Dark Matter–Dark Energy Interaction and the Shape of Cosmic Voids

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Abstract

Interaction between dark matter (DM) and dark energy (DE) is one of the not completely solved problems in cosmology that has been studied extensively. This interaction affects cosmic structures. In this regard, the shape of cosmic voids can be influenced by the DM and DE interaction. Here, employing the dynamical DE model constrained by observational data, we study the effects of this interaction on the ellipticity of cosmic voids. With this aim, we apply the linear growth of density perturbation in the presence of interaction. The probability-density distribution for the ellipticity of cosmic voids is investigated. The results confirm that the ellipticity of cosmic voids increases when the DM and DE interaction is considered.

1. Introduction

Based on observational data, dark matter (DM) and dark energy (DE) interact nongravitationally (Costa et al. 2014; Wang et al. 2016). SN Ia Union 2.1 data have been applied to reconstruct the interaction between DE and DM (Yang et al. 2015). Cosmological models with direct couplings between DM and DE have been probed by cosmological observations (van de Bruck & Mifsud 2018). Coupling between DE and DM, with an energy transfer either from DM to DE, or the reverse, has been constrained by the cosmological data (Guo et al. 2007; Barreiro et al. 2010; He et al. 2011; Koivisto & Nunes 2013; Pilyan et al. 2014; Yang & Xu 2014; Valiviita & Palmgren 2015; Fay 2016; Murgia et al. 2016; Yang et al. 2017, 2019; An et al. 2018; van de Bruck & Mifsud 2018).

Different observational data such as cosmic microwave background (CMB) shift parameter, baryon acoustic oscillation (BAO); lookback time and Gold supernovae sample (Micheletti et al. 2009); optical, X-ray, and weak lensing data from galaxy clusters (Abdalla et al. 2009); and relaxed galaxy clusters (Abdalla et al. 2010) show energy decay from DE into DM (Cardenas et al. 2019). Energy transfer from DM to DE has also been suggested (Wang & Wang 2014; Kumar & Nunes 2017).

The effects of the interaction coupling between dark components on the evolution of the universe have been studied (Zimdahl et al. 2001; Binder & Kremer 2006; Valiviita et al. 2008; Jackson et al. 2009; Sun & Yue 2012). Coupling between DM and DE is compatible with an accelerated expansion of the universe (Zimdahl et al. 2001; Jackson et al. 2009). A nonrelativistic DM component that interacts with DE can affect the behavior of the deceleration parameter, density parameters, and luminosity distance (Binder & Kremer 2006). Interaction between DE and DM changes from negative to positive as the expansion of our universe changes from decelerated to accelerated (Valiviita et al. 2008; Sun & Yue 2012). Solving the coincidence problem by considering the coupling between DE and DM has been explored (Gonzalez & Quiros 2008; He & Wang 2008).

Interaction between DE and DM has been studied using the CMB data (Pavon et al. 2004; Amendola et al. 2007; Linton et al. 2018). Employing the WMAP results for the location of the CMB peaks shows that interacting models are consistent with the observational bounds (Pavon et al. 2004). The presence of a constant coupling between DE and DM increases the tension between the CMB data from the analysis of the shift parameter in models with constant DE equation of state parameter and SN Ia data (Amendola et al. 2007). The effects of interaction on the CMB and linear matter power spectrum have been investigated (Linton et al. 2018).

DM–DE interaction can affect the structure formation at different scales and times. Coupling between DE and cold DM (CDM) fluid results in the evolution of CDM and baryon distributions in structure formation (Baldi et al. 2010), instability in the dark sector perturbations at early times (Valiviita et al. 2008), large-scale deviations in the power spectrum (Duniya et al. 2015), and late-time transitions from DM to DE domination (Dutta et al. 2018). Structure growth has been investigated in the coupled DE models (Calder-Cabreral et al. 2009; Baldi & Viel 2010; Simpson 2010; Carbore et al. 2013; Carlesi et al. 2014; Bonometto et al. 2015; Giocoli et al. 2015; Pace et al. 2015; Tamanini 2015; Poutsioud & Gram 2016, L’Huillier et al. 2017). An enhancement (suppression) of the growth factor takes place when the energy transfer in the background goes from DM to DE (DE to DM) (Calder-Cabreral et al. 2009). The growth of large-scale structure is suppressed because of the elastic interaction between DM and DE (Simpson 2010). The standard coupled DE model gives the enhanced growth of linear CDM density fluctuations (Carbone et al. 2013). DM and DE coupling increases the growth of the perturbations and the effective friction term in nonlinear dynamics (Pace et al. 2015). Coupling in the dark sector, which leads to a bulk dissipative pressure, can suppress structure formation at small scales (Tamanini 2015). Considering the DM–DE interaction, structure growth is suppressed and the tension between CMB observations and structure growth inferred from cluster counts can be explained (Poutsioud & Gram 2016). The structure growth rate is also influenced by the DM–DE interaction (Bean et al. 2008; Schaefer 2008; Marcondes et al. 2016; Mifsud & van de Bruck 2017). With the DM–DE couplings, the structure growth rate shows a different time evolution (Schaefer 2008). Considering the large coupling strength, the instability leads to the exponential
growth of small-scale modes (Bean et al. 2008). Employing the GLAMER gravitational lensing code verifies that the coupling between DE and CDM is confirmed from the redshift evolution of the normalization of the convergence power spectrum, as well as nonlinear structure formation (Giocoli et al. 2015). Applying the growth index parameterization, an analytic formula for the growth rate of structures in a coupled DE model has been presented (Marcondes et al. 2016). Disformal coupling between DM and DE results in intermediate scales and time-dependent damped oscillatory features in the matter growth rate function (Mifsud & van de Bruck 2017).

Cosmic voids, the empty spaces in the large-scale structure of the universe, are influenced by DE. A dynamical DE component forms these voids in response to gravitationally collapsing matter (Dutta & Maor 2007). Clustering of DE and the DE density perturbations alter the structure formation within voids (Mota et al. 2008). The evolution of the ellipticity of cosmic voids is an important probe of the DE equation of state (Lee & Park 2009; de Lavaux & Fairbairn 2011; Pisani et al. 2015). The properties of DE affect the shape of voids through the ellipticity distribution of voids in large-scale structures (Biswas et al. 2010). Cosmological simulations employing different models for DE verify the sensitivity of void shapes to the nature of DE (Bos et al. 2012).

Interaction between DM and DE also alters cosmic voids (Mainini 2009; Elyiv et al. 2015; Sutter et al. 2015; Pollina et al. 2016; Adermann et al. 2017, 2018; Hashim et al. 2018). In cosmological models with coupling between DE and DM, a further contribution to the Integrated Sachs Wolfe effect arises during the matter-dominated era due to the DE perturbations associated with very large voids of matter (Mainini 2009). Void catalogs can be applied to distinguish a model of coupled DM–DE from ΛCDM cosmology due to the properties of cosmic voids (Sutter et al. 2015). DM–DE coupling leads to larger voids as well as broader, shallower, and undercompensated profiles for large voids (Sutter et al. 2015). Applying two void finders and a halo catalog extracted from the CODECS simulations, which are the largest suite of publicly available cosmological and hydrodynamical simulations of interacting DE cosmologies, the interacting DE models have been investigated (Elyiv et al. 2015). Filling factor, size distribution, and stacked profiles of cosmic voids can be affected by the DE coupling (Pollina et al. 2016). In cosmological models with evolving and interacting dark sectors, N-body simulations confirm that the presence of a coupled dark sector can be observable through the void statistics (Adermann et al. 2017). The coupling of the dark sector slows down the evacuation of matter from voids (Adermann et al. 2017). Studying the structural properties of cosmic voids in a coupled DM–DE model confirms that the void merger rate within this model is greater than that in a ΛCDM one (Adermann et al. 2018). A coupled DM–DE model results in more large voids and delays the matter evacuation from voids because of the drag force acting on baryonic particles moving out of voids (Adermann et al. 2018). N-body simulations of interacting DE model have been done to explore the structural properties of the cosmic voids (Hashim et al. 2018). Their results show that the internal structural properties of cosmic voids such as the void density profile are different from the ΛCDM one. According to the above discussions, we can deduce that the DM–DE interaction can affect the shape of cosmic voids. Here, we study the ellipticity of cosmic voids in the evolving DE models considering the DM–DE interaction.

2. Cosmological Model with Dynamical Interacting Dark Energy

In this section, we describe the cosmological framework in which we investigate the cosmic voids with interacting DE. First, the energy exchange between DM and DE and the approach to quantify the coupling between dark sectors are presented. Then, applying the dynamical DE equation of state, we illustrate the linear growth of density perturbation in the coupled cosmology.

2.1. Interacting Dark Sectors

To describe the DM–DE interaction, we introduce \( \rho_{\text{int}}^\text{DM} \) as the DM–DE interaction energy density. \( \rho_{\text{int}}^\text{DM} \) denotes the energy density transfer from DE to DM. The rate of energy density exchange is also given by (Cai & Wang 2005; Amendola et al. 2007; He & Wang 2008; Valiviita et al. 2008; Jackson et al. 2009; Wang & Wang 2014; Kumar & Nunes 2016; Yang et al. 2017),

\[
Q = \frac{d\rho_{\text{int}}^\text{DM}}{dt},
\]

in which \( Q > 0 \) means that the direction of energy transfer is from DE to DM and for \( Q < 0 \) this direction is from DM to DE. The rate of energy density exchange is proportional to the DM density energy, i.e., \( Q = \eta H \rho_{\text{DM}} \) (Cai & Wang 2005; Amendola et al. 2007; He & Wang 2008; Wang & Wang 2014; Kumar & Nunes 2016; Yang et al. 2017). The parameter \( \eta \) determines the coupling between dark sectors or the strength of the interaction between DM and DE. This parameter characterizes the degree of the deviation from the noninteracting DE and DM. The value \( \eta = 0 \) presents the noninteracting case. In addition, \( H \) is the Hubble parameter.

One of the important attempts in studying the DM–DE interaction is constraining the value of \( \eta \) using the observational data. In the present work, we apply the constrained value of the coupling parameter in the interacting dark energy model using the observational data (Yang et al. 2017), including the cosmic chronometer data, the latest estimation of the local Hubble parameter value, the joint light curves sample, the BAO distance measurement data set, and the CMB data from Planck 2015 measurements.

2.2. Linear Growth of Density Perturbation

We start from the Friedmann equations (applying the units with \( c = 1 \))

\[
a^2 + k = \frac{8\pi G}{3} \rho a^2,
\]

\[
a^2 + k + 2\ddot{a} = -8\pi G P a^2.
\]

Here, the total energy density, \( \rho \), is given by the matter energy density, \( \rho_{\text{M}} \), radiation energy density, \( \rho_{\text{R}} \), and DE density, \( \rho_{\text{DE}} \), i.e., \( \rho = \rho_{\text{M}} + \rho_{\text{R}} + \rho_{\text{DE}} \). Moreover, the total pressure, \( P \), is related to the matter pressure, \( P_{\text{M}} \), radiation pressure, \( P_{\text{R}} \), and DE pressure, \( P_{\text{DE}} \), by \( P = P_{\text{M}} + P_{\text{R}} + P_{\text{DE}} \). In addition, \( k = -1, 0 \), and 1 for an open, flat, and closed universe, respectively. In the present work, we neglect the matter pressure, i.e., \( P_{\text{M}} = 0 \), and apply the radiation EOS \( P_{\text{R}} = \frac{1}{3} \rho_{\text{R}} \). Additionally, the DE EOS is considered as \( P_{\text{DE}} = w_{\text{DE}}(z) \rho_{\text{DE}} \), with two different DE parameterizations as follows:

\[
w_{\text{DE}}(z) = -1.0,
\]
In the equations, the redshift $z$ is related to the scale factor by $a = (1 + z)^{-1}$. The first model is $\Lambda$CDM and the second one is a generalized evolving equation of state (EOS; Barboza et al. 2009). Here, we consider the values of $w_0$, $w_f$, and $\beta$ obtained in the interacting DE model (Yang et al. 2017) constrained using the observational data (i.e., $w_0 = -0.944$, $w_f = -0.419$, and $\beta = 0.350$). It should be noted that in the following calculations we apply the $w_{DE1}$ for the DE EOS of noninteracting DE model and the $w_{DE2}$ for the DE EOS of an interacting DE model.

The linear growth of the matter density perturbation, $D(a) = \delta \rho_M/\rho_M$, is as follows (Bonnor 1957; Heath 1977; Percival 2005; Lee & Park 2009)

$$D(a) = \frac{5\Omega_M E(a)}{2} \int_0^a \frac{da'}{[a'E(a')]^2}. \quad (6)$$

In the above equation, $E(a) = H/H_0$. In a spatially flat universe in which $k = 0$ and for the case of noninteracting DM and DE, the function $E(a)$ is given by (Percival 2005; Lee & Park 2009)

$$E_N(a) = [\Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_{DE} a^{f(a)}]/2, \quad (7)$$

where $\Omega_R$, $\Omega_M$, and $\Omega_{DE} = 1 - \Omega_M - \Omega_R$ are the radiation, matter, and DE density parameter at the present time and $f(a)$ is as follows:

$$f(a) = -\frac{3}{\ln a} \int_0^{\ln a} [1 + w(a')] d\ln a'. \quad (8)$$

However, in the present work, we are interested in the linear growth factor taking the DM–DE interaction into account. In the case of interacting dark sectors, the function $E(z)$ has the following form (Yang et al. 2017):

$$E_I(z) = [\Omega_R (1 + z)^4 + \Omega_B (1 + z)^3 + \Omega_{DM} (1 + z)^{3-\eta}] + \frac{(1 + z)^3}{g(z)} I(z)]^{1/2}. \quad (9)$$

Here, $\Omega_B$ and $\Omega_{DM} = \Omega_M - \Omega_B$ are the baryonic matter and DM density parameters at the present time. Moreover,

$$g(z) = \exp \left(- \frac{3}{2} \int \frac{w_{DE}(z)}{1 + z} dz. \quad (10)$$

and

$$I(z) = \Omega_{DE,E}(0) + \eta \Omega_{DM} \int_0^z (1 + z)^{-1-\eta} g(z) dz. \quad (11)$$

Figure 1 presents the linear growth factor for the cases of noninteracting and interacting dark sectors. The values of different parameters in the linear growth factor are $\Omega_R = 8.6 \times 10^{-5}$ and $\Omega_M = 0.276$ for the noninteracting case and $\Omega_R = 8.6 \times 10^{-5}$, $\Omega_B h^2 = 0.02240$, $\Omega_{DM} h^2 = 0.1259$, $\eta = 0.00378$, and $h = 0.704$ (Yang et al. 2017) for the interacting case. The linear growth factor decreases with the redshift for both noninteracting and interacting dark sectors. The DM–DE interaction enhances the linear growth factor. This shows that the energy transferring from DE to DM increases the growth of matter density perturbation. The effects of the DM–DE interaction on $D(z)$ are more significant at lower values of the redshift.
where $\mu$ and $\nu$ are the void’s oblateness and sphericity, respectively. $R_L$ denotes the Lagrangian void scale and $\delta_v$ is the density contrast threshold for the formation of a void. Moreover, $\lambda_1$ and $\lambda_2$ are the eigenvalues of the local tidal shear tensor (Bos et al. 2012; Rezaei 2019). $\sigma(z, R_L)$, which is called the linear rms fluctuation of the matter density field smoothed on a Lagrangian void scale of $R_L$ at redshift $z$, is given by (Lee & Park 2009; Chongchitnan & Silk 2010; Bos et al. 2012)

$$\sigma^2(z, R_L) = D^2(z) \int_0^\infty \frac{k^2}{2\pi^2} P(k) W^2(kR_L) dk.$$  \hspace{1cm} (13)

Here, the linear growth of density perturbation, $D(z)$ was introduced in Equations (6), (7), and (9) for noninteracting and interacting dark sectors. $W(kR_L)$, the spherical top-hat function of radius $R_L$, has the following form:

$$W(kR_L) = 3 \left[ \sin(kR_L) \over (kR_L)^3 - \cos(kR_L) \over (kR_L)^2 \right].$$  \hspace{1cm} (14)

Additionally, $P(k)$ is the linear matter power spectrum today and depends on the matter transfer function $T(x)$ (Weinberg 2008; Chongchitnan & Silk 2010). The standard linear matter power spectrum considered is

$$P(k) = AkT^2(x).$$  \hspace{1cm} (15)

In the above equation, the coefficient $A$ should be calculated with the condition $\sigma(R_L = 8 h^{-1} \text{ Mpc}) = \sigma_8$. The cosmological parameters related to the noninteracting and interacting cases are considered to calculate the linear matter power spectrum in these two models. Additionally, the values of $\sigma_8$ and $H_0$ that have been applied in this work are $\sigma_8 = 0.776$ and $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the noninteracting case and $\sigma_8 = 0.840$ and $H_0 = 68.13 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the interacting one (Yang et al. 2017).

The probability-density distribution for the ellipticity of cosmic voids considering noninteracting and interacting models is plotted in Figure 2. We have set the void density contrast as $\delta_v = -0.9$. The probability-density distribution in the interacting model is shifted toward higher values of the ellipticity compared to the noninteracting one. Thus, when the energy transfers from DE to DM, the cosmic voids are less spherical. The DE-DM coupling leads to higher values of the ellipticity of cosmic voids.

4. Results

In this section, we report our results regarding the shape of cosmic voids in the interacting cosmological model. The dependency of the ellipticity of cosmic voids on the redshift as well as the void scale are explained. We also compare the results in the interacting model with those in the $\Lambda$CDM one.

4.1. Mean Ellipticity and Maximum Ellipticity of Cosmic Voids: Redshift Dependency

The mean ellipticity of cosmic voids that can be obtained using the probability-density distribution (Lee & Park 2009),

$$\langle \varepsilon \rangle = \int_0^1 \varepsilon p(\varepsilon; R_L, z) d\varepsilon,$$  \hspace{1cm} (16)

depends on the redshift, void scale, and the coupling between dark sectors. Moreover, the probability-density distribution has a maximum value at a certain value of the ellipticity called the maximum ellipticity, presented by $\varepsilon_{\text{max}}$, which is also affected by the redshift, void scale, and DE-DM coupling. Figure 3 presents the values of $\langle \varepsilon \rangle$ and $\varepsilon_{\text{max}}$ versus the redshift. Both $\langle \varepsilon \rangle$ and $\varepsilon_{\text{max}}$ reduce as the redshift increases, in agreement with the results of $N$-body simulations of structure formation in dynamical DE cosmologies (Bos et al. 2012). Considering the interacting model, $\langle \varepsilon \rangle$ and $\varepsilon_{\text{max}}$ show higher values at each redshift. In fact, the mean ellipticity of cosmic voids in the interacting model is affected by the level of clustering, i.e., $\sigma_8$. This result has also been confirmed by $N$-body simulations in dynamical DE cosmologies (Bos et al. 2012). A strong correlation between $\sigma_8$ and mean ellipticity has been predicted in $N$-body simulations of structure formation (Bos et al. 2012).
4.2. Mean Ellipticity and Maximum Ellipticity of Cosmic Voids: Scale Dependency

Figure 4 indicates that $\langle \varepsilon \rangle$ and $\varepsilon_{\text{max}}$ depend on the Lagrangian void scale, $R_L$. Considering both noninteracting and interacting models, $\langle \varepsilon \rangle$ and $\varepsilon_{\text{max}}$ have an oscillatory behavior with the variation of the void scale. This behavior occurs long with an overall reduction of $\langle \varepsilon \rangle$ and $\varepsilon_{\text{max}}$ with the higher values of the void scale. Our results verify that at each value of $R_L$, DM–DE interaction increases the values of $\langle \varepsilon \rangle$ and $\varepsilon_{\text{max}}$. According to high-resolution hydrodynamical N-body simulations of coupled DE cosmologies, cosmic voids with coupled DE are also emptier and contain less neutral hydrogen compared to the $\Lambda$CDM one (Baldi & Viel 2010), which effectively alleviates the tensions between simulations and observations in voids.

5. Summary and Conclusions

The evolving DE model constrained by the observational data has been employed to explore the ellipticity of cosmic voids in the presence of DM and DE interaction. This interacting model is based on observational data (cosmic chronometer data, the CMB data from Planck 2015 measurements) leads to higher values of the linear growth factor compared to the noninteracting one. DM–DE interaction shifts the probability-density distribution toward greater values of ellipticity. Our results confirm that the mean and maximum ellipticity of cosmic voids in the interacting model are larger compared to the noninteracting one.

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