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Report

Re-ionisation Phase of the Universe

Submitted by

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Chapter 1

Abstract

This abstract provides an overview of the re-ionization phase, highlighting its significance, mechanisms, observational evidence, and current research. The formation of the first stars and galaxies initiated the transition, with their energetic photons ionizing the neutral hydrogen, resulting in a fully ionized Inter-Galactic Medium (IGM). The process involved ultraviolet radiation, supernovae, and supermassive black holes.

The re-ionization phase of the universe represents a crucial transition from a neutral to an ionized state of the intergalactic medium (IGM). It occurred after approximately 380,000 to 400,000 years post-Big Bang, lasting several hundred million years. The first luminous sources, such as early galaxies and quasars, emitted intense ultraviolet radiation, ionizing the surrounding hydrogen gas.

Understanding re-ionization is vital for comprehending the early universe's evolution, structure formation, and galaxy origins. Observations like the cosmic microwave background (CMB) radiation, Lyman-alpha forest, and Gunn-Peterson trough provide valuable insights. Challenges include limited observational data, necessitating indirect probes and statistical techniques. Future telescopes like JWST and SKA promise to unveil more details.

Current research focuses on refining theoretical models, studying high-redshift galaxies and quasars, and investigating feedback processes' role in re-ionization. Collaboration among cosmologists, astrophysicists, and theorists is crucial due to the complex interplay between processes and the intergalactic environment.

In conclusion, the re-ionization phase is a captivating topic in cosmology, with ongoing advancements in observations, models, and simulations revealing insights into the early universe's evolution and cosmic structure formation.

Keywords: cosmology, re-ionization, galaxy formation, first stars

Chapter 2

Introduction

2.1 Before Re-ionisation Phase

The universe goes through several phase transitions during its formative stages. Cosmic re-ionization is the last of them, where ultraviolet and X-ray radiation escape from the first generations of galaxies heating and ionizing their surroundings and subsequently the entire intergalactic medium (Wise, 2019).

Before the epoch of re-ionization, the universe entered a fascinating and relatively unexplored period known as the "pre-reionization" or "pre-recombination" era. This era extends from the time of the Big Bang to approximately 380,000 years after, when recombination occurred and the first neutral atoms formed. It is an epoch of immense interest to cosmologists as it encompasses the very early stages of cosmic evolution and the formation of the building blocks that led to the structure and composition of the universe as we know it today.

In the earliest moments after the Big Bang, the universe was a hot and dense "soup" of particles, primarily consisting of photons, protons, electrons, and small amounts of other elementary particles. At such extreme temperatures, the energies of particles were high enough to prevent stable atoms from forming. Instead, the universe was a plasma, where particles constantly collided and interacted.

During the first few minutes after the Big Bang, a process called nucleosynthesis took place. Protons and neutrons combined to form the nuclei of light elements such as hydrogen and helium. The abundance of these primordial elements provides critical clues about the conditions of the early universe. After nucleosynthesis, the universe rapidly expanded and cooled, allowing electrons to bind with nuclei and form atoms.

Approximately 380,000 years after the Big Bang, the universe reached a critical temperature of around 3,000 Kelvin, marking the onset of recombination. At this point, the density of photons decreased enough for electrons to combine with protons, forming neutral hydrogen atoms. The release of these free electrons led to the decoupling of photons from matter, resulting in the escape of the CMB radiation. The CMB is a relic radiation that permeates the universe, providing a snapshot of the universe at that time.

In the era of pre-reionization, the universe consisted mainly of neutral hydrogen gas and trace amounts of other elements. It was a time when the universe was relatively dark and devoid of significant light-emitting sources. This lack of ionizing radiation allowed neutral atoms to dominate the intergalactic medium (IGM), and the universe appeared opaque to photons with energies below the ionization threshold of hydrogen.

During this era, the universe underwent gravitational collapse and the formation of the first structures. Density fluctuations, imprinted during the inflationary period, grew due to the attractive force of gravity. Overdense regions gradually collapsed, leading to the formation of protogalaxies, dark matter halos, and the first generation of stars (Barkana & Loeb, 2001).

One of the most critical processes that occurred during the era of pre-reionization was the formation of the first stars, often referred to as Population III stars. These stars were born from the primordial gas composed primarily of hydrogen and helium, with trace amounts of lithium and other light elements. Due to the absence of metals (elements heavier than helium), the physics of these stars differed significantly from subsequent generations.

Population III stars were massive and short-lived, with masses possibly exceeding hundreds of times that of the Sun. They formed in regions of high-density fluctuations within dark matter halos and initiated a cascade of events that shaped the subsequent evolution of the universe. The radiation from these stars played a crucial role in the subsequent process of re-ionization, marking a transition from the dark ages to the epoch of re-ionization (Yoshida et al., 2003).

In conclusion, the pre-reionization era represents a pivotal chapter in the cosmic history, encompassing the formation of the universe's basic structure and the birth of the first stars. While challenging to study directly, ongoing theoretical advancements, simulations, and indirect observational probes continue to deepen our understanding of this intriguing epoch, offering insights into the early evolution and fundamental processes that shaped our universe.

2.1.1 The Dark Ages

During the earliest cosmic epochs, characterized by exceedingly high redshifts, the fabric of the universe displayed an extraordinary level of homogeneity, while the temperatures of matter and radiation steadily declined in tandem with the expansion of space. It was at a redshift of $z \approx 1100$ when the universe reached a pivotal turning point : atoms materialized as the temperature plummeted to a remarkably low value of around 3000 K, instigating the recombination of the once-ionized plasma. This pivotal epoch, known as the recombination era, ushered in a profound transformation, whereby the cosmic landscape became suffused with the ethereal glow of the Cosmic Microwave Background (CMB), imbuing the universe with a captivatingly uniform and resplendent aura of blackbody radiation. As the relentless march of cosmic time progressed, the temperature continued its descent, leading to the gradual transition of the CMB into the realm of infrared wavelengths. This transformative shift rendered the universe seemingly devoid of discernible light, casting it into an enigmatic darkness that would persist until the emergence of the first generation of stars. The significance of this interval, known as the Dark Age of the universe, is unveiled through meticulous observations, which provide us with details regarding the state of the cosmos during the last scattering of the CMB at a redshift of approximately $z \approx 1100$, as well as the subsequent detection of galaxies and quasars up to redshifts as high as 6.5. While theoretical predictions indicate that the formation of the earliest stars and galaxies likely transpired much earlier, the advancement of technology and the detection of increasingly faint celestial objects beckon us toward the potential discovery of galaxies at progressively higher redshifts. However, as we venture beyond a redshift range of 10 to 20, the theoretical framework of Cold Dark Matter (CDM) with Gaussian fluctuations postulates a stark reality – the scarcity of dark matter halos capable of hosting luminous objects, even for low-mass halos, renders the discovery of any objects beyond a redshift of 20 exceedingly tough. Indeed, we approach the realm of the Dark Age, a period characterized by relative quiescence preceding the formation of cosmic structures, where the atomic gas remains primarily homogeneous, with only a minuscule fraction transitioning into the nascent molecules of H_2, HD, and LiH as the temperature progressively cools. Among the few proposed strategies for investigating this enigmatic epoch lies the prospect of detecting secondary anisotropies imprinted on the CMB by lithium atoms during their recombination at a redshift of approximately 400, manifesting through a resonance line at 670.8 nm that would now be redshifted to the far-infrared region, albeit challenging to observe owing to the foreground emission by cosmic dust.

2.1.2 Epoch of recombination

The epoch of recombination, a crucial phase in the evolution of the universe, marks the moment when the primordial plasma of ions and electrons transitioned into a predominantly neutral state. This pivotal event occurred approximately 380,000 years after the Big Bang, when the universe had expanded and cooled enough for atoms to form. During the early stages of the universe, the extreme heat and density prevented the formation of stable atoms. Instead, the cosmos was filled with a hot and ionized plasma composed primarily of protons, electrons, and photons. Photons were continually scattering off the free electrons, resulting in a cosmic fog that impeded the propagation of light. As the universe expanded, the temperature gradually decreased, eventually reaching a critical threshold of about 3000 Kelvin. At this point, a process known as recombination took place. Recombination involved the capture of free electrons by protons to form stable hydrogen atoms, which led to a sudden drop in the number of free electrons. The recombination process was driven by two main factors: the decreasing temperature and the decreasing density of the universe, both subject to the expansion of the space. As the universe expanded, the density of matter decreased, allowing the plasma to become more transparent. The decreasing temperature also played a crucial role by reducing the kinetic energy of the particles, enabling them to combine and form stable atoms. During recombination, the photons previously scattering off the free electrons were able to travel through space relatively unimpeded. This event allowed the universe to transition from an opaque plasma to a transparent gas. The photons that were released during recombination have since been stretched and redshifted due to the expansion of the universe, forming the Cosmic Microwave Background (CMB) radiation that permeates the cosmos.

2.2 The First Stars

The timing of the formation of the very first star in the universe is not a straightforward question, given the random nature of primordial density fluctuations. The collapse of a halo and the birth of a star depend on the rarity of the fluctuation considered. For instance, a 5% fluctuation in the density field could lead to the formation of a star at a redshift (z) of approximately 30.

To delve deeper, we can inquire about the moment when the light from this first star would have been observable from a random location in the universe. Since light travels through the past light-cone, the observer can survey a larger volume by looking farther away. However, this also means observing further back in time, necessitating a higher primordial density fluctuation for star formation. Assuming the observer detects just one collapsed halo with a virial temperature (T_{vir}) exceeding 2000 K on the past light-cone (in line with the Cold Dark Matter model), the appearance of the first star in the sky would occur at $z \approx 38$, when the universe was approximately 75 million years old. Remarkably, this star would have formed from a 6.3% density fluctuation, with an extremely low probability of only 3×10^{-10}. *The Virial Temperature (T_{vir}) is a measure of the characteristic temperature of a gravitationally bound system, such as a dark matter halo or a galaxy. It is defined as the temperature at which the kinetic energy of the particles within the system is equal to the gravitational potential energy, resulting in a state of equilibrium.*

As we expand our view, the ability to observe the earliest stars in the universe has improved significantly. By surveying a much larger volume than the observer at redshift, $z \approx 38$, we can now detect stars that formed at even higher redshifts. The highest redshift star observable in the sky is estimated to have formed from an 8% fluctuation at $z \approx 48$. Although current technology may not allow us to directly detect this faint initial star, the existence of brighter sources opens up possibilities for discovering more primitive objects beyond the most distant known galaxies at $z \approx 6.5$. It is worth considering that the presence of non-Gaussian primordial fluctuations on small scales could potentially lead to unexpected findings of objects at even higher redshifts. The most important effect that the formation of stars had on their environment is the reionization of the gas in the universe. Even though the baryonic matter combined into atoms at $z \approx 1100$, the intergalactic matter must have been reionized before the present. The evidence comes from observations of the spectra of quasars, more of which has been discussed in the next sections of this project.

2.3 Objectives

- To investigate the phenomenological evolution of the Universe from a cosmological lens, incorporating concepts from General Relativity.
- To understand the phase of Cosmic Re-ionisation, its observations and related challenges.

Chapter 3

Re-ionisation : Background Concepts and Observation

3.1 Concepts from Cosmology

Cosmology is the scientific exploration of the entire universe. Extensive surveys of galaxies on a large scale strongly suggest that the universe adheres to the Cosmological Principle, which asserts that the fundamental properties of the universe appear the same to all observers when observed at sufficiently large scales, exceeding 300 million parsecs. Essentially, when traveling through space, the overall structure of the universe would appear indistinguishable. At these immense scales, the universe exhibits both *isotropy* and *homogeneity*. Isotropy implies that there are no privileged directions within the universe; it appears uniform and identical in all directions. Homogeneity signifies a uniform density and an evenly distributed arrangement of galaxies, regardless of the observer's viewpoint.

An isotropic and homogeneous universe can be treated as one entity. One can use general relativity to describe its dynamics, starting with the (Friedmann-Lemaître-Robertson-Walker) FLRW space-time metric,

$$ds^2 = c^2dt^2 - a^2(t)\left(\frac{dr^2}{1 - Kr^2} + r^2 d\Omega^2\right) \tag{3.1}$$

Within this context, we define ds, dt, and dΩ as intervals characterizing space-time, time, and angle, respectively, whereas c symbolizes the speed of light, a fundamental constant. The variable *r* represents a spherical coordinate that describes a particular observer, emphasizing that it does not necessarily serve as a measure of distance between two observers. Furthermore, the constant K assumes distinct values (-1, 0, or +1), signifying the possible curvatures of space: negative curvature corresponding to *elliptical geometry*, zero curvature representing a *flat Euclidean geometry*, and positive curvature indicating a *hyperbolic geometry*.

The scale factor $a(t)$ represents the expansion of the universe, with the convention of setting $a = 1$ at the present day. In other words, when the universe was only half of its current size, $a = 1/2$. The scale factor is also associated with the cosmological redshift $z = 1/a - 1$, which serves as a common measure of distance and time in cosmology. A solution to the Friedmann-Lemaître-Robertson-Walker (FLRW) metric is given by the Friedmann equation:

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(t) = \frac{8\pi G}{3}\rho - \frac{Kc^2}{a^2} \tag{3.2}$$

"The Hubble parameter, denoted as $H(t)$, characterizes the rate of expansion (positive) or contraction (negative) of the universe. In 1927, Edwin Hubble made a groundbreaking discovery by observing that galaxies situated farther away exhibited higher recession velocities. This observation provided compelling evidence for the expansion of the universe. The present-day value, often represented as H_0, is typically expressed in units of $km * s^{-1} * Mpc^{-1}$, which serves as an indicator of the slope in the relationship between velocity and distance."

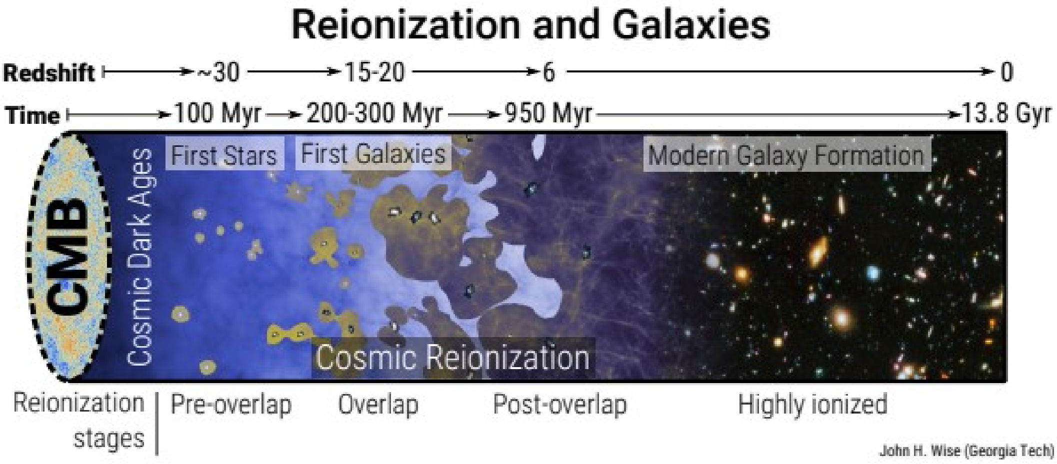

Figure 3.1: Cosmic timeline of the universe before (top) and after (bottom) recombination along with the stages of reionization. The galaxy survey image is taken from the Hubble Ultra Deep Field.

The total mass-energy density ρ of the universe encompasses diverse components, namely, non-relativistic (cold) matter (ρ_m), radiation (ρ_r), and vacuum energy (ρ_Λ). These components contribute to the evolution of the universe in distinct ways. Non-relativistic matter experiences geometric dilution as space expands, characterized by a scaling behavior of $\rho_m \propto a^{-3}$. Radiation, on the other hand, undergoes both geometric dilution and a softening effect caused by its frequency being cosmologically redshifted, with $\rho_r \propto a^{-4}$. Finally, the pervasive and uniform vacuum energy, often referred to as the cosmological constant or dark energy, is associated with a density scaling of $\rho_\Lambda \propto a^0$. This intricate interplay of mass-energy components contributes to the complex dynamics and evolution of the universe.

It proves beneficial to introduce the concept of the critical density, denoted as ρ_c, obtained by solving Equation 2 for ρ when setting K to zero. The critical density serves as the demarcation between an open universe, perpetually expanding, and a closed universe that ultimately collapses in on itself. Current constraints on the mass-energy components stem from various experiments and sources, such as the cosmic microwave background, supernovae, galaxy clusters, and large-scale structure. These observations have revealed that the universe is flat, with approximately 69%, composed of dark energy, 26% of cold dark matter (DM), and 5% of baryons, while a minute fraction 9.310^5 consists of radiation [13]. These percentages, denoted as $\Omega_i \equiv \rho_i/\rho_c$, are always presented in relation to the critical density, such that $\Omega_\Lambda, \Omega_c, \Omega_b$, and Ω_r approximate to $0.69, 0.26, 0.05, 9.3 \times 10^5$, respectively. Unless explicitly stated otherwise, these cosmological parameters are assumed throughout this article.

By integrating the Friedmann equation, the behavior of the scale factor, a, or equivalently, $(1+z)^{-1}$, can be determined. In a radiation-dominated universe, the scale factor is proportional to $t^{1/2}$, while in a flat matter-dominated universe (referred to as the Einstein-de Sitter or EdS universe), it scales as $t^{2/3}$. Conversely, in a vacuum-dominated universe, the scale factor exhibits exponential expansion. The most recent observational constraints indicate a flat universe with the presence of a cosmological constant ($\rho_\Lambda > 0$), hence the scale factor, $a(t)$, steadily increases with time, signifying an expanding and accelerating universe.

By understanding how the universe evolves over time, we can also gain insights into the mean temperature of the universe, assuming it is filled with a perfect fluid. Starting from a hot Big Bang, the universe undergoes several phase transitions, some of which are linked to the separation of the four fundamental forces – gravity, strong, weak, and electromagnetic. The formation of all large-scale structures is initiated by quantum fluctuations that exponentially expand during the inflationary epoch (around $t \sim 10^{-36} - 10^{-32}$ seconds after the Big Bang), eventually evolving into the galaxies depicted in the cosmic timeline illustrated in Figure 1.

Along this cosmic journey, a significant event occurred when the primordial gas transitioned from an ionized to a neutral state, commonly referred to as either recombination or the surface of last scattering. As the density of free electrons abruptly declined, photons became detached from matter and streamed away, giving rise to the cosmic microwave background (CMB).

After photons decouple, the universe enters a phase known as the "Dark Ages". During this time, the absence of stars or galaxies creates a dark and desolate environment. From this starless, neutral, and cold state, the universe gradually undergoes reionization as nascent galaxies and their constituents contribute to the illumination and transformation of the cosmos.

3.1.1 Ionisation and Re-combination

The radiation from the first luminous objects will ionize and heat the surrounding Intergalactic Medium (IGM) once it escapes from their host halos. These are known as cosmological H II regions. The ionization and recombination of hydrogen atoms ($H + \gamma \leftrightarrow H^{+} + e^{-}$) are dominant processes in H II regions. Ionizations occur when photons with energies $E > I_H = 13.6\,eV$ interact with neutral hydrogen atoms, where their excess energies are subsequently thermalized. Recombinations occur when the Coulomb force attracts protons and electrons, which becomes efficient at temperatures $T \leq 10^4\,K$. One recombination releases a photon with an energy that is the sum of the kinetic energy of the electron and the binding energy of the quantum state, I_H/n^2. If the electron recombines into an excited state ($n > 1$), the electron will quickly decay into the ground state in a series of transitions.

In a region with ionizing radiation, the gas approaches ionization balance with the recombination rate equaling the ionization rate. We can equate these two rates and solve for the ionization fraction $x_e \equiv n_e/n_H$ of the gas at equilibrium. Here n_e and n_H are the electron and hydrogen number density, respectively.

By equating the recombination and ionization rates, we can show that H II regions are highly ionized, having ionization fractions nearly equal to one and neutral hydrogen fractions around 10^{-4}. They are thus well described by a fully ionized plasma. The ionization flux, however, decreases as the distance squared from the star, resulting in the medium being the most ionized near radiation sources with it decreasing rapidly with increasing distance.

3.1.2 Large-Scale Structures of the Cosmos

On smaller scales, the universe exhibits a lack of isotropy and homogeneity. By observing our own Milky Way and other galaxies, it becomes evident that matter is distributed unevenly. In regions devoid of light pollution, one can witness the intricate arrangement of dense stellar fields stretching across the entire celestial expanse, interspersed with dark dust lanes. Our galaxy, in particular, is characterized by its clumpy nature and dynamic activity, featuring stellar clusters, cold molecular clouds, warm ionized regions, and remnants of explosive supernovae.

Moving to slightly larger scales, these "island universes" assemble into groups and clusters, comprising dozens to hundreds of galaxies, respectively. These cosmic structures are interconnected by extensive filaments, forming what is known as the cosmic web (refer to Figure 3.2). This intricate network encompasses all observable cosmic structures, including groups, clusters, superclusters, filaments, walls, and voids. When we zoom out to view hundreds of megaparsecs, the density of galaxies appears to approach uniformity, and the cosmic web exhibits repetitive patterns, hinting at the validity of the Cosmological Principle.

The cold dark matter (CDM) paradigm (refer to the next subsection) provides an excellent explanation for the formation of large-scale structures in the universe, accurately predicting galaxy number densities and their clustering. As dark matter comprises the majority of cosmic matter, it exerts significant gravitational influence on the dynamics of these structures. In CDM cosmology, the fundamental constituents are gravitationally collapsed dark matter halos, which have *decoupled* from the expanding universe. During halo collapse, equilibrium is achieved between the gravitational potential and the thermal and kinetic energies of the dark matter and gas. The spherically symmetric collapse of a halo in an expanding universe reveals that its mean density at the collapse time is $18\pi^2$ times the critical density, denoted as ρ_c. It is important to note that the density varies as a^{-3}, corresponding to $(1+z)^3$ due to cosmological effects. From a given halo mass M_h and the halo mean density $\rho_h = 18\rho_c(1+z)^3$, three essential halo properties can be derived.

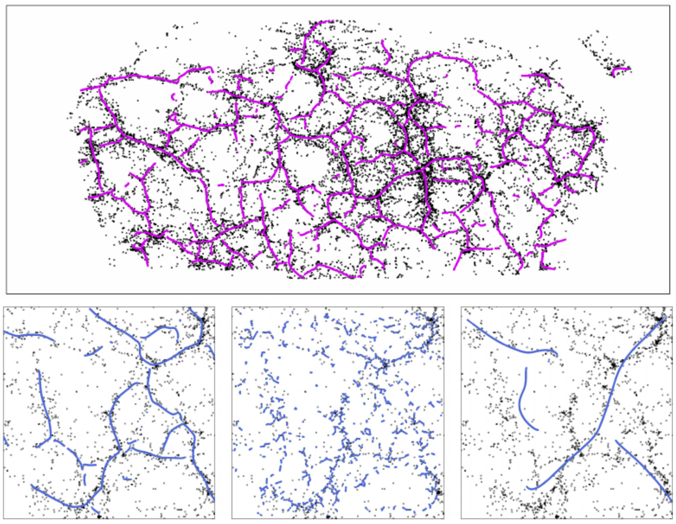

Figure 3.2: The Cosmic Web. This is a slice of the observed Universe from the Sloan Digital Sky Survey. We apply the density ridge method to detect filaments. The top row is one example for the detected filaments. The bottom row shows the effect of smoothing. Bottom-Left: optimal smoothing. Bottom-Middle: under-smoothing. Bottom-Right: over-smoothing. Under optimal smoothing, we detect an intricate filament network. If we under-smooth or over-smooth the dataset, we cannot find the structure.

- Halo Radius

$$r_h = \left(\frac{M_h}{\left(\frac{4\pi}{3}\right) \rho_h (1+z)^3} \right)^{1/3}$$

(3.3)

- Circular Velocity of the System

$$V_c = \sqrt{\frac{GM_h}{r_h}}$$

(3.4)

- Virial Temperature

$$T_{vir} = \frac{mV^2}{c^2 k_b}$$

(3.5)

3.1.3 H II Regions and their development

A radiation source can only provide a finite number of ionizing photons per second, limiting the possible ionizations in the surrounding region. Recombinations occur concurrently with ionizations in the highly ionized H II region majority of which is found in the Inter-Galactic Medium(IGM). The equilibrium state of the ionization front, known as the Stromgren radius (R_s), can be determined by balancing the total number of ionizations and recombinations. The Stromgren radius is larger for more luminous sources and lower-density ambient gas.

Figure 3.3 shows the evolution of an H II region from initial ignition to the final equilibrium state. The newborn star is surrounded by a dense medium, and the radiation front propagates through it at near-light speed, heating the region to over 10,000 K. As the gas expands, a shock wave sweeps up most of the material, leaving behind a more diffuse gas. The density and recombination rate decrease, causing the Stromgren radius to increase over time. Eventually, the H II region reaches pressure equilibrium with the ambient medium, and both the shock front and ionization front stall at the final Stromgren radius.

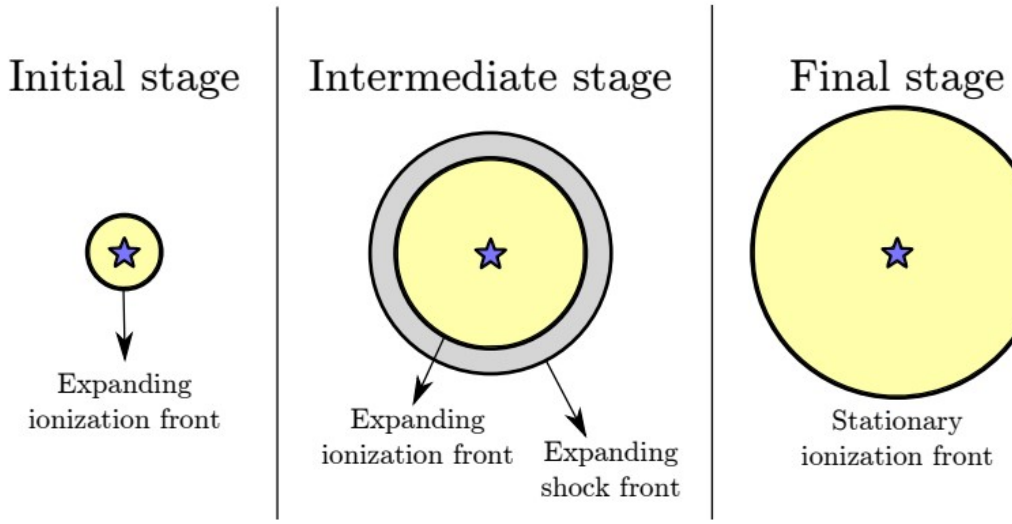

Figure 3.3: Three stages of H II region evolution. Left: Formation of a massive star leads to the creation of an H II region as its UV radiation ionizes and heats the nearby interstellar medium. Middle: Over time, the heated region expands and drives an outgoing shockwave, causing gas to be pushed away from the star. Right: The H II region reaches pressure equilibrium with the ambient medium, resulting in a stabilized state. *Source : J. Wise, 2019*

In the context of reionization, this scenario extends to galaxies, where ionizing radiation creates cosmological H II regions, playing a crucial role in the process of reionization.

3.1.4 Λ CDM Model

The Lambda Cold Dark Matter (ΛCDM) model, referred to in the last subsection, stands as the prevailing cosmological framework, offering a comprehensive depiction of the universe's structure and evolution. This intricate model encompasses crucial elements to account for the observed phenomena and dynamics on vast cosmic scales.

Foremost, the ΛCDM model incorporates the enigmatic concept of dark energy, symbolized by Λ, as a driving force behind the universe's accelerated expansion. Dark energy represents an elusive form of energy permeating all of space-time, ascribed to a constant energy density that endures throughout cosmic epochs. Its introduction stemmed from the need to reconcile observations of distant supernovae and the overall geometry of the universe.

Complementing dark energy, the ΛCDM model embraces the presence of cold dark matter (CDM), a form of non-baryonic matter that eludes electromagnetic interactions but exerts gravitational influence. The term "cold" denotes the comparatively sluggish movement of CDM particles, which exhibit velocities considerably below the cosmic speed limit. It is through the agency of CDM that the gravitational effects responsible for the formation of galaxies, galaxy clusters, and the intricate cosmic web are elucidated.

To elucidate the cosmic tapestry, the ΛCDM model relies on the principles of general relativity to explicate the behavior of gravity on cosmic scales. It further posits a period of rapid cosmic expansion known as cosmic inflation during the universe's early epochs. This inflationary phase bestows an elegant explanation for the uniformity observed in the cosmic microwave background radiation and the overarching homogeneity characterizing the universe on large scales.

Moreover, the ΛCDM model seamlessly integrates the tenets of the standard model of particle physics, serving as a touchstone for comprehending the behavior of fundamental particles and their interactions. By accounting for the known particles, including quarks, leptons, and gauge bosons, along with their electromagnetic, weak, and strong interactions, this model furnishes a framework for understanding the underlying fabric of the cosmos.

In totality, the Lambda Cold Dark Matter model encompasses an intricately interwoven tapestry that adeptly elucidates a vast array of cosmological observations. It successfully accounts for the cosmic mi-

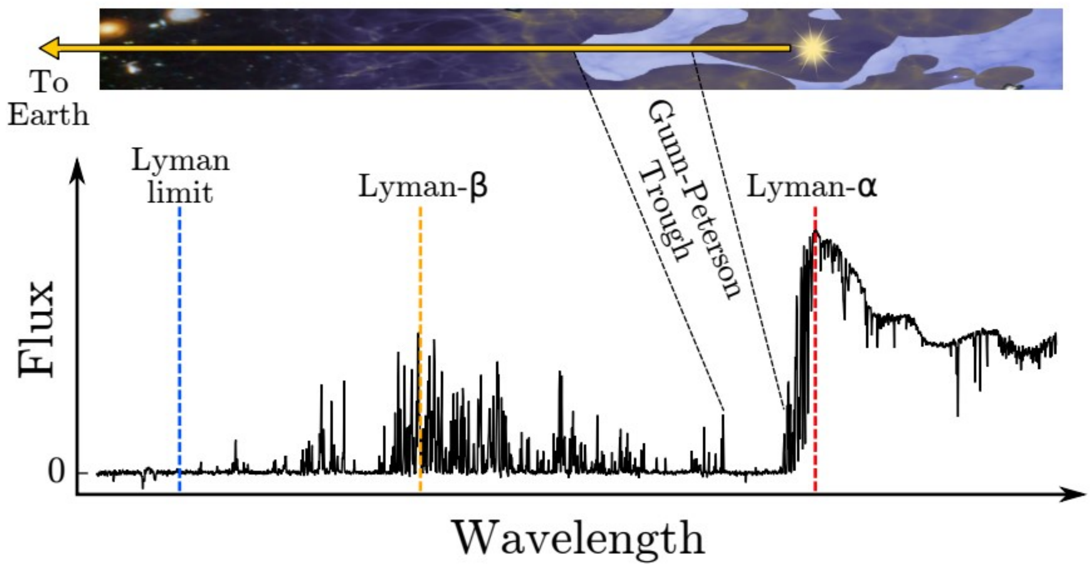

Figure 3.4: Light from distant quasars, powered by supermassive black holes, can probe the ionization and thermal state intergalactic medium. Overdense clumps of intergalactic gas absorb some fraction of light from the intrinsic spectrum (bottom) when the photons ionize any neutral hydrogen. Only lines in the Lyman series, down to the Lyman limit (912 A), with Ly α (1215 A) and Ly β (1026 A) being the strongest. Absorption lines from clouds at various redshifts create a Ly forest. When these lines becomes numerous enough, it creates a Gunn-Peterson trough that is indicative of an elevated neutral hydrogen fraction and the end of the Epoch of Reionization. *Source : J. Wise, 2019*

crowave background radiation, the intricate distribution and clustering of galaxies, the growth of cosmic structures, and the overarching dynamics and evolutionary trajectory of the universe at large.

3.2 Observational Evidence

Having delved into the fundamental principles of astrophysics and the theoretical underpinnings of re-ionization, we now embark on an exploration of cosmic re-ionization through the lens of key observations. A multitude of independent techniques offer valuable insights into this transformative era, enabling us to measure the ionization and thermal characteristics of the intergalactic medium (IGM) as well as the properties of galaxies emerging during the Epoch of Re-ionization (EoR). However, the inherent challenges arise from the vast distances traversed by photons from the farthest reaches of the observable universe to our terrestrial vantage point, necessitating lengthy exposure times and the utilization of large-scale telescopes. In the subsequent sections, we shall unravel the underlying physics governing each observational method, while also examining the latest empirical constraints that have furthered our understanding of this remarkable cosmic epoch.

3.2.1 Lyman α forest

The Lyman α forest encompasses a vast array of narrow absorption lines, arising from clouds within the intergalactic medium (IGM) situated between distant quasars and our observation point. Each cloud, existing at a specific redshift z, produces an absorption line at a wavelength of $1215(1+z)$ Å. As redshift increases, the abundance of these lines becomes more pronounced, providing valuable insights into clouds with column densities ranging from $\log(N_{HI}/cm^{-2}) = 12$ to 16. Eventually, their abundance becomes significant enough to obscure the background light, transforming into a characteristic *Gunn-Peterson trough* (see the next sub-section) at around $z \sim 6$. An illustrative spectrum in Figure 3.4 exhibits a dense Lyman α forest, exhibiting minimal transmission between Lyman α and Lyman β wavelengths (1026 Å).

Interestingly, this particular spectrum demonstrates increased transmission at shorter wavelengths, implying a higher degree of ionization as redshift decreases. An important constraint on the ionized fraction is the ”dark fraction” observed in QSO(Quasi-Stellar Objects) spectra within the Lyman α forest, indicating the presence of either neutral patches or residual neutral hydrogen in ionized regions. At a redshift of $z = 5.9$, the dark fraction in the Lyman α forest establishes a lower limit of $x_e > 0.94$, indicating a high degree of ionization.

The Lyman Alpha ($Ly\alpha$) forest is highly relevant to the context of the reionization phase of the cosmos. During the epoch of reionization, neutral hydrogen in the intergalactic medium (IGM) gets ionized by the intense radiation emitted from early galaxies and quasars. The $Ly\alpha$ forest provides valuable information about the neutral hydrogen distribution in the IGM during this epoch.

As the ionizing radiation passes through the IGM, it encounters clouds of neutral hydrogen, which manifest as absorption lines in the spectra of distant quasars. These absorption lines, known as the $Ly\alpha$ forest, contain information about the density, distribution, and ionization state of the neutral hydrogen gas in the early universe.

By studying the $Ly\alpha$ forest, astronomers can investigate the progression of re-ionization. The abundance and characteristics of the Ly forest absorption lines change with redshift, allowing us to trace the evolution of neutral hydrogen and the ionization state of the IGM over cosmic time.

The $Ly\alpha$ forest serves as a probe of the ionization history and the nature of ionizing sources during the re-ionization era. It helps constrain the timing, duration, and spatial variations of the re-ionization process, shedding light on the formation and evolution of the first galaxies, their radiation output, and the overall ionizing photon budget required for re-ionization.

In summary, the $Ly\alpha$ forest provides a powerful observational tool to study the reionization phase of the cosmos, offering insights into the interplay between ionizing sources, neutral hydrogen, and the evolving structure of the early universe.

3.2.2 Gunn-peterson Effect and trough

The Gunn-Peterson effect refers to the phenomenon observed in the spectra of distant quasars where a complete absorption of photons occurs at specific wavelengths corresponding to the Lyman-alpha transition of neutral hydrogen in the intergalactic medium (IGM). It provides evidence for the presence of neutral hydrogen and the epoch of re-ionization in the early universe.

According to the Gunn-Peterson effect, as light from a distant quasar passes through the IGM, the neutral hydrogen in the IGM absorbs the photons at the Lyman-alpha wavelength, resulting in a significant decrease in the observed flux at that wavelength.

This absorption occurs because the IGM is mostly neutral during the epoch of re-ionization. The neutral hydrogen in the IGM absorbs the high-energy photons emitted by the quasar, causing a region of complete absorption, known as a Gunn-Peterson trough, in the quasar’s spectrum at the Lyman-alpha wavelength.

The Gunn-Peterson trough (indicated in figure 3.4) refers to a significant absorption feature observed in the spectra of distant quasars at high redshifts. The trough appears as a region of near-zero transmission in the Lyman-alpha (Ly) forest, which is a series of absorption lines caused by neutral hydrogen gas in the intergalactic medium (IGM) along the line of sight between a distant quasar and an observer. The presence of a Gunn-Peterson trough in the spectrum of a distant quasar indicates that there was a significant amount of neutral hydrogen in the IGM during the epoch of reionization. Observations of the Gunn-Peterson effect help astronomers understand the process of reionization and the evolution of neutral hydrogen in the early universe.

3.2.3 Cosmic Microwave Background

While the absorption spectra of Quasi-Stellar Objects (QSOs) provide valuable insights into the later stages of cosmic reionization, an equally significant probe comes from the photons of the Cosmic Microwave Background (CMB) that embark on a remarkable journey from the surface of last scattering to reach Earth. During this voyage, these photons have the potential to undergo Thomson scattering with free electrons. This scattering process introduces polarization in the CMB at larger angular scales, which in turn is quantified by the Thomson scattering optical depth, denoted as $\tau_{\rm es}$. This integrated measure, although limited in revealing the intricate details of the reionization history, offers approximate indications of the timing of reionization. A completely ionized Inter-Galactic Medium (IGM) between redshifts $z = 0$ and $z = 6$ corresponds to a τ_{es} value of 0.039. The remaining portion of the integral (which is used to quantify the ultra-violet background (UVB) by the hydrogen ionisation rate)

$$\Gamma(z) = 4\pi \int_{\nu_{912}}^{\infty} J_\nu(z)\sigma_{\mathrm{HI}}(\nu)d\nu/h\nu$$

encompassing higher redshifts ($z > 6$), hinges upon the reionization history parameterized by $\bar{x}_{\mathrm{e}}(z)$, representing the average ionization fraction. Here σ_{HI} is the photoionization cross-section, J_ν is the specific intensity, and $\nu_{912} = 3.28 \times 10^{15}$ Hz is the frequency of the Lyman limit.

3.3 Conclusion

The following conclusions based on the study of re-ionisation so far:

- Cosmic reionization, the final phase transition in the cosmic timeline, concluded approximately one billion years after the Big Bang, supported by robust observational evidence. The pivotal role in this transformative process was played by the earliest generations of galaxies, which served as the fundamental building blocks for all subsequent galaxies. Understanding the epoch of reionization holds significant implications for theories of galaxy formation and cosmology.
- However, crucial questions remain regarding the precise timing, progression, nature, and the specific contributions of the primordial galaxies during this epoch. These inquiries are poised to be addressed through upcoming advancements, including the James Webb Space Telescope, ground-based 30-m class telescopes, and advancements in CMB and 21-cm experiments. These cutting-edge tools, expected to be operational within the next decade, promise to unveil new insights into the reionization era and the galaxies responsible for this transformative transition. By comprehensively studying both the reionized universe and the role of early galaxies, we can deepen our understanding of this formative period in cosmic history.

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References

[1] Cosmic Reionization (J. Wise, 2019)

[2] Topology of Reionisation times: concepts, measurements and comparisons to gaussian random field predictions (E. Thélie, D. Aubert, N. Gillet, J. Hiegel, and P. Ocvirk, 2023)

[3] Cosmic Dawn and Reionization: Astrophysics in the Final Frontier (Asantha Cooray, 2020.

[4] The Dark Age of the Universe (Jordi Miralda-Escude, 2003)

[5] Lyman-Alpha Forest: Features, Detection Scenarios and Simulations (Andi Tao, 2022)

[6] Observational constraints on key-parameters of cosmic reionisation history (A. Gorce, M. Douspis, N. Aghanim, and M. Langer, 2018)

[7] Distinguish the f(T) model from CDM model with Gravitational Wave observations (Yi Zhang, Hongsheng Zhang, 2021)

[8] Barkana R, Loeb A. In the beginning: the first sources of light and the reionization of the universe. Phys. Rep.. 2001 Jul;349:125–238.

[9] Hirano S, Hosokawa T, Yoshida N, et al. Primordial star formation under the influence of far ultraviolet radiation: 1540 cosmological haloes and the stellar mass distribution. MNRAS. 2015 Mar;448:568–587.