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Astronomical Spectroscopy: An Introduction to the Atomic and Molecular Physics of Astronomical Spectra

2nd Edition

天文光谱学

——天文光谱的原子与分子物理学导论

第二版

（影印版）

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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

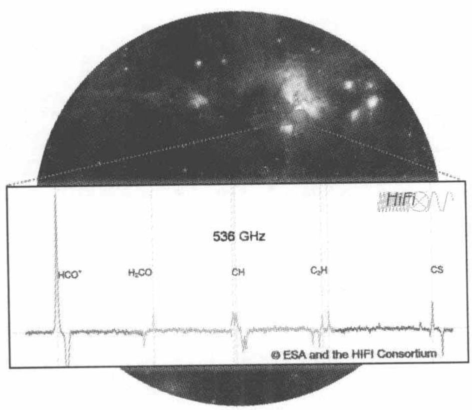
王恩哥

2010年5月于燕园

Astronomical Spectroscopy

An Introduction to the Atomic and Molecular Physics of Astronomical Spectra

2nd Edition



Jonathan Tennyson
University College London, UK

World Scientific
NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Preface

This book follows closely a lecture course I gave entitled 'Astronomical Spectroscopy' to third-year undergraduate students at University College London between 1998 and 2003. The students who attended had done a prior introductory course on Quantum Mechanics which covered the hydrogen atom but no further atomic physics or spectroscopy. A similar level of prior knowledge is assumed in the current work.

In writing a book of this sort there are many people whose help has been essential for completion of the enterprise. First I must thank Bill Somerville who inaugurated the course Astronomical Spectroscopy and taught it for two years before me. He selflessly shared his lecture notes and other materials with me. I like to would thank Ceinwen Sanderson for turning my hand scrawled lecture notes into LaTeX, and my colleagues Tony Lynas-Gray, Bill Somerville, Peter Storey and Jeremy Yates for their extensive comments on the draft of the book. I owe a debt of gratitude to my graduate students Bob Barber and Natasha Doss who checked all the problems and found many errors. I thank all of them for the corrections: any errors that remain are all mine.

I must also thank the students who attended my Astronomical Spectroscopy course. It was great fun to teach, not least because the latest developments in astrophysics often fed straight into the lectures. Particular thanks are due to the class of 2003 who made a number of helpful comments and suggestions on the contents of the book.

A book on spectroscopy thrives on good illustrations and I have shamelessly plundered the literature and other sources for spectra to illustrate this one. I must thank Xiaowei Liu for help with digitising many of the published spectra, and my student Iryna Rozum, my son Matthew and David Rage for their help with the other illustrations. Can I thank the journals and many authors who greeted my requests to reproduce their work with prompt enthusiasm, and especially those authors who adapted figures at my request? Each journal and author is individually acknowledged in the figure captions.

Finally I must give very warm acknowledgement to the many UCL astronomers past and present who have answered my many questions on astrophysics with a patience their frequent stupidity probably did not deserve. Particularly high on this list are Pete Storey and Mike Barlow but the rest of the varied lunch crew should not be forgotten. Without you my knowledge of things astronomical would be the same as it was the day I arrived at UCL — nothing.

Jonathan Tennyson
London
July 2004

In making a second edition I have taken the opportunity to add a chapter on the effects of magnetic fields on atomic spectra and to increase the coverage of molecular spectroscopy. The launch of high resolution infra red telescopes, recently Herschel and soon JWST, the development of extremely powerful ground-based long-wavelength telescopes such as ALMA, and the start of spectroscopic study of extra-solar planets have all acted to increase the astronomical importance of molecular spectroscopy. Indeed it is one of the joys of the study of astronomical spectroscopy that the constant discoveries drive the need for ever deeper understanding of the spectroscopy of atomic and molecular species which in turn enrich our appreciation of the Universe around us.

In preparing this second edition I would like to thank the many people who made very positive comments on the first edition and the (surprisingly) few who found errors in it. I am grateful to Bob Barber, Pete Storey, Michael Down, Stephen Harrison and Dermot Madden for their comments on the manuscript and, again, those astronomers who have allowed me to use their work to illustrate important points in spectroscopy.

Jonathan Tennyson
London
October 2010

Contents

Chapter 1

Why Record Spectra of Astronomical Objects?

'We will never know how to study by any means the chemical composition (of stars), or their mineralogical structure.'

– Auguste Comte (1835)

1.1 A Historical Introduction

In the first part of the 19th century, astronomers began to make parallax measurements which revealed for the first time how distant even the closest stars are from us. Since travel to the stars was, and still is, impossible with foreseeable technology, many scientists believed that the composition and character of the stars would forever remain a mystery. This view is pithily summarised by the quote from the positivist French philosopher Auguste Comte (1798–1857) given above.

Today, the composition of stars, and indeed of the diffuse material in the large spaces in between the stars, is well known. How did this situation come about? In fact the first steps to finding the solution to the problem had been taken even before Comte began writing.

In 1814, Joseph von Fraunhofer (1787–1826) used one of the high-quality prisms he had manufactured to diffract a beam of sunlight, taken from a slit in his shutters, onto a whitewashed wall. Besides the characteristic colours of the rainbow, which had been observed in this fashion since Newton, he saw many dark lines (see Fig. 1.1). He meticulously catalogued the exact wavelength of each dark line — which are still known today as Fraunhofer lines — and labelled the strongest of them with letters. Many of these labels, such as the sodium D lines (see Sec. 6.4) are

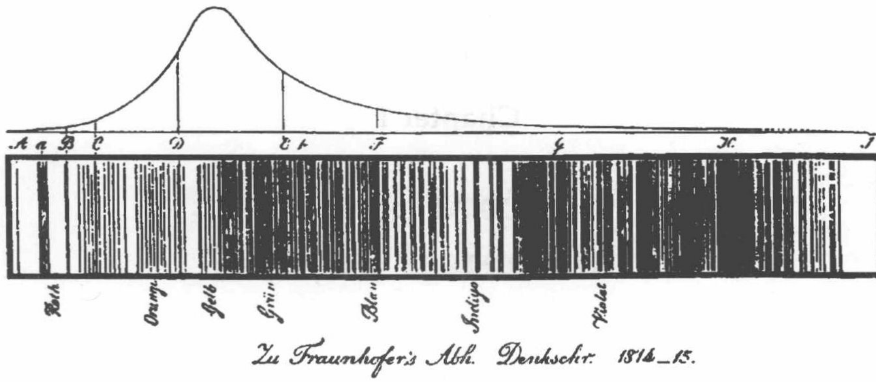


Fig. 1.1 The solar spectrum as recorded by Fraunhofer.

still used today. Fraunhofer not only recorded the first astronomical spectrum, he recorded the first-ever high-resolution spectrum. Fraunhofer's spectrum was the first to resolve discrete line transitions.

Fraunhofer did not know what caused the dark lines he observed. However he performed a similar experiment using light from the nearby red-star Betelgeuse and found that the pattern of dark lines he observed changed significantly. Fraunhofer concluded correctly that most of those features were somehow related to the composition of the object he was observing. In fact some of the lines were due to the Earth's atmosphere, the so-called telluric lines. For example, the features Fraunhofer marked A and B in his solar spectrum are actually due to molecular oxygen in our own atmosphere.

The first real step in understanding Fraunhofer's observations came in the middle of the 19th century with the experiments of Gustav Kirchhoff (1824–1887) and Robert Bunsen (1811–1899). These scientists studied the colour of the light emitted when metals were burnt in flames. They found that in certain cases the wavelength of the emitted light gave an exact match with the Fraunhofer lines. The sodium D lines, which give sodium street lights their characteristic orange colour, were one such example. These experiments demonstrated that the Fraunhofer lines were a direct consequence of the atomic composition of the Sun.

Any understanding of how these lines came about had to wait until the arrival of the 20th century with the revolution of scientific theory represented by quantum mechanics. The developments of quantum mechanics and spectroscopy have always been closely linked. As it is through the study of spectra that we have learnt of many of the riches in the Universe around us, the development of astrophysics has also been closely linked to that of spectroscopy and quantum mechanics. This book aims to give an introduction to the spectroscopy of atoms and molecules that are important for astrophysics. This book is not a text on quantum mechanics, and indeed, some basic knowledge of quantum mechanics is assumed, for it is not possible to understand or interpret spectra without some understanding of quantum mechanics.

Hearnshaw (1986) gives a fascinating historical view of the relationship between astronomy, spectroscopy and the technical developments in both fields (see further reading).

1.2 What One Can Learn from Studying Spectra

Essentially all information about astronomical objects outside the solar system comes through the study of electromagnetic radiation (light) as it reaches us. This light can contain much detailed information which is only obtained by careful analysis. Generally speaking, one can classify the information obtained by observing light according to the spectral resolution; that is the degree of sensitivity to different wavelengths, used to make the observation. One can classify such observations using the following general categories.

When one looks at the night sky with the naked eye, most astronomical bodies appear white. White light is actually light that is composed of many wavelengths which are not resolved into their different colours. Monitoring white light gives the positions of objects in the night sky. It can be used to construct maps of stars and galaxies. It can also be used to plot the movements of heavenly bodies such as comets through the night sky.

If one looks carefully at some celestial objects, such as the planets Mars and Jupiter, or stars such as Betelgeuse, one can see that these objects are tinged with a certain colour. Using instruments with low resolving power, it is possible to separate the light arriving at Earth into broad band colours. Observing colours tells us something about temperatures. For example, blue stars are hotter than red ones; objects that emit X-rays, such as the solar corona, are very hot, whereas cold objects may only emit electromagnetic radiation of very long wavelengths such as radio waves.

The most detailed astrophysical information is only obtained from high-resolution studies which involve detecting the light arriving at the earth as a function of its component wavelengths. This allows detailed spectroscopic features to be identified separately from broad band features such as colour. At the highest resolution, such studies not only yield the central wavelength of any feature, often referred to as a line, but also the shape of the feature. Such studies can yield significant extra information and this book is largely devoted to the physical basis of this information and how it can be interpreted.

To interpret an astronomical spectrum, one needs considerable knowledge of atomic and molecular physics. This knowledge usually comes from laboratory studies which provide the basic physical parameters necessary for understanding the astronomical spectrum. There is a direct relationship between these physical parameters and the astronomical information that can be obtained by observing spectra. Thus for any line observed in an astronomical spectrum, one can potentially use laboratory data to extract the following information.

The **composition** of the object being observed can be inferred by knowing which atom (or ion or molecule) produces the observed transition.

The **temperature** and other physical conditions can be deduced from assigning the actual transition being observed to precise energy levels in the atom. Transitions take place between many different states in a particular atom. Knowing which states are involved gives direct information on the degree of excitation of the system. This can be used to determine the physical conditions, such as the temperature or density of the environment local to the system.

The **abundance** of the species undergoing the transition can only be determined if the intrinsic strength of the transition being observed is known. Line strengths can be hard to determine in the laboratory. Astronomically, the strength of a transition is directly related to the number of atoms undergoing the transition under suitable conditions of optical depth (see below). Knowledge of the intensity of transitions is therefore important for determining the abundance of any species.

Motions of the species being observed relative to the earth, or indeed the whole region containing the species, lead to a shift in the wavelength of the line; this shift is known as the Doppler shift. The Doppler shift is the change in the line position from the position measured in the laboratory. This shift is given by the Doppler formula,

$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda}, \tag{1.1}$$