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Behavior of interacting Ricci dark energy in logarithmic $f(T)$ gravity

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Abstract

In the present work, we have considered a modified gravity model dubbed as 'logarithmic $f(T)$ gravity' as reported by Bamba et al. (J. Cosmol. Astropart. Phys 1101:21, 2011) and investigated the behavior of Ricci dark energy interacting with pressureless Dark Matter. We have chosen the interaction term in the form $Q = 3H\delta\rho_m$ and investigated the behavior of the Hubble parameter H as a function of the redshift z. For this reconstructed H, we have investigated the behavior of the fractional density contribution due to the Ricci dark energy and torsion. Subsequently, we investigated the equation of state parameter w_{RDE} which is found to have a phantom-like behavior for all choices of c^2 in the Ricci dark energy density.

Keywords: Logarithmic $f(T)$ gravity; Ricci dark energy; Dark Matter (DM)

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Background

The accelerated expansion of the universe is well established by the works of [1,2]. The 'dark energy' (DE), characterized by negative pressure, is responsible for this cosmic acceleration [3-6]. The importance of modified gravity for late acceleration of the universe has been reviewed by [7,8]. Various modified gravity theories have been proposed so far. These include $f(R)$ [9,10], $f(T)$ [11-14], $f(G)$ [15,16], Hořava-Lifshitz [17,18], and Gauss-Bonnet [19,20] theories. One of the newest extended theories of gravity is the so-called $f(T)$ gravity, which is a theory formulated in a spacetime possessing absolute parallelism [12]. Some fundamental aspects of $f(T)$ theories have been studied in the works of [21] and [22]. In this theory of modified gravity, the teleparallel Lagrangian density described by the torsion scalar T has been promoted to be a function of T, i.e., $f(T)$, in order to account for the late time cosmic acceleration [23,24]. Some relevant works in $f(T)$ theory must be mentioned here. Jamil et al. [25] derived the exact solutions of static wormholes in $f(T)$ modified gravity theory. Jamil et al. [26] investigated the null, weak, strong, and dominant energy conditions in generalized teleparallel gravities. Jamil et al. [27] studied the statefinder parameters $\{r, s\}$ in $f(T)$ cosmology. Jamil et al. [28] studied the Noether symmetries of $f(T)$ cosmology involving matter and DE. Jamil et al. [29] tried to resolve the Dark Matter (DM) problem in the light of $f(T)$ modified gravity theory, successfully obtaining the flat rotation curves of galaxies containing DM as component. They also obtained the density profile of Dark Matter in galaxies. Jamil et al. [30] studied the interacting DE model in the framework of $f(T)$ modified gravity theory for a particular choice of $f(T)$. Bamba et al. [31] studied the generalized second law of thermodynamics in the framework of $f(T)$ modified gravity.

Models of DE include quintessence [32], quintom [33], phantom [34], Chaplygin gas [35], tachyon [36], h-essence [37], etc. Other relevant works on models of DE have been recently done. Setare [38] studied the interacting holographic dark energy (HDE) model in non-flat universe. Setare [39] studied the bulk brane interaction in order to obtain the equation of state (EoS) parameter for the HDE model in non-flat universe enclosed by the event horizon. Setare [40] studied the cosmological application of the HDE model in the framework of Brans-Dicke cosmology. Setare et al. [41] considered the HDE model in a non-flat universe from the viewpoint of statefinder parameters. All DE models can be classified according to the behavior of the equation of state parameter w_D as follow [33]: (1) Cosmological constant: its EoS parameter is exactly

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equal to −1, that is, $w_{\mathrm{DE}} = -1$; (2) Quintessence: its EoS parameter remains above the cosmological constant boundary, that is, $w_{\mathrm{DE}} \geq -1$; (3) Phantom: its EoS parameter lies below the cosmological constant boundary, that is, $w_{\mathrm{DE}} \leq -1$; and (4) Quintom: its EoS parameter is able to evolve across the cosmological constant boundary. Inspired by the holographic principle [42,43], a new model of DE, dubbed as Holographic DE (HDE), has been recently proposed and studied.

Recently, Gao et al. [44] proposed the Ricci scalar curvature as infrared cutoff of the system; this model is now known as Ricci dark energy (RDE) model. With a proper choice of parameters involved, the equation of state parameter of the RDE model can cross the value −1, so it has a quintom-like behavior [45]. We must remember here that the Ricci scalar curvature for a Friedmann-Robertson-Walker (FRW) universe is given by $R = -6\left(\dot{H} + 2H^2 + \frac{k}{a^2}\right)$, where H is the Hubble parameter, a is the scale factor, and k is the curvature parameter which can assume the values −1, 0, and +1 which yield, respectively, an open, a flat, and a closed FRW universe. The energy density of the RDE model can be written as $\rho_{\mathrm{RDE}} = 3c^2\left(\dot{H} + 2H^2 + \frac{k}{a^2}\right)$, where c^2 is a constant positive parameter. For a flat FRW universe, $k = 0$ and hence $\rho_{\mathrm{RDE}} = 3c^2\left(\dot{H} + 2H^2\right)$.

Interacting DE models have gained immense interest in recent times. Works in this direction include [46-51]. A remarkable work on the interacting DE in modified gravity is done by [52]. In a recent work, Jamil et al. [50] examined the interacting dark energy model in $f(T)$ cosmology assuming dark energy as a perfect fluid and choosing a specific cosmologically viable form $f(T) = \beta\sqrt{T}$. Interacting RDE was considered in [46], where the observational constraints on interacting RDE were investigated. In another recent work, Pasqua et al. [53] reconstructed the potential and the dynamics of the tachyon, K-essence, dilaton, and quintessence scalar field models according to the evolutionary behavior of the interacting logarithmic entropy-corrected holographic RDE model. Moreover, Pasqua et al. [54] also reconstructed the potential and the dynamics of the some scalar field models like tachyon, K-essence, dilaton, quintessence, and Modified Chaplygin Gas according to the evolutionary behavior of the interacting power-law entropy-corrected holographic RDE model. Pasqua [55] reconstructed the potential and the dynamics of the some scalar field models for power-law and logarithmic entropy-corrected Ricci viscous dark energy. Jamil et al. [56] have considered a variable gravitational constant G in flat FRW universe filled with the mixture of DE, DM, and radiation, and they derived some information on the deceleration parameter q and the statefinder parameters $\{r, s\}$. The statefinder parameters have been calculated in two particular cases: (1) pressure p is constant and (2) pressure p is variable. Jamil et al. [57] investigated the behavior of DE interacting with DM and unparticle in the framework of loop quantum cosmology for four toy models. They found that there are only two attractor solutions, i.e., DE-dominated and DM-dominated universe. The other two models, instead, are unstable, since they predict either a DE-filled Universe or an Universe totally devoid of it. Farooq et al. [58] studied phantom energy interacting with variable modified Chaplygin gas and new modified Chaplygin gas, and they also reconstruct potentials for these models. Sheykhi et al. [59] studied some cosmological applications of the interacting HDE model in the framework of Brans-Dicke cosmology with chameleon scalar field non-minimally coupled to the matter field. Jamil [60] calculated the varying G correction to the statefinder parameters for different models of DE, i.e., interacting DE model, HDE model, New Agegraphic dark energy model, and the generalized Chaplygin gas model. In the present work, we have considered an interacting RDE in the 'logarithmic $f(T)$ gravity' proposed by [61]. In the said form of $f(T)$ gravity, the form of $f(T)$ is proposed as $f(T) = \beta T_0 \left(\frac{\alpha T_0}{T}\right)^{-1/2} \ln\left(\frac{\alpha T_0}{T}\right)$, where α is a positive constant and $\beta = \frac{1-\Omega_m^{(0)}}{2\alpha^{-1/2}}$, with $\Omega_m^{(0)}$ being the present day value of Ω_m and T_0 the present day value of T.

This logarithmic $f(T)$ gravity model is basically constructed on a phenomenological approach. Therefore, the motivation to examine this model is that if we consider the interaction between the Ricci dark energy and Dark Matter in this model, we can obtain some desirable cosmological consequence.

The paper is organized as follow. In the "An overview of $f(T)$ gravity" section, we give an overview of $f(T)$ modified gravity theory. In the "Interacting RDE" section, we describe the main features of the interacting RDE model. In the "Discussion" section, we discuss the results obtained. Finally, in the "Concluding remarks" section, we write the conclusions of this work.

An overview of $f(T)$ gravity

In the framework of $f(T)$ theory, the action I of modified TG is given by [24]

$$I = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[f(T) + L_m\right], \tag{1}$$

where L_{m} is the Lagrangian density of the matter inside the universe, g is the determinant of the metric tensor $g^{\mu\nu}$, and G is the Newton's gravitational constant. We here consider a flat FRW universe filled with the pressureless matter. In units of $8\pi G = 1$, the modified Friedmann equations in the framework of the $f(T)$ modified gravity theory are given by [12,24]

$$H^2 = \frac{1}{3}\left(\rho + \rho_T\right) \tag{2}$$

$$2\dot{H} + 3H^2 = -(p + p_T) \tag{3}$$

where

$$\rho_T = \frac{1}{2}(2T f_T - f - T) \tag{4}$$

$$p_T = -\frac{1}{2}\left[-8\dot{H}T f_{TT} + (2T - 4\dot{H})f_T - f + 4\dot{H} - T\right] \tag{5}$$

with [12]

$$T = -6\left(H^2\right). \tag{6}$$

In Equations (4) and (5), we have that f_T and f_{TT} are, respectively, the first and the second derivative of $f(T)$ with respect to T and the overdot indicates a derivative with respect to the cosmic time t.

As we are considering interaction between pressureless Dark Matter and RDE, we have $\rho = \rho_m + \rho_{\mathrm{RDE}}$ and $p = p_{\mathrm{RDE}}$ in Equations (2) and (3). As stated before, in the logarithmic $f(T)$ modified gravity theory, we have [61]

$$f(T) = \beta T_0 \left(\frac{\alpha T_0}{T}\right)^{-1/2} \ln\left(\frac{\alpha T_0}{T}\right), \tag{7}$$

where $\beta = \frac{1-\Omega_m^{(0)}}{2\alpha^{-1/2}}$ and α is a positive constant. In [61], Bamba et al. have shown that for the form of $f(T)$ gravity considered, the EoS parameter w stays above -1 when plotted against redshift z. In the present work, we shall investigate the behavior of the EoS parameter when interacting RDE is considered in the said form of modified gravity. In the next section, we shall briefly describe the mathematical background of the RDE model.

Interacting RDE

The metric of a spatially flat, homogeneous, and isotropic universe in FRW model is given by

$$ds^2 = dt^2 - a^2(t)\left[dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right], \tag{8}$$

where $a(t)$ is the scale factor, t indicates the cosmic time, r represents the radial component, and (θ, ϕ) are the angular coordinates of the metric. The conservation equation is given by

$$\dot{\rho} + 3H(\rho + p) = 0. \tag{9}$$

As we are considering interaction between RDE and Dark Matter, the conservation equation will take the following form

$$\dot{\rho}_{\mathrm{total}} + 3H(\rho_{\mathrm{total}} + p_{\mathrm{total}}) = 0, \tag{10}$$

where $\rho_{\mathrm{total}} = \rho_{\mathrm{RDE}} + \rho_m$ and $p_{\mathrm{total}} = p_{\mathrm{RDE}}$ (as we are considering pressureless Dark Matter, $p_m = 0$). It is already stated that [44]

$$\rho_{\mathrm{RDE}} = 3c^2\left(\dot{H} + 2H^2\right). \tag{11}$$

Since in the case of interaction, the components do not satisfy the conservation equation separately, we need to reconstruct the conservation equation by introducing an interaction term Q. Considering the interaction term Q as $Q = 3H\delta\rho_m$ [62-64], where δ is the interaction parameter (which gives indication on the strength of the interaction), the conservation equation takes the form

$$\dot{\rho}_{\mathrm{RDE}} + 3H(\rho_{\mathrm{RDE}} + p_{\mathrm{RDE}}) = 3H\delta\rho_m \tag{12}$$

and

$$\dot{\rho}_m + 3H\rho_m = -3H\delta\rho_m. \tag{13}$$

In the following section, we shall discuss the behaviors of the various cosmological parameters when the interacting RDE is considered in the framework oflogarithmic $f(T)$ modified gravity theory.

Discussion

Solving conservation Equation (13), we get under interaction

$$\rho_m = \rho_{m0}a^{-3(1+\delta)}. \tag{14}$$

Using Equations (6) and (7), we get ρ_T from Equation (4), and then, we use it in Equation (2) along with Equation (14), obtaining the following differential equation

$$c^2\dot{H} + \frac{1}{3}a^{-3(1+\delta)}\rho_{m0} + 2H^2\left(c^2 + \frac{\beta H_0}{\sqrt{\alpha}H}\right) = 0. \tag{15}$$

From Equation (15), we get the new expression of H (which is denoted by $\tilde{H}$) under the said interaction considered in logarithmic $f(T)$ gravity and we plot against redshift $z = a^{-1} - 1$ in Figure 1 for three different conditions of c^2, i.e., $c^2 < 0.5$, $= 0.5$, and > 0.5. The three cases are indicated by solid, dashed, and dotted lines, respectively. Following [61], we take $\Omega_m^{(0)} = 0.26$ while plotting $\tilde{H}$. As we go from higher to lower redshifts, we observe that the reconstructed Hubble parameter $\tilde{H}(z)$ is exhibiting a decaying pattern. The rate of decay is sharper in the case of $c^2 < 0.5$ than the other two cases. To view the behavior of the logarithmic $f(T)$, we have plotted it against z in Figure 2. The plot is based on the solution given in Equation (15) used in Equations (6) and (7). We observed that $f(T)$ is exhibiting similar decaying pattern to that of the Hubble parameter. In Figure 3, we plot the magnitude of torsion as a function of redshift z. We observe that with the evolution of the universe, the magnitude of the torsion is decaying from higher to lower redshifts.

In Figure 4, we have plotted the sum of the fractional densities contributed by the torsion and the Ricci dark energy, i.e., $\Omega_T + \Omega_{\mathrm{RDE}} = \frac{\rho_T}{3\tilde{H}^2} + \frac{\rho_{\mathrm{RDE}}}{3\tilde{H}^2}$ under the interaction in the proposed model of $f(T)$ gravity. We observe that, for all the choices of c^2 made, the quantity $\Omega_T + \Omega_{\mathrm{RDE}}$ increases with the evolution of the universe. However, Figure 5 shows that the density contribution due to torsion is decaying with the evolution of the universe and

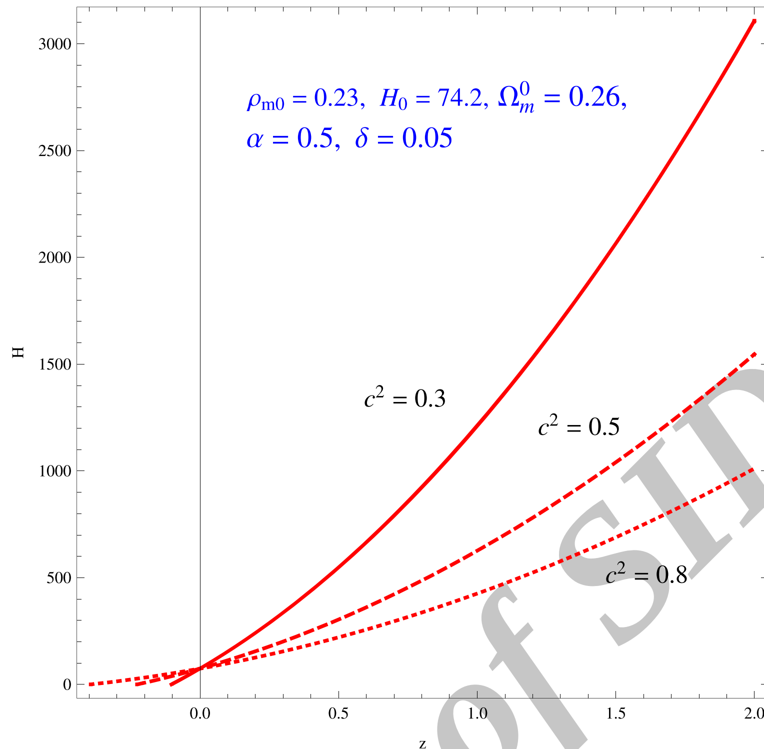

Figure 1 This figure plots the reconstructed Hubble parameter $\tilde{H}$ (based on Equation (15)) for interacting RDE under logarithmic $f(T)$ gravity. We have taken $\Omega_m^0 = 0.26$ and $\delta = 0.05$.

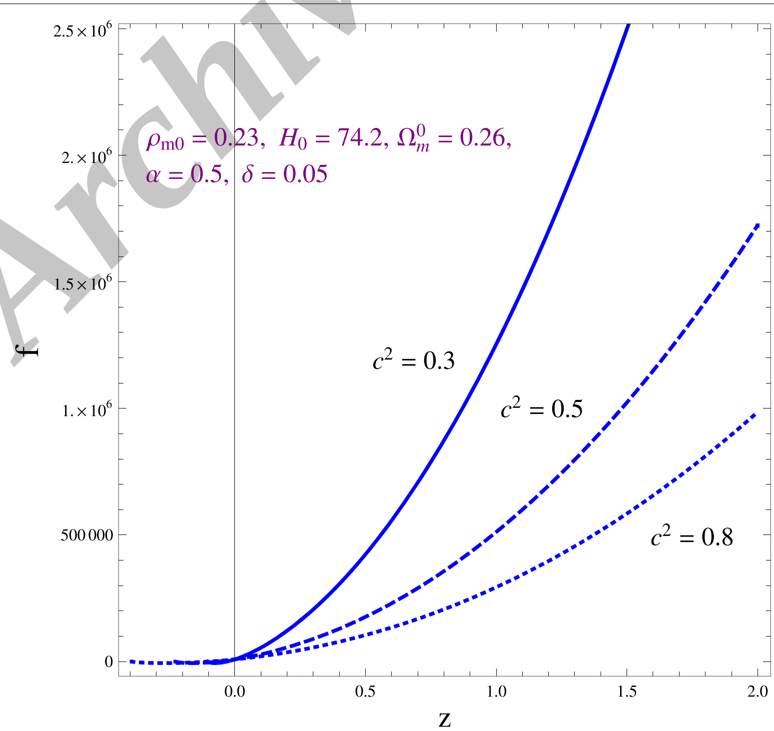

Figure 2 This figure plots the $f(T)$ (using solution of Equation (15) in Equations (6) and (7)) against redshift z. We have taken $\Omega_m^0 = 0.26$ and $\delta = 0.05$.

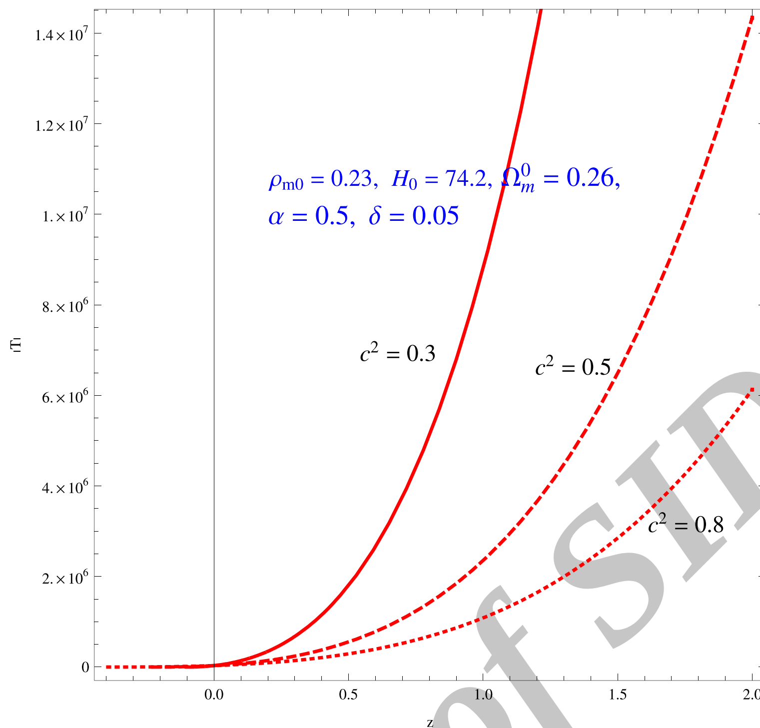

Figure 3 This figure plots the magnitude of torsion $|T|$ (using solution of Equation (15) in Equation (6)) against redshift z. We have taken $\Omega_m^0 = 0.26$ and $\delta = 0.05$.

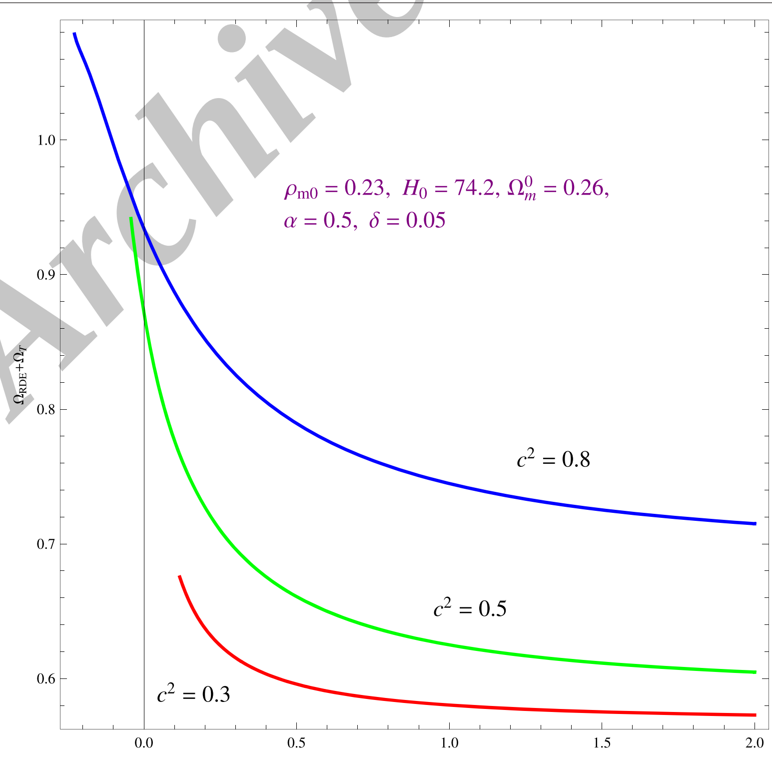

Figure 4 This figure plots the $\frac{\rho_{RDE}+\rho_T}{3\tilde{H}^2}$ against redshift z. Here, $\tilde{H}$ is the reconstructed Hubble parameter. We have taken $\Omega_m^0 = 0.26$ and $\delta = 0.05$. The red, green, and blue lines correspond to $c^2 < 0.5$, $= 0.5$, and > 0.5, respectively.

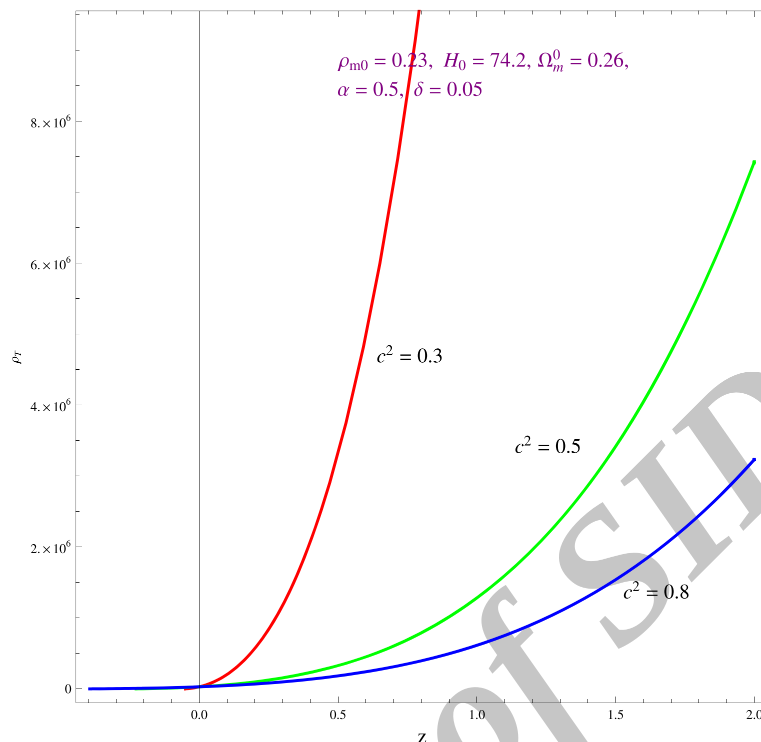

Figure 5 This figure plots the density contribution due to torsion, i.e., ρ_T against redshift *z*. We have taken $\Omega_m^0 = 0.26$ and $\delta = 0.05$. The red, green, and blue lines correspond to $c^2 < 0.5$, $= 0.5$, and > 0.5, respectively.

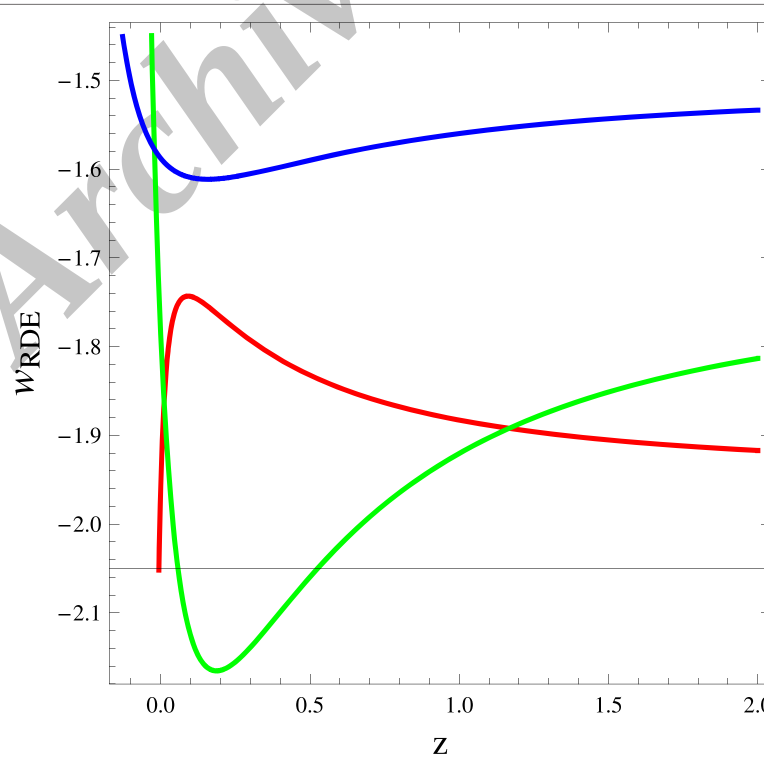

Figure 6 Evolution of w_{RDE} with redshift *z*. The red, green, and blue lines correspond to $c^2 < 0.5$, $= 0.5$, and > 0.5, respectively.

tending to 0 in very late universe. Hence, we understand that the density contribution of Ricci dark energy is growing significantly with the evolution of the universe. This is consistent with the fact that the universe has evolved from matter-dominated to DE-dominated phase. In Figure 6, we plot the equation of state parameter w_{RDE} for different values of c^2 and the red, green, and blue lines correspond to $c^2 < 0.5$, $= 0.5$, and > 0.5, respectively. In all cases, we observe that $w_{\mathrm{RDE}} < -1$, which indicates a phantom-like behavior [33].

Concluding remarks

In the present work, we have considered a modified gravity model dubbed as 'logarithmic $f(T)$ gravity,' and we investigated the behavior of Ricci dark energy model interacting with pressureless Dark Matter. We have chosen the interaction term in the form $Q = 3H\delta\rho_m$, and we investigated the behavior of the Hubble parameter H as a function of the redshift z. For this reconstructed H, we have investigated the behavior of the density of the Ricci dark energy ρ_{RDE} and density contribution due to torsion ρ_T. All the said cosmological parameters have a decaying behavior going from higher to lower redshifts for all values of c^2 considered in this work. However, the sum of the fractional densities of the Ricci dark energy model and of the torsion is observed to have an increasing pattern, which indicates a transition from matter dominated to dark energy-dominated universe. Subsequently, we studied the equation of state (EoS) parameter w_{RDE} in this situation. In [61], which is the main motivation behind this study, the logarithmic $f(T)$ gravity was found not crossing the phantom-divide line. In the present paper, we considered interacting Ricci dark energy in the said form of gravity, and we found too that the phantom-divide line crossing cannot be realized. Rather, w_{RDE} is found to stay below -1 which indicates a phantom-like behavior. In [65], it was reported that the Ricci dark energy has a phantom-like behavior in Einstein gravity for $c^2 < 0.5$. However, in the present work, the equation of state parameter shows a phantom-like behavior for all choices of c^2 we made.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
The original problem was conceived by RG and SC. AP took active role in some calculations and plots. The manuscript has been finalized jointly by RG, SC, and AP. All authors read and approved the final manuscript.

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