1
Introduction

1.1
First Light and Reionization

The emergence of the first sources of light in the Universe and the subsequent reionization of hydrogen mark the end of the ‘Dark Ages’ in cosmic history, a period characterized by the absence of discrete sources of light. Despite its remote timeline, this epoch is currently under intense theoretical investigation and is beginning to be probed observationally.

There are various reasons why studying this epoch is important. The first reason is that the reionization of hydrogen is a global phase transition affecting the range of viable masses for galaxies. Before reionization small galaxies will be shielded by neutral hydrogen fromionizing UV radiation and therefore will be able to form moreeasily. After reionization and the establishment of a UV backgroundthe formation of very small galaxies is hampered [70, 77, 219] (these issues will be discussed in Chapters 3 and 5).

The second reason to study this epoch is that it makes it possible to probe the power spectrum of density fluctuations emerging from recombination at scales smaller than are accessible by current cosmic microwave background experiments (this can be done by different techniques, as discussed in Chapters 2 and 5).

Finally, in a Universe where structures grow hierarchically, the first sources of light act as seeds for the subsequent formation of larger objects. Thus, the third reason to study this period is that by doing so we may learn about processes relevant to the formation of the nuclei of present-day giant galaxies and perhaps on the connection between the growth of black holes and evolution of their host galaxies (these issues will be briefly touched upon in Chapter 3).

Once established, the importance of studying The End of the Dark Ages one might wonder how realistic it is to expect to be able to understand anything about something so remote and different from the conditions in the local Universe and with so few observational constraints when, e.g., star formation in our own galaxy is not yet fully understood. The practitioners of this field are confident that two facts make the formation of structures in the Dark Ages easier to study theoretically than similar processes occurring at other epochs:

From First Light to Reionization. Massimo Stiavelli

ISBN: 978-3-527-40705-7

Tab. 1.1 Adopted cosmological parameters.

H_0	70 km s^{-1} Mpc^{-1}	
Ω_m	0.26	including Ω_b
Ω_Λ	0.74	
Ω_b	0.045	
Y	0.26	He fraction by mass
$T_{\mathrm{CMB},0}$	2.728 K	present-day CMB temperature
σ_8	0.75	CDM power spectrum normalization

1. the formation of the first structures is directly linked to the growth of linear perturbations,

   and

2. these objects have a known – and extremely low – metallicity set by the end-product of the primordial nucleosynthesis.

Thus, our chances of success depend on our confidence in understanding the initial conditions and on the absence of many additional physical processes that are at play in the local Universe such as magnetic fields or torques generating angular momentum. For the same reasons we should expect our success at predicting the properties of following generations of objects to be less secure.

1.2
The Cosmological Framework

We adopt the standard cosmological framework of the Hot Big Bang theory and the values of the cosmological parameters derived from the WMAP concordance model [251] and shown in Table 1.1. In general, all numerical results will be derived for these cosmological parameters but we will on occasion discuss how different values of the cosmological parameters would impact the result.

The most critical of these cosmological assumptions is that dark matter is in the form of cold dark matter (CDM) as this guarantees a significant amplitude of the low-mass perturbations at very early epochs. Should dark matter be, e.g., in the form of warm dark matter, e.g., ~1 keV neutrinos, the low-mass power spectrum would be suppressed and the scenario for first light stars would be entirely different from the one discussed here (see brief discussion in Chapter 2).

1.3
Organization of this Book

This subject as well as the rest of cosmology or, more generally, physics is based on the interplay of theory and observations. One could imagine starting from an overview of the observational results and then moving on to their theoretical interpretation. I believe that such an approach would lead to many repetitions as several modern observational results can only be understood within a rather sophisticated theoretical framework. Thus, I have chosen the opposite approach of starting with theory. Students reading this book should not be led to believe that the logical structure that I have adopted has any resemblance to the actual historical development of the discipline. In reality, progress in this field (and elsewhere) is always made by multiple iterations of theory and observations. Each new observational results spawns several theoretical efforts, some of which are confirmed by follow up observations while some are falsified. The surviving theories of today are robust because they have undergone multiple cycles of 'natural' selection! The study of the Dark Ages has not yet undergone a full cycle of confrontation with observations. Thus, the level of reliability of any specific result and conclusion is not as high as that of the basic ideas and physical processes.

This book is structured into two parts. The first part is focused on all theoretical aspects of the formation of the first light sources and of the reionization of hydrogen. Whenever possible I have tried to use analytical arguments to highlight the physical processes at play, to derive approximate analytical results and to draw conclusions on their basis. However, in modern cosmology we have come to rely on numerical simulations for many detailed predictions or interpretation of data and I have described the results of simulation whenever necessary. As computing power continues to improve, increasingly more complex simulations with a more ambitious description of the physics and more elaborate algorithms become possible. Thus, one would expect that the results of present-day state-of-the-art simulations might be superseded or amended in the next few years. I hope that the basic physical insight derived from the analytical results will remain valid.

The second part of the book is dedicated to observational techniques and to present and future observations. We are now able to probe the evolution of the luminosity function of galaxies to redshift 6 and beyond. This allows us to begin probing the end of the Dark Ages. Future facilities will open up major new possibilities in this subject. Among them, I will devote particular attention to the James Webb Space Telescope, once dubbed 'The First Light Machine' and to the experiments, such as LOFAR, aimed at studying the reionization process through its signature in the neutral-hydrogen background.

The subject of this book is specialistic and it would be hard or impossible to propose exercises in the classical sense. However, I have added to many chapters a section containing suggestions for indepth study or calculations that are relevant to the subject matter and would increase the understanding of the subject by the reader. Often, there will be more than one way to complete these calculations but generally what is more interesting is the calculation itself and the related uncertainties than the numerical result.

The book also includes an appendix where some of the equations used in the main text are derived and discussed in more detail.

1.4

Key Observations in this Field

The main observables available to probe first light and reionization will be discussed in detail in the second part of the book, however, a quick overview may be useful to set the stage for the theory section.

Direct detection of Population III objects and of the first galaxies will be very challenging and it will be attempted by future deep imaging survey using techniques now in use at lower redshift, like the Lyman-break technique. Individual Population III stars could be detected most easily as supernovae and establishing the frequency of such objects is a crucial parameter affecting the feasibility of such surveys. Early objects may leave a signature in the backgrounds that could either be detected directly or through a fluctuation analysis (see Section 6.7). Detecting this signature may be simpler than detecting individual objects.

Polarization measurements with a microwave background experiment like WMAP enable us to constrain the Thompson optical depth (see (2.13) and Chapter 4) which is essentially a density-weighted number of free electrons along the line of sight. We can also probe directly the presence of neutral hydrogen by using the Gunn–Peterson trough [103] and the properties of Lyman α emitters. The Gunn–Peterson trough is essentially resonant Lyman α absorption of the UV continuum of distant objects for wavelengths below that of Lyman α. While diffuse neutral hydrogen present within some redshift interval will scatter the continuum, local hydrogen can scatter line emission and provide a somewhat complementary test to the Gunn–Peterson test. As we will see in Chapter 5, Gunn–Peterson trough constraints from distant quasars indicate that hydrogen is reionized at $z < 6$. Finally, a new promising area is that of 21-cm studies aiming at probing the distribution of neutral hydrogen at high redshift through detection of the 21-cm line emission or, in the most ambitious cases, of 21-cm line absorption over the cosmic microwave background (see Chapter 5).