The cosmological behaviour and the statefinder diagnosis for the New Tsallis agegraphic dark energy

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In this work, we have considered the recently proposed new Tsallis Agegraphic Dark Energy model (NTADE) (Mod. Phys. Lett. A 34, 1950086, 2019) within the framework of a flat Friedmann-Robertson-Walker (FRW) Universe by taking various values of the parameter δ. The NTADE model shows the current phase transition of the Universe from decelerated to accelerated phase. The NTADE EoS parameter shows a rich behaviour as it can be quintessence-like or phantom-like depending on the value of δ. For discriminating the NTADE model from ΛCDM, we have plotted the statefinder parameters r(z), s(z) and (r, s), (r, q) pair. The NTADE model shows distinct evolutionary trajectories of their evolution in (r, s) and (r, q) plane. An analysis using the snap parameter and the ωD − ωD pair dynamical analysis have also been performed.

I. INTRODUCTION

According to a sequence of past and latest observational data [1–6], the dark sector of our Universe is filled with two dark fluids, namely the dark energy (DE) and dark matter (DM). The former fluid drives the current accelerating stage of the Universe while the later i.e. DM is responsible for the structure formation of the Universe. It is also observed from the observational data that about ninety six percent of the total energy density of the Universe is coming from this combine dark component where in particular, the contribution of DE is around sixty eight percent of the total energy allocation of the Universe while the DM contributes approximately twenty eight percent of the total energy allocation of the Universe. Although, the origin, evolution and the characteristics of these dark sector of the DE are not distinctly recognized yet. However, the nature of DM appears to be partially known by indirect gravitational effects, although, the DE has endured being exceptionally mysterious. As a consequence, in the last couple of years, various cosmological models have been considered to be the simplest model leading to two independent evolution of these dark components where DE and DM are conserved separately. While a more generalized form of the cosmological models are available in which DE and DM are permitted to interact with each other [7–12].

To describe the accelerated expansion of the cosmos motivated by holographic principle [13–10], M. Li suggested holographic dark energy (HDE) where IR cutoff was taken care by future event horizon [17]. After that Agegraphic dark energy (ADE) model was suggested by Cai by taking length measure as the age of the Universe [18]. Furthermore, by considering conformal time as a time scale, Wei and Cai suggested the New agegraphic dark energy (NADE) model [19]. ADE models gained a lot of interest after the proposal and its cosmological consequences were investigated with observational constraints [20, 21]. Different entropies are also used for the investigation of the cosmological and gravitational scenario. Firstly, it has been shown that differences between Tsallis and Bekenstein entropies can describe DE, modify Friedmann equations, and even make a bridge between Verlinde and Padmanabhan approaches of emergent gravity [22]. Recently, three new form of dark energy models namely, the Tsallis holographic dark energy (THDE) [23], the Rényi holographic dark energy (RHDE) [24] and the Sharma- Mittal holographic dark energy (SMHDE) [25] are proposed based on holographic principle and generalized entropy formalism [26–32]. These models of holographic dark energy can be used to clarify or explain the cosmic acceleration of the universe [33, 34]. The Friedmann equations has been derived by using the Tsallis entropy considering the apparent horizon as IR cut off in FRW Universe, to describe the Universe dynamics [43]. Furthermore, to explain the evolution of the FRW Universe, the Friedmann equations get modified for large-scale gravitational systems using the non-extensive Tsallis entropy on the relativistic cosmology background [44].

Recently, the authors proposed a new DE model called Tsallis agegraphic dark energy (TADE) with time scale as IR cut-off and new Tsallis agegraphic dark energy (NTADE) with the conformal time as system IR cut-offs [35]. The cosmological parameters such as the deceleration parameter q, the energy density parameter ΩD, the equation of state parameter (EoS) ωD and squared sound speed v_s² are investigated to study the evolution of the Universe filled with the TADE and the pressure-less DM. in [35]. They proposed that the late time acceleration of the Universe can be observed by the TADE and

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NTADE models with and without interaction. Now, modified gravity also became a necessary component of theoretical cosmology. To explain the qualitative transformation of the gravitational interaction in the very early and/or very late Universe, it is aimed as a generalization of general relativity. Appropriately, nowadays modified gravity may not only represent the late-time acceleration and early-time inflation but also introduce the unified consistent classification of the Universe evolution eras series: inflation, matter/radiation, and DE dominance (For a more recent review see [46]). In this viewpoint, recently, Zadeh investigated the cosmological consequences of the NTADE models with and without interaction in some of the modified gravity for example, modified Chern-Simons gravity [47], Horava-Lifshitz cosmology [48], and flat Fractal Cosmology [49].

As discussed above, the DE phenomenon can be analyzed by a large number of models. Hence, it is very important to differentiate among these DE models. To achieve this, statefinder pair $(r; s)$ was proposed in [50, 51], which is a notable geometrical indicative to eliminate the degeneracy in the present value of Hubble parameter $H$ and the present value of the deceleration parameter $q$ of different dark energy models. Since $(r; s)$ plane has distinct evolutionary trajectories for different dark energy models. Hence, it is used extensively by researchers to discriminate among many modified theories of gravity and various models of dark energy in the literature. The statefinder pair $(r; s)$ [50] [51], are defined as

$$r = \frac{\ddot{a}}{aH^2}; \quad s = \frac{r - 1}{3(q - \frac{1}{2})},$$  \hspace{1cm} (1)

where $a$, $H$ and $q$, represent the scale factor, Hubble parameter and deceleration parameter, respectively.

After the proposal of statefinder diagnostic, firstly, the HDE models were discriminated from $\Lambda$CDM by Zhang [52] through this diagnostic for the different best fit values of constant $c$, which plays a very significant role in HDE models. In [53], Wei and Cai explored the ADE models with and without interaction through statefinder diagnostic and $\omega_D - \omega_D'$ pair and proposed that the ADE models can easily be discriminated from the $\Lambda$CDM model. Gao et al. proposed the Ricci dark energy (RDE) [54] model and it is explored through statefinder diagnostic by considering ricci scalar as Universe horizon in a flat FRW Universe [55]. In [56], the authors used this geometrical tool to make a classification and a discrimination about the modified polytropic Cardassian models.

In the DGP braneworld as well as the HDE in standard cosmology, the evolution of the deceleration parameter, EoS parameter and the statefinder parameters have been investigated considering both GO and Hubble horizon as IR cutoff in a flat FRW Universe [57]. For both proposed cutoff, they found that depending on the model parameters, the statefinder pair parameters $(r; s)$ become constant and restored those of $\Lambda$CDM model for the appropriate choice of the model parameters. The statefinder diagnostic has been applied in Palatini formalism on a series of $f(R)$ gravity models in a flat FRW Universe for series of the chosen model parameters to see if they distinguish from one another [58]. The statefinder diagnostic is a useful method for discriminating various DE models. The cosmological evolution and the geometrical behavior using the statefinder diagnostic of the interacting NADE model has been investigated in a flat FRW Universe [59] [60]. The polytropic gas DE models have been explored through the statefinder diagnostic and $(\omega_D, \omega_D')$ pair in a flat FRW Universe and proposed that these models mimic the standard LCDM model at the early time [61].

Recently, the THDE, RHDE and SMHDE models are investigated with and without interaction between DE and DM from the statefinder viewpoint for different values of the non-extensive parameter $\delta$ [62] [63]. A direct comparison has also been performed for these recently proposed DE models through statefinder diagnostic [64]. The statefinder parameters of the different DE models in non-flat FRW Universe have also been examined with and without interaction in [66] [70]. The statefinder parameter diagnostic is also used to discriminate various dark energy models such as the RDE, the new HDE, the new ADE and the standard HDE model [71].

Let us stress the similarity and difference of this work with other works. More recently, the TAEDE models are investigated considering the statefinder diagnostic and the $(\omega_D, \omega_D')$ pair with and without interaction in a flat FLRW Universe [72] [73], while they have not considered the new Tsallis agegraphic dark energy (NTADE) models. Therefore, in the present contribution, we shall investigate the cosmological behavior of the non-interacting new Tsallis agegraphic dark energy (NTADE) cosmological model and discriminate the NTADE model through the statefinder diagnostic and the $(\omega_D, \omega_D')$ pair. Also, the evolutionary trajectories the statefinder parameters are plotted by taking the NTADE energy density value $(\Omega_D^0, \Omega_D^0 = 0.70)$, in consideration of Planck 2018 results VI- LCDM cosmology [4].

The rest of the paper is organized as: the New Tsallis agegraphic Dark Energy and cosmological parameters such as deceleration parameter, the NTADE EoS parameter are discussed in Sec. II. To discuss the geometrical behavior of our model, we obtain statefinder parameters in Sec. III. Analysis of the $\omega_D - \omega_D'$ pair has been discussed in Sec.IV. At last in Sect. V, we finish up our outcomes.
II. NEW TSALLIS AGEGRAPHIC DARK ENERGY

For a flat FRW Universe filled with NTADE and pressure less fluid, the first Friedmann equation is written as

\[ H^2 = \frac{1}{3m_p^2} (\rho_m + \rho_D), \]  

(2)

where \( \rho_D \) is NTADE energy density and \( \rho_m \) is pressure less matter density. The fractional energy density is easily instigate by \( \Omega_n = \frac{\rho_n}{3m_p^2 H^2} \) for \( n = m \) and \( D \). Utilizing, this definition, the energy density parameter for matter and NTADE are \( \Omega_m = \frac{\rho_m}{3m_p^2 H^2} \) and \( \Omega_D = \frac{\rho_D}{3m_p^2 H^2} \), respectively. By putting the energy density parameter for matter and NTADE in Eq. (2), we will find \( \Omega_m = 1 - \Omega_D \) and the energy densities ratio \( \Omega_m/\Omega_D = r = 1 - \Omega_D \).

The conservation law for matter density and NTADE is defined as:

\[ \dot{\rho}_m + 3H \rho_m = 0, \]  

(3)

\[ \dot{\rho}_D + 3H \rho_D (1 + \omega_D) = 0. \]  

(4)

In this model, the conformal is characterized as \( dt = a \partial \eta \) prompting \( \dot{\eta} = \frac{1}{a} \) and accordingly

\[ \eta = \int_0^a \frac{da}{Ha^2}, \]  

(5)

and

\[ \rho_D = B\eta^{2\delta - 4}, \]  

(6)

where \( \eta = \left( \frac{3H\Omega_m}{H} \right)^{\frac{1}{2\delta - 4}} \). Using conservation equations given in Eq. (3) and Eq. (4), consolidating the derivative of Eq. (2) with time and using Eq. (6) and its time derivative, we get:

\[ \frac{\dot{H}}{H^2} = \frac{3}{2} (1 - \Omega_D) + \frac{(\delta - 2) \Omega_D}{a \eta H}, \]  

(7)

by Eq. (7), the deceleration parameter is

\[ q = -1 - \frac{\dot{H}}{H^2} = \frac{1}{2} - \frac{3}{2} \Omega_D - \frac{(\delta - 2) \Omega_D}{a \eta H}. \]  

(8)

By substituting Eq. (6) and its time derivative into Eq. (4) we find the EoS parameter as:

\[ \omega_D = -1 - \frac{2\delta - 4}{3a \eta H}. \]  

(9)

Using Eq. (6) and Eq. (7), we get the derivatives of energy density parameter

\[ \dot{\Omega}_D = \frac{(2\delta - 4) \Omega_D}{a \eta H} + 2 \Omega_D H (1 + q), \]  

(10)

\[ \Omega_D' = \frac{(2\delta - 4) \Omega_D}{a \eta H} + 2 \Omega_D (1 + q). \]  

(11)

Where, prime and dot give the derivative with respect to \( \log a \) and time respectively.

By using Eq. (9) and its time derivative we get the derivative of EoS parameter with respect to \( \log a \)

\[ \omega_D' = \frac{(2\delta - 4) \Omega_D}{3a \eta H} \left[ \frac{1 + (\delta - 2) \Omega_D}{a \eta H} - \frac{3}{2} (1 - \Omega_D) \right]. \]  

(12)

The evolutionary behavior of the deceleration parameter and EoS parameter is plotted for the NTADE model versus redshift \( z \) by finding its numerical solution using the initial values of \( \Omega_m \) as \( \Omega_{m0} = 0.30 \) and \( H_0 = 67 \).
The deceleration or acceleration of the Universe is described by the deceleration parameter $q$. The Universe is in accelerating or decelerating phase accordingly if $q < 0$ or $q > 0$, respectively. At present, it is seen that the Universe is accelerating with the goal that the estimation of the deceleration parameter lies in the range of $-1 \leq q < 0$. By Fig. 1, we observe the behavior of the deceleration parameter against redshift ($z$). It is clear through Fig. 1, that the NTADE model transits from an early decelerating phase to a present accelerated phase for distinct values of the parameter $\delta$ in both panels.

The modified cosmological scenario has been constructed by applying the first law of thermodynamics and using the Tsallis entropy that possess the usual one as a particular limit [74]. Moreover, Odinstov et al. [36], proposed this modified cosmological scenario with varying exponent $\delta$ by applying the non-extensive thermodynamics. Also, it is proposed that this modified cosmological scenario may deliver a description of both inflation and late-time acceleration of the Universe with varying-exponent from the first law of thermodynamics [36].
In Fig. 2 we depict the energy density for NTADE $\Omega_D$ and energy density of matter $\Omega_m$ as a function of redshift. From this figure, we can see that we obtain the usual thermal history of the universe, namely the successive sequence of matter and dark-energy epochs. It is also proposed by researchers that concerning the universe evolution at late times, the new terms that appear due to the non-extensive varying exponent constitute an effective dark energy sector [36, 40, 75, 76]. As we showed, the universe exhibits the usual thermal history, with the successive sequence of matter and dark-energy epochs, and with the transition to acceleration in agreement with the observed behavior.

The EoS parameter $\omega_D$ with respect to $z$ is plotted for different parameter $\delta$ in Fig. 3. From the upper panel of Fig. 3, we observe that the NTADE EoS parameter $\omega_D$ lies in the quintessence region, not crosses the phantom divide line and finally approaches the CC i.e. ($\omega_D = -1$) at the future for $\delta = 0.4, 0.6$ and 0.8. From the lower panel of Fig. 3, it is also clear that the NTADE EoS parameter $\omega_D$ lies in the phantom region, not crosses the phantom divide line and finally approaches the CC i.e. ($\omega_D = -1$) in the future for $\delta = 2.7, 2.8$ and 2.9. It is worth noting that the NTADE EoS parameter gives a nice behavior and it can be quintessence-like and phantom-like depending upon the different values of $\delta$. The similar behavior of the deceleration and the EoS parameter has also been observed in [36].

### III. NTDAE : STATEFINDER ANALYSIS

In this section, we discuss the NTDAE model without interaction through the statefinder and snap parameter analysis. From the definitions of Eq. 1, we may write

$$r = 1 + \frac{9}{2} \Omega_D \omega_D (1 + \omega_D) - \frac{3}{2} \omega_D^2 \Omega_D,$$  

$$s = (1 + \omega_D) - \frac{\omega_D'}{3 \omega_D}.$$  

In cosmology, the snap parameter is defined as [47]

$$A_4 = \frac{\ddot{a}}{aH^4}.$$  

Snap (the fourth order time derivative) is also sometimes called jounce [47]. This parameter appears in the fourth order term of the Taylor expansion of the scale factor around $a_0$, where the subscript 0 denotes the present-day value. The snap parameter $A_4$ can be expressed as elementary function of the the density parameter $\Omega_m$ [79].

$$A_4 = 1 - \frac{9}{2} \Omega_m.$$  

The different DE models can be discriminated against each other and from the $\Lambda$CDM model using first statefinder parameters $r$, second statefinder parameter $s$, $(r,s)$ plane and $(r,q)$ plane. Several dark energy models show distinct evolutionary trajectories of their evolution in $(r,s)$ and $(r,q)$ plane. Now, we use $r$ (first statefinder parameter), $s$ (second statefinder parameter), $(r,s)$ plane and $(r,q)$ plane to discriminate the NTDAE model for different values of the parameter $\delta$, while fixing other parameters according to the best-fit observational values. Also, an important purpose of any diagnostic is that it allows us to discriminate between a given DE model and the simpler of all models - $\Lambda$CDM. This is exactly done by the statefinder. The value of first statefinder parameter $r$ remains pegged at unity i.e. $r = 1$ for the $\Lambda$CDM model, even as the matter density evolves from a large initial value to a small late-time value. It is easy to show that $(r,s) = (1,0)$ is a fixed point for $\Lambda$CDM [50, 51].

The evolutionary trajectory of the statefinder pair $(s,r)$ for the NTDAE model is graphed in Fig. 4, for both the panels. From the upper panel of Fig. 4, we observe that the statefinder evolution trajectories start near the point $\{r = 0.7, s = 0.34\}$ and ends at the $\Lambda$CDM fixed point $(r = 1, s = 0)$. The statefinder analysis has also been performed for the HDE, THDE, ADE and RDE models by the authors in [40, 52, 53, 62]. The HDE, ADE and the THDE models have shown quite similar behavior in the $s - r$ plane to the NTDAE model without interaction, while the NTDAE model has different evolutionary behavior as compared to the RDE model in the $s - r$ plane [59]. The evolutionary trajectories of the lower panel of Fig. 4, evolve above the $r = 1$ and finally approaches to the $\Lambda$CDM fixed point.

In Fig. 5, we have plotted the evolutionary trajectories of the statefinder pair $(q - r)$ for the NTDAE model for both the panels. The fixed point $(q = 0.5, r = 1)$ presents the SCDM i.e. the matter dominated and $(q = -1, r = 1)$ presents the SS model i.e. de-Sitter universe, respectively. The evolutionary trajectories of the $(q - r)$ plane of the NTDAE model starts from the matter-dominated universe i.e. SCDM $(r = 1, q = 0.5)$ in the past and decreases monotonically and finally reaches to the de-Sitter expansion (SS) $(q = -1, r = 1)$ for different values of $\delta$ (upper panel). The evolutionary trajectories of the $(q,r)$ plane for $\delta = 0.8$ starts with another fixed point (upper panel). While the evolutionary trajectories of the lower panel are horizontal line segment approaching towards the de-Sitter expansion (SS) $(q = -1, r = 1)$ for different values of $\delta$. Expanding the scale factor to fourth order with respect to time is physically meaningful, since cosmological data already allow to measure the third-order term: the jerk parameter [79]. The snap parameter may be important for observations involving redshifts $z \sim 1$. and higher,
where the expansion of cosmological quantities in powers of $z$ cannot be limited only to linear and quadratic terms [80]. In [78], the authors proposed that $A_n$ parameters evolve with time with odd $A_{2n+1}$ (even $A_{2n}$) remaining larger (smaller) than unity. All $A_n$ parameters approach unity in the distant future. We have plotted the snap parameter $A_4$ against redshift $z$ in Fig. 6 for different $\delta$. It can be seen from Fig. 6, $A_4$ evolves from past to present and increases monotonically at the future. It is interesting to note that the snap parameter $A_4$ remains smaller than unity and approaches unity in the distant future: $A_4 \to 1$ when $z \to -1$.

In this section, we study the $\omega_D - \omega'_D$ pair dynamical analysis for the NTDAE model which is widely used in the previous works. The fixed point $\omega_D = -1$, $\omega'_D = 0$ denotes the standard ΛCDM in the $\omega_D - \omega'_D$ plot. The scopes of the DE quintessence model have been explored in [81] in the $\omega_D - \omega'_D$ plane. The dynamical property of other dark energy models have been utilized from $\omega_D - \omega'_D$ viewpoint [82–84].

The evolutionary trajectories of $\omega'_D$ and $\omega_D$ plane are plotted in Fig. 7 for the NTDAE model for different values of $\delta$ in the upper and lower panel. From the upper panel of Fig. 7, we observe that the evolutionary traject-
FIG. 6: Evolution of the snap parameter $A_4$ with respect to redshift $z$. Here $\Omega_m = 0.30$, $H(z = 0) = 67$ and $B = 3$.

FIG. 7: The diagram of $\omega_D - \omega_D'$ for without interaction NTADE for different model parameters $\delta$. Here $\Omega_m = 0.30$, $H(z = 0) = 67$ and $B = 3$

tories vary in quintessence $\omega > -1$ and finally attains to $\Lambda$CDM ($\omega = -1$). while in the lower panel of Fig. 7, the evolutionary trajectories vary in the phantom region $\omega > -1$ and finally attains to $\Lambda$CDM ($\omega = -1$). In both the panels, the phantom divide line is not crossed.

V. CLOSING REMARKS

In the present work, we have discusses New Tsallis Agegraphic dark energy model without interaction by taking various values of non-extensive parameter $\delta$ within framework of a flat FRW Universe. The main objective of this article is to distinguish the NTADE model from the $\Lambda$CDM model through statefinder diagnostic. We can

summarize our results as:
- We observe from the evolutionary behavior of the deceleration parameter $q$ that, it exhibits a transition from the early decelerated phase to late time accelerated phase.
- It can be observed that the NTADE EoS parameter shows a rich behaviour, it can be quintessence-like or phantom-like depending on the value of $\delta$.
- The evolutionary trajectory in $(s,r)$ plane of the NTADE model shows that it approaches the $\Lambda$CDM fixed point $(r = 1, s = 0)$ at the future.
- The evolutionary behavior of $(q,r)$ plane of the
The NTADE model indicates that it evolves from the matter dominated Universe i.e. SCDM \((r = 1, q = 0.5)\) in early time and approaches to the point \((q = -1, r = 1)\) i.e. the de Sitter expansion (SS) in the far future for various values of the parameter \(\delta\).

- We observe from the dynamical analysis \(\omega_D - \omega_{\rho_D}\) pair for the NTADE model that the evolution trajectories lie either in the quintessence region or phantom region depending on the value of the parameter \(\delta\).

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