^{-1}
Galaxy	20 kpc	200 km s^{-1}
Local Group	1 Mpc	100 km s^{-1}
Cluster	5 Mpc	1 000 km s^{-1}

Given the sizes of various systems and the speed with which individual objects move in these systems, one can calculate the typical orbit time for each of these structures. At the smallest scale,④ the Earth takes one year to go around the Sun, while the farthest planet, Pluto, takes about 250 years. The timescale associated with galaxies is considerably larger. For example, a star like the Sun will take about 200 million years to complete one orbit in our galaxy; and a galaxy will take about 5 billion years to go from one end of a cluster to the other end. It is interesting to compare these numbers with the ages of different objects in our universe. It is estimated that the age of the Earth is about 4.6 billion years; in other words, the Earth has completed more than 4 billion orbits around the Sun since its formation. The typical lifetime of a star like the Sun is about 10 billion years, which is a factor of 50⑤ higher than the orbital time in the galaxy, i.e., a star like the Sun can make about 50 orbits in its lifetime. The ages of bigger structures like galaxies, clusters etc. are far less certain, but — as we shall see in the later chapters — are likely to be about 13 billion years. This is the timescale over which most cosmic phenomena take place.

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① coherently: consistently 连贯地,一致地

② a delicate balance: a fine balance easy to be broken up 均势

③ which keeps our universe going: which makes our universe exist as it is/as we see it today

④ At the smallest scale: At the very least 起码

⑤ a factor of 50: 50 的因数