Brimming Emptiness: A Study of Formation, Evolution and Dynamics of Cosmological Voids

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ABSTRACT
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Key words: large-scale structure – cosmological voids – void galaxies

1 INTRODUCTION

The scale of observable universe is immense. And on these mega-parsec scales, the distribution of matter is not uniform but rather forms a sprawling intricate nexus of galactic filaments, the largest known structures in the Universe, to form what is referred as the *cosmic web* (Bond et al. 1996). Although the most prominent and defining features of the cosmic web are the filaments, it is the vast under-dense regions called cosmological voids, practically devoid of any galaxy, which occupy the most of the space in the Universe (Libeskind et al. 2018; van de Weygaert 2014). Thus, voids are integral to understanding the spatial organization and evolution of the cosmic web (Icke 1984; Sahni et al. 1994; Sheth & van de Weygaert 2004; Einasto et al. 2011; Aragon-Calvo & Szalay 2013).

The insights aided by surveying projects like the 2dF (Two-degree field) Galaxy Redshift Survey (Colless et al. 2001) and the Sloan Digital Sky Survey (Tegmark et al. 2004) building upon early galaxy redshift surveys (Chincarini & Rood 1975; Gregory et al. 1978; Zeldovich et al. 1982) established voids as an integral component of the cosmic web. With further developments, it has now been realized that voids not only represent an integral part of the cosmic web but also act as excellent probes and measures of global cosmology (van de Weygaert 2014).

Voids contain a considerable amount of information on the underlying cosmological scenario and on global cosmological parameters. Notable cosmological imprints are found in the outflow velocities and accompanying redshift distortions (Martel & Wasserman 1990; Dekel & Rees 1994; Ryden & Melott 1996). The pristine low-density environment of voids represents an ideal and pure setting for the study of galaxy formation and the influence of cosmic environment on the formation of galaxies (Kreckel et al. 2011, 2012). Furthermore, voids have also been believed to have played a prominent role in the reionization process in the early Universe (Furlanetto et al. 2006; Morales & Wyithe 2010).

In this review of these crucial features of the cosmic web, we will start with building the foundations of cosmology and will explore how large-scale structures of the Universe can be quantitatively described. After that, we will build upon the existing reviews (van de Weygaert & Platen 2011; van de Weygaert 2014) to understand the formation, evolution and dynamics of voids and will comment on their current state of research by discussing theoretical models and how they complement to observations. We will also explore the void galaxies, the lonesome galaxies located in the voids, as they provide key constraints on our understanding of galaxy formation in a cosmological context (Kreckel et al. 2014). We will also discuss the discourses the study of cosmic voids has transpired in broader domains of cosmology relating to dark energy and the standard cosmological model. In the end, after contemplating the results, we will discuss the future of the research in this field.

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2 THE LARGE-SCALE UNIVERSE

In order to formally study large-scale structures of the Universe like cosmological voids, it is essential to be well-versed through fundamentals of physical cosmology. In this section, we will lay the foundations that trace their origins all the way back to Einstein's theory of general relativity and will develop techniques that enable us to quantitatively describe the large-scale Universe.

2.1 The Friedmann Equations

In 1922, using Einstein's field equations of gravitation for the Friedmann–Lemaître–Robertson–Walker metric and a perfect fluid with a given mass density ρ and pressure p, Alexander Friedmann derived his equations that govern the expansion of space in homogeneous and isotropic models of the universe (Friedman 1922). They are as follows:

$$\frac{\dot{a} + kc^2}{a^2} = \frac{8\pi G\rho + \Lambda c^2}{3} \tag{1}$$

and

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3} \tag{2}$$

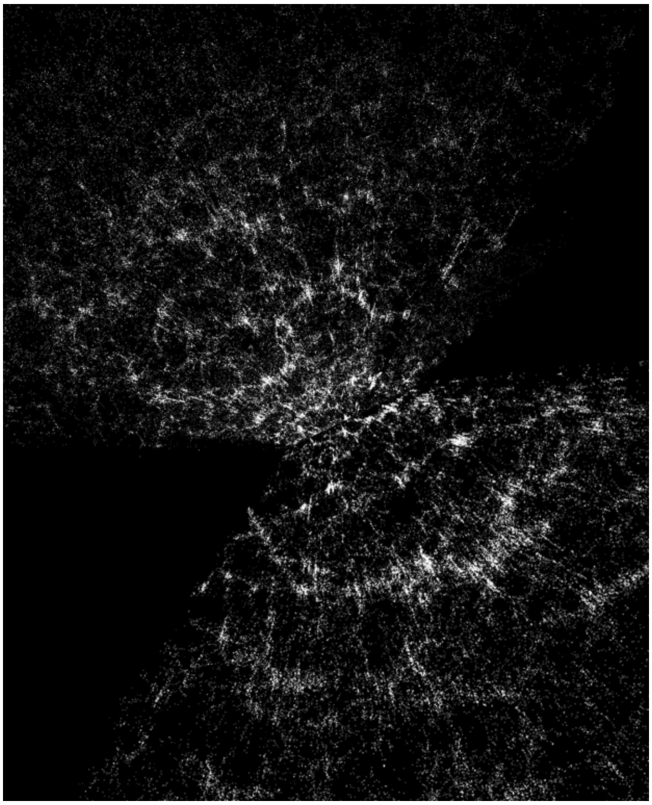

Figure 1. SDSS is the largest and most systematic sky survey in the history of astronomy. It is a combination of a sky survey in 5 optical bands of 25% of the celestial (northern) sphere. Each image is recorded on CCDs in these 5 bands. On the basis of the images/colours and their brightness a million galaxies are subsequently selected for spectroscopic follow-up. The total sky area covered by SDSS is 8452 square degrees. This image is taken from a movie made by Subbarao, Surendran and Landsberg (see website: `https://astro.uchicago.edu/research/cosmus.php`). It depicts the resulting redshift distribution after the 3rd public data release. It concerns 5282 square degrees and contained 528,640 spectra, of which 374,767 galaxies (van de Weygaert & Platen 2011).

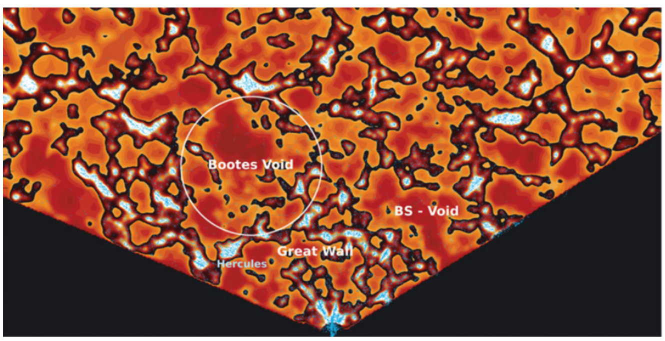

Figure 2. SDSS density map and galaxies in the a region of the SDSS galaxy redshift survey region containing the canonical Boötes void. The galaxies in the SDSS survey are superimposed as dark dots. The underdense voids are clearly outlined as the lighter region outside the high-density weblike filamentary and wall-like features (van de Weygaert 2014).

Here a is a dimensionless quantity called the scale factor and it is a function of time. The scale factor acts as a parameter which describes the relative expansion rate of the Universe. $\dot{a}$ and $\ddot{a}$ are with respect to time. k is a constant for a particular solution, G is the Newton's gravitational constant and Λ is the cosmological constant.

These equations lie at the core of every theoretical model in physical cosmology and the evolution of large-scale structures like filaments and voids is described most accurately by them.

2.2 Distance Measures

As the Universe is expanding with time, we need a framework to specify the distances between any two points in space at any point in time. This is important when it comes to analytically study large-scale structures of the Universe. The most well-known consequence of expansion of space is the cosmological redshift, defined as the fractional Doppler shift of its emitted light resulting from radial motion (Hogg 2000):

$$z \equiv \frac{\nu_e}{\nu_o} - 1 = \frac{\lambda_o}{\lambda_e} - 1 \tag{3}$$

where ν is the frequency, λ is the wavelength and subscripts e and o denote emitted and observed quantities respectively, *Hubble's law* is the observation that all sufficiently distant objects from Earth are moving away from it at speeds proportional to their distances.

There are many ways in which distances in cosmology are defined and they all are asymptotic to each other for small redshifts. Further, it is actually convenient to express these distances as functions of redshift since it is always an observable.

The *comoving distance* is one of the most important distance type and can be contrasted with *proper distance* as the distance which remains constant over cosmological time as it takes account for the expansion of the Universe. It is defined as:

$$d_C(z) = d_H \int_0^z \frac{dz'}{E(z')} \tag{4}$$

along the line of sight (LOS), where d_H is the *Hubble distance*, given by $d_H = c/H_0 \approx 3000\, h^{-1}$ Mpc $= 9.26 \times 10^{25}\, h^{-1}$ m, c being speed of light and H_0 is *Hubble parameter* at the present. The symbol h is the *dimensionless Hubble constant* and considered a unit itself. The Hubble constant is provides the mathematical form of the Hubble's law as $H_0 = v/D$ where v is the velocity of separation and D is cosmological time-dependent proper distance. Further, we define the *dimensionless Hubble parameter* (Peebles 1993):

$$E(z) = \frac{H(z)}{H_0} = \sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda} \tag{5}$$

Here, Ω_r, Ω_m and Ω_Λ are normalized values of the present radiation energy density, matter density, and *dark energy density,* respectively with $\Omega_k = 1 - \Omega_r - \Omega_m - \Omega_\Lambda$ determining the curvature.

In due course, we will see that catalogs courtesy of sky surveying projects like the *Sloan Digital Sky Survey* (SDSS) often report distances related to large scale-structures like voids in form of comoving distance so it is necessary to understand this development.

3 FORMATION, EVOLUTION AND DYNAMICS OF VOIDS

$$\frac{d^2\mathcal{R}_\mathrm{m}}{dt^2} = -4\pi G\rho_u(t)\left[\frac{1+\delta}{3} + \frac{1}{2}\left(\alpha_m - \frac{2}{3}\right)\delta\right]\mathcal{R}_\mathrm{m} - \tau_\mathrm{m}\mathcal{R}_\mathrm{m} + \Lambda R_m \tag{6}$$

3.1 Void Dyanmics

3.1.1 The Homegenous Ellipsodidal Model

3.2 Void Sociology

4 VOID GALAXIES

5 RESULTS

6 DISCUSSIONS

7 CONCLUSIONS

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DATA AVAILABILITY

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APPENDIX A: SOME EXTRA MATERIAL

If you want to present additional material which would interrupt the flow of the main paper, it can be placed in an Appendix which appears after the list of references.