The Bridge Effect of Void Filaments

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ABSTRACT
Cosmic filaments play a role of bridges along which matter and gas accrete onto galaxies to trigger star formation and feed central black holes. Here we explore the correlations between the intrinsic properties of void galaxies and the linearity $R_L$ of void filaments (degree of filament’s straightness). We focus on void regions since the bridge effect of filaments should be most conspicuous in the pristine underdense regions like voids. Analyzing the Millennium-Run semi-analytic galaxy catalogue, we identify void filaments consisting of more than four galaxies (three edges) and calculate the means of central black hole mass, star formation rate, and stellar mass as a function of $R_L$. It is shown that the void galaxies constituting more straight filaments tend to have higher luminosity, more massive central black holes and higher star formation rate. Among the three properties, the central black hole mass is most strongly correlated with $R_L$. It is also shown that the dark halos constituting straight filaments tend to have similar masses. Our results suggest that the fuel-supply for central black holes and star formation of void galaxies occurs most efficiently along straight void filaments whose potential wells are generated by similar-mass dark halos.

Key words: cosmology:theory — large-scale structure of universe

1 INTRODUCTION
The spatial distribution of galaxies in the universe is quite anisotropic, forming a filamentary web on large scales, which is often called the cosmic web. The existence of cosmic web has been explained as a natural phenomenon caused by the large-scale coherence in the primordial tidal field (Bond et al. 1996). The physical properties of the galaxies located in the cosmic web are believed to be related to the merging/accretion history of the underlying dark halos, which in turn are affected not only by the local density but also by the tidal fields as manifested by the cosmic web. Although the effect of the tidal field on the galaxy’s properties is expected to be weaker than that of the density field, several numerical and observational evidences have recently been reported for the tidal influences on dark halos and galaxies. For instance, Desjacques (2008) has shown by N-body simulations that the tidal effect from the surrounding matter distribution causes earlier virializations of dark halos embedded in overdense environments. Hahn et al. (2008) have claimed using the results from high-resolution N-body experiments that the high densities of the regions with strong tidal forces induce the assembly bias (Gao et al. 2005). The link between the tidal field and galaxy properties have been also detected in real observations. It has been recently shown that the galaxy morphology and luminosity depend on the large scale tidal field (Lee & Erdogdu 2007; Lee & Lee 2008). When the density is constrained to a narrow range, more luminous and late-type galaxies are found to reside in regions with higher ellipticity.

In previous works, however, what has drawn little attention is the effect of the directions of the tidal forces on the galaxy properties. If the halo formation and the merging/accretion events occur preferentially along filaments, i.e., in the directions of the principal axes of the tidal field, the tendency of the spatial alignments of the tidal field should be taken into account when the tidal influences on the galaxy properties are explored. Very recently, Porter et al. (2008) have reported that the star formation rate of a galaxy is observed to be enhanced when it falls along a supercluster filament. This observational evidence suggests that the merging and accreting along the coherent directions of the tidal field trigger the star formation more efficiently.

In practice, the degree of the tidal alignment can be quantified by measuring the straightness of a filament. The more straight a filament is, the stronger the tidal alignment is. Here, we propose a hypothesis that the highly coherent accretion of matter and flow of gas along straight filaments trigger the star formation and feed the central black holes most efficiently. We call it the bridge effect of the filaments. To test this hypothesis, we investigate the cross-correlations...
between the stellar mass, central black hole mass, and star formation rate of the void galaxies and the straightness of the filaments where the galaxies are located. The reason that we consider only void regions for this investigation is that the strong effect of the density field can be controlled to a minimum level in the extreme underdense regions like voids.

The organization of this paper is as follows. In §2, we analyze the data from the Millennium Run semi-analytic catalogue. In §3, we explore the correlations between the properties of void galaxies and the linearity of host filaments. A summary of the results and the final conclusion are given in §4.

2 DATA

We use the void catalogue that was constructed in our previous work (Park & Lee 2007), by applying the void-finding algorithm of Barrow et al. (1985) to the Millennium-Run semi-analytic galaxy catalogue (Springel et al. 2005). As done in our companion paper (Park & Lee 2009, hereafter PL09), we first select those large voids which contain more than 30 galaxies and then apply the filament finding algorithm of Barrow et al. (1983) to the selected voids. The filament finding algorithm of Barrow et al. (1983) basically utilizes the minimal spanning tree (MST) technique to identify filamentary structures. A detailed description of the filament-identification in the Millennium voids is provided in PL09. Here we provide a concise summary of it.

For each selected void, we construct a MST of the void galaxies as follows: A starting galaxy (i.e., a node) is linked to its nearest neighbor galaxy by a straight line (i.e., an edge). This partial tree is extended by connecting it to the next nearest neighbor void galaxy. When all galaxies in a given void are connected, a MST is obtained. Then, we reduce the MST of each void to identify the filaments through pruning and separating processes. Each MST is pruned at the $p$-level by removing the small-scale twigs. The pruned MSTs are separated into several distinct shorter pieces by removing those edges longer than a given length-threshold, $l_e$. The level of pruning and the length threshold are set at $p = 5$ and $l_e = \bar{l} + \sigma_l$, respectively, where $\bar{l}$ and $\sigma_l$ denote the mean edge-length averaged over all unreduced MSTs and its standard deviation, respectively (PL09). It is worth mentioning that the pruning level was set at $p = 4$ in PL09 where the void filaments were found from the dark halos identified by the Friends-of-Friends (FOF) algorithm since the size distribution of void filaments were found to become stabilized at $p \geq 4$. Now that the void filaments are found using not the FOF halos but the galaxies in the current analysis, we notice that the size distribution of void filaments becomes stabilized when the pruning level is $p \geq 5$. The origin of this difference in the value of $p$ lies in the fact that the galaxies correspond to the smaller-size substructures of the FOF halos. When the galaxies are used to construct the MSTs, the MSTs have more twigs and more superfluous small-scale noise. That is why a higher level $p = 5$ is required to prune the MSTs.

The size of each filament, $S$, is measured as the spatial extent of the filament galaxies (see eq.[1] in PL09), and the linearity of a given filament $R_L$, which is introduced to quantify the filament straightness, is measured as the ratio of the end-to-end distance to the total length (Barrow et al. 1983). The range of $R_L$ is $[0,1]$ and the degree of the filament straightness increases with $R_L$. Note that the value of $R_L$ is biased toward the small value of $S$. The shortest filaments that contain only one edge (i.e., two nodes) have $R_L = 1$ by definition. To study the correlations between the properties of void galaxies and the linearity of void filaments, it should be required to select only long filaments since the short filaments are dominant in the high linearity section, causing a bias in the measurement of correlations. In other words, to find true correlations between $R_L$ and void galaxy’s properties, it is necessary to put some lower limit ($n_c$) on the number of filament’s edges. Fig. 1 plots the mean sizes of the void filaments as a function of $R_L$, for the five different cases of the edge-threshold ($n_c = 1, 2, 3, 4$ and 5 as dotted, dot-dashed, dashed, solid and long dashed line respectively). As can be seen, for all cases $\langle S \rangle$ decreases as $R_L$ increases. But, for $n_c \geq 4$ (long-dashed and solid lines), $\langle S \rangle$ does not decreases significantly with $R_L$ in the high-linearity range of $R_L > 0.7$. Using this empirical result, we choose $n_c = 4$ and select only those filaments which consist of 4 edges or more (i.e., five galaxies or more).

Table 1 lists the statistical properties of the void filaments. The first row corresponds to the case where no edge threshold is applied (one edge or more), while the second one corresponds to the case that only those filaments with $n_c = 4$ are considered. As can be seen, the mean linearity of the void filaments is low when the edge-threshold, $n_c = 4$, is applied. It indicates that the short-size filaments dominate the high-linearity section. Fig. 2 illustrates two examples of the void filaments with two different values of $R_L$, demonstrating clearly that the higher the value of $R_L$ is, the more straight a filament is.

![Figure 1](image-url)
3 THE BRIDGE EFFECT

3.1 Linearity vs. Galaxy Property

The void filaments correspond to deep potential wells within which excess of matter and gas can exist in otherwise extremely underdense environments. They bridge the void galaxies onto which matter and gas from the surrounding large scale structures accrete and flow along their longest-axis directions. Therefore, the coherent accretion and flow of matter and gas may occur more efficiently in more straight filaments. It is expected that there may be a link between the physical properties of void galaxies and the linearity of their parent filaments, caused by this bridge effect of void filaments.

We measure $R_L$ of the selected void filaments and bin the values of their linearity $R_L$. Then, we calculate the mean values of central black hole mass ($M_{\text{CBH}}$), stellar mass ($M_{\text{star}}$), total mass ($M_{\text{total}}$), and the star formation rate (SFR) of the void galaxies constituting a given void filaments with $R_L$ in a differential range of $[R_L, R_L + dR_L]$.

Here $M_{\text{total}}$ means the sum of all gas masses in the catalogue. Fig. 3 plots the means of the central black hole mass (top-left), stellar mass (top-right), total gas mass (bottom-left), and star formation rate (bottom-right) as a function of parent filament’s linearity, $R_L$. In each panel the dotted line corresponds to the mean value averaged over all void filaments. The errors are calculated as $\langle \Delta P^2 \rangle^{1/2}/\sqrt{N_b}$ where $N_b$ is the number of void filaments belonging to a given bin of $R_L$ and $P_G$ represents a given galaxy property. As can be seen, the four different properties show a similar trend. The mean value of galaxy’s property increases as the value of $R_L$ increases. That is, the void galaxies constituting more straight filaments tend to be more luminous, more massive, having more massive central black holes and higher star formation rate.

To see which property is most strongly correlated with $R_L$, we calculate the linear correlation coefficient between $R_L$ and $P_G$ as:

$$\xi_{P_G} = \frac{\langle R_L P_G \rangle}{\sqrt{\langle R_L^2 \rangle \langle P_G^2 \rangle}}$$

Table 2 lists the values of $\xi_{P_G}$ for the four different galaxy properties. As can be seen, the central black hole mass is most strongly correlated with $R_L$. The star formation rate is also quite strongly correlated with $R_L$. This results indicate that the the coherent matter-accretion and gas-flow along the straight filaments feed the central black holes and trigger the star formation efficiently.

Table 1. Edge-cut $n_c$, total number of void filaments $N_f$, mean number of void filaments per a void ($\bar{n}_f$), mean length of void filaments ($\bar{R}_f$) in unit of $h^{-1}\text{Mpc}$, and mean linearity of void filaments ($\bar{R}_L$).

| $n_c$ | $N_f$ | $\bar{n}_f$ | $\bar{R}_f$ | $\bar{R}_L$ |
|------|------|------------|------------|------------|
| 1    | 58554| 4          | 9.2        | 0.73       |
| 4    | 29755| 2          | 13.8       | 0.56       |

1 $M_{\text{total}} = M_{\text{star}} + M_{\text{bulge}} + M_{\text{coldGas}} + M_{\text{hotGas}} + M_{\text{ejected}} + M_{\text{CBH}}$
Figure 3. Means of the central black hole mass (top-left), the stellar mass (top-right), the total mass (bottom-left), and the star formation rate (bottom-right) averaged over the constituent galaxies as a function of the host filament’s linearity. In each panel the horizontal dotted line corresponds to the mean values averaged over all filaments.

Table 2. The linear correlation coefficients.

| \(\xi_{\text{CBH}}\) | \(\xi_{\text{star}}\) | \(\xi_{\text{total}}\) | \(\xi_{\text{SFR}}\) |
|---------------------|--------------------|---------------------|---------------------|
| 0.89                | 0.69               | 0.67                | 0.85                |

3.2 Linearity vs. Halo Mass

Now that strong correlations between the linearity of void filaments and the physical properties of void galaxies are found, we would like to investigate the dependence of the mass of void halos on the linearity of their filament’s linearity, using the catalogue of the filaments of void halos that was constructed in PL09. For each filament of void halos, we determine the maximum mass \(M_{\text{max}}\) and the minimum mass \(M_{\text{min}}\) among the masses of the constituent halos. Then, we calculate the means of \(M_{\text{max}}\) and \(M_{\text{min}}\) as a function of \(R_L\).

Fig. 4 plots \(\langle M_{\text{max}} \rangle\) and \(\langle M_{\text{min}} \rangle\) as a function of \(R_L\) in the left and right panels, respectively. The errors in each panel is calculated as \((\Delta M^2)^{1/2}/\sqrt{N_b}\). As can be seen, the value of \(\langle M_{\text{max}} \rangle\) decreases almost monotonically with \(R_L\).
while the value of $\langle M_{\min} \rangle$ increases monotonically with $R_L$. It indicates that the differences among the masses of void halos are smaller when the parent filaments are more straight. To see this more clearly, we calculate the mean values of $M_{\max} - M_{\min}$ as a function of $R_L$ which is plotted in Fig. 5. It is now obvious that the difference decreases as $R_L$ increases. In other words, the dark halos that constitute straight filaments tend to have similar masses. The efficient matter-accretion along straight filaments tend to synchronize the masses of void halos and regulate the shapes of potential wells of the void filaments to be flat.

4 SUMMARY AND DISCUSSION

We have found strong correlations of the stellar mass, central black hole mass and star formation rate of void galaxies with the linearity of their parent filaments. Among the three properties of void galaxies, the masses of the central black holes are mostly strongly correlated with the linearity of void filaments. The existence of this cross-correlations indicates the bridge effect of void filaments. Matter and gas from the surrounding large-scale structures accrete and flow onto the void galaxies more efficiently along the more straight filaments. The dark halos constituting straight filaments are found to have similar masses, which implies that the potential wells generated by straight void filaments have rather flat-shaped bottoms. The efficient accretion of matter along straight filaments tend to reduce mass difference among the constituent void halos.

It is interesting to note that our results may provide an explanation on high specific star formation rate of void galaxies and high activity of void AGNs found in data from the Sloan Digital Sky Survey (Constantin et al. 2008; Rojas et al. 2002). The void filaments should be more straight on average than the wall filaments since the non-linear effect that can distort the filaments is less strong in void regions. Thus, matter-accretion and gas-flow along more straight void filaments are likely to supply more efficiently fuel for the stars and AGNs of the void galaxies.
It is, however, worth noting that our results are subject to the specific choice of the void-finding algorithm and the filament-finding algorithm. Unlike bound halos, neither voids nor filaments can be uniquely defined. As shown in the current seminal work of Colberg et al. (2008), the voids identified by the HV02 algorithm tend to be relatively large in size compared with those found by different void-finders. Thus, if other algorithms were used, then it would have been difficult to find long filaments in voids.

Besides, our results are based on numerical data from the Millennium Run simulations. To confirm the existence of the bridge effect of void filaments, an observational analysis dealing with real data is required. Unfortunately, however, it is quite unlikely to obtain any meaningful statistics about the bridge effect of void filaments from the currently available observational data. As first pointed out by Peebles (2001), the observed voids look apparently much emptier than the simulated voids, containing very few galaxies (e.g., Foster & Nelson 2009). It is believed that this discrepancy between simulation and observation on voids indicates not the failure of the concordance cosmology but the limitation of current observational technique. Anyway it would be extremely difficult to find as many void filaments as necessary for statistical analysis from the current available observational data. Hence, we think that an observational test of our results is beyond the scope of this paper. It is concluded that our numerical finding of the bridge effect of void filaments may provide a new insight about how galaxies form and evolve in a ΛCDM cosmology.

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