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By

V. Sahni, B.S. Sathyaprakash and S.F. Shandarin

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Voids and their evolution in the adhesion model*

V. Sahni[1], B.S. Sathyaprakash[1], S.F. Shandarin[2]
[1]Inter-University Center for Astronomy and Astrophysics,
Post Bag 4, Ganeshkhind, Pune 411 007, India;
[2]Department of Physics and Astronomy,
University of Kansas, Lawrence, Kansas 66045, U.S.A.

Abstract. Properties of voids are studied using the adhesion approximation. In an Einstein-De Sitter Universe with a scale invariant spectrum $P(k) \propto k^n$, $-1 \leq n < 1$, the mean void size grows in proportion to $a(t)^{2/(n+3)}$ at late times.

Voids in the distribution of galaxies appear to be a fundamental feature of the Universe on scales greater than several Mpc. Theoretically one might define voids either as regions in which matter is underdense, or as regions matter from which has not yet shell-crossed. The latter is the operative definition which we shall use when studying voids in the adhesion approximation.

The dynamics of underdense regions differs when viewed in the framework of (a) linear perturbation theory (hereafter LT), and (b) in the context of nonlinear approximations such as the Zeldovich approximation (hereafter ZA) and the adhesion model (hereafter AM). In a spatially flat matter dominated Universe the linearised gravitational potential remains unchanged with time. The Poisson equation $\delta\rho/\rho = a\nabla^2\phi$ then suggests: $\delta\rho/\rho < 0 \Rightarrow \nabla^2\phi < 0$; *ie* underdense regions in LT are associated with regions in Lagrangian space where

$$\lambda_1(\vec{q}) + \lambda_2(\vec{q}) + \lambda_3(\vec{q}) < 0 \tag{1}$$

λ_i are eigenvalues of the deformation tensor $\partial^2\phi/\partial q_i \partial q_j$. Linear theory also predicts $\delta\rho/\rho \propto a(t)$, $a(t)$ being the scale factor of the Universe. For underdense regions the density contrast is bounded from below by $\delta\rho/\rho \geq -1$, as a result LT predictions for underdensities begin to progressively deteriorate as $(\delta\rho/\rho)_{lin} \to -1$.

ZA describes motion as a mapping between the initial (Lagrangian) and the final (Eulerian) comoving coordinate of a fluid element:

$$\mathbf{x} = \mathbf{q} - a(t)\nabla\Phi \tag{2}$$

where Φ is the linear velocity potential ($\phi \propto \Phi$, if the Universe is flat and matter dominated.) A consequence of (2) is that underdense regions in the Zeldovich approximation are described by

$$\frac{\rho}{\bar{\rho}} = \Big[[1 - a(t)\lambda_1(\mathbf{q})][1 - a(t)\lambda_2(\mathbf{q})][1 - a(t)\lambda_3(\mathbf{q})]\Big]^{-1} < 1 \tag{3}$$

which is satisfied when

$$\lambda_1(\vec{q}), \lambda_2(\vec{q}), \lambda_3(\vec{q}) < 0. \tag{4}$$

Clearly the Zeldovich condition (4) is more restrictive than (1). As a result voids according to ZA define a subclass of voids determined using linear theory. A common aspect of voids

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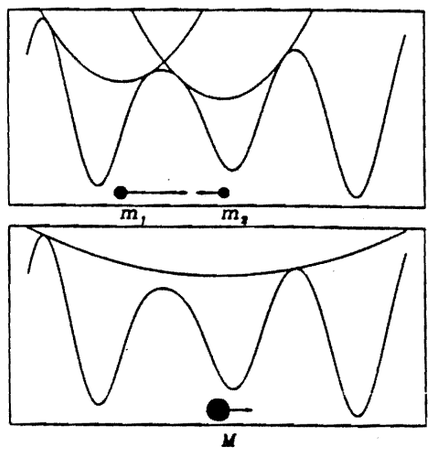


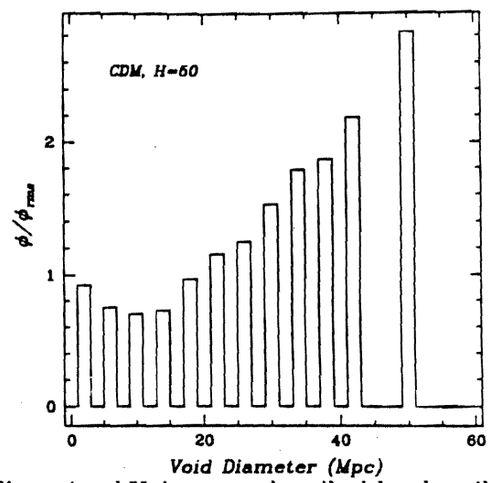
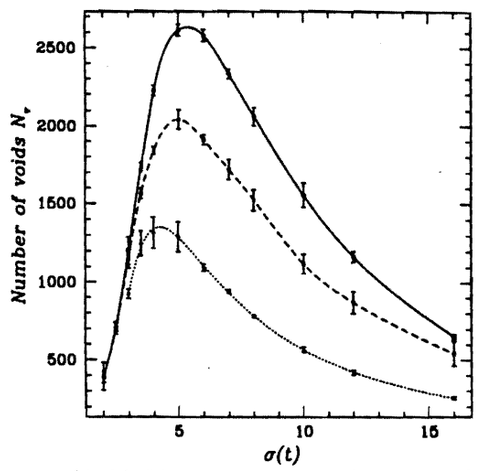


Fig. 1. (Left) Caustic formation in a model one-dimensional Universe as described by the adhesion model. The apex of the oscullating paraboloid describes the location of clumps; its radius of curvature is proportional to the growing mode of the linear density contrast. The top panel corresponds to an epoch when pancakes have just begun to form, the lower panel shows the merger of clumps and the associated dissapearence of small voids.

Fig. 2. (Right) The value of the primordial gravitational potential evaluated at the Lagrange center of a void is shown as a function of the void diameter (in units of its *rms* value ϕ_{rms}) for one realisation of the COBE - normalised CDM model.

defined in both LT and ZA is that since the inequalities (1) and (4) are local in nature, a region once designated to be a *void* remains void-like forever. One might however question the validity of using either (1) or (4) to define voids in the nonlinear regime after pancakes and other nonlinear objects have formed. Indeed, in order to follow the formation and evolution of voids into the strongly nonlinear epoch one must either use N-body simulations or extensions of the Zeldovich approximation such as the adhesion model [1,2,5,4,3].

In the adhesion model (AM) voids are defined as those regions matter from which has not yet shell crossed. This definition of voids is dynamic since matter continuously flows out of voids, and onto caustics such as pancakes, filaments and clumps, which form at the void periphery and mark the boundary between two neighboring voids. According to the geometrical interpretation of AM illustrated in figure 1 and discussed elsewhere ([4,3]), voids in Lagrange space are usually (but not always) associated with peaks in the linear gravitational potential. Since peaks of ϕ are also regions where $\lambda_i < 0$, one might expect the AM definition of voids to be identical to the Zeldovich prescription(4). This is in fact the case during the early stages of gravitational instability when pancakes are forming, at later stages however, neighboring voids compete for space which very often leads to void contraction and even disappearence under the influence of external shear. (Competition between neighboring voids prevents voids from being completely spherical, which would have been the case had they been isolated.) This aspect of the disappearence of voids is schematically illustrated in figure 1 which shows two successive epochs in the development of structure in a one dimensional Universe. In the uppermost figure caustics have just begun to form, all peaks of ϕ act as potential sites for void formation during this epoch. The lower figure illustrates a later epoch when clumps M_1 and M_2 have merged into a larger clump of mass $M \geq M_1 + M_2$. The location of M virtually coincides with the smallest of the three



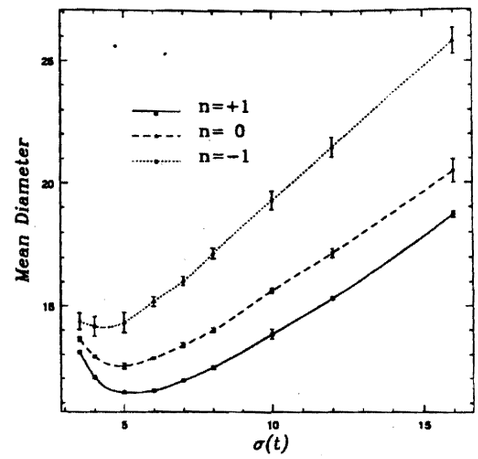


Fig. 3. (Left) The number of voids shown plotted against the scale factor for truncated power-law initial spectra: $n = 1$ (solid line), $n = 0$ (dashed line) and $n = -1$ (dotted line). Error bars indicate the *rms* dispersion from three simulations with different random phases.

Fig. 4. (Right) The mean void diameter is shown as a function of the scale factor for the same power spectra as in the previous figure.

peaks of ϕ illustrating that not all peaks of the potential contribute to void formation at later epochs. We therefore find that voids in AM form a diminishing (with time) subset of voids defined according to ZA.

We also find that a strong correlation exists between the sizes of voids in Euler space and the value ϕ evaluated at the center of the void. This suggests that matter which finally occupies large voids, was swept into these regions from neighborhoods where the value of the primordial potential was large. The correlation between the height of the primordial potential ϕ and the void diameter is shown in figure 2 for the three dimensional cold dark matter model (see [4] for details).

Other generic features of void formation and evolution determined using the adhesion model are summarised below. We find that as the Universe expands the number of voids in a given simulation first increases and then begins to decrease after having attained a maximum value. This is illustrated in figure 3 for truncated power-law spectra: $P(k) \propto k^n, n = 0, \pm 1$. $k \leq k_c$; $P(k) = 0$, $k \leq k_c$, $k_c = 16 \times k_f$. (k_f is the wavenumber of the fundamental mode). The associated behaviour of the mean void size $\bar{D}_{void}$ is shown in figure 4. The large initial value of $\bar{D}_{void} \simeq D_{box}$ is a consequence of the fact that during the early stages of gravitational instability most of the matter in the Universe has still not shell-crossed. The Universe can, at this early epoch, be regarded as a single large percolating void. As pancakes form in the primordial void they tesselate the latter into a number of smaller voids causing $\bar{D}_{void}$ to drop. The value of the mean void diameter continues to decrease as structure formation proceeds. The minimum value of $\bar{D}_{void}$ (maximum value of N_{void}) is reached when celular structure is completely formed. This occurs when $k_{NL}^{-1} \simeq R_*$ *ie* the scale length going nonlinear becomes comparable to R_* – the mean distance between peaks of the primordial potential. ($R_* = \sqrt{3}\sigma_1/\sigma_2$. σ_j are the moments of the distribution of ϕ: $\sigma_j^2 = \frac{1}{2\pi^2}\int dk k^2 k^{2j} |\phi_k|^2$.) It is interesting that the associated value of the *rms* density contrast $\sigma_* = \langle(\delta\rho/\rho)^2\rangle^{1/2} = \sigma(k_{NL}^{-1} = R_*)$ appears to be insensitive to the value of the

spectral index as demonstrated in figure 3. Prior to this epoch when $k_{NL}^{-1} < R_*$ the primary mode of gravitational instability is caused by pancaking – matter flowing from within voids into pancakes and then along them into filaments and clumps. During later epochs ($k_{NL}^{-1} > R_*$) the dominant mode of gravitational instability is hierarchical clustering which features the merger of clumps and the elimination of small voids. The number of voids in our simulations decreases during the hierarchical epoch, and the mean void size increases. For scale invariant spectra $P(k) \propto k^n$, $-1 \leq n < 1$ the increase in the mean void diameter is described by $\bar{D}_{void} \propto a(t)^{2/(n+3)}$.

Our studies also indicate that voids can be populated by substructure such as mini-Zeldovich pancakes. The likelyhood of a void being populated increases with its size and decreases with the cosmological epoch. Increasing observational evidence of substructure within voids seems to support the viewpoint that voids formed by gravitational instability as described initially by the Zeldovich approximation and later on by the adhesion model [3].

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