Atomic Astrophysics and Spectroscopy

Spectroscopy allows the precise study of astronomical objects and phenomena. Bridging the gap between physics and astronomy, this is the first integrated graduate-level textbook on atomic astrophysics. It covers the basics of atomic physics and astrophysics, including state-of-the-art research applications, methods and tools.

The content is evenly balanced between the physical foundations of spectroscopy and their applications to astronomical objects and cosmology. An undergraduate knowledge of physics is assumed, and relevant basic material is summarised at the beginning of each chapter.

The material is completely self-contained and contains sufficient background information for self-study. Advanced users will find it useful for spectroscopic studies. Websites hosted by the authors contain updates, corrections, exercises and solutions, and news items from physics and astronomy related to spectroscopy. Links to these can be found at www.cambridge.org/9780521825368.

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Preface

This text is aimed at students and researchers in both astronomy and physics. Spectroscopy links the two disciplines; one as the point of application and the other as the basis. However, it is not only students but also advanced researchers engaged in astronomical observations and analysis who often find themselves rather at a loss to interpret the vast array of spectral information that routinely confronts them. It is not readily feasible to reach all the way back into the fundamentals of spectroscopy, while one is involved in detailed and painstaking analysis of an individual spectrum of a given astrophysical object. At the same time (and from the other end of the spectrum, so to speak) physics graduate students are not often exposed to basic astronomy and astrophysics at a level that they are quite capable of understanding, and, indeed, that they may contribute to if so enabled.

Therefore, we feel the need for a textbook that lays out steps that link the mature field of atomic physics, established and developed for well over a century, to the latest areas of research in astronomy. *The challenge is recurring and persistent: high-resolution observations made with great effort and cost require high-precision analytical tools, verified and validated theoretically and experimentally*.

Historically, the flow of information has been both ways: astrophysics played a leading role in the development of atomic physics, and as one of the first great applications of quantum physics. As such, it is with basic quantum mechanics that we begin the study of astrophysical spectroscopy. The atomic physics and the astrophysics content are intended to be complementary, and attempt to provide a working knowledge in the two areas, as necessary for spectral analysis and modelling. The emphasis is on the introductory theoretical basics, leading up to a practical framework for applications of atomic spectroscopy. While we limit ourselves to atomic physics, we have attempted to highlight and delineate its reach into the main areas of astronomy.

The link between basic-to-advanced atomic physics and spectral analysis is increasingly important in ever more sophisticated astrophysical models. But the challenge of writing a book such as this one has been to find a balance between basic physics treatment that is not superficial, and state-of-the-art astrophysical applications that are not too technical. Though that defined and delimited the scope, it was still clear from the outset that the material should encompass a wide variety of topics. But what is essential and what is superfluous is, to some extent, a matter of subjective judgement. The level of depth and breadth of each topic is subject to these constraints. However, owing to the objective needs before us, we have tried to be as comprehensive as possible (limited by our own expertise, of course).

The text is evenly divided into atomic physics and astrophysics. The first seven chapters form the foundational elements of atomic processes and spectroscopy. The next seven chapters deal with astrophysical applications to specific objects and physical conditions. Each chapter follows the same plan. We begin with the essentials that all readers should be able to follow easily. However, towards the end of each chapter we outline some of the more advanced or specialized areas. The subject matter is broadly divided into 'basic' material in both areas, and 'advanced' material that incorporates state-of-the-art methods and results. The underlying atomic physics is intended as an introduction to more specialized areas, such as spectral diagnostics, astrophysical models, radiative transfer, plasma opacities, etc.

Emphasizing the unifying and connecting themes, the text is planned as follows. Following the Introduction, the next six chapters cover 'basic' collisional and radiative atomic structure and processes. The second part of the text, the other seven chapters, are the 'applications' of the physical framework developed in the first part. Chapters 8 and 9 describe the interaction of radiation with matter and spectral formation. The remainder of the text, Chapters 10–14, deals with descriptions of astronomical sources: stars, nebulae, active galactic nuclei and cosmology. A special chapter is devoted to a description of

the largest single application of atomic physics to astronomy: stellar opacities (Chapter 11). However, the content of these chapters is *not* designed to be exhaustive, but mainly to exemplify spectral formation in astrophysical environments. Each of Chapters 10–14 contains tables and sample spectra characteristic of the particular astrophysical source(s). The appendices provide some of the tools, and some of the atomic data, needed in spectral modelling. However, they are not comprehensive and readers are advised to consult the websites described below.

Supplementary to the present text are the authors' websites.[1] They will provide continual updates and revisions related to atomic data and developments in atomic astrophysics. Eventually, this facility is designed to be user-interactive, with features such as on-line calculation of spectral line intensities and ratios, model calculations of ionization fractions, etc., using up-to-date atomic data.

[1] www.astronomy.ohio-state.edu/ ∼pradhan and www.astronomy.ohio-state.edu/ ∼nahar.

Acknowledgements

The material in this book is partially based on several courses that Anil Pradhan has taught over the years. First of all, it is from a course on Theoretical Spectroscopy taught to astronomy graduate students at the Ohio State University every alternate year for nearly 20 years. Some of the material is also derived from graduate courses taught on atomic structure at the University of Windsor, scattering theory at the University of Colorado, and advanced undergraduate causes on stellar astrophysics at Ohio State. In addition, teaching introductory astronomy courses to non-science majors at Ohio State has been a valuable exercise in learning that, in addition to the discovery of wondrous new objects, some of the most basic and common phenomena in the Universe remain poorly understood (and *that* is the fun and raison d'etre for doing astronomy!).

But it is in the inspiration derived from our teachers and mentors wherein lies the foundation. The first acknowledgement – indeed a debt of gratitude – is due to Mike Seaton, advisor and mentor for over three decades. Mike was among the foremost pioneers who developed atomic astrophysics into the discipline it is today. Although he was not aware of this effort, and, regrettably, would not see it, Mike's monumental contributions are self-evident throughout the text. Nearly a decade ago, Dimitri Mihalas first suggested to Anil Pradhan the need for a book such as this. Dimitri has since then encouraged and advised on several aspects of the presentation, so well exemplified in his classic *Stellar Atmospheres*. From the observational side, Don Osterbrock continually pointed out over many years the specific needs for astrophysical diagnostics that could be fulfilled by the state-of-the-art atomic physics he appreciated so well. We also regret that Don is no more to see the fruit of his inspiration, howsoever imperfect this may be.

A number of our colleagues have read parts of the material and made numerous suggestions. We are especially grateful to our long-time collaborator, Werner Eissner, for revisions of the chapter on atomic structure. Special thanks are due to former student, postdoc, and now a valued colleague, Max Montenegro, for expertly and patiently (re-)drawing most of the figures in the book. Among the several colleagues who reviewed the material, Gerry Newsom and Bob Wing made particularly valuable comments on the chapters on stars, emission lines and nebulae. We also thank Dirk Grupe, Hong Lin Zhang, Prajaval Shastri, Bob Williams, Belinda Wilkes and David Branch, who read and suggested many corrections or improvements. But although all the material in the text has been reviewed by at least one of them, any errors, omissions and inaccuracies are entirely our responsibility. All we can say is that, fortunately, we have the electronic means to correct or revise any material, and would greatly appreciate readers pointing those things out to us. We shall endeavour to post all updates on the special website meant for this book (with due acknowledgement).

Finally, we would like to acknowledge the immense support and motivation derived from our families, to whom this work is dedicated. Anil Pradhan would like to thank his wife, Indira, and children, Alka and Vivek, his mother, Sarojini (who is no more), grandparents, Laksman Swarup and Phoolmati Pradhan, and parents Mahesh Chandra and Kunj Bala Pradhan. Sultana Nahar is grateful for inspiration from parents, Abdul Razzaq and Shamsun Nahar, teachers and family, especially her son, Alburuj R. Rahman.