Dean&Francis

ISSN 2959-6157

Cosmic Evolutionary Dynamics: Tracing the Universe's Development

Zhengcheng Zhang

School of Physics and Astronomy, Sun Yat-Sen University, Zhuhai, China

Corresponding author: zhangzhch26@mail2.sysu.edu.cn

Abstract:

The universe emerged from a singularity and, after the Big Bang, inflated and expanded into a more complicated stage when the dark matter and the dark energy formed structures, the epoch of recombination. After that, the universe became even more complex since the diminutive cosmic structures built up, gradually forming the very first star and consequently the first galaxy, the large-scale structures through galaxies clustering. This paper briefly introduces the process of cosmic evolution, from the very start of the entire universe to the web-like universe that we observe today, traces the universe's development by concentrating on several observational evidence that support or improve the cosmological models, and introduces some observational instruments, including the James Webb Space Telescope and the Vera C. Rubin Observatory, and global projects like Square Kilometer Array, which may greatly propel the observational and theoretical cosmology in the future.

Keywords: cosmic evolution; universe's development; cosmic observation.

1. Introduction

Cosmic evolution refers to the gradual development of the universe from its earliest state following the Big Bang[1] to its current structure, which includes galaxies, stars, and planetary systems. Understanding cosmic evolution is vital for gaining insights into the rudimentary processes that govern the universe, such as the formation of matter, dark matter, dark energy, and large-scale structures like galaxies and galaxy clusters, which helps us trace how the universe has transitioned through various phases, from the dense and hot singularity of the early universe to the more structured, complex and cooler state that we can see in the dark night. With the fundamental Big Bang Theory and the concept of the dark matter and dark energy, key events like the inflationary period, cosmic microwave background radiation, and star formation epochs, such as the epoch of reionization, provide critical information for improving models of the universe development: from its past, present to the future. Studying cosmic evolution also helps address some of the most profound questions in cosmology, including the nature of dark matter and dark energy, the candidates for potential mankind intergalatic immigration and the ultimate fate of the universe. It is a field that integrates knowledge from various branches of physics, including general relativity, quantum mechanics[2], and thermodynamics, to explain the large-scale structure and behavior of the universe over billions of years.

This paper aims to explore the dynamics of cosmic evolution, which involves fathoming the mechanisms behind the expansion of the universe, the formation and evolution of galaxies and stars, and the role of dark matter and dark energy in shaping cosmic structures. What's more, the paper tries to trace key developmental stages of the universe, mainly by studying the phases such as the Big Bang, nucleosynthesis, recombination, and galaxy formation to trace the timeline of the cosmic evolution and the transitions between its major developmental stages, coming up with several observational results and significant instruments, for instance, the evolution of galaxies at a wide range of redshift over a specific epoch and James Webb Space Telescope.

2. Theoretical Framework

2.1 Big Bang Theory

Big bang theory, the most compelling and widely accepted theory to describe the cosmic evolutionary dynamics, claims that the whole universe began from a fierce explosion of singularity, a point that the density and temperature is infinitely high. In an extremely small amount of time, the density and temperature of universe dropped precipitously, while nucleosynthesis happened and generated several light elements [1]. This expansion led to an abundance of elements and formed the primordial universe at 15 billion years ago. In the perspective of quantum cosmology, universe emerged from a quantum era, containing fluctuations, large-scale correlations and homogeneity properties since all these spatially separated regions own a common quantum origin [2] based on the inflationary theory.

2.2 Cosmic Inflation

Since the big bang occurred, the universe history had been through a period of rapid and exponential expansion. Einstein's field equation describes the whole universe with a homogeneous and isotropic picture, and Friedmann presented the solutions to this cosmological model based on the general relativity as well as the cosmology principle. These two equations provide an insight to the expansion of the universe in a quantitative way by introducing a scale factor $a(t)$ and the Hubble constant. Through simultaneous equations, it reveals that the acceleration of the expansion is relevant to the mass distribution in the universe [3]. Fully comprehending the processes in the rapid expansion helps astronomers solve a series of issues including the horizon problem, the flatness problem, and monopole problem, providing a basic framework for understanding the dark matter and dark energy. The quantum fluctuations within this expansion were the bedrock of the large-scale observable structure what we probe today.

2.3 Structure Formation

In order to explain the discrepancies between theoretical predictions and observed phenomena that the universe seemed to be expanding in an accelerating rate, astronomers introduced dark matter(DM) and dark energy into the framework of structure formation, which may approximately compose 27% and 68% of the whole cosmos. We can refer from their names that it is extremely arduous to directly detect dark matter and dark energy since they fail to reflect, radiate as well as absorb light, and only known intereaction is through gravity. The leading theroies assume that the DM decoulped from photons quite earlier than the baryons, thus providing more time to grow its pertubation for a collapse of the baryonic fluctuations during the epoch of recombination , and utimately begetting strcture formation[4].

3. Key Stages of Cosmic Development

3.1 Recombination and the Cosmic Microwave

As mentioned above, the epoch of recombination is a process when the protons were ready to capture free electrons and form atomic hydrogen after the universe cooled down sufficiently. Consequently, the density of free electrons dropped, resulting in the decoupling of radiation and matter since the opaque universe turned transparent to light, giving birth to the cosmic background radiation which has traveled almost unperturbed until today, found peaked in microwave region of the spectrum[5]. Thus, it's called cosmic microwave background(CMB) and was discovered at an antenna temperature of 3K, revealing that the early universe at high redshifts was hot and desne, considering $T=T0(1+z)$, where z is the redshift, $T0= 2.726 \pm 0.010$ K(Mather et al., 1994) is the temperature nowadays, T is the temperature of primordial universe.

3.2 Formation of the First Stars and Galaxies

As einstein speculated in the cosmological principle, the CMB validates that the universe is indeed smooth on the large scale. However, it presents inhomogeneity on the small scale from stars to galaxies and other abundant cosmic structures. Then what leads to the formation of the very first stars? It's presently accepted that these meatl-free stars had formed due to the density fluctuations. To

ISSN 2959-6157

be specific, they formed from the gravitational collapse of dense regions within the dark matter halos instead of a gas of primordial composition[6]. When primordial gas condenses within dark matter wells, emiting copious radiation, it forms the first galaxies which are minute and irregular but luminous.

3.3 Galaxy Clustering and Large-Scale Structures

Since the first galaxies have formed, countless initial structures formed, following a hierarchical pattern: small clumps merged to form larger structures. It causes the clumps take the form of an intersecting sheet and filament, which are isolated by some immense empty regions called voids, containing very few galaxies and matter, like a web. Thus, to picture the entire universe on the large scale figuratively, such kind of foam-like structure is called cosmic web[7]. As the universe continues to evolve, the cosmic web devolpes into a complex network of filaments with dense strands of dark matter and galaxies, connecting massive galaxy clusters like nodes when the galaxies inside the web evolve and increase the universe prosperity. The expansion of universe begets the voids grow larger so that the cosmic web become more pronounced, buliding up the web-like appearance what we observe today.

4. Observational Evidence

4.1 Techniques and Instruments

In order to verify their hypotheses and further comprehend the evolution of the universe, scientists had launched several space telescopes for detection since 1990s. For instance, the Hubble Space Telescope(HST), a low earth orbit telescope running perfectly for 34years, with sensitive instruments which enable it to view star-forming galaxies in distant early universe, covers a broad wavelength from infrared to ultraviolet, and it has conducted over 1.6 million observations up to now. Besides Hubble, the James Webb Space Telescope(JWST), launched in 2021, is consequential to the astronomical observations. Utilizing ultra-deep near-infrared surveys of the universe, and following up with mid-infrared photometry and low-resolution spectroscopy, JWST aims to learn about reionization where neutral hydrogen was reionized by radiation from the first massive stars[8]. Additionally, it helps compare the earliest galaxies to today's ellipticals as well as understand how galaxies assemble over billions of years, through its marvellous capability to see through thick dust. These indispensable telescopes are able to obtain observational data easily and precisely, thus greatly propel the validation of evolution models.

4.2 Key Observations

JWST not only probed elements in the early universe for the first time but also measured the Hubble constant at a , by observing Type Ia supernovae and Cepheid variable stars via Cosmic Distance Ladder, indicating that the universe is expanding at a faster rate than previously predicted. Futhermore, HST's observations revealed the existence of large-scale structure, including galaxy clusters and superclusters as well as the CMB, which defends the evolution models, while JWST is excepted to push these results to a higher precision. Through JWST's observations, astonomers are able to consolidate the cosmic evolution models with series of data, such as the explanation for the issue that some very young galaxies in the early universe evolved into something similar to their adjacent relatively late galaxies[9]; classification for the structral and morphological evolution of multitidunous galaxies at a wide range of redshift: $1.5 < z < 6.5$, illustrating how galaxy structure has developed over a specific epoch[10]. Besides, by manipulating the deep-field surveys, JWST may even unveil the fisrt star, once obscure, in the early universe if it successfully probes the explosion of the fisrt supernovae, which can provide some precious information about the fisrt generation of stars[11], thus enabling the scientists to push their verification and modification of the cosmic evolution models further.

5.Results

5.1 Insights into Early Universe

It has been tested that the gravitational lensing of CMB correlated with the large-scale sturctures by analyzing the several tracers of large-scale structure and CMB[12]. Since CMB is strongly related with the epoch of reionization and structure formation of the early universe, findings from observation of CMB, such as temperature and polarization, provide scientists insights into the early universe, for instance, an updated cosmological parameters in a higher precision thus a validation to the cosmological models. Noticeably, the Hubble constant in this research is $H0 = (67.4 \pm 0.5) km\ s^{-1}\ Mpc^{-1}$.This mission in 2018, utilizing the Planck measurements to investigate the CMB anistropies, reveals that standard 6 parameters in the spatially-flat ΛCDM cosmology, which has a power-law spectrum of adiabatic scalar perturbations, perform a outstanding consistency from the observations of temperature, gravitational lensing as well as polarization, separately and in combination[13]. Moreover, neutrino, a type of particle hardly interacts with other matters while contributing relatively small numbers to the CMB, has been under reviewed, considering universe made up of 40% of neutrino during the epoch that dominated by radiation, at temperatures above about 1 eV, and 10 % of neutrino in the epoch of recombination[14]. Hence, using the collected data from CMB, measuring the may tell us something about the early universe. However, a finding that determines to discover feasiblity of replacing neutrino with a relativistic fluid, which may push our comprehension further to the detection of the cosmic neutrino background, failed to approve that, instead, it analyzes that seeing the neutrino as a collisionless particle fits with the data better[14].

5.2 Simulation Technique

Besides those observations of the distant universe that are not only time-consuming and costly, simulation sometimes may be a faster and more straightforward way for individual scholars or a team to preliminarily test their theoritical framework. The Thesan project is one of the most renowned simulation project that mainly focuses on a series of cosmological radiation-magneto-hydrodynamic simulations at an enormous volume of the Epoch of Reionization, a specific epoch in the early universe. The simulations employ the state-of-the-art Arepo-RT(an efficient radiation hydrodynamics solver) moving mesh hydrodynamics code, in order to precisely spot the interaction between gas and ionizing photons, coupled to well-tested galaxy formation from another simulation project, and dust models to predict the properties of galaxies correctly.
6.Discussion

6.1 Comparison with Theoretical Models

Based on the high precison observational data, there have been countless amendment on the existing theories over last few decades, since the cosmology is always inclined to pursue a more refined and accurate models to decipt the universe, accounting for the features that we probe. For all the observational evidence mentioned above, some propel the verification of the classical theory, such as the classification of galaxies at different redshift[10], displaying the evolution of the intergalatic structure, the compelling analysis of correlation of the large-scale structure and the CMB lensing, which also calls for a better resolution on the theoretical uncertainty in the galaxy-convergence cross-spectrum[12]; some add more details to the existing framework, like the Planck mission that measures the cosmological parameters; some claim challenges or assumptions to the theories to better describe the observational results: a well-estabished explanation for the issue that some very young galaxies in the early universe that evolved into something similar to their adjacent relatively late galaxies. Besides, some researchers who concentrate on the dark energy and propose an assumption that cosmological consequences of topological defect network, which may form in the early universe, tied closely to the stochastic gravitational wave background and the CMB anisotropies. Simulation work based on the theoretical provide another intuitionistic and efficacious method for scholars to compare their results with the models, for instance, the N-body simulations that help solve non-linear covariant perturbations equations.

6.2 Limitations and Challenges

Given that cosmic observations entail a lot of noise when measuring, many sorts of contamination of data from different sources are ineivitable. The high surface density of faint sources causes contamination and overlapping spectra, making it difficult to isolate individual spectra. Moreover, under some circumstances to probe the emission line, ensuring the completeness in detecting targets is arduous, especially at the faint end of the luminosity function, where galaxies may be below the detection threshold. For example, the detection of CMB, while quite informative, faces foreground contamination from radiation of countless galaxies and detecting tiny temperature fluctuations and subtle polarization patterns remains challenging due to the requisite extreme sensitivity of detectors. Furthermore, there is a unresolved issue of the Hubble constant that different methods of measuring it, listing the CMB and those obtained from nearby galaxies as examples, yield significantly conflicting results. This discrepancy is known as the Hubble tension. When it comes to the detection itself, though chiche, it is technically difficult to probe dark matter and dark energy through gravitational lensing and galaxy rotation curves, introducing unknown uncertainties. Additionally, though large-scale cosmological simulations are crucial for fathoming the universe's evolution, they strictly rely on assumptions about initial conditions and parameters like the distribution of dark matter and dark energy. Consequently, these assumptions may affect the accuracy of the results and differ from observations.

7. Future Prospects

7.1 Upcoming Missions and Surveys

Considering JWST's high resolution and infrared capability to detect distant subjects in dust-enshrouded regions, and that JWST has just launched into the space in 2021, JWST is probably one of the most potential telescopes

ISSN 2959-6157

in the next decade, expected to revolutionize our comprehension of the early universe, star formation, and the evolution of galaxies. Besides, the Vera C. Rubin Observatory excepted to run in 2025 and located in Chile, will conduct the Legacy Survey of Space and Time (LSST), a decade-long survey of the southern sky, creating a large and detailed map of the universe, better understanding the distribution of dark matter and dark energy through gravitational lensing and large-scale cosmic structure. LSST utilizes a method: add up the multiple observations altogether before subtracting the sky background for the least data loss, to resolve the observational problems of low surface brightness light, which is more than 100-times fainter than the dark night sky and, found mostly in massive clusters at a low redshift and local galaxy streams, covering many degrees of sky.

7.2 Advances in Technology

Thinking more ambitiously, scholars from all over the world have been working on a technologically advanced astronomical projects that they has ever planned since 1980s, the Square Kilometer Array Observatory(SKAO), which has an effective collecting area of one square kilometer, allowing for unprecedented sensitivity to faint cosmic radio signals. SKAO will employ phased array systems that consist of thousands of individual antennas to probe the early universe and test the general relativity. These arrays can digitally combine signals from different antennas to form multiple beams pointing in different directions, enabling SKAO to detect large areas of the sky very quickly, vastly improving its observing power. AI and machine learning techniques are also integrated into the data analysis procedures, promoting the automatic pattern recognition and anomaly detection in enormous datasets.

8. Summary

In conclusion, the listed contemporary findings of the cosmic evolution validate the cosmological models, while some observations require several diminutive amendments to the cosmological parameters. However, the Hubble tension still remains unsolved and in order to further the cosmology, it is desperate to construct telescopes, such as the SKAO and the Vera C. Rubin Observatory, with a refined sensitivity and seek for more detailed results in the least uncertainty. The simulation technique that based on the models and the analytical of vast data may also require the improvement of AI technique and more effort into the quantum computer for better power in compute. With all these methods, astronomers are able to resolve the existent problems of cosmic evolutionary dynamics and push the theoretical framework further in the future.

References

[1] Bharat Ratra, Michael S. E. Vogeley. The Beginning and Evolution of the Universe. Publications of the Astronomical Society of the Pacific, 2007, 120(865): 237-238.

[2] Francesco Gozzini, Francesca Vidotto. Primordial Fluctuations From Quantum Gravity. Frontiers in Astronomy and Space Sciences, 2019, 1-2.

[3] Edvard Mörtsell. Cosmological histories from the friedmann equation: The universe as a particle. European Journal of Physics, 2016, 37(5): 1-3.

[4] Stefano Profumo, Leonardo Giani, Oliver F. Piattella. An Introduction to Particle Dark Matter. Universe, 2019, 5(10): 2-3.

[5] Eric Gawiser, Joseph Silk. The cosmic microwave background radiation. Physics Reports, 2000, 333:1-2.

[6] Benedetta Ciardi, Andrea Ferrara. The first cosmic structures and their effects. Space Science Reviews, 2005, 116(3-4): 2-6.

[7] Jose Gaite. The fractal geometry of the cosmic web and its formation. Advances in Astronomy, 2019, 2019: 1-4.

[8] Phillip A. Sabelhaus, John E. Decker. An overview of the James Webb Space Telescope (JWST) project. SPIE Astronomical Telescopes + Instrumentation, 2004, 5487: 551-552.

[9] Nikita Lovyagin, Alexander Raikov, Vladimir Yershov, Yuri Lovyagin. Cosmological Model Tests with JWST. Galaxies, 2022, 10(6): 1-4.

[10] Leonardo Ferreira, Christopher J. Conselice, Elizaveta Sazonova, et.al. The JWST Hubble Sequence: The Rest-frame Optical Evolution of Galaxy Structure at $1.5 < z < 6.5$. The Astrophysical Journal, 2023, 955(2):1-2.

[11] Daniel J. Whalen, Chris L. Fryer, Daniel E. Holz, Alexander Heger, S. E. Woosley, Massimo Stiavelli, Wesley Even, Lucille H. Frey. Seeing The First Supernovae At the Edge of the Universe with JWST. The Astrophysical Journal Letters, 2012, 762(1): 1-2.

[12] Christopher M. Hirata, Shirley Ho, Nikhil Padmanabhan, Uroš Seljak, Neta A. Bahcall. Correlation of CMB with large-scale structure. II. Weak lensing. Phys. Rev. D, 2008, 78(4): 1-2.

[13] N. Aghanim, et.al. Planck 2018 results: VI. Cosmological parameters. Astronomy & Astrophysics, 2018, 641: 1-4.

[14] Elena Sellentin, Ruth Durrer. Detecting the cosmological neutrino background in the CMB. Phys. Rev. D, 2015, 92(6): 1-2, 8.