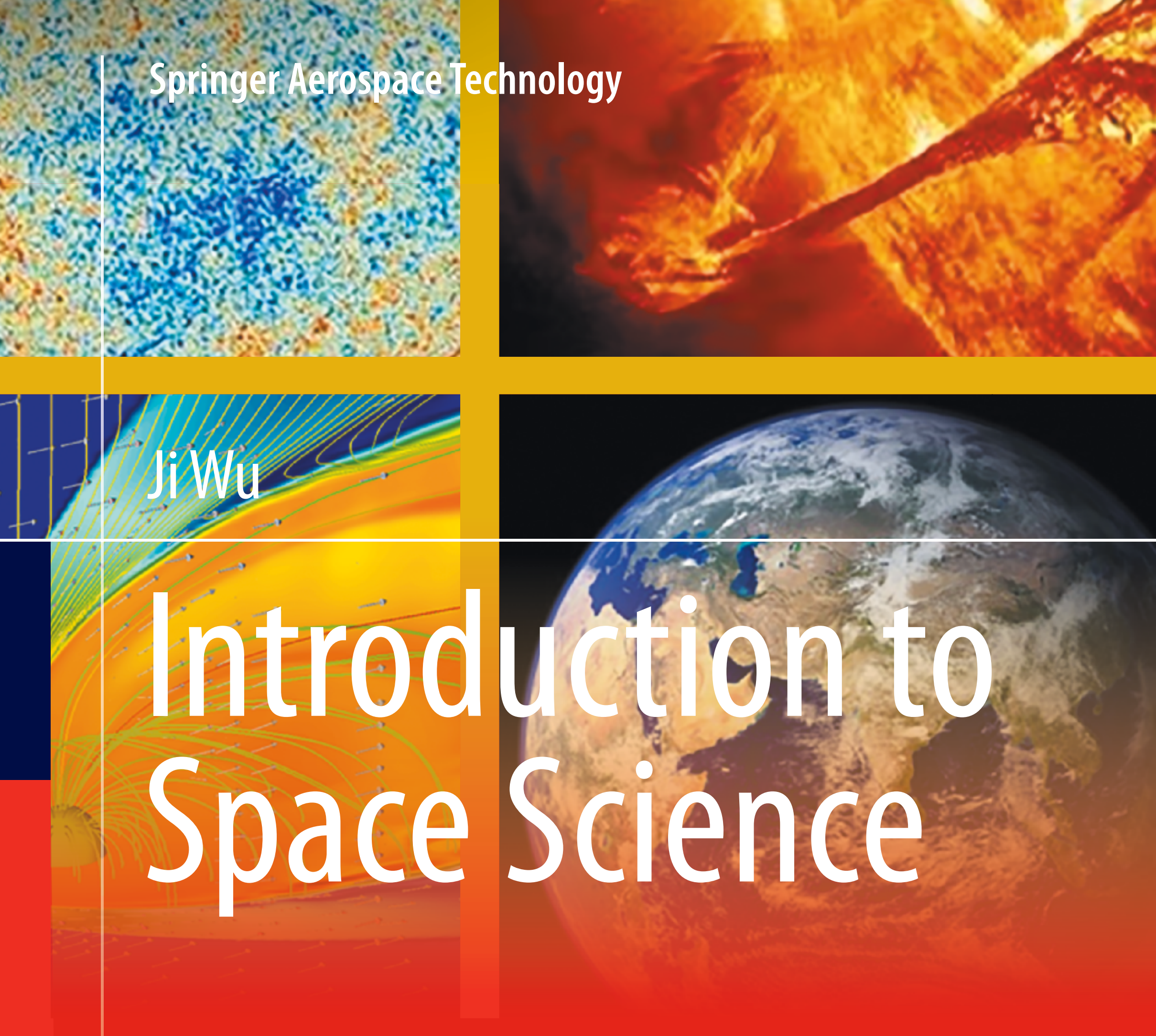

Springer Aerospace Technology

Ji Wu

Introduction to Space Science

Science Press
Beijing

Springer

Springer Aerospace Technology

The series explores the technology and the science related to the aircraft and spacecraft including concept, design, assembly, control and maintenance. The topics cover aircraft, missiles, space vehicles, aircraft engines and propulsion units. The volumes of the series present the fundamentals, the applications and the advances in all the fields related to aerospace engineering, including:

- structural analysis,
- aerodynamics,
- aeroelasticity,
- aeroacoustics,
- flight mechanics and dynamics
- orbital maneuvers,
- avionics,
- systems design,
- materials technology,
- launch technology,
- payload and satellite technology,
- space industry, medicine and biology.

The series' scope includes monographs, professional books, advanced textbooks, as well as selected contributions from specialized conferences and workshops.

The volumes of the series are single-blind peer-reviewed.

To submit a proposal or request further information, please contact:

Mr. Pierpaolo Riva at pierpaolo.riva@springer.com (Europe and Americas) Mr. Mengchu Huang at mengchu.huang@springer.com (China)

The series is indexed in Scopus and Compendex

More information about this series at https://link.springer.com/bookseries/8613

Ji Wu

Introduction to Space Science

Science Press
Beijing

Springer

Ji Wu
National Space Science Center
Beijing, China

Translated by
Yongjian Xu
National Space Science Center
Beijing, China

Qingjiang Bai
National Space Science Center
Beijing, China

ISSN 1869-1730 ISSN 1869-1749 (electronic)
Springer Aerospace Technology
ISBN 978-981-16-5750-4 ISBN 978-981-16-5751-1 (eBook)
https://doi.org/10.1007/978-981-16-5751-1

Jointly published with Science Press
The print edition is not for sale in China Mainland. Customers from China Mainland please order the print book from Science Press.

Translation from the Chinese language edition: *Introduction to Space Science* by Ji Wu, © China Science Publishing & Media Ltd (Science Press) 2020. Published by China Science Publishing & Media Ltd (Science Press). All Rights Reserved.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

Space science adopts the spacecraft as the main tools to carry out scientific research and experiments, which is an integral part of the space endeavor. For China, with the gradual increase of comprehensive national power and the emergence of science and technology innovation as the main driving force of development, it is the inevitable choice, to vigorously promote the development of space science, which will trigger a wave of intensive demands for space technology, and provide theoretical guidance and support for the development of space applications.

I have known Professor Ji Wu, the author of this book, for a long time. As the former Director General of the National Space Science Center (NSSC) of the Chinese Academy of Sciences (CAS) and the President of the Chinese Society of Space Research (CSSR), one of the key players in promoting the development of space science in China in recent years, he has done substantial work and made tremendous contributions to the development of space science in China. This book is based on the development of China's space programs and Prof. Ji Wu's personal experience in so many years, and at the same time draws on the practices of spacefaring nations and institutions, which makes a good reading for scientists, engineers, and project managers. This book can also be used as a textbook and reference for related courses in universities and colleges.

For young students who are new to the space sector, they need to get familiar with the origin and background of the space programs. This book traces back to the early days of human observation of space and cosmos, reviews the development of science to reveal the asperation intention of space exploration, and introduces the history of space technology with the focus on launch vehicles which helps to overcome the gravity of the Earth to enter space. This will greatly broaden the horizons of these young students.

For the people with engineering background in space sector, Chaps. 3 and 4 are very unique in that after a comprehensive and macroscopic introduction to several important branches of space science, the key scientific frontiers of each branch are briefly described, which can greatly stimulate their curiosity. Besides, for people who are no longer engaged in scientific research, and only participate in these space science missions as engineers or managers, they will be proud of doing their bit in the exploration of such interesting scientific frontiers. Therefore, the introduction of this background knowledge is essential for all those involved in space science missions.

After presenting the necessary background knowledge of space exploration, this book provides a systematic overview of the major systems of space technology, highlighting the orbit, launcher, and spacecraft/satellite systems, with particular focus on the relationship between payloads and orbits, launcher and spacecraft in scientific missions. This knowledge is essential for both engineers and scientists who are involved in space science missions. For engineers, they need to understand the requirements of a space science mission and the payloads, while for scientists, they need to know the engineering constraints and boundaries of orbits, launch vehicles, and spacecraft.

This book differentiates itself from purely scientific and technical monographs with substantial discussions on space science mission management. In our long time cooperation, Prof. Ji Wu has been responsible for specific technical work, as well as important management work in many major space missions, especially space exploration missions. Therefore, he has rich experience in systems engineering. The experience in management issues introduced in this book is based on the 60 years' development of Chinese space program, as well as his personal experiences in leading the implementation of major space science missions. As the reading unfolds, the reader can have the panoramic view, from a mission manager's perspective, of the entire process of a science mission from mission planning, pre-research, selection, approval, development, launch, operations, and evaluation, with the prevailing principle of maximizing scientific output, which is articulated by the author to the fullest extent. I believe that those engaged in space science missions would benefit greatly from reading this book, which would facilitate their future research work.

Finally, the author discusses the relationship between space science, space technology, and space applications in very concise language and with the help of diagrams. It can be seen that these three integral aspects are mutually dependent, mutually supportive, and mutually reinforcing.

All in all, this book makes a fascinating reading. It is a summary and overview of the development of the space endeavor in China in the last 60 years. I hope that the present and future scientists, engineers, and project managers of space science missions could read the book, which can also serve as an introductory textbook for young students who will enter the space sector. It is hoped that the publication of this book will inject new momentum into the space science endeavor in China and promote its faster, better, and sustainable development.

Beijing, China
May 2020

Academician Peijian Ye

Preface

Although humans have been observing and recording the stars and the cosmos for thousands of years, it is only in the last 60 years or so that we have, in the real sense, entered the space age. Space science is an emerging interdisciplinary field, which thrives from the development of space technology and uses the spacecraft as the tools to conduct research in space. Compared with other traditional disciplines, space science, as a basic research area, is government dominated and its research directions are planned accordingly. Since its expected scientific output may lead to discoveries and breakthroughs in major basic science frontiers, it belongs to the basic research. However, the implementation of a space science mission requires integration of various disciplines and systems engineering technology, especially the space technology, and relies on the spacecraft as the platform of observation and experiment to achieve scientific objectives. In addition, due to the uniqueness of scientific discoveries, the requirements on the space technologies by a space science mission are constantly becoming higher and higher, leading to innovations and upgrading in space technology. Transforming these new technologies into applicable technologies on the ground can even give rise to new strategic industries and drive the development of economy and society. In this respect, it is also a part of national space activities with the potential to enhance the space technology capacity.

Traditional basic science education based on individual disciplines aims to train professionals in specific disciplines, such as physicists, astronomers, space physicists, planetary scientists, atmospheric and ionospheric physicists, solid Earth physicists, and life scientists. In the traditional curriculum, seldom do they have the opportunity to learn related knowledge of large systems engineering, such as the space systems engineering. But in the future, when the abovementioned professionals are engaged in space science research, they will turn into space scientists, who need to understand orbital dynamics, space environment, various space vehicles like spacecraft/satellites, as well as knowledge of systems engineering management. In the traditional education system to train the engineers, be it mechanical, electrical, or material, the focus of education is on feasibility, reliability, repeatability, and implementability, and the graduates can directly participate in the engineering implementation. But when involved in a space science mission, these engineers often do not understand the language of the scientists who are striving to explore the unknown, and they are unwilling to accept the engineering and technical challenges and risks brought about by the new requirements. However, prioritizing the scientific objectives prevails in a space science mission, from mission proposal to operations, and science and engineering are closely bonded together. On one hand, scientists without basic knowledge of space technology and systems engineering cannot communicate with the mission development and research team, and are incapable of coordinating the mission development with hundreds of participants, which leads to the failure of realizing their dreams. On the other hand, engineers who fail to understand the language of science cannot understand the requirements of scientific detection and observation, and cannot make reasonable improvements to the engineering design to best meet the needs of the scientific objectives.

This book, from a top-down, interdisciplinary, and systematic perspective, aims to provide a systematic introduction of the knowledge on the frontiers of various branches of space science disciplines, space technology, and systems engineering, to highlight the characteristics of space science missions as compared with other space missions, to lay the fundamental systematic knowledge for scientists and engineers who wish to engage and participate in space science missions in the future, and to cultivate scientists and engineers as potential principle investigators, chief designers, and project managers.

The outline of this book is as follows: Chaps. 1 and 2 focus on the reasons to conduct research in space and the history of space exploration; Chaps. 3 and 4 introduce the major frontier issues in space astronomy, planetary science, space solar physics, space physics, space Earth science, microgravity science, and space life sciences, respectively; Chap. 5 introduces the space systems engineering and its systems; Chaps. 6–8 introduce the technical foundations for space science missions, including orbit, attitude and TT&C, scientific payloads and its application environment, mission planning, and operations. Chaps. 9–12 focus on the key factors of space science mission management, including mission proposal and its selection, mission development and the duty of scientists and engineers, quality management and risk control, full mission lifecycle management, and output evaluation. Chap. 13 introduces the international cooperation in space science missions; Chap. 14 introduces the space science programs in China; Chap. 15, as the wrap up of the book, not only gives definitions to space science, space technology, and space applications, but also discusses their relationships.

This book is based on my two-semester course for the graduate course of the School of Astronomy and Space Science, University of the Chinese Academy of Sciences. This book received substantial support from Associate Prof. Bai Qingjiang, the course assistant, as well as the necessary help from Prof. Zheng Jianhua from the National Space Science Center of the Chinese Academy of Sciences and Alvaro Gimenez, former Science Director of the European Space Agency. My thanks also go to colleagues from several departments of the National Space Science Center for their assistance, including the Space Science and Deep Space Exploration Study Center, the Space Science Program Center, and the Space Science Mission Operation and Control Center.

My thanks go to the translators of this book for their devoted effort to bring it into the current shape. Mr. Xu Yongjian is responsible for the translation of Chaps. 1–8 and Chap. 13, and Ms. Bai Qingjiang is responsible for Chaps. 9–12 and Chaps. 14 and 15.

Finally, my gratitude also goes to Zhu Pingping, the Editor of the Science Press, for her hard work, which has enabled efficient publication of this book.

Beijing, China Ji Wu
April 2020

Contents

About the Author

Prof. Ji Wu is President of the Chinese Society of Space Research (CSSR) and former Director General of the National Space Science Center (NSSC) of Chinese Academy of Sciences (CAS). He is full member of IAA (International Astronautics Academy), fellow of the IEEE Geoscience and Remote Sensing Society, member of the Advisory Board of Luxembourg Government for Space Resources, and member of the Advisory Committee of UAE Space Agency. He once served as Vice-President of the Committee for Space Research (COSPAR) (2010–2018), Head of the Strategic Priority Program on Space Science of CAS, Chief Designer of the application system of Double Star Program, Principle Investigator of Yinghuo-1, and Project Manager of Scientific Payload System of Chinese Lunar Exploration Program Chang'e-1 and Chang'e-3.

Chapter 1
Reasons to Conduct Research in Space

1.1 Introduction

What are the reasons to conduct research in space? For many disciplines, even including astronomy, research could be carried out on the ground. For example, Galileo Galilei (1564–1642) pioneered the practical ground observation of celestial bodies using telescopes. Another example is the employment of ground-based radars to observe and study the ionosphere. Even so, there's still a lot of research that can't be done on the ground, which necessitates the research in space. This chapter will focus on the reasons to go into space.

From the beginning of the space age, the fundamental and foremost objective of entering space to carry out research is to unveil the mystery of space and increase our knowledge of space. Before the launch of the first artificial satellite in 1957, the outer space reaching beyond the atmosphere is shrouded in mystery, where the neutral atmosphere thins out and is ionized by the ultraviolet light from the Sun when reaching further out, hence creating the ionosphere. But, questions remain to be answered, e.g., how the electrons and ions in the ionosphere are distributed and how do they move? What effect does the Earth's magnetic field exert on these charged particles?

After gaining access to space, for the first time in human history, we have the opportunity to observe the Planet Earth from hundreds or even thousands of kilometers away. When we observe it from such a distance, our perceptions of the Earth become very different. The changes that the Earth presents to us become systematic, such as the formation and movement of typhoons.

What's more, once break free the obstacles of the atmosphere, we have the liberty to make full use of the resources of the entire electromagnetic spectrum. Previously, the low-frequency electromagnetic waves, terahertz, and infrared wavelengths, as well as wavelengths beyond the ultraviolet that are normally blocked by the atmosphere. Entering into space enables us to observe the universe in full electromagnetic spectrum.

J. Wu, *Introduction to Space Science*, Springer Aerospace Technology,
https://doi.org/10.1007/978-981-16-5751-1_1

For an in-orbit spacecraft, the centrifugal force generated by its rotation around the Earth is offset by the gravitational force of the Earth, providing us an equivalent microgravity environment for a long period of time. Previously, our understanding of the kinetic properties of matter and the rule of life activity is actually based on the condition of the gravity of the Earth. So, if we remove the gravity, will the movement of matter and life remain the same?

In short, gaining access to space is to enter a larger laboratory where the experiments previously impossible on the ground can be carried out.

1.2 To Explore the Unknown Space Environment

Before the space age, the human knowledge of space was limited to speculations and theoretical conjectures. The atmosphere thinned out, but then what? The ultraviolet light from the Sun ionizes atoms in the atmosphere, allowing electrons to escape and correspondingly form the ionosphere. The answer was not clear in 1901, when Guglielmo Marconi (1874–1937), an Italian radio engineer, successfully transmitted a radio signal across the Atlantic. Marconi was puzzled for a long time by the fluctuation of radio waves, which apparently traveled a winding path to reach the destination thousands of kilometers away.

We now know that, for a transmission distance of more than 5000 km from the west coast of Europe to the east coast of the United States, the radio waves reached the receivers with the help of ionospheric reflections. It turns out that Marconi's first successful transoceanic radio communication in 1901 verified the existence of the ionosphere.

The human knowledge about ionosphere stops there. By that time, we still didn't know where the upper boundary of the ionosphere is, or how positively charged ions and negatively charged electrons in the ionosphere behave. Only after 1957 did the answers to these questions become clear. Therefore, to study the unknown space environment is the core of space research. This is especially the case for the first artificial satellite launched by the Soviet Union on October 4, 1957, and the first American artificial satellite launched on January 31, 1958. Malfunctions were detected on the instruments for both satellites and American scientists tended to believe that the malfunction is not due to the instrument itself but rather to the existence of intense high-energy particle zone in the near Earth space, which was later identified and consequently named as Van Allen belt. This is the first major discovery in the space history of mankind.

1.3 To Break Free the Barrier of Atmosphere to Electromagnetic Wave

Since Galileo pointed his telescope into space, human beings have broken the limitations of space observation with the naked eye and began to use scientific instruments to observe the universe. The spectrum of electromagnetic waves we can observe

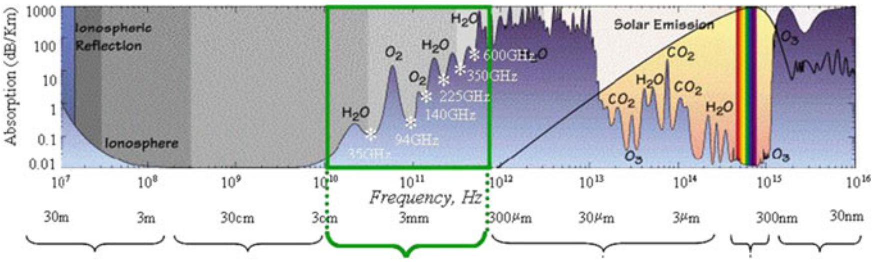

Fig. 1.1 Atmospheric absorption across the electromagnetic spectrum

was then gradually expanded to radio waves. However, the protective atmosphere proves to be an obstacle for the ground-based observations using ultraviolet and low-frequency radio spectrum. Figure 1.1 shows the atmospheric absorption spectrum diagram, in which the ordinate is the atmospheric absorption expressed in decibels loss per kilometer.

Since 1957, humans began to break the atmospheric barrier by placing observational instruments on satellites. New images of the universe and the Sun were obtained in wave lengths such as infrared, ultraviolet, X-ray, and low-frequency electromagnetic waves. Since then, space astronomy and space solar physics flourished as individual disciplines in their own names.

In addition, the atmosphere can absorb the electromagnetic waves, which, in turn, makes it possible to carry out space-based observation of the physical characteristics of the Earth's atmosphere. For example, the frequency in the vicinity of the temperature absorption line can be used to observe the distribution of atmospheric temperature at different altitudes, and the frequency in the vicinity of the water vapor absorption line can be used to observe the distribution of atmospheric water vapor, etc. These technological breakthroughs have promoted the development of space Earth science.

1.4 To Utilize the Orbital Altitude Resources

From the mountain top, you can see farther. In general, the altitude of satellite orbit is above 500 km. Geosynchronous Earth Orbit (GEO) is as high as 36,000 km. The natural field of view of the human eye is about 45°, which is also the field of view of a standard camera. Accordingly, for Earth observation, the width of more than 400 km can be obtained at an altitude of 500 km (the width covered by push-sweep camera on an operating satellite is called swath), and cities such as Beijing, Moscow, and New York can be seen in a panoramic view. If the Earth is observed in Geosynchronous Earth Orbit, the field of view of the entire Earth is less than 18°. By designing remote sensors with different field of views, we can obtain ground images with different swaths, making possible the systematical observation of the Earth.

Therefore, the satellite orbit promises the unprecedented altitudes where the Earth observation can be conducted and the data obtained can be used to study the large-scale phenomena of the Earth system, such as typhoon, ocean currents, El Nino, the atmospheric pollution caused by volcanic eruptions, and even the global water cycle, biosphere, energy cycle, ice and snow cycle and lithosphere, etc. This provides the most important observation platform for space Earth science to study the Earth as a system. After the technical realization of putting a satellite in Geosynchronous Earth Orbit, human beings can continuously and comprehensively monitor the changes of the Earth.

1.5 To Unveil the Mystery of the Earth's Gravitational Field

We live on the Earth under the effect of 1G gravitational field. To put it in a figurative way, all the kinetic properties of matter and the rule of life activity lie beneath the veil of 1G gravitational field on the surface of the Earth.

Using space as platform, it is possible to carry out on-board scientific experiments that cannot be done otherwise on the ground. Among these on-board experiments, the microgravity science experiments [1] are the most prominent ones. The centrifugal force generated by the spacecraft as it orbits the Earth offsets the Earth's gravity, hence creating a continuous and stable artificial microgravity environment. Such an environment may reveal the kinetic properties of matter, which are impossible to be discovered due to the effect of gravity. The studies of the laws of physics, e.g., the law of fluid physics, combustion, and semiconductor material growth, are collectively known as microgravity science.

In addition to the study of laws of physics, some fundamental issues in life science can also be examined in space microgravity environment, such as the cultivation of cells and plants, which gives birth to space life science. Of course, when studying the life science issues, consideration should be given to the effects of space particle radiation and the influence of weakened Earth's magnetic field.

With the increase of manned space activities, the required period of stay for astronauts in space becomes longer and longer. Can animals and human beings live in space for a long time? These new scientific questions posed by man's entry into space can also be deemed as part of space medicine.