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Dark Energy

暗能量

李淼 等 编著

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《中外物理学精品书系》
编 委 会

序　　言

物理学是研究物质、能量以及它们之间相互作用的科学。她不仅是化学、生命、材料、信息、能源和环境等相关学科的基础，同时还是许多新兴学科和交叉学科的前沿。在科技发展日新月异和国际竞争日趋激烈的今天，物理学不仅囿于基础科学和技术应用研究的范畴，而且在社会发展与人类进步的历史进程中发挥着越来越关键的作用。

我们欣喜地看到，改革开放三十多年来，随着中国政治、经济、教育、文化等领域各项事业的持续稳定发展，我国物理学取得了跨越式的进步，做出了很多为世界瞩目的研究成果。今日的中国物理正在经历一个历史上少有的黄金时代。

在我国物理学科快速发展的背景下，近年来物理学相关书籍也呈现百花齐放的良好态势，在知识传承、学术交流、人才培养等方面发挥着无可替代的作用。从另一方面看，尽管国内各出版社相继推出了一些质量很高的物理教材和图书，但系统总结物理学各门类知识和发展，深入浅出地介绍其与现代科学技术之间的渊源，并针对不同层次的读者提供有价值的教材和研究参考，仍是我国科学传播与出版界面临的一个极富挑战性的课题。

为有力推动我国物理学研究、加快相关学科的建设与发展，特别是展现近年来中国物理学者的研究水平和成果，北京大学出版社在国家出版基金的支持下推出了《中外物理学精品书系》，试图对以上难题进行大胆的尝试和探索。该书系编委会集结了数十位来自内地和香港顶尖高校及科研院所的知名专家学者。他们都是目前该领域十分活跃的专家，确保了整套丛书的权威性和前瞻性。

这套书系内容丰富，涵盖面广，可读性强，其中既有对我国传统物理学发展的梳理和总结，也有对正在蓬勃发展的物理学前沿的全面展示；既引进和介绍了世界物理学研究的发展动态，也面向国际主流领域传播中国物理的优秀专著。可以说，《中外物理学精品书系》力图完整呈现近现代世界和中国物理

科学发展的全貌，是一部目前国内为数不多的兼具学术价值和阅读乐趣的经典物理丛书。

《中外物理学精品书系》另一个突出特点是，在把西方物理的精华要义“请进来”的同时，也将我国近现代物理的优秀成果“送出去”。物理学科在世界范围内的重要性不言而喻，引进和翻译世界物理的经典著作和前沿动态，可以满足当前国内物理教学和科研工作的迫切需求。另一方面，改革开放几十年来，我国的物理学研究取得了长足发展，一大批具有较高学术价值的著作相继问世。这套丛书首次将一些中国物理学者的优秀论著以英文版的形式直接推向国际相关研究的主流领域，使世界对中国物理学的过去和现状有更多的深入了解，不仅充分展示出中国物理学研究和积累的“硬实力”，也向世界主动传播我国科技文化领域不断创新的“软实力”，对全面提升中国科学、教育和文化领域的国际形象起到重要的促进作用。

值得一提的是，《中外物理学精品书系》还对中国近现代物理学科的经典著作进行了全面收录。20 世纪以来，中国物理界诞生了很多经典作品，但当时大都分散出版，如今很多代表性的作品已经淹没在浩瀚的图书海洋中，读者们对这些论著也都是“只闻其声，未见其真”。该书系的编者们在这方面下了很大工夫，对中国物理学科不同时期、不同分支的经典著作进行了系统的整理和收录。这项工作具有非常重要的学术意义和社会价值，不仅可以很好地保护和传承我国物理学的经典文献，充分发挥其应有的传世育人的作用，更能使广大物理学人和青年学子切身体会我国物理学研究的发展脉络和优良传统，真正领悟到老一辈科学家严谨求实、追求卓越、博大精深的治学之美。

温家宝总理在 2006 年中国科学技术大会上指出，“加强基础研究是提升国家创新能力、积累智力资本的重要途径，是我国跻身世界科技强国的必要条件”。中国的发展在于创新，而基础研究正是一切创新的根本和源泉。我相信，这套《中外物理学精品书系》的出版，不仅可以使所有热爱和研究物理学的人们从中获取思维的启迪、智力的挑战和阅读的乐趣，也将进一步推动其他相关基础科学更好更快地发展，为我国今后的科技创新和社会进步做出应有的贡献。

《中外物理学精品书系》编委会　主任

中国科学院院士，北京大学教授

王恩哥

2010 年 5 月于燕园

Preface

The dark energy problem is a longstanding issue:

In 1917, Einstein added a cosmological constant term in his field equation, to obtain a static Universe. However, he removed this cosmological constant in 1931 because of the discovery of the cosmic expansion. Due to losing the opportunity to predict the expansion of the Universe, Einstein claimed that this is the biggest blunder in his life.

In 1967, Zel'dovich reintroduced the cosmological constant by taking the vacuum fluctuations into account. But in quantum field theory, the expectation value of the vacuum fluctuations diverges as k^4. If we take a cutoff at the Planck or electroweak scale, the predicted value of the cosmological constant Λ is still 117 or 52 orders of magnitude larger than the observed value. This discrepancy is known as the "fine-tuning problem", and has perplexed theorists for several decades.

In 1998, Based on the analysis of 34 nearby and 16 distant type Ia supernovae, Riess *et al.* first discovered the acceleration of expansion of the Universe. Soon after, utilizing 18 low-redshift and 42 high-redshift supernovae, Perlmutter *et al.* confirmed the discovery of cosmic acceleration. This discovery declares the return of the cosmological constant, now termed as "dark energy". This leads to the so-called "coincidence problem": why the current dark energy density is of the same order of matter density?

To solve these puzzles and understand the cosmic acceleration, in the last decade, theorists have proposed numerous theoretical models and have written thousands of papers on this subject. Unfortunately, so far the nature of dark energy is still a mystery. On the observational side, astronomers have also spent enormous efforts on probing dark energy. Since 1998, observational evidences of dark energy have been definitely confirmed and highly improved through many cosmological observations, such as the type Ia supernovae, the baryon acoustic oscillations, the cosmic microwave background, the weak gravitational lensing, the galaxy cluster survey, and so on. Therefore, the dark energy problem, which challenges our understanding of fundamental physical laws and the nature of the cosmos, has become one of the central problems in theoretical physics and modern cosmology. In this situation, a book introducing the current state of research on dark energy is very necessary. We write this book based on those considerations. The book is an extended version of our previous review article [Commun. Theor. Phys. **56** (2011) 525], and it consists of three parts:

In the first part, we start with an introduction to preliminary knowledge. Fundamentals for a modern understanding of cosmology, including general relativity, matter components and FRW cosmology, are summarized and briefly introduced. Thus this part serves as a preparation and foundation for our introduction to the dark energy in the next two parts.

The second part reviews some of major theoretical ideas and models of dark energy. In this part, we first briefly review the history of the problem of the cosmological constant. After this, we follow Weinberg's classical review in 1989, and divide the old approaches reviewed by Weinberg into five categories. Then, we add three more categories in order to include most of the more recent ideas and models. Eight classes of dark energy models are reviewed: models based on symmetry; anthropic principle; tuning mechanism; modified gravity; quantum cosmology; holographic principle; back-reaction and phenomenological constructions.

The third part is devoted to reviewing some observational and numerical works. First, we will introduce some basic knowledge of statistics. Then, we will review the mainstream cosmological observations probing dark energy. Next, we will provide a brief overview of the present and future dark energy projects. Finally, we will review the current numerical studies on cosmic acceleration, including the observational constraints on specific theoretical models, and the model-independent reconstructions from observational data.

The aim of this book is to provide a sufficient level of understanding of dark energy problem, so that the reader can both get familiar with this area quickly and also be prepared to tackle the scientific literature on this subject. It will be useful for graduates students and advanced undergrads in physics or astronomy to obtain an overall glance of the current dark energy research, and it will also be helpful for researchers who are interested in this subject to design their own research programs.

We would like to express our appreciation for the kind invitation of the Peking University Press. We are also very grateful to our editor Xiao Liu, for the kind support and encouragement. Many thanks to Prof. Xin Zhang for valuable suggestions about the contents and styles of this book. We thank Prof. Robert Brandenberger, Dr. Yi-Fu Cai, Prof. Qing-Guo Huang and Prof. Richard Woodard for the useful discussions. We also thank Prof. Robert Kirshner for the helpful suggestions.

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Contents

Part I

Preliminaries in a Nutshell

1
Gravitation

For a quick review of gravitation, we start from the equations of Newtonian gravity. The gravitational force acting on a test mass m is

$$F = -m\nabla\Phi, \tag{1.1}$$

where Φ is called the Newtonian potential, which is determined by the Poisson equation

$$\Delta\Phi = 4\pi G\rho, \tag{1.2}$$

where ρ describes the mass distribution of a gravitational source, and G is the Newton's gravitational constant.

Newtonian gravity captures some features of our universe. However, mass sums up. As a result, on cosmological scales, Newtonian gravity breaks down. For a systematic description of our universe, the theory of general relativity is inevitably required.

In the remainder of this chapter we briefly review the two key concepts in general relativity: what if spacetime is curved and what makes spacetime curved. Here we are by no means trying to provide a logical introduction for general relativity. Instead, we pragmatically highlight parts of the theory which are building blocks for a phenomenological description of dark energy, as well as set up our conventions.

1.1 The Curved Spacetime

It is for a long time a great mystery why our space is well described by Euclidean geometry. In the spatial two dimensional story, numerous attempts are made to prove the "parallel axiom" and eventually the axiom turns out