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Probing the Cosmic Void Hypothesis: Current Evidence and Influence in Shaping the Universe

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Abstract. The Hubble tension—the significant discrepancy between the measured values of the Hubble constant (H_0) in the early and late universes—poses a fundamental challenge to the existing cosmological paradigm. This paper explores the local void hypothesis, which proposes that the Milky Way resides within a massive Kinan-Bage-Cowi (KBC) void, and attempts to explain the Hubble tension. By integrating multi-wavelength galaxy surveys with cosmological simulations, the gravitational effects of the void are systematically analyzed. The study focuses on elucidating how anomalous outward velocities caused by underdense regions distort the redshift-distance relationship, leading to artificially inflated estimates of local H_0. Furthermore, using baryon acoustic oscillation (BAO) data, this paper conducts a multi-faceted comparative test of predictions from homogeneous universe models and those based on voids. The ultimate goals include rigorously assessing the feasibility of voids in resolving the Hubble tension, thoroughly analyzing their broad implications for large-scale homogeneity hypotheses, and demonstrating the necessity of incorporating local structure into precision cosmological studies.

Keywords: Keenan-Barger-Cowie Void, Hubble constant, redshift, Cosmic Microwave Background, homogeneity.

1. Introduction

The cosmological principle states that the universe is homogeneous and isotropic on large scales. This is considered to be the foundation of modern cosmology. The principle underlies the ΛCDM model and allows us to extrapolate universal properties with evidence [1]. From the hot and dense state during Big Bang to the large-scale structure we observe today, the principle has led our understanding of how the universe evolves for decades. However, a persistent and growing challenge to this basic assumption has developed, in the form of the Hubble tension. There is a significant discrepancy between the value of the Hubble constant (H_0) directly ascertained in the local universe and indirectly concluded from the early cosmic microwave background radiation (CMB). While the CMB that is anchored by the Planck satellite data suggests $H_0 \approx 67.4$ km s^{-1} Mpc^{-1}, another measurement of distance ladder using Cepheid variables and Type Ia supernovae find a higher value, consistently around 73 km s^{-1} Mpc^{-1} [2]. As this discrepancy is at a significance level exceeding 5σ, it suggests a potential crisis in cosmology, which implies either systematic error that

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is currently unknown or the need of more modern physics beyond the standard model during measurement.

One compelling and increasingly well-supported solution proposes that there is a more local perspective towards the discrepancy. This is the local void hypothesis. It describes our Milky Way galaxy as positioning in a vast and under-dense region of space, which is a cosmic void [3]. The existence of such a local low-density region is not merely a theoretical speculation; it is an observational fact, which is now well-documented and known as the Keenan-Barger-Cowie (KBC) void. It is specifically named for the astronomers who provided concrete evidence for it in 2013. In all observations electromagnetic spectrum, typically from near-infrared galaxy counts to X-ray cluster surveys and radio wave analyses, they conform to a certain big picture: This KBC void is immense, extending roughly 300 megaparsecs, which is nearly a billion light-years in radius [4]. This makes it one of the largest known structures in the universe. Within this vast volume, the density of matter is estimated to be about 20-30% lower than the cosmic average.

The gravitational implications of Earth being in such a structure are profound and solid. According to general relativity, underdensity of a region creates a gravitational potential hill. Matter in this “hill”, with the nature of seeking to move towards the density uphill, will flow outwards from the center with low density towards the denser walls surrounding the void. This results in a continuous outward flow of galaxies—a expanding field abiding the rule of Hubble constant. As the Earth is located near the center of the void [3], this motion imposes a rather significant effect on the light we receive from distant planets. The Doppler shift caused by this outflow adds an extra component to the cosmological redshift of sources. Consequently, the observed redshift of a galaxy is inflated; it is higher than it would be if it were solely due to the universe's homogeneous expansion.

This effect is at the very center of the proposed role for the void in explaining the Hubble tension. Originally, the measurement of H_0 depends on defining a close correspondence between redshift (z) and distance (d), encapsulated in the equation $cz \approx H_0 d$ for small redshifts [2]. Astronomers tediously measure distances to close galaxies via standard candles such as Cepheids and supernovae and then match those distances against their measured redshifts. If a substantial fraction of that redshift is not a result of a distant, cosmological origin but rather a result of the peculiar velocities imprinted through a local void, though, then the essential relationship is corrupted. The redshift we measure is too great for a certain distance. If astronomers then compute $H_0 = cz/d$, they unintentionally include this non-cosmological contribution, overestimating the true, universal Hubble constant. The local void hypothesis, then, offers a simple yet physically motivated account for the Hubble tension. It suggests not that the higher local measurement for H_0 is wrong but rather that it is a local measurement contaminated through our special location. Its measurement from the CMB, revealing the mean, universal expansion measure at a time very far before the void formed, is still the true Hubble constant [5]. Because the discrepancy is then not a sign of something new in the early universe but rather a testament to the might of a gravitational anomaly on a local scale to pervert our cosmic view, it's a harsh exception from the presumed cosmological principle on a scale so deep as to impact our deepest measurements of the cosmos, implying that we must first learn our local cosmic address before we can reliably measure the universe's expansion on a universal scale.

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2. Investigation of the KBC Void

2.1. Observational evidence for the KBC Void

The emergence of the KBC Void is not a result of theoretical simulations; instead, it is a conclusion driven by observational data. In this way, the discovery and depiction of the KBC Void provides evidence to the field of observational cosmology, especially galaxy surveying through the systematic mapping of the large-scale structure of the cosmos. The detection of such an underdensity is best done through the number of galaxies in some specified volume of space, which is an algorithm that is based upon the underlying assumption that light traces out mass [6]. Whilst dark matter holds the budget of the universe's mass, the galaxies themselves shine like beacons as they cluster in the more densely populated areas and are thin on the ground in the more sparse areas in between. As such, there being some clear deficiency in galaxies in some vast, continuous volume is direct testimony for the presence of some cosmic void.

The process of mapping the KBC Void began in earnest with wide-field optical and near-infrared (NIR) surveys. In the aspect of investigation towards local underdensity, early studies made by Maddox et al. and Shanks used optical catalogues to provide initial clues. However, a critical obstacle has significantly hampered optical observations, which is the obscuration from interstellar dust within our own Milky Way galaxy. This dust lies in the plane of the galaxy, specifically centered on the Milky Way's galactic equator, a region known as the “Zone of Avoidance” [7]. This region blocks a significant portion of our optical view of the extragalactic sky during observation, potentially reducing the visibility of nearby structures. With the appearance of large-scale NIR survey, most importantly the Two Micron All-Sky Survey (2MASS), the identification and quantification of the KBC Void experienced a significant breakthrough [8]. In fact, NIR light has a much longer wavelength than optical light, allowing it to penetrate interstellar dust effectively. This provides a drastically clearer and more complete vision of galaxy distributions, as well as minimizing the obscuration bias that plagued earlier studies.

It was the detailed examination of the 2MASS data that caused Keenan, Barger, and Cowie (2013) to officially recognize and characterize the void that now shares their names—the KBC void. Their procedure was to calculate the number density of galaxies as a function of distance from us [8]. By utilizing NIR luminosities, which is a decent proxy for stellar mass, they were able to build a durable picture of the local universe's matter distribution. Information gained was remarkable. They found that their results indicated a profound and consistent underdensity extending out some 300 Mpc (about 1 billion light-years). Over this enormous volume, the galaxy density—and by extension the density of matter—was determined to be around 20-30% below the mean density of the universe [8]. This was no small, nearby oddity but an enormous “hole” in the cosmic web, with our Local Group of galaxies located not only nearby but, more importantly, in the midst of this void.

However, there is still some uncertainty about the size of the KBC void. Although its minimum radius can be estimated to be 150–200 million parsecs based on the turning point where the density tends to the mean, the exact outer boundary of the void has not yet been clearly defined. There are two main reasons for this situation. First, although the effect of the Milky Way foreground obscuration can be partially alleviated by near-infrared surveys, it cannot be completely eliminated, resulting in the existence of some unobservable regions. Second, at scales exceeding about 300 million parsecs, the low-density characteristics of the void gradually become difficult to distinguish from the natural fluctuations of the cosmic web itself [7]. To distinguish a single void structure from other surrounding filamentary structures and voids, it is necessary to rely on survey data with a wider coverage and more sophisticated statistical analysis methods. Therefore, although existing

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studies strongly support that the KBC void can extend to about 300 million parsecs, its exact size and boundary demarcation are still an active research topic, and some published results even suggest that the actual scale of the structure may be larger [6].

Two important inferences can be drawn from these observational evidences. First, the conclusion that our local region of the universe is not representative of the average density of the universe has been strongly supported. The fact that we are in a large-scale low-density region directly challenges the universality of the cosmological principle on the billion-light-year scale. More importantly, in terms of Hubble tension, the scale and low density of the KBC void are sufficient to produce significant gravitational effects. The scarcity of matter means that we are actually located on the "peak area" of a gravitational potential. The resulting movement of matter - including the inflow and outflow of galaxies and the corresponding special speeds - constitutes a direct physical mechanism that can reasonably explain the phenomenon of high local Hubble constant measurements [4]. Therefore, the discovery of the KBC void has shifted the focus of the debate from whether the structure exists to what the cosmological effects it brings are; this shift has also made it leap from a striking large-scale structure to a key role in solving one of the major problems in modern cosmology.

2.2. Implications of the KBC Void

A massive underdense region like the KBC void is not a passive entity in the universe; it exerts a profound and active influence through gravity, not only dynamically changing the motion of our Local Group of galaxies, but also fundamentally interfering with our measurements of the expansion of the universe. Its gravitational effects are most evident in the formation of peculiar velocities of galaxies. According to general relativity, underdense regions can be considered as highlands of gravitational potential. Matter tends to migrate along density gradients, so galaxies located within the void—including the Local Group—are subject to a net repulsive force, being pushed away from the center of the void and toward the denser “wall” structure of the surrounding cosmic web [9]. This mechanism explains the currently observed motion of the Local Group of galaxies at approximately 260 km/s, which is moving it away from the center of the KBC void. This motion constitutes a significant portion of our peculiar velocity in the universe, superimposed on the uniform Hubble flow.

The void’s effects go far beyond inducing local motion. It also stimulates large-scale coherent flows, causing galaxies throughout the underdense region to tend to flow outward [4]. This phenomenon poses a fundamental problem for cosmologists who are trying to measure the expansion of the universe through the redshift-distance relationship. The redshift signal of galaxies actually contains two components: the cosmological redshift due to Hubble expansion and the Doppler redshift caused by special motions [1]. In the void region, the outward motion of galaxies adds additional degenerate Doppler redshifts, thereby systematically increasing the measured redshift value. If astronomers directly attribute all these redshifts to the expansion of the universe using the formula $v = H_0 d$, they will overestimate the Hubble constant. As a result, the expansion rate in this region appears to be higher - not because the universe is actually expanding faster there, but because we are inside a huge void and the gravitational effect distorts the redshift signal used in local measurements [1].

Therefore, the existence of KBC voids challenges the basic framework of modern cosmology and weakens the strict applicability of the cosmological principle on the scale of hundreds of megaparsecs. It means that the Hubble constant may not be a global single parameter that can be measured consistently everywhere; local gravitational effects can cause the measured apparent

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Hubble constant to deviate from the global value. This provides an elegant, physically based explanation for the Hubble tension: the higher values measured by local distance steps (such as Cepheid variables and supernovae) are contaminated by void dynamics, while the lower values from the cosmic microwave background reflect the true, undisturbed global expansion rate [4]. Therefore, acknowledging the influence of voids is not equivalent to introducing additional correction terms, but rather emphasizes that our special position in the structure of the universe permanently changes the perspective from which we observe the expansion of the universe. This controversy may not necessarily point to new physics in the early universe, but more likely stems from our inadequate understanding of how local structure affects basic cosmological observables. This new paradigm shift requires us to make detailed mapping of our local environment a prerequisite for accurate cosmology - only by first understanding our position in the universe can we more accurately reconstruct the expansion history of the entire universe.

2.3. Frontiers in solving Hubble tension

Exploring the KBC void will remain a key research direction for addressing major cosmological tensions, especially the Hubble constant controversy. With the help of next-generation observational equipment and interdisciplinary methods, subsequent research will systematically deepen our understanding of the KBC void. The size of the void is currently estimated to be between 150 and 200 Mpc, but its exact boundary remains unclear due to foreground obscuration, which poses significant difficulties for accurate mapping. The soon-to-be-launched James Webb Space Telescope (JWST) and Euclid Space Telescope will use high-resolution infrared and optical sensing technology to achieve detailed imaging of dust-obscured regions (such as the Milky Way's avoidance zone), thereby identifying bright and dark dwarf galaxies and faint filamentary structures within the void [10]. These observations are expected to clarify the actual extent of the void and the sparse characteristics of matter - according to theoretical speculation, its density may be 15% to 50% lower than that of the surrounding area [3].

On the other hand, radio astronomy projects such as the Square Kilometer Array (SKA) will map the distribution of neutral hydrogen and the speed of galaxy motion with higher precision, helping researchers simulate the gravitational effects of the KBC void on nearby galaxies, such as explaining the motion of the Milky Way away from the void at a speed of about 260 km/s [11]. Combined with data from gravitational wave detectors such as LIGO and cosmic microwave background (CMB) surveys, multi-messenger astronomy methods will further examine the impact of the KBC void on the formation of large-scale structures and even deduce its possible dark energy-like effects.

In terms of theoretical modeling, researchers will optimize the ΛLTB inhomogeneous cosmological model to simulate the evolution of the void and its impact on the Hubble tension, and even explore its possibility as an alternative theory to dark energy [12]. With the help of advanced computational tools such as machine learning, the team will also systematically analyze large-scale data from survey projects such as the Dark Energy Spectroscopic Instrument (DESI) to distinguish local deviations caused by the KBC from global cosmological parameters, thereby collaboratively reconciling the existing contradictions in the Hubble constant [12]. These efforts are not only aimed at determining whether low-density voids are the cause of core cosmological anomalies, but will also open up new ways to study gravity, dark matter, and the mechanism of accelerated expansion of the universe using cosmic voids as new probes.

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3. Future prospects and missions

Although the KBC void may have a profound impact on cosmology, its research still faces multiple challenges from the observational and theoretical levels. These obstacles make it difficult for the academic community to reach a clear consensus. In terms of observation, the most direct difficulty lies in determining the actual scope and internal structure of the void. The interstellar gas and dust in the Milky Way disk form a so-called "Zone of Avoidance", which seriously obscures the optical and near-infrared observations of the extragalactic sky, resulting in the possibility that key areas at the edge of the void may be covered, making the mapping results incomplete and bringing uncertainty to the estimation of its true diameter [10]. In addition, the galaxies in the void region itself are sparse, distant, and mostly dim low-mass dwarf galaxies, which are difficult to detect even in the absence of foreground obstructions [10]. The lack of a sufficient number of observational samples makes it extremely difficult to construct a detailed density distribution map of the void or to determine the special velocities of the internal galaxies with high confidence. The current statistical error is still as high as several orders of magnitude. It can be said that our current mapping is like depicting in a dark room with only a few randomly distributed, faintly glowing candles, some of which are also obscured by a veil.

These observational difficulties are further exacerbated by long-standing theoretical disagreements. The focus of the controversy is mainly on the basic parameters of the void, especially the contrast between its size and density. Some galaxy surveys support that its size can reach 300 million parsecs (Mpc) and its density is extremely low, but some studies believe that the data is more consistent with a smaller, shallower structure that is consistent with the expectations of the ΛCDM model. Such disagreements arise from the uncertainty in the understanding of the internal structure of the void: is it a uniform "bubble" or a network composed of weak filamentary structures? A deeper issue involves the material composition of the void: it lacks luminous matter in the optical band, but does this mean that dark matter is also scarce? Some theoretical models believe that the void region is empty in all material components, while others point out that dark matter may be concentrated in it, but it has not yet formed luminous galaxies [1]. This uncertainty is crucial to accurately simulate the gravitational effects of the void and its impact on the motion of the Local Group of galaxies and the local Hubble property. Without a clear theoretical framework for the origin, size and material distribution of the void, it is difficult to establish a reliable model to quantify its impact on the Hubble tension, so this hypothesis is still in a reasonable but not fully confirmed state.

4. Conclusion

In summary, the KBC void hypothesis not only challenges fundamental cosmological principles but also addresses the Hubble tension. This discussion focuses on providing a rationale for the KBC void, a massive, low-density void extending approximately 300 million parsecs, with a matter density 20-30% lower than the cosmic average, and its gravitational influence. By analyzing multi-wavelength survey data and simulations, this paper reveals how our location within this void induces a peak in gravitational potential energy, generating a unique outward velocity; this effect overestimates redshifts and artificially inflates local measurements of the Hubble parameter. The study further illustrates how this mechanism, without altering the standard ΛCDM model, can reconcile the discrepancy between measurements of H_0 based on local tracer objects (such as Cepheid variables and supernovae) and global measurements based on the cosmic microwave background.

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Future developments in this research should focus on the following key areas: First, leveraging new-generation observatories such as the James Webb Space Telescope (JWST) and the Square Kilometer Array (SKA), we can achieve even higher-precision mapping of the precise boundaries and density distribution of cosmic voids. Second, employing a more refined ΛLTB model combined with machine learning methods is also a possibility for improving the accuracy of simulations of void structure evolution. Furthermore, we can further explore the distribution characteristics of dark matter within voids and its relationship to visible matter. Overall, uncovering the nature of KBC voids not only holds the promise of reconciling current controversies in Hubble constant measurements but also has the potential to profoundly alter our fundamental understanding of the mechanisms of cosmic structure formation and the boundaries of large-scale uniformity.

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