The First Galaxies

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Editors

The First Galaxies

Theoretical Predictions and Observational Clues

Springer

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Cover illustration: The cover image is a montage of a simulated JWST image of the Hubble Ultra Deep Field, showing distant galaxies as JWST may see them in the near-infrared, some of the ALMA antennas present on the Chajnantor in 2012 (image credit: Babak Tafreshi), and an image of the James Webb Space Telescope. The simulated Hubble Utra Deep Field was made by deconvolving the original HST near-infrared image with the corresponding point-spread function, and then convolving with the expected JWST point-spread function. This process brings out finer details in the image compared with what can be seen in the original, but does not add new features that were too faint to be seen with the HST but that will be visible with JWST.

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Preface

About 300,000 years after the big bang, at a redshift of $z \sim 1,100$, the Universe entered the Dark Ages. At this time the primordial gas had cooled enough to become neutral, but possessed a very smooth density distribution. This is evident in images of the cosmic microwave background, showing density fluctuations only of the order 1/100,000. In this smooth and rapidly expanding primordial gas, no structures capable of producing ionizing photons were present or even close to being formed. Fast-forward 700 million years, to a redshift of $z \sim 7$, and the Universe is close to fully ionized, with stars, galaxies, and even supermassive black holes present. Through dedicated studies, using the latest space- and ground-based facilities, we can now investigate the physics of the primordial gas at the very start of the Dark Ages. We can also study the properties of galaxies and quasars as they emerge towards the end of the re-ionization epoch. Very little, however, is known about the processes taking place during the 700 million years in between. This is the epoch where the first stars form, the first metals are produced, and the first generation of galaxies and supermassive black holes are assembled. Detailed understanding of the history of the Universe during this time is amongst the most outstanding questions in modern astrophysics and cosmology.

There have been significant efforts from both theoretical and observational sides to learn more about the physical processes taking place during the Dark Ages. Nevertheless, as we push the observational boundaries to higher redshifts and further back in cosmic history, we have yet to find a primordial star or galaxy, as predicted by theoretical models and simulations. Observing objects this close to the Dark Ages has proved to be very difficult, requiring new instruments and larger telescopes. This is a very active field of observational research, on which the design of future generations of ground- and space-based observatories is focused. A related and equally challenging problem that needs explaining from both an observational and theoretical perspective is the presence of supermassive black holes at the end of the re-ionization epoch. However, the emergence of primordial galaxies and the first supermassive black holes may very well be intrinsically linked, as revealed by the detection of dust and metals in quasars at the very highest redshifts. In the end, the properties of the first galaxies as well as the first supermassive black holes are likely to be shaped in large part by the very first generation of stars.

While observers often strive to find the most distant galaxies in order to learn about the early Universe, we now know that there exist stars in our Milky Way halo and in some of our satellite dwarf galaxies that are old enough to have formed during the first few hundred million years of the age of the Universe, possibly in the epoch of Dark Ages. These stars offer a unique probe of the physical conditions that prevailed when they were formed. With the aid of new sensitive detectors and large telescopes, high-resolution spectroscopy of these systems has just become possible. This is the emerging science of astro-archaeology, done in our own backyard.

Despite significant recent progress on both the theoretical and observational fronts, there are many questions that remain unanswered. In fact, how do we even define the first galaxies? Can we simulate the conditions in the early Universe and learn about star and galaxy formation through theory? What came first, the supermassive black holes that we know existed when the Universe was only a few hundred million years old, or the galaxies that host them? We know that some of the early quasars contain large amounts of dust and metals produced in stellar processes, suggesting a close connection between stars and black holes.

Of equal importance to the observations of distant galaxies is the interpretation of the data. Due to large distances and highly redshifted light, as well as the weakness of the absorption lines in ultra-metal-poor stars in our own backyard, observations are difficult to obtain and are often not as complete as we would wish. A high redshift means that the ultraviolet and optical light, which is the part of the electromagnetic spectrum where stars emit most of their energy, is shifted to infrared wavelengths. For the most part, it is impossible to obtain spectra of large samples of high redshift galaxies and we have to rely on broadband photometry and comparison with synthetic spectra. By combining the light output from a set of stars with different ages, different metallicities and with a specified star formation history, possibly adding some dust extinction, it is possible to model how the spectral energy is distributed as a function of wavelength. This can then be compared with observations and, depending on how well the synthetic template fits the broadband observations, we can deduce various properties of the distant galaxies. This process, on which a large part of our current knowledge about the most distant objects rely, has pitfalls and contains assumptions that may or may not be justified. It is therefore important to critically discuss how we extract information from the observational data in order to understand how much credence should be given to the results.

These and many similar questions are dissected in this book: *The First Galaxies: Theoretical Predictions and Observational Clues*. Here we bring together observers, theorists as well as experts on stellar population modeling and astro-archaeology for a discussion of where we stand today in terms of observations and theory, and what can be learned in the near future as new and evermore sensitive observational facilities become available. The aim of this book is to use observations to challenge current theories and use theories to direct future observations. The book grew out of a Joint Discussion at the XXVIIth General Assembly of the International Astronomical Union in Rio de Janeiro in 2009, where leading experts assembled to give the current status of this research field. This book is not a summary of this meeting, but rather a comprehensive exposition of the underlying concepts, principles, and techniques.

The research concerning the first galaxies and the early Universe is progressing rapidly and new advances can be found in the literature every week, with new instruments planned to tackle these problems rapidly becoming available. Because of this rapid advance of the field, the authors were tasked with not just summarizing where we stand today but also projecting which direction the research in the various areas is likely to take in the future. In addition, the authors describe the tools and techniques that are being used (or will be used) to pursue this research. The aim is to make the book a resource for graduate students wanting to acquire the technical background as well as being exposed to the forefront research. We believe this book will be a valuable resource for the next generation of astrophysicists and for anyone interested to learn about this research area and quickly become acquainted with the state-of-the-art research.

The book is divided into three main themes:

1. **The First Sources of Light:** What are the sources of the very first light in the Universe? How was the Universe re-ionized and when did this happen? This part also gives an overview of the theoretical framework for understanding this epoch of cosmic history as well as explores the potential for observing the primordial hydrogen gas as it is becoming ionized.
2. **The First Galaxies and Normal Stellar Populations:** Here a critical review is presented of the observational and theoretical modeling that are currently providing us with data on the first normal galaxies and supermassive black holes as they emerge from the Dark Ages. The galaxies and their content as we see them 700 million years after the big bang appear to be quite mature in terms of development, hence the term "normal," but what are the properties of these galaxies, their stellar and gaseous content? What clues do they hold regarding processes taking place in the Dark Ages?
3. **Tools & Techniques:** This theme describes how astronomers use the techniques of stellar archaeology and fitting synthetic spectral energy distributions to broadband photometric data to extract information on the early Universe. This part also contains a chapter on the potential of future facilities to observe the first galaxies.

The coming decade promises to be a very exciting one, most likely allowing us to answer one of the fundamental questions: *What are our cosmic origins?* Most major discoveries leading to paradigm shifts have not been predicted beforehand. It is therefore very likely that serendipity will play a crucial role in our quest for understanding how the first stars, galaxies and supermassive black holes formed and what role they played in re-ionizing the Universe. It is thus important to equip oneself with a comprehensive set of tools, such as the material covered in this book. After all, there is wisdom to the old adage that fortune favors the prepared mind.

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