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A structural and dynamical study of the Hercules supercluster

Vitor H. Y. Fugivala[1], Rogério Monteiro-Oliveira[2,1] & André L. B. Ribeiro[1]

[1] Universidade Estadual de Santa Cruz; e-mail: vitor.fugivala@gmail.com, albr@uesc.br
[2] Academia Sinica Institute of Astronomy and Astrophysics; e-mail: rogerionline@gmail.com

Abstract. Superclusters of galaxies are non-virialized structures spanning tens of megaparsecs in space, composed of clusters, cosmic filaments and voids. However, there is no consensus on the exact definition of a supercluster. In this study, we adopt the definition of a supercluster as a gravitationally bound large-scale structure that will collapse in the future. We use the Hercules supercluster ($z \approx 0.038$) as a laboratory to test different methods of detection and characterization. Three methods are highlighted: galaxy cluster membership classification via machine learning, luminosity-density field estimation and theoretical radius calculation in a spherical collapse model. The latter two methods allowed us to delineate the boundaries of Hercules and identify five Abell clusters within it (A2151, A2147, A2152, A2153, and A2159), along with three additional substructures (A, B, and C). Despite that, we cannot assert that all these objects are gravitationally connected. We also identified that the densities of A2153 and A2159 closely resemble the background density, suggesting that these clusters may not be situated at Hercules' redshift. A dynamic study will be necessary to determine which structures truly belong to the supercluster, thus providing a framework to explore other superclusters and refine the cataloging of cosmic web components.

Resumo. Superaglomerados de galáxias são estruturas não virializadas que ocupam dezenas de megaparsecs no espaço, compostos por aglomerados, filamentos e vazios cósmico. No entanto, não há consenso quanto à definição exata de um superaglomerado. Neste trabalho adotamos a definição de superaglomerado como uma estrutura em grande escala gravitacionalmente ligada, que irá colapsar no futuro. Utilizamos o superaglomerado de Hércules ($z \approx 0.038$) como laboratório para testar diferentes métodos de detecção e caracterização. Destacamos três métodos: classificação de pertencimento de galáxias a aglomerados via aprendizado de máquina, estimativa do campo de densidade de luminosidade e cálculo do raio teórico no modelo de colapso esférico. Os dois últimos métodos permitiram delinear os limites de Hércules e identificar cinco aglomerados de Abell em seu interior (A2151, A2147, A2152, A2153 e A2159), além de outras três subestruturas (A, B e C). Apesar disso, não podemos afirmar que todos esses objetos estão ligados gravitacionalmente. Também identificamos que as densidades de A2153 e A2159 se assemelham muito à densidade de fundo, sendo possível que estes aglomerados não estejam situados no *redshift* de Hércules. Um estudo dinâmico será necessário para afirmar quais estruturas realmente fazem parte do superaglomerado, com isso teremos um arsenal para explorar outros superaglomerados e aprimorar a catalogação das componentes da teia cósmica.

Keywords. galaxies: clusters: general – large-scale structure of Universe

1. Introduction

In the current understanding of the universe, the standard cosmological model (ΛCDM) incorporates dark energy and cold dark matter to explain the large-scale structure and accelerated expansion of the cosmos. Within this framework, clusters of galaxies are the most recent virialized structures, formed by accretion of smaller and less massive halos. Moving to the next scale, we find superclusters of galaxies, the largest overdense regions extending over tens of megaparsecs; these gigantic structures intertwine with cosmic voids to shape the cosmic web (Einasto et al. 1980). Superclusters are found in a variety of dynamic states, as they host interactions between clusters of galaxies and also filaments that supply these with gas (Kuchner et al. 2022).

There is no universal agreement on how to define a supercluster. In this study, we will use the definition of a supercluster as a gravitationally bound large-scale structure, which will collapse in the future. The most usual detection procedure is carried out using a friends-of-friends algorithm, by connecting overdense neighboring regions within a linking length. However, this approach can include structures that are not bound to the supercluster. We pick the Hercules supercluster as a laboratory to test the accuracy of various detection methods in recognizing gravitationally linked structures.

The main body of the Hercules supercluster is comprised of Abell clusters A2151, A2152 and A2147 (Barmby & Huchra 1998). Other studies suggest that additional clusters are members of Hercules, such as A2153 and A2159 (Santiago-Bautista et al. 2020). Furthermore, Einasto et al. (2001) proposes that there are 12 Abell clusters within Hercules' neighborhood. These few examples illustrate how different methods and definitions can lead to different pictures of a supercluster.

In this work, we map Hercules supercluster's density field using both spectroscopic and photometric data, identify its boundaries using a luminosity-density threshold and two theoretical radii. We aim to produce a broader view of the supercluster's history and future with this study.

2. Methods

We used data from the Sloan Digital Sky Survey (SDSS) DR17 located inside a circular region with radius of 4.5° centered on $\alpha, \delta = (240.57792, +16.020)$, with an apparent magnitude completeness limit of $m_r \leq 17.78$.

In the first step, we implemented a kernel density estimator to calculate the luminosity-density field (Fig. 1), given by

$$D(r) = \sum_{i=1}^{N} K(r_i, \sigma) L_i, \quad (1)$$

where $K(r_i, \sigma)$ is the Epanechnikov kernel used to smooth the galaxy distribution and $\sigma = 8h^{-1}$ Mpc is the smoothing parame-

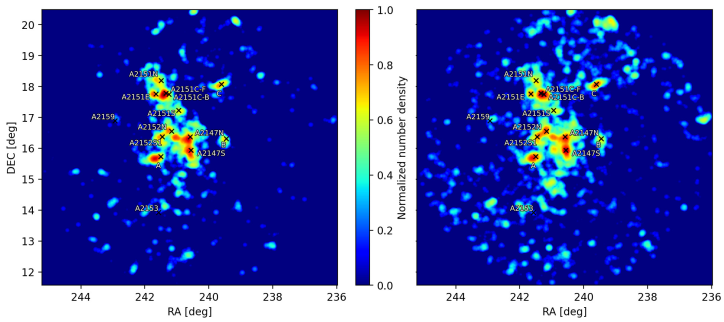

Figure 1. Left side: smoothed number density map for 1240 SDSS's SpecObj galaxies in the Hercules supercluster (radius of ~12.4 Mpc) within a redshift slice of $0.02832 \leq z \leq 0.04899$. Right side: 2922 photometrically selected galaxies identified as cluster members by RPM algorithm within $z \geq 0$. Substructures are marked with black cross marks.

ter,

$$K(r,\sigma) = \begin{cases} \frac{3}{4}\left[1-\left(\frac{r}{\sigma}\right)^2\right], & r \leq \sigma, \\ 0, & r > \sigma. \end{cases} \quad (2)$$

L_i is the r-band luminosity weight of a galaxy located in r_i,

$$L_i = 10^{-0.4(M_{r_i} - M_{r\text{com}})}, \quad (3)$$

where $M_{r_{\text{com}}} \leq -18.40$ is the completeness limit in luminosity.

The first method is a machine learning method developed by Lopes & Ribeiro (2020) to determine galaxy cluster membership based on photometric properties (Fig. 1, right side), such as photo-z, *ugriz* magnitudes, colors, among others. We employ this method to obtain a density map that is not solely dependent on spectroscopic information, which is not always available.

For the second method, we used the *spatial.ConvexHull* algorithm from Python library *SciPy* to compute the smallest convex polygon that encloses galaxies above a density threshold of luminosity-density D = 8.0 L_{mean} (Fig. 2). This value is used by Einasto et al. (2001) to define a supercluster.

Finally, in the third method, we employed two theoretical radii (r_0) to define a shell within which all mass inside is expected to remain bound to the central gravitational attractor in a distant future (Fig. 3), considering a spherical collapse model on an expanding universe (Busha et al. 2003; Dünner et al. 2006),

$$\frac{M_{\text{obj}}}{10^{12} M_\odot} \geq \begin{cases} 1.18 h_{70}^2 \left(\frac{r_o}{1\text{Mpc}}\right)^3 \\ 3 h_{70}^2 \left(\frac{r_o}{1\text{Mpc}}\right)^3 \end{cases}, \quad (4)$$

using a total estimated mass of $M_{\text{obj}} = 2.1 \pm 0.2 \times 10^{15} M_\odot$ for the Hercules supercluster by Monteiro-Oliveira et al. (2022).

3. Results and Conclusions

We obtained the luminosity-density map of the Hercules supercluster using both spectroscopic and photometric redshifts (Fig. 1). We can see the substructures identified by Monteiro-Oliveira et al. (2022) marked with crosses. It is noticeable that A2153 and A2159 show weak density values on both maps, suggesting that they might not belong to Hercules' redshift range.

We also identified the 3D structure enveloping the Hercules supercluster (Fig. 2) based on a luminosity-density threshold value. In Fig. 3 we can see that all substructures are inside the three obtained boundaries. However, this does not imply that they are gravitationally bound.

A dynamical analysis is required to check which structures are actually members of Hercules. Future work will involve studying the peculiar velocity field in the supercluster region and dynamical simulations using the physical parameters of the substructures, mainly their masses.

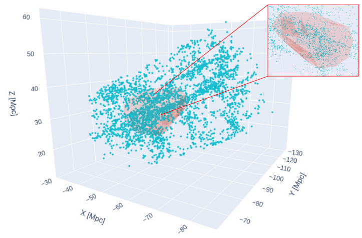

Figure 2. Hercules supercluster boundaries traced by a convex hull enclosing a region with luminosity-density $D > 8.0\, L_{\text{mean}}$.

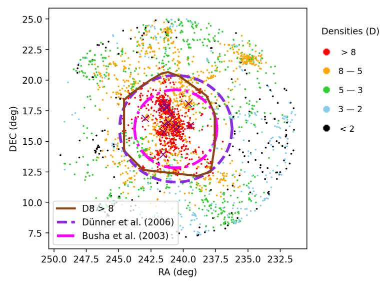

Figure 3. Same data from Fig. 1, left side, and Fig. 2. Galaxies are divided by colors representing the luminosity-density (D) values on their positions in units of the mean luminosity-density of the field. The brown line shows the projection of the red contour in Fig. 2. Cross marks correspond to substructures from Fig. 1. Pink and purple circles correspond to theoretical radii from spherical collapse models (Eq. 4).

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