The Universe as a Cellular System

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ABSTRACT

Cellular systems are observed everywhere in nature, from crystal domains in metals, soap froth and cucumber cells to the network of cosmological voids. Surprisingly, despite their disparate scale and origin all cellular systems follow certain scaling laws relating their geometry, topology and dynamics. Using a cosmological N-body simulation we found that the Cosmic Web, the largest known cellular system, follows the same scaling relations seen elsewhere in nature. Our results extend the validity of scaling relations in cellular systems by over 30 orders of magnitude in scale with respect to previous studies. The dynamics of cellular systems can be used to interpret local observations such as the “local velocity anomaly” as the result of a collapsing void in our cosmic backyard. Moreover, scaling relations depend on the curvature of space, providing an independent measure of geometry.

Key words: Cosmology: large-scale structure of Universe; galaxies: kinematics and dynamics, Local Group; methods: data analysis, N-body simulations
A critical value $n_{\text{crit}}$ will in average collapse. This critical degree in $n_{\text{crit}} \sim 18$ at the present time. The Lewis law in addition to von Neumann law implies that below a critical radius $R_{\text{crit}} \sim 9h^{-1}$ Mpc voids collapse and above it they expand (Sutter et al. (2014)).

3 DISCUSSION

3.1 A collapsing void in our cosmic backyard

The geometry and dynamics of our own local cosmic environment has some similarities to a collapsing void scenario. In particular the existence of a population of luminous galaxies off the plane of the local wall (Peebles & Nusser 2011). If our local wall was formed by the collapse of a small void one would expect galaxies at opposite walls of the collapsing void to pass through the newly formed wall (Benitez-Llambay et al. 2013). This scenario is plausible given our position at the edge of a large supercluster in which the Milky Way and its surrounding voids are embedded inside a large shallow overdensity. We in fact have a dramatic example of such collapsing structures in our own cosmic backyard. Just opposite to the local void there is a filament of galaxies, the Leo Spur (Tully 2008), on the farther side of the “southern void” (the small void opposite to the Local Void) at a distance of ~ 7 Mpc approaching to us as a whole with a radial velocity of ~ 200 km/s. At that distance the velocity discrepancy with the unperturbed Hubble flow is of the order of 700 km/s! This “local velocity anomaly” (Tully 2008) cannot be fully explained by the nearby massive structures (Tully et al. 2008). It is, however, consistent with the void-in-cloud scenario described by Sheth & van de Weygaert (2004). From figures 2a and 2c we have that $R_{\text{crit}} = 18$ and $R_{\text{crit}} \sim 9$ Mpc comoving. If we add the Hubble expansion factor to convert to an observable velocity then $R_{\text{crit,obs}}$ is of the order of ~ 1 Mpc which is significantly lower than the radius of the “southern void” (~ 3.5 Mpc, Tully 2008). $R_{\text{crit,obs}}$ is the mean radius and so we should not be surprised to find variations due to particular LSS configurations. This high value in the rate of collapse of the southern void is worth further study.

3.2 The Void network as a standard ruler

In general cellular scaling relations assume a Euclidean geometry, however other space metrics are possible. The derivation of the von Neumann law assumes a flat geometry where the integral of the mean curvature $k$ around a cell is $2\pi$ (Avron & Levin (1992) generalized the von Neumann law to curved spaces as $dA/dt = K((n - 6) + (3A/\pi R^2))$, where $R$ is the radius of curvature. Roth et al. (2012) found a departure from the euclidean von Neumann law in 2D froth on a spherical dome interpreted as a result of the positively curved space being able to accommodate larger angles than the flat space. In the case of the network of Voids we should expect a dependence on the space metric resulting from different geometrical constraints. The Lewis, Aboav and von Neumann laws directly reflect the metric of space by means of the void-connectivity and size and therefore can provide a standard ruler for cosmology. The Lewis and Aboav relations can be measured from galaxy catalogues.
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APPENDIX A: COMPUTER SIMULATIONS AND VOID CATALOGUES

The results presented in this work are based on a N-body computer simulation containing $128^3$ dark matter particles inside a box of 256 $h^{-1}$ side with the standard ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.73$, $\sigma_8 = 0.8$. Starting at $z = 80$ we evolved the box to the present time using the N-body code GADGET-2 (Springel 2005) and stored 32 snapshots in logarithmic intervals of the expansion factor starting at $z = 10$. While the particle number may seem too low in fact for LSS studies it is sufficient since the smallest voids we are interested in are larger than a few Mpc in radius. The low particle number imposes a low-pass filter, removing unwanted structures arising from over-segmentation in the watershed method used to identify voids.

A1 Void identification and tracking

From the particle distribution at each of the 32 snapshots we computed a continuous density field on a regular grid of $512^3$ voxel size using a Lagrangian Sheet approach (Abel et al. 2012; Shandarin et al. 2012) as described in Aragon-Calvo & Yang (2014). The Lagrangian nature of this density estimation and interpolation method allows us to compute accurate densities at very early times and also at latter times inside voids where the particle arrangement is still close to a regular grid (see Fig. A2). Next we identified voids using the floating-point implementation of the watershed transform in the Spine pipeline (Aragón-Calvo et al. 2014). In order to further minimize over-segmentation of voids arising from spurious splitting of voids between snapshots we merged voids in adjacent snapshots if a void at a given snapshot had more than 70% of its volume in the next snapshot. The distribution of void sizes at two times is shown in Fig. A1. The effective void radius was computed from its volume as $R_{\text{void}} = ((3/4\pi)V_{\text{void}})^{1/3}$. For each void we identified its adjacent voids (voids that share a common wall) and created a void-graph with nodes corresponding to void centers and edges joining adjacent voids (this void-graph is a triangulation and is the dual of the cosmic web-graph which is a cellular system). This void-graph was used to compute the Lewis and Aboav relations in Fig. 2. In order to trace the evolution of individual voids (for the von Neumann relation) we created a void progenitor line in a similar way as in done by Aragon-Calvo et al. (2010b) but performing the linking across time (adjacent snapshots) instead of scale (hierarchical space).
Figure A1. Distribution of void sizes $R_{void}$ at $z = 0$ (solid line) and $z = 10$ (dashed line).

Figure A2. Density field computed with the Lagrangian Sheet approach $z = 0$. This density estimation is optimal for the near-regular particle distribution in the under-dense regions inside voids.

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