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Bisous model—Detecting filamentary patterns in point processes[☆]

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ABSTRACT

The cosmic web is a highly complex geometrical pattern, with galaxy clusters at the intersection of filaments and filaments at the intersection of walls. Identifying and describing the filamentary network is not a trivial task due to the overwhelming complexity of the structure, its connectivity and the intrinsic hierarchical nature. To detect and quantify galactic filaments we use the Bisous model, which is a marked point process built to model multi-dimensional patterns. The Bisous filament finder works directly with the galaxy distribution data and the model intrinsically takes into account the connectivity of the filamentary network. The Bisous model generates the visit map (the probability to find a filament at a given point) together with the filament orientation field. Using these two fields, we can extract filament spines from the data. Together with this paper we publish the computer code for the Bisous model that is made available in GitHub. The Bisous filament finder has been successfully used in several cosmological applications and further development of the model will allow to detect the filamentary network also in photometric redshift surveys, using the full redshift posterior. We also want to encourage the astro-statistical community to use the model and to connect it with all other existing methods for filamentary pattern detection and characterisation.

1. Introduction

Galaxies, the main building blocks of our Universe, are not uniformly distributed in space. Instead, they form various structures: groups, clusters, chains, filaments, sheets, etc. Galactic filaments are the most prominent part of such a structure, containing nearly half of the total mass of the Universe (Jasche et al., 2010; Tempel et al., 2014c).

Until now, the properties of galactic filaments have not yet been utilised fully. Compared, 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 their length, width and connectivity, can be used to measure the large-scale structure and to test cosmological as well as galaxy formation models. However, detection and definition of filaments has remained problematic so far. Although filamentary structures are easily recognised visually in galaxy survey data, their complicated hierarchical nature does not allow a straightforward mathematical extraction and quantification.

A variety of methods has been proposed (e.g. based on Minkowski functionals, local topological measures, minimal spanning trees, tessellations, skeleton analysis, kinematics) that attempt to tackle the problem, briefly overviewed by Cautun et al. (2014). These include the methods that classify all the cosmic web elements simultaneously (Hahn et al., 2007; Aragón-Calvo et al., 2010; Falck et al., 2012; Hoffman et al., 2012; Smith et al., 2012; Cautun et al., 2013; Leclercq et al., 2015) or are specifically meant for filament detection (Bond et al., 2010; González and Padilla, 2010; Sousbie, 2011; Alpaslan et al., 2014; Chen et al., 2015).

The first attempts of filament identification have already given some surprising results. For example, filaments have been found in voids (Beygu et al., 2013) and other low-density environments (called tendrils: Alpaslan et al., 2014). These examples demonstrate the potential of filament studies to take us closer to understanding the structure formation in the Universe.

In the current paper we use the Bisous model, a probabilistic filament finder that takes an advantage of the Bayesian framework

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[☆] This code is registered at the ASCL with the code entry ascl:1512.008.

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and is straightforward to apply to observational datasets. Our approach to filament detection uses a marked point process that takes into account the connectivity of the filamentary network, i.e. whether or not a given filament is linked to other filament(s). The mathematical basis of the method has been described and proved in Stoica et al. (2005a,b, 2007b, 2010, 2014). This model for filament detection has been developed especially for application to observational datasets in cosmology. In Tempel et al. (2014c) we applied the Bisous model to the Sloan Digital Sky Survey (SDSS) data and published a catalogue of filaments for the SDSS.[1]

The Bisous model fits well in a Bayesian framework that may be considered as an advantage over the conventional methods. 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 in the model. To tackle the large parameter space and global optimisation, the model uses the Markov-chain Monte Carlo (MCMC) sampling together with simulated tempering and simulated annealing.

Tempel et al. (2014b) tested the Bisous model on simulated data. Although they used only the spatial distribution of galaxies/haloes as input, the detected filaments turned out to follow also the underlying velocity field of the simulation, thus indicating that the recovered Bisous filaments are real dynamical structures, not just apparent configurations of galaxies. Similar conclusions were reached by Libeskind et al. (2015), using observations of the local Universe.

Filaments are in the non-linear dynamical stage of evolution between the linear and fully virialised objects, and filament evolution in simulations has gained a lot of focus during recent years. For example Bond et al. (2010) analysed the evolution of the distribution of filaments and their properties. They found that most of the filaments are already in place from high redshifts and that most of their evolution is restricted to changes in filament size. Choi et al. (2010) showed that filament widths are most sensitive to the non-linear growth of structure. Recently, an in-depth study of galactic filaments in simulations was made by Cautun et al. (2014). To move further on, the evolution of actual filaments detected from observations has to be analysed and compared with simulations. This requires advanced observational methods for filament identification, such as the Bisous model.

During recent years, the Bisous model has been extensively used to analyse the filamentary structure in general and to study the influence of the filamentary environment on galaxy/group evolution and formation. Tempel et al. (2013) and Tempel and Libeskind (2013) showed that the alignment of major axes of galaxies with respect to galactic filaments depends on galaxy morphology. Guo et al. (2015) showed that isolated galaxies that are located in filaments have up to two times more satellites and the satellites tend to be aligned with galactic filaments (Tempel et al., 2015). The alignment of structures seems to be a universal trend, having been confirmed in various studies since Tempel and Tamm (2015) showed that galaxy pairs in filaments are very well aligned with the underlying structure. The analysis presented in Tempel et al. (2014a) indicates that the distribution of galaxies and groups along the filaments has also some regularity. These successful applications of the Bisous filament finder form a good ground to develop the model further for other astronomical applications.

The aim of this paper is to review the model presentation, in order to emphasise those mathematical and applied aspects of the Bisous model directly linked with the computational use and numerical implementation of the model. We also want to encourage the astro-statistical community to use the Bisous model, and to compare and connect this model with other methods for filamentary pattern detection and characterisation.

The general outline of the paper is the following. In Section 2 we give a brief description of the mathematical background and tools used. Section 3 explains the motivation and strategies to choose the parameters for the Bisous model. Section 4 outlines the algorithm used to extract single filament spines from the model output. An example is given in Section 5 and the conclusions are presented in Section 6. The computer code for the Bisous filament finder is made available through GitHub[2] and Appendix gives a brief description of how to download and install the program.

2. Mathematical tools

In this section we briefly describe the main tools we use to detect the filamentary pattern in the galaxy distribution. We outline the key points that are important to understand the code for the Bisous model. The description follows Tempel et al. (2014c), for details of the mathematical model we refer to Stoica et al. (2005a, 2007b, 2010).

2.1. Bisous model

The marked point process we use for filament detection is different from conventional point processes used in the field. The Bisous process models the structure outlined by galaxy positions, not the distribution of galaxies themselves.

We designate K as a finite volume ($0 < \nu(K) < \infty$), where a finite number of galaxies ($\mathbf{d} = \{d_1, \dots, d_n\}$) are observed. Our aim is to model the filamentary network outlined by the positions of galaxies.

The main hypothesis of our work is that the filamentary network can be modelled by a random configuration of connected and aligned cylinders—a realisation of a marked point process. Here the points (objects) are the centres of cylinders and marks are the length and orientation of cylinders (given with a uniform law). Note that this is different from the common use of point processes in cosmological studies, where the points are centres of galaxies. In the Bisous model, the centres of galaxies are just used to calculate the probability for filaments (see below).

A cylinder is an object given by its centre $k \in K$ and the shape parameters. The shape of a cylinder is characterised by its radius r, the length h, and the orientation vector $\omega = \left(\sqrt{1-\tau^2}\cos(\eta), \sqrt{1-\tau^2}\sin(\eta),\ \tau\right)$. We denote the cylinder together with its mark (the set of parameters) by $s(y) = s(k, r, h, \omega) \subset K$.

Each cylinder $s(y)$ has two end points. Around these points spheres of radius r_{a} are centred, forming the attraction regions. These regions are used to define the connectivity and alignment rules for the model (see Section 2.2). The basic cylinder within a field of galaxies is illustrated in Fig. 1.

Let $\mathbf{y} = \{y_1 = (k_1, m_1), \dots, y_n = (k_n, m_n)\}$ be a configuration of cylinders, where the cylinder mark is denoted by m_i. The "simplest" random configuration of cylinders is the stationary Poisson process of unit intensity. This process is constructed in two steps. First, the number of cylinders n is chosen according to a Poisson distribution of the parameter $\nu(K)$. Then the cylinder marks (lengths and the orientation vectors) are chosen, independently and identically distributed with $\nu(M)$, the given marks distribution over the marks space M (see Tempel et al., 2014c). In

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[1] The catalogue is available at http://cosmodb.to.ee.

[2] https://github.com/etempel/bisous.