"Let there be Light": THE EMERGENCE OF STRUCTURE OUT OF THE DARK AGES IN THE EARLY UNIVERSE

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Summary

Cosmology is by now a mature experimental science. We are privileged to live at a time when the story of genesis (how the Universe started and developed) can be critically explored by direct observations. Looking deep into the Universe through powerful telescopes we can see images of the Universe when it was younger, because of the finite time it takes light to travel to us from distant sources.

Existing data sets include an image of the Universe when it was 0.4 million years old (in the form of the cosmic microwave background), as well as images of individual galaxies when the Universe was older than a billion years. But there is a serious challenge: in between these two epochs was a period when the Universe was dark, stars had not yet formed, and the cosmic microwave background no longer traced the distribution of matter. And this is precisely the most interesting period, when the primordial soup evolved into the rich zoo of objects we now see.

The observers are moving ahead along several fronts. The first involves the construction of large infrared telescopes on the ground and in space that will provide us with new photos of the first galaxies. Current plans include ground-based telescopes which are

24-42 meter in diameter, and NASA's successor to the Hubble Space Telescope, called the James Webb Space Telescope. In addition, several observational groups around the globe are constructing radio arrays that will be capable of mapping the three-dimensional distribution of cosmic hydrogen in the infant Universe. These arrays are aiming to detect the long-wavelength (redshifted 21-cm) radio emission from hydrogen atoms. The images from these antenna arrays will reveal how the non-uniform distribution of neutral hydrogen evolved with cosmic time and eventually was extinguished by the ultra-violet radiation from the first galaxies. Theoretical research has focused in recent years on predicting the expected signals for the above instruments and motivating these ambitious observational projects.

1. Introduction

1.1. Observing Our Past

When we look at our image reflected off a mirror at a distance of 1 meter, we see the way we looked 6.7 nanoseconds ago, the light travel time to the mirror and back. If the mirror is spaced $10^{19}\ \mathrm{cm} \simeq 3$ pc away, we will see the way we looked twenty one years ago. Light propagates at a finite speed, and so by observing distant regions, we are able to see what the Universe looked like in the past, a light travel time ago (Figure 1). The statistical homogeneity of the Universe on large scales guarantees that what we see far away is a fair statistical representation of the conditions that were present in our region of the Universe a long time ago.

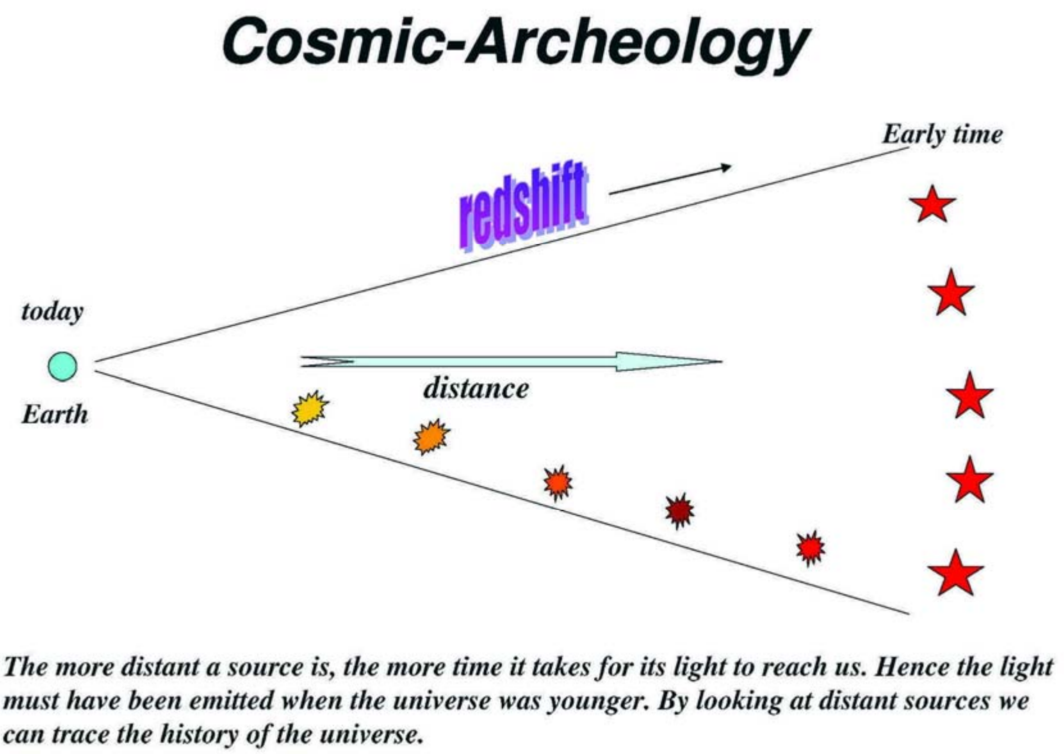

Figure 1. Cosmology is like archeology. The deeper one looks, the older is the layer that is revealed, owing to the finite propagation speed of light

This fortunate situation makes cosmology an empirical science. We do not need to guess how the Universe evolved. Using telescopes we can simply see how it appeared at earlier cosmic times. In principle, this allows the entire 13.7 billion year cosmic history of our universe to be reconstructed by surveying the galaxies and other sources of light to large distances (Figure 2). Since a greater distance means a fainter flux from a source of a fixed luminosity, the observation of the earliest sources of light requires the development of sensitive instruments and poses challenges to observers.

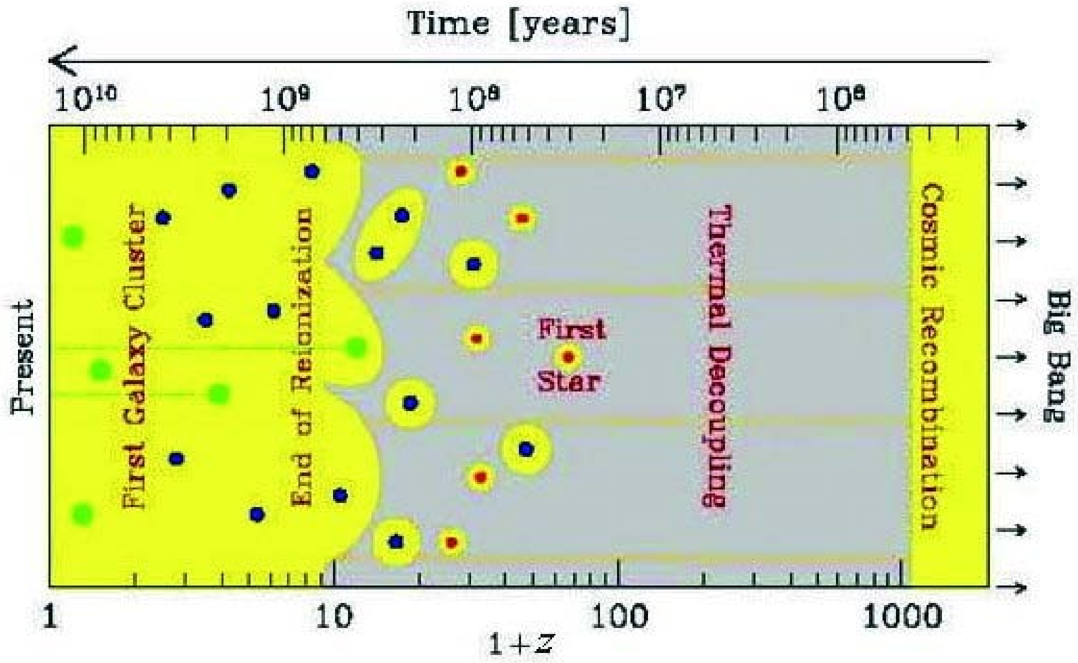

Figure 2. Overview of cosmic history, with the age of the universe shown on the top axis and the corresponding redshift on the bottom axis. Yellow represents regions where the hydrogen is ionized, and gray, neutral regions. Stars form in galaxies located within dark matter concentrations whose typical mass grows with time, starting with $\sim 10^5 M_\odot$ (red circles) for the host of the first star, rising to $10^7 - 10^9 M_\odot$ (blue circles) for the sources of reionization, and reaching $\sim 10^{12} M_\odot$ (green circles) for present-day galaxies like our own Milky Way. Astronomers probe the evolution of the cosmic gas using the absorption of background light (dotted lines) by atomic hydrogen along the line of sight. The classical technique uses absorption by the Lyman-α resonance of hydrogen of the light from bright quasars located within massive galaxies, while a new type of astronomical observation will use the 21-cm line of hydrogen with the cosmic microwave background as the background source

As the universe expands, photon wavelengths get stretched as well. The factor by which the observed wavelength is increased (i.e. shifted towards the red) relative to the emitted one is denoted by $(1+z)$, where z is the cosmological redshift. Astronomers use the known emission patterns of hydrogen and other chemical elements in the spectrum of each galaxy to measure z. This then implies that the universe has expanded by a factor of $(1+z)$ in linear dimension since the galaxy emitted the observed light, and cosmologists can calculate the corresponding distance and cosmic age for the source galaxy. Large telescopes have allowed astronomers to observe faint galaxies that are so far away that we see them more than twelve billion years back in time. Thus, we know directly that galaxies were in existence as early as 850 million years after the Big Bang, at a redshift of $z \sim 6.5$ or higher.

We can in principle image the Universe only if it is transparent. Earlier than $400\,000$ years after the big bang, the cosmic hydrogen was broken into its constituent electrons and protons (i.e. "ionized") and the Universe was opaque to scattering by the free electrons in the dense plasma. Thus, telescopes cannot be used to electromagnetically image the infant Universe at earlier times (or redshifts $>10^3$). The earliest possible image of the Universe was recorded by the COBE and WMAP satellites, which measured the temperature distribution of the cosmic microwave background (CMB) on the sky (Figure 3).

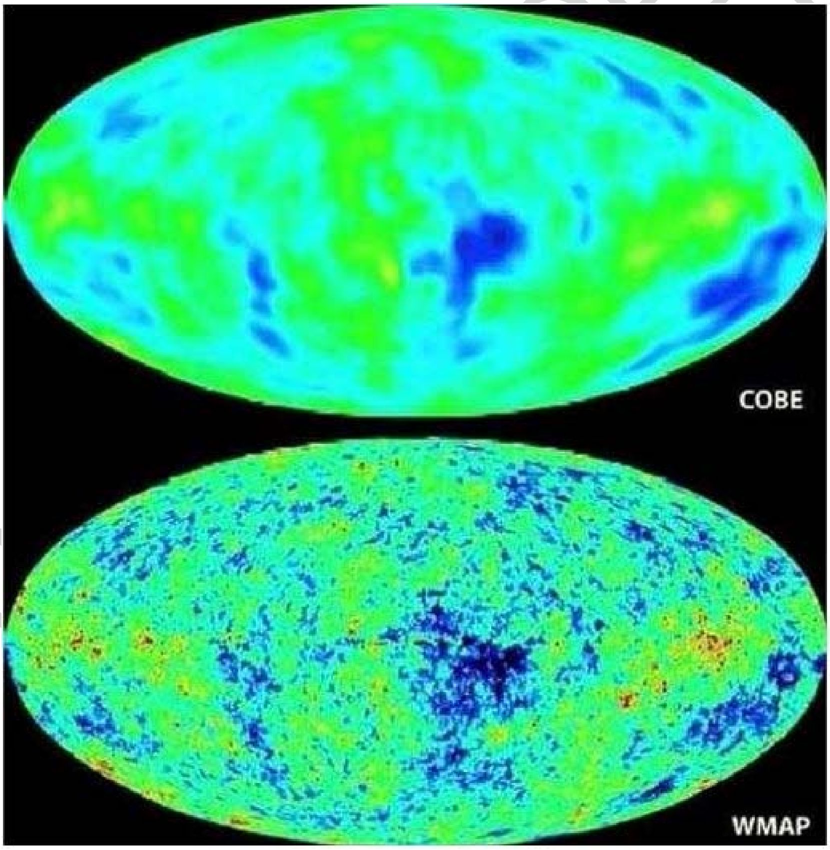

Figure 3. Images of the Universe shortly after it became transparent, taken by the *COBE* and *WMAP* satellites (see http://map.gsfc.nasa.gov/ for details). The slight density inhomogeneities in the otherwise uniform Universe imprinted a map of hot and cold spots (shown here as different colors) in the CMB that is observed today. The existence of these anisotropies was predicted three decades before the technology for taking these images became available, in a number of theoretical papers including Sachs & Wolfe (1967), Rees & Sciama (1968), Silk (1968), Sunyaev & Zeldovich (1970), and Peebles

& Yu (1970).

The CMB, the relic radiation from the hot, dense beginning of the universe, is indeed another major probe of observational cosmology. The universe cools as it expands, so it was initially far denser and hotter than it is today. For hundreds of thousands of years the cosmic gas consisted of plasma of free protons and electrons, and a slight mix of light nuclei, sustained by the intense thermal motion of these particles. Just like the plasma in our own Sun, the ancient cosmic plasma emitted and scattered a strong field of visible and ultraviolet photons. As mentioned above, about $400\,000$ years after the Big Bang the temperature of the universe dipped for the first time below a few thousand degrees Kelvin. The protons and electrons were now moving slowly enough that they could attract each other and form hydrogen atoms, in a process known as cosmic recombination. With the scattering of the energetic photons now much reduced, the photons continued traveling in straight lines, mostly undisturbed except that cosmic expansion has redshifted their wavelength into the microwave regime today. The emission temperature of the observed spectrum of these CMB photons is the same in all directions to one part in $100\,000$ (Figure 3), which reveals that conditions were nearly uniform in the early universe.

It was just before the moment of cosmic recombination (when matter started to dominate in energy density over radiation) that gravity started to amplify the tiny fluctuations in temperature and density observed in the CMB data. Regions that started out slightly denser than average began to contract because the gravitational forces were also slightly stronger than average in these regions. Eventually, after hundreds of millions of years of contraction, the overdense regions stopped expanding, turned around, and eventually collapsed to make bound objects such as galaxies. The gas within these collapsed objects cooled and fragmented into stars. This process, however, would have taken too long to explain the abundance of galaxies today, if it involved only the observed cosmic gas. Instead, gravity is strongly enhanced by the presence of dark matter – an unknown substance that makes up the vast majority (83%) of the cosmic density of matter. The motion of stars and gas around the centers of nearby galaxies indicates that each is surrounded by an extended mass of dark matter, and so dynamically-relaxed dark matter concentrations are generally referred to as "halos".

According to the standard cosmological model, the dark matter is cold (abbreviated as CDM), i.e., it behaves as a collection of collisionless particles that started out at matter domination with negligible thermal velocities and have evolved exclusively under gravitational forces. The model explains how both individual galaxies and the large-scale patterns in their distribution originated from the small initial density fluctuations. On the largest scales, observations of the present galaxy distribution have indeed found the same statistical patterns as seen in the CMB, enhanced as expected by billions of years of gravitational evolution. On smaller scales, the model describes how regions that were denser than average collapsed due to their enhanced gravity and eventually formed gravitationally-bound halos, first on small spatial scales and later on larger ones. In this hierarchical model of galaxy formation, the small galaxies formed first and then merged or accreted gas to form larger galaxies. At each snapshot of this cosmic evolution, the abundance of collapsed halos, whose masses are dominated by dark matter, can be computed from the initial conditions using numerical simulations. The common understanding of galaxy formation is based on the notion that stars formed out of the gas that cooled and subsequently condensed to high densities in the cores of some of these halos.

Gravity thus explains how some gas is pulled into the deep potential wells within dark matter halos and forms the galaxies. One might naively expect that the gas outside halos would remain mostly undisturbed. However, observations show that it has not remained neutral (i.e., in atomic form) but was largely ionized by the UV radiation emitted by the galaxies. The diffuse gas pervading the space outside and between galaxies is referred to as the intergalactic medium (IGM). For the first hundreds of millions of years after cosmological recombination, the so-called cosmic "dark ages", the universe was filled with diffuse atomic hydrogen. As soon as galaxies formed, they started to ionize diffuse hydrogen in their vicinity. Within less than a billion years, most of the IGM was re-ionized. We have not yet imaged the cosmic dark ages before the first galaxies had formed. One of the frontiers in current cosmological studies aims to study the cosmic epoch of reionization and the first generation of galaxies that triggered it.

1.2. The Expanding Universe

The modern physical description of the Universe as a whole can be traced back to Einstein, who assumed for simplicity the so-called "cosmological principle": that the distribution of matter and energy is homogeneous and isotropic on the largest scales. Today isotropy is well established for the distribution of faint radio sources, optically-selected galaxies, the X-ray background, and most importantly the cosmic microwave background (hereafter, CMB). The constraints on homogeneity are less strict, but a cosmological model in which the Universe is isotropic but significantly inhomogeneous in spherical shells around our special location, is also excluded.

In General Relativity, the metric for a space which is spatially homogeneous and isotropic is the Friedman-Robertson-Walker metric, which can be written in the form

$$ds^2 = c^2 dt^2 - a^2(t)\left[\frac{dR^2}{1-kR^2} + R^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right], \qquad (1)$$

where c is the speed of light, $a(t)$ is the cosmic scale factor which describes expansion in time t, and (R,θ,ϕ) are spherical comoving coordinates. The constant k determines the geometry of the metric; it is positive in a closed Universe, zero in a flat Universe, and negative in an open Universe. Observers at rest remain at rest, at fixed (R,θ,ϕ), with their physical separation increasing with time in proportion to $a(t)$. A given observer sees a nearby observer at physical distance D receding at the Hubble velocity $H(t)D$, where the Hubble constant at time t is $H(t) = d\,a(t)/dt$. Light emitted by a source at time t is observed at $t=0$ with a redshift $z = 1/a(t) - 1$, where we set $a(t=0) \equiv 1$ for convenience.

The Einstein field equations of General Relativity yield the Friedman equation

$$H^2(t) = \frac{8\pi G}{3}\rho - \frac{k}{a^2}, \qquad (2)$$

which relates the expansion of the Universe to its matter-energy content. The constant k determines the geometry of the universe; it is positive in a closed universe, zero in a flat universe, and negative in an open universe. For each component of the energy density ρ, with an equation of state $p = p(\rho)$, the density ρ varies with $a(t)$ according to the thermodynamic relation

$$d(\rho c^2 R^3) = -p d(R^3). \qquad (3)$$

With the critical density

$$\rho_C(t) \equiv \frac{3H^2(t)}{8\pi G} \qquad (4)$$

defined as the density needed for $k = 0$, we define the ratio of the total density to the critical density as

$$\Omega \equiv \frac{\rho}{\rho_C}. \qquad (5)$$

With Ω_m, Ω_Λ and Ω_r denoting the present contributions to Ω from matter (including cold dark matter as well as a contribution Ω_b from ordinary matter ["baryons"] made of protons and neutrons), vacuum density (cosmological constant), and radiation, respectively, the Friedman equation becomes

$$\frac{H(t)}{H_0} = \left[\frac{\Omega_m}{a^3} + \Omega_\Lambda + \frac{\Omega_r}{a^4} + \frac{\Omega_k}{a^2}\right], \qquad (6)$$

where we define H_0 and $\Omega_0 = \Omega_m + \Omega_\Lambda + \Omega_r$ to be the present values of H and Ω, respectively, and we let

$$\Omega_k \equiv -\frac{k}{H_0^2} = 1 - \Omega_m. \qquad (7)$$

In the particularly simple Einstein-de Sitter model ($\Omega_m = 1, \Omega_\Lambda = \Omega_r = \Omega_k = 0$), the scale factor varies as $a(t) \propto t^{2/3}$. Even models with non-zero Ω_Λ or Ω_k approach the Einstein-de Sitter scaling-law at high redshift, i.e. when $(1+z) \gg |\Omega_m^{-1} - 1|$ (as long as Ω_r can be neglected). In this high-z regime the age of the Universe is

$$t \approx \frac{2}{3H_0\sqrt{\Omega_m}}(1+z)^{-3/2} \approx 10^9\,\mathrm{yr}\left(\frac{1+z}{7}\right)^{-3/2}. \quad (8)$$

Recent observations confine the standard set of cosmological parameters to a relatively narrow range. In particular, we seem to live in a universe dominated by a cosmological constant (Λ) and cold dark matter, or in short a ΛCDM cosmology (with Ω_k so small that it is usually assumed to equal zero) with an approximately scale-invariant primordial power spectrum of density fluctuations, i.e., $n \approx 1$ where the initial power spectrum is $P(k) = |\delta_\mathbf{k}|^2 \propto k^n$ in terms of the wavenumber k of the Fourier modes $\delta_\mathbf{k}$ (see §1 below). Also, the Hubble constant today is written as $H_0 = 100h\,\mathrm{km\,s^{-1}Mpc^{-1}}$ in terms of h, and the overall normalization of the power spectrum is specified in terms of σ_8, the root-mean-square amplitude of mass fluctuations in spheres of radius $8h^{-1}$ Mpc. For example, the best-fit cosmological parameters matching the WMAP data together with large-scale gravitational lensing observations are $\sigma_8 = 0.826$, $n = 0.953$, $h = 0.687$, $\Omega_m = 0.299$, $\Omega_\Lambda = 0.701$ and $\Omega_b = 0.0478$.

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Biographical Sketch

Abraham (Avi) Loeb is a theoretical physicist working on astrophysics and cosmology. He is currently a professor of astronomy and the director of the Institute for Theory and Computation (ITC) at Harvard University. Loeb was born in Israel in 1962 and took part in the national Talpiot program before receiving a BSc, MSc, and PhD degrees (in Plasma Physics) at age 24 from the Hebrew University in Jerusalem.

Between 1988-1993, he was long-term member at the Institute for Advanced Study in Princeton, where he started to work in theoretical astrophysics. In 1993 he moved to Harvard University as an assistant professor in the department of astronomy, where he was tenured three years later. He was given a number of awards including the Guggenheim Fellowship in 2002. He also holds a visiting professorship at the Weizmann Institute of Science. He is broadly regarded as an authority on studies of the first stars and of supermassive black holes in galaxies. His published work includes nearly 300 papers in refereed journals, as well as a book and a patent.

Prof. Loeb has worked on broad range of research areas in astrophysics and cosmology, including the first stars, the epoch of reionization, the formation and evolution of massive black holes, gravitational lensing, gamma-ray bursts, and 21-cm cosmology. Some of his papers are considered as pioneering in areas that have become by now the focus of established communities of astrophysicists. In particular, Loeb was among the first theorists to trigger the current research on the first stars and quasars. In a series of papers with his students and postdocs, he addressed how and when the first stars and black holes formed and what effects they had on the young universe. In 2006 Prof. Loeb was featured in a cover story of TIME magazine on the first stars and in a Scientific American article on the dark ages of the Universe. In 2008 Prof. Loeb was featured in a cover story of Smithsonian magazine on black holes and in a cover story of Astronomy magazine on the future collision between the Milky-Way and Andromeda. In 2010 Loeb wrote a new book, entitled "How Did the First Stars and Galaxies Form?", published by Princeton University Press (http://press.princeton.edu/titles/9373.html). The book provides a comprehensive description of the topic covered here, at a level suitable for a non-specialist.