Do we live in an under-dense region?

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Abstract. According to the Cosmological Principle, matter structures and radiation are expected to be homogeneously and isotropically distributed in the universe at sufficiently large scales. An open question in observational cosmology is to estimate the size of such scale from the data. In the case of the cosmic background radiation, it seems clear that such scale corresponds to the horizon scale at matter-radiation decoupling, that is, at $\sim 1$°, but the problem is still open for the size of the homogeneity scale. But, due to the growth of structures in the evolving universe the homogeneity scale depends on the redshift of the data in analyses. Here we study this problem for data in the local universe by analyzing the 21cm HI-line sources using the public catalog ALFALFA, with median redshift $\langle z \rangle = 0.025$. We use the scaled counts-in-spheres method to establish the approximate size of the homogeneity scale in the local universe. In this analysis one compares the data sample with respect to a randomly generated homogenous sample. Defining the scale of transition to homogeneity as the scale at which the scaled counts-in-spheres estimator reaches the limiting value 1 within 1%, we find that this transition scale is $r_H \approx 69$ Mpc, in excellent accordance with what is expected considering that the HI-line sources come from low-mass blue galaxies which have an anti-bias $b$ with respect to the matter fluctuation field (with $b \approx 0.48 \sim 0.68$ depending on the composition of the sample), from which one expects a transition scale in the local universe of $56 < r_H < 79$ Mpc.

1. Introduction

Since the Hubble results [1], the astronomical community believed that the universe expands decelerated. However, the discovery in 1998 [2] that the universe is currently in an accelerating expansion phase produced a challenge to modern cosmology. According to Einstein equations, if the background space-time is Friedmann-Robertson-Walker (FRW), the source for the acceleration should be a fluid with the unfamiliar property that it exerts a negative pressure over itself, continuously increasing the universe expansion rate. But the problem is that a real fluid with such properties is unknown; this fluid is termed the dark energy.

Since then, alternative scenarios have been proposed in the literature to explain the accelerating expansion of the universe without appealing to the (existence of the) dark energy. One possible solution claims that, if the local universe is an under-dense region then the dimm light (photons traveling along the intergalactic media) coming from type Ia supernovae (SNIa) do not need to be explained as emitted from an extremely far object, as it would be if the universe expands accelerated, instead they could have been emitted from a nearer SNIa but travelled at different speeds when inside and outside the void region. This alternative approach is known as Lemaitre-Tolman-Bondi (LTB) due to the general relativity metric developed by these authors with which one constructs locally under-dense (or void) region (i.e., an inhomogeneous space) surrounded by a FRW spacetime [3].
The Cosmological Principle assumes that matter structures \[4, 5\] and radiation \[6, 7, 8, 9, 10\] are expected to be homogeneously and isotropically distributed in the universe at sufficiently large scales (see, e.g., \[11, 12\] for anisotropic features at large-angles in the cosmic background radiation or \[13\] for anisotropic radiation in compact spaces). Efforts are been done to estimate the size of such scale from the data \[14, 15, 16, 17, 18\]. Such analyses are particularly interesting due to the possibility that the LTB hypothesis can be rigorously tested using several cosmological probes, including publicly available astronomical data from the local universe like the ALFALFA catalog. This is what we planned to analyze here. In section 2 we present the data utilized in our analyses, while in section 3 we detail our methodology, and in section 4 we present our preliminary results. Finally, in section 5 we draw our conclusions and final remarks.

2. The ALFALFA catalog

The Arecibo Legacy Fast ALFA survey \[19, 20\] consists on astronomical data of the HI emission sources. At the time these analyses were done the publicly available survey was \textbf{alpha.70} (or \(\alpha.70\)). In order to avoid systematic errors, noise, and non-extragalactic emission sources we have chosen \textbf{code 1} detection sources, which is the subset of data suggested by the collaboration \[20\]. This dataset comprises 18,984 extragalactic objects, with median redshift \(\langle z \rangle = 0.025\). Every source is regarded as an object which spherical coordinates are given by the adopted distance, right ascension and declination (see Figures 1, 2, and 3).

![Figure 1](image.png)

**Figure 1.** Distance histogram distribution for the extragalactic objects with \textbf{code 1} in the catalog \(\alpha.70\).
3. The Methodology and Data Analyses

We use the scaled count in spheres method to assess the homogeneity scale in the local universe. Considering the survey geometry and incompleteness [17], we generated a randomly set of data (see Figures 4 and 5), in the same region of the survey.

The scaled count-in-spheres $N_{center}(r)$ is calculated through extragalactic data and random generated data according to

$$N_{center}(r) = \frac{1}{N} \sum_{i}^{N} \frac{n_{gal}^{i}(< r)}{n_{rand}(< r)}, \quad (1)$$
Figure 4. Distance histogram distribution for the random catalog. For the small fraction of negative distances we consider their absolute value.

Figure 5. Angular distribution of the objects in the simulated random catalog.

where \( n_{\text{gal}}^i(< r) \) is the number of extragalactic objects inside a sphere of radius \( r \) centered in the position of the \( i \)-extragalactic object. In the same way, \( n_{\text{rand}}^i(< r) \) is the number of random generated objects. \( N \) is the total number of objects, that is 18,984.

The fractal dimension is defined as follows [17]

\[
D_2(r) \equiv \frac{d \ln N(< r)}{d \ln r} + 3.
\]

(2)

For a homogeneous distribution \( N(r) \) is proportional to \( r^3 \), thus \( D_2(r) = 3 \), while for a fractal distribution the fractal dimension is a number between 2 and 3. It is worth to mention here
that there are several approaches to define $N$, as can be seen, e.g., in reference [18], one of these methods being the calculation of $N_{\text{center}}$ used here [15, 17, 18]. In particular, one can also use the two-point correlation function to define an estimator for the scaled count-in-spheres $N(r)$ (for other applications of the two-point correlation function, see e.g., [21, 22]).

4. Results

The scaled count-in-spheres methodology was applied to the sample of the ALFALFA.70 survey, a public catalog recently released [19] of 21cm HI-line extra-galactic sources. Our preliminary results are summarized in figure 6, where the curve goes down very fast at 100 Mpc in accordance with simulations done for matter fluctuations where the scale expected is $\sim 100$ Mpc [23]. One also observes that the scaled count-in-spheres curve oscillates, probably due to under- and over-densities, but then obtain a level of stability at $\sim 260$ Mpc.

![Figure 6. Scaled count-in-spheres versus radial distance. In this plot we consider distances from 50 to 500 Mpc, there are 19 bins (dot points): the inicial point is $r_0 = 50$ Mpc, and from this we consider 18 equal bins of size 25 Mpc. The best-fit to the data corresponds to a polynomial of degree six, and the intersection with the horizontal red line (that represents the constant value $N_{\text{center}} = 1.01$, that is, the threshold below which one considers that the homogeneity is attained) occurs at the scale $r_H = 69.0072$ Mpc.](image)

5. Conclusions anf Final remarks

Our preliminary analyses are concentrated in Figure 6, where we show that the intersection of the green line, which is the best-fit of the data (dot points), with the red line (that represents the constant value $N_{\text{center}} = 1.01$, which is the threshold below which the homogeneity is achieved) defines the homogeneity scale [17]. This intersection occurs at the scale 69.0072 Mpc, a value that is in good accordance with the value obtained for the galaxy distribution in the SDSS DR6 [14]. In figure 6 we also observe some oscillations at distances 300 – 400 Mpc are possibly
due to the presence of over-density regions (galaxy clusters?) while oscillations at scales $200 - 300$ Mpc possibly due to under-density regions.

Moreover, considering that the HI-line sources come from low-mass blue galaxies which have an anti-bias $b$ with respect to the matter fluctuation field (with $b \simeq 0.48 - 0.68$ depending on the composition of the sample), from which one deduces that the transition scale expected in the local universe for our sample is $56 < r_H < 79$ Mpc [17].

Finally, although these analyses are preliminary we can say that, despite the presence of regions with over and above the mean number density of extra-galactic objects, the 3-dimensional scale of homogeneity is achieved at the predicted scale [17], i.e. $r_H = 69.0072$ Mpc, confirming the consistency of the CP through the ALFALFA local universe dataset.

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