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# The First Galaxies in the Universe

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*To our families*

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## Preface

This book captures the latest exciting developments concerning one of the most fascinating unsolved mysteries about our origins: *how did the first stars and galaxies form?* This era, known as the *Cosmic Dawn* because these sources were the first to illuminate our Universe, assumes central importance in our understanding of the history of the Universe. Most research on this question has been theoretical so far. But the next decade or two will bring about a new generation of large telescopes with unprecedented sensitivity that promise to supply a flood of data about the infant Universe during its first billion years after the Big Bang. Among the new observatories are the James Webb Space Telescope (JWST) – the successor to the Hubble Space Telescope, and three extremely large telescopes on the ground (ranging from 24 to 42 meters in diameter), as well as several new arrays of dipole antennae operating at low radio frequencies. The fresh data on the first galaxies and the diffuse gas in between them will test existing theoretical ideas about the formation and radiative effects of the first galaxies, and might even reveal new physics that has not yet been anticipated. This emerging interface between theory and observation will constitute an ideal opportunity for students considering a research career in astrophysics or cosmology. With this in mind, the book is intended to provide a self-contained introduction to research on the first galaxies at a technical level appropriate for a graduate student.

The book is organized into three parts that largely build upon each other. The first part, *Fundamentals of Structure Formation*, includes chapters on basic cosmology, linear perturbation theory, nonlinear structure formation, and the intergalactic medium. This provides a broad introduction to studies of cosmological structure and galaxy formation with applications well beyond the first galaxies themselves. The first three chapters provide a crucial introduction to the rest of the book; the fourth (on the intergalactic medium) is not essential for many of the later chapters but is important for understanding the reionization process as well as many of the most important observational probes of the Cosmic Dawn.

The second part, *The First Structures*, focuses on the physics driving the formation of these objects, as well as the physics that determines their influence on subsequent generations of objects. We review the formation of the first stars and black holes, the importance of stellar feedback, the basic principles of galaxy evolution, and the epoch of reionization. Many of the principles contained here also have wide application to other areas of extragalactic astrophysics, though we focus on their application to the first galaxies. The first two chapters in this part build upon each other, but the others can be approached largely independently.

The third part, *Observations of the Cosmic Dawn*, describes several directions in

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which we hope to observe the most distant galaxies in the coming decades. This part begins with a discussion of galaxy surveys and then moves on to two unique probes of this era: the Lyman- $\alpha$  and 21 cm lines of neutral hydrogen. It concludes with brief discussions of several other techniques. The chapters in this section are largely independent of each other and may be read in any order.

We have also included several appendices. Appendix A and Appendix B provide useful lists of primary sources for further reading. Throughout the text, we reference seminal papers as well as some recent calculations with endnotes; these are collected in Appendix A. In Appendix B, we list useful overviews in the form of books and review papers. In Appendix C, we include fundamental constants and conversion factors. Finally, in Appendix D we summarize the cosmological parameters assumed in this book (see also §1.4).

Note that, both for the sake of brevity and because the current cosmological measurements are reasonably secure, most of the equations do not explicitly state their dependence on such factors as the baryon density, Hubble constant, or cold dark matter density. Inserting these dependencies is a useful exercise, and we encourage the interested readers to check their understanding in this way.

Various introductory sections of this book are based on an undergraduate-level book, entitled “How Did the First Stars and Galaxies Form?” by one of us (A.L.), which followed a cosmology class that he had taught over the past two decades in the Astronomy and Physics departments at Harvard University. Other parts relate to overviews that both of us wrote over the past decade in the form of review articles. Where necessary, selected references are given to advanced papers and other review articles in the scientific literature.

The writing of this book was made possible thanks to the help we received from many individuals. First and foremost, we are grateful to our families for their support and patience during the lengthy writing period of the book. Needless to say, the content of this book echoes many papers and scientific discussions we had over the years with our students, postdocs, and senior collaborators, including Dan Babich, Rennan Barkana, Jon Bittner, Laura Blecha, Judd Bowman, Frank Briggs, Avery Broderick, Volker Bromm, Chris Carilli, Renyue Cen, Benedetta Ciardi, T.J. Cox, Mark Dijkstra, Daniel Eisenstein, Claude-André Faucher-Giguère, Richard Ellis, Idan Ginsburg, Zoltan Haiman, Lars Hernquist, Jackie Hewitt, Loren Hoffman, Bence Kocsis, Girish Kulkarni, Adam Lidz, Andrei Mesinger, Matt McQuinn, Joey Muñoz, Ramesh Narayan, Peng Oh, Ryan O’Leary, Rosalba Perna, Tony Pan, Ue-Li Pen, Jonathan Pritchard, Fred Rasio, Martin Rees, Doug Rubin, George Rybicki, Athena Stacy, Dan Stark, Yue Shen, Nick Stone, Anne Thoul, Hy Trac, Eli Visbal, Stuart Wyithe and Matias Zaldarriaga. We did not attempt to provide a comprehensive reference list of the related literature, since such a list would be out of date within a few years in this rapidly evolving frontier. Instead we focused pedagogically on the underlying physical principles that will remain relevant in the future, and referred the reader to representative papers, review articles, and books for further reading. We thank Nina Zonnevylle and Uma Mirani for their assistance in obtaining permissions for the figures of the book, Fred Davies, Lauren Holzbauer, Joey Muñoz and Ramesh Narayan for their help with several figures, and Natalie Mashian, Doug Rubin, and Anjali Tripathi for their comments on the



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–A. L. & S. F.