Introduction to Galaxy Formation and Evolution

Present-day elliptical, spiral and irregular galaxies are large systems made of stars, gas and dark matter. Their properties result from a variety of physical processes that have occurred during the nearly 14 billion years since the Big Bang.

This comprehensive textbook, which bridges the gap between introductory and specialised texts, explains the key physical processes of galaxy formation, from the cosmological recombination of primordial gas to the evolution of the different galaxies that we observe in the Universe today.

In a logical sequence, it introduces cosmology, illustrates the properties of galaxies in the present-day Universe, then explains the physical processes behind galaxy formation in the cosmological context, taking into account the most recent developments in this field. This text ends on how to find distant galaxies with multi-wavelength observations, and how to extract the physical and evolutionary properties of galaxies based on imaging and spectroscopic data.

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From Primordial Gas to Present-Day Galaxies

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Brief Contents

Contents

Preface

Why This Book?

The study of galaxy formation and evolution is one of the most active and fertile fields of modern astrophysics. It also covers a wide range of topics intimately connected with cosmology and with the evolution of the Universe as a whole. The key to decipher galaxy formation and evolution is to understand the complex physical processes driving the evolution of ordinary matter during its gravitational interplay with dark matter halos across cosmic time. The central theme is therefore how galaxies formed and developed their current properties starting from a diffuse distribution of gas in the primordial Universe. This research field requires major efforts in the observation of galaxies over a wide range of distances, and in the theoretical modelling of their formation and evolution. The synergy between observations and theory is therefore essential to shed light on how galaxies formed and evolved. In the last decades, both observational and theoretical studies have undergone rapid developments. The availability of new telescopes operating from the ground and from space across the entire electromagnetic spectrum opened a new window on distant galaxies. At the same time, major observational campaigns, such as the Sloan Digital Sky Survey, provided huge samples of galaxies in the present-day Universe with unprecedented statistics and allowed one to define the 'zero-point' for evolutionary studies. In parallel, the theoretical models experienced a major advance thanks to the improved performance of numerical simulations of galaxy formation within the cosmological framework.

The idea for this book originated from the difficulties we faced when teaching our courses. We lacked a single and complete Master-level student textbook on how galaxies formed and evolved. This textbook aims to fill a gap between highly specialised and very introductory books on these topics, and enables students to easily find the required information in a single place, without having to consult many sources.

The aim of the book is twofold. The first is to provide an introductory, but complete, description of the key physical processes that are important in galaxy formation and evolution, from the primordial to the present-day Universe. The second is to illustrate what physical and evolutionary information can be derived using multi-wavelength observations. As the research field of galaxy formation and evolution is relatively young and rapidly evolving, we do not attempt to give a complete review of all topics, but rather we try to focus on only the most solid results.

Readership and Organisation

This textbook assumes a background in general physics at the Bachelor level, as well as in introductory astronomy, fundamentals of radiative processes in astrophysics, stellar evolution and the fundamentals of hydrodynamics. Although this book is primarily

intended for students at Master degree level, it can be used as a complement to Bachelor-level courses in extragalactic astrophysics, and we think it can also be a valuable guide to PhD students and researchers.

The content of the chapters is organised as follows. After a general introduction to the field of galaxy formation and evolution (Chapter 1), the book starts with a brief overview on the cosmological framework in which galaxies are placed (Chapter 2). The aim of this chapter is to provide the reader with the key information useful for the rest of the textbook: the Big Bang model, the expansion of the Universe, redshift, the look-back time, the cosmological parameters and the matter–energy cosmic budget. Then, the book continues with a set of four chapters dedicated to the properties of present-day galaxies seen as the endpoint of the evolution that has occurred during the time frame spanned by the age of the Universe (≈13.8 billion years). In particular, Chapter 3 illustrates the statistical properties of galaxies (e.g. morphologies, sizes, luminosities, masses, colours, spectra) and includes a description of active galactic nuclei. The structure, components and physical processes of star-forming and early-type galaxies are presented in Chapter 4 and Chapter 5, respectively. Chapter 4 includes also a description of our own Galaxy seen as a reference benchmark when studying the physics of star-forming galaxies from the 'inside' and with a level of detail not reachable in external galaxies. Chapter 6 deals with the influence of the environment on galaxy properties, and with the spatial distribution of galaxies on large scales. Then, Chapter 7 focuses on the general properties of dark matter halos, and their hierarchical assembly across cosmic time: these halos are crucial because they constitute the skeleton where galaxy formation takes place. Chapter 8 deals with the main 'ingredients' of galaxy formation theory through the description of the key physical processes determining the evolution of baryons within dark matter halos (e.g. gas cooling and heating, star formation, chemical evolution, feedback processes). The subsequent Chapter 9 is dedicated to the evolution of primordial baryonic matter in the early Universe, from the cosmological recombination to the formation of the first luminous objects a few hundred million years after the Big Bang, and the consequent epoch of reionisation. Chapter 10 provides a general description of the theoretical models of the formation and evolution of different types of galaxies, including an introduction to the main methods of numerical modelling of galaxy formation. Finally, Chapter 11 presents a general overview of galaxy evolution based on the direct observation of distant galaxies and their comparison with present-day galaxy types.

References

As of writing this book, there are tens of thousands of refereed papers in the literature on galaxy formation and galaxy evolution; not to mention several books on galaxies and cosmology available on the market. This implies that choosing the most significant references for a book like this is really challenging. The difficulty is exacerbated by the very fast evolution of this research field. For these reasons, our choice has been pragmatic and minimalistic. We excluded references before 1900, and we decided to reduce as much as possible the citations to research articles (including our own papers), unless they present a major discovery or a turning point for a given topic, or they are particularly useful for students. Instead, we much preferred to cite recent review articles because they provide an

introductory and as much as possible unbiased source of information that is more suitable for students. However, also in this case, it was not feasible to cite all the reviews available in the literature. In the same spirit, the figures selected from the literature were chosen based on their clarity and usefulness to students. Finally, we also suggested a few books where readers can find more details on several topics treated in this textbook. The obvious consequence is that the reference list is unavoidably incomplete. We apologise to any author whose publications may have been overlooked with the selection approach that we adopted.

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This book has benefited from the input of colleagues and students who have helped us in a variety of different and crucial ways. Many of the figures in this book have been produced *ad hoc* for us. We are grateful to the authors of these figures, to whom we give credit in the captions. Here we also wish to explicitly thank our colleagues who have taken the time to read parts of the text, and/or gave us comments and advice that were fundamental to improve the quality of the book. These are: Lucia Armillotta, Ivan Baldry, Matthias Bartelmann, James Binney, Fabrizio Bonoli, Fabio Bresolin, Volker Bromm, Marcella Brusa, Luca Ciotti, Peter Coles, Romeel Davé, Gabriella De Lucia, Mark Dickinson, Enrico Di Teodoro, Elena D'Onghia, Stefano Ettori, Benoit Famaey, Annette Ferguson, Daniele Galli, Roberto Gilli, Amina Helmi, Giuliano Iorio, Peter Johansson, Inga Kamp, Amanda Karakas, Rob Kennicutt, Dusan Kereš, Leon Koopmans, Mark Krumholz, Federico Lelli, Andrea Macciò, Mordecai Mac Low, Pavel Mancera Piña, Antonino Marasco, Claudia Maraston, Federico Marinacci, Davide Massari, Juan Carlos Muñoz-Mateos, Kyle Oman, Tom Oosterloo, Max Pettini, Gabriele Pezzulli, Anastasia Ponomareva, Lorenzo Posti, Mary Putman, Sofia Randich, Alvio Renzini, Donatella Romano, Alessandro Romeo, Renzo Sancisi, Joop Schaye, Ralph Schönrich, Mattia Sormani, Eline Tolstoy, Scott Tremaine, Tommaso Treu, Mark Voit, Marta Volonteri, Jabran Zahid, Gianni Zamorani and Manuela Zoccali.