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Detecting multi-scale filaments in galaxy distribution

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Abstract. The main feature of the spatial large-scale galaxy distribution is its intricate network of galaxy filaments. This network is spanned by the galaxy locations that can be interpreted as a three-dimensional point distribution. The global properties of the point process can be measured by different statistical methods, which, however, do not describe directly the structure elements. The morphology of the large-scale structure, on the other hand, is an important property of the galaxy distribution. Here, we apply an object point process with interactions (the Bisous model) to trace and extract the filamentary network in the presently largest galaxy redshift survey, the Sloan Digital Sky Survey (SDSS data release 10). We search for multi-scale filaments in the galaxy distribution that have a radius of about 0.5, 1.0, 2.0, and 4.0 h^{-1}Mpc. We extract the spines of the filamentary network and divide the detected network into single filaments.

Keywords. Methods: data analysis, methods: statistical, large-scale structure of Universe.

1. Introduction

Large galaxy redshift surveys reveal that the Universe has a salient weblike structure, called the cosmic web (Jõeveer & Einasto 1978; Bond *et al.* 1996). The cosmic web consists of highly complex geometrical patterns. Of these patterns, the most dominant ones are galaxy clusters at the intersections of filaments and filaments at the intersections of walls. These web elements display structures and substructures over a wide range of scales. Their hierarchical and interconnected nature is the defining characteristics of the web. However, identifying and describing the cosmic network is not a trivial task due to the overwhelming complexity of the structures, their connectivity and the intrinsic multi-scale nature.

Translating the visual impression of the cosmic web into an algorithm that classifies the local geometry into different environments is not a trivial task, and much work is being done in this direction. In this work, the detection of filaments is performed using a marked point process with interactions, called Bisous model (Stoica *et al.* 2005). This model approximates the filamentary network by a random configuration of small segments or cylinders that interact and connect while building the network. The model was already successfully applied to observational data and to mock catalogues (Stoica *et al.* 2007,2010). This approach has the advantage that it works directly with the original point process and does not require smoothing to create a continuous density field. Our method can be applied to relatively poorly sampled data sets, as the galaxy maps are; it can be applied both to observations and simulations.

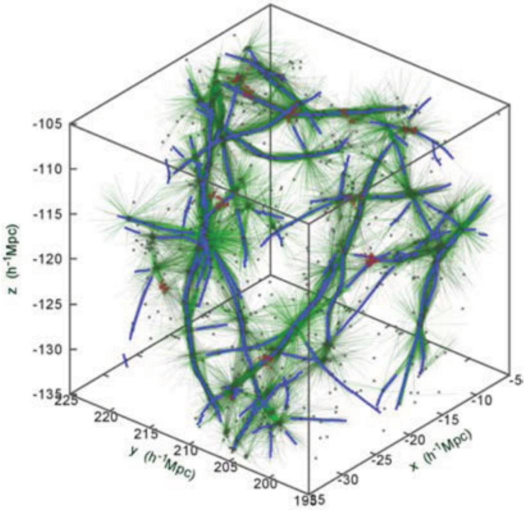

Figure 1. Detected filamentary pattern (cylinder axes) in a small sample volume within a pattern of galaxies (points). Galaxies in groups with 10 or more members are shown with red points; other galaxies are shown with grey points. Green lines show the cylinders from 1000 realisations (it corresponds to the visit map) used to extract the filament spines. The extracted filament spines are shown with blue lines.

2. Galaxy sample

The present work is based on the Sloan Digital Sky Survey (York *et al.* 2000) data release 10 (Ahn *et al.* 2014). We use the galaxy and group samples as compiled in Tempel *et al.* (2014b) that cover the main contiguous area of the survey. The flux-limited catalogue extends to 574 h^{-1}Mpc and includes 588193 galaxies and 82458 groups. In Tempel *et al.* (2014b) the finger-of-god effect is suppressed using the detected galaxy groups.

3. Bisous model

The catalogue of filaments is built by applying an object point process with interactions (the Bisous process; Stoica *et al.* 2005) to the distribution of galaxies. The method and parameters are exactly the same as in Tempel *et al.* (2014a), where the Bisous model was applied to the SDSS DR8 data. The assumed scale (radius) for the extracted filaments in the current study is roughly 0.5, 1.0, 2.0, and 4.0 h^{-1}Mpc.

A detailed description of the Bisous model is given in Stoica *et al.* (2007,2010) and Tempel *et al.* (2014b). In the Bisous algorithm, random segments (thin cylinders) based on the positions of galaxies are used to form the filamentary network according to the connection and alignment rules between these segments. The morphological and quantitative characteristics of these complex geometrical objects can be obtained by following a straightforward procedure: constructing a model, sampling the probability density describing the model, and, finally, applying the methods of statistical inference. In practice, after fixing the approximate scale of the filaments, the algorithm returns filament detection probability and filament orientation fields. The filament probability field is detected using a Markov-Chain Monte-Carlo scheme that effectively samples a large parameter space. A deterministic filamentary pattern spine can be extracted based on the detection probability and filament orientation fields. Using this method, we extract single filaments in the survey.

The Bisous model takes full advantage of the Bayesian data analysis, one of the most successful and increasingly popular tools in statistical analysis nowadays. The application of Bayesian analysis grants the Bisous model a big advantage over the other methods – the probabilistic nature. The Bisous model does not attempt to classify the web into strict components. Instead, it assigns a confidence estimate to each detected structure. The filamentary network is modelled as a whole and the connectivity between structures is intrinsically implemented to the model.

Figure 1 shows the result of Bisous model. The filament probability field is shown with green lines and the orientation of lines illustrates the filament orientation field. The detected filament spines are shown as blue lines.

4. Implications

The major driving force shaping the cosmic web is the large-scale tidal field. The gravitational collapse amplifies any initial anisotropies to give rise to highly asymmetrical structures, exhibiting strong planar or filamentary characteristics. Since filaments are the dominant features in the cosmic web, a better understanding of them could reveal the principal structure formation and evolution processes and the energy state of the Universe at different cosmological epochs. Since dark energy affects the speed of structure formation, the statistics of galaxy filaments would provide insight into the driving forces behind the web formation. Distinctive signatures of different dark energy models can be detected by analysing the statistics of cosmic structures.

Until now, the full research potential of galactic filaments has not yet been utilised. Comparing e.g. with galaxy clusters and cosmic voids, filaments are very rarely used as a probe of cosmology and also the role of filaments in galactic evolution is poorly known. In principle, statistics of galaxy filament properties, such as length, width and connectivity, can be used to measure the large-scale structure and to test cosmological as well as galaxy formation models.

Galaxy formation and evolution is largely affected by the environment where they reside. One of the unknowns of galaxy formation is the dominant scale (and structure) that determines the formation scenario of a given galaxy. The answer to this question is not straightforward, since the speed of structure evolution itself depends on the large-scale environment. Therefore it is not easy to disentangle general structure evolution from galaxy evolution.

Analysing the multi-scale nature of cosmic structures will potentially help to understand some of the unknown factors in structure and galaxy formation scenarios.

References

Ahn, C. P., Alexandroff, R., Allende Prieto, C., *et al.* 2014, *ApJS*, 211, 17

Bond, J. R., Kofman, L., & Pogosyan, D. 1996, *Nature* 380, 603

Jõeveer, M. & Einasto, J. 1978, in M. S. Longair, J. Einasto (eds.), *Large Scale Structures in the Universe*, Proc. IAU Symposium No. 79, 241

Stoica, R. S., Gregori, P., & Mateu, J. 2005, *Stochastic Processes and their Applications*, 115, 1860

Stoica, R. S., Martínez, V. J., & Saar, E. 2007, *Journal of the Royal Statistical Society Series C*, 56, 459

Stoica, R. S., Martínez, V. J., & Saar, E. 2010, *A&A*, 510, A38

Tempel, E., Stoica, R. S., Martínez, V. J., Liivamägi, L. J., Castellan, G., & Saar, E. 2014a, *MNRAS*, 438, 3465

Tempel, E., Tamm, A., Gramann, M., Tuvikene, T., Liivamägi, L. J., Suhhonenko, I., Kipper, R., Einasto, M., & Saar, E. 2014b, *A&A*, 566, A1

York, D. G., Adelman, J., Anderson, Jr., J. E., *et al.* 2000, *AJ*, 120, 1579