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Cosmological simulations to investigate properties of gas and dark matter filaments

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Abstract. Filaments are the largest known structures in the universe. They are made up of stars, gas and dark matter and are gravitationally bound structures. Filaments of the cosmic web play an important role in the formation of galaxies, since it is in this region that most of the gas is found. In this work, our objective was to characterize the properties of the filaments, in a cosmological simulation. To this end, we analyzed the distribution of gas and dark matter in a filament region at redshift 2.3. With the code GADGET-2, we performed a hydrodynamic simulation of the ΛCDM Universe, with 256^3 gas particles, 256^3 dark matter particles and a box 10 Mpc wide. From this, we measured a radial density profile with the baryonic and dark component of the filaments. Then we performed a theoretical density profile fit. We found that 26% of the gas contained in the Universe is considered hot. Moreover, we constructed a radial temperature profile and found that, in the central regions, large filaments present higher temperature when compared to smaller filaments. Our best fit results suggest that there is a core of constant density in the density profile. We analyzed a filament of size 2.5 Mpc and found that the core density and core radius, respectively, are $\rho_0 = 1.9 \times 10^{-28}$ g cm^{-3}, $r_0 = 31$ kpc for gas and $\rho_0 = 8.2 \times 10^{-28}$g cm^{-3}, $r_0 = 33$ kpc for dark matter. The other filament we analyzed is 1 Mpc long and we obtained $\rho_0 = 3.6 \times 10^{-28}$ g cm^{-3}, $r_0 = 33$ kpc for gas and $\rho_0 = 3.2 \times 10^{-28}$ g cm^{-3}, $r_0 = 21$ kpc for dark matter. The results suggest that the smaller filaments are more compact, that is, they have a smaller nucleus and higher central density.

Resumo. Filamentos são as maiores estruturas conhecidas no universo. Eles são constituidos de estrelas, gás e matéria escura e são estruturas gravitacionalmente ligadas. Os filamentos da teia cósmica desempenham um papel importante na formação das galáxias, visto que, é nessa região que a maior parte do gás é encontrada. Neste trabalho, nosso objetivo foi caracterizar as propriedades dos filamentos, em uma simulação cosmológica. Para isso, analisamos a distribuição de gás e matéria escura em uma região de filamento em redshift 2.3. Com o código GADGET-2, realizamos uma simulação hidrodinâmica do Universo ΛCDM, com 256^3 partículas de gás, 256^3 partículas de matéria escura e uma caixa com 10 Mpc de largura. A partir disso, medimos um perfil de densidade radial com a componente bariônica e escura dos filamentos, em seguida, realizamos um ajuste de perfil de densidade teórico. Além disso, encontramos que 26% do gás contido no Universo é considerado quente. Ademais, medimos um perfil radial de temperatura e encontramos que, nas regiões centrais, os filamentos grandes apresentam maior temperatura quando comparados com filamentos menores. Os resultados do nosso melhor ajuste sugerem haver um núcleo de densidade constante no perfil de densidade. Analisamos um filamento de tamanho 2.5 Mpc e obtivemos que a densidade do núcleo e o raio do núcleo, respectivamente, são $\rho_0 = 1.9 \times 10^{-28}$ g cm^{-3}, $r_0 = 31$ kpc para gás e $\rho_0 = 8.2 \times 10^{-28}$g cm^{-3}, $r_0 = 33$ kpc para matéria escura. O outro filamento que analisamos tem 1 Mpc de comprimento e encontramos $\rho_0 = 3.6 \times 10^{-28}$ g cm^{-3}, $r_0 = 33$ kpc para gás e $\rho_0 = 3.2 \times 10^{-28}$ g cm^{-3}, $r_0 = 21$ kpc para a matéria escura. Os resultados sugerem que os filamentos menores são mais compactos, ou seja, apresentam um núcleo menor e densidade central mais elevada.

Keywords. Cosmology: miscellaneous – large-scale structure of Universe – dark matter

1. Introduction

Large galaxy surveys such as the Sloan Digital Sky Survey (SDSS) and the Two-degree-Field Galaxy Redshift Survey (2dF-GRS) have performed large sweeps of the sky and have catalogued millions of galaxies. These observations have evidenced the presence of anisotropic structures in the nearby Universe, such as filaments, halos and large voids. These structures are consequences of a gravitational instability of a medium that was relatively homogeneous at the beginning of the Universe. The non-linear density fluctuations evolved until reaching the configuration observed today. Cosmological simulations arise to explain the formation and evolution of these structures (Ramsøy et al. 2021). In this work, we measured the density distribution of gas and dark matter along large and small filaments and the behavior of gas temperature.

2. Simulation

In this work, we performed a hydrodynamic cosmological simulation with the GADGET2 code and using the parameters described by the cosmological model ΛCDM, with: $\Omega_m = 0.3158$, $\Omega_b = 0.0494$, $\Omega_\Lambda = 0.6842$, $H_0 = 67.3$ km s^{-1} Mpc^{-1} (Planck Collaboration. 2016). We simulated a Universe of side 10 Mpc. This box size provided a great resolution of the filamentary structures. For this simulation, we used 256^3 gas particles and 256^3 dark matter particles leading to a mass resolution of $M_{\rm DM} = 6.5 \times 10^6$ M$_\odot$ and $M_{\rm gas} = 1.2 \times 10^6$ M$_\odot$. The simulation started at $z = 99$ and progressed to $z = 2.3$, because we aimed to study the properties of the filaments at high redshift (see Fig 1). All these initial conditions were generated by the monofonIC code. At the end of the simulation, dark matter halos were found using the ROCKSTAR code.

Filaments are elongated structures with intermediate densities. We defined as a filament all particles located between pairs of halos, which are relatively close to each other in a three-dimensional coordinate system. Together, a visual inspection was carried out to elect the candidates for filaments. In Fig. 2 we have an example of a structure chosen as a filament.

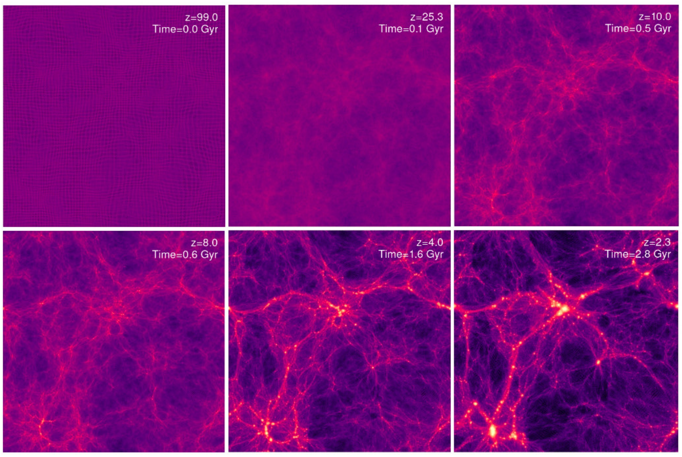

Figure 1. Time evolution of a hydrodynamic cosmological simulation, where the colors represent the density of matter in the Universe.

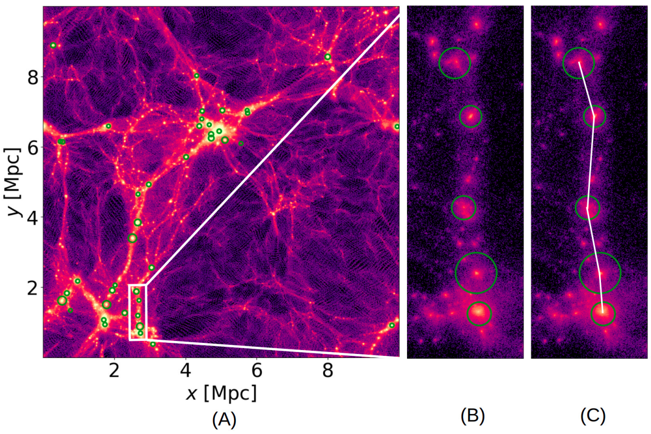

Figure 2. Image (A) refers to the visualization of the cosmological simulation with their respective dark matter halos circled in green, at $z = 2.3$. In image (B), we have a regional enlargement of (A), where a filament structure that can be analyzed is illustrated. In part (C) the central axis of each segment of the filament is shown. Each one undergoes a translation and two rotations to perform the radial density profile.

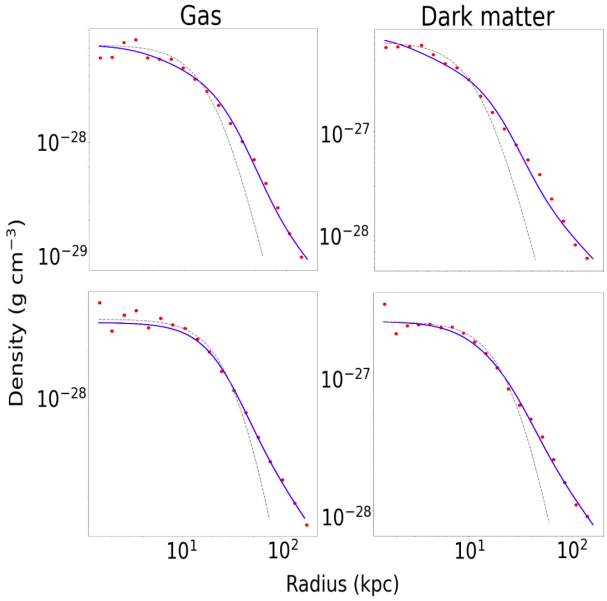

Figure 3. Radial density profile of two filaments the first one (top) of 1.0 Mpc and the other (bottom) of 2.5 Mpc long, where the red dots represent the average density of the cylindrical shells for each average radius, the gray and blue curve are fitted density profiles.

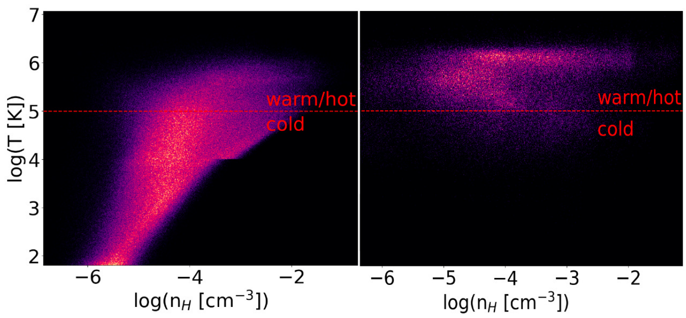

Figure 4. On the left is the gas phase diagram of the entire simulation and on the right is the phase diagram of the filamentary region. The red line separates the hot and cold gas, where the hot gas is the one with a temperature greater than 5 × 10 5 K.

3. Results

We analyzed two filaments, the first one of size 2.5 Mpc and the second with 1 Mpc (see Fig. 3). To measure the radial density profile, we use the following equation (Ramsøy et al. 2021):

$$\rho(r) = \frac{\rho_0}{\left[1 + (r/r_0)^2\right]^2} + \frac{\rho_1 r_1}{r} \tanh\left(\frac{\pi r}{2 r_1}\right). \quad (1)$$

Our best fit results suggest a constant density core in the density profile. We found, to the largest filament, a core density and a core radius, respectively, are $\rho_0 = 1.9 \times 10^{-28}$ g cm^{-3}, $r_0 = 31$ kpc for gas and $\rho_0 = 8.2 \times 10^{-28}$g cm^{-3}, $r_0 = 33$ kpc for dark matter. To the smaller filament we found $\rho_0 = 3.6 \times 10^{-28}$ g cm^{-3}, $r_0 =$ 33 kpc for gas and $\rho_0 = 3.2 \times 10^{-28}$ g cm^{-3}, $r_0 = 21$ kpc for dark matter. The results suggest that the smaller filaments are more compact, that is, they have a smaller nucleus and higher central density.

Furthermore, we constructed a phase diagram of the entire simulation, Fig. 4, and found that 26% of the Universe's gas fraction has temperatures greater than 5×10^5 K, at $z = 2.3$. Also, we found that almost all the gas in the filament region is hot.

4. Conclusion

We obtained that 26% of the gas in the Universe is hot, at $z = 2.3$. In addition, we selected two filaments, one large and one small, and found that all analyzed filaments have a central core where the density remains constant. This core is larger for large filaments. Furthermore, the central density in small filaments is higher than in large ones, that is, small filaments are more compact. However, when it comes to temperature, the more central regions of the larger filaments are hotter.

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References

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