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978-0-521-85593-8 - Galaxies in the Universe: An Introduction, Second Edition

Linda S. Sparke and John S. Gallagher III

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Galaxies in the Universe: An Introduction

Galaxies are the places where gas turns into luminous stars, powered by nuclear reactions that also produce most of the chemical elements. But the gas and stars are only the tip of an iceberg: a galaxy consists mostly of dark matter, which we know only by the pull of its gravity. The ages, chemical composition and motions of the stars we see today, and the shapes that they make up, tell us about each galaxy's past life. This book presents the astrophysics of galaxies since their beginnings in the early Universe. This Second Edition is extensively illustrated with the most recent observational data. It includes new sections on galaxy clusters, gamma ray bursts and supermassive black holes. Chapters on the large-scale structure and early galaxies have been thoroughly revised to take into account recent discoveries such as dark energy.

The authors begin with the basic properties of stars and explore the Milky Way before working out towards nearby galaxies and the distant Universe, where galaxies can be seen in their early stages. They then discuss the structures of galaxies and how galaxies have developed, and relate this to the evolution of the Universe. The book also examines ways of observing galaxies across the electromagnetic spectrum, and explores dark matter through its gravitational pull on matter and light.

This book is self-contained, including the necessary astronomical background, and homework problems with hints. It is ideal for advanced undergraduate students in astronomy and astrophysics.

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University of Wisconsin, Madison



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Preface to the second edition

This text is aimed primarily at third- and fourth-year undergraduate students of astronomy or physics, who have undertaken the first year or two of university-level studies in physics. We hope that graduate students and research workers in related areas will also find it useful as an introduction to the field. Some background knowledge of astronomy would be helpful, but we have tried to summarize the necessary facts and ideas in our introductory chapter, and we give references to books offering a fuller treatment. This book is intended to provide more than enough material for a one-semester course, since instructors will differ in their preferences for areas to emphasize and those to omit. After working through it, readers should find themselves prepared to tackle standard graduate texts such as Binney and Tremaine's *Galactic Dynamics*, and review articles such as those in the *Annual Reviews of Astronomy and Astrophysics*.

Astronomy is not an experimental science like physics; it is a natural science like geology or meteorology. We must take the Universe as we find it, and deduce how the basic properties of matter have constrained the galaxies that happened to form. Sometimes our understanding is general but not detailed. We can estimate how much water the Sun's heat can evaporate from Earth's oceans, and indeed this is roughly the amount that falls as rain each day; wind speeds are approximately what is required to dissipate the solar power absorbed by the ground and the air. But we cannot predict from physical principles when the wind will blow or the rain fall. Similarly, we know why stellar masses cannot be far larger or smaller than they are, but we cannot predict the relative numbers of stars that are born with each mass. Other obvious regularities, such as the rather tight relations between a galaxy's luminosity and the stellar orbital speeds within it, are not yet properly understood. But we trust that they will yield their secrets, just as the color–magnitude relation among hydrogen-burning stars was revealed as a mass sequence. On first acquaintance galaxy astronomy can seem confusingly full of disconnected facts; but we hope to convince you that the correct analogy is meteorology or botany, rather than stamp-collecting.

We have tried to place material which is relatively more difficult or more intricate at the end of each subsection. Students who find some portions heavy going at a first reading are advised to move to the following subsection and return later to the troublesome passage. Some problems have been included. These aim mainly at increasing a reader's understanding of the calculations and appreciation of the magnitudes of quantities involved, rather than being mathematically demanding. Often, material presented in the text is amplified in the problems; more casual readers may find it useful to look through them along with the rest of the text.

Boldface is used for vectors; italics indicate concepts from physics, or specialist terms from astronomy which the reader will see again in this text, or will meet in the astronomical literature. Because they deal with large distances and long timescales, astronomers use an odd mixture of units, depending on the problem at hand; Appendix A gives a list, with conversion factors. Increasing the confusion, many of us are still firmly attached to the centimeter–gram–second system of units. For electromagnetic formulae, we give a parallel-text translation between these and units of the *Système Internationale d'Unités* (SI), which are based on meters and kilograms. In other cases, we have assumed that readers will be able to convert fairly easily between the two systems with the aid of Appendix A. Astronomers still disagree significantly on the distance scale of the Universe, parametrized by the Hubble constant H_0 . We often indicate explicitly the resulting uncertainties in luminosity, distance, etc., but we otherwise adopt $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Where ages are required or we venture across a substantial fraction of the cosmos, we use the benchmark cosmology with $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

We will use an equals sign ($=$) for mathematical equality, or for measured quantities known to greater accuracy than a few percent; approximate equality (\approx) usually implies a precision of 10%–20%, while \sim (pronounced 'twiddles') means that the relation holds to no better than about a factor of two. Logarithms are to base 10, unless explicitly stated otherwise. Here, and generally in the professional literature, ranges of error are indicated by \pm symbols, or shown by horizontal or vertical bars in graphs. Following astronomical convention, these usually refer to 1σ error estimates calculated by assuming a Gaussian distribution (which is often rather a bad approximation to the true random errors). For those more accustomed to 2σ or 3σ error bars, this practice makes discrepancies between the results of different workers appear more significant than is in fact the case.

This book is much the better for the assistance, advice, and warnings of our colleagues and students. Eric Wilcots test flew a prototype in his undergraduate class; our colleagues Bob Bless, Johan Knapen, John Mathis, Lynn Matthews, and Alan Watson read through the text and helped us with their detailed comments; Bob Benjamin tried to set us right on the interstellar medium. We are particularly grateful to our many colleagues who took the time to provide us with figures or the material for figures; we identify them in the captions. Bruno Binggeli, Dap Hartmann, John Hibbard, Jonathan McDowell, Neill Reid, and Jerry Sellwood

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re-analyzed, re-ran, and re-plotted for us, Andrew Cole integrated stellar energy outputs, Evan Gnam did orbit calculations, and Peter Erwin helped us out with some huge and complex images. Wanda Ashman turned our scruffy sketches into line drawings. For the second edition, Bruno Binggeli made us an improved portrait of the Local Group, David Yu helped with some complex plots, and Tammy Smecker-Hane and Eric Jensen suggested helpful changes to the problems. Much thanks to all!

Linda Sparke is grateful to the University of Wisconsin for sabbatical leave in the 1996–7 and 2004–5 academic years, and to Terry Millar and the University of Wisconsin Graduate School, the Vilas Foundation, and the Wisconsin Alumni Research Foundation for financial support. She would also like to thank the directors, staff, and students of the Kapteyn Astronomical Institute (Groningen University, Netherlands), the Mount Stromlo and Siding Spring Observatories (Australian National University, Canberra), and the Isaac Newton Institute for Mathematical Sciences (Cambridge University, UK) and Yerkes Observatory (University of Chicago), for their hospitality while much of the first edition was written. She is equally grateful to the Dominion Astrophysical Observatory of Canada, the Max Planck Institute for Astrophysics in Garching, Germany, and the Observatories of the Carnegie Institute of Washington (Pasadena, California) for refuge as we prepared the second edition. We are both most grateful to our colleagues in Madison for putting up with us during the writing. Jay Gallagher also thanks his family for their patience and support for his work on ‘The Book’.

Both of us appear to lack whatever (strongly recessive?) genes enable accurate proofreading. We thank our many helpful readers for catching bugs in the first edition, which we listed on a website. We will do the same for this edition, and hope also to provide the diagrams in machine-readable form: please see links from our homepages, which are currently at www.astro.wisc.edu/~sparke and [~jsg](http://www.astro.wisc.edu/~jsg).