Surface Tension of Cosmic Voids as a Possible Source for Dark Energy

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ABSTRACT

The cosmological constant is estimated by considering the surface tension of supervoids in a void-dominated cosmic fluid by which we can get a possible source of dark energy. Looking at voids as bubbles, we define the concept of surface tension which is shown to have an almost constant value for supervoids that are enclosed by superclusters. The surface tensions of voids are computed by dimensional method for galaxies and superclusters with different values for each group. At large scale which vast voids are dominant the positive cosmological constants obtained of order \((\approx +10^{-52}\text{m}^{-2})\), which are very close to those given by Planck.

Key words: cosmology: theory – cosmology: dark energy – cosmology: large scale structure of Universe

1 INTRODUCTION

As we know the existence of a type of material fluid with negative pressure remains an unsolved puzzle in physics and cosmology, because the lowest perceived pressure for any type of ordinary matter fluid is zero. But one of the ways to justify the current accelerating expansion in the universe is to have negative pressure for the cosmic fluid at large scale (Riess et al. 2004; Perlmutter et al. 1999; Spergel et al. 2003; Ade et al. 2016; Cheng 2010; Srivastava 2008).

In the ideal gas law it is assumed that the particles are point-like without any volumes and interactions, but in the present physical cosmic fluid, there exist some over-dense and under-dense regions that some phenomena occurring between cosmic objects, for example the merging of them is a common phenomenon at cosmological scale. Galaxies and galaxy clusters, and even voids are all always evolving and merging together to form larger ones. Although the volume of the merged galaxies are small fractions of the total cosmic volume, but taking into account the contribution of vast voids, the volumes of these voids become large fractions of the present cosmic web and their contributions will grow up (Cowie 2015; Pisani et al. 2015; Hamaus et al. 2016; Khanpour et al. 2017; Koren 2017). As voids expand, galaxies are squeezed in between them, and sheets and filaments form the void boundaries. This view is supported by computer simulations and numerical studies (Van De Weygaert & Platen 2011; Padilla et al. 2005; Martel & Wasserman 1990). Also, novel cosmological constraints obtained from cosmic voids and exact calibrations demonstrates that can be expect the immense potential to use cosmic voids for cosmology in current and future data Hamaus et al. (2020).

Scientists usually consider only matter (galaxies and their clusters) as the active part of the universe, so telescopes and probes focus on this part of the cosmic fluid. But the much larger under-dense part of the current universe, the supervoids, are considered as the ineffective part in the dynamics of the universe. In this article for the first time, we take the role of cosmic voids very seriously and consider the effect of theirs surface tension on global and local scale to solve important unresolved problems in physical cosmology. Several papers have pointed out that vast voids are not only a key element of the cosmic mass and volume distribution, but also one of the purest probes for global cosmic parameters (Bos et al. 2012; Pisani et al. 2015; Hamaus et al. 2016). We consider the current cosmic fluid as a mixture of two evolving and merging parts. These include the over-dense galactic part on the one hand and the under-dense voids part on the other. Given that voids make up a much larger contribution of the current cosmic fluid, we will show that this void-dominant fluid will create additional effective negative pressure (with a negative ‘cosmic equation of state’ i.e. \(w_{\text{eff}} < 0\), on the large scale. As an important consequence of this hypothesis, we will also be able to obtain possible estimates for the cosmological constant by dimensional calculating of the surface tensions on the supervoids boundary that enclosed by superclusters. Our hypothesis is related to the surface tension of supervoids, in which their average effect can create an effective negative pressure at cosmic scales.

Our main thesis of this paper is the surface tension of cosmic voids due to the existence of inhomogeneities and hence their role in global expansion is closely related to the “backreaction” issue (Rässänen 2011; Wiltshire 2011; Clarkson et al. 2011; Buchert & Rässänen...
we will introduce void-dominated cosmic fluid (Buchert et al. 2015). By definition, backreaction is the effect of inhomogeneities caused by matter and geometry on the global expansion of the universe (Buchert et al. 2015). In some papers, Green and Wald believe that backreaction of inhomogeneities is irrelevant in cosmology (Green & Wald 2011, 2013). As we know, in Newtonian context only inhomogeneities of the matter part can be considered and the geometry part is considered flat. Newtonian limit of GR automatically implies that the geometry is Euclidean, in particular that the intrinsic curvature vanish everywhere (Buchert & Räsänen 2012; Buchert 2018). But when we consider the global scale of the universe, the Newtonian framework - due to neglecting the role of curved geometry- can not provide the desired results, and the Buchert-Ehlers theorem results in a zero backreaction (Buchert & Ehlers 1997).

In a recent new work, the effect of inhomogeneities in the Newtonian framework with a non-Euclidean topology is investigated Vigneron (2021). The effect of the backreaction in the context of general relativity have been widely studied (Buchert 2000, 2001; Buchert et al. 2020), in which both the role of matter and geometric inhomogeneities are considered on a global scale. So the consequence will be the non-zero backreaction, and hence it can affect the dynamics and the accelerating expansion of the universe. The model presented here can achieve this important request with a heuristic calculation of the surface tension from the void-cluster interface.

The model presented in this paper is in the context of relativistic cosmology. To achieve this goal we have already considered second-order terms in the cosmic equation of state as

$$P = wp + bp^2,$$

that the details are given in Khanpour et al. (2017).

Why the role of supervoids and their surface tension is taken seriously in this article? When we consider significant the second term- as an interacting term- in the EoS of cosmic fluid; there must be physical objects that are interacting (or merging) with each other on the cosmic scale. Because the scales are so large, the best possible candidate for these merging objects are the largest ones i.e. merging supervoids that are enclosed by superclusters (Sutter et al. 2014; Cowen 2015).

By taking into account the effect of the merging of vast voids on the cosmic web together with the enlargement of empty spaces over time at low redshift in N-body simulations Aderrmann et al. (2017), as well as its similarity to the behavior of bubbles in hot overflowing milk Yusofi & Mohsenzadeh (2010); the idea of using bubble surface tension will be considered as a possible model for studying effects of supervoids pressure in accelerating expansion. Recently, similar to our idea, the surface tension hypothesis has also been proposed by Ortiz to explain the accelerated expansion of the universe and some other important challenges of physical cosmology Ortiz (2020). In his paper the cosmic system under study was considered homogeneous and isotropic, while the formation of cosmic structure and its inhomogeneities is ignored. But in our work, inhomogeneities in the structure of the universe are the main factor of the production of supervoids/superclusters and resulting their surface tension.

So in the Sec. 2 we will introduce void-dominated cosmic fluid and by the drops-bubbles mixed fluid model show that in such a fluid we will have an effective negative pressure at large scale. In the Sec. 3 and 4, by a dimensional calculating of the surface tension, we will obtain a possible estimation for the values of cosmological constants for two groups of cosmic objects i.e. superclusters and galaxies. Some results, predictions and discussions on the model will be presented in final section.

Figure 1. The cosmic web is mostly occupied by supervoids: The wight and red areas are superclusters and filaments of galaxies, blue areas are voids and wight dots are single galaxies inside the cosmic voids (https://sci.esa.int/web/planck/-/51104-numerical-simulation-of-the-cosmic-web; with permission).

Figure 2. Schematic of void-dominated cosmic fluid that occupied by supervoids: Negative pressure with effective force of supervoids on galaxies in the walls (black circle) acts as the positive pressure with effective attractive force on local scale (yellow circle).

2 PRESSURE AND SURFACE TENSION OF COSMIC VOIDS

Let’s consider the current cosmic web in Fig. 1 containing a network of the voids, in which several clusters and filaments, small and vast voids are merging to each other (see the area bounded to the black rectangular in Fig. 2). What is certain is that the universe is in the void-dominated state in the large scale overview. The continuous merging of voids causes the bubbles to grow larger, and this increasing in the bubble radius results in an extra effective repulsive force on the particles (i.e., galaxies) on the surface of the bubbles (i.e., voids). Under such conditions, cosmic fluid is clustered like merging bubbles and is situated in the void-dominated phase.

In the model proposed in this paper, we imagine galaxies and their clusters as ‘drops’ and under dense spaces (voids) between them as ‘bubbles’ Yusofi & Mohsenzadeh (2010). In a mixture of water drops and bubbles, bubbles on their surface move the fine drops away from their center to make themselves larger, while large drops
attract fine drops to their center to grow larger. If the void wall forms a set of galaxy clusters and superclusters, we will have a bubble whose difference in internal and external pressure comes from the Young-Laplace formula (Butt et al. 2003; Reichl 2016)

\[ \Delta P = \frac{2y}{\bar{r}}. \]  

(1)

Here, \( y \) represents the surface tension for drop (bubble) with average radius \( \bar{r} \). The clusters of galaxies behave like drops, so their pressure on the test particles/galaxies is positive with an attractive gravity force (yellow circle in Fig. 2). These galaxies experience attractive force in the clusters-dominated areas at local scales, but at large scale that we have void-dominated areas, the situation is completely different. Galaxies that mostly accumulate on the surface of voids, would experience effective negative pressure, because of the fact that voids inclosed by superclusters are expanding, and hence pushing the galaxies away from each other. Therefore, inspired by (1), two factors are effective in the pressure of voids on cosmic scales. The first factor is the surface tension \( y \), due to the attraction between material particles that make up the disk-shaped objects on the surface of voids, and the second factor is due to the curvature \( (\frac{1}{\bar{r}}) \) of these cosmic voids.

Because the net effective pressure of the cosmic web at large scale essentially dominated by voids and their pressure, in which the curvature term \( (\frac{1}{\bar{r}}) \) takes a negative sign in this case (see Fig. 2). Here the negative sign means that the average pressure on galaxies from the expanding supervoids at cosmic scales acts in reverse to the pressure from the superclusters at local scales, and causing the galaxies to move away. Fortunately, the observational data confirm negative pressure that EoS parameter \( w \) has a very narrow range around \( w = -1 \) with more likelihood to the side of \( w \leq -1 \) (Srivastava 2008; Aghanim et al. 2020).

In what follows, we will show that the negative pressure coming from surface tension and curvature of voids can justify the presence of dark energy at large scale, and probably dark matter in local scales.

3 DIMENSIONAL CALCULATION OF SURFACE TENSION

The supervoids make up the main volume of the universe at cosmic scale. Therefore, the thickness of the walls is small compared to the large volume of the supervoids and they can almost be considered as an idealised surface. The presence of a separating surface between the under-dense and the over-dense areas creates a surface tension that produce pressure difference between them. However, the interior of walls is well observed and the effect of wall thickness could be investigated in a more accurate model.

Given the above ideal assumption for the surface tension of supervoids, if we consider the location of clusters on the surface of supervoids, as a result of this consideration, the mass and energy of galaxies and their clusters are distributed on the shells of voids. Therefore, the energy-to-area ratio i.e. surface tension \( y \) for the disc-shaped objects can be calculated by using the following,

\[ y_i = \frac{\text{Energy}}{\text{Area}} = \frac{M_\text{e} c^2}{\pi R_i^2}. \]  

(2)

In the above relation \( M_\text{e} \) and \( R_i \) are binding mass and mean radius of the cosmic objects such as galaxies, clusters and superclusters (Fig. 3). For example, the amount of surface tension or surface energy for the Laniakea supercluster with \( M_\text{e} = 1.0 \times 10^{47}\text{kg} \) and \( R_3 = 2.4 \times 10^2\text{m} \) is obtained as,

\[ y_3 \approx 0.50 \times 10^{15}\text{J.m}^{-2}. \]  

(3)

Because the surface tension is an intensive quantity (Butt et al. 2003; Zemansky 2011), it is expected that the approximate values of surface energy for the superclusters at large scale are the same order (~ \( O(10^{15})\text{J.m}^{-2} \)), but the energy density is not the same for these objects.

4 AN ESTIMATION OF THE COSMOLOGICAL CONSTANT WITH VAST VOID PRESSURE

In the standard cosmology with cosmological constant \( \Lambda \), we have (Cheng 2010; Srivastava 2008)

\[ \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3}(\rho_\text{matter}) + \frac{\Lambda c^2}{3} - \frac{k c^2}{a^2}. \]  

(4)

Considering contribution of voids energy density \( \rho_\text{void} \), instead of cosmological constant in the void-dominated (or quasi-vacuum dominated Yusofi (2018)) cosmic fluid, we can modify Friedmann’s equation to

\[ \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3}(\rho_\text{matter}) + \frac{\rho_\text{void}}{c^2} - \frac{k c^2}{a^2}. \]  

(5)

Since a void-dominated phase of cosmic fluid can be regarded as a quasi-vacuum dominated state i.e. \( \rho_\text{void} = \rho_\Lambda \), therefore two relations (5) and (4) are equivalent and we can define

\[ \Lambda = \frac{8\pi G \rho_\text{void}}{c^2}, \]  

(6)

with consideration \( \rho_\text{void} = P_\text{void}/w c^2 \),

\[ \Lambda = \frac{8\pi G P_\text{void}}{w c^2}. \]  

(7)

After formation of the structure in the cosmic scales, its dominant part is supervoids that are enclosed by superclusters. The effective pressure supposed in these scales stems from the surface tension produced on the interface between supervoids and superclusters. Therefore, due to the predominance of voids in large structure heterogeneities, the pressure difference in (1), can be equivalent to the effective pressure caused by the voids i.e. \( \Delta P \approx P_\text{void} \) and we can write,

\[ \Lambda = \frac{8\pi G}{w c^2} \frac{2y}{\bar{r}_\text{void}}. \]  

(8)

According to the relation obtained above, \( \Lambda \) in addition to the surface tension \( y \), depends another factor i.e. \( (\frac{1}{\bar{r}}) \), which is similar to the

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curvature term, we can choose both negative and positive sign for it depending on whether under study is global or local. Therefore, we can expect a positive and negative cosmological constant for global and local scales, respectively. We also note that according to the sign of curvature term one can talk of a de Sitter world matter ($\Lambda_{cs}$, positive, pressure negative) or an anti-de Sitter world matter ($\Lambda_{ns}$, negative, pressure positive) Cohen-Tannoudji & Gazeau (2021).

Since the effective force on galaxies from surface tension of supervoids at global scale is repulsive (with negative effective pressure), for dark energy EoS i.e.,$(w < 0)$, relations (2), (8) and (??) lead to a cosmological constant with the positive sign as follows,

$$\Lambda = \frac{16G M_i}{w_{	ext{cs}} c^2 R_{i}^2} > 0.$$  

(9)

According to a recent study, an intergalactic void is responsible for pushing the galaxies such as Andromeda or Milky Way at increasing speed through the universe Hoffman et al. (2017). Cosmic voids typically have a diameter of 100 Mpc i.e. $r_{\text{void}} = 1.54 \times 10^{24}$ m. Also, $G = 6.67 \times 10^{-11}$ m$^3$kg$^{-1}$s$^{-2}$, $w_{\text{Planck}} = -1.03 \pm 0.03$, and $c = 3 \times 10^8$ m.s$^{-1}$. By putting (3) and these values in equation (9), we can estimate the following value for the cosmological constant for $\gamma = 0.50 \times 10^{15}$ J.m$^{-2}$,

$$\Lambda = 1.2979 \times 10^{-52} \text{m}^{-2}.$$  

(10)

By using of the Planck 2018 values of $\Omega_{\Lambda} = 0.6889 \pm 0.0056$ and $H_0 = 67.66 \pm 0.42$(km/s)/Mpc, $\Lambda$ has the value of Aghanim et al. (2020)

$$\Lambda_{\text{obs}} = 3 \Omega_{\Lambda} \left( \frac{H_0}{c} \right)^2 = 1.1056 \times 10^{-52} \text{m}^{-2}.$$  

(11)

The cosmological constant value in relation (9) depends on both the surface energy and the radius of different voids, but for a mean size of the cosmic voids, the order obtained for cosmological constant at cosmic scale $\Lambda_{cs}$, in each case is very close to the observational value (11) and according to the first four rows of Table 1. is in the following range

$$0.6645 \times 10^{-52} \text{m}^{-2} \leq \Lambda_{cs} \leq 1.6172 \times 10^{-52} \text{m}^{-2}.$$  

(12)

Fortunately, the observational value (11) for cosmological constant is in this range. Looking at Table 1, we will find that smaller surface energy and cosmological constant are obtained for larger cosmic objects. At large scale due to the presence of galactic superclusters on the one hand and supervoids on the other, we will obtain the least value of surface tension. Therefore, the cosmological constant value, for example for Laniakea supercluster is equal to (10), which is very close to the observational value for the cosmological constant (11).

In Table 1, by considering the mass and approximate radius of the disc-shaped cosmic objects, we could obtain the surface tension for the two groups of objects. Then we will get the cosmological constant corresponding to each surface tensions according to (8). The values obtained in Table 1 show that for larger objects we will have smaller surface tension and therefore less cosmological constant and vice versa. The lowest surface tension is related to the superclusters that make up the walls of large cosmic voids, but the largest surface tension is related to the galaxies that make up the walls of local voids. So correspondingly, the maximum amount of cosmological constant for galaxies is $\Lambda_{\text{max}} = 2307.2800 \times 10^{-52} \text{m}^{-2}$ approximately 3472 times that of the minimum of it ($\Lambda_{\text{min}} = 0.6645 \times 10^{-52} \text{m}^{-2}$).

As a consequence of the dominance of supervoids with negative curvature at cosmic scale, we have shown by an interesting heuristic line of reasoning, that almost constant surface energy for the superclusters on the boundaries of supervoids acts as a cosmological constant and consequently acts as a driver in the accelerating motion of galaxies at large scales.

Many studies have shown that the presence of inhomogeneities in the structure of the universe plays a role in global expansion Rässänen 2011; Wiltshire 2011; Clarkson et al. 2011; Buchert & Rässänen 2012; Buchert et al. 2015). So more precisely in our model superclusters and supervoids as the largest present inhomogeneities are the result of structure formation. These two largest objects in the universe can coexist and can produce effective pressure in global and local scales. So far we have shown that the effective pressure caused by supervoids on a global scale acts as a potential source of dark energy. On the other hand, we speculate that collective force from merging supervoids may act as a possible source for dark matter. On this basis, we also predict that there are places in the universe that can not have dark matter. We will address this issue in the near future work.

5. SUMMARY AND SOME POSSIBLE CONSEQUENCES OF THE MODEL

We have proposed that the present cosmic fluid composed of two dynamical parts. On the one hand matters are clustering and on the other hand voids are merging, simultaneously. Since the dominant volume of the present cosmic web is formed by merging voids, based the our model, the negative pressure or repulsive gravity is inevitable at large scale. That is, the cosmic gas is considered as mixture of so many voids (bubbles), each of supervoids has repulsive force on galaxies, and hence the total effective pressure of the universe at large scale would become negative or repulsive. In other words, voids merge with other voids to form larger voids. As a result of this process, the galaxies on the shell of supervoids move away from each other. As an interesting point, the merging of the cosmic voids at their surfaces may produce both additional contracting (positive pressure) at local over-dense scales and accelerating (negative pressure) at large under-dense ones, simultaneously.

By dimensional calculating of the surface energy on the boundary of voids, we have obtained almost the same value of surface tensions for the supervoids enclosed by superclusters from the order of $O(10^{15})$ J.m$^{-2}$. Also, we have calculated acceptable range for global cosmological constant values that the observational value for $\Lambda$ is in this range.

| i. Cosmic object | $M_i$ (10$^{17}$kg) | $R_i$ (10$^{24}$m) | $\gamma_i$ (10$^{15}$J.m$^{-2}$) | $\Lambda_i$ (10$^{-52}$m$^{-2}$) |
|------------------|-------------------|-------------------|----------------------|-------------------|
| 1. Corona Sc     | 0.20              | 1.50              | 0.25                 | 6.6645            |
| 2. Virgo Sc      | 0.03              | 0.50              | 0.34                 | 0.8970            |
| 3. Laniakea Sc   | 1.00              | 2.40              | 0.50                 | 1.2979            |
| 4. Caelum Sc     | 4.00              | 4.30              | 0.62                 | 1.6172            |
| 5. Milky Way     | 0.00002           | 0.00087           | 75.74                | 1975.32           |
| 6. Andromeda     | 0.00003           | 0.001             | 85.98                | 2242.68           |
| 7. UGC02885      | 0.000004          | 0.00036           | 88.46                | 2307.28           |
As we know, the scale of the largest supervoids grows in the standard model and in the proposed model with cosmological time, and this probably has an effect on the cosmic equation-of-state and effective pressure of cosmic fluid. The effective equation-of-state for the cosmic fluid in our model has a negative value which is of the order of “1”. Since, our calculations are dimensional and approximate, so small changes in the amount of $w_{\text{eff}}$ do not have much effect on our calculations and results. In addition, it should be noted that in the real model the voids are very non-spherical and our results are at most a rough order-of-magnitude argument.

The key point of this work is that the universe has evolved from a matter-dominated cosmic fluid to a void-dominated one (instead of a vacuum-dominated). Therefore, the presence of such supervoids in this period is considered as the possible driver of the universe expansion and creates additional pressure on ordinary matter.

Highlights include:

1. The present cosmic fluid consists of two coexistent evolving parts, namely merging superclusters and merging supervoids.
2. In the proposed model, we have considered a fundamental role for cosmic voids and their surface tensions in the dynamics of the present universe at global scale.
3. Both negative effective pressure at the global scale and positive ones at local scales are introduced.
4. The almost constant surface tension on the supervoids shells reproduces a cosmological constant whose magnitude is as same as that confirmed by observational Planck data.

Since, the cosmological constant value depends on surface energy of clusters and the radius of voids, i.e. $\Lambda \sim \gamma/r_{\text{void}}$, at large-scale which supervoids are dominant, we have obtained very small values for the cosmological constants for the model of order $\left(10^{-52}\text{m}^{-2}\right)$, which are very close to those given by Planck 2018. However, on local scales we were led to the larger values with negative sign ($\Lambda_k \approx -10^{-49}\text{m}^{-2}$). It can be speculated that the surface tensions of supervoids on a local scale provide an additional effective force that holds galaxies, clusters, and superclusters together. Finally, the validity of the proposed model can also be further examined in the three years of observed dark energy survey data (DES Y3) Abott et al. (2021) as well as the Euclid mission Amendola et al. (2018). As a final point, we also expect that the proposed model is capable to solve the Hubble tension. Attempts are being made to investigate this issue.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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